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Preface

Scope and purpose

Semiconductor diode lasers have developed dramatically in the last decade as key components in a host of new applications, with optical fibre communications and data storage devices as the original and main driving forces behind the enormous progress in diode laser technologies. The increase of laser output power, accompanied by improved laser reliability and widened laser wavelength range in all single-emitter and multi-element emitter devices, gave rise to the penetration of diode lasers into other mass-markets and emerging applications, such as laser pumping, reprographics, data recording, displays, metrology, medical therapy, materials processing, sophisticated weaponry, and free-space communications. As a consequence, diode lasers continue to represent a high percentage of the worldwide commercial laser revenues, 51% of the \$6.4B in 2010 with 10% growth forecasted for 2011 (Laser Focus World, 2011)¹. Huge progress has been made in high power, single transverse mode lasers over recent years, followed by new applications and along with increased requirements for device engineering, reliability engineering and device diagnostics.

This book is a fully integrated novel approach, covering the three closely connected fields of diode laser engineering, reliability engineering and diagnostics in their development context, correlation and interdependence. It is exactly the blend of the underlying basic physics and practical realization, with its all-embracing, complementary issues and topics that has not been dealt with so far in the current book literature in this unique way. This includes practical, problem-related design guidelines as well as degradation-, reliability- and diagnostic-related aspects and issues for developing diode laser products operating in single transverse mode with high power and reliability. And it is this gap in the existing book literature, that is, the gap between device physics in the all-embracing context, and the practical issues of real device exploitation, which is going to be filled by the publication on hand. Research and practical experience gained in industry and higher level education have provided a lot of empirical evidence that the market is in need of a book to fill this gap.

¹ Laser Focus World, (2011). *Laser Markets - Annual Review and Forecast*: in *eNewsletter*, February 8, 2011

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The book provides a novel approach to the development of high power, single transverse mode, edge-emitting (in-plane) diode lasers, through addressing the complementary topics of device engineering (Part I), reliability engineering (Part II) and device diagnostics (Part III) in altogether nine chapters. Diode laser fundamentals and standard material, fabrication and packaging issues are discussed first. In a subsequent section a comprehensive and elaborate account is given on approaches and techniques for designing diode lasers, emitting high optical power in single transverse mode or diffraction limited beams. This is followed by a detailed treatment of the origins of laser degradation including catastrophic optical damage and an exploration of the engineering means to address for effective remedies and enhanced optical strength. The discussion covers also stability criteria of critical diode laser characteristics and key laser robustness factors. Clear design considerations are discussed in great detail in the context of reliability-related concepts and models, and along with typical programs for reliability tests and growth. A final extended third part of advanced diagnostic methods covers in depth and breadth, for the first time in book literature, functionality-impacting factors such as temperature, stress and material instabilities. It also presents the basics of those diagnostic approaches and techniques and discusses the diagnostic results in conjunction with laser product improvement procedures.

Main features

Among the main features characterizing this book are, that it is:

1. Providing a novel approach of high power, single transverse mode, in-plane diode laser development by addressing the three complementary areas of device engineering, reliability engineering and device diagnostics in the same book and thus closes the gap in the current book literature.
2. Addressing not only narrow stripe lasers, but also other single-element and multi-element diode laser devices, such as broad area lasers, unstable resonator lasers, tapered amplifier lasers, phase-locked coherent linear laser arrays and high power incoherent standard 1 cm laser bars, designed by applying the various known principles to achieve high power emission in a single transverse mode or diffraction-limited beam.
3. Furnishing comprehensive practical, problem-oriented guidelines and design considerations by taking into account also reliability related effects, key laser robustness factors, and functionality impacting factors such as temperature, stress and material instabilities, and dealing with issues of fabrication and packaging technologies.
4. Discussing for the first time in depth and breadth diagnostic investigations of diode lasers, and using the results for improving design, growth and processing of the laser device in the development phase.

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5. Covering in detail the basics of the diagnostic approaches and techniques, many of which pioneered by the author to be fit-for-purpose, and indicating the applicability of these techniques and approaches to other optical and electrical devices.
6. Demonstrating significance of correlations between laser operating characteristics and material parameters, and showing how to investigate and resolve effectively thermal management issues in laser cavities and mirrors.
7. Providing in-depth insight into laser degradation modes including catastrophic optical damage, and covering a wide range of concepts and technologies to increase the optical robustness of diode lasers.
8. Discussing extensively fundamental concepts and techniques of laser reliability engineering, and providing for the first time in a book details on setting up and operating a typical diode laser reliability test program used in industry for product qualification.
9. Representing an invaluable resource for professionals in industry and academia engaged in diode laser product R&D, for academics, teachers and post-graduates for higher educational purposes, and for interested undergraduates to gain first insights into the aspects and issues of diode laser technologies.
10. Featuring two hundred figures and tables illustrating numerous aspects of diode laser engineering, fabrication, packaging, reliability, performance, diagnostics and applications, and an extensive list of references to all addressed technical topics at the end of each of the nine chapters.

Addressed niche markets

The underlying synergetic laser development approach will make this much needed guidebook, a kind of vade mecum of high practical relevance, a great benefit to a broad worldwide readership in industry, higher education, and academic research. Professionals including, researchers and engineers in optoelectronics industries who work on the development of high quality, diode laser products, operating in single transverse mode with high optical output power and high reliability, will regard this book as an invaluable reference and essential source of information. The book will also be extremely useful for academics, teachers and post-graduates for higher educational purposes or satisfying their requirements, if they are just interested in gaining first insights into the aspects and issues associated with the optimization of these diode laser products.

Book context

The book is based primarily on the author's many years of extensive and complex experience in diode laser engineering, reliability and diagnostics. The author

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accumulated his highly specialized knowledge and skills in hands-on and managerial roles both in global and start-up companies in cutting-edge optoelectronics industries, including IBM, Hewlett-Packard, Agilent Technologies, and IBM/JDSU Laser Enterprise (today part of Oclaro) – starting in the early nineties with his decisive and formative collaboration, as core member of the Laser Enterprise team, the spin-out of IBM Research, pioneering and commercializing its pre-eminent 980-nm pump laser technology for applications in terrestrial and submarine optical communications networks.

The inspiration to write exactly this book has come from the author's extensive semiconductor consulting experience, providing a realistic insight into the very obvious need for a practical, synergetic approach to diode laser development, along with the realization that there has not been any such publication available yet to meet these needs – both at industry and higher educational level. The author is confident, therefore, that the book on hand will be welcomed worldwide by the addressed, specialized readership with high, and growing demand, so that further editions are required much earlier than expected.

Acknowledgments

I would like to thank my former colleagues in the various semiconductor laser development departments for many thought-provoking discussions and helpful support, especially to Drs. Hans Brugger, Dan Clark, Dan Guidotti, Andrew Harker, Tony Hawkrigge, Amr Helmy, Dan Mars, Andy McKee, Heinz Meier, Pat Mooney, John Oberstar, Mike Parry, Julia Shaw, Simon Stacey and Steve Wang.

Thanks equally go to my customers worldwide for their ongoing, encouraging requests in the past years for writing exactly this all-embracing book.

Special thanks for useful discussions and supportive communication to: Prof. Dan Botez, University of Wisconsin, USA; Prof. Dieter Bimberg, Technical University Berlin, Germany; Prof. Petr Eliseev, University of New Mexico, USA and Lebedev Physics Institute, Russia; Prof. Charlie Ironside, University of Glasgow, UK; Dr. Bob Herrick, JDSU Inc., USA; and Dr. David Parker, SPI Lasers, UK.

Special thanks also to my production editor Gill Whitley for all her cooperation and support, and for shepherding this book to publication with undiminished commitment and reliability. Lastly, I would like to express my deepest thanks to Ashley Gasque, a very experienced, most perceptive and resourceful acquisitions editor with CRC Press, USA, whose idea of a book based on my full-day short course at the SPIE Photonics West 2010, triggered off this publication.

Peter W. Epperlein
Colchester, Essex, UK
May 2012

About the author

Dr. Epperlein is currently Technology Consultant with his own semiconductor technology consulting business, Pwe-PhotonicsElectronics-IssueResolution, and residence in the UK. He provides technical consulting services worldwide to companies in photonics and electronics industries, as well as expert assistance to European institutions through evaluations and reviews of novel optoelectronics R&D projects for their innovative capacities including competitiveness, disruptive abilities, and proper project execution to pre-determined schedules.

He looks back at a thirty year career in cutting-edge photonics and electronics industries with focus on emerging technologies, both in global and start-up companies, including IBM, Hewlett-Packard, Agilent Technologies, Philips/NXP, Essient Photonics and IBM/JDSU Laser Enterprise. He holds Pre-Dipl. (B.Sc.), Dipl. Phys. (M.Sc.) and Dr. rer. nat. (Ph.D.) degrees in physics, magna cum laude, from the University of Stuttgart, Germany.

Dr. Epperlein is a well-recognized authority in compound semiconductor and diode laser technologies. He accumulated the broad spectrum of his professional competencies in most different hands-on and managerial roles, involving design and fabrication of many different optical and electrical devices, and sophisticated diagnostic research with focus on the resolution of issues in design, materials, fabrication and reliability, and including almost every aspect of product and process development from concept to technology transfer and commercialization. He has a proven track record of hands-on experience and accomplishments in research and development of optical and electrical semiconductor devices, including semiconductor diode lasers, light-emitting diodes, optical modulators, quantum well devices, resonant tunneling devices, field-effect transistors, and superconducting tunneling devices and integrated circuits.

His extensive investigations of semiconductor materials and diode laser devices have led to numerous world-first reports on special effects in laser device functionality. Key achievements and important contributions to the improvement of development processes in emerging semiconductor technologies include his pioneering development and introduction of novel diagnostic techniques and approaches. Many have been adopted by other researchers in academia and industry, and his publications of these pioneering experiments received international recognition, as demonstrated by thousands of references, for example, in Science Citation Index and Google, advanced search exact phrase for 'PW or Peter W Epperlein'. Many of those unique

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results added high value to the progress of new product or emerging technology development processes.

Dr. Epperlein authored or co-authored more than seventy peer-reviewed journal and conference technical papers, has given more than thirty invited talks at international conferences and workshops, and published more than ten invention disclosures in the IBM Technical Disclosure Bulletin. He has served as reviewer of numerous proposals for publication in technical journals and he was awarded five IBM Research Division Awards for achievements in diode laser technology, quality management and laser commercialization.

Dr. Epperlein started his career in emerging superconductor technologies in the late seventies, with sophisticated design, modelling and measurements on superconducting materials, tunneling effects, devices and integrated circuits in his more than five years collaboration in the then revolutionary IBM Josephson Junction Superconducting Computer Project (dropped by IBM end of 1983), which included a two-year International Assignment from the IBM Zurich Research Laboratory to the IBM Watson Research Center, N.Y., USA until the mid-eighties.

This term was followed by a fundamental career re-orientation from emerging superconductor to emerging semiconductor technologies, comprising more than twenty-five years in the fields of semiconductor technologies, optoelectronics, fibre-optic communications, and with his first role to start as core member of the pioneering IBM Laser Enterprise (LE) Team, to become a spinout of IBM Research in the early nineties. He contributed significantly to research, development and commercialization of the pre-eminent pump diode laser technology for applications in optical communication networks in the early nineties along with the transition of the LE-Research Team into a competitive market leader IBM/JDSU LE some five years later.

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well. The effects at both larger and smaller well thicknesses account for the existence of a minimum in the J_{th} versus d dependence.

1.3.5 Transverse vertical and transverse lateral modes

The distribution of the propagating optical fields in the laser cavity can generally be characterized by two independent sets of modes, transverse electric (TE) and transverse magnetic (TM) ones. As already discussed above, these are subdivided into transverse vertical modes, which are perpendicular to the active layer, and transverse lateral modes, which are parallel to the active layer. TE modes have polarizations with the electrical field vector parallel to the active layer as opposed to TM modes where the light is polarized perpendicular to the active layer. Semiconductor diode lasers usually operate in the TE mode due to the lower threshold gain $g_{th}(\text{TE}) < g_{th}(\text{TM})$, which is also true for the technologically important, pseudomorphic, compressively strained InGaAs/AlGaAs QW lasers (Coleman, 1993).

The transverse vertical mode is formed by the standing wave between the heterojunctions of the active layer structure, which determines the confinement strength of the optical field, and the conditions for fundamental transverse vertical mode operation. The latter will be discussed in detail in Chapter 2, whereas the optical confinement issue was briefly discussed in Sections 1.1.1.4 and 1.3.3. The following section gives a rundown of possible vertical confinement structures along with their key features.

The transverse lateral mode is determined by the standing wave in the direction parallel to the active layer. Fundamental mode operation is strongly determined by the effective, lateral width and structure of the active region and the change of refractive index from the active region to adjacent layers. Structures for stabilizing the transverse lateral mode have already been briefly dealt with in Section 1.1.1.5. Sections 1.3.5.2 and 2.1.4 will discuss this topic in more detail.

1.3.5.1 Vertical confinement structures – summary

Double-heterostructure

- Example: n-AlGaAs/GaAs/p-AlGaAs. $d_{GaAs} \approx 0.08\text{--}0.2\ \mu\text{m}$.
- Efficient carrier confinement due to band discontinuities.
- Optical confinement factor Γ_{iv} large ≈ 0.6 (0.9) at $d = 0.2$ (0.6) μm .
- Threshold current density large, typically 1 kA/cm².

Single quantum well

- Well thickness L_z typically in range of 5 to 10 nm.
- Lasing wavelength adjustable by changing L_z and/or barrier height.
- $\Gamma_{iv,qw} \propto \Delta n_r L_z^2$ is very low. Example: $\Gamma_{iv,qw} \lesssim 1\%$ for an InGaAsP/InP SQW with $L_z = 10\ \text{nm}$.

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- Without the optical confinement structure, threshold current density is high caused by high losses due to spreading of the mode into the lossy cladding layers and gain saturation at high carrier densities due to the constant density of states of the $n = 1$ subband. This makes the threshold current more sensitive to increased cladding losses, increasing with temperature because of higher free-carrier absorption at high temperatures.

Strained quantum well

- Lattice-mismatch between well and barrier. Generated strain is elastically relaxed by deformation of the well material if $L_z < L_{z,crit}$.
- Access to certain wavelengths not available from any lattice-matched III–V compound semiconductor system. Example: ~ 900 – 1100 nm band wavelengths only accessible by pseudomorphic, compressively-strained InGaAs/AlGaAs QW lasers.
- Threshold current density is reduced and slope efficiency of power output versus drive current characteristic is increased by a reduced density of states and thus of the reduced hole effective mass due to a strain-induced separation of light-hole and heavy-hole valence bands.
- Temperature dependence of lasing characteristics is improved with higher characteristic temperatures.
- High mode selectivity: TE polarized light emission for electron to heavy-hole recombinations for compressive strain as opposed to TM polarized light emission for electron to light-hole recombinations for tensile strain.

Separate confinement heterostructure SCH and graded-index SCH (GRIN-SCH)

- To improve significantly photon and carrier confinement of SQW.
- To counteract carrier overflow from well under high injection.
- To fully exploit reduced density of states in QWs to achieve lasing at low carrier injection.
- Optimum SCH or GRIN-SCH thickness (waveguide layer) for a given composition difference between cladding layer and waveguide layer is that, which maximizes the QW optical confinement factor $\Gamma_{iv,qw} \propto \Delta n_r L_z^2$. Example: $d_{SCH} \cong 170$ nm and $d_{GRIN-SCH} \cong 300$ nm for a maximum $\Gamma_{iv,qw} \cong 3.5\%$ for SQW ($L_z = 10$ nm) AlGaInP/GaInP lasers emitting in the 650 nm band.

Multiple quantum well (MQW)

- Low threshold current densities due to strong optical confinement.
- At high loss: MQW is always better than SQW due to the higher differential gain in the gain–current curve. In contrast, the saturated gain of the SQW is not large enough to reach threshold gain.

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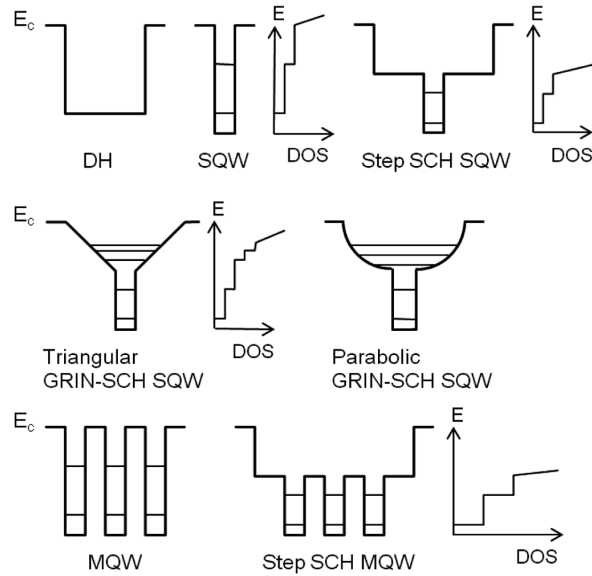


Figure 1.24 Schematic illustration of band structure (conduction band only shown for clarity) of various active region structures including DH, SQW, GRIN-SCH, and MQW and corresponding energy (E) dependent density of states (DOS) for some of them.

- At low loss: SQW is always better than MQW due to both its lower J_{tr} (only states of one QW have to be inverted) and lower internal loss ($\Gamma_{iv,qw}\alpha_i$ scales with number of wells)

Figure 1.24 shows the schematics of the various active layer structures along with some associated density of states (DOS).

1.3.5.2 Lateral confinement structures

As mentioned in Section 1.1.1.5, transverse lateral confinement has to be realized for current, carriers, and photons to achieve high performance of edge-emitting diode lasers. There are practically three types of implementation approaches: gain guiding provides current confinement, weak index-guiding current, and photon confinement, and strong index guiding provides current, carrier, and photon confinement. In the following we describe the concept and key features of each of the approaches.

Gain-guiding concept and key features

As illustrated in Figure 1.25, gain guiding is generated by injecting current through an aperture in a dielectric insulating layer. Other techniques include the formation of a current path by Zn diffusion or by restricting the current flow to an opening in high-resistivity areas created by ion implantation (see also Figure 1.6). The active region of all these structures is planar and continuous. The optical mode distribution

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energies higher than the band discontinuities are generated in the transition. Auger recombination and intravalence band absorption can be mitigated by modifying the valence band structure in strained QW structures (cf. Section 1.1.4.1). The Auger recombination rate is also lower in a MQW than a SQW laser. This follows from the fact that the Auger rate varies as N^3 where the carrier density at threshold is $N_{th} \cong 2.5 \times 10^{18} \text{ cm}^{-3}$ for a SQW and $\cong 8 \times 10^{17} \text{ cm}^{-3}$ (Agrawal and Dutta, 1993) for a MQW laser, leading to a lower Auger rate by a factor of 30 and a corresponding improvement in T_0 for a MQW laser. The internal optical loss can be reduced by using QW structures due to the very low optical confinement and thus helps to improve the temperature characteristics.

The key factors affecting the temperature characteristics of the slope efficiency include free-carrier absorption and intravalence band absorption in the active layer and confinement layers, with the effect of increasing the overall optical loss coefficient α_i and decreasing the internal quantum efficiency η_i with increasing temperature. Other contributing factors such as Auger recombination and carrier overflow play a minor role, because the rate of these processes is practically constant and independent of temperature, since the carrier density is clamped at threshold and does not actually change in the slope efficiency regime at current levels beyond threshold.

1.3.8 Mirror reflectivity modifications

Optimization of the diode laser performance requires modification of the intrinsic power reflectivity of cleaved facets, which is about 0.32 for GaAs (cf. Equation 1.12), by creating one end mirror with high reflectivity and the other facet with a low reflectivity for coupling out the laser power. However, there are tradeoffs to be considered, such as the threshold current decreases but the differential quantum efficiency decreases too (cf. Equation 1.50) with increasing mean mirror reflectivity (see Figure 1.32). To maintain a reasonable differential quantum efficiency one would need to reduce the internal loss of the waveguide.

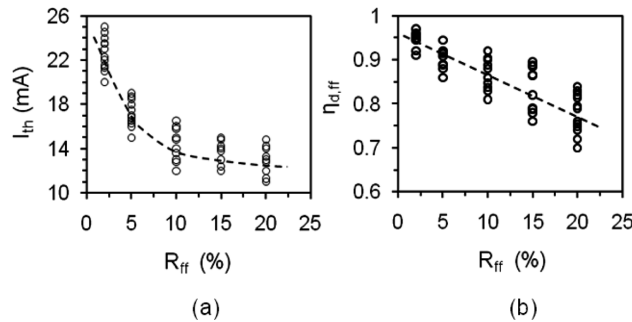


Figure 1.32 Plots of experimental threshold currents I_{th} (a) and front-facet differential quantum efficiencies $\eta_{d,ff}$ (b) versus front-facet reflectivities R_{ff} for ridge waveguide compressively-strained InGaAs/AlGaAs GRIN-SCH SQW lasers 4 μm wide. Dashed lines are trendlines.

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The reflectivity of cleaved facets can be modified by dielectric coatings. Coating the facets with appropriate thin dielectric layers has the additional advantage of passivating and protecting the sensitive mirror facets from degradation effects and thereby enhancing considerably the effective laser output and damage level. Chapters 3 and 4 will deal in detail with degradation modes and laser facet passivation technologies. Figure 1.33a shows a typical coating of the low-reflectivity front mirror and high-reflectivity back mirror for an edge-emitting, high-power FP diode laser. It also illustrates the reflection and transmission of light at the interfaces of a single dielectric film on a semiconductor. Stringent requirements are imposed on the optical robustness of laser mirror coatings, which include:

- high transparency at the lasing wavelength;
- chemical, stoichiometric, and mechanical stability under high optical power exposure and extreme environmental conditions;
- excellent adhesion to facet surface;
- ideally zero mechanical stress;
- prevention or suppression of gradual and sudden laser facet degradation mechanisms;
- high reliability and long lifetimes under application-specific conditions.

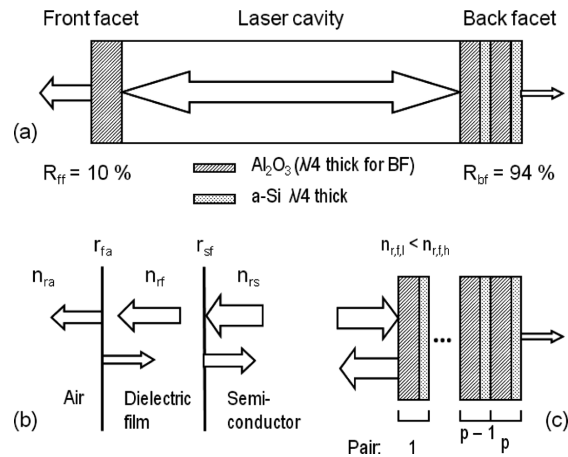


Figure 1.33 Schematic illustration of mirror coating approaches for high-power edge-emitting diode lasers. (a) Typical low-reflectivity front-facet single-layer coating and high-reflectivity back-facet (BF) Bragg stack coating. (b) Reflection and transmission of light at the surfaces of a semiconductor laser facet coated with a single dielectric film where r_{fa} and r_{sf} denote the reflection coefficients at the surfaces of the film/air and semiconductor/film, respectively. (c) Reflection and transmission at a Bragg mirror stack consisting of pairs (p = number) of dielectric layers each a quarter-wavelength thick and each pair comprising a high refractive index $n_{r,f,h}$ and low refractive index $n_{r,f,l}$ film.

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If there are no optical absorption and scattering losses in the dielectric, the power reflectivity R_f of the single film with thickness d_f and refractive index $n_{r,f}$ can be expressed by the equation for normal incidence

$$R_f = \frac{r_{sf}^2 + r_{fa}^2 + 2r_{sf}r_{fa} \cos 2\beta}{1 + r_{sf}^2 r_{fa}^2 + 2r_{sf}r_{fa} \cos 2\beta} \quad (1.57)$$

where

$$r_{sf} = \frac{n_{r,s} - n_{r,f}}{n_{r,s} + n_{r,f}} \quad (1.58)$$

$$r_{fa} = \frac{n_{r,f} - n_{r,a}}{n_{r,f} + n_{r,a}} \quad (1.59)$$

$$\beta = \frac{2\pi}{\lambda_0} n_{r,f} d_f \quad (1.60)$$

and $n_{r,s}$ and $n_{r,a}$ are the refractive indices of the semiconductor and air, respectively, and λ_0 is the lasing wavelength in vacuum (Figure 1.33b). Equation (1.57) was derived by Born and Wolf (1999 [originally 1959]) on the basis of the characteristic (transfer) matrix for the film within the Fresnel reflectivity formalism for plane electromagnetic waves. Changes for the *modal* reflectivity of a diode injection laser are expected to be no greater than 15% (Ikegami, 1972). The reflectivity in Equation (1.57) changes periodically with β , that is, with a periodicity in thickness of $\lambda_0/(2n_{r,f})$ of the dielectric film. The maximum value of R_f can be found when $\cos 2\beta = 1$, that is, for thicknesses $d_f = m\lambda_0/2n_{r,f}$ (for $m = 1, 2, 3, \dots$) and becomes for normal incidence

$$R_{fmax} = \left(\frac{n_{r,s} - n_{r,a}}{n_{r,s} + n_{r,a}} \right)^2 \quad (1.61)$$

which is independent of $n_{r,f}$. R_{fmax} is the natural reflectivity for an uncoated mirror. The minimum value of Equation (1.57) is achieved at $\cos 2\beta = -1$, that is, for thicknesses $d_f = m\lambda_0/4n_{r,f}$ (for $m = 1, 3, 5, \dots$) and becomes for normal incidence

$$R_{fmin} = \left(\frac{n_{r,s}n_{r,a} - n_{r,f}^2}{n_{r,s}n_{r,a} + n_{r,f}^2} \right)^2. \quad (1.62)$$

This equation gives the condition for an anti-reflective coating, which would be strictly achieved at normal incidence for

$$n_{r,f} = \sqrt{n_{r,s}n_{r,a}}. \quad (1.63)$$

An effective anti-reflective (AR) coating on a 980 nm InGaAs/AlGaAs laser facet can be achieved by depositing a thin Al_2O_3 film of thickness $d_f = m\lambda_0/4n_{r,f}$

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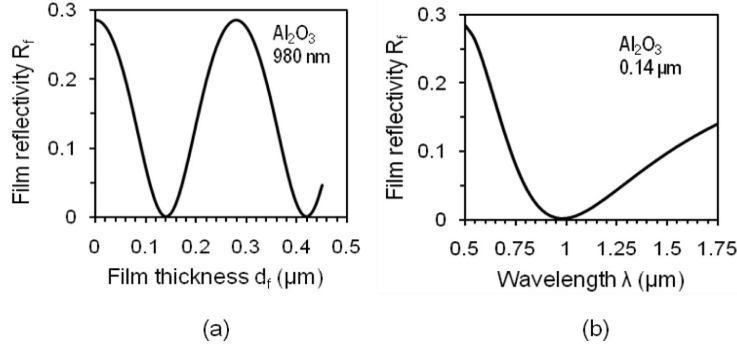


Figure 1.34 (a) Plot of the reflectivity R_f versus Al_2O_3 film thickness d_f calculated according to Equation (1.57) for the low-reflectivity front facet of a 980 nm InGaAs/AlGaAs laser. A 10% front-mirror reflectivity can be achieved at a thickness of 190 nm. (b) Calculated reflectivity R_f versus wavelength λ for 140 nm Al_2O_3 film thickness as found at the first minimum in the R_f versus d_f dependence in (a). The minimum in (b) is close to 980 nm as expected.

(for $m = 1, 3, 5, \dots$), because Al_2O_3 with an index $n_{r,f} \cong 1.76$ at a wavelength of 980 nm meets the condition in Equation (1.63) well by using $n_{r,s} \cong 3.28$ for $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$. Al_2O_3 has all the properties expected from an effective, efficient, and reliable mirror coating material (see above).

Figure 1.34a plots the reflectivity versus Al_2O_3 film thickness calculated according to Equation (1.57) for the low-reflectivity front facet of a 980 nm InGaAs/AlGaAs laser. As expected, the periodic dependence has a periodicity in thickness of $\lambda_0/(2n_{r,f})$ and the maxima and minima points are close to 29% and 0.1%, respectively. A 10% front-mirror reflectivity can be achieved at a thickness of 190 nm. The reflectivity versus wavelength dependence calculated for 140 nm Al_2O_3 thickness, as found at the first minimum in the R_f versus d_f dependence, is plotted in Figure 1.34b. The minimum in the figure is close to 980 nm as expected.

Periodically stratified films are highly reflective coatings. They are formed by so-called Bragg stacks, which are pairs of films with high $n_{r,f,h}$ and low refractive index $n_{r,f,l}$ and a thickness of each film set at a quarter-wavelength of $\lambda_0/4n_{r,f}$ (see Figure 1.33c). The constructive interference in the multilayer stack results in dramatically high reflectivity values, which can be increased close to unity by increasing the number p of periods of double films and the index ratio $n_{r,f,h}/n_{r,f,l}$ between the high and low refractive index films. For normal incidence the reflectivity of such a Bragg reflector has been derived by using the transfer matrix method (Born and Wolf, 1999) and is given by

$$R_{\text{stack}} = \left(\frac{1 - \left(\frac{n_{r,f,h}}{n_{r,s}} \right) \left(\frac{n_{r,f,h}}{n_{r,a}} \right) \left(\frac{n_{r,f,h}}{n_{r,f,l}} \right)^{2p}}{1 + \left(\frac{n_{r,f,h}}{n_{r,s}} \right) \left(\frac{n_{r,f,h}}{n_{r,a}} \right) \left(\frac{n_{r,f,h}}{n_{r,f,l}} \right)^{2p}} \right)^2. \quad (1.64)$$

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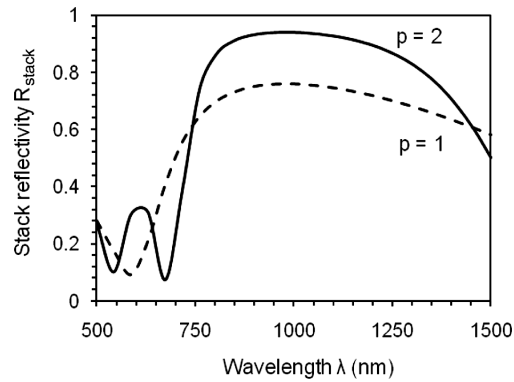


Figure 1.35 Spectral reflectivity of a periodic multilayer Bragg reflector calculated for the high-reflectivity back mirror of a 980 nm InGaAs/AlGaAs laser. Two pairs ($p = 2$) of quarter-wavelength-thick Al_2O_3 and a-Si layers provide a high reflectivity of $>90\%$ in a broad wavelength range ~ 850 to 1200 nm with a maximum of 94% at 980 nm.

The spectral reflectivity has been calculated with Equation (1.64) for the high-reflectivity (HR) back mirror of a 980 nm InGaAs/AlGaAs laser by using the standard coating materials of Al_2O_3 with $n_{r,fl} = 1.76$ and a-Si (amorphous-Si) with $n_{r,fh} = 3.69$ (Ioffe Physico-Technical Institute, 2006). Figure 1.35 shows a reflectivity of 0.76 for $p = 1$ and 0.94 for $p = 2$ at $\lambda = 980$ nm. A reflectivity of ≥ 0.9 is achieved in a rather broad wavelength range ~ 850 to 1200 nm. Alternative coating material combinations of TiO_2 ($n_{r,fh} = 2.78$) with SiO_2 ($n_{r,fl} = 1.45$) offer the advantage of developing reduced facet heating by laser light absorption due to the negligible absorption of TiO_2 at wavelengths $\gtrsim 450$ nm. However, due to the lower index of TiO_2 , three periods, $p = 3$, would be required to obtain a reflectivity $> 90\%$.

1.4 Laser fabrication technology

The purpose of this section is to give a brief overview of key steps for fabricating edge-emitting laser devices including laser wafer growth, processing, and packaging. While a variety of epitaxial growth techniques have been used to grow diode lasers, the two most important techniques for the growth of high-power diode lasers for both research and commercial applications are molecular beam epitaxy (MBE) and organometallic vapor-phase epitaxy (OMVPE), also referred to as metal–organic chemical vapor deposition (MOCVD). MOCVD, which comes in low-pressure (~ 0.1 atm) and atmospheric pressure systems, uses metal–organic precursors such as group-III alkyls and group-V hydrides as gas sources to react on a heated substrate to form the epitaxial film. In contrast, MBE is carried out under ultrahigh vacuum (UHV; $< 10^{-10}$ Torr) with thermal beams of atoms evaporated from heated effusion cells and directed to the atomically flat and contaminant-free surface of a substrate held at high temperature to form the layer.

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they deform plastically under stress. However, soft solders become unstable during long-term laser operation, because of thermal fatigue and creep which increases in strength with decreasing melting point and when the mechanical stress is stronger than the solder's elasticity limit. This degradation and creep of the solder sensitively impacts the coupling efficiency of the laser light into a fiber. On the other hand, hard solders such as Au-rich AuSn enable long-term and reliable stability of the bonded laser die. However, AuSn shows very little creep, which may be a concern, because thermal expansion mismatches, for example, between the laser submount and the structure underneath, almost invariably lead to some degree of warpage, which cannot be allowed to vary with time in service. The mechanical stress per unit length, S_{bond} , can be approximated by (Fukuda, 1999)

$$S_{bond} = |\alpha_{HS} - \alpha_{die}| (T_{bond} - T_{amb}) E_{Ym} \quad (1.65)$$

where α_{HS} and α_{die} are the thermal expansion coefficients of the heat sink and laser die, respectively, T_{bond} is the bonding temperature, which is close to the melting point of the solder, T_{amb} is the ambient temperature, and E_{Ym} is Young's modulus of the laser die.

An example should demonstrate the effect: bonding a GaAs laser die to an AlN material generates a compressive stress in the die at 25 °C of $\cong 6 \times 10^8$ dyn/cm² when a hard solder such as Au-rich AuSn ($T_{bond} \cong 280$ °C) is used and $\cong 2 \times 10^8$ dyn/cm² when the soft solder InSn ($T_{bond} \cong 120$ °C) is used. Here we also used 6.6×10^{-6} °C⁻¹ and 4×10^{-6} °C⁻¹ for the thermal expansion coefficient of GaAs and AlN, respectively, and 8.6×10^{11} dyn/cm² for Young's modulus of GaAs. The stress generated in the die with soft solders can easily be released via plastic deformation into the solder layer, whereas high mechanical stress levels in excess of 10^9 dyn/cm² caused by hard solders cannot be released into the hard solder, but will trigger the growth of slip dislocations in the laser chip, which will impact its performance and reliability.

1.4.3.3 Optical power coupling

Many diode laser applications require, but also prefer, fiber delivery systems, where the laser beam is coupled into an optical fiber to transport the light to the application.

The incident (acceptance) angle of light into a step index fiber with a core refractive index $n_{r,co}$ larger than the index $n_{r,cl}$ of the cladding has to be such that the beam reaches the core-cladding interface at an angle $\geq \theta_{cr}$, the critical angle for total reflection, in order to be captured and propagated as a bound mode. The geometry of light coupling into an optical fiber is illustrated in Figure 1.38.

The light-capturing capability of the fiber can be expressed by the fiber numerical aperture (NA), which is the sine of the largest angle θ_a contained within the cone of acceptance and is given as

$$NA = \sin \theta_a \quad (1.66a)$$

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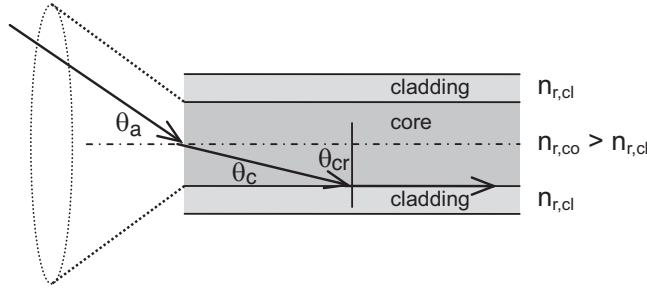


Figure 1.38 Schematics for calculating the numerical aperture of a step-index optical fiber. Correlation between acceptance angle θ_a cone and critical angle θ_{cr} for total reflection at the fiber core/cladding interface.

and using Snell's law we obtain after some manipulation

$$NA = \sqrt{(n_{r,co}^2 - n_{r,cl}^2)} \quad (1.66b)$$

$$NA = n_{r,co} \sin \theta_c \quad (1.66c)$$

where $\theta_c = 90^\circ - \theta_{cr}$ is the supplementary angle for total reflection. Equation (1.66c) is a useful expression for the NA and relates it to the index of the core and the maximum angle at which a bound ray may propagate. The acceptance angle θ_a is then given by

$$\theta_a = \arcsin(NA) = \arcsin \sqrt{(n_{r,co}^2 - n_{r,cl}^2)}. \quad (1.67)$$

Typical NA values for single-mode (SM) and multi-mode (MM) fibers are 0.1 and 0.2–0.3, respectively. The higher the NA, the more modes in the fiber, which means the larger the dispersion of this (MM) fiber. The higher the NA of an SM fiber, the higher its attenuation, because a significant proportion of optical power travels in the cladding, which is highly doped to achieve a high index contrast for SM.

In the following, we discuss the optical requirements to achieve the highest possible coupling of optical power from an SM diode laser into an SM optical fiber. This can be achieved by matching both the amplitude and phase of the laser mode to the amplitude and phase of the fiber mode. Technical realizations including quantitative coupling efficiencies, dependencies, and alignment tolerances will also be discussed.

In Section 1.3.5.3, we discussed how light emitted from the usually elliptical NF spot propagates freely into space and broadens strongly in both directions by diffraction – stronger in the transverse vertical than transverse lateral direction. Important information about setting up quantitative conditions for mode matching can be obtained by determining the laser mode field radii ($1/e^2$ intensity points) and wavefront

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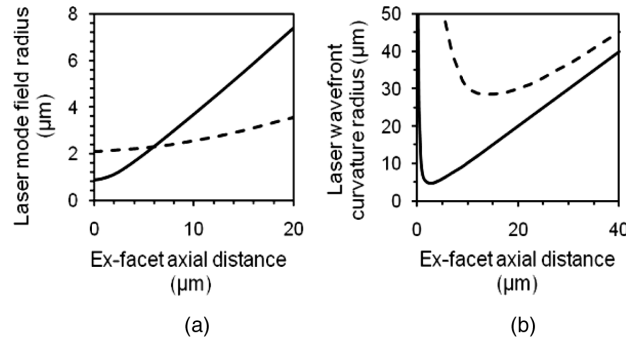


Figure 1.39 (a) Mode field radii of an InGaAs/AlGaAs ridge laser calculated as a function of the axial distance from the facet for the transverse vertical (solid line) and transverse lateral (dashed line) direction. (b) Laser wavefront curvature radii calculated as a function of the axial distance from the facet for the transverse vertical (solid line) and transverse lateral (dashed line) direction.

radii of curvature (measure for phase) as a function of the axial distance from the laser facet for transverse vertical and transverse lateral directions.

Figure 1.39a shows the mode field radii versus axial distance calculated for a narrow-stripe laser (Epperlein *et al.*, 2000). As expected, the mode field radii increase with increasing axial distance, faster in the transverse vertical direction with a linear increase for $\gtrsim 5 \mu\text{m}$ in this example. The FF angles can be taken from the asymptotic angles in the transverse vertical and lateral directions and are $\cong 22^\circ$ and $\cong 9^\circ$, respectively, in this case. Both curves intersect at $\cong 6 \mu\text{m}$ where the transverse vertical and lateral mode field radii are the same and hence the amplitude distribution is circular (see Figure 1.28c).

The shapes of the phase fronts also change in the axial direction with the phase constant at the facet, which is expressed by the large radii of the wavefront curvature in both directions (Figure 1.39b). At large distances the radii of curvature become equal to the axial distance, which means that the phase fronts are spheres centered at the facet. For both directions, the radii have minima at different locations in the case of an elliptical NF spot, whereas for circular intensity distributions the locations of the minima are the same. The distance from the facet to the minimum is called the Rayleigh range and marks the division between the NF and FF.

From Figure 1.39 we can see that there are two locations where matching the phases and amplitudes of the laser mode and fiber mode (expressed by the mode field radius, which is half the distance between the points in the fiber where the electric field amplitude decays to $1/e$ of its peak value) can be done best. At the facet, the phase of the laser mode is planar and therefore only the amplitude needs to be matched to the fiber, which can be accomplished by using an elliptical core fiber in case the NFP is elliptical. The laser phase is only planar very close to the facet, which requires the fiber to be located very close to the facet to achieve high coupling. The other place is at the crossover point (Figure 1.39a) where the amplitude distribution is circular.

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Mode amplitude matching can be achieved by selecting a fiber with a mode field radius, which equals that of the laser ($\cong 2 \mu\text{m}$ in the example). Figure 1.39b shows that mode matching is not that straightforward at the mode field radii crossover point, because the radii of curvature in both directions are very different at this point ($\cong 6 \mu\text{m}$ in the transverse vertical and $>40 \mu\text{m}$ in the transverse lateral direction in the example). However, over the core of the fiber ($\cong 2 \times 2 \mu\text{m} = 4 \mu\text{m}$) the phase fronts are to a good approximation cylindrical and to match them a cylindrical lens is required, which is best realized by a fiber tipped with a wedge lens.

In summary, by placing a wedge-lensed fiber, which has a mode field diameter equal to the diameter of the laser intensity distribution at the position where the intensity distribution is circular, both the phase and amplitude of the modes can be matched. The best form for the wedge is a hyperbola; however, a simple wedge or double wedge is easier to fabricate and can match the phase sufficiently well to realize high ($>80\%$) coupling efficiencies, in case the mode amplitude is also well matched. If the laser mode is circular, the best form for the phase matching lens is a hyperboloid, which can be well approximated by a cone, equivalent to the simple wedge lens in the case of an elliptically shaped NF (laser mode). It should be pointed out that the lens only serves to match the phase.

Bulk optical systems can be used when the beam is allowed to expand to a size that is considerably larger than the fiber mode field diameter and is then focused with a discrete lens. The best lenses are aspheric lenses that can be designed to have no spherical aberration and hence phase matching should be good; however, they cannot match the elliptical spot of the laser to the standard circular core of the fiber, because they magnify equally in vertical and lateral planes and therefore a cylindrical or acylindrical lens would have to be added to correct this. There is, nevertheless, a very smart commercially available solution (Blue Sky Research, Inc., 2010). A diffraction-limited acylindrical $\mu\text{Lens}^{\text{TM}}$ placed directly in front of the laser captures nearly 100% of the emitted power and converts the divergent elliptical output beam into a beam with a spherical wavefront and nearly circular profile. The beam behaves as if it was emitted from an ideal point source with a certain low divergence angle, and, if required, can then be precisely focused to a round spot using bulk optics.

To optimize coupling efficiencies, the optical coupling system comprising active and passive elements has to be aligned either passively or actively. In active alignment, the alignment between the components is performed under operation of the laser, whereas in passive alignment, the laser is not operated and the components are mounted on bonding pads patterned on the submount or heat sink.

Single-mode diode laser packaging invariably involves active alignment along a total of six axes, mainly due to manufacturing variances in the laser, laser assembly, and optical fiber core center. The various elements are aligned and fixed one by one and the monitored optical power is maximized. Hard soldering and laser welding are used for bonding and fixing the various components, including the diode laser on a heat sink, a photodiode, which monitors the laser output through the back facet, a thermistor that monitors the temperature, and various optical elements to the submount to achieve high reliability for a high-performance laser product in a butterfly package. The actual fiber is mounted inside a so-called fiber tube subassembly, which is welded to the wall of the package, and the fiber is threaded in through a hole and

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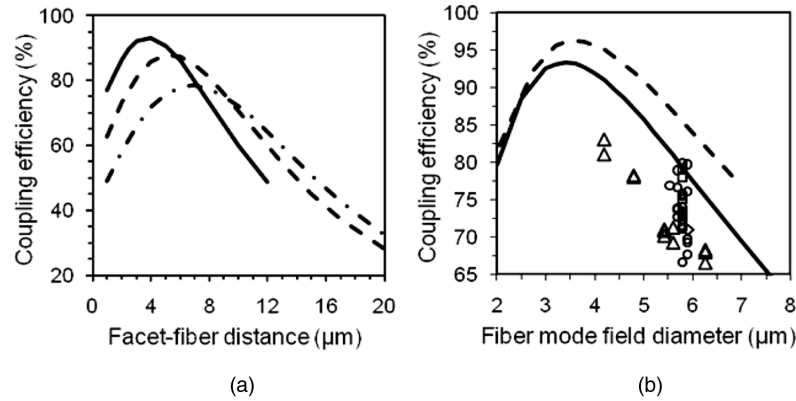


Figure 1.40 (a) Coupling efficiency versus laser facet–fiber tip distance calculated for laser light emitted under $11^\circ \times 26^\circ$ far-field divergence angles into 24.5° wedge-lensed fibers with mode field diameters of $5.9\ \mu\text{m}$ (solid line), $4.7\ \mu\text{m}$ (dashed line), and $3.6\ \mu\text{m}$ (dot-dashed line). (b) Coupling efficiency versus fiber mode field diameter calculated for laser emission into 24.5° wedge-lensed fibers (solid line) and fibers with parabolically shaped lenses (dashed line). Experimental points from various different runs for coupling laser light into wedge-lensed fibers.

attached to the submount or optical bench in front of the laser chip. Regarding loss of coupling due to misalignment, it is important to consider both mode amplitude and phase mismatching.

However, there is a conflict because systems that are more tolerant of amplitude mismatches are less tolerant of phase mismatches and vice versa. This can be illustrated by a simple example: butt coupling between two fibers. For the same linear displacement, there will be a smaller mismatch of the amplitudes with a larger mode field diameter (MFD). In contrast, for the same phase error, the smaller MFD allows a larger angular error. To achieve $>90\%$ coupling efficiency in a lensed fiber system, the lateral alignment accuracy is required to be better than $50\ \mu\text{m}$, something that takes very careful process optimization to maintain while fixing the fiber by laser welding. The coupling efficiency drops from its maximum value toward larger facet–fiber distances with a typical rate of $\cong 5\%$ per micrometer (see Figure 1.40a).

Figures 1.40 and 1.41 show the dependence of the coupling efficiency on (i) the free-space distance between the laser facet and fiber tip, (ii) the fiber MFD, (iii) the FF angle of the laser in transverse lateral direction $\theta_{\parallel}$, and (iv) the FF angle in transverse vertical direction $\theta_{\perp}$ (Epperlein *et al.*, 2000).

Key results are as follows:

- Calculated coupling efficiencies $>90\%$ at a facet–fiber gap of $\cong 4\ \mu\text{m}$ for a laser with FF angles $11^\circ \times 26^\circ$ and a 24.5° AR-coated wedge-lensed fiber with $\text{MFD} = 3.6\ \mu\text{m}$.
- Calculated coupling efficiencies $>90\%$ at $\text{MFD} \cong 3.5\ \mu\text{m}$ for a 24.5° wedge-lensed fiber and for a laser with FF angles $10^\circ \times 25^\circ$ with experimental coupling values lower by $\lesssim 10\%$.

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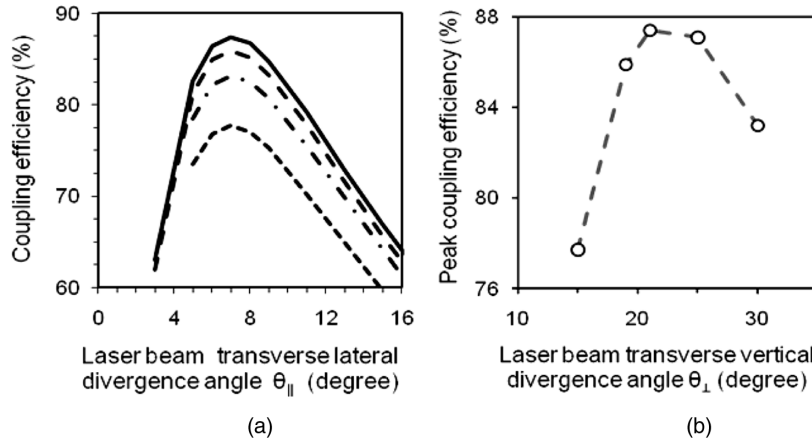


Figure 1.41 (a) Coupling efficiency versus laser transverse lateral divergence angle calculated for laser light emitted at transverse vertical angles of 21° (solid line), 19° (long dashed line), 30° (dot-dashed line), and 15° (short-dashed line) into a 24.5° wedge-lensed single-mode fiber with a mode field diameter of 5.9 μm . (b) Peak coupling efficiency versus laser transverse vertical divergence angle calculated for laser light emitted at a transverse lateral angle of 7° into a 24.5° wedge-lensed single-mode fiber with a mode field diameter of 5.9 μm .

- Calculated coupling efficiencies $>85\%$ at $\theta_{||} \cong 7^\circ$ for a transverse vertical FF angle $\theta_{\perp} = 21^\circ$ and a 24.5° wedge-lensed single-mode fiber with MFD = 5.9 μm .

In the preceding subsections, we discussed optical coupling for single-mode diode lasers with diffraction-limited beams in both transverse directions. However, broad-area lasers typically 100 μm wide and 1 cm laser bars have a relatively poor beam quality, which is usually expressed by the beam parameter product (BPP), defined as half the beam waist diameter in focus times half the FF divergence angle. The output beam of these lasers is characterized by a highly asymmetric profile with regard to beam dimension and divergence angle. In the case of a laser bar, typical values for the source width are 10 mm in the slow-axis direction and 1 μm in the fast-axis direction with typical beam divergence angles of 5° and 35°, respectively. This means that the resulting BPPs are highly asymmetric: in the slow direction $\text{BPP} \cong 400 \text{ mm} \times \text{mrad}$, which is far beyond the diffraction limit; and in the fast direction $\text{BPP} \cong 1 \text{ mm} \times \text{mrad}$, which is nearly diffraction limited (Köhler *et al.*, 2010). Efficient fiber coupling of such a diode laser is only possible if the different BPPs are adapted by shifting beam quality from one direction to the other and special symmetrization optics are applied for reshaping the beam (Bachmann *et al.*, 2007). This symmetrization of the BPPs is equivalent to a minimization of the overall beam parameter product $\text{BPP}_{\text{total}} = (\text{BPP}_{\text{slow}}^2 + \text{BPP}_{\text{fast}}^2)^{1/2}$. The smallest possible BPP is achieved with a diffraction-limited Gaussian beam and is proportional to

tapered lasers, monolithic flared amplifier master oscillator power amplifiers, phase-locked coherent diode laser bars, and incoherent standard 1 cm high-power laser bars with high fill factors.

2.1 Basic high-power design approaches

2.1.1 Key aspects

The limiting factors for high-power operation under continuous wave (cw) conditions in narrow-stripe single spatial mode diode lasers can be grouped into two categories. First, in thermal rollover the laser efficiency gradually decreases with increasing drive current due to the increase of temperature in the active layer by Joule heating effects, which eventually leads to a saturation or even decrease of power, and, second, in catastrophic optical damage (COD) mainly the mirrors are damaged by local melting due to the high absorption of laser light at nonradiative recombination centers. However, the damage can also further extend from the surface along the cavity or originate from hot spots in the bulk of the cavity, which are caused by highly nonradiative crystalline phase changes and structural defects such as dislocations.

When operating a single-mode diode laser at high power, single-mode behavior has to be achieved in both transverse vertical and lateral directions. This issue will be dealt with in the next sections. The laser has also to be designed in such a way that high-power operation is obtained with specified transverse vertical and lateral beam divergence angles to maximize the coupling of power into a single-mode fiber, if required. This issue will be discussed in detail further below supported by numerical modeling and experimental results. It should also be noted that highly reliable and long-term operation under high output power has to be realized (see Chapters 3–6).

Some key parameters for realizing high-power operation can be revealed from the equation for the output power $P_{out,f}$ from the front-facet of a single-emitter device

$$P_{out,f} = \frac{h\nu}{q} \eta_i \frac{1}{1 + \frac{1}{\frac{1 - R_f}{1 - R_r} \sqrt{\frac{R_r}{R_f}}}} \frac{\alpha_m}{\alpha_i + \alpha_m} (I - I_{th}) \left(\frac{I_{eff}}{I_{eff} + I_{leak}} \right) \Theta(T) \quad (2.1)$$

where η_i is the internal quantum efficiency, R_f and R_r the reflectivities of the front and rear mirrors, α_m the mirror loss (cf. Equation 1.50), α_i the internal optical loss, I_{th} the threshold current, I_{eff} the effective current contributing to lasing, I_{leak} the leakage current, and $\Theta(T)$ the term representing the thermal power rollover due to heating effects. Equation (2.1) was derived from Equations (1.48) and (1.49); the last two terms were added to consider all major contributing parameters or effects. The reflectivity term is close to unity within $\sim 3\%$ for typical reflectivities $R_f = 0.1$ and $R_r = 0.9$. However, the other factors in Equation (2.1) are essential in achieving high optical power.

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These factors and measures such as output power scaling, laser cavity length scaling, vertical and lateral waveguide designs, materials and fabrication optimizations, carrier and photon loss minimizations, and thermal management will be discussed in the following sections.

2.1.2 Output power scaling

It is well established that the laser output power can be dramatically increased by making the laser cavity longer. This is mainly due to a lowering of the thermal resistance leading to an improved cooling of the laser chip with the consequence that the thermal rollover power is increased. However, it has also been observed that the threshold current is increased and the external quantum efficiency is decreased in long-cavity lasers.

To counteract this and to maximize the output power four key figures have to be considered in the length scaling process of a diode laser. According to Harder (2008), these figures are (i) the roundtrip gain g , (ii) the external differential quantum efficiency η_d , (iii) the photon lifetime in the cavity τ_{ph} , and (iv) the asymmetry of the laser cavity defined by the ratio P_r of the power behind the front and rear mirror. Setting the rear-mirror reflectivity equal to unity allows the four key figures to be written as (cf. Equations 1.23, 1.32, 1.50; Agrawal and Dutta, 1993)

$$g = \frac{1}{\Gamma_{iv}} \left[\alpha_i + \frac{1}{2L} \ln \left(\frac{1}{R_f} \right) \right] \quad (2.2)$$

$$\eta_d = \eta_i \frac{\frac{1}{2L} \ln \frac{1}{R_f}}{\alpha_i + \frac{1}{2L} \ln \frac{1}{R_f}} = \eta_i \frac{\alpha_m}{\alpha_i + \alpha_m} \quad (2.3)$$

$$\tau_{ph} = \frac{1}{v_{gr} \left[\alpha_i + \frac{1}{2L} \ln \left(\frac{1}{R_f} \right) \right]} \quad (2.4)$$

$$P_r = \frac{(1 + R_f)}{2\sqrt{R_f}} \quad (2.5)$$

where v_{gr} is the group velocity (cf. Section 1.3.6). It is not possible to adjust the values of Γ_{iv} , α_i , and R_f in such a way to keep all four figures constant while simultaneously increasing the cavity length L to improve the thermal rollover power. Instead, g and η_d are kept fixed and τ_{ph} (*constant photon lifetime scaling* approach) or P_r (*constant power ratio scaling* approach) are adjusted (Harder, 2008). The rules for *constant photon lifetime scaling* are

$$\Gamma_{iv}(L) = \Gamma_{iv}(L_0); \alpha_i(L) = \alpha_i(L_0); R_f(L) = R_f(L_0)^{L/L_0} \quad (2.6)$$

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where $L > L_0$ is the longer cavity length. In this approach, higher power can be obtained by cleaving longer cavities from the same material and reducing R_f according to Equation (2.6) but still maintain the same value for η_d . However, P_r also becomes larger with increasing L , which facilitates the longitudinal spatial hole burning effect. This drawback can be mitigated by using a slightly flared active waveguide (Guer mache *et al.*, 2005).

The rules for *constant power ratio scaling* are

$$R_f(L) = R_f(L_0); \Gamma_{iv}(L) = \frac{L_0}{L} \Gamma_{iv}(L_0); \alpha_i(L) = \frac{L_0}{L} \alpha_i(L_0). \quad (2.7)$$

In this approach, which is the preferred one for long cavities, also R_f is constant, and hence this scaling type is also called *constant mirror reflectivity scaling*. Both Γ_{iv} and α_i have to be reduced linearly with increasing L , which is considered a demanding task in the design and fabrication of the vertical structure. The constant power ratio scaling approach has the additional advantage that it makes parameters such as the average optical power in the active layer, drive current density, heat generation density, and spectral stability independent of the cavity length (Harder, 2008).

2.1.3 Transverse vertical waveguides

2.1.3.1 Substrate

The effects of substrate orientation on the quality of epitaxial material and laser performance have already been mentioned in Section 1.4.1. These effects are dependent on the materials used and will be discussed in more detail in the following.

Usually the substrates used for devices have a (100)-oriented surface. Some examples will be given on the effects of misorientation from the exact (100) orientation by some degrees. Chand *et al.* (1994) observed that by misorienting (100) GaAs substrates toward $\langle 111 \rangle_A$ by 3 to 4° the incorporation of impurities like oxygen is reduced in AlGaAs, and the AlGaAs/GaAs heterointerfaces are smoother and sharper. Similar positive results were found in AlGaAs lasers grown on GaAs substrates oriented 2° toward the $\langle 110 \rangle$ direction, which led to a reduction of loop dislocations formed at the interface between the substrate and first epitaxial layer (Epperlein *et al.*, 2000, unpublished).

In general, slight substrate misorientations and lower defect densities result in improved laser performances and lifetimes. These results were confirmed by Chen *et al.* (1987) who demonstrated that similarly tilted substrates led to improved optical quality and lower threshold current densities in (Al)GaAs quantum well (QW) lasers grown on GaAs substrates. More importantly, the surface morphology of the growth on misoriented (100) substrates, and hence threshold current density, is less sensitive to deviations from optimum growth conditions than in (100) substrates, which makes it easier to grow low threshold current material. According to the authors, these enhanced results can be ascribed in part to the fact that misoriented surfaces have steps terminated with Ga. As atoms incident on the surface can then form three bonds, two to the Ga atoms on the (100) surface and one to the Ga

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of the threshold current than corresponding lattice-matched MQW devices. Critical thickness calculations clearly showed that this degradation is caused by a degradation of crystal quality suffering from critical thickness. Devices with 4 and 6 wells are free from inelastic, plastic strain relaxation and dislocation formation effects, whereas devices with more than 8 wells are unstable. Finally, it should be noted that the latter effect can be compensated by using a strain-compensating scheme.

In strained-layer MQW structures the net strain is accumulated, which means that the allowable strain in a SQW is reduced. By using strain-compensating barrier layers with a strain, which is opposite to that in the well layer, each well is then exposed to a similar accumulated strain originating from the underlying layer. This approach can also be applied to generate high strain levels in a SQW with the goal to extend the wavelength range, for example, by using GaAsP barriers in highly strained InGaAs/GaAs QW lasers the lasing wavelength could be extended to 1060 nm (Bugge *et al.*, 1998). *Strain-compensated lasers* also show a higher reliability because of the reduced driving force for strain-activated defect generation. Another positive effect of strained barriers could include the adjustment of the band structure to enhance the performance of certain diode lasers. In this way, the use of tensile-strained GaAlInP barriers in red-emitting lasers could improve the carrier confinement, reduce the absorption of laser light at the mirror facet, and thus enhance the optical strength of the laser (Valster *et al.*, 1997).

2.1.3.5 Fast-axis beam divergence engineering

The beam divergence property is of great importance whenever laser power is required to be coupled efficiently into another device enabling high-power, high-brightness applications including pumping fiber amplifiers, optical storage, and direct material processing. The requirement is not only for high output power but also for narrow beam divergence. Conventional GRIN-SCH QW structures with their tight optical confinement in the transverse vertical (fast-axis) direction usually yield large divergence angles $\theta_{\perp} > 30^{\circ}$. However, this results in highly asymmetric elliptical far-field patterns with high aspect ratios > 3.5 , which require sophisticated optical systems to achieve acceptable coupling efficiencies (cf. Section 1.4.3.3). Tuning the composition of the cladding and GRIN-SCH layers or reducing their thicknesses can lower $\theta_{\perp}$ to $\approx 25^{\circ}$ in InGaAs/AlGaAs lasers, but at the expense of lower kink-free powers and efficiencies and higher threshold currents; $\theta_{\perp}$ decreases at a rate of $\cong 1^{\circ}$ per 1% AlAs mole fraction reduction in these lasers.

Expanding the optical mode in the transverse vertical direction is now a proven and powerful concept to reduce strongly the divergence angle with the additional advantages of:

- maintaining the low threshold current;
- lower risk of COMD failures at high-power operation;
- single-mode operation and suppression of higher order mode lasing; and
- suppression of beam filamentation effects.

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There are many different approaches to realize this concept, each with its own pros and cons. In the following, we try to categorize the different approaches and discuss the major technologies.

Thin waveguides

By thinning the active waveguide layer much below the thickness used in conventional designs, the fast-axis divergence angle can be strongly reduced and the maximum output power limited by COD increased. Narrow-stripe (Al)GaAs lasers with thin active waveguides of only $\cong 0.04 \mu\text{m}$ thickness, which is typically about five times less than in conventional lasers, yield $\theta_{\perp} \cong 16^{\circ}$ and $P \cong 200 \text{ mW}$ (Hamada *et al.*, 1985). However, the strong spreading of the mode far into the cladding layers leads to significant free-carrier absorption resulting in an increase of threshold current and decrease in differential external quantum efficiency. This drawback can be mitigated by the so-called thin tapered-thickness approach where the active waveguide is thicker in the bulk of the laser cavity than near the mirrors. In this way, the fast-axis divergence angle and threshold current can be controlled independently and values of 10° and 60 mA , respectively, from (Al)GaAs devices $3.5 \mu\text{m}$ wide have been obtained (Murakami *et al.*, 1987). Another approach includes an asymmetrically expanded optical mode toward the substrate side by increasing the refractive index of the n-cladding layer relative to that of the p-cladding. This design can furnish low divergence angles $\theta_{\perp} \cong 23^{\circ}$, $\theta_{\parallel} \cong 9^{\circ}$, low threshold currents $I_{th} \cong 40 \text{ mA}$, and high kink-free powers of 600 mW from 980 nm strained InGaAs/AlGaAs DQW lasers $3.5 \mu\text{m}$ wide and $1500 \mu\text{m}$ long (Shigihara *et al.*, 2002).

The above experimental values for $\theta_{\perp}$ can be confirmed to a good approximation with values calculated on the basis of the formula (cf. Equation 1.43) discussed in Section 1.3.5.3. In general, lasers based on the thin-waveguide structure approach may be sensitive to instabilities, which could be caused by the weak localization of the mode, refractive index changes due to current injection, and variations in the fabrication processes.

Broad waveguides and decoupled confinement heterostructures

Broad-waveguide (BW) SCH lasers have been developed primarily to achieve high cw power levels by providing concomitantly both a large equivalent transverse vertical mode spot size d/Γ_{iv} as well as low internal cavity losses $\alpha_i \leq 1 \text{ cm}^{-1}$ with no sacrifice in wall-plug efficiency at high drive current levels; here d is the active layer thickness and Γ_{iv} the transverse vertical confinement factor. From the definition of the internal optical power density at COMD, $\overline{P_{COMD}}$, Botez (1999b) derived an expression for the maximum cw power

$$P_{max,cw} = \left(\frac{d}{\Gamma_{iv}} \right) W \left(\frac{1 - R_f}{1 + R_f} \right) \overline{P_{COMD}} \quad (2.8)$$

where W is the stripe width and R_f the front-facet reflectivity. One way to increase d/Γ_{iv} is to use a BW-SCH structure by expanding the fundamental mode through

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increasing the SCH guiding layer thickness t_c . The SCH layer with index $n_{r,w}$ is sandwiched between cladding layers which have an index $n_{r,cl} < n_{r,w}$. Accurate analytical approximations for d/Γ_{iv} and $\theta_{\perp}$ have been given by Botez (1999b) as

$$\frac{d}{\Gamma_{iv}} \cong t_c (0.31 + 2.1/D^{3/2}) \sqrt{\pi/2} \quad \text{for } \pi < D < 3\pi \quad (2.9)$$

$$\theta \cong 1.18 \tan^{-1} (\lambda/\pi w_0) \quad (2.10)$$

where w_0 is the equivalent near-field Gaussian waist

$$w_0 = t_c (0.31 + 2.2/D^{3/2} + 30/D^6) \quad (2.11)$$

and D is the normalized waveguide thickness defined as

$$D = (2\pi/\lambda) t_c (n_{r,w}^2 - n_{r,cl}^2)^{1/2} \quad (2.12)$$

and where $n_{r,w}$ and $n_{r,cl}$ are the refractive indices of the waveguide layer and cladding layer, respectively, λ is the vacuum wavelength, and $n_{r,w} > n_{r,cl}$.

For large $d/\Gamma_{iv} \gtrsim 0.66 \mu\text{m}$ values, $0.97 \mu\text{m}$ emitting InGaAs/InGaAs(P)/GaAs BW-SCH QW lasers $100 \mu\text{m}$ wide and 2 mm long with high values for $T_{\eta} \cong 1800 \text{ K}$ and $\eta_d > 85\%$, high cw power levels of 11 W and low fast-axis divergence angles $\theta_{\perp} \cong 22^\circ$ could be obtained. These devices are designed for $t_c \cong 1 \mu\text{m}$, which is lower than the cutoff thickness for the second-order mode. The experimental $\theta_{\perp}$ data are in excellent agreement with calculations based on Equation (2.10). Further decrease of $\theta_{\perp}$ can be obtained by decreasing the index step, $\Delta n_r = n_{r,w} - n_{r,cl}$, which is consistent with the thin-waveguide concept discussed in the previous subsection.

A major problem with the BW concept is that low divergence angles and high powers with low-risk COD failures can be obtained, but at the expense of the excitation of higher order transverse vertical modes at high injection currents.

In the context of the BW-SCH approach, we want to discuss the decoupled confinement heterostructure (DCH) concept (Hausser *et al.*, 1993). In the DCH design, the electronic and optical confinements are decoupled by an internal barrier, and hence both can be optimized independently. It is characterized by a broadened waveguide and thin carrier block layers sandwiching the active region. These barrier layers have to be thick enough to prevent carrier leakage, while being as thin as possible ($< 40 \text{ nm}$) so as not to appreciably affect the optical waveguiding. Crucial for a proper operation of the barriers is that they are highly n(p)-type doped on the n(p)-side of the junction with typically $3 \times 10^{18} \text{ cm}^{-3}$. Thus, these highly doped thin barrier layers pose no obstacle to majority carrier injection into the active layer, and they act as efficient barriers for the minority carriers in order to prevent carrier leakage. Undoped barrier layers not only lead to carrier leakage of minority carriers, but also inhibit an efficient injection of majority carriers.

Numerical simulations have shown that the leakage currents depend sensitively on barrier width, barrier doping, and barrier material. The simulations showed that hole (electron) leakage in an InGaAsP/InP DCH laser system can be suppressed to

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$\sim 1\%$ (14%), which compares to $\sim 24\%$ (27%) in a symmetric SCH structure (Hausser *et al.*, 1993). The smaller improvement in electron leakage may be due to the fact that the thin barrier layers are less efficient for electrons due to their much lower mass compared to that of holes. The suppression of carrier leakage in DCH lasers leads to lower internal optical losses and an increase in the characteristic temperature T_0 .

By lowering the confinement factor Γ_{iv} , and in combination with the reduced optical losses, the hole burning effect and hence filamentation can be suppressed (see Section 2.2.1.6). This leads to more stable single-mode lasers with higher single-mode power operation. In addition, the DCH structure allows lowering of the Al content in the waveguide and cladding layers of Al-based lasers compared to SCH lasers. The effect results in less laser heating, improved power conversion efficiency, and higher reliability due to a lower electrical and thermal resistivity. Thus, optimized InGaAs/AlGaAs SQW DCH lasers have delivered 9.5 W cw for devices 100 μm wide (thermal rollover limited). Narrow devices with buried ridge waveguides 4–6 μm wide emitted up to 1.3 W cw thermal rollover power and 0.7 W cw single transverse lateral mode, kink-free power in FWHM beam divergence angles of 20° and 8° in the fast-axis and slow-axis directions, respectively (Yamada *et al.*, 1999).

Low refractive index mode puller layers

The intensity profile of the optical mode is engineered by manipulating the spatial variation of the refractive index of the cladding layers in such a way as to achieve both small beam divergence and low threshold current. This is realized by implementing a lower refractive index layer between the GRIN-SCH confinement and cladding layer on both sides of the waveguide.

The design principle is to maximize the mode intensity in the center of the active layer to achieve low threshold currents and to expand the optical field outside into the claddings to achieve small beam divergence angles (Yen and Lee, 1996a). The optical mode in the GRIN-SCH QW region is tightly confined, whereas outside of the low-index layers the mode spreads because the lasing mode index is reduced by the two low-index layers to be close to the index of the claddings.

This effect is illustrated in Figure 2.2 by comparing the calculated near-field profile of the new structure to that of the conventional one in InGaAs/AlGaAs GRIN-SCH QW devices; the calculations have been carried out by using the commercial simulation package LASTIP (Crosslight Software Inc., 2009). The corresponding experimental transverse vertical far-field profiles (Figure 2.3) show a reduction of $\theta_\perp$ from 32° to 19° for these nonoptimized InGaAs/AlGaAs lasers, which also showed no change in the threshold current (Epperlein *et al.*, 2000, unpublished).

In general, $\theta_\perp$ decreases with increasing Al content (corresponds to decreasing index) and thickness of the AlGaAs mode puller layers, and with decreasing Al content in the AlGaAs claddings. The reason is clear that as the cladding index increases to be closer to the lasing mode index, the lasing mode becomes more expanded leading to a smaller $\theta_\perp$ and increased I_{th} . Further decreasing the Al content of the claddings is critical since the cladding index can exceed the fundamental mode index. As a result, there is no guided mode in the waveguide (Lin *et al.*, 1996).

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- InGaAs/AlGaAs lasers, 10 μm wide, 1.5 mm long, and with a threshold current of 200 mA, emit at 980 nm in single-mode 1.2 W cw into a narrow far-field pattern with angles $\theta_{\perp} \cong 4^{\circ}$ and $\theta_{\parallel} \cong 3.5^{\circ}$. The 10 μm wide devices showed single transverse lateral mode operation up to high pump currents, which demonstrates the potential of the LPBC structure for single lateral mode operation in wider stripe lasers (Maximov *et al.*, 2008).

2.1.3.6 Stability of the fundamental transverse vertical mode

A major problem with some of the approaches discussed in the preceding section for expanding the optical mode is that low beam divergence angles and high COMD power levels may be obtained but at the expense of the excitation of higher order transverse vertical modes at high injection currents. This is particularly the case for approaches based on conventional waveguides such as broad waveguides or mode puller schemes employing the insertion of low refractive index layers or passive waveguide layers into the claddings on both sides of the gain-generating active region.

If the modal spot size or more precisely the equivalent transverse spot size d/Γ_{iv} exceeds a critical value, the effective waveguide width (thickness) may exceed the cutoff thicknesses for higher order mode excitations and the differences in the optical confinement factor between fundamental and higher order modes become very small. According to Botez (1999b), this can occur for 970 nm InGaAs/InGaAsP/InGaP BW structures with $d/\Gamma_{iv} \cong 0.42, 0.58$, and $0.75 \mu\text{m}$, leading to effective waveguide widths (thicknesses) of $\cong 0.53, 1.1$, and $1.58 \mu\text{m}$, which correspond to the cutoff thickness for first-, second-, and third-order mode excitation, respectively.

In addition, the power reflectivity of higher order modes is larger than that of the fundamental mode (Casey and Panish, 1978). Consequently, at relatively thin waveguide thicknesses $\gtrsim 0.5 \mu\text{m}$ multiple transverse vertical mode operation may degrade the far-field pattern and cause kinks in the P/I characteristics due to mode switching effects.

Another drawback with these approaches may originate from the high sensitivity of the field confinement at the large spot sizes to minor changes in the refractive index caused by current injection as well as compositional and temperature instabilities.

Altogether, it appears that these approaches enable only in a very limited design and operational space a reliable and robust laser operation with a stable optical mode. Similar limitations may also be true for the thin waveguide structure approach. Spot-size converters, however, may be very effective in achieving the lowest far-field divergence patterns of $7^{\circ} \times 6^{\circ}$ with nearly circular beam shapes, but impose great requirements on the design and fabrication of tapered waveguides to achieve the highest possible transformation of the optical mode and power in a reliable and reproducible way.

In the LPBC approach, the mode localization strength depends sensitively on the thickness and refractive index of the core layer comprising the active QW structure and forming the actual optical defect feature. Any variation of the defect thickness may

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change the localization of the fundamental mode and hence the confinement strength relative to that for higher order modes. However, even for up to 30% variations in the defect thickness, the leakage of higher order modes remains much larger and therefore continues to provide single-mode lasing and low fast-axis beam divergence of typically 8° for the fundamental mode. In principle, the LPBC approach enables the design of ultrabroad waveguides in a very robust way, which includes the insensitivity to variations over a wider range of active region thicknesses and refractive indices.

Finally, it has been demonstrated experimentally that the LPBC laser design is capable of delivering single lateral mode cw powers of up to 3 W from stripe lasers 10–20 μm wide emitted into a low transverse lateral far-field angle of $\lesssim 2^\circ$ (Maximov *et al.*, 2005).

2.1.4 Narrow-stripe weakly index-guided transverse lateral waveguides

2.1.4.1 Ridge waveguide

In Chapter 1, we discussed a weakly index-guiding approach realized in rib and ridge waveguide types of lasers. Common to these designs is that the thickness of at least one layer is laterally nonuniform. In both types of scheme, the lateral laser structure can be modified such that an effective refractive index step of $<10^{-2}$ is generated under the rib or ridge zone. This index step is larger than the carrier-induced index suppression leading then to a relatively stable index-guiding of the lateral mode. In rib lasers, the thickness, for example, of the waveguide layer or the active layer, can be varied laterally. However, current spreading in the p-cladding layer can affect the threshold current density.

In ridge lasers, where the ridge is formed in the upper p-cladding by etching and embedded in a dielectric layer, the loss of effective current by current spreading is less pronounced. However, carrier diffusion in the active layer, which extends beyond the ridge, affects the threshold current, but also produces a continuous lateral variation of gain and index. The partial overlap of the mode with the dielectric layer forms an effective index step with a size determined by the height of the ridge and the residual thickness to the active layer, which is the thickness of the remaining p-cladding layer outside the ridge. A sensitive adjustment of the etch depth is required to provide enough effective lateral index step for single lateral mode operation. The beam quality and fundamental mode operation of ridge waveguide lasers are sensitively dependent on the design of critical ridge dimensions and their control during device fabrication. These topics will be discussed in more detail in Section 2.3 below.

Narrow ridge waveguide, single-emitter lasers have been extensively investigated and are widely employed in many key application areas because of their:

- simple fabrication technology requiring only one single epitaxial growth step;
- low optical losses;
- low threshold currents;

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a two-step MOCVD process. The first step is up to the high-index guide layer (to be patterned to the lateral anti-resonant reflectors) and includes the vertical n-cladding, active waveguide structure and a current blocking layer used in the finished so-called self-aligned stripe (SAS) device geometry to restrict current injection to the low-index core region. The ARROW pattern is defined by conventional photolithography and wet chemical etching prior to the second growth step, which includes the thick vertical p-type cladding layer and the p^+ -doped contact layer. The lateral effective index step is designed such that the reflector regions with typical widths of $0.9\text{ }\mu\text{m}$ are anti-resonant for the fundamental ARROW mode. The injected current is self-aligned to the low-index core region by the current blocking layers (reverse-biased junctions). The thicknesses of these layers are chosen such that the effective refractive index in the regions outside the high-index reflectors is identical to that in the core region (Yang *et al.*, 1998).

Mode calculations on a 2D ARROW waveguide structure (Yang *et al.*, 1998) show that the dominant mechanism for higher order mode discrimination is lateral edge radiation loss resulting in a low loss of $\sim 2\text{ cm}^{-1}$ for the fundamental mode and high losses of $>16\text{ cm}^{-1}$ for the higher order modes calculated for a 970 nm InGaAs/InGaAsP laser structure. Such a large difference in edge losses and the immunity to gain-spatial hole burning are essential prerequisites for operating the laser in single spatial mode to high drive currents in excess of 10 times threshold. Calculations also show that the mode discrimination is large over a wide range of effective index step size, which leads to more relaxed fabrication tolerances and hence reproducible device parameters.

Measured far-field patterns show transverse lateral divergence angles as low as 4.5° from core devices $6.5\text{ }\mu\text{m}$ wide in single-mode operation (Yang *et al.*, 1998). The best single-mode output powers of 300 mW cw are from single-core structures $4\text{ }\mu\text{m}$ wide emitting into a narrow transverse lateral far-field pattern with half-width angle $\theta_{||} = 9^\circ$ (Mawst *et al.*, 1992a).

2.1.4.6 Stability of the fundamental transverse lateral mode

In the preceding sections, we have briefly described the strengths and weaknesses of the various approaches with respect to stable and reproducible operation of diode lasers in the fundamental transverse lateral mode. In this section, we discuss and summarize the major features of each technique relating to this stability issue.

In general, a major challenge for high-power diode lasers is the lateral mode instabilities that arise from the conflicting design requirements for high output power and single transverse lateral mode operation. In the sections above, we have shown that a large optical mode size is required for various reasons to achieve a narrow and preferably circular far-field pattern and to avoid damage to the facets. In the fast-axis direction, the optical confinement is determined by the layer structure, and the waveguide in this direction has to be thin enough to support only the fundamental mode even at high output powers. In the transverse lateral direction, a small refractive index step is required to suppress the higher order modes in the waveguide with a large lateral mode size. In various studies, it has been shown that the coherent superposition

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of the various transverse lateral modes is responsible for the formation of kinks in the *P/I* characteristics and far-field beam steering effects (Guthrie *et al.*, 1994; Schemmann *et al.*, 1995). Therefore, to achieve high-power single-mode output, two approaches can be taken to design waveguides either that support only the fundamental lateral mode or that allow higher order lateral modes but with a gain insufficient to reach lasing threshold.

The mode stability of ridge lasers is primarily determined by the waveguide geometry and layer composition where the dominating parameters are the ridge width and residual waveguide thickness in the etched regions outside the ridge. In Section 2.3, we discuss the results of a sensitivity analysis performed on the dependence of the fundamental mode and far-field pattern in the transverse lateral direction on these parameters. These results show a very limited window for fundamental mode operation determined by relatively narrow ranges of ridge widths, residual thicknesses, and slow-axis beam divergence angles for a given vertical laser structure. Proven practical approaches to obtain in the etching process the optimum residual thickness leading to single-mode devices with low threshold current and slow-axis beam divergence angle include applying the ridge etch, first at specific locations of a companion wafer, before applying a beveled etch across the actual laser wafer. This procedure can enhance the yield of fit-for-purpose laser devices.

For a given ridge width, the number of modes supported by a ridge waveguide, and their lasing conditions, depend on both the difference in effective refractive index between the regions within and outside the ridge and the transverse lateral gain distribution which couples to the field. However, this built-in index step can be very different to the actual index profile caused by detrimental effects such as index changes by carrier injection (Xu *et al.*, 1996), local thermal heating, and mechanical stress, resulting in the emergence of higher order lateral modes. For instance, time-dependent measurements on the laser beam quality degradation show that the temperature profile in the cavity plays a significant role in the transverse lateral guiding of the lasing modes (Hunziker and Harder, 1995).

Other approaches affecting the discrimination between the fundamental and higher order modes as well as the threshold current are to reduce the ridge height and p-cladding layer thickness (Wu *et al.*, 1995). In Section 2.2, we describe how, from the point of view of a lateral index step, a low-ridge and thin p-cladding device can be considered as equivalent to a high-ridge, thick p-cladding device and can deliver the same low-index step of $\sim 3 \times 10^{-3}$ required for stable single-mode operation. In addition, we describe results from numerical studies (Chen *et al.*, 2009) on the lateral mode behavior impacted by effects such as self-heating, spatial hole burning, lateral carrier distribution, and gain profile variation with increasing input current.

Most of the topics discussed above as potential parameters determining the stable fundamental lateral mode operation of ridge waveguide lasers are also valid for planar BH lasers realized by a QWI process, which leads to real refractive index lateral waveguides. This includes parameters such as effective waveguide width and height, p-cladding thickness, and all perturbing contributions with the potential to cause the generation of higher order optical modes as discussed above. The compositional modification in the QW structure, especially in strained material systems, raises the

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question of QW material quality after the intermixing process, which could give rise to mode instabilities. In general, it has been demonstrated that no degradation in the quality of the QW takes place: for instance, PL spectra show that strained QWs are still coherently strained, and InGaAs/GaAs SQWs disordered by shallow As implantation and thermal annealing show good structural integrity. However, on the other hand, compositional interdiffusion in lattice-matched InGaAs/InP systems can give rise to a strained structure after the QWI process. High-resolution transmission electron microscopy lattice images show no misfit dislocations in these disordered structures and the lasers show no degradation in threshold current.

The weakly index-guided buried-stripe laser has the built-in advantage of maintaining stable fundamental transverse lateral mode operation up to high power even with the occurrence of spatial hole burning. However, the laser device has to be carefully designed and fabricated, requiring a low transverse lateral index step of $\sim 3.5 \times 10^{-3}$, a narrow buried-stripe width of 2.2 μm , and a defect-free etching of the stripe and optimum regrowth of the upper layers. A novel double etch-stop structure and associated selective etching processes can realize these requirements to maintain the stability of the mode. The geometrical and compositional tolerances acceptable for stable transverse lateral mode operation are not known. One reason for achieving stable mode operation is that in this structure the thickness of the p-type cladding layer outside the buried-stripe region, which significantly affects the transverse lateral mode, can be controlled more precisely than, for example, in a ridge waveguide. In addition, the fabrication process involves a self-alignment process, which supports the geometrical specifications to be met for transverse lateral mode operation. Furthermore, long cavity structures provide better thermal conditions and reduce the effective injected carrier density in the active region, which, in turn, leads to a very stable transverse lateral mode. In addition, the thickness of the cladding layers is 2.2 μm in order to suppress resonant mode coupling between the ordinary mode in the laser waveguide (laser mode) and an unusual mode (substrate mode) propagating in the transparent substrate, which has a larger refractive index than the cladding layers. The thick cladding layers lead to an improved linearity of the P/I characteristic due to the elimination of substrate mode-induced mode hopping. Finally, stable transverse lateral mode operation is also demonstrated in long-term laser stress tests performed at high optical output power and high temperature (Horie *et al.*, 2000).

Slab-coupled waveguide lasers with a large, properly designed passive rib waveguide support in principle only one bound spatial mode due to coupling of the higher order modes into the slab modes. However, only slight changes in waveguide geometry can lead to mode changes, such as devices with wider ribs (e.g., increase from 4.6 to 5.4 μm) and shallower etch depths have lower lateral index confinements, which can contribute to the emergence of mode instabilities at higher power levels. These instabilities are thermal in origin as demonstrated in pulsed measurements with increasing pulse length at constant current. This means that the emergence of higher order lateral modes is due to a thermally induced increase in refractive index in the rib region. The low modal loss of these lasers permits very long devices, making it easier to handle power dissipation at high-power operation without thermal waveguiding, and therefore can lead to more stable modes. It has been found that the cw power at

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which mode instabilities occur increases with cavity length and correlates with the electrical power dissipation per unit length, which indicates again the role of thermal gradient effects in the mode instability issue by enabling the formation of higher order modes. It has also been shown that there is a maximum cw output power, which depends on the modal optical loss and the normalized series resistance, which is the product of the series resistance and device length. Devices with calculated optimum lengths of typically 1 cm show stable mode behavior over the entire drive current range up to the COMD power level with no signs of beam steering, but with only a slight widening of the beam divergence angles at higher currents, most likely due to thermal effects (Donnelly *et al.*, 2003).

The single-mode operation of the ARROW diode laser relies on the large built-in lateral refractive index step formed by the central low-index core region and the surrounding high-index, quarter-wave anti-resonant reflecting regions. The fundamental spatial ARROW mode exhibits low loss over a relatively large range in index step while the first-order mode suffers a large loss. This ensures stable single-mode operation to high output power levels and strong discrimination against higher order lateral modes. The large mode discrimination over a wide range of effective index steps demonstrates a relatively large tolerance window of fabrication parameters over which single-mode operation can be obtained. However, unequal widths of the two quarter-wave reflectors due, for instance, to a slight deviation of the photolithography alignment, can cause the emergence of an asymmetrical shoulder in the transverse lateral far-field beam pattern (Yang *et al.*, 1998).

Regarding transverse vertical mode stability, it has been shown that ARROW devices with a high transverse vertical optical confinement factor $\Gamma_{tv} = 3\%$ reach the threshold for higher order modes much earlier than devices with low $\Gamma_{tv} = 1\%$, due both to gain profile distortion and to distortion of the effective index profile in the device core with increasing drive current. Devices with cores 8.5 μm wide and $\Gamma_{tv} = 1\%$ can stay single-mode to more than 40 times threshold, which permits the projection of stable single-mode operation up to >1 W power levels. In contrast, core lasers 10 μm wide become multimode at about 10 times threshold with experimental stable single-mode powers to 300 mW for $\Gamma_{tv} = 1.5\%$ diode lasers (Chang *et al.*, 2002).

2.1.5 Thermal management

The previous discussions in this chapter have dealt intensively with design approaches aimed at achieving high optical output power of narrow-stripe diode lasers. These approaches were elaborated in Sections 2.1.1–2.1.4. Whenever relevant in the course of the previous chapter and this chapter, we have pointed to the significance of having an effective thermal management in place. Equation (2.1) summarizes the direct and indirect involvement of relevant temperature-related parameters for realizing high optical output power. Thermal management is an important factor not only to achieve high output powers, but also, as we will see in later chapters, to obtain long operational lifetimes and high reliability by minimizing temperature-dependent laser degradation effects.

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Finally, we determine the condition to match the slow-axis numerical aperture (NA) of a diode laser to the NA of a fiber. In analogy to the NA of a fiber (see Equation 1.66b) we can write

$$\begin{aligned} (\text{NA})^2 &= (n_{r,\text{eff}}^{\text{in}})^2 - (n_{r,\text{eff}}^{\text{out}})^2 \\ &= (n_{r,\text{eff}}^{\text{out}} + \Delta n_{r,\text{tl}})^2 - (n_{r,\text{eff}}^{\text{out}})^2 \\ &\cong 2n_{r,\text{eff}}^{\text{out}} \Delta n_{r,\text{tl}} \end{aligned} \quad (2.21)$$

from which the index step as a function of the NA is obtained as

$$\Delta n_{r,\text{tl}} = \frac{(\text{NA})^2}{2n_{r,\text{eff}}^{\text{out}}}. \quad (2.22)$$

Typical NAs of single-mode and multimode fibers are 0.1 and 0.2, which lead to small index steps of 1.5×10^{-3} and 6×10^{-3} , respectively, by using a typical value of 3.3 for the refractive index. In Section 2.1.4, we described various technologies that can be used to fabricate transverse lateral waveguides with small-index steps.

2.2.1.2 Fundamental mode waveguide optimizations

Waveguide geometry; internal physical mechanisms

The ridge waveguide structure has proven to be the simplest and most straightforward way of achieving high-power single spatial mode diode laser operation. Far-field patterns and single-mode operation can be controlled easily. However, stringent dimensional tolerances are required to achieve good performance in these weakly index-guided laser devices. This includes particularly ridge width and height as well as the residual thickness of the p-type cladding layer, which can be linked to the ridge height. Detrimental effects include changes in refractive index profile by local thermal heating and carrier injection, spatial hole burning, lateral current spreading, and gain profile variations.

Numerical studies performed on the lateral mode behavior of (Al)GaInP QW lasers with ridge widths of 2.4–3.6 μm , residual thicknesses of 0.1–0.2 μm , and a constant p-cladding thickness of 2 μm have produced the following major results (Chen *et al.*, 2009). The cutoff condition for single fundamental lateral mode operation is mainly dependent on the effective lateral index step and ridge width. The emergence of the first-order mode is sensitive to the ridge height as the ridge width is increased, and can be effectively suppressed by narrow and shallow ridge geometries. The lateral carrier distribution in the active region is strongly affected by the ridge height, which changes the lateral gain profile and influences the lateral modes. Devices with wider ridges have sufficient modal gain to meet the threshold condition of the first-order lateral mode. The threshold current of the first-order lateral mode increases with decreasing ridge width and height.

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This can be understood by the fact that narrower ridge widths provide better lateral confinement of electrons and holes. Consequently, carriers confined in the ridge center support the fundamental mode at low drive currents. At higher currents above the threshold current of the fundamental mode, however, the lateral carrier distributions, which overlap with the optical mode profile of the fundamental mode, are used up by the increased stimulated emission. This means a more pronounced lateral spatial hole burning effect at higher currents with the consequence that the higher order mode is then favored due to the improved match between the optical mode profile and the lateral gain distribution.

In addition to carrier spatial hole burning, temperature-induced refractive index change between the inside and outside ridge regions is another mechanism responsible for the emergence of higher order modes. Although narrower ridge widths may cause anti-guiding effects due to strong increases in carrier density at high drive currents, the temperature-induced index difference becomes larger with increasing current and may push the laser device beyond the cutoff condition. This effect is also stronger for higher ridge structures due to their poor heat dissipation. Lasers with higher ridge heights are also more susceptible to spatial hole burning and therefore more prone to the emergence of higher order lateral modes.

Different ridge heights have also a different effect on current spreading in the lateral direction. Simulations show (Chen *et al.*, 2009) that the electron and hole concentration within the active region is larger for a high-ridge than for a low-ridge structure, which leads to a higher lateral interband gain profile, in particular at the ridge boundary of the high-ridge structure. This higher gain profile, however, supports the emergence of higher order lateral modes in high-ridge laser devices.

These results are confirmed by independent self-consistent 2D modeling (Xu *et al.*, 1996), in particular that low-ridge devices have a higher first-order lateral mode threshold current than high-ridge devices, which is also consistent with the considerable increase in kink power measured in laser devices just by decreasing the ridge height. Furthermore, the modal gain of the first-order lateral mode of low-ridge lasers increases with injected current at a slower rate ($\sim 6\%$) than that of high-ridge devices. Depending on the value of the mirror loss, the gain/current curves of low-ridge and high-ridge devices may cross each other before the first-order mode lasing occurs, which would reverse the order in the occurrence of the kink in the P/I characteristics of the two laser types. The simulations show that for a ridge waveguide laser, which supports only one lateral mode in the “unbiased” state, it is still possible for the first-order mode to emerge at higher injection currents, caused by a carrier-induced strong change of the built-in lateral refractive index profile and spatial hole burning (self-focusing) effects. They also support the experimental results where the use of low-ridge and thin p-claddings results in ridge lasers with low thresholds and high single-mode output power (Wu *et al.*, 1995).

The latter study shows that, from an index-step point of view, a low-ridge ($\cong 130$ nm), thin p-cladding ($\cong 250$ nm) InGaAs/AlGaAs QW laser device is equivalent to a high-ridge ($\cong 1200$ nm), thick p-cladding ($\cong 1300$ nm) device leading to an index step of $\cong 3 \times 10^{-3}$. The fact that low-ridge, thin p-cladding devices do not show the strong threshold effect as the ridge width is narrowed, demonstrates that the

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index step is the key parameter that determines device performance. These devices operate in a single spatial mode up to high cw power levels if the ridge width is sufficiently narrow (Wu *et al.*, 1995).

Figures of merit

In another approach, systematic simulations have been carried out (Laakso *et al.*, 2008) to investigate the dimensional range that ensures stable single transverse mode operation of InGaAs/AlGaAs ridge waveguide edge-emitting lasers over the whole bias range by employing both a fast 2D mode solver and the commercial software package LASTIP (Crosslight Software Inc., 2010). A quantitative figure of merit, based on the “under-the-ridge” active layer total optical confinement factor ($\Gamma = \Gamma_{iv}\Gamma_{tl}$), indicates the likelihood of single transverse modal behavior over a broad range of ridge widths and residual thicknesses. The definition of a figure of merit for stable single transverse mode operation is associated with the maximization of the following expression (Laakso *et al.*, 2008):

$$\Gamma_{1m} = (g\Gamma_1 - g\Gamma_m) / g\Gamma_1 = (\Gamma_1 - \Gamma_m) / \Gamma_1 \quad (2.23)$$

where Γ_1 and Γ_m are the confinement factors of the $m = 1$ (fundamental) and $m > 1$ transverse modes, respectively, and g is the local gain.

The evaluation of the single transverse mode operation space can be simplified by studying just Γ_{12} and Γ_{13} , because $\Gamma_2 > \Gamma_4, \Gamma_6$, etc., and $\Gamma_3 > \Gamma_5, \Gamma_7$, etc. Therefore, Γ_{12} and Γ_{13} as well as the product $\Gamma_{12} \times \Gamma_{13}$ can be considered as useful *figures of merit*. For large Γ_{12} (resp. Γ_{13}) values close to one, the second (third) and all higher even (odd) modes are suppressed, whereas for lower values the ridge waveguide is likely to operate in a transverse multimode regime. Stable single mode operation is achieved when both Γ_{12} and Γ_{13} , that is, the product $\Gamma_{12} \times \Gamma_{13}$, have large values close to unity.

Figure 2.12 summarizes the major trend of results obtained from simulations carried out for ridge widths in the range of 2 to 8 μm and residual p-cladding layer thicknesses between 0 and 600 nm of InGaAs QW lasers with GaAs waveguide layers 140 nm thick, Al_{0.6}Ga_{0.4}As cladding layers 1500 nm thick, and p⁺-GaAs contact layers 200 nm thick (Laakso *et al.*, 2008).

Stable single-mode operation can be achieved over a relatively wide range of residual thicknesses, in particular for each ridge width up to about 4 μm . However, the lowest possible thickness ensuring a large value for $\Gamma_{12} \times \Gamma_{13}$ should be targeted, because high residual thicknesses cause a reduction in confinement and gain of the fundamental transverse mode resulting in an increased threshold current. Stable single-mode operation is harder to achieve for ridge widths around 5 μm and above, because of the very precise control required to get the high $\Gamma_{12} \times \Gamma_{13}$ value. The size of a high $\Gamma_{12} \times \Gamma_{13}$ area depends on the overlap of high Γ_{12} and high Γ_{13} areas, which can be tuned by the transverse vertical optical mode profile by changing the waveguide thickness and/or the index contrast between the waveguide and cladding layers.

A sensitivity analysis performed by changing the waveguide thickness by ± 60 nm around the original value of 140 nm and AlAs mole fraction by ± 0.1

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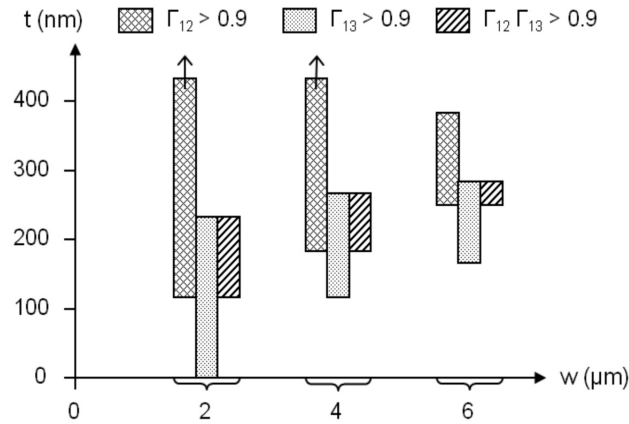


Figure 2.12 Relative and normalized confinement factors Γ_{12} and Γ_{13} and their product $\Gamma_{12}\Gamma_{13}$ calculated for a series of InGaAs/AlGaAs QW ridge waveguide lasers with different widths w and residual thicknesses t . Large values $\Gamma_{12} > 0.9$ ($\Gamma_{13} > 0.9$) mean that the second (third) and all even (odd) modes are suppressed. Single transverse mode operation is achieved when $\Gamma_{12} \times \Gamma_{13} > 0.9$. (Selected data adapted from contour plots of Figure 3 in Laakso *et al.*, 2008.)

around the original value of 0.6 shows that, for example, by reducing the waveguide thickness to 80 nm or decreasing the AlAs mole fraction to 0.5, the area of high $\Gamma_{12} \times \Gamma_{13}$ values can be increased (Laakso *et al.*, 2008).

To demonstrate the size of the effect, Table 2.1 gives as an example for the low and high residual thickness values found for $\Gamma_{12} \times \Gamma_{13} > 0.9$, a ridge width of 2 μm , and four waveguide thickness/AlAs mole fraction combinations. Finally, the investigations showed that, by expanding the transverse vertical near-field pattern into the p-cladding region, single-mode operation could be achieved even with relatively wide and shallow ridge structures having a lower voltage and series resistance. However, the advantages of a wider ridge might be cancelled by an increased threshold current due to a lower confinement factor and higher free carrier absorption of the transverse vertical mode with a higher portion of intensity now in the p-side cladding layer.

Transverse vertical mode expansion; mirror reflectivity; laser length

In Section 2.1.3.5, we discussed concepts to maintain fundamental transverse mode operation at high output power emission and prevent among other things COMD by enlarging the near-field size of the fundamental mode. An improved suppression of higher order lateral modes can be achieved, in particular, by using a layer structure that supports an optical mode asymmetrically expanded toward the substrate into the n-cladding layer of a ridge structure (Shigihara *et al.*, 2002) or by employing a longitudinal photonic bandgap crystal approach for the mode expansion (Maximov *et al.*, 2008). This single-mode improvement can be explained by the facts that, first, the field expansion reduces the influence of the refractive index caused by the ridge profile and, second, the interaction is weaker between the optical field and the ridge

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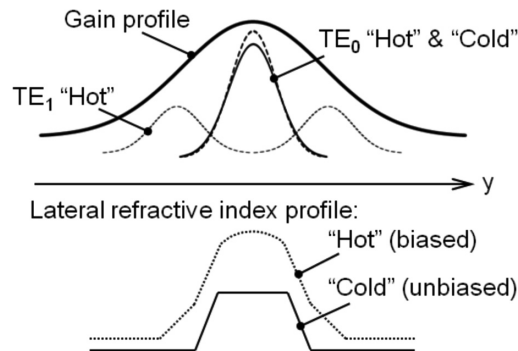


Figure 2.32 Schematic representation of the fundamental and first-order lateral modes in a laser ridge waveguide structure at “cold” (unbiased; solid line) and “hot” (biased; dotted lines) conditions. Qualitative illustration of the emergence of the first-order transverse lateral mode with increasing temperature based on the change of the built-in (cold) refractive index profile and available gain distribution.

regions (Chen *et al.*, 2009; Xu *et al.*, 1996; Wu *et al.*, 1995). The higher gain profile in high-ridge (low- t) structures will then support the emergence of the first-order lateral mode.

Second, and finally, the periodic shape of the kink power versus residual thickness plot in Figure 2.31 (only one period or cluster shown) can be explained with the hybrid mode kink model, which phase-locks the fundamental and first-order lateral mode in coherent conditions. This model has been described in Section 2.2.1.5 and has been developed to explain the periodic kink power versus cavity length dependence (Schemmann *et al.*, 1995). The condition for the emergence of a kink is that Equation (2.26) has to be met. In the case of a fixed cavity length L (as in Figure 2.31), this can be achieved by adjusting the beat length L_b (cf. Equation 2.25) via a change in the propagation constants (refractive indices) of both the lateral modes (cf. Equation 2.24) caused by changing the residual thickness (ridge height). Phase locking occurs only if the difference between the refractive indices of the two lateral modes is not too big, which for a 980 nm laser is around 5×10^{-4} .

2.4 Selected large-area laser concepts and techniques

2.4.1 Introduction

In the previous sections of this chapter, in particular, but also in the previous chapter, we have discussed various common approaches and techniques used in design, materials, and process technologies to achieve single-mode diode laser waveguides capable of delivering the highest kink-free optical powers of 1 W and above from a few micrometer-wide apertures. High-power, narrow-stripe, single-mode lasers can easily be coupled into single-mode fibers and have a dominant application in pumping Er-doped fiber amplifiers for optical communication network systems. To

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overcome power limitations generally encountered with conventional narrow-stripe single-mode lasers, such as ridge waveguide or buried-heterostructure devices, numerous novel structures have been developed with an increased transverse horizontal mode size for output powers in excess of 1 W, but still emitting in a single mode or diffraction-limited beam to deliver high-brightness, broad-area semiconductor lasers. High-power coherent light sources with diffraction-limited beam profiles are needed to allow beam propagation over large distances and good focusing of high optical power into small spots or single-mode fibers in applications such as solid-state laser end pumping, harmonic generation (frequency doubling), free-space optical communication systems, optical memories, printing, direct diode material processing, and military applications.

The simplest configuration is the single-element broad-area laser with a wide output facet in the transverse horizontal direction and a large optical cavity in the transverse vertical direction to achieve a large optical mode volume in order to reduce intrinsic heating effects, optical power density, and therefore facet degradation for high-power operation. However, these gain-guided devices suffer from a strong loss of beam quality, mainly caused by self-focusing and filamentation processes (see Section 2.2.1.6) and multiple lateral mode oscillations, effects that usually occur as the lateral waveguide width exceeds $\sim 10\text{ }\mu\text{m}$. As discussed in Section 2.2.1.6, the formation of filaments is caused by self-focusing of the intracavity laser field in the gain medium. The overlap of the fundamental mode with the gain region is strongly reduced, because the mode's lateral dimension is constricted when the filamentation has emerged.

The consequence is that the inversion, which is not depleted by the fundamental mode, then becomes available to the higher order lateral modes, dramatically increasing the likelihood of multiple mode operation. It has been demonstrated that broad-area devices, in which two counter-propagating beams are present, are susceptible to filamentation at low optical power densities (Lang *et al.*, 1994; Tamburrini *et al.*, 1992). This is in contrast to devices, which avoid counter-propagating beams, such as the unstable resonator laser (see Section 2.4.3), and which are more resistant to filamentation formation up to much higher powers (Goldberg and Mehuys, 1992; Walpole *et al.*, 1992).

Monolithic and multi-chip solutions have been proposed and demonstrated aimed at achieving high-power lasers with single-lobe diffraction-limited beams that can be focused with relatively simple optics. Multi-chip laser devices include external cavity geometries and external injection of broad-area amplifiers, which, however, will not be discussed in this text.

On the other hand, monolithic structures include different conceptual techniques but are not limited to (i) broad-area lasers in different configurations including tailored gain profiles, Gaussian reflectivity facets, and lateral grating-confined tilted waveguides, (ii) unstable resonator lasers, (iii) tapered devices, (iv) master oscillator flared power amplifiers, and (v) laser bar arrays. We will discuss these approaches and techniques in detail in the following sections of this chapter. However, we will not discuss the LPBC concept for application in the 2D structure of a broad-area laser device. We discussed this concept in Section 2.1.3.5 in the context of the 1D structure

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of a narrow single-mode laser and showed the potential of the LPBC structure for the development of high-power single-mode broad-area lasers (Maximov *et al.*, 2008).

A number of issues had to be resolved in the development of some of these techniques. These include an efficient coupling of the output power into a single-lobed far-field pattern, high operating stability over a wide range of powers and temperatures, and a high discrimination of the modes up to high power at sufficient uniformities of gain and refractive index for achieving single-mode operation. In particular, the high nonlinearity and strong coupling between gain and refractive index in semiconductor diode lasers pose a great challenge to the realization of single-mode broad-area lasers.

In the following, we describe the principle of operation, key characteristics, and key performance data of the various monolithic solutions listed above. We should mention that a series of state-of-the-art optical output power data for standard broad-area lasers 100 μm wide, tapered amplifier lasers, and 1 cm laser bar arrays can be found in Tables 1.3, 1.4, and 1.5, respectively.

2.4.2 Broad-area (BA) lasers

2.4.2.1 Introduction

Conventional broad-area (BA) lasers already show at low powers degraded and undesirable slow-axis far-field patterns with non-Gaussian, so-called top-hat shapes superimposed by multiple lobes. In addition to the causes mentioned above, reasons for this degradation can be seen in three aspects (Harder, 2008).

First, higher order lateral modes are extracting the lateral gain profile more effectively than the fundamental mode in particular due to the increased spatial hole burning at high power. In Section 2.4.2.2, we show how this detrimental effect can be mitigated by tailoring the spatial gain profile via nonuniform current injection into the laser device.

Second, at high-power operation the temperature in the waveguide rises and the increase is higher in the center than at the edges due to a poorer heat extraction efficiency, which causes a temperature difference ΔT leading to a lateral difference in the refractive index Δn_r and hence to the formation of a thermal waveguide. Analogous to the formula derived for the NA of a fiber (see Equation 1.66b), the NA of this thermal waveguide can be evaluated according to

$$\text{NA}^2 = (n_r + \Delta n_r)^2 - n_r^2 \cong 2n_r(\Delta n_r/\Delta T)\Delta T \quad (2.30)$$

where n_r is the index of the waveguide at the edges. Taking only a small $\Delta T = 5 \text{ K}$ (see Chapter 9), a typical value of $4 \times 10^{-4} \text{ K}^{-1}$ for the temperature coefficient of the index (cf. Section 1.3.6) and $n_r = 3.3$ for AlGaAs results in $\text{NA} \cong 0.11$. Thermal waveguiding is certainly an issue for the slow-axis NA degradation and can be reduced by efficient heat extraction and heat sinking of the laser chip. However, an ideal solution would be an athermal waveguide structure showing no dependence of its modal index on temperature.

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Third, gain guiding can be caused by changes in the lateral gain profile and refractive index due to carrier injection. In Sections 2.2 and 2.3, we discussed various approaches and techniques to improve the slow-axis beam divergence pattern of narrow-stripe diode lasers. Similarly, mode filter schemes for BA diode lasers have been developed. We will present two of them below in Sections 2.4.2.3 and 2.4.2.4.

For completeness, we should mention a technique that is outside the mainstream of common techniques for engineering the intrinsic materials and design parameters of a BA laser to achieve a single-lobed diffraction-limited spot. A spectrally resolved phase manipulation technique, external to the laser cavity, is used to reshape the multiple lateral mode emission of a conventional BA diode laser into a diffraction-limited single-lobe spot. A mode conversion efficiency of 60% with a total insertion loss of 25% has been demonstrated with conventional bulk optical elements and a binary phase mask for a commercially available 980 nm BA laser with a width of 100 μm and length of 1 mm. Using custom designs of the optical elements will allow a laser-to-fiber coupling efficiency of $>50\%$. Advanced designs can reduce the device to a single optical element inserted between the diode laser and optical fiber (Stelmakh, 2007).

2.4.2.2 BA lasers with tailored gain profiles

Conventional BA semiconductor lasers have a nearly uniform lateral gain profile. This results in devices with very wide and unstable slow-axis far-field patterns, which are caused by filamentation and lateral multimode effects. Poor mode discrimination between the fundamental and higher order modes leads to the multi-lobed far-field pattern. Without making the device narrower, this issue can only be solved by creating a nonuniform spatial gain distribution within the device, which favors the fundamental mode and suppresses the higher order modes, then resulting in a single-lobed, diffraction-limited far-field pattern.

This led to the proposal and demonstration of a new type of semiconductor laser: the tailored-gain BA semiconductor diode laser (Lindsey and Yariv, 1988). The 2D gain tailoring is achieved by a predetermined pattern of current injecting and no-current injecting contacts over the surface of the laser device by varying the fractional coverage per unit area of injecting to no-injecting contact. This can be achieved by using a halftone pattern of dots (or any other shapes) which has been formed on a photoresist mask for structuring the contact layer. The technique is reminiscent of the halftone process used in the graphics industry to reproduce a photograph on the printed page. The lateral current injection profile can vary, for example, from a minimum at one side to a maximum at the other, or from a minimum to a maximum to a minimum, resulting in the formation of an asymmetric or symmetric, linear, gain-tailored BA laser, respectively.

The following example may illustrate the effect: in the asymmetric version, the peak gain at one side is fixed by the requirement that at threshold the modal gain of the lasing mode must equal the optical losses, whereas the gain at the opposite side is set at transparency. Calculations for a $0\text{--}60\text{ cm}^{-1}$ linear gain profile across 60 μm width produced theoretical modal gains for the higher order lateral modes, which

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are between 5 and 8 cm⁻¹ less than that of the fundamental mode, which makes it difficult for these modes to reach threshold. This mode discrimination is much higher than with conventional uniform gain BA lasers 60 μm wide, which have modal gains only < 1 cm⁻¹ lower for higher order modes than for the fundamental mode.

Another important difference between uniform and nonuniform gain profiles is the shape of the far-field (FF) patterns. Unlike uniform gain profile lasers, the FF patterns of higher order modes in nonuniform gain profile devices are single-lobed and only slightly displaced from that of the fundamental mode. This means that when gain saturation at high power causes the emergence of higher order modes, the slow-axis FF pattern will stay single lobed albeit somewhat wider. This theoretical prediction is in agreement with experiments and can be considered as a useful feature of BA lasers with asymmetric linear gain profiles (Lindsey and Yariv, 1988). In contrast, higher order modes of symmetric gain structures do not have single-lobed FF patterns.

The experimental slow-axis FF angles of BA lasers 60 μm wide with asymmetrically tailored gain profiles are $\cong 2.5^\circ$, that is, very close to the diffraction limit of $\cong 2^\circ$, and this is also the same for the symmetric gain structure. This value has to be compared to the $\cong 15^\circ$ of the multi-lobed FF pattern obtained for a conventional, uniform gain BA laser with the same width. The gradient in the gain profile plays a crucial role in device performance at high power. Above threshold, gain saturation reduces the gain preferentially in the high-gain areas and thus the nonuniform gain profile tends to become more like that of a conventional BA laser with a uniform gain. This negative effect can be minimized by increasing the gradient in the gain profile. Doubling the value of 0.25%/μm used in the last example produces a single-lobed FF pattern up to much higher power levels and with practically unchanged widths of $\cong 2.5^\circ$. The threshold current of this new class of diode laser is only about 5% higher than that of a conventional, uniform gain BA laser.

Finally, filamentation does not occur in asymmetric gain profile BA lasers in contrast to conventional BA lasers with uniform gain. This result is unexpected and not yet fully understood (Lindsey and Yariv, 1988).

2.4.2.3 BA lasers with Gaussian reflectivity facets

The basic idea of this approach is to achieve lateral mode discrimination in BA diode lasers by applying a smooth spatial mode filtering at the output mirror. This can be accomplished by laterally varying the reflectivity profile of the output facet. The spatial filtering takes place only in the transverse lateral direction parallel to the active layer. Numerical simulations using a beam propagation scheme based on a fast Fourier transform procedure have been used to calculate the optical field and lateral modes in gain-guided AlGaAs double-heterostructure BA lasers (McCarthy and Champagne, 1989). The lasers used in the simulations were 40 μm wide and had a length L between 100 and 400 μm. The rear facet was uncoated with a uniform reflectivity and the front-facet intensity reflectivity profile is a Gaussian function in transverse lateral position y as follows:

$$R_f(y) = R_{f,0} \exp \left\{ -(y/w_f)^2 \right\} \quad (2.31)$$

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in these cases this reflection dominates the cavity modes. This has the effect of broadening the laser linewidth, but it locks the wavelength to the FBG so that multiline operation and *mode hopping* are suppressed. These external feedback effects can drive the laser in the high-power regime into a bistable state between single-mode and *coherence collapse* states (Tkach and Chraplyvy, 1986; Davis *et al.*, 2005). While the laser device experiences an increase in high-frequency noise, low-speed operation is very significantly enhanced, because instabilities associated with mode hopping are removed.

3.2 Classification of degradation modes

This section describes the different degradation modes of a diode laser that can be observed during normal operation or accelerated aging. There are several types of degradation modes in relation to the initial period of degradation, degradation rate, and degree of degradation and which can be grouped by the location of degradation. In the following, we give a classification of these degradation modes by type and location, and describe their specific characteristics and techniques to reduce or eliminate them.

3.2.1 Classification of degradation phenomena by location

Degradation phenomena can be classified by the location of degradation: external degradations occur outside the laser crystal, whereas internal degradations occur only inside the laser crystal. In the first category are degradations of the mirror, contact electrode, and chip solder. The second category includes degradations of the active layer including the p–n junction.

The description of degradation modes in the following two subsections is only meant to be brief within this overview. Full details on every degradation mode can be found in Section 3.1 above and following Section 3.2.2.

3.2.1.1 External degradation

Mirror degradation

This degradation comprises mirror oxidation and COMD.

Mirror oxidation occurs with a much higher rate in 0.85 μm high-Al content AlGaAs/GaAs systems than in 1.3 μm and 1.5 μm band InGaAsP/InP lasers where the oxidation phenomenon is not conspicuously observed due to a very slow oxidation rate. The long-term stability and lifetime of the laser are affected by facet oxidation. The thickness of the oxide layer is proportional to the square root of operating time, and depends on the output power energy, power density, moisture, and composition of the active layer. The oxidation process occurs even in an atmosphere with a low partial pressure of oxygen of around 10^{-6} Torr and its rate increases with increasing Al content. Oxygen in the mirror surface has been clearly detected by Auger electron spectroscopy (Kajimura, 1980). An alternative spectrochemical analysis technique is energy-dispersive x-ray (EDX). Both techniques are performed by exciting the

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sample with the electron beam using scanning electron microscopy (SEM). X-ray production and Auger electron production are, however, competing processes; that is, the excited atom will relax either by emission of an x-ray or an Auger electron, with the x-ray emission more probable for elements of high atomic number.

With respect to the facet oxidation mechanism, it is enhanced effectively by the formation of photoinduced carriers resulting in breakage of the bonds at the facet. Defects can form at the interface between oxide and semiconductor with the potential to enable nonradiative carrier recombination and thus generate facet heating. This in combination with other processes, including strong optical absorption of emitted laser light at the facet and large surface currents due to the large concentrations of native traps at the cleaved facet surface, can trigger a positive feedback loop. The loop comprises in the sequence the processes of optical absorption, carrier generation, nonradiative recombination, facet heating, bandgap reduction, and back to the starting point with an even stronger optical absorption. This process can ultimately lead to thermal runaway and thus COMD and meltdown of the mirror facet. (See Sections 3.2.2.2 and 3.2.2.3 for details on degradation mode features and degradation elimination. See Section 4.1 for facet surface properties acting as microscopic origins for mirror degradation.)

Contact degradation

Contact degradation is caused by diffusion of the electrode metal and by the alloy between the electrode metal and the semiconductor during laser operation at high currents associated with Joule heating of the contact region. The degraded region is outside the active region where an alloy reaction occurred, but high currents and strong heating can drive the alloy reaction toward the active region. There are two ways of establishing an Ohmic contact: by Schottky-type and alloy-type electrodes. In Section 3.1.1.4, we discussed in detail the degradation of both Ohmic contact types in the context of investigating the stability criteria of critical diode laser parameters.

According to these discussions, alloy-type electrodes are susceptible to degradation under practical laser operating conditions. During operation, alloy layers of the metal/group-V elements and metal/group-III elements are formed where the former layers have a higher electrical resistance than the latter ones (Piotrowska *et al.*, 1981). This forces the current to flow in the metal/group-III element alloy layer with the consequence that alloy spikes can form under the current flow, which can finally lead to degradation of the active region. In contrast, Schottky-type contacts are quite stable under practical operating conditions because of the inert metal/semiconductor interface. However, degradation can occur under severe operating conditions. A depletion layer of the group-III elements can form at the interface caused by out-diffusion of group-III elements. The electrical resistance of the depletion layer is high, and therefore the current tends to concentrate in that part of the layer consisting of metal/group-III element alloy with lower electrical resistance. Thus, alloy spikes can grow and ultimately damage the active layer. Moreover, in another reaction at a Schottky-type electrode, grain boundary diffusion of the group-III element into the

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electrode metal can occur and thereby cause an increase in thermal and electrical resistance during long-term operation (Fukuda *et al.*, 1988).

Solder degradation

At the interface between metal and solder, effects such as metal diffusion, intermetallics formation, and thermal fatigue can occur. These effects depend on the materials used for the electrode and solder. They can influence the laser performance and reliability because of the resulting changes in electrical and thermal characteristics. Thermal resistance can increase due to thermal fatigue, which results from crack formation at the bonding solder metal under thermal cycle stresses or power cycling. This is more likely to happen with soft solders having a low melting point such as Sn, In, and Sn-rich AuSn than with hard solders including Au-rich AuSn or AuSi. Although soft solders act initially as absorbers of mechanical stress, they degrade gradually during long-term aging, however.

In cases where the current flow path is not homogeneous, voids, hillocks, and whiskers can form at the bonding site. Voids form in regions where the current density and the mass flux of the metal ions change from low to high, whereas hillocks and ultimately whiskers grow in regions where the current density and mass flux change from high to low. Apart from the current density, variations in temperature, diffusion coefficient of metal ions, and metal layer resistivity are further driving forces for the mass transport due to *electromigration*. Whiskers and reactions at the semiconductor/solder interface can cause local short circuits in the active p–n junction with sudden damage to the laser. Examples are the growth of In whiskers up to 2 μm long at high current densities or Sn whiskers generated from soft Sn-rich AuSn (Mizuishi, 1984) and penetration of Sn from the AuSn solder into the semiconductor (Mizuishi *et al.*, 1982).

Another type of void formation can occur at the bonding site where interdiffusion between solder material such as Sn and electrode material such as Au can take place, ultimately forming SnAu intermetallics. Voids can form at the interface in the Sn layer due to a Sn grain boundary diffusion rate that is higher than that of bulk diffusion of Au into Sn (Nakahara and McCoy, 1980). Voids of this type are called Kirkendall voids (Smigelskas and Kirkendall, 1947). Grain boundary diffusion is a surface-activated process and takes place at the surfaces of the grains of the Au layer, whereas bulk diffusion is a direct bulk-to-bulk process. Intermetallic and void formations increase the thermal and electrical resistance.

The use of hard solders having a high melting point reduces or eliminates the instability and reliability issues induced by the use of soft solder metals, which, however, are easier to use in the fabrication process.

3.2.1.2 Internal degradation

Active region degradation and junction degradation

The majority of degradation phenomena occur in the active region. Detailed accounts on the various relevant failure mechanisms are given in Section 3.1.1.1 above and

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in the Sections 3.2.2.1 and 3.2.2.2 below dealing with rapid degradation and gradual degradation of the active region. We want to refer to these sections for insightful information on the specific features and root causes of these individual degradation modes as well as approaches and techniques for suppressing or eliminating them.

The structure and fabrication process of buried-heterostructure (BH) lasers (see Section 1.3.5.2 and Figure 1.27) introduce new degradation modes that cannot be observed in planar-type, non-BH lasers. The usual BH structure is formed by a two-step crystal growth process involving mesa etching after the first growth step down to the n-cladding including the active layer, and then burying the active region in a regrowth process in the second growth step. The BH degradation is induced by the increase in defects at the defective BH interface under current injection. The increased defect density leads to an increase in nonradiative recombination current. The injected carrier lifetime decreases and thus increases the threshold current. Cross-sectional electron beam-induced current (EBIC) (see details of the technique in Part III) images can show local breakdown of the p–n junction accompanied by leakage current (Mizuishi *et al.*, 1983). The reason for this degradation is the formation of deep-level defects at the p–n junction leading to nonradiative recombination. This degradation mode can be suppressed by achieving a defect-free BH interface, for example, by an appropriate treatment of the etched sidewalls of the active layer before regrowth.

3.2.2 Basic degradation mechanisms

Figure 3.3 shows a schematic diagram of the major failure modes at constant current operation of the laser device. Based on the rate of change in device characteristics, in

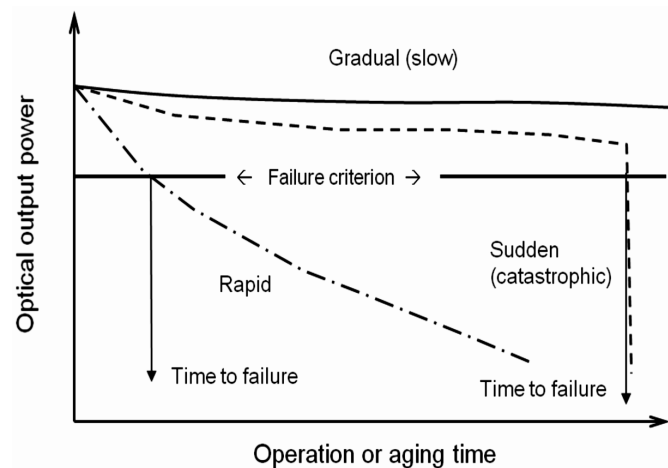


Figure 3.3 Schematic representation of typical degradation modes and time-to-failure condition of diode lasers operated under constant current.

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this case in optical output power, we can roughly categorize them into rapid, gradual, and sudden modes. At constant current operation a decrease in optical output is observed during degradation. In contrast, if a laser is operated at a constant optical output power the drive current is increased during laser degradation in order to maintain constant output power. If rapid degradation is eliminated, there is still the gradual degradation that occurs over a long period and which determines ultimately the lifetime of the laser. A device can also degrade suddenly after an initial rapid or gradual course of degradation, which usually occurs in a catastrophic way at laser mirror surfaces (see Sections 3.1.1.2, 3.2.1.1, 3.2.2.3, and 4.1) or in the bulk of the cavity at certain defects. These defects can include point defects such as vacancies and interstitials, or line defects such as dislocations, or planar and 3D defects such as dislocation loops, point defect clusters, precipitates, and voids. The formation of these defects can occur during nonoptimized epitaxial growth and device fabrication processes, but some of the defects might also be created during high-power operation of the laser device itself.

The figure also shows schematically the level of degraded power that the laser has to reach to become a failure. The definition of such failure criteria is dependent on the requirements of the laser application and determines the individual time to failure. A typical failure criterion for diode lasers is a 10% drop in initial optical output power. As we will see in Chapters 5 and 6, by life testing a large ensemble of laser devices, we can get statistical data on both the median time to failure at which 50% of the devices tested failed and the failure rate.

3.2.2.1 Rapid degradation

Features and causes of rapid degradation

- The degradation process occurs in the active region, which causes the internal absorption loss to increase and the injected carrier lifetime to be shortened, because of an increase in nonradiative recombination (cf. Section 3.1.1.1 above). The result is a rapid decrease in external differential quantum efficiency and optical output power and an increase in threshold current. Typical lifetimes $\lesssim 100$ h.
- Main causes are the generation and growth of dislocations, and sometimes precipitate-like defects with an excess of host atoms such as In and P for InP-based devices. The latter can occur during epitaxy by thermal decomposition of InP prior to the growth of an InP buffer layer. It can also occur by thermal decomposition at the interface between InP and the InGaAsP active layer. These root causes give rise to the formation of DLDs, which are extended, linear regions of greatly reduced radiative efficiency. They can grow in the $\langle 100 \rangle$ and $\langle 110 \rangle$ directions when observed perpendicular to the $\langle 001 \rangle$ substrate, which is usually the active region plane. The $\langle 100 \rangle$ DLD crosses an active stripe oriented along the $\langle 110 \rangle$ direction at 45° (Figure 3.4). These nonradiative regions, acting also as light absorbers, can be observed, for example, in electroluminescence

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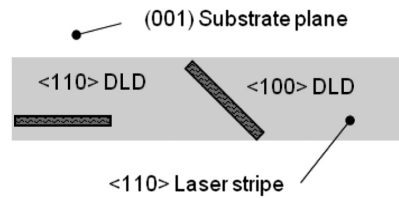


Figure 3.4 Schematic representation of typical dark-line defects (DLDs) oriented in the $\langle 100 \rangle$ and $\langle 110 \rangle$ directions on a (001) substrate plane with the laser stripe in the $\langle 110 \rangle$ direction.

(EL) topographs, EBIC images, and photoluminescence (PL) images. These techniques will be described in Chapters 7 to 9.

- The $\langle 100 \rangle$ dislocation network grows by the so-called recombination-enhanced dislocation climbing (REDC) motion from a dislocation that originally existed in the active region. In the *phonon-kick model* (Gold and Weisberg, 1964), the energy required for defect reaction is emitted in a nonradiative recombination process between electronic states in the dislocation or other defects such as point defects. It is then transformed into lattice vibrational states (phonons) via multi-phonon generation at defect sites (Henry and Lang, 1977) giving rise to the climb process. In this model, the defects are mainly interstitial atoms or vacancies. By absorbing interstitial atoms at a dislocation (Petroff and Kimerling, 1976) or emitting vacancies from a dislocation (O'Hara *et al.*, 1977), the dislocation network grows and extends along the $\langle 100 \rangle$ direction (Figure 3.5).
- The dominant parameters for REDC include (Ueda, 1996): (i) deep levels associated with point defects or dangling bonds in dislocation cores; (ii) activation energy for point defect generation and migration; and (iii) nonradiative recombination rate at defects. DLD growth is intrinsic to the material. It may be influenced by effects such as dopant type and density and migration of metal atoms from the electrode.
- In materials with wider bandgaps, REDC and therefore dislocation network growth occur more easily. It exists in GaAs, AlGaAs, GaP, GaAsP, Ga-rich InGaAsP lattice matched to GaAs, but not in InP and In-rich InGaAsP lattice matched to InP. The last two experimental results are in agreement with calculations made on the deep trapping levels of anion vacancies in the $\text{In}_{1-y}\text{Ga}_y\text{As}_{1-x}\text{P}_x$ alloy system (Buisson *et al.*, 1982; Dow and Allen, 1982). According to these calculations, vacancy levels are located outside the bandgap in In-rich InGaAsP on InP, whereas vacancy levels are located deep within the bandgap in Ga-rich InGaAsP on GaAs. This confirms the ease of REDC and DLD formation in the latter system and demonstrates that rapid degradation due to DLD formation cannot occur that easily in the former material.

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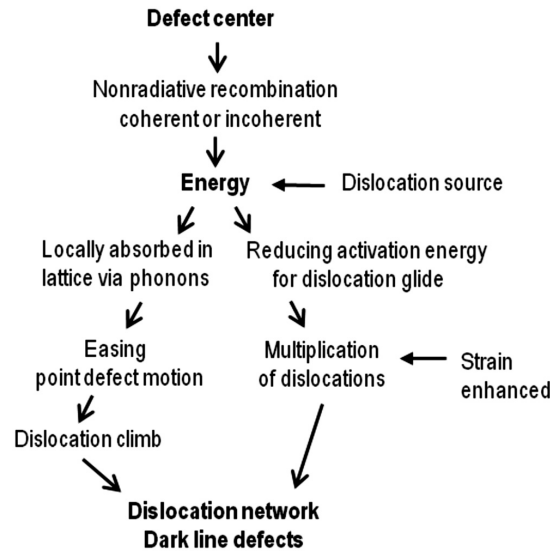


Figure 3.5 Simplified formation process of dislocation networks in a semiconductor diode laser leading to dark-line defects.

- The growth velocity of $\langle 100 \rangle$ DLD in degraded GaAs/AlGaAs lasers is also much higher than that in degraded InGaAsP/InP lasers: at room temperature, it is $\sim 100 \mu\text{m/h}$ (Imai *et al.*, 1979) compared to $\sim 0.5 \mu\text{m/h}$ (Fukuda *et al.*, 1983), respectively.
- The dislocation network for $\langle 110 \rangle$ DLD is caused by mechanical stress. Its growth rate depends on the magnitude of stress and on the bonding strength of the host atoms. In III–V compound semiconductors, the slip plane under mechanical stress is the (111) plane and the projection of this plane onto the (001) plane is the $\langle 110 \rangle$ direction (Fukuda, 1999). If the mechanical stress is $\gtrsim 10^8 \text{ dyn/cm}^2$, the slip dislocation grows from the surface or interface under current injection and, when it reaches the active layer, $\langle 110 \rangle$ DLDs are formed. The dislocations may be introduced initially by relaxation of the stress via recombination-enhanced dislocation glide (REDG) motion during operation (Figure 3.5).
- Rapid degradation caused by the generation of $\langle 110 \rangle$ DLDs due to REDG occurs in AlGaAs/GaAs devices. However, in InGaAsP/InP lasers no $\langle 110 \rangle$ DLDs are observed in the active region during operation at room temperature.
- Driving forces for REDG include (Ueda, 1996): (i) local temperature rise at the active p–n junction; (ii) background strain field due to factors such as lattice mismatch in the active region, formation of contact electrodes, dielectric layer for current confinement; and (iii) nonradiative recombination energy and rate.

Elimination of rapid degradation

- Use low dislocation density or dislocation-free substrates that are commercially available to avoid propagation of threading dislocations into the active layer (see Section 1.4.1.1).
- Avoid crystal growth-induced defects, particularly dislocation-type defects at the interface between substrate and epitaxial layers. The elimination of $\langle 100 \rangle$ DLDs is related to the quality of the epitaxial growth process of the structure.
- Minimize internal stress in the laser structure, in particular at the interface between the active waveguide and cladding layers to reduce strain-enhanced formation of REDC and REDG leading to DLDs. In particular, the elimination of $\langle 110 \rangle$ DLDs is related to the processing steps after the epitaxial layer growth, which includes minimizing mechanical stress.
- Add Al (AlAs mole fraction $\cong 0.05$) to the active GaAs layer of AlGaAs/GaAs lasers, which reduces the defect density by gettering oxygen and changes the stress type in the active layer from tension to compression (Olsen and Ettenberg, 1977). This drastic change in stress is correlated with improved lifetimes up to two orders of magnitude (Thompson, 1979) through a reduced DLD concentration (Kishino *et al.*, 1976).
- Eliminate defects induced during fabrication processes such as diffusion, dielectric and metal depositions, ion implantation, and annealing by optimizing the conditions for these processes.
- Avoid stress and mechanical damage during laser device fabrication: (i) elastic strain due to difference in thermal expansion between epitaxial layers and contact metallization and dielectrics; (ii) external stress due to bonding and soldering processes and laser wafer cleaving; (iii) scratches and cracks (source of dislocations) induced during laser device handling.

3.2.2.2 Gradual degradation*Features and causes of gradual degradation*

- Gradual and slow long-term decrease of optical output power and increase of threshold current with operating or aging time. The gradual degradation mode determines the maximum lifetime, that is, over 30 years for modern high-power single-mode diode lasers at specified operating conditions.
- Degradation rate tends to increase as the Al content is increased in the active layer of AlGaAs/GaAs lasers to much higher AlAs mole concentrations than recommended to reduce the DLD density (see Section 3.2.2.1 above). Increased stress due to mismatch between substrate and active layer may be a root cause, but also as the AlAs mole fraction in the active layer approaches that of an indirect bandgap AlGaAs (~ 0.45).

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- Protect the mirror surface by appropriate passivation layers and dielectric films to minimize the surface state density N_s and thus the surface recombination velocity, and hence strong optical absorption and heating (see Chapter 4 for details). The surface recombination velocity is given by the well known expression

$$v_{s,n} = N_s v_{th} \sigma_{s,n} \quad (3.6)$$

where it is assumed that the material is p-type and electrons are minority carriers, and where v_{th} is the carrier thermal velocity and $\sigma_{s,n}$ the electron capture cross-section at the surface trap level. A similar expression holds for holes as minority carriers in n-type material. The COMD power level P_{COMD} can be increased by using a facet-coating material with relatively high thermal conductivity. For example, Al_2O_3 facet coatings are more efficient than SiO_2 coatings with $\text{cw } P_{COMD}(\text{Al}_2\text{O}_3) \cong 3 \times P_{COMD}(\text{uncoated})$ and $\text{cw } P_{COMD}(\text{SiO}_2) \cong 1.5 \times P_{COMD}(\text{uncoated})$ (Imai *et al.*, 1978).

- Apply effective nonabsorbing mirror structures (see Chapter 4 for details).
- Control and minimize during crystal growth and device fabrication processes the generation of defects participating in nonradiative recombination.
- Apply appropriate mode spot widening techniques (see Section 2.1.3.5 and Chapter 4) to decrease the output power density at the facet and thus the damage.

3.3 Key laser robustness factors

In summarizing the detailed descriptions in this chapter on diode laser degradation modes and mechanisms, the following parameters can be considered as the key factors determining the robustness of a diode laser:

- *Materials of the active region.*
- *Transverse lateral confinement.*
- *Thermally assisted defect migration into the active layer.*
- *Stress and defects.*
- *Current density-enhanced degradation effects.*
- *Catastrophic optical damage.*
- *Electrical overstress and electrostatic discharge.*

At the end of this section, we will give additional information and information not yet discussed on the last two parameters in the list above, respectively. First, however, we derive a quantitative figure of merit for evaluating the occurrence of COMD. Second, we discuss the basics of electrostatic discharge (ESD), which is

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a subset of the electrical overstress (EOS) category. We describe the impact of both effects on diode lasers and state some standard precautions to control and eliminate ESD.

EOS and ESD are external factors causing diode lasers to fail due to their extreme sensitivity to excessive current levels and current spikes. The high sensitivity of diode lasers to fast overshoot events such as ESD is due to the lasers' fast response time with rise times in the picosecond regime. In a wider sense, the prevention of these effects can be viewed as a measure to enhance laser robustness, although these detrimental effects actually belong within a laser protection strategy. Such a strategy comprises (ILX Lightwave Corp., 2003):

- test and measurement instrumentation, which may give rise to damage mechanisms like overcurrent and spikes;
- system setup components responsible for radiated electrical transients;
- laboratory environment inducing fast transients;
- human contact, laser handling, and packaging releasing ESD.

Nevertheless, we consider EOS/ESD as relevant factors determining the robustness of a diode laser and hence justify within this context an appropriate description of their relevant features and methods to suppress or eliminate them.

First, we discuss the COMD-related issue. The optical near-field (NF) area is one of the crucial parameters for maximizing the power level at COMD. In general, the COMD levels of lasers with smaller NF areas are obviously lower than COMD levels of lasers with larger NF areas. The spreading of the mode in the transverse vertical and transverse lateral directions determines the size of the NF area. The former is determined by the vertical layer structure and can be as large as $\sim 1 \mu\text{m}$ by using one of the mode expansion methods discussed in Section 2.1.3.5. In contrast, the latter is given by the width of the lateral waveguide, which is typically in the order of 2–4 μm for single-mode lasers.

We can now define an optical intensity factor (OIF) as the inverse value of the NF area (with units of $(\mu\text{m}^2)^{-1}$); that is, the higher this factor, the greater the probability for COMD to occur. Further, we define an optical acceleration factor (OAF) as the optical intensity factor to the power n (with units of $(\mu\text{m}^2)^{-n}$), where the exponent n is a characteristic number of the specific laser type, roughly between about 1 and 3. This acceleration factor actually determines the time to the COMD event; that is, the larger this factor, the shorter the time to COMD. Its definition corresponds to the general definition of lifetime of a device or system exposed to an applied stress (see Chapters 5 and 6).

NF spot areas, OIFs, and OAFs have been calculated for 980 nm InGaAs/AlGaAs GRIN-SCH SQW ridge waveguide lasers 4 μm wide as a function of the transverse vertical and transverse lateral far-field beam angles that are the more easily accessible parameters. Tables 3.1a–c list OIF data and data of OAFs equal to OIFs to the power of 2 and 3, respectively. The data are grouped in three categories according to their severity to COMD failure. This classification is based on empirical experience with

Table 3.1 Optical intensity factors (OIFs) and optical acceleration factors (OAFs) calculated for 980 nm InGaAs/AlGaAs GRIN-SCH SQW ridge waveguide lasers 4 μm wide as a function of slow-axis and fast-axis far-field beam divergence angles. (a) OIFs defined as the inverse of near-field spot areas have units of $(\mu\text{m}^2)^{-1}$. (b) OAFs defined as OIFs to the power 2 have units of $(\mu\text{m}^2)^{-2}$. (c) OAFs defined as OIFs to the power 3 have units of $(\mu\text{m}^2)^{-3}$. Data in dark-grey areas predict high probability of COMD events or low COMD levels, whereas data in unshaded areas indicate safe operation with respect to COMD. The data in the light-grey areas represent some kind of transitional regime between high and low degrees of COMD robustness. The data highlighted in bold are from different sources of leading state-of-the-art high-power, highly reliable, single-mode, and single-emitter in-plane diode laser products. The OAF can be considered as a useful figure of merit for assessing the likelihood for the occurrence of COMD events over the entire far-field beam divergence angle range.

Fast-axis far field angle [deg] $\longrightarrow$

	25	30	35	40	45	50	
6	0.43	0.51	0.59	0.68	0.76	0.83	Optical Intensity Factor OIF:
8	0.57	0.68	0.79	0.90	1.01	1.11	
10	0.71	0.85	0.99	1.12	1.26	1.39	Inverse of near field area
12	0.85	1.02	1.19	1.35	1.51	1.67	
14	1.00	1.19	1.38	1.57	1.76	1.94	
16	1.14	1.36	1.58	1.80	2.01	2.22	
18	1.28	1.53	1.78	2.02	2.26	2.49	(a)

Slow-axis far field angle [deg] $\downarrow$

	25	30	35	40	45	50	
6	0.18	0.26	0.35	0.46	0.57	0.70	Optical Acceleration Factor OAF :
8	0.32	0.46	0.63	0.81	1.01	1.24	
10	0.51	0.72	0.98	1.27	1.58	1.93	OAF = (OIF) ⁿ⁼²
12	0.73	1.04	1.41	1.82	2.28	2.78	
14	0.99	1.42	1.91	2.47	3.10	3.78	
16	1.29	1.85	2.49	3.23	4.04	4.93	
18	1.63	2.33	3.15	4.08	5.10	6.22	(b)

	25	30	35	40	45	50	
6	0.08	0.13	0.21	0.31	0.43	0.58	Optical Acceleration Factor OAF :
8	0.18	0.32	0.50	0.73	1.02	1.38	
10	0.36	0.62	0.97	1.42	1.99	2.69	OAF = (OIF) ⁿ⁼³
12	0.62	1.06	1.67	2.46	3.44	4.63	
14	0.99	1.69	2.64	3.89	5.45	7.34	
16	1.47	2.51	3.94	5.80	8.12	10.93	
18	2.09	3.57	5.59	8.23	11.53	15.53	(c)

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- Ensure the coatings meet the optical, electrical, thermal, and mechanical conditions described in Section 1.3.8 and pass environmental test conditions, including low-temperature endurance, high-temperature resistance, temperature cycling, thermal shock, humidity resistance, vibration, and shock stability (Chapter 6).

4.2.2 Facet passivation techniques

4.2.2.1 E2 process

This process was originally developed by IBM Laser Enterprise (now AvaneX/Bookham = Oclaro), an independent business unit of IBM Research in Rüschlikon (Zurich), Switzerland, in the early 1990s, for high-power, highly reliable, single-mode 980 nm compressively-strained InGaAs/AlGaAs GRIN-SCH SQW ridge waveguide pump diode laser products for terrestrial and submerged optical communication systems applications. The E2 process is a follow-up development of an E1 process where “E” stands for enhanced (Gasser and Latta, 1992).

Essentially, the process consists of the following steps: a specially sized piece of material is cut out of a completely processed laser wafer, inserted and adjusted in a hinge-like mechanical fixture, and then mounted in an ultrahigh-vacuum evaporation system. A scribe mark, which defines the position of the cleave is adjusted to the rotation axis of the hinge. Scribing is usually performed outside the vacuum system with a diamond-tipped scriber. At a base pressure of $\sim 10^{-10}$ Torr cleaving is carried out by a 90° rotation of the hinge mechanism leaving the cleaved bar in one half of the hinge cleaver and the remaining material in the other half. Both freshly cleaved facet faces are immediately coated in situ with a thin amorphous Si (a-Si) film by an electron-beam evaporator. In the original E2 process, the reflectivity coatings of the facets were performed outside the vacuum system in a separate deposition system. The coating for the front facet with a typical reflectivity of 10% is usually made of a single layer of Al₂O₃ whereas the back facet has a high reflectivity >90% realized by a stack of pairs of high and low refractive index layers a quarter wavelength thick, such as TiO₂ and SiO₂, respectively (cf. Section 1.3.8).

The thickness of the a-Si layer should be below 10 nm to avoid heating effects and the formation of a quantum state in the valence band of the Si well layer. The latter results from quantum mechanical calculations performed on a “particle in an asymmetric box” formed by the GaAs/a-Si/Al₂O₃ structure with bandgap energies of 1.42, 1.7, and 9.9 eV, respectively. Different band diagrams have been proposed for the GaAs/a-Si/Al₂O₃ system, including a type-II staggered band alignment for the GaAs/a-Si interface (Katnani and Margaritondo, 1983; Capasso and Margaritondo, 1987), and a type-I straddled band alignment for unstrained crystalline heterostructures (Tiwari and Frank, 1992). The existence of such quantum states in the a-Si layer would cause carriers to diffuse into the a-Si layer with the prospect of recombining nonradiatively (Tu *et al.*, 1996).

Tu *et al.* (1996) applied a deviation to the original E2 process by executing the cleave while the samples were exposed to a flux of Si, thereby minimizing

the time the facet was exposed to the residual gases in the vacuum chamber. The shorter exposure time led to higher threshold powers for COMD and relaxed requirements for the pressure in the vacuum system. Low surface recombination velocities $\sim 3 \times 10^4$ cm/s have been obtained for the a-Si/Al₂O₃ coating (Tu *et al.*, 1996). The original E2 passivation principle has been dramatically improved over the years by IBM Corp. aimed at achieving higher throughput and lower cost. Fully automated systems with sophisticated in situ scribing and cleaving devices (Bauer *et al.*, 1991) are now available, meeting industry standards of high throughput and low fabrication costs.

Diode lasers with E2 passivation technology have developed to state-of-the-art performance and reliability and offer pre-eminent laser products for most demanding high-power, single-mode, and ultrahigh-reliability applications. Kink-free powers >1.4 and 1.8 W rollover powers have been reported from narrow 980 nm InGaAs/AlGaAs lasers with ridge waveguides 4 μ m wide and E2 passivated facets showing no COMD events and maximum power densities >100 MW/cm² and ultra-long lifetimes over 30 years at operating conditions above 1 W and 25 °C (Lichtenstein *et al.*, 2004; Bookham, Inc., 2009).

4.2.2.2 Sulfide passivation

There are several studies on using sulfur treatment for facet passivation (Kamiyama *et al.*, 1991; Lambert *et al.*, 2006; Kawanishi *et al.*, 1990). The treatment is usually performed chemically utilizing an ammonium sulfide (NH₄)₂S solution in which the cleaved laser bars are submersed for a period of typically 5–10 min at 25 °C, followed by deionized water rinsing and blowing dry. These soak times give the maximum increase in COMD level.

Thus, the COMD power level of 110 mirrors of 780 nm AlGaAs high-power lasers has been doubled to 220 mW cw operation. Auger electron spectroscopy and x-ray photoelectron spectroscopy measurements showed that the sulfur treatment strongly reduces the surface oxides of Ga, Al, and As atoms and leaves a sulfide layer of these constituent atoms. The improved COMD power level by the sulfide passivation has been ascribed to a reduced surface recombination caused by the oxides. This finding is confirmed by measurements of the reverse leakage current, which has been found to be reduced for sulfide passivated facets. A reduced reverse leakage current directly relates to the removal of conductive surface states and to the passivation of surface states that could trigger an oxidation process. Similar COMD power-level improvements have been obtained for AlGaInP visible diode lasers. In this case, transmission electron microscopy and energy dispersive x-ray measurements confirmed that most of the oxide at the mirror facets is replaced by sulfur after the treatment.

The quality of the sulfide passivated facet tends to degrade quickly, requiring a post-deposited layer, though also stable operation of >2000 h has been achieved at higher temperature and power operation. SiN_x encapsulation has proven to be an effective method for preserving the positive effects of the sulfide passivation such as reduced surface recombination by inhibiting the oxidation process of the

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air-exposed semiconductor. SiN_x deposited by electron cyclotron resonance chemical vapor deposition has proven to be superior to that deposited by plasma-enhanced chemical vapor deposition (Hobson *et al.*, 1995).

4.2.2.3 Reactive material process

A passivation layer comprising a reactive thin film is deposited on the air-cleaved laser facet to getter oxygen, water, and other reactive contaminants. The film consists of a highly reactive material such as the electropositive Al, which readily removes contaminants from the facet by reactive out-diffusion into this overlayer. Its layer thickness, however, must be controlled carefully to be sufficiently thick to react with an optimum amount of contaminants. On the other hand, it has to be sufficiently thin in order that the reactive material is substantially consumed in the oxidation or gettering process to render the thin layer, which is initially conductive, electrically nonconductive and therefore does not short-circuit the junction of the laser device (Tihanyi and Bauer, 1983).

Preferred Al layer thicknesses are in the range of 2.5 to 5.0 nm or 7.5 nm obtained from Auger spectroscopy depth-profiling measurements on Al-coated air-cleaved GaAs/AlGaAs DH laser facets. The minimum thickness of ~ 2.5 nm is sufficient to getter any oxygen, oxide, or water present on the cleaved sample into the reactive Al film in the form of electrically nonconducting Al_2O_3 . The reduction in oxygen level at the laser facet is at least by a factor of five. The empirically determined upper limit of ~ 5 nm is for devices with subsequent overcoatings used to modify the reflectivity. For devices with no reflectivity-modifying coatings, this thickness can be increased to ~ 7.5 nm by considering the surface oxidation of the passivation layer itself.

Due to the rapid and effective gettering actions of these layers, no shunting of the laser current through these coatings in the preferred thickness range has been observed. The passivation layer substantially improves the adhesion of any mirror overcoating for reflectivity modification. Other chemically reactive materials that can be used as thin passivation layers include Si, Ta, V, Fe, Mn, and Ti. The metal reactive materials may be deposited by sputtering using an Ar^+ -ion beam in a vacuum chamber with an Ar partial pressure of $\sim 6 \times 10^{-5}$ Torr for ~ 10 – 20 s, whereas Si could be deposited either in a hydrogen environment or as a silane compound (Tihanyi and Bauer, 1983).

4.2.2.4 N^2IBE process

The native nitride ion beam epitaxy (N^2IBE ; Nitrel[®] trademark of Comlase AB, Sweden) process belongs to the category of nitridization passivation technologies developed since the early 1980s and known for their excellent properties. These include the removal of surface states, the formation of a higher bandgap surface layer leading to a reduced optical absorption, the prevention of chemical contamination, and resistance to water, oxygen, and reoxidation.

The N^2IBE process is a facet passivation technology suitable for all material platforms covering the 400–1700 nm wavelength range and including materials such

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cladding. These detrimental effects can be mitigated by thinning the active layer only near the facets and increased COMD levels can be obtained. We will discuss this approach in Section 4.4.3 below.

There are numerous methods to fabricate window layer type and nonabsorbing mirror structures. In the following, we describe some selected and proven techniques.

4.3.2 Window grown on facet

This approach involves the formation or regrowth of a thin wide-bandgap semiconductor material directly on the facet surface. It is rather simple and it allows selection of the proper window layer independent of the internal laser structure. To establish the highest integrity of the cleaved facet prior to the window layer, deposition is of critical significance.

4.3.2.1 ZnSe window layer

The window layer is a ZnSe layer 5 nm thick deposited on an essentially contamination-free facet surface. Preparing contamination-free facets can be achieved by cleaving in vacuum followed by in situ deposition or by air-cleaving followed by facet cleaning in vacuum with an appropriate method and in situ deposition of ZnSe. ZnSe has a bandgap energy of 2.75 eV corresponding to a 450 nm wavelength and can be grown on GaAs with low mechanical stress and a lattice-mismatch of only $\sim 0.27\%$. High crystal quality can be achieved at a low growth temperature of 300 °C. ZnSe can be formed on the mirror facets by any suitable deposition and growth technique. After completion of the ZnSe window layer formation, the facets are AR/HR coated.

ZnSe window lasers not only have a substantially improved resistance to COMD, but also exhibit a far lower gradual degradation rate of the laser output in accelerated aging tests. Thus, Al-free 980 nm InGaAs/InGaAsP/InGaP QW lasers passed without failure a series of stress tests including a “snap test” (500 mA dc for a short period, three times), a “purge test” (100 °C, 150 mA dc, 140 h), a post-purge “snap test” (same as first test) and an aging test (85 °C, 300 mA dc, 10^3 h). In contrast, lasers with vacuum-cleaved facets but without ZnSe fail due to COMD during either the third or fourth test (Chand, 1997). The COMD power density level is 10 MW/cm², which is twice as high as that for facets without ZnSe windows. This figure is expected to be dramatically improved for depositing ZnSe windows on oxide-free facets (Syrbu *et al.*, 1996).

4.3.2.2 AlGaInP window layer

Thin undoped (Al_{0.7}Ga_{0.3})_{0.5}In_{0.5}P window layers were grown by low-pressure MOCVD on the cleaved facets of MBE-grown strained SQW AlGaInP ridge lasers 4 μ m wide and 1200 μ m long emitting at a wavelength of 680 nm. A kink-free maximum optical output power of ~ 300 mW has been obtained, which is about twice as much as that of the conventional laser without window layer, where the power

was limited by COMD. The threshold current of ~ 100 mA and slope efficiency of ~ 0.75 W/A are the same as those of the conventional laser, which indicates that the window layer does not affect the laser properties. Slow-axis and fast-axis far-field measurements up to 150 mW confirm the fundamental transverse mode operation. This technique applied to AlGaInP lasers appears to be promising, considering that these lasers are inherently very susceptible to facet degradation at high power (Watanabe *et al.*, 1994).

4.3.2.3 AlGaAs window layer

Maximum cw powers of 300 mW, limited only by thermal rollover, stable fundamental transverse mode operation up to 120 mW cw, and high reliability under 100 mW cw operation at 50 °C for >6000 h have been achieved for 830 nm $\text{Al}_{0.08}\text{Ga}_{0.92}\text{As}/\text{Al}_{0.31}\text{Ga}_{0.69}\text{As}$ DH lasers with active layers 60 nm thick, cavities 250 μm long, ridge waveguides, and $\text{Al}_{0.5}\text{Ga}_{0.5}\text{As}$ window layers 25 μm long at both facets. Lasers without a window structure have a COMD limited output power of ~ 160 mW, which is about half that of window lasers. Threshold current and external quantum efficiency are the same for both laser types, which is due to the fact that in the window region there is no generation of carriers by injection or light absorption, which could lead to free-carrier losses (Naito *et al.*, 1989). Extensive life tests showed that the degradation rate is not dependent on output power, but only on current and temperature. This is attributed to the strong suppression of mirror degradation. The thermal activation energy of the degradation rate is high at ~ 0.85 eV, and lifetimes $> 10^5$ h have been estimated for 100 mW cw operation at 25 °C (Naito *et al.*, 1991).

The window structure was prepared by etching down to the lower $\text{Al}_{0.31}\text{Ga}_{0.69}\text{As}$ guide layer and regrowing by MOCVD the high AlAs content window layer, which also serves as the upper cladding in the center part of the laser. Prior to the regrowth, the etched wafer is cleaned at 750 °C under AsH_3 flow for several minutes. A small V/III ratio of ~ 10 in the regrowth was chosen for suppressing defect formation. Laser chips are formed by cleaving and are AR/HR coated and mounted junction-side down on Si heat sinks in solder bonded onto copper blocks (Naito *et al.*, 1989).

4.3.2.4 EMOF process

EMOF, which stands for epitaxial mirror on facet, is a proprietary window layer process originally developed by the startup Spectracom, acquired by ADC Telecommunications, Inc. in 1999. Facets are cleaved along (110) planes under vacuum and a nonabsorbing epitaxial mirror layer is deposited simultaneously in a batch process on each cleaved bar placed in a cassette. The nature of the material has not been disclosed, but it is a wide-bandgap material grown by MBE at low temperature to a thickness that achieves 9% reflectivity for the front-facet mirror. In reliability tests of 980 nm InGaAs GRIN-SCH SQW ridge lasers 4 μm wide, no power dependence of the degradation rate could be detected. Extremely low degradation rates of 4×10^{-7} per hour after 5000 h for 350 mW cw ex-facet have been achieved (Whitaker, 2000).

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4.3.2.5 Disorder ordering ordered InGaP

Window-type regions in visible InGaAsP diode lasers can be produced by employing a property of the GaInP active material to change its bandgap as a function of the degree of ordering of the alloy crystallography. $\text{Ga}_x\text{In}_{1-x}\text{P}$ exists in two phases, ordered and disordered, which differ in the atomic arrangement of group-III atoms. In the ordered phase, a monolayer superlattice consisting of a periodic arrangement of Ga-rich planes and In-rich planes is naturally formed under special epitaxial conditions. The bandgap energy increases by typically 50 meV when changing from the ordered phase to the disordered phase (Gomyo *et al.*, 1987). The ordered phase grows on a standard (100) substrate whereas the disordered phase grows on a substrate misoriented relative to the (100) plane. Thus, a window laser can be formed by growing GaInP on a structured substrate with the center section on a (100) plane forming the cavity and the inclined end sections misoriented relative to (100) forming the window layers with higher bandgap energy (Minagawa and Kondow, 1989).

This feature of bandgap engineering can also be used for designing index-guided transverse lateral waveguides, a technique we want to mention here without further discussion, only to complete the list of relevant approaches discussed in Section 2.1.4.

The phase change from the ordered to random disordered alloy can also be achieved by impurity-induced disordering by diffusing Zn into the ordered GaInP regions. Various kinds of Zn diffusion techniques have been realized including solid phase diffusion using ZnO film (Arimoto *et al.*, 1993), vapor phase diffusion of Zn in a closed tube (Ueno *et al.*, 1990), and selectively enhanced Zn diffusion into the active layer in the mirror region by an n-GaAs capping layer (Itaya *et al.*, 1991). The latter approach yielded a COMD-free maximum power >80 mW cw and 400 mW for pulsed operation of gain-guided lasers with active layers 60 nm thick, stripes 7 μm wide, window regions 20 μm long, p-side down mounted configuration, and without facet coatings. The power of 80 mW is limited by thermal saturation and is five times as high as that of nonwindow structure lasers. Fundamental transverse mode high-power cw operation of >150 mW has been realized in compressively-strained 670 nm AlGaInP/GaInP DQW window structure lasers without degradation. Stable operation of >1500 h has been observed for 50 mW operation at 50 °C (Arimoto *et al.*, 1993).

4.3.3 Quantum well intermixing processes

4.3.3.1 Concept

Quantum well intermixing (QWI), also called QW disordering, involves the interdiffusion of constituent atoms across the interface of a well-barrier structure resulting in a controlled modification of the material composition (see Sections 2.1.4.2 and 3.1.1.3). This causes a change in the confinement profile and subband edge structure in the QW leading to a blueshift of the effective bandgap energy and thus a modification of the refractive index.

The degree of intermixing depends on the technique applied, its parameters such as the type and concentration of impurities to enhance the interdiffusion, and

the process temperature and time. The presence of point defects like vacancies or interstitials in the structure is mandatory for the QW disordering process to occur. These point defects diffuse through the structure and thereby allow the atoms, for example, group-III elements Al and Ga in an AlGaAs/GaAs QW structure, to hop from one lattice site to another across the interface, resulting in the intermixing of the well material with the barrier material.

Thermal annealing alone can lead to interdiffusion of constituent atoms for sufficiently high temperatures and long times. Typical temperatures are $>800^\circ\text{C}$ and $>600^\circ\text{C}$ for InGaAs/GaAs and InGaAs/InP QW structures, respectively. QWI, however, can take place at lower temperatures in the presence of point defects. Key technologies for introducing point defects include impurity-induced disordering, impurity-free vacancy diffusion, and to a lesser extent laser-induced annealing. QWI can be localized to selected regions so that bandgap engineering is only effective in these selected areas of the QW structure.

In Section 2.1.4.2, we described how this effect could be used to produce low-loss transverse lateral waveguide structures. Furthermore, QWI can also be used in realizing NAMs by producing the compositional disordering of QW or DH laser structures at the ends of the laser cavity, where they act as a window for laser emission and a barrier for electron-hole pairs. Figure 4.4 illustrates the principle of a QWI-NAM. As described previously, there are many different types of intermixing techniques, which are discussed in a series of review articles (e.g. Li, 2000, 1998; Yu and Li, 1998). In the following, we discuss some relevant methods along with their key properties and results achieved in NAM applications.

4.3.3.2 Impurity-induced disordering

Ion implantation and annealing

Ion implantation has been employed to enhance the disordering of QW structures by using implants such as Si and subsequent high-temperature annealing. High-temperature annealing is applied to anneal the implantation damage and accelerate the layer disordering process. The ion implantation process can be made effectively impurity-free if a matrix element is used as the implanted species, thus avoiding a potential degradation of the laser performance. Examples are P^+ implants in InGaAsP/InP lasers (Noël *et al.*, 1996) and As^{4+} ions implanted in InGaAs/GaAs QW lasers (Charbonneau *et al.*, 1995). In addition, nonelectrically active impurity implantation, such as B, F (O'Neill *et al.*, 1989), Ar (Myers *et al.*, 1990), and N (Hashimoto *et al.*, 2000) implants used for the impurity-induced interdiffusion process, avoid the problems linked to free-carrier absorption and unintentional doping of the window layer. The latter would lead to conductivity and hence leakage current and increased nonradiative recombination, which would diminish the COMD robustness of the facet.

Crucial parameters are implant species, ion energies, doses and fluxes, post-implantation annealing temperature, time, and capping layer material used in the annealing process. Implantation of low-energy ions along particular crystallographic

densities than other cw techniques, absence of a melt-phase, and layer composition selectivity by tuning the laser energy to the bandgap energy of the selected layer. As mentioned above, the poor spatial resolution due to lateral heat flow at cw laser irradiation can be improved to below 20 μm by using a pulsed laser. The absorption of pulsed high-fluence photons in a QW structure locally increases the density of point defects, which enhance the QWI process in a subsequent high-temperature annealing treatment (Shin *et al.*, 1998).

4.3.4 Bent waveguide

Nonabsorbing etched-mirror structures based on a bent-waveguide concept, in which the guided laser beam exits from the active waveguide layers into the nonabsorbing cladding layer with higher bandgap energy, have been demonstrated for AlGaAs/GaAs SQW GRIN-SCH ridge lasers 3.5 μm wide (Gfeller *et al.*, 1992a, 1992b). The bent-waveguide structure in the mirror regions is formed by overgrowing a wet-etched channel 1 μm deep with 22° sloped walls in the n^+ -GaAs (001) substrate by MBE. Exact wafer orientation is necessary to obtain symmetrical growth conditions on both channel slopes. The resulting kink in the active waveguide then allows decoupling of the beam into the cladding. Simulations showed that the beam is almost completely decoupled without distortion provided the slope angle of the bent waveguide is $>20^\circ$ and the NAM section length is $<15 \mu\text{m}$ for a channel depth of 1 μm , otherwise the beam recouples partially into the active waveguide.

Pulsed COMD power levels are four times higher for NAM lasers with $\sim 300 \text{ mW}$ compared to conventional etched-mirror lasers with $\sim 70 \text{ mW}$. In general, cw-operated etched-mirror lasers with NAM sections are free of COMD. A maximum, thermal rollover-limited COMD power level of 165 mW cw has been achieved with fundamental transverse lateral mode operation up to 80 mW. Due to beam divergence in the short NAM section a minor mirror coupling loss occurs, which causes an acceptable increase in the threshold current of, for example, $\sim 12\%$ for a NAM section 5 μm long relative to a conventional laser. The far-field patterns are not disturbed by the presence of the NAM section. Typical slow-axis and fast-axis beam divergence angles are 11° and 23° , respectively. Figure 4.5 shows schematically the NAM section and near-field and far-field patterns taken at two positions, one at a conventional facet outside the NAM section and the other where the beam partially recoupled into the active waveguide.

Mirror temperatures measured for different NAM section lengths reflect the overlap of the optical field intensity with the absorbing waveguide profile and are anti-correlated with the COMD levels. Typical temperature rises are 50 K at 30 mW cw for conventional etched mirrors compared to only 20 K in the NAM section. The origin of the remaining temperature rise of 20 K may be due to nonradiative recombination of diffused carriers from the pumped laser section or to optical power absorption at surface defects of the etched mirrors. Details of these temperature and COMD measurements including the measurement technique (Epperlein, 1993a, 1997) will be discussed in Part III.

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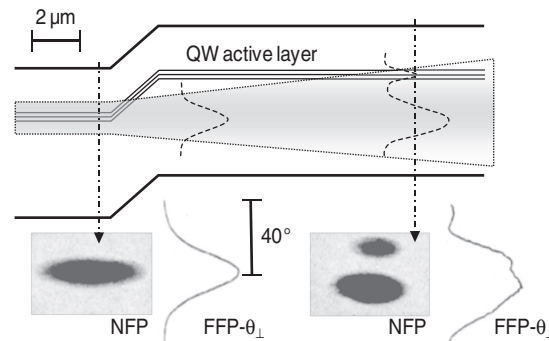


Figure 4.5 Scheme of a bent-waveguide nonabsorbing mirror (NAM) structure, illustrating the flared propagation of the beam (profile shown as light grey) in the unguided NAM region and the anticipated mode profiles at locations without and with partial recoupling of the beam into the displaced active waveguide. Experimental verification of the beam recoupling effect by near-field patterns (black) and transverse vertical far-field patterns at two distinct locations, one far ($>10\ \mu\text{m}$) in the NAM section with recoupling and the other at a conventional facet. Approximate scale along cavity axis only.

4.4 Further optical strength enhancement approaches

4.4.1 Current blocking mirrors and material optimization

4.4.1.1 Current blocking mirrors

The function of current blocking mirrors is to avoid the injection of electron-hole pairs near the facet surface. In this way, facet heating caused by nonradiative surface recombination and surface currents can be minimized and hence the positive feedback cycle to COMD interrupted. The use of a high-resistivity material for realizing the noninjection region is an effective approach, though also other techniques have been developed (Figure 4.6), which can be applied in combination with one of the NAM structures discussed above.

Rinner *et al.* (2003) reported a facet temperature reduction by a factor of 3–4 and increased COMD levels of InGaAs/AlGaAs SQW lasers junction In-soldered down on copper heat sinks with SiN current blocking layers $30\ \mu\text{m}$ long at the front facet (Figure 4.6a). The “aspect ratio” of 15 between the blocking layer length of $30\ \mu\text{m}$ and the total thickness $2\ \mu\text{m}$ of all p-layers above the active layer is sufficient to prevent current spreading toward the facet. In addition, the highly doped p-cap layer is removed in the SiN current blocking region.

Herrmann *et al.* (1991) developed a segmented contacts approach. Here the top electrode was segmented in three parts consisting of a gain section $340\ \mu\text{m}$ long and two mirror contact sections each $20\ \mu\text{m}$ long of ridge (Al)GaAs QW lasers $4\ \mu\text{m}$ wide. The influence of a separately controllable potential in the mirror region on the temperature was studied. There is an optimum potential of 0 V, easily obtainable by grounding the mirror contacts, leading to a substantial temperature reduction of the

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usually ready for shipment. These devices are ultimately subject to the next two degradation phases of random and wear-out failures. As we will see further down, the initial early failure rate region can be modeled by a Weibull hazard function.

The long, fairly flat region is called the stable failure period because here failures seem to occur in a random fashion at a relatively constant rate enabling a mean time between failures (MTBF) to be expressed, as we will discuss further below. Most of the useful life of a device should take place in this region of the curve and reliability testing is conducted here to determine values for the failure rate. Defects not as severe as those in the infant mortality region cause failures here, but predominantly random environmental or operating events, which can overstress a device. Failures here are called extrinsic, because they result from events external to the device. Mathematically, the constant failure rate of the exponential life distribution is perfectly suited to model such random failures (see Section 5.2).

The final part of the curve is characterized by an increasing failure rate and is called the wear-out failure regime. This is the region, in which a major failure mechanism progresses to the point, where it can cause failure of all the surviving devices. Here microscopic defects grow over time, shortening the useful device life dramatically. It is possible, but unlikely, that more than one failure distribution will be involved in the wear-out region. The failures are usually considered to be intrinsic. A major objective of manufacturing high-reliability diode lasers and supportive reliability tests is to shift the onset of the wear-out region far enough in time so that it does not impact the specified life of the laser product. Wear-out failure can be combated by developing robust laser designs, damage-resistant materials, and defect-free laser wafer growth and processing. The wear-out regime can be best fitted by the statistics of the lognormal and Weibull life distributions (see next section).

5.2 Failure distribution functions – statistical models for nonrepairable populations

5.2.1 Introduction

There are many statistical probability distribution functions, including the normal, lognormal, Weibull, and exponential functions. The normal distribution is not as common in reliability work as the others. The two-parameter continuous normal, or Gaussian, distribution is ideally suited for dealing with the statistics of random events, numbers, and phenomena. It is also frequently used to model measurement errors of almost any kind. Many populations encountered in industrial applications have bell-shaped symmetrical distributions that can be nicely modeled by the normal distribution. However, it rarely fits the failure distributions empirically determined in reliability work. The vast majority of reliability results have been modeled by the lognormal, Weibull, or exponential failure distribution. Therefore, we will focus on these functions and will not include the normal distribution in the discussions below.

There are some significant parameters in reliability terminology, including t_{50} , t_{16} , t_{75} , which designate the times by which 50%, 16%, 75% of the devices in a population have failed. The location parameter, also called measures of central values

or measures of location of a distribution, locates it in time. The shape parameter, also called measures of variation, gives a quantitative measure of the shape or spread of a distribution. The relevant parameters for each distribution will be given below.

5.2.2 Lognormal distribution

5.2.2.1 Introduction

The lognormal is not a separate distribution function; it can simply be derived by taking the natural logarithms of all data points and analyzing the transformed data as a normal distribution. If a normal distribution of the random variable x has the mean μ and standard deviation σ then $t_f = e^x$ is the random failure time variable of a lognormal distribution with the quantities $t_{50} = e^\mu$ and σ .

Alternatively, starting with a lognormal distribution population of variables t_f and with a median t_{50} and shape parameter σ , then the population of logarithmic failure times $x = \ln t_f$ is normal with a mean value of $\mu = \ln t_{50}$ and standard deviation σ . The logarithm of a lognormal distribution is a normal distribution. The parameter σ can be considered as a shape parameter for the lognormal distribution. It is not the standard deviation of the population failure times, but is, in units of logarithmic time, the standard deviation of the population of logarithmic failure times fitted by a normal distribution.

5.2.2.2 Properties

The PDF $f(t)$ for the lognormal distribution is given by

$$f(t) = \frac{1}{\sigma t \sqrt{2\pi}} \exp \left\{ -\frac{1}{2} \left(\frac{\ln t - \mu}{\sigma} \right)^2 \right\} \quad (5.13)$$

while the CDF $F(t)$ has the form

$$F(t) = \frac{1}{\sigma \sqrt{2\pi}} \int_0^t \frac{1}{x} \exp \left\{ -\frac{1}{2} \left(\frac{\ln x - \mu}{\sigma} \right)^2 \right\} dx. \quad (5.14)$$

The reliability function is

$$R(t) = 1 - F(t) \quad (5.15)$$

and the failure rate is

$$\lambda(t) = \frac{f(t)}{1 - F(t)}. \quad (5.16)$$

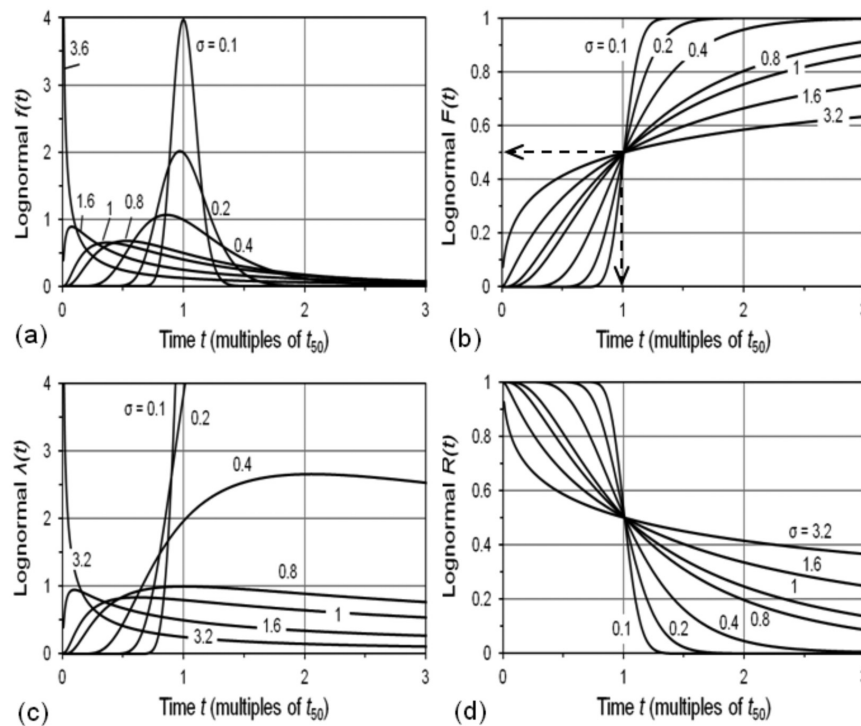
The lognormal is, like the normal distribution, a two-parameter function with the important quantities (Condra, 1993) listed in Table 5.1.

The shape parameter σ strongly influences the shape of the PDF $f(t)$ and CDF $F(t)$. Figure 5.3 shows the curves calculated for a series of σ values. As we will see

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Table 5.1 Definitions and formulae of important lognormal distribution parameters.

Parameter	Definition
Mean (arithmetic average)	$t = \exp\{\mu + (\sigma^2/2)\}$
Median (t_{50})	$t = e^\mu$
Mode (peak location of $f(t)$)	$t = \exp\{\mu - \sigma^2\}$
Location parameter	e^μ
Shape parameter	σ
s (estimate of σ)	$\ln(t_{50}/t_{16})$

**Figure 5.3** The lognormal life distribution function. Plots of (a) probability density function $f(t)$, (b) cumulative distribution function $F(t)$, (c) failure rate $\lambda(t)$, and (d) reliability function $R(t)$ calculated as a function of time t (in units of median time t_{50}) and at different values of the shape parameter σ . The dashed lines in (b) indicate the 50% failure point corresponding to the median time t_{50} .

in the next section, their shapes resemble those calculated for a Weibull distribution. This similarity indicates that both functions can fit the same set of experimental data. Whether a lognormal or a Weibull will work better for a set of data can be decided from the shape of the histogram of the logarithm of data. If the shape is symmetrical and bell-like, the lognormal will match the data, whereas if the histogram is left skewed, the fit of the data is better done with a Weibull (Tobias and Trindade, 1986).

Also shown in Figure 5.3 are the reliability function $R(t)$ derived from $R(t) = 1 - F(t)$ and the failure rate function $\lambda(t)$ calculated by using $\lambda(t) = f(t)/(1 - F(t))$ for the same set of σ values. In Section 5.3 it is shown, how to extract values for the shape parameter σ and the median time t_{50} . The shapes of these curves are also very similar to the shapes taken on by the Weibull failure rate (see next section). Failure rate curves with large values of σ are similar in shape to curves with small β values of the Weibull distribution. For large $\sigma > 2$ values the failure rate practically decreases throughout life with a strong initial rate decreasing with time. Typical high values of $\sigma \sim 4$ indicate early manufacturing problems leading to failures not under control. With increasing maturity of manufacturing, the σ value approaches one, which reflects roughly a constant failure rate. However, small σ values $\lesssim 0.5$ describe a failure rate increasing with time, which represents the wear-out failure regime. Thus, the lognormal distribution can describe all three failure rate regions: namely, that of early failures, stable failures, and wear-out failures.

5.2.2.3 Areas of application

The model underlying the lognormal distribution is called a *multiplicative growth model*. In essence, this model says that at any instant of time, the process undergoes a random increase of degradation that is proportional to its present state. The multiplicative effect of all these random growth processes ultimately builds up to failure (Tobias and Trindade, 1986). Whenever a multiplicative degradation process is occurring, in which a defect gets progressively worse due to accumulated damage, the lognormal model tends to apply. The main requirement is that the change in the degradation process at any time is a small random proportion of the accumulated degradation up to that time. Examples of such gradual degradation processes involve many failure mechanisms, including diffusion effects, corrosion processes, chemical reactions, oxide growth, and crack growth propagation in electrical and optical semiconductor devices.

5.2.3 Weibull distribution

5.2.3.1 Introduction

The Weibull is a three-parameter distribution function. By adjusting the shape parameter β and the timescale parameter η , which is also called the characteristic life parameter α , a large variety of functional behavior can be created to fit a wide range of experimental life-test data. Both β and η must be >0 and the distribution is a life

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not present and the planning process is more straightforward compared to the other life distributions (Tobias and Trindade, 1986). Thus, the exponential model is a useful trial model in the experimental planning stage by giving early consideration to sample sizes and durations of the reliability tests.

5.3 Reliability data plotting

5.3.1 Life-test data plotting

In the previous section we discussed analytical techniques for the lognormal, Weibull, and exponential life distributions. As demonstrated in the various figures above, all the major forms of reliability distributions including $f(t)$, $F(t)$, $R(t)$, and $\lambda(t)$ can be plotted, where, however, the cumulative distribution function $F(t)$ is the most practical one. Required is to have simple graphical procedures that allow checking of the applicability of a distribution model to the experimental reliability data. This implies having a simple linear plot of the number of failures versus time, from which relevant reliability parameters can be quickly and easily derived. The task is to linearize the various nonlinear reliability functions. In the following sections, we will discuss relevant practical approaches for plotting reliability data.

5.3.1.1 Lognormal distribution

A lognormal probability plot is a plot of Equation (5.14). There are different options for generating a probability plot. However, we will discuss here only the standard approach by plotting the cumulative percent failures versus the failure times on (electronic) lognormal probability paper. To illustrate the concept, we consider the failures of a collection of InGaAs/AlGaAs QW diode lasers age accelerated at high temperature and high constant current operation over a long period of time. There are four steps involved in generating the probability plotting:

1. Rank order the failure times from the smallest to the largest value. For example, if the rank order of a failure is i and the total number of failures is j , then i ranges from 1 to j . In the example of Table 5.3, $j = 15$.
2. Estimate the cumulative percent for each failure data point. There are several equations commonly used for this. However, statistically the most accurate concept for estimating the population CDF or $F(t_i)$, called median ranks, is defined by

$$F(t_i) = \frac{i - 0.3}{N_0 + 0.4} \times 100 (\text{cumulative}\%); i = 1, 2, 3, \dots, j \leq N_0 \quad (5.31)$$

where N_0 is the sample size at the beginning of the test, which in our example in Table 5.3 is equal to the number of total failures. The other methods yield slightly different $F(t_i)$ values by a couple of percent at the start and end

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Table 5.3 Estimation of cumulative distribution function $F(t)$ by using median ranks (col. (c)) of failures in highly accelerated aging tests of InGaAs/AlGaAs diode lasers. Transformation of $F(t)$ data used for Weibull probability plotting (col. (d)) and exponential probability plotting (col. (e)) as a function of failure times t_i (col. (a)).

(a)	(b)	(c)	(d)	(e)
Failure time t_i [h]	Failure count i	Median rank $F(t_i) = \frac{i-0.3}{N_0+0.4}$ $N_0 = 15$	$-\ln[1-F(t_i)]$	$1/[1-F(t_i)]$
102	1	0.045 (4.5%)	0.046	1.048
250	2	0.110 (11.0%)	0.117	1.124
400	3	0.175 (17.5%)	0.192	1.212
660	4	0.240 (24.0%)	0.274	1.316
800	5	0.305 (30.5%)	0.364	1.439
970	6	0.370 (37.0%)	0.462	1.587
1300	7	0.435 (43.5%)	0.571	1.770
1350	8	0.500 (50.0%)	0.693	2.000
1600	9	0.565 (56.5%)	0.832	2.299
2000	10	0.630 (63.0%)	0.994	2.703
2200	11	0.695 (69.5%)	1.187	3.279
2600	12	0.760 (76.0%)	1.427	4.167
3000	13	0.825 (82.5%)	1.743	5.714
3800	14	0.890 (89.0%)	2.207	9.091
4500	15	0.955 (95.5%)	3.101	22.222

of the rank order range. Given the inaccuracies generally experienced in data collection and evaluation, these differences hardly have any practical influence on the final test results and conclusions.

3. Plot each cumulative failure percent (column (c) in Table 5.3) versus its time to failure (column (a) in Table 5.3). Figure 5.6 shows the plot for our example.
4. Draw a best-fit straight line through the plotted data points. In the figure this was achieved by an electronic least squares fit.

The figure shows quite some scatter of the data around the least squares fit straight line with major deviations toward median to longer times. This indicates that the lognormal model does not fit the data well. Nevertheless, by using the definitions in Section 5.2.2 and Table 5.1 for the median time t_{50} and the shape parameter σ the plot yielded 1153 h and 1.166 for these parameters, respectively. The relatively short median time is a consequence of the highly accelerated life tests. We will discuss this

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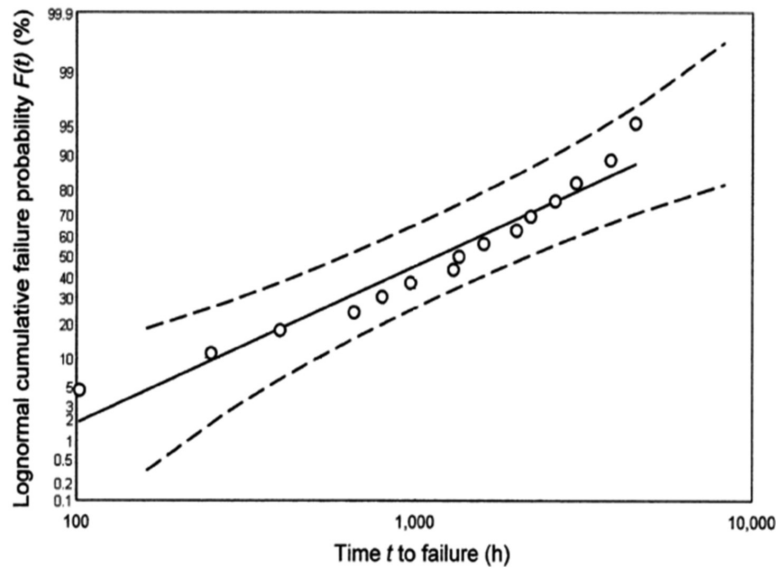


Figure 5.6 Lognormal probability plotting of the cumulative failure percent $F(t)$ values versus failure times calculated in Table 5.3 for the failure events in highly accelerated aging tests on InGaAs/AlGaAs diode lasers. The solid line in the lognormal probability graph represents the least-squares fit and the dashed lines the calculated 90% two-sided confidence limits.

topic in Section 5.5. According to the discussion in Section 5.2.2.2 and Figure 5.3, such low values of σ of around one reflect roughly a constant failure rate behavior and it may well be that the data are better matched by a Weibull or exponential failure distribution model (see the following sections).

Finally, the dashed lines in the figure are the 90% two-sided confidence bounds with 95% one-sided lower confidence limit and 95% one-sided upper confidence limit of the sample data for the selected distribution model. There are standard mathematical procedures for evaluating confidence limits, but a discussion of them would be beyond the scope of this text. For this information the reader is referred to relevant references including Epstein and Sobel (1953), Jordan (1984), Sudo and Nakano (1985), Nash (1993), O'Connor (2002), Tobias and Trindade (1986), and Dummer and Griffin (1966). We will, however, return to the topic briefly in Section 5.4 below, and discuss the confidence limits on MTTF estimates by giving the relevant mathematical expressions.

5.3.1.2 Weibull distribution

A Weibull probability plot is a plot of Equation (5.18). To realize this, we want to discuss two methods. The first comprises the standard procedure by plotting the $F(t_i)$ data versus failure times t_i on Weibull probability graph paper. The second method comprises a linearization of Equation (5.18) with subsequent plotting of the

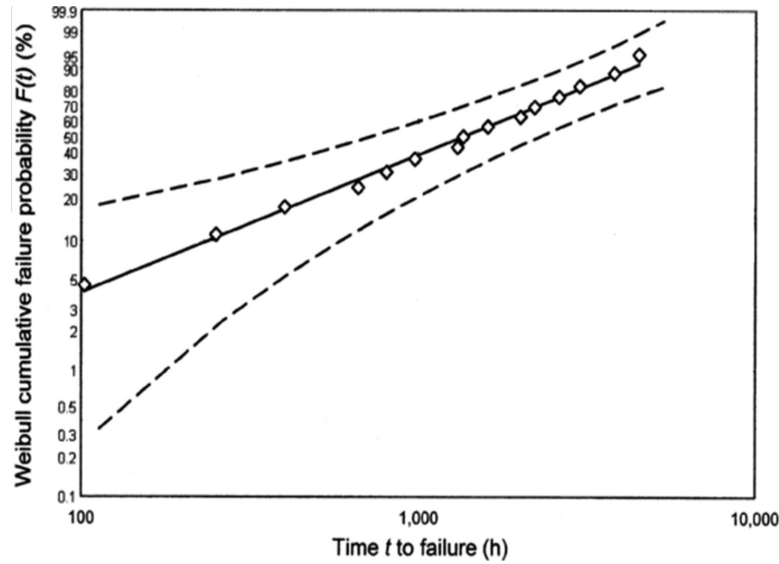


Figure 5.7 Weibull probability plotting of the cumulative failure percent $F(t)$ values versus failure times calculated in Table 5.3 for the failure events in highly accelerated aging tests on InGaAs/AlGaAs diode lasers. The solid line in the Weibull probability graph represents the least-squares fit and the dashed lines the calculated 90% two-sided confidence limits.

transformed data. We use the same example and highly accelerated failure data as in the previous section (see Table 5.3) to illustrate both methods.

Figure 5.7 shows a plot of the cumulative percent failures $F(t_i)$ versus failure times t_i on Weibull graph paper. The data are matched by the Weibull model much better than by the lognormal distribution shown in Figure 5.6. Using the definitions in Table 5.2 for relevant Weibull parameters and the plot in Figure 5.7, the timescale parameter η , also called the characteristic life parameter α (time at $F = 63.2\%$), has been derived to 1890 h (highly accelerated) and the important shape parameter β to 1.085. The value of the β parameter close to one indicates a nearly constant failure rate, which can actually be ascribed to the exponential distribution. However, as the β value is slightly above one, a weak wear-out component with a failure rate increasing in time might be involved in the aging process.

The second method is based on rewriting Equation (5.18) in the form ($\gamma = 0$ for simplicity) (Tobias and Trindade, 1986)

$$1 - F(t) = \exp \left\{ - (t/\eta)^\beta \right\} \quad (5.32)$$

and taking natural logarithms of both sides twice to get

$$\ln \{ -\ln [1 - F(t)] \} = \beta \ln t - \beta \ln \eta. \quad (5.33)$$

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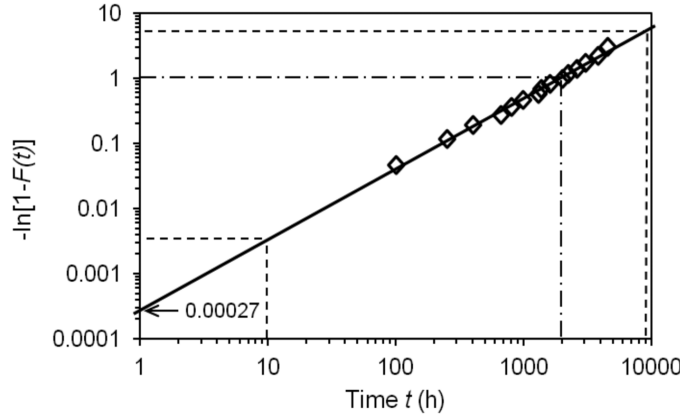


Figure 5.8 Weibull probability plotting of the transformed cumulative failure percentage variable $-\ln[1 - F(t)]$ versus failure times calculated in Table 5.3 for the failure events in highly accelerated aging tests on InGaAs/AlGaAs diode lasers. Dashed lines represent x, y coordinates of points on the anticipated straight-line least-squares fit used to calculate the shape parameter β from the slope of the straight line. The intercept is used to calculate a value for the timescale parameter η . The dotted-dashed lines give the coordinates for deriving a value for η from the condition of the transformed variable $-\ln[1 - F(\eta)] = 1$ for $t = \eta$.

Obviously, in a $\ln\{-\ln[1 - F(t)]\}$ versus $\ln t$ plot, Equation (5.33) represents a straight line of slope β and intercept $-\beta \ln \eta$.

Figure 5.8 shows the experimental dependence of $-\ln[1 - F(t_i)]$ versus t_i in a log-log plot for our example by using the data listed in Table 5.3 and the median ranks to estimate $F(t_i)$. The data fit reasonably well on a straight line, confirming also in this representation that the Weibull distribution can describe the data. To estimate the slope we pick, say, $t_1 = 10$ h and $t_2 = 9000$ h, which correspond to $y_1 = 0.0031$ and $y_2 = 5$, respectively. The intercept is found at $t = 1$ (where $\ln 1 = 0$) and amounts to 0.000 27. From these data average values for the shape parameter β and timescale parameter η (characteristic life α) have been calculated as

$$\bar{\beta} = \frac{\ln(5/0.0031)}{\ln(9000/10)} \cong 1.086 \pm 0.024 \quad (5.34)$$

$$\bar{\eta} = 0.00027^{-1/1.086} \cong (1932 \pm 130) \text{ h}. \quad (5.35)$$

Within the measurement errors, these results are in excellent agreement with the results derived from the probability paper plot in Figure 5.7.

Another procedure can be developed by replacing the left-hand side of Equation (5.33) by $\ln H(t)$, where $H(t)$ is the cumulative hazard expressed in Equation (5.8) and which can be linked to $F(t)$ by using Equation (5.4). A plot of $H(t)$ versus t on log-log paper would then yield again the shape parameter β from the slope of the straight line and the timescale parameter η from the intercept if the assumed Weibull

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5.4.4 Reliability estimations

The confidence limits on reliability estimates for exponentially distributed failures can be obtained by using the method in Section 5.4.2 above and the expression

$$R = \exp\{-\lambda t\} = \exp\{-t/\text{MTTF}\}. \quad (5.48)$$

If we take the lower and upper estimates for the MTTF of 1105 h and 2761 h, respectively, calculated at the 90% confidence level for our diode laser test example in Section 5.4.2, then the lower and upper reliability limits can be estimated as

$$R(l) = \exp\{-t/1105\} \quad \text{and} \quad R(u) = \exp\{-t/2761\}. \quad (5.49)$$

Thus, we can estimate with 90% confidence that the reliability of these highly stressed (temperature and current) lasers will be between 0.913 and 0.964 over the first 100 h or between only 0.405 and 0.696 over 1000 h.

Another example is the reliability calculation of a system with N components, such as lasers in an optical fiber communication system, each of which has a constant failure rate λ_i for $i = 1, 2, \dots, N$ within an exponential failure distribution. Considering in addition that each component must operate for the system to work, we can calculate the system reliability R_s by using

$$R_s = \exp\left\{-\sum_{i=1}^N \lambda_i t\right\} \quad (5.50)$$

where the failure rate of the system is the sum of the failure rates of its components. Let us consider a system with $\text{MTTF} = 10 \text{ years} = 8.76 \times 10^4 \text{ h}$ with 1000 lasers all with the same failure rate λ , which can then be calculated according to

$$\begin{aligned} R_s &= \exp\{-\lambda_s t\} = \exp\{-t/\text{MTTF}\} = \exp\{-t/8.76 \times 10^4\} \\ &= \exp\left\{-\sum_{i=1}^{1000} \lambda_i t\right\} = \exp\{-1000\lambda t\}. \end{aligned} \quad (5.51)$$

From Equation (5.51) a very low failure rate $\lambda = 1/(8.76 \times 10^4 \times 10^3) \text{ h}^{-1} \cong 11 \text{ FITs}$ has been obtained for the individual components demonstrating the extremely high requirements demanded from the reliability of the individual components in a system.

5.5 Accelerated reliability testing – physics–statistics models

5.5.1 Acceleration relationships

Under normal use conditions, it is not possible to obtain a reasonable amount of test data within a reasonable test time if the components have high reliability and long lifetimes. Therefore, tests are performed at much higher stress conditions to get

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failure data at relatively small test sample sizes and practical test times and that can then be fitted to life distribution models. Typical stresses include temperature, current, optical power, voltage, and humidity taken singly or in combination (see below). For example, raising the temperature of the item under test can be understood in terms of accelerating the aging mechanisms that are temperature dependent following the Maxwell–Boltzmann law.

It is crucial that the right levels of increased stress are chosen so that the failure mechanisms are not changed at higher stresses, but only the times to failure are shortened. Such a process represents true acceleration. The acceleration factor (AF) is defined as the ratio of the failure time at the use test condition (u) to that at an elevated stress condition (s). Under a linear acceleration assumption, every test failure time and distribution function is multiplied by the same AF constant value to obtain projected results during use. The key equations relating the random time to failure, PDF $f(t)$, CDF $F(t)$, and failure rate function at use condition to a stress condition can be written (Tobias and Trindade, 1986) in their most general form for true and linear acceleration conditions as follows:

$$t_u = \text{AF} \times t_s \quad (5.52)$$

$$f_u(t) = \left(\frac{1}{\text{AF}}\right) f_s\left(\frac{t}{\text{AF}}\right) \quad (5.53)$$

$$F_u(t) = F_s\left(\frac{t}{\text{AF}}\right) \quad (5.54)$$

$$\lambda_u(t) = \left(\frac{1}{\text{AF}}\right) \lambda_s\left(\frac{t}{\text{AF}}\right). \quad (5.55)$$

5.5.1.1 Exponential; Weibull; and lognormal distribution acceleration

In the following, we will see how these four equations are transformed when applied to the three life distributions.

Assuming Equation (5.22) for the CDF of the exponential distribution is also valid at high stresses, leading to failures occurring with a constant failure rate λ_s , we get

$$F_u(t) = F_s\left(\frac{t}{\text{AF}}\right) = 1 - \exp\left\{-\lambda_s \frac{t}{\text{AF}}\right\} = 1 - \exp\left\{-\frac{\lambda_s}{\text{AF}} t\right\} = 1 - \exp\{-\lambda_u t\}. \quad (5.56)$$

This means that the F function at use conditions remains exponential with the new failure rate parameter $\lambda_u = \lambda_s/\text{AF}$. Equation (5.56) implies that if an exponential model fits the data at a certain stress condition, then it also matches at any other stress condition as long as true and linear acceleration conditions are met. The simple inverse relationship of the failure rate with the acceleration factor applies only for the exponential life distribution.

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If the data at stress condition can be matched by $F_s(t)$ of a Weibull distribution with shape parameter β_s and timescale parameter η_s , Equation (5.18) can be written ($\gamma = 0$ for simplicity) as

$$F_s(t) = 1 - \exp \left\{ - (t/\eta_s)^{\beta_s} \right\} \quad (5.57)$$

and transforms to use stress as

$$F_u(t) = F_s \left(\frac{t}{AF} \right) = 1 - \exp \left\{ - \left(\frac{t}{AF} \times \frac{1}{\eta_s} \right)^{\beta_s} \right\} = 1 - \exp \left\{ - \left(\frac{t}{\eta_u} \right)^{\beta_u} \right\} \quad (5.58)$$

where $\eta_u = \eta_s \times AF$ and $\beta_u = \beta_s = \beta$.

This shows that if the Weibull model is valid at one stress level, then it is also valid at another stress condition provided there is true and linear acceleration. It is crucial that the shape parameter β remains the same. This means that, if there is Weibull acceleration in a test, then it is expected that the shape parameter will be the same for all the cells with different stress levels (corresponding to the slope of the different parallel straight lines of the Weibull data plots, see Figures 5.7 and 5.8). If this is not the case, then either the Weibull distribution is the wrong model to fit the data or the true and linear acceleration condition is not met.

By using Equations (5.20) and (5.55) the relationship between the Weibull failure rate at stress and use conditions can be obtained as

$$\lambda_u(t) = \frac{1}{AF} \frac{\beta}{\eta_s} \left(\frac{t}{AF \times \eta_s} \right)^{\beta-1} = \frac{1}{AF^\beta} \frac{\beta}{\eta_s} \left(\frac{t}{\eta_s} \right)^{\beta-1} = \frac{1}{AF^\beta} \lambda_s(t). \quad (5.59)$$

Equation (5.59) shows that the failure rate is multiplied by $1/AF$ only when $\beta = 1$ and the data fit an exponential distribution.

Finally, it can be shown that by applying Equation (5.54) to the lognormal CDF F_s at stress conditions with the characteristic parameters $t_{50,s}$ and σ_s (see Section 5.2.2.2), again a lognormal distribution can be found at use conditions with $\sigma_u = \sigma_s = \sigma$ and $t_{50,u} = AF \times t_{50,s}$, where σ_u and $t_{50,u}$ are the use parameters for the lognormal shape parameter and median time, respectively. The reader is referred to Tobias and Trindade (1986) for details on making the acceleration transformation of the timescale given by $F_u(t) = F_s(t/AF)$. As with the Weibull, true linear acceleration does not change the type of distribution. It is also expected that different stress cells of data will yield the same shape parameter.

5.5.2 Remarks on acceleration models

In the previous section, we saw that the acceleration factor between stresses can be calculated by knowing the failure rate constants, scale parameters, or the median times at two stress levels. If the acceleration factor is already known, then the results from the stress tests can be converted to use condition reliability projections. However, if the acceleration factor is not known, then the stress data have to be used to fit an

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appropriate acceleration model, which can be used to extrapolate to use conditions. Different failure mechanisms may be involved in the accelerated aging process, which follow different life distributions and may also have different acceleration models. Therefore, accelerated aging tests have to be designed carefully to produce unique data from only one failure mode, which may be accelerated by more than one stress factor.

In the following we discuss three general well-established model forms including (i) the Arrhenius model describing thermally activated mechanisms, (ii) the inverse power law describing the life of an item inversely proportional to an applied stress, and (iii) the Eyring model considering a temperature term and additional nonthermal stress terms.

5.5.2.1 Arrhenius model

The Arrhenius model has been used with great success to describe thermally activated mechanisms regardless of the underlying life distributions – lognormal, Weibull, or exponential. It describes the temperature dependence of features such as median time t_{50} , timescale parameter η (characteristic life parameter α), or $\text{MTTF} = 1/\lambda$ or any other percentile of a life distribution as a rate equation

$$R = R_0 \exp\{-E_a/k_B T\} \quad (5.60)$$

where R is the reaction rate, R_0 is a constant, E_a is the activation energy in units of eV, $k_B = 8.617 \times 10^{-5}$ eV/K is the Boltzmann constant, and T is the reaction temperature in units of K. If this relationship holds, then the time to failure is inversely proportional to the reaction rate. For convenience we take $t_{50,f}$ which can be written as

$$t_{50,f} = A \exp\{E_a/k_B T\} \quad (5.61)$$

where A is a constant and $t_{50,f}$ is the time to reach 50% failures. The acceleration factor (AF) between temperature T_1 and temperature $T_2 > T_1$ is then given by

$$\text{AF} = \frac{R_2(T_2)}{R_1(T_1)} = \frac{t_{50,1}(T_1)}{t_{50,2}(T_2)} = \exp\left\{\frac{E_a}{k_B} \left(\frac{1}{T_1} - \frac{1}{T_2}\right)\right\} \quad (5.62)$$

and is independent of the chosen cumulative percentage of failure. Equation (5.62) shows that, knowing E_a , the acceleration factor between any two temperatures can then be calculated. Conversely, knowing the acceleration factor, the activation energy E_a can be calculated from

$$E_a = k_B (\ln \text{AF}) \frac{1}{\left(\frac{1}{T_1} - \frac{1}{T_2}\right)}. \quad (5.63)$$

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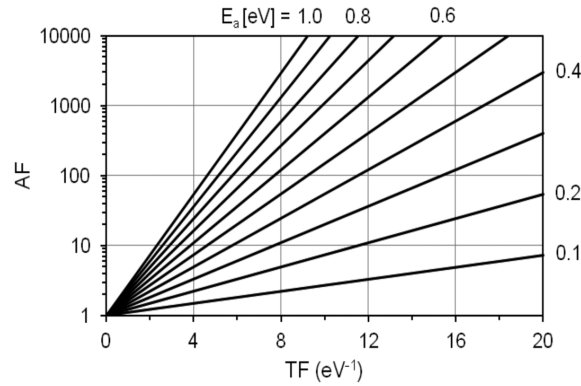


Figure 5.11 Acceleration factor AF versus parameter TF calculated for a range of thermal activation energies E_a . TF is defined as in Equation (5.64) and measured in units of $(\text{eV})^{-1}$, and the temperatures $T_2 > T_1$ are in Kelvin (K). AF can be read from the graph for a given E_a and pair of temperatures yielding TF.

Equation (5.63) is valid for any life distribution. A useful plot of AF versus TF for a range of E_a values (Figure 5.11) can be generated from Equation (5.62) where

$$TF = k_B^{-1} (T_1^{-1} - T_2^{-1}) = 11605 \times (T_1^{-1} - T_2^{-1}) [\text{eV}^{-1}]. \quad (5.64)$$

TF is measured in units of $(\text{eV})^{-1}$ and the temperatures T are in units of Kelvin (K), which are obtained by adding 273.16 to the temperature in degrees Celsius ($^{\circ}\text{C}$).

Example for illustration: We apply the Arrhenius formalism to our example used throughout Section 5.3. Diode lasers were highly stressed at high temperatures of $120^{\circ}\text{C} \hat{=} 393\text{ K}$ heat sink temperature resulting in $TF = 9.4 (\text{eV})^{-1}$ for a use temperature of $25^{\circ}\text{C} \hat{=} 298\text{ K}$, which leads to $AF = 410$ read off Figure 5.11 or calculated from Equation (5.62) for $E_a = 0.64\text{ eV}$. This activation energy has been determined separately and is a typical value for the stressed InGaAs/AlGaAs QW lasers in the wear-out regime. The timescale parameter (at the failure percentile $F = 63.2\%$) at use conditions η_u can then be calculated using the Weibull model, which fits the failures well (see Section 5.3.1.2). It amounts to $\eta_u = \eta_s \times AF = 7.7 \times 10^5\text{ h} \cong 88\text{ years}$ using $\eta_s = 1890\text{ h}$ and $AF = 410$.

Using the available data, we can also calculate the probability that the lasers survive, say, 10 years. The failure probability is given by Equation (5.58) and is calculated as $F_u(t = 10\text{ years} = 8.76 \times 10^4\text{ h}) \cong 9 \times 10^{-2}$ by using $AF = 410$, $\beta_s = 1.085$, and $\eta_s = 1890\text{ h}$. Thus, the survival probability of the lasers after 10 years is $1 - F(10\text{ years}) \cong 0.91$ ($\sim 91\%$).

Alternatively to Equation (5.63), a procedure based on more than two temperature cells can be derived from the key Arrhenius formula in Equation (5.61) and can yield,

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Critical laser parameters for long-term stability and reliability will be determined. Essential for successful reliability investigations are the test preparations, which include procuring effective test equipment and defining sample sizes, and test durations of the experiments. The central portion of this chapter deals extensively with the technical aspects of the individual building blocks of the reliability engineering program including specifications, conditions, and results of the various test procedures for the laser chip, subcomponents, and module. We will also describe how the collection, analysis, and reporting of reliability data play an integral part in the program. In the final sections, the advantages and benefits of a reliability growth program and a reliability engineering program will be described, including a reliability cost model for determining an optimum reliability point by balancing the initial and post-production costs.

6.1 Reliability test plan

6.1.1 Main purpose; motivation; and goals

The implementation of a reliability engineering program (REP) adds great value to an organization's assets and success. To succeed in today's highly competitive and technologically complex industrial laser markets with increasing performance and reliability demands, knowledge of product reliability is mandatory, as is the ability to control it in order to produce products at an optimum level of reliability. In real terms, this means yielding the minimum life-cycle costs for the user and minimizing the manufacturer's life-cycle costs of such a product without compromising the product's reliability and quality.

This complex goal can be achieved by the implementation of an effective and efficient REP. However, a condition for success is to have a culture of reliability in the organization that requires everybody involved in the planning, concept and design, production and delivery of a product to understand the need for a healthy REP for the organization's success. An essential step in this direction is to have the support of the organization's senior management, which can usually be obtained by emphasizing the financial benefits resulting from a successful, living REP in the form of increased customer goodwill and satisfaction, positive image and favorable reputation, increased sales revenue and positive impact on future business, and enhanced competitive advantage. Equally important are the support and understanding of the technical personnel responsible for the implementation and operation of the REP. Only then can the REP contribute to the success of the organization's high-quality and high-reliability products.

Reliability engineering provides the theoretical and practical tools with which the capability of products can be specified, designed-in, predicted, tested, and demonstrated with regard to the performance of their desired functions for the required periods of time without failure, in specified environments, and with the desired confidence. It covers all aspects of a product's life from its conception, subsequent design, and production through to the end of its practical use life. A highly reliable product is

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as good as the inherent reliability of the product and the quality of the manufacturing processes. Reliability is the most important quality factor of a product or, in other terms, quality is based on reliability.

The REP is an essential component of a good product life-cycle management program comprising the following goals:

- To evaluate the inherent reliability of a product or manufacturing process.
- To pinpoint potential areas for reliability improvement.
- To identify the most likely failures as early as possible in the product life cycle.
- To identify appropriate actions to eliminate failures or mitigate the effects of these failures.

The overriding goal is to use the reliability information at the highest level to assess the financial impact of the reliability of the products and to improve the overall product reliability, leading to decreased overall lifetime costs and consequently to an improvement in the financial strength of the organization. However, a proper balance must be struck between reliability and other business aspects such as time to market, manufacturing costs, sales, product features, and customer satisfaction.

6.1.2 Up-front requirements and activities

Important foundations for an REP are the clear definitions of reliability specifications for a product and what constitutes a failure. It is also critically important to provide a methodical way of examining the proposed design of a product for possible ways in which failure can occur. We will discuss the basics of the failure modes and effect analysis approach revealing the criticality of failure modes.

6.1.2.1 Functional and reliability specifications

The definition of reliability is the ability of a product to perform its intended mission under given conditions for a specified time without failing. This means that clear, unambiguous, and detailed reliability specifications must be agreed in line with the conditions in the reliability definition addressing failure rate, effective use time, usage limitations, and operating environment. An example from the highly demanding applications of pump lasers in submerged optical communication systems may illustrate the situation:

- Wear-out failure rate at 200 mW single-mode power in fiber: $<0.2\%$ at 25°C , with 95% upper confidence limit over 27 years.
- Sudden failure rate at 200 mW single-mode power in fiber: $<2\%$ at 25°C , with 95% upper confidence limit over 27 years (≈ 80 FITs).

Setting clearly specified reliability goals requires the involvement of the customer and design, manufacturing, and quality engineers from the manufacturer's organization. Of course, the ideal situation is when the organization has solid reliability

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expertise and the background required to define realistic goals and specifications to be met by the product under use operation. In the formulation process of the reliability specifications, it is also essential to consider financial aspects such as planning for warranty and production part costs, so that in the end a proper balance of realistic reliability performance expectations and financial issues can be achieved.

6.1.2.2 Definition of product failures

Another critical issue is the definition of what constitutes a failure, which can be decisive as to whether a product meets the reliability tests. It is imperative to agree commonly accepted definitions of product failures across all parties involved in the product development processes and for various different reasons. These groups may have different definitions of product failure, which may yield radically different results from a test. Universally agreed failure definitions may have the benefit of minimizing the tendency to rationalize away certain failures, particularly in the early stages of the product development. This may result in a lower risk of releasing products into the field with poorly defined but very real failure modes. Communications and the management of the REP may also become more effective and error-free. In the case of a complex product with a number of distinct failure modes, the implementation of a multi-tiered failure definition structure may ease the assessment and analysis of the different failures by logging them under individual codes into a database.

Typical failure criteria for pump diode lasers are, for example, a 5% reduction in optical power ex-facet during accelerated life tests at high temperature and power or 50% increase in threshold current at the rated power.

6.1.2.3 Failure modes, effects, and criticality analysis

The most commonly used form of risk analysis is the failure modes, effects, and criticality analysis (FMECA). It is formalized in the standard MIL-STD-1629 (e.g., ReliaSoft Corporation, 2011a) as a structured analysis of potential failure modes and their effects on the product. The aim is to reduce or eliminate failures in products or processes by identifying and applying appropriate corrective actions. In this way, failures are prevented from reaching the customer and hence the highest yield, quality, and reliability can be assured and the cost of quality can be reduced both in the organization and at the customer.

There is a design FMECA, used by product design engineers, which addresses potential product failures, and a process FMECA, used by process design engineers, which addresses potential manufacturing process failures, which ultimately could lead to product failures. Both types are independent of each other and can be produced separately.

Conducting an FMECA is a multifunctional team effort requiring the input of many disciplines including design, manufacturing, testing, quality, reliability, failure analysis, packaging, and marketing. One of the most important factors for the successful implementation of an FMECA program is timing. It is meant to be a *before-the-event* action and not an *after-the-fact* exercise. To achieve its greatest value, it

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levels, which means a higher percentage of device failures in the same step duration. In principle, it should be possible to determine both the failure rate at any stress level, by plotting the failure data from the various steps, and the failure rate distribution for each failure mechanism. This would then allow the prediction of the product reliability, which could be considered an additional benefit of step stress testing (Iuculano and Zanini, 1986; Bai *et al.*, 1989; Nelson, 1975, 1980; Miller and Nelson, 1983).

6.1.6.2 Accelerated life tests

As discussed in Section 5.5, the purpose of accelerated testing is to get within reasonable test times sufficient failure data to then allow prediction of the lifetime of the product under use conditions. Common stress factors applied in diode laser accelerated lifetime tests are temperature, current, or optical power in either an automatic current control (ACC) or automatic power control (APC) configuration. In the following, we describe typical accelerated tests for pump laser chips and laser modules.

Laser chip

Laser chips are soldered to a heat sink mounted on a submount assembly, which includes a reverse-biased protection diode. The submount assembly also has a pin photodiode for monitoring the power and a thermistor for temperature control in the module (see Section 1.4.3). The submounted lasers undergo a burn-in process and are screened for threshold current, slope efficiency, kink power, forward voltage, peak wavelength, spectral width, and far-field angles before they are mounted onto the test sites. Every submount receives an ACC burn-in typically at 350 mA, 70 °C for 96 h and with a failure criterion of >10% the threshold current increase.

A typical matrix life-test program is shown in Table 6.2 aimed at identifying and modeling acceleration factors for wear-out and steady-state reliability. Test conditions

Table 6.2 Typical matrix accelerated life-test plan for submounted single-mode high-power diode laser chips. Applicable standards: MIL-STD-883(D), Method 1005 (IHS, Inc., 2008); TR-NWT-000468 (Telcordia Inc., 2011).

Cell	Heat sink temperature [° C]	Drive current [mA]	Optical power [mW]	Sample size / wafer	Minimum test time [h]	Failure criterion
A	70	500	~250	80 / 5	4000	5% drop in peak power ex-facet
B	70	250	~130	80 / 5	4000	
C	100	500	~200	80 / 5	4000	
D	100	250	~100	80 / 5	4000	
E	120	500	~150	80 / 5	4000	
F	120	250	~80	80 / 5	4000	

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and sample sizes are more severe and higher, respectively, than those recommended in the relevant standards MIL-STD-883D Method 1005 Condition B (IHS, Inc., 2008) and Bellcore TR-NWT-000468 (Telcordia Inc., 2011).

The temperatures T_h are the temperatures measured on the heat sink of the laser submount assembly. The junction temperatures T_j are much higher and depend on the drive current and/or output power and can be either calculated using the actual thermal resistance R_{th} (see Equation 2.37) or measured via the wavelength shift determined in a spatially resolved electroluminescence experiment (see Part III).

A typical value for T_j is 145 °C using $R_{th} = 42$ °C/W, $I_{dr} = 500$ mA, and $P = 200$ mW at $T_h = 100$ °C in the calculation. It is anticipated that failures arise in cells A, C, and E within 2000 h test time, yielding a target sudden failure rate figure of <100 FITs at 2000 h.

Typical results of highly accelerated lifetime tests on submounted InGaAs/AlGaAs pump diode lasers aged at high temperatures and drive currents (common practice) have been discussed in Sections 5.3 and 5.5. Depending on the values of the thermal activation energy and current exponent used for calculating the temperature and current acceleration factors, lifetimes can be expected to be above 1×10^6 h > 110 years at use conditions of 25 °C and 250 mA (for 200 mW ex-facet) for both the sudden failure rate and wear-out regimes.

In the accelerated tests, defined in Table 6.2, the optical power is monitored as a function of stress time and failures are counted when the power drops by $\geq 5\%$ of the rated peak power level, for example, 200 mW at $T_h = 100$ °C. Other important operating parameters to be measured periodically during the life tests include threshold current, slope efficiency, kink power, and peak wavelength. In general, the following trends can be expected at stress conditions: for example, $T_h = 100$ °C, $I_{dr} = 500$ mA, $P \sim 200$ mW. The changes (Epperlein *et al.*, 2001, unpublished) usually occur gradually in the first few thousand hours of aging and saturate after ~ 5000 h:

- Threshold current: average increase $\sim 5\%$.
- Slope efficiency: average reduction $\sim -5\%$.
- Kink: typical changes in kink currents $< \pm 10\%$.
- Wavelength: maximum increase $\sim +6$ nm.

In addition to the standard accelerated lifetime tests, so-called *benign life tests* should be executed on diode lasers for applications in demanding areas such as submarine optical communication networks that require the utmost product reliability to avoid the extremely high repair/replacement costs in case of product failure. The aim of these tests is to simulate real-life conditions and demonstrate that no unexpected behavior occurs under such conditions. Thus, an upper confidence limit can be placed on the correctness of the models derived from the matrix life tests. Typical test conditions are 180 devices driven at maximum rated optical power at 50 °C for 4000 h.

Laser module

Submounted lasers chips with the photodiode and thermistor attached undergo a burn-in and screening process, as described above, before they are inserted into a fibered module. The module is housed in a 14-pin butterfly hermetic package (see Figure 1.37), which contains a thermoelectric-cooled optical platform. This platform includes the diode laser on a heat sink controlled by the photocurrent from the back-facet monitor photodiode. The laser beam is tightly coupled to a highly stable fiber alignment system. The platform temperature is monitored by a thermistor whose output is used to control the thermoelectric cooler current via an external feedback circuit. The fiber exits the package via a hermetically sealed feedthrough tube (see Section 1.4.3 and Figure 1.37).

The goal of accelerated aging tests of pump laser modules is to demonstrate their endurance (in combination with environmental tests) and to evaluate median lifetimes, failure rates, and thermal activation energies. The test methods and failure criteria are based on the standards Bellcore Advisory TA-NWT-001312 and Technical Reference TR-NWT-000468. The former is now being replaced by Telcordia GR-1312-CORE, the latter by GR-468-CORE (Telcordia Inc., 2011). The accelerated aging test conditions are listed in Table 6.3.

The modules are aged under ACC conditions in special package test systems, where the ovens are adjusted to maintain the selected package temperature T_p monitored with a thermocouple outside the package on the test board. The module thermistor controls the cooler to maintain a constant submount temperature T_s . The systems provide in situ monitoring of photocurrent, laser current, and cooler current and voltage. The modules are removed periodically, for example, every 120 h, from the test ovens for measurements of the P/I characteristics, from which key operating parameters such as threshold current, slope efficiency, and kink power are determined. Alternatively, there are systems that provide for in situ measurements of the P/I .

The failure criterion is given by the end of life (EOL), which is determined by a 50% increase in laser current at the specified fiber-coupled power as recommended in the Bellcore standards. To derive wear-out time to failure, the criterion is applied for

Table 6.3 Typical matrix accelerated life-test plan for single-mode high-power diode laser modules. T_s = submount temperature, T_p = package temperature. Applicable standards: TR-NWT-000468, TA-NWT-001312 (Telcordia Inc., 2011).

Cell	T_s [° C]	T_p [° C]	I_{dr} [mA]	Sample / wafer size	Minimum test time [h]	Failure criterion
A	25	70	400	15 / 3	5000	End of life 50% drop in in-fiber power
B	25	85	400	15 / 3	5000	
C	30	85	400	15 / 3	5000	
D	55	85	400	15 / 3	5000	

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each module by using a linear extrapolation of the time dependence of the drive current $I_{dr}(t)$ during the life test. However, the results of this analysis depend very strongly on the period of time over which the linear extrapolations are made. Therefore, it is important to use the same aging time period, typically 5–10 kh, for this process for comparing different module groups.

Data of long-term projections confirm that the pump laser modules of all leading manufacturers are inherently mature and extremely reliable products. Thus, median lives $> 8 \times 10^5$ h > 90 years at 200 mW in-fiber power, 25 °C, and maximum wear-out failure rates < 1000 FITs are standard figures. The thermal activation for wear-out relative to the package temperature T_p is usually negligibly small ($E_a < 0.1$ eV). Root causes for degradation in the module can be attributed both to the movement of the fiber tip relative to the laser emission area occurring in the early failure regime with some saturating effect, and to the submounted laser itself, in particular at longer times.

6.1.6.3 Environmental stress testing – laser chip

The purpose of these tests is to examine the robustness of the submounted laser chip with an attached wire bond and to expose weaknesses and latent defects that may result in field failures if corrective action is not taken. In general, the various tests can be divided into three groups: temperature endurance, mechanical integrity, and special tests. These different types of tests along with typical results are discussed below by means of single-mode high-power InGaAs/AlGaAs SQW laser devices, but are in general also valid for other diode laser types as required.

Temperature endurance

Table 6.4 lists the temperature endurance test comprising a temperature cycling test and its conditions and effects according to Bellcore TR-NWT-000468 recommendations. The requirements are that the in-spec devices maintain their specified characteristics within the allowable change limits after completion of the test.

Table 6.4 Temperature endurance test plan for submounted single-mode high-power diode laser chips.

Test	Conditions	References	SS	Potential effects
Temperature cycling (unbiased)	–40 to +70 °C; 50 cycles with fast 12 min ramps and short 15 min dwells	MIL-STD-883D method 1010. Bellcore TR- NWT-000468 Issue 1	11	Distortion due to expansion and contraction, peeling, cracking due to liquid evaporation, fatigue, cracks in finished surfaces. Changes in electro-optical characteristics
Notes:				
SS = sample size				
MIL-STD-883D method 1010 (IHS, Inc., 2008)				
Bellcore TR-NWT-000468 (Telcordia Inc., 2011)				

Part III

DIODE LASER DIAGNOSTICS

Overview

As diode laser applications continue to demand increasingly higher optical output power and longer lifetime data, the stress on the material, particularly at the susceptible mirror facets, poses an ever-growing technological challenge. That is, it has become both increasingly vital and more intricate to identify and analyze the real root causes of specific performance degradation modes at the ultimate laser operating conditions, at which laser performance and reliability are affected at much lower defect densities. In addition, the growing demand for the highest laser functionality and yield makes it indispensable to develop superior materials and device technologies so that they can excel the current and meet the next generation of laser performance requirements. In this sense, material and device characterization employing powerful diagnostic and analytical techniques within the laser product development process will play an increasingly important role and thus continue to make vital contributions to the advancement of the state-of-the-art.

These diagnostic investigations should be implemented as an integral part of the diode laser development plan. The objective is to reveal potential causes for failures in performance and reliability *before* the devices are put through life tests and *before* they are deployed in the field. This proactive and preventive action is in contrast to failure analysis (FA) activities, which are executed only when a device *has failed*.

It is *not the intention* of this part of the text to elaborate on FA techniques and approaches. Although many books and numerous articles in scientific journals have been published on FA of diode lasers, we want to mention briefly in the following some commonly used FA techniques for information and comparison. These can be divided into the general categories of destructive versus nondestructive, contactless versus with contacts, and plan view (view from the top) versus cross-section view detection (view from the side).

Optical microscopic inspection can very quickly detect the first fingerprints of device failure, for example, caused by mechanical damage or contamination. Epitaxial

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defects, cracks, topography changes, poor morphology, growth roughness, and metal lifting can be easily detected when the microscope is equipped with differential interference contrast (Nomarski).

Electroluminescence (EL) images can be generated by forward biasing the laser to below-threshold operation and detect the integral or spectrally resolved spontaneous emission. This can be achieved in plan view by detecting the light through an opening in the top metal contact or at the device back side with a thinned substrate and without metal contact. Side view EL images can be obtained via a lateral window realized by cleaving the laser in close proximity along the cavity. This approach has been applied for measuring spatially resolved operating temperatures in the cavity and will be described in Chapter 9. EL imaging is particularly suited to study the development of dark-line defects (DLDs) caused by luminescence killing dislocation networks in the laser cavity (see Chapter 3). EL line scans across a defect structure provide useful quantitative information.

Useful information on the extent of device degradation can be obtained quickly from P/I and V/I characteristics. The former can provide information on the location of the failure due to changes, for example, in threshold current, slope efficiency, and peak optical power. From the latter we can derive information on potential changes in contact integrity resulting in changes in device resistance and turn-on voltage. The leakage current of reverse-biased devices is an indicator of the size of impact caused, for example, by DLD networks and electrostatic discharge (ESD) events. In general, leakage currents due to ESD are much higher due to the damage to the depletion zone in the active region.

Scanning electron microscopy (SEM) is well established for imaging the microstructure of solid surfaces and detecting failures such as delamination, oxidation, contamination, and melting showing up at the surface. It combines high spatial resolution (max. ~ 1 nm) with depth of field in the same image, requires minimal sample preparation, but cannot detect root causes hidden below the surface. SEM on cross-sections obtained by cleaving through the laser structure provides useful information on the thickness and position of the individual layers in the vertical structure. The contrast in these SEM images is caused by the secondary electron emission intensity, which is sensitive to the different compositions of the layers, that is, chemical makeup and surface work function. Using a suitable composition- and doping-sensitive stain etch before taking the SEM image is a further option to highlight relevant features such as layer cross-sections or defect structures.

Electron beam-induced current (EBIC) is a technique that can be run in an SEM by generating electron-hole pairs within the effective electron beam volume of excitation. Electrons and holes are collected within the depletion zone of the p-n junction of the diode laser where they are separated by the electric field, resulting in a small current, which flows through an external circuit, and after amplification is used to modulate the intensity of the viewing screen of the microscope. EBIC is very suitable for evaluating the electrical properties of the semiconductor and in particular electrically active defects such as dislocations. Carriers recombine at such sites before they can be collected at the n-region and p-region, which leads to a lower current level. This then make these areas appear dark on the EBIC screen. Cross-sectional EBIC is

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useful in locating the p–n junction in the growth direction whereas plan view EBIC shows the lateral distribution of active defects in the junction plane. In Chapter 8, we discuss the application of EBIC in evaluating the effects of stress-enhanced defect formation and migration in diode lasers.

The cathodoluminescence (CL) signal is generated by the radiative recombination of minority carriers excited by the electron beam in an SEM. CL requires no bias, electrical connectivity, or junction, and emission emerges from all excited layers that have a direct bandgap. Nonradiative carrier recombination at electrically active defect sites dramatically reduces the CL efficiency. A common setup for light excitation and collection consists of a polished ellipsoidal mirror where at one focal point the electron beam enters through a hole in the mirror and impinges on the sample. For light collection, usually a light pipe sits at the other focal point. Alternatively, arrays of photodiodes can be used in place of the light pipe. The detector signal is used to modulate the intensity of the viewing screen to generate the CL image. CL images can be detected in plan view and cross-sectional view. Spectrally resolved CL images require cooling of the sample on a low-temperature stage in the SEM system to liquid nitrogen or helium temperatures depending on the specific requirements, and to spectrally detect the CL signal in a monochromator. Cooling the sample reduces both detrimental phonon broadening and thermally-activated nonradiative recombination events via deep-trap defect centers. In general, both effects narrow the spectral lines and dramatically increase the signal of any luminescence spectrum. In addition, many weak transitions can only be detected at very low temperatures below the boiling point of liquid helium at 4.2 K.

Transmission electron microscopy (TEM) is employed to image physical features of structures such as spatial uniformity of quantum wells, integrity of interfaces, defects including precipitates, inclusions, stacking faults, microloops, and dislocations at a very high spatial resolution in the subnanometer regime, if required. TEM requires sample thicknesses well below 1 μm , which is a challenging task for preparation when applying the conventional methods including grinding and ablating. However, preparation is eased and produces more reproducible and satisfying results by using a modern focused ion-beam (FIB) technique, where a gallium beam cuts away the unwanted material to finally leave a thin membrane. TEM can be applied on cross-sectional and plan view samples. Cross-sectional TEM requires knowledge of the spatial origin of device failure so that it is included when cutting the sample. Practical lateral limits are some tens of micrometers for plan view samples, which are cut along the laser cavity and include the active region, usually the dominant part in the development of bulk failure mechanisms.

Scanning laser techniques are useful in evaluating the uniformity of epitaxial layers and semiconductor wafers regarding the two-dimensional distribution of composition, dopants, and defects. Section 7.1 below describes a scanning laser technique producing within minutes a digital photoluminescence (PL) image of a full 2 inch silicon-doped GaAs wafer. By removing the contact electrode layers and thinning the top and/or back side of the laser device so that the information of interest is within the total depth given by the sum of light penetration and carrier diffusion length, the technique can be applied successfully to analyze failed laser devices. Apart from

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collecting the PL signal, the carriers generated by the excitation laser with an above-bandgap energy can be collected and used in a manner similar to EBIC. This mode is called optical beam-induced current (OBIC) and is less demanding and costly in its realization but yields effectively the same results within a resolution of a couple of micrometers. By rastering the laser beam with a below-bandgap energy across the sample a so-called thermally induced voltage alteration (TIVA) image can be obtained. In this case, the laser beam merely heats the sample and localized heating can be pronounced at extended defect sites causing a change in resistance, which in turn causes a change in voltage of a constant current biased device. The change in voltage is used to plot the image as a function of the position of the exciting laser beam spot. This technique and similar laser probe techniques are suitable for detecting and isolating faults such as open junctions and shorts, in particular in integrated circuits (ICs).

The following description gives an overview of the topics to be dealt with in Chapters 7, 8, and 9. Many of the new diagnostic approaches and techniques described here were pioneered and adjusted by the author specifically for applications in diode laser research and optimization. They have yielded numerous world's first results and many have been adopted by other researchers in academia and industry.

The various diagnostic data on parameters such as impurity trapping in active layers, deep traps at active layer interfaces, laser operating temperatures, stress fields and crystallographic material instabilities, as well as the various root causes and correlations have provided invaluable insights into the significance of these parameters in laser operation. They have contributed significantly to a more detailed understanding of potential degradation mechanisms of laser functionality and thus have furnished the knowledge for effectively optimizing laser design, fabrication processes, laser performance, and reliability. The following chapters report the immense endeavors in pursuit of these goals and also describe the novel techniques, approaches, and diagnostic data in detail.

We will discuss the vast experimental data set obtained from various types of single transverse mode diode lasers regarding the most different material-oriented and device-linked effects including:

- wafer substrate optical uniformity;
- impurity trapping in active layers;
- deep-level defects at active layer interfaces;
- local operating temperatures at mirror facets of different technologies and vertical device structures;
- local operating temperatures along laser cavities;
- mirror temperature topographs;
- temperature-monitored degradation processes;
- mechanical stress in ridge waveguide structures;

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- detection of “weak spots” in diode laser mirror facets;
- stress-induced formation, migration and separation of electrically active defects;
- structural and compositional disorder in mirror facets; and
- recrystallization effects in mirror coatings.

Correlations of these parameters with laser performance and reliability data are also discussed. The basics of the employed measurement techniques and approaches are described, which include:

- photoluminescence (PL) scanning;
- low-temperature PL spectroscopy;
- EL spectroscopy with high spatial resolution;
- laser microprobe Raman scattering spectroscopy;
- microspot reflectance modulation or thermoreflectance;
- EBIC; and
- deep-level transient spectroscopy.

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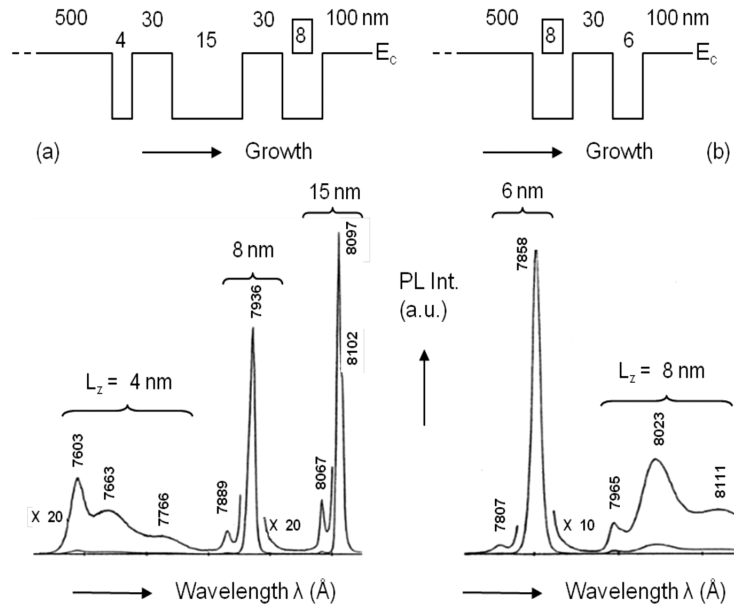


Figure 7.6 Photoluminescence (PL) spectra of AlGaAs/GaAs multi-quantum well (MQW) structures at low temperatures of 2 K. For clarity only the simplified conduction band portion of the MQW structures is shown. (a) MQW with 4, 15, 8 nm wide in-a-sequence MBE-grown QWs. (b) MQW with 8, 6 nm wide in-a-sequence grown QWs. Focus is on the shape of the PL spectrum of the 8 nm QW in (a) and (b).

7.2.3 Discussion of quantum well PL spectra

7.2.3.1 Exciton and impurity-related recombinations

A typical 2 K PL spectrum of a MQW sample with SQWs 4, 15, and 8 nm wide is shown in Figure 7.6a where the 4 nm QW is the first in-a-sequence-grown well after the bottom AlGaAs cladding layer 500 nm thick. The spectrum of this 4 nm well shows a sharper peak on the high-energy side end and two broader peaks on the low-energy side (only visible with signal expansion by 20 $\times$), whereas the spectra of the subsequently grown 15 and 8 nm wells with 30 nm barriers each exhibit a dominating, high-intensity sharp emission, without signal expansion.

The peak on the high-energy side of the 4 nm QW spectrum and the strong narrow lines in the 8 and 15 nm well spectra can be attributed to the intrinsic $n = 1$ free heavy-hole exciton recombination, FE(e1–hh1), with a photon energy E_{1h} . We can exclude impurity (acceptor) bound exciton luminescence, which occurs only occasionally with an almost unobservable emission, Stokes-shifted from E_{1h} by about 4 meV.

The lower intensity, sharp peaks on the high-energy sides (signal expanded 20 $\times$) of the dominating peaks in the 15 and 8 nm well spectra can be assigned to the $n = 1$ free light-hole exciton recombination, FE(e1–lh1), with a photon energy E_{1l} .

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These E_{1h} and E_{1l} assignments have been concluded from the dependence of the PL intensity on excitation power and lattice temperature. The intrinsic PL intensity is nearly linear in excitation power, as expected for a monomolecular (excitonic) recombination process, and decreases by about 20% when the sample temperature is increased from 2 to ~ 30 K. For details see Epperlein and Meier (1990). PLE spectroscopy measurements and subband calculations confirm these assignments.

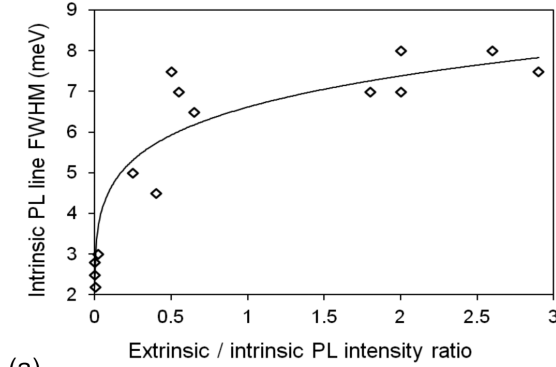
Figure 7.6b shows the spectrum of a MQW where an 8 nm SQW is grown first with a subsequent 6 nm well growth. In contrast, the 8 nm well now shows the reduced signal emission with two broader peaks on the low-energy side and the 6 nm well the dominating, high-intensity sharp emission with a narrow peak again on the high-energy side after signal expansion $10\times$. The various narrow emissions on the high-energy sides of the sub-spectra can again be ascribed to free exciton recombinations.

On the other hand, the extrinsic PL, that is, the intensity of the luminescence on the low-energy side of the intrinsic peak of the 4 nm well in Figure 7.6a and the 8 nm well in Figure 7.6b, tends to saturate at higher excitation powers (Epperlein and Meier, 1990). The presence of a limited number of impurities can plausibly account for such a saturation. This effect and the energy of the transition strongly suggest that it can be ascribed to the recombination of free electrons in the $n = 1$ quantum confined state with neutral acceptors in the QW, marked as $(e1, A^\circ)$. Donor-acceptor pair recombination can be ruled out for three reasons: (i) the intensity of the extrinsic peak is not very sensitive to temperature in the range of 2 to 20 K; (ii) the energy of the peak responds only slightly to the excitation intensity; and (iii) to temperature. Further evidence of the involvement of acceptors in the formation of the broad extrinsic PL emissions and their identification will be discussed in the next section.

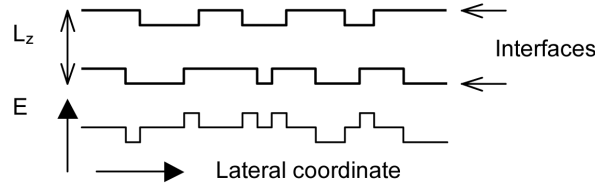
Moreover, the presence of extrinsic QW PL correlates with the linewidth of the intrinsic exciton PL emission and with the thickness of the bottom cladding and barrier layers.

Figure 7.7a shows the intrinsic FWHM of the dominating intrinsic heavy-hole exciton recombination of different, nominally 8 nm wide wells plotted as a function of the extrinsic PL intensity normalized to the intrinsic intensity. These QWs have exciton wavefunctions, which only weakly penetrate into the barrier layers and therefore are sensitive to interfacial disorder. The figure shows that samples with practically no extrinsic PL have small linewidths of typically 2.5 meV indicating smooth and abrupt interfaces. The linewidth increases with increasing extrinsic PL signal and tends to saturate.

Figure 7.7b describes a simple model for the average interface roughness $\overline{\Delta L_z}$ based on the L_z dependence of the quantum confined energy (cf. Equation 1.19) and by using the maximum observed FWHM of 8 meV. The model calculates $\overline{\Delta L_z} \cong 0.02$ nm and evaluates the lateral extension of the roughness expressed by the ratio between the island-covered area A_{with} and the island-free area $A_{w/o}$ to roughly 10%. It is well known that monolayer fluctuation steps of the well thickness can be the source of formation of deep-levels and nonradiative recombination centers, which can strongly impact the efficiency and threshold of the diode laser and its long-term



(a)

Model : QW interface roughness ΔL_z 

$$\Delta E = (dE/dL_z) \times \Delta L_z$$

with $E \propto 1/L_z^2$ (see Eq. 1.19)

$$|\Delta E_{FWHM}| \cong |\Delta E| = (2E/L_z) \overline{\Delta L_z}$$

With $\Delta E_{FWHM} \cong 8$ meV, $E = 1.55$ eV, $L_z = 8$ nm:

average QW thickness fluctuation $\overline{\Delta L_z} \cong 0.02$ nm

For a constant island step height, e.g. $a_0/2 \approx 2.5$ Å

ratio island-covered area A_{with} to island-free area $A_{\text{w/o}}$:

$$(b) \quad A_{\text{with}}/A_{\text{w/o}} \approx \overline{\Delta L_z} / a_0/2 \approx 10\%$$

Figure 7.7 (a) Linewidth of the 2 K PL emission of the 8 nm well plotted as a function of the extrinsic acceptor-related PL intensity normalized to the intrinsic exciton-related PL intensity of the 8 nm well at low excitations of 1 W/cm². (b) Simple interface roughness model estimating an average QW thickness fluctuation and ratio between island-covered area and island-free area. Solid line: calculated trendline.

lifetime. Line broadening due to band filling via charge transfer from the acceptor impurities at the interfaces was estimated to play only a minor role.

7.2.3.2 Dependence on thickness of well and barrier layer

More information on the acceptors involved in the (e1,A°) transition, in particular on their energetic states and identification, has been obtained by determining the acceptor

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binding energy $E(A^\circ)$ as a function of L_z , which varied in the range $\sim 1\text{--}12$ nm in many samples grown at the residual MBE background pressure.

$E(A^\circ)$ was evaluated in the usual way (Miller *et al.*, 1982) from $E(A^\circ) = E_{1h} - E(e1, A^\circ) + B(1h) = E_g - E(e1, A^\circ)$, where E_{1h} is the $n = 1$ free heavy-hole (hh) exciton transition energy, $E(e1, A^\circ)$ the energy of the broad peak(s) of the extrinsic PL, $B(1h)$ the binding energy of the $n = 1$ ground state hh exciton, and E_g the $n = 1$ QW energy gap. $E(A^\circ)$ is the energy necessary to transfer a hole from A° to the $n = 1$ hh level in the valence band of the well. The actual L_z values of the various QWs were determined from calculations of the transition energies and by using the experimental E_{1h} values.

The experimental data plotted as $E(A^\circ)$ versus L_z fall distinctly into a low-energy and high-energy branch and increase with decreasing L_z . The interested reader is referred for further details to the original publication of Epperlein and Meier (1990). This splitting into two components can be expected, since the acceptor density of states is strongly enhanced at the well center and interface positions (Masselink *et al.*, 1984b; Bastard, 1981). The lowering of the binding energy for on-edge impurities compared to on-center impurities is a direct consequence of the repulsive interface potential, which tends to push the hole charge distribution away from the attractive ionized acceptor center leading to a reduced effective Coulomb attraction.

It was demonstrated for the first time that the experimental data in the upper and lower branch are in good agreement with calculations (Masselink *et al.*, 1984b) for the ground state of neutral carbon acceptors (C°) at the center and at the interfaces of $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}/\text{GaAs}$ QWs, with typical binding energies $E(C^\circ)$ of 37 and 23 meV for a 6 nm QW, respectively (Epperlein and Meier, 1990). In addition, control experiments on samples grown in a beryllium background atmosphere leading to higher binding energies of ~ 27 meV at the interface of a 6 nm well confirmed the involvement of neutral carbon acceptors in the formation of the broad extrinsic PL peaks shown in Figure 7.6.

The extrinsic ($e1, A^\circ$) PL intensity increases with increasing thickness of the bottom AlGaAs cladding layer or AlGaAs barrier layer in the MQW as clearly demonstrated in Figure 7.8. This dependence shows that AlGaAs > 100 nm thick underlying the GaAs well is required to build up a sufficiently high impurity level for detection. From the above observations and experimental results, that is, that prelayers grown near the normal interface (AlGaAs on GaAs) do not have a measurable effect on the extrinsic PL of the test QW, the following model of the incorporation of carbon acceptors in the QW structure can be derived.

Due to the lower solubility of impurities in AlGaAs than in GaAs, they stay afloat on the AlGaAs growth surface and are progressively trapped in a thin layer (Meynadier *et al.*, 1985) at the inverted interface upon deposition of the GaAs. The atomic scale interface roughness deduced from the linewidth measurements (Figure 7.7) are most likely due to the growth-inhibiting nature of carbon (Phillips, 1981), such as, for example, by preventing the lateral propagation of the atomic layers due to the pinning steps on the surface. This irregular structure of the interface is the source for the formation of performance and reliability-impacting defect centers. A

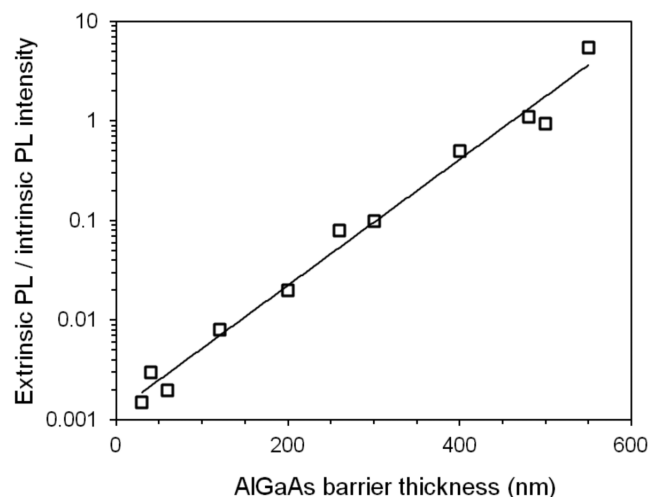


Figure 7.8 Normalized extrinsic PL intensity versus $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ lower cladding or barrier layer thickness of QWs nominally 8 nm wide at 2 K and 1 W/cm². The ratio is corrected for its excitation intensity dependence; $\gtrsim 1\%$ normalized extrinsic, acceptor-related PL intensity obtainable for 150 nm and thicker AlGaAs barriers. Solid line: calculated trendline.

saturation of the intrinsic FWHM PL (see Figure 7.7), equivalent to a maximum roughness detectable with the excitonic PL as an optical probe in QWs, appears to be conclusive from this model.

7.2.3.3 Prelayers for improving active layer integrity

The trapping of detrimental impurity centers in the nominally undoped test QW or active QW in a diode laser can be efficiently suppressed by growing thin GaAs prelayers before the actual QW. These undesired impurities can be found in the residual MBE background atmosphere released for example during outgassing of the Al oven and shutter.

Figure 7.9 shows that the extrinsic impurity-related QW PL intensity normalized to the intrinsic exciton-related QW PL intensity can be suppressed below 1% by a GaAs SQW prelayer with a thickness of at least 5 nm. This dependence is similar to the one shown for the first time by Epperlein and Meier (1990). Similarly strong suppression can be obtained by using SL prelayers with the same total GaAs thickness. The results in Figure 7.9 are in agreement with the model of impurity incorporation described above.

It has been demonstrated that InGaAs/AlGaAs QW GRIN-SCH lasers with GaAs prelayers positioned in the lower AlGaAs cladding layer before the GRIN-SCH layer showed a higher efficiency and lower threshold current and, in particular, a positive effect on laser reliability compared to devices without such prelayers gettering the segregating impurities during growth.

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of the opaque semiconductor surface, which means that the $\mathbf{k}$ vectors of the incident and scattered light are anti-parallel to each other or, in other words, the scattered light is collected by the same lens as that through which the incident light is focused.

Raman selection rules determine the existence of Raman-active phonons for certain choices of the incident and scattered polarizations and scattering geometries (for details see, e.g., Yu and Cardona, 2001). According to these, at an ideal (110) facet, scattering at transverse optical (TO) phonons is allowed by symmetry, whereas scattering at longitudinal optical (LO) phonons is symmetry forbidden. The symmetry-allowed scattering configurations written in the so-called Porto notation $\mathbf{k}_i(\mathbf{e}_i, \mathbf{e}_s)\mathbf{k}_s$, where $\mathbf{k}_i$ and $\mathbf{e}_i$ are the wavevector and polarization vector of the incident light and $\mathbf{k}_s$ and $\mathbf{e}_s$ the wavevector and polarization vector of the scattered light, respectively, can be written as

$$\bar{1}\bar{1}0(1\bar{1}0, 1\bar{1}0)110 \quad (7.7)$$

for the parallel-scattering geometry and

$$\bar{1}\bar{1}0(1\bar{1}0, 100)110 \quad (7.8)$$

for the crossed-polarization configuration.

As examples, scattering at AlGaAs leads to two modes, GaAs-like and AlAs-like zone center TO phonon modes. In contrast, scattering at AlGaInP shows a one-mode behavior, that is, only one Raman AlGaInP TO phonon mode (Bayramov *et al.*, 1981).

At real (110) facets the translational symmetry can be destroyed by structural and compositional disorder, surface electric fields, strain, or other perturbations, which results in a relaxation of the $\mathbf{k}$ -conservation law. As mentioned above, this allows Raman scattering at phonons of any $\mathbf{K}$ vector ($\mathbf{K} \neq 0$) including first-order transverse optical (TO), longitudinal optical (LO), transverse acoustic (TA), longitudinal acoustic (LA) phonons, and second-order phonons such as 2TO and 2TA.

7.4.5 Raman for facet temperature measurements

By using the ratio I_S/I_{AS} between the integrated intensities of the Stokes (S) and anti-Stokes (AS) Raman lines of the appropriate TO phonon mode in the material system under investigation, the local mirror temperature T can be determined as follows (Compaan and Trodahl, 1984):

$$\frac{I_S}{I_{AS}} = C_1 \left(\frac{1 - R_{AS}}{1 - R_S} \right) \left(\frac{\alpha_{AS} + \alpha_i}{\alpha_S + \alpha_i} \right) \left(\frac{n_{r,AS}}{n_{r,S}} \right) \left(\frac{\omega_i - \Omega}{\omega_i + \Omega} \right)^3 \exp\{\hbar\Omega/k_B T\} \quad (7.9)$$

where R is the reflectivity, α the absorption coefficient, and n_r the refractive index of the facet material at frequencies ω_S and ω_{AS} . C_1 is a correction factor due to the different responses of the detector and gratings at Stokes and anti-Stokes frequencies.

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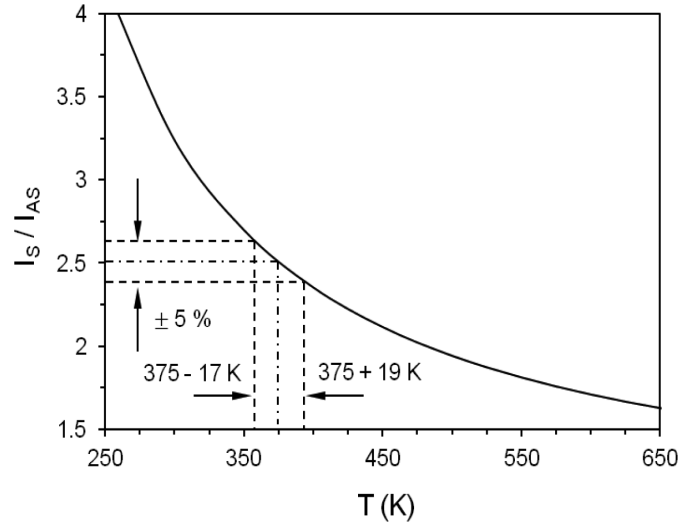


Figure 7.21 Calculated sensitivity of the mirror temperature T on the Stokes/anti-Stokes intensity ratio I_S/I_{AS} of a suitable phonon mode in the Raman spectrum; $\hbar\Omega = 33$ meV is used for the GaAs TO phonon and 0.9 for the total correction factor in the calculation.

For a backscattering geometry, R can be calculated for the Stokes and anti-Stokes light from (see also Equation 1.12)

$$R = \frac{(n_r - 1)^2 + \kappa^2}{(n_r + 1)^2 + \kappa^2} \quad (7.10)$$

where κ is the extinction coefficient. By using ellipsometry data for n_r and κ (Aspnes *et al.*, 1986) of the major materials GaAs, AlGaAs, InGaAs, and AlGaInP used in the Raman studies of this text, a typical TO phonon energy $\hbar\Omega \cong 33$ meV, and the energy of the incident laser $\hbar\omega_i \cong 2.7$ eV, the total correction factor in front of the exponential term can be calculated as $C_1 \times C_2 \cong 0.9$. The temperature dependence of the S- and AS-Raman susceptibilities has been neglected in the calculations.

The sensitivity of T on I_S/I_{AS} was calculated on the basis of Equation (7.9) by using the values of the phonon energy and correction factor in the previous paragraph. Figure 7.21 shows that a $\pm 5\%$ error in a typical value 2.5 for I_S/I_{AS} leads to a roughly ± 20 K error in temperature of 375 K corresponding to $I_S/I_{AS} = 2.5$. Of course, at higher I_S/I_{AS} values the error in temperature is lower, whereas at lower values it is much higher. The I_S/I_{AS} intensity ratio is very insensitive to temperature changes at high-temperature levels, which hampers accurate temperature measurements.

7.4.5.1 Typical examples of Stokes- and anti-Stokes Raman spectra

Figure 7.22 shows typical examples of AS- and S-Raman spectra of a cleaved, uncoated facet of an AlGaAs/GaAs GRIN-SCH SQW laser 3 μm wide (Brugger and

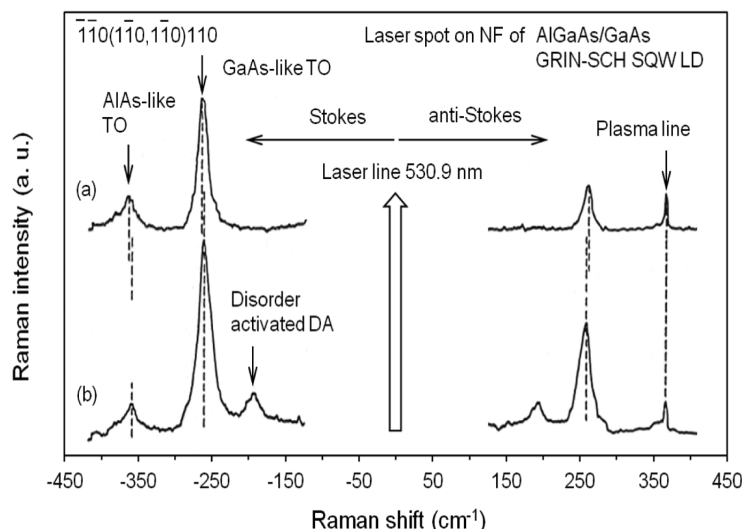


Figure 7.22 Raman spectra of a cleaved, uncoated (110) facet in the near-field (NF) of an (Al)GaAs GRIN-SCH SQW ridge laser 3 μm wide during operation: (a) 5 mW per facet, laser not degraded; (b) 18 mW per facet, laser degraded. (Parts adapted in modified form from Brugger and Epperlein, 1990.)

Epperlein, 1990). The probe laser was focused on the optical near-field spot. The upper curves were taken from the nondegraded laser at a cw power of 5 mW per facet. The spectra, detected in symmetry-allowed, parallel-scattering configuration, show the first-order GaAs-like and AlAs-like TO phonon modes, as expected. The spectra show the typical two-mode behavior in contrast to AlGaInP with a one-mode spectrum, as we will show in the next example below. The Ar^+ -ion laser plasma line recorded in the spectra can be used as a very useful energy reference for measurements of very accurate frequency shifts and to obtain qualitative information on changes in surface roughness via intensity fluctuations of the elastically scattered Rayleigh light (see also Section 8.1).

The lower curves in Figure 7.22 were recorded from the same mirror region and at the same low excitation intensity of $\lesssim 100 \text{ kW/cm}^2$ (leading to a temperature rise $< 10 \text{ K}$), but after heavy degradation of the laser with a strong increase in threshold current. The laser was here operated at 18 mW/facet resulting in a significant heating of the facet. This can be seen in a shift of the phonon lines to lower energies and broadening of the linewidths caused by anharmonic effects in the crystalline material. However, most importantly, the S/AS intensity ratio is decreased with the higher temperature. The absolute intensities of the AS and S signals are also higher due to the temperature-dependent change of the Bose–Einstein occupation number (Equations 7.4a, 7.4b), optical material constants, and the resonance curve of the Raman susceptibility (Compaan and Trodahl, 1984). The line at 195 cm^{-1} can be attributed to a disorder-activated (DA) phonon mode. Its existence demonstrates

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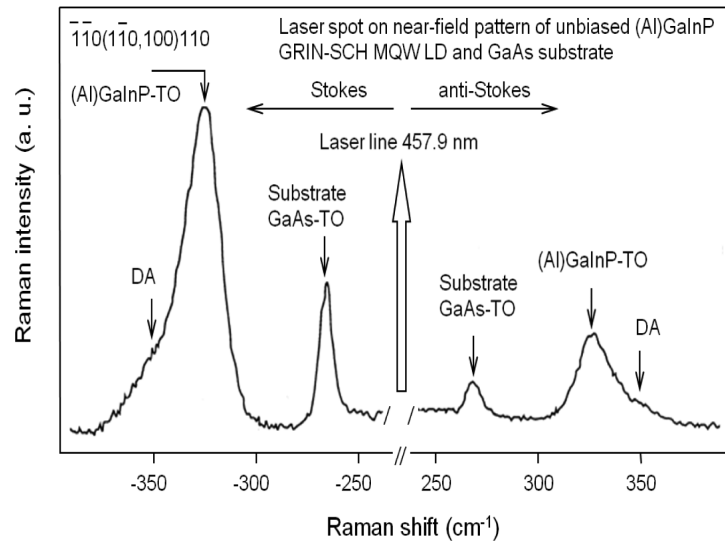


Figure 7.23 Raman spectra of a cleaved, uncoated (110) mirror facet of an unbiased (Al)GaInP GRIN-SCH MQW ridge laser 5 μm wide on a GaAs substrate. Excitation laser spot in parts on near-field pattern and in parts on GaAs substrate. (Parts adapted in modified form from Epperlein *et al.*, 1992.)

strong crystal damage at the facets of the degraded laser. We discuss this mode in detail in the context of revealing the microscopic root causes of enhanced facet temperatures and linked COMD probability (see Section 8.1).

In contrast, Figure 7.23 illustrates the one-mode Raman spectrum of (Al)GaInP. It shows the first-order Stokes and anti-Stokes spectra of a nondegraded facet of an unbiased AlGaInP/GaInP GRIN-SCH MQW ridge laser 5 μm wide detected in symmetry-allowed, crossed-polarization geometry (Epperlein *et al.*, 1992). The focused ($\sim 1 \mu\text{m}$), low-power (1–2 mW) probe laser beam irradiated part of the near-field region and part of the GaAs substrate. With this probing condition the temperature gradient expected between the hot (Al)GaInP regions and the GaAs substrate could be evaluated in one spectrum recorded at different drive currents and power levels (see next section). The spectra show the GaAs substrate TO phonon mode well separated from the (Al)GaInP TO phonon peak exhibiting the widely accepted one-mode behavior of AlGaInP. The peak appearing as a shoulder at $\pm 350 \text{ cm}^{-1}$ on the high-energy side of this peak can be attributed to one-phonon optical transitions due to disorder in the crystal structure (Bayramov *et al.*, 1981).

7.4.5.2 First laser mirror temperatures by Raman

Figure 7.24 shows mirror temperature ΔT versus power P calculated from Stokes- and anti-Stokes GaAs-like TO phonon modes of cleaved uncoated and coated

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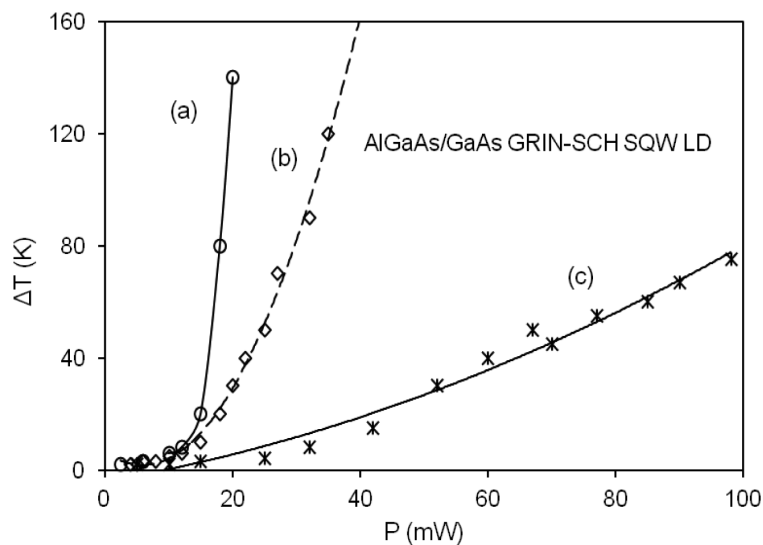


Figure 7.24 Measured temperature rises ΔT at mirror facets inside the near-field spot of (Al)GaAs GRIN-SCH SQW lasers as a function of cw optical output power P : (a) 3 μm wide ridge, cleaved and uncoated mirror; (b) 8 μm wide ridge, cleaved and uncoated mirror; (c) 8 μm wide ridge, cleaved and passivation-coated Al_2O_3 mirror $\lambda/2$ -thick. Solid/dashed lines are guides to the eye. (Data adapted in modified form from Brugger and Epperlein, 1990.)

AlGaAs/GaAs lasers with different ridge widths (Brugger and Epperlein, 1990; Brugger *et al.*, 1990). The temperature data consider the small temperature increases due to self-heating of the low-power excitation laser (see previous section). The temperature increase ΔT is relative to the temperature at threshold current with $P \cong 0$. The narrower the ridge, the higher are the temperatures due to the higher power densities and the more pronounced is the nonlinear $\Delta T/P$ dependence.

Typical values for cleaved uncoated mirrors are $\Delta T > 100$ K for $P > 5$ mW per 1 μm ridge width. Once degradation has occurred, a continuous increase of ΔT can be observed as a function of time at constant P (not shown; see also critical facet temperature to COMD event in Chapter 9). ΔT can go up to 10^3 K on highly degraded uncoated mirrors. On the other hand, passivation-coated mirrors with transparent Al_2O_3 layers $\lambda/2$ -thick show temperatures strongly reduced by about a factor of 10 compared to cleaved uncoated devices with the same widths (Figure 7.24c). These optical thicknesses of $\lambda/2$ lead to no interference losses and leave the reflectivity at about 30%, the value for cleaved uncoated GaAs mirrors. The degradation threshold of these laser facets is about five times higher than for uncoated ones, which can be ascribed to the passivation of dangling bonds at the cleaved surface and therefore a reduction of effective nonradiative recombination centers and surface recombination velocity, as discussed in Chapter 4.

Introduction

This chapter investigates three phenomena closely linked to the performance and reliability of diode lasers. The first phenomenon is related to specific, microscopic root causes of degradation processes in the susceptible mirror facets. It has been found by Raman microprobe spectroscopy that the strength of lattice disorder is positively correlated with the local facet temperature and negatively correlated with the power level at catastrophic optical mirror damage (COMD) of etched (Al)GaAs laser mirrors. By using different analysis techniques the atomic origin of the lattice disorder effect could be identified. The second phenomenon deals with the formation of mechanical stress in the active layer under the ridge waveguide of (Al)GaAs laser devices. Raman and photoluminescence (PL) measurements have yielded camel hump-like stress profiles with maximum compressive stress amplitudes of ~ 5 kbar at the ridge slopes and reduced compressive or tensile stress components toward the ridge center. The development of high stress gradients between the compressive and tensile stress fields can lead to well-pronounced stress-enhanced defect formation and migration effects, which can have a sensitive impact on laser performance. The third phenomenon concerns the stability of mirror coatings during strong laser radiation exposure. Strong and fast silicon recrystallization effects have been observed in coating layer stacks comprising amorphous ion-beam (IB) deposited silicon layers in contrast to plasma-enhanced chemical-vapor deposited (PECVD) silicon. The recrystallized silicon leads to a reduction in mirror reflectivity due to a reduced refractive index and to a movement of the optical mode and shrinkage of the lateral near-field pattern.

8.1 Diode laser mirror facet studies by Raman

8.1.1 Motivation

The specific, microscopic origins for degradation processes in the susceptible mirror facets are usually not well known. Furthermore, a detailed systematic and quantitative investigation of the relationships between facet temperature, microscopic root causes for degradation, and relevant laser performance parameters has to our knowledge not yet been published. In this context, we have probed for the first time the lattice disorder in laser mirrors by Raman microprobe spectroscopy and correlated the strength of disorder to local facet temperature and power level at COMD.

8.1.2 Raman microprobe spectra

The Stokes Raman spectra in Figure 8.1 were detected in crossed-polarization geometry from a series of six dry-etched, $\lambda/2$ -Al₂O₃-coated, (110) facets of (Al)GaAs SQW ridge lasers 5 μm wide on the same laser bar (Epperlein *et al.*, 1993).

The spectra show the symmetry-allowed GaAs-like and AlAs-like TO phonon modes and additional, normally forbidden modes in AlGaAs. These can be ascribed

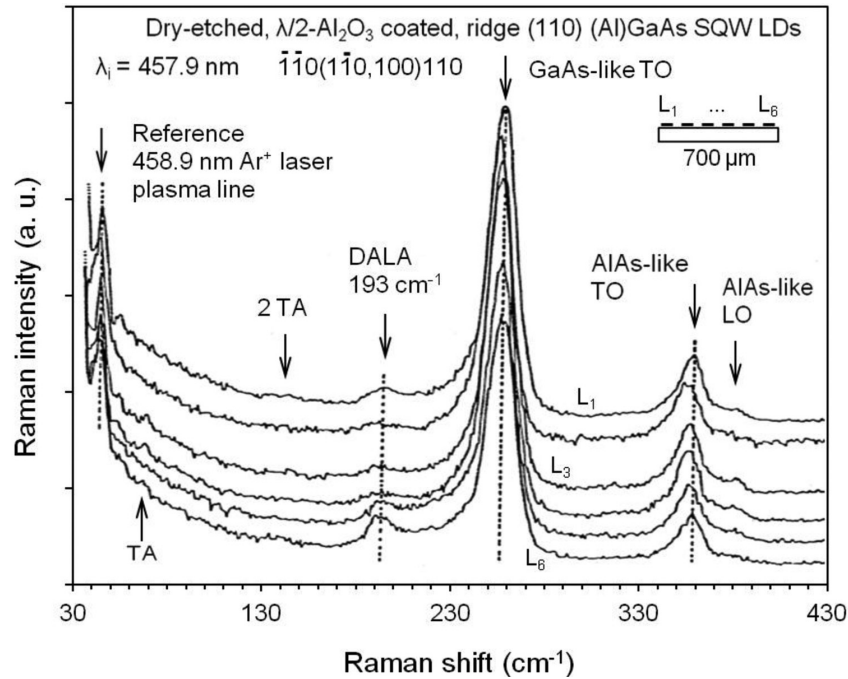


Figure 8.1 Typical Stokes Raman spectra detected in air at room temperature in a crossed-polarization geometry from a series of six dry-etched, $\lambda/2$ - Al_2O_3 -coated, (110) facets in the near-field spots of (Al)GaAs SQW ridge lasers $5\text{ }\mu\text{m}$ wide on the same laser bar over a length of $700\text{ }\mu\text{m}$.

to the first-order AlAs-like longitudinal optical ($\text{LO}(\Gamma)$), short-wavelength ($K > 0$) transverse acoustic ($\text{TA}(\text{L})$) and second-order $2\text{TA}(\text{L})$ phonon modes (Jusserand and Sapriel, 1981), which become Raman active as a consequence of disorder (softening of k -conservation law, see Section 7.4.4).

The spectra generally show the AlAs-like LO and not the GaAs-like LO mode in as-grown facets, which indicates the presence of disorder mainly in the AlAs sublattice. The origins of the disorder-activated mode at 193 cm^{-1} will be elaborated in detail in the next section. The Ar^+ laser 458.9 nm plasma line was used for Rayleigh scattering investigations and calibration. The spectra recorded from the six lasers shift up to 3 cm^{-1} across a distance of $700\text{ }\mu\text{m}$. The stronger the 193 cm^{-1} mode, the stronger is the blueshift of the entire spectrum, which indicates the presence of compressive strain in the mirror region increasing the level of disorder even further by inhomogeneous atomic displacement. The observed peak shifts of up to 3 cm^{-1} correspond to strain amplitudes up to 5 kbar in the mirror surfaces, which may originate from the adhesion of the dielectric overlays varying from sample to sample (see Section 8.2; Epperlein *et al.*, 1990).

TO phonon scattering, strongly indicate the presence of excess As in the AlGaAs facet. Furthermore, this finding is supported by energy dispersive x-ray (EDX) and Rayleigh scattering measurements as a function of the 193 cm^{-1} mode/GaAs-like TO mode intensity ratio (Figure 8.3).

Figure 8.3a shows the increase of the As concentration normalized to the Ga concentration with increasing normalized 193 cm^{-1} mode intensity. The existence of elemental As in the dry-etched laser mirrors is most likely due to oxidation during the removal of the etch mask in an oxygen plasma ashing process or due to a disturbed stoichiometry leaving excess As behind. The normalized 193 cm^{-1} Raman mode intensity fluctuates on a micrometer scale indicating the presence of As clusters and hence a locally varying enhanced strength of compositional disorder.

Since Rayleigh scattering is sensitive to local mass density fluctuations due to alloy disorder and clustering effects, the positive correlation between normalized Rayleigh scattering intensity and relative 193 cm^{-1} mode intensity in Figure 8.3b is further direct proof of the existence of disorder in the laser mirrors studied.

Finally, as mentioned above, the stronger the relative 193 cm^{-1} mode intensity, the stronger the blueshift observed for the entire spectrum. This indicates the presence of compressive strain in the mirror region increasing the level of disorder even further by inhomogeneous atomic displacement (Figure 8.3c and Figure 8.1).

In summary, according to the different measurements, we can now ascribe the 193 cm^{-1} mode to Raman scattering at the E_g -TO phonon of elemental As and DALA phonon in AlGaAs. The relative intensity of the 193 cm^{-1} mode can be used as a useful measure for the degree of compositional and structural disorder in laser mirror facets.

8.1.4 Facet disorder – facet temperature – catastrophic optical mirror damage robustness correlations

For the first time quantitative correlations between lattice disorder, local mirror temperature rise ΔT , and COMD power level have been established (Epperlein, 1993; Epperlein *et al.*, 1993) (Figure 8.4).

The cw COMD power level decreases, whereas ΔT increases with increasing strength of disorder. The third correlation is the decrease of COMD with increasing ΔT , as expected. This anti-correlation between COMD and ΔT clearly demonstrates for the first time in a quantitative manner the significance of lattice disorder in optical power absorption and thus in nonradiative carrier recombination, which leads to facet surface heating and thus shortens laser lifetimes. In this respect, the contribution of elemental As to heating seems to be significant, because of its large complex refractive index (Renucci *et al.*, 1973), particularly a large extinction coefficient which causes a large absorption ($\alpha \cong 4 \times 10^5\text{ cm}^{-1}$) of the 830 nm laser radiation. The thickness of the As clusters could be estimated to be in the region of 3 nm. In principle, the relationships in Figure 8.4 can be used to predict laser lifetimes from the strength of disorder measured at virgin mirror facets.

Finally, Figure 8.5 shows the Stokes Raman spectrum after the occurrence of COMD. Compared to the as-grown facet, the relative strength of the integrated

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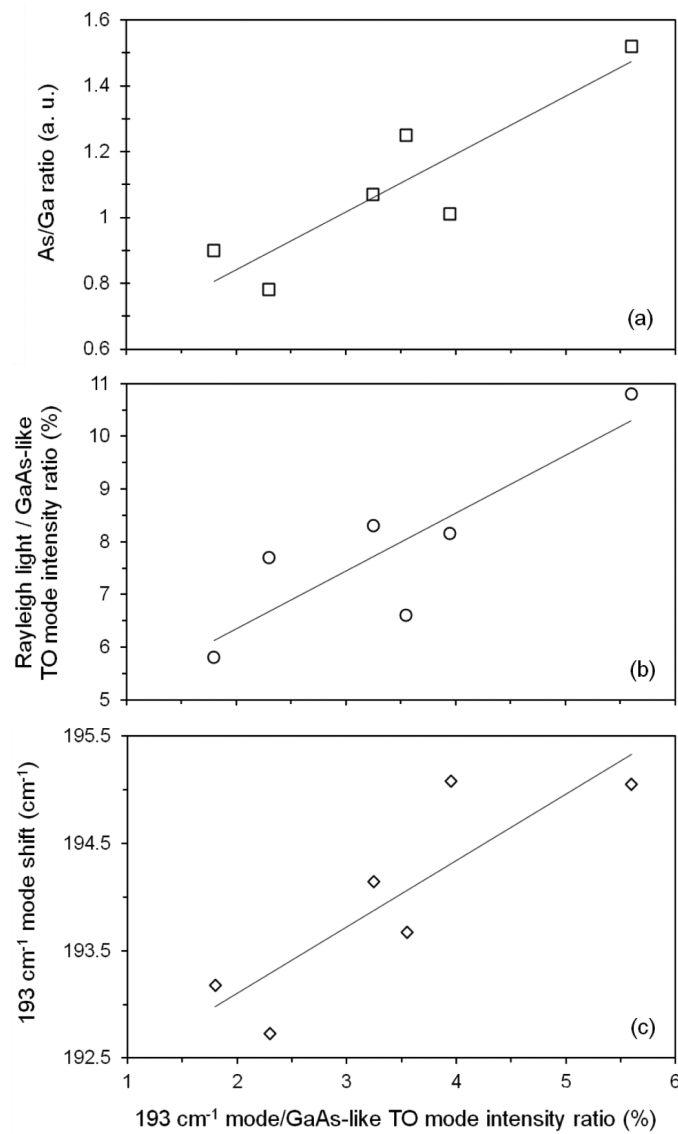


Figure 8.3 Normalized 193 cm^{-1} Raman mode intensity detected in the near-field pattern of dry-etched (110) (Al)GaAs laser mirrors dependent upon (a) the As/Ga ratio from EDX spectroscopy measurements, (b) the normalized elastic Rayleigh light scattering intensity, and (c) the 193 cm^{-1} mode shift. Solid lines are least-squares fits. (Adapted in extended form from Epperlein *et al.*, 1993.)

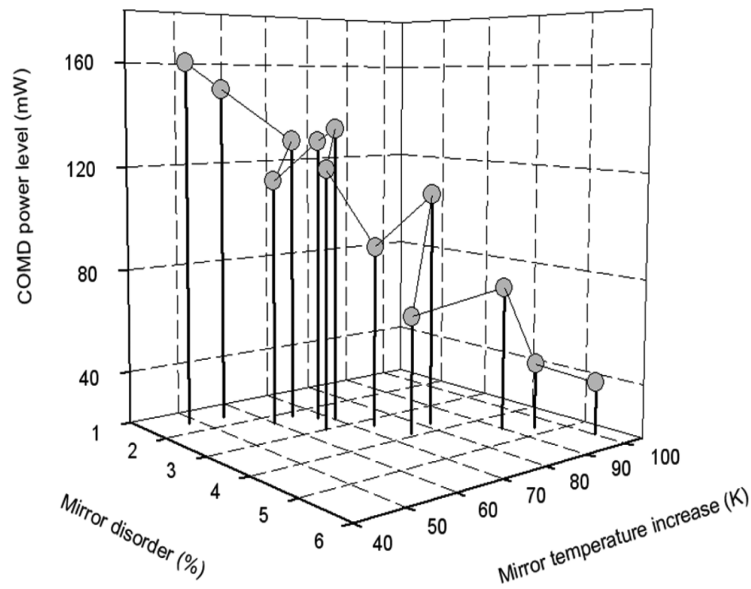


Figure 8.4 COMD cw power levels, mirror temperature rises at 30 mW, and mirror disorder strengths measured as the normalized 193 cm^{-1} Raman mode intensities on dry-etched (Al)GaAs laser mirrors. Significant correlations constituted for the very first time: COMD power level versus lattice disorder strength, mirror temperature rise versus lattice disorder strength, COMD power level versus mirror temperature rise.

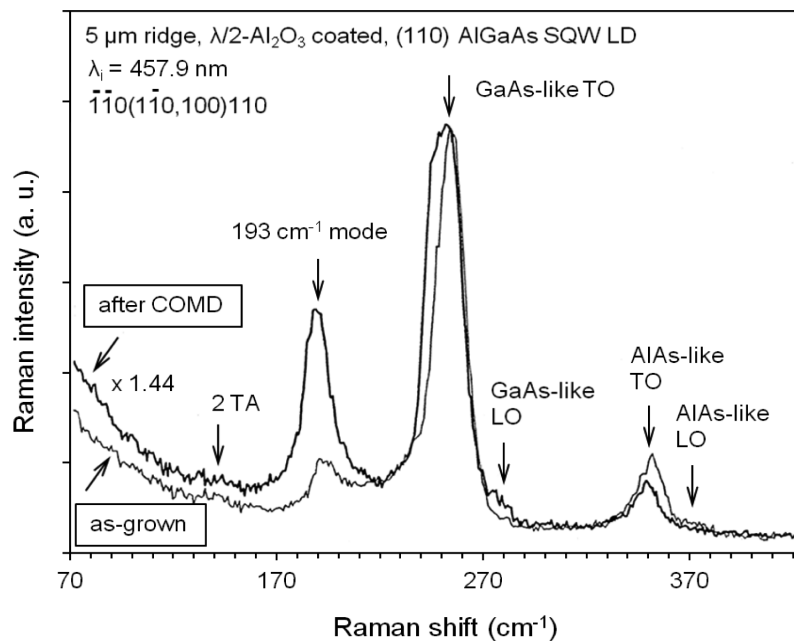


Figure 8.5 Comparison between a typical Stokes Raman spectrum of a dry-etched (110) (Al)GaAs laser mirror before (thin line) and after COMD event (thick dark line).

8.2.2 Measurements – Raman shifts and stress profiles

Figure 8.6 shows a series of first-order Stokes Raman GaAs-like TO phonon modes detected with a high spatial resolution of better than $1\text{ }\mu\text{m}$ on the cleaved (110) facets of ridge (Al)GaAs GRIN-SCH SQW laser devices $5\text{ }\mu\text{m}$ wide at different locations along the active layer. The laser power density for exciting the Raman spectra was very low ($<100\text{ kW/cm}^2$) causing a negligible self-heating effect with no measurable impact on the Raman spectra. The top spectrum was recorded far away from the strained region around the ridge and therefore its peak position of 261 cm^{-1} can be taken as the reference point for the spectral shifts observed when approaching the ridge structure. Stress in the crystal affects the frequency of the phonons and hence the position of the Raman peak. Typically, it is possible to observe and detect stress by analyzing the shift in the Raman mode position, but it can also affect the mode shape and induce broadening and deformation of the Raman peak.

Mode shifts of three different laser devices are shown in detail in Figure 8.7. Typical maximum positive shifts of $+2\text{ cm}^{-1}$ can be found close to both ridge slopes. Inside the ridge the Raman mode exhibits lower positive shifts or even negative shifts with respect to the reference point as shown by one device in Figure 8.7. The mode shift profiles of the three different samples are similar in the overall camel hump-like shape, but are differently well-pronounced in shape and strength at the ridge slopes, inside and outside the ridge regions. These mode shift profiles indicate the distribution of mechanical stress in the ridge waveguide structure, which may vary qualitatively and quantitatively from sample to sample.

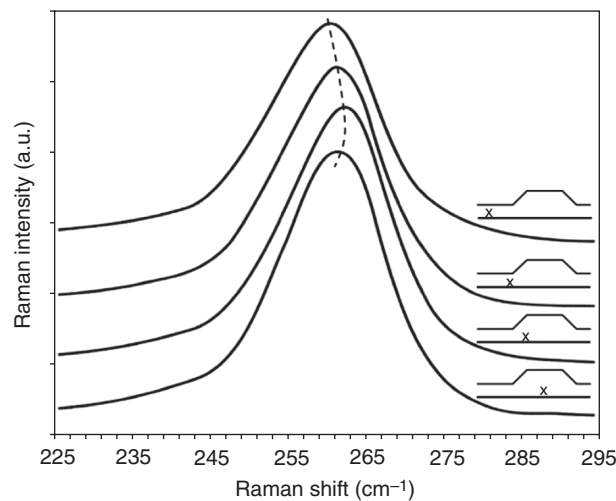


Figure 8.6 Typical first-order Stokes GaAs-like TO phonon Raman mode spectra at different locations (marked by x) along the active layer of uncoated (110) ridge (Al)GaAs SQW laser mirror facets. (Parts adapted in modified form from Epperlein *et al.*, 1995.)

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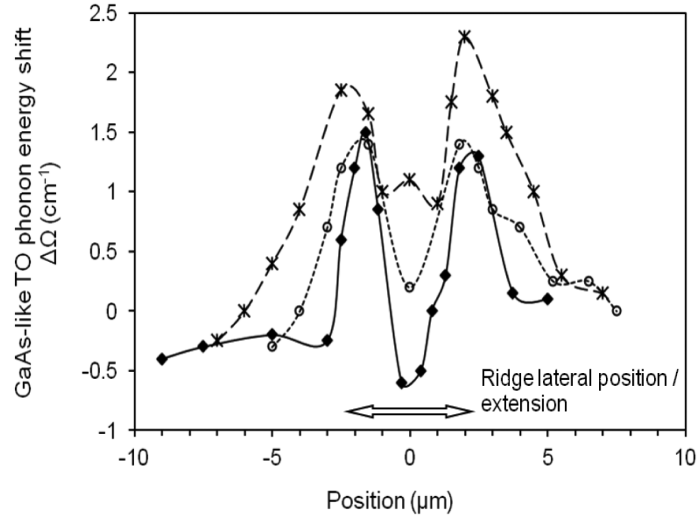


Figure 8.7 GaAs-like TO phonon Raman mode energy shift measured along the active layer of cleaved, uncoated (110) ridge (Al)GaAs SQW laser facets 5 μm wide of three different devices (data marked by different symbols). Measurement points are connected as a guide to the eye.

Using the relationship between compression and pressure (Murnaghan, 1944)

$$P = \frac{B_0}{B'_0} \left\{ \left(\frac{a_0}{a} \right)^{3B'_0} - 1 \right\} \quad (8.1)$$

and the experimental (hydrostatic) pressure dependence of the GaAs TO phonon mode (Trommer *et al.*, 1980)

$$\Delta\omega_{TO} = 1.12 \times 10^3 \left(\frac{-\Delta a}{a_0} \right) - 2.28 \times 10^3 \left(\frac{-\Delta a}{a_0} \right)^2 \quad (8.2a)$$

$$\frac{-\Delta a}{a_0} = 1 - \frac{a}{a_0} \quad (8.2b)$$

where $B_0 = 7.25 \times 10^{11}$ dyn/cm² is the (GaAs) bulk modulus, $B'_0 = (\partial B_0 / \partial P)_T$ the bulk modulus pressure derivative, $B'_0 = 4.67$ for GaAs, a_0 the lattice constant, and a the lattice constant under compression, the following conversion between mode shift in wavenumber cm⁻¹ units and pressure in kbar units could be derived:

$$1 \text{ cm}^{-1} \text{ GaAs TO phonon mode shift} \hat{=} 2.2 \text{ kbar.} \quad (8.3)$$

Accordingly, the mode shift profiles in Figure 8.7 can be converted to stress profiles. There are high compressive stress amplitudes of up to 5 kbar measured

in the backscattering geometry by focusing the 457.9 nm line of an Ar^+ laser with a power ≤ 1 mW onto a spot with diameter ~ 1 μm . The detection and further processing of the Raman signal has been described in detail in Section 7.4.

8.3.3 Silicon recrystallization by internal power exposure

8.3.3.1 Dependence on silicon deposition technique

The Raman spectra of as-deposited PECVD and IB Si layers show a broad asymmetric peak close to 475 cm^{-1} with a typical linewidth of 70 cm^{-1} (Figure 8.13) (Epperlein and Gasser, 1995). The spectra strongly resemble those usually observed for amorphous silicon (a-Si) (Tsang *et al.*, 1985) and thus verify that the as-deposited

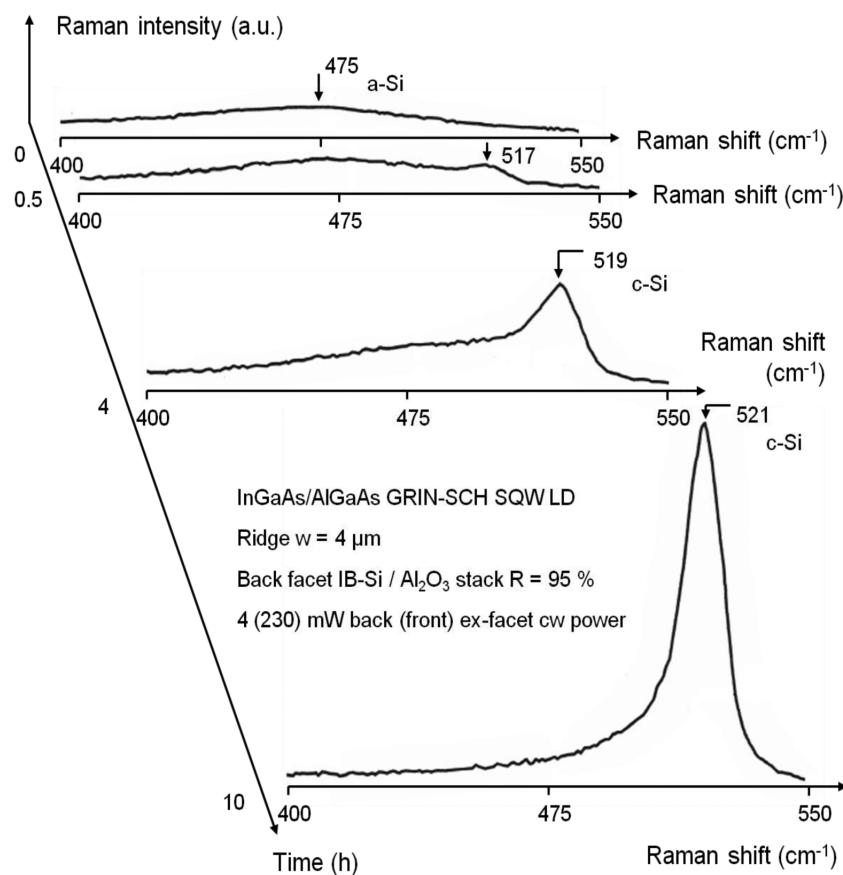


Figure 8.13 Typical Stokes Raman scattering spectra of silicon layers $\lambda/4$ -thick in ion beam (IB) deposited Si/ Al_2O_3 back-facet coating stacks of $4\text{ }\mu\text{m}$ ridge InGaAs/AlGaAs SQW lasers at 4 (230) mW back- (front-)facet power emission and 980 nm lasing wavelength for different operation times. (Parts adapted in modified form from Epperlein and Gasser, 1995.)

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Si layers were amorphous. The broad peak arises from the relaxation of the normal Raman selection rules for scattering from a crystal as a result of the loss of translational symmetry in the amorphous phase (see Section 7.4.4).

However, the IB a-Si and PECVD a-Si layers behaved quite differently under strong laser emission. Figure 8.13 shows for the first time the change in the Stokes Raman IB a-Si spectrum with increasing exposure time to strong internal laser power (Epperlein and Gasser, 1995). In particular, the hydrogen-free IB a-Si layers show an additional sharp line with a position in the range of 517 to 521 cm^{-1} and a size dependent on the exposure time. This line can be attributed to scattering from the threefold degenerate, $K = 0$, optical phonon of crystalline Si (c-Si) (Tsang *et al.*, 1985). The line clearly exhibits an increase in intensity relative to that of the a-Si mode with time. After ~ 10 h at 200 mW, the c-Si peak intensity saturates indicating a nearly complete recrystallization of a-Si to c-Si.

By deconvoluting the spectra and using integrated Raman backscattering cross-sections in the two phases, the volume fraction of crystallinity ρ in the two-phase system of Si microcrystallites embedded in the a-Si matrix can be calculated.

Figure 8.14 shows the dependence of ρ on operating time at 4 (230) mW back-(front-)facet cw power emission. It is strongest within the near-field spot and decays rapidly to zero toward the substrate at a distance of ~ 5 μm . The figure also gives the maximum energy absorbed in the Si layers with increasing recrystallization time. Moreover, the c-Si Raman peak shifts to higher energies with increasing time (crystallinity) (Figure 8.13), which can be interpreted as a particle size effect (Tsu,

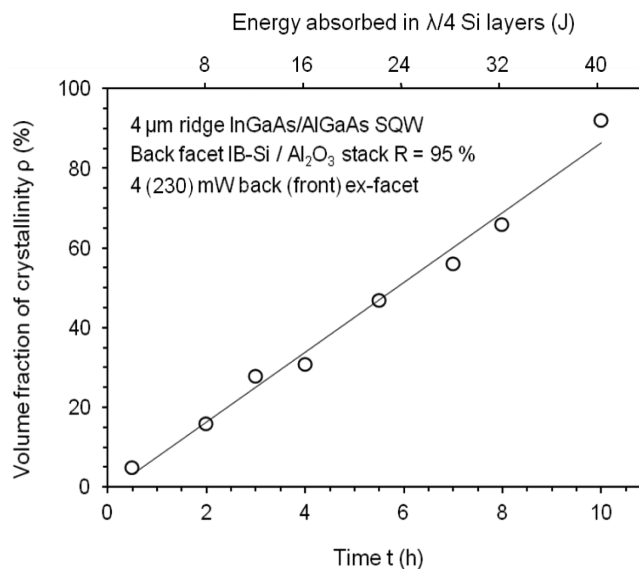


Figure 8.14 Volume fraction of crystallinity of Si layers in the back-facet coating stacks of InGaAs/AlGaAs ridge lasers recrystallized under 4 (230) mW back- (front-)facet cw power emission and at 980 nm lasing wavelength at different operation times. The maximum energy absorbed in the Si layers as a function of time (crystallinity) is indicated in the upper axis.

1981). The Si crystallite size was estimated to be ~ 5 nm for $\rho \cong 5\%$ and > 10 nm for $\rho \cong 100\%$.

In contrast, PECVD a-Si remains amorphous, independent of exposure time and cw optical power emission. This structural stability can be ascribed to the large amount of ~ 10 at.% of hydrogen in the a-Si films (Mei *et al.*, 1994) prepared in a glow discharge decomposition of silane, SiH_4 . Whereas hydrogen is known to be essential for good electrical performance of a-Si based devices by saturating randomly distributed dangling bonds, it protects the PECVD a-Si from recrystallization.

8.3.3.2 Temperature rises in ion beam- and plasma enhanced chemical vapor-deposited amorphous silicon coatings

Another distinctive feature of IB a-Si and PECVD a-Si is the temperature in the respective silicon layer. Figure 8.15 shows plots of the temperature increases ΔT versus operating current I and optical power P for both IB-Si and PECVD-Si. The data were obtained from the Stokes/anti-Stokes intensity ratios of the a-Si Raman mode and give directly the temperatures in the silicon layers. The ΔT data are with respect to 300 K and allow for the low heating effect (< 10 K) of the probe laser intensity. The power scale is valid for both lasers with IB-Si and PECVD-Si coating layers, which have practically the same slope efficiency. The temperatures in IB-Si are at least higher by a factor of two compared to those in PECVD-Si containing stacks. This is mainly due to the higher absorption coefficient α of IB a-Si, which is

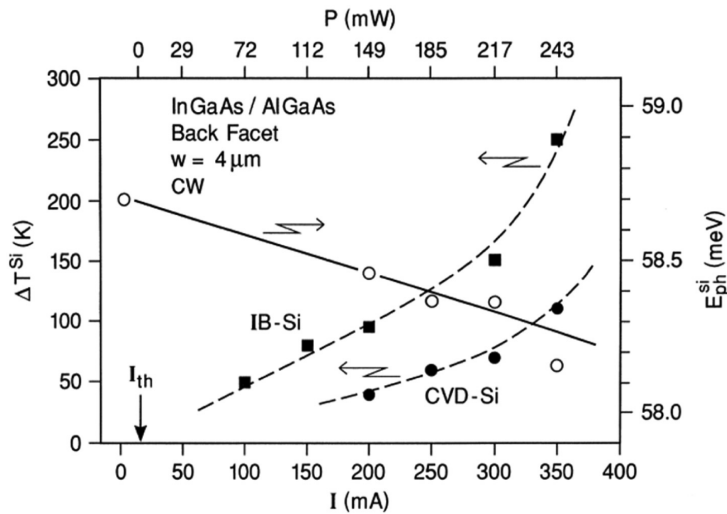


Figure 8.15 Temperature rises ΔT measured in the ion beam (IB) and plasma-enhanced chemical vapor-deposited (PECVD) amorphous silicon (a-Si) layers in back-facet coating stacks of InGaAs/AlGaAs ridge lasers as a function of current I and optical power P by using the Stokes/anti-Stokes Si Raman mode intensity ratio. The temperature (drive current) dependence of the Si phonon energy $E_{\text{ph}}^{\text{Si}}$ is also shown. (Parts adapted in modified form from Epperlein and Gasser, 1995.)

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Introduction

The main focus of this chapter is on a detailed description of the fundamental concept, physical realization, diverse applications, and results of the novel thermoreflectance technique pioneered and successfully introduced by the author as a powerful, highly versatile, experimental approach for characterizing diode lasers (Epperlein, 1990, 1993, 1997; Epperlein and Martin, 1992; Epperlein and Bona, 1993). The thermoreflectance technique has been adopted by many researchers in academia and industry for temperature monitoring of electronic devices (e.g., Schaub, 2001; de Freitas *et al.*, 2005; Ju *et al.*, 1997) and optical devices in particular diode lasers (e.g., Wawer *et al.*, 2005; Piwoński *et al.*, 2005, 2006; Xi *et al.*, 2005; Mansanares *et al.*, 1994).

We will discuss further mirror temperature measurements including a nonabsorbing mirror structure, devices with different heat spreader configurations, facet treatments, and a line scan perpendicular to the active layer toward the substrate side. In addition, we present a comparison between the properties of both thermoreflectance and optical spectroscopies, such as Raman and photoluminescence, demonstrating the various benefits of the thermoreflectance technique. Moreover, by using a special electroluminescence technique, the sharp decrease in the temperature from the mirror surface into and along the laser cavity could be measured for the first time with a high, submicrometer spatial resolution (Epperlein and Bona, 1993; Epperlein, 1997).

Finally, measurements on real-time temperature-monitored laser degradation processes and two-dimensional mirror temperature distributions, successfully made for the first time by employing the newly developed thermoreflectance technique (Epperlein, 1990, 1993, 1997), will be discussed. The former activity includes processes such as critical facet temperature to the COMD event, development of the facet temperature with increasing operation time, and temperature associated with

dark-line defects, whereas the latter activity also compares the experimental temperature maps to numerically modeled ones.

9.1 Thermoreflectance microscopy for diode laser diagnostics

9.1.1 Motivation

In the preceding two chapters, we have described how Raman microprobe spectroscopy can be employed to measure local laser mirror temperatures with sufficient spectral and spatial resolution even though the measurement accuracy at higher temperatures is limited (see Figure 7.21) due to the exponential term involved in the evaluation process (see Equation 7.9) using the Stokes/anti-Stokes phonon mode intensity ratio.

The Raman signal detection sensitivity (see Section 7.4.3) has been dramatically improved since the first application of Raman for measuring laser mirror temperatures (Todoroki, 1986). This implies also the use of much lower laser power densities ($\gtrsim 10^2 \times$ less) for exciting the Raman scattering signal. These are now typically low ($\lesssim 100 \text{ kW/cm}^2$, corresponds to $\sim 1 \text{ mW}$ in $\sim 1 \text{ }\mu\text{m}$ spot size) for a state-of-the-art setup resulting in low temperature rises $< 10 \text{ K}$ of a laser die mounted on a heat sink (see Section 7.4).

Furthermore, to achieve the maximum temperature signal on a laser facet, the probe laser spot has to be aligned within the near-field spot where the laser intensity is highest. Also here, different powerful techniques have been developed, including simultaneous imaging of the probe laser spot and near-field pattern by using a microscope (see Figure 9.3 below) or the approach described in Section 7.4.3 and Figure 7.5. A very efficient and effective approach is given by using the p–n junction of the diode laser itself as a photocell. Centering the laser spot can then be easily achieved by maximizing the photovoltage by moving the laser spot in the near-field pattern.

Further advantages of using Raman spectroscopy in temperature measurements are its inherent strength to probe simultaneously the properties of the laser material at any location of the laser mirror surface (see Sections 8.1, 8.2, and 8.3). This conventional, nondestructive, contactless, and powerful optical characterization technique is well established; however, it can be time consuming and measures the data point-by-point, which may be a drawback, in particular in laser temperature measurements.

Although not discussed in this text, we should mention that the temperature information can also be derived from the energy shift of the photoluminescence (PL) signal offering, however, some advantages over Raman, such as higher signal levels and fewer (one) measurement runs per temperature point. The energy shift of a PL signal, for example, from the bulk or a quantum-confined area of a material, is predominantly determined by the temperature dependence of the bandgap energy.

Figure 9.1 shows the temperature dependence of the energy gap calculated using the empirical relation (Varshni, 1967) given in the figure. The energy shifts are small

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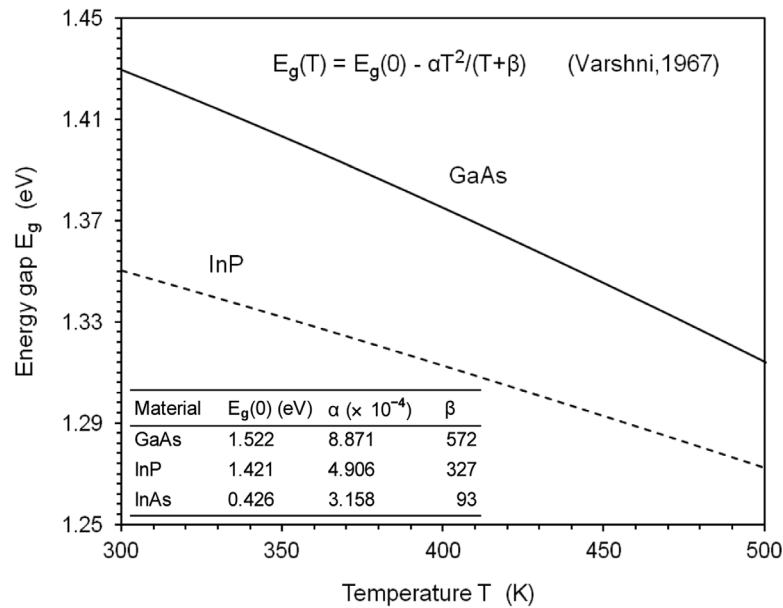


Figure 9.1 Calculated temperature dependence of the bandgap energy of some semiconductor compounds using the empirical expression in the figure.

with 5.4 meV/10 K for GaAs the largest of the three materials listed, followed by InP with 3.7 meV/10 K and InAs with 3.1 meV/10 K. However, given the fact that the PL lines are fairly broad for temperatures $\gtrsim 300$ K, it is very difficult to measure the temperature better than ~ 5 K in a reliable way. Thus, the essential drawbacks of insufficient sensitivity, speed, and amount of data per unit time exist also here.

Another approach is based on analyzing the laser radiation itself emerging from the mirror facet (Sweeney *et al.*, 2003). Under certain conditions the authors derived a simplified expression $I \propto E^2 \times \exp(-E/k_B T)$ for the radiation intensity I of photons with energy E emitted from the facet, which is no longer dependent on the effective bulk absorption coefficient and optical confinement factor. By plotting $\ln(I/E^2)$ versus E the authors claim to deduce the temperature from the slope of the plot in the high-energy Boltzmann tail of the facet emission. However, considering both the huge experimental and data evaluation effort involved in the procedure and the limited validity of the expression derived for the radiation intensity (see above), this technique cannot be regarded as a reliable, practicable, and versatile technique for diode laser mirror characterization. This is also underlined by the fact that the technique did not deliver in cw measurements on InGaAs/AlGaAs QW lasers the critical temperature to COMD at $\Delta T \sim 120$ K, which is now a well-established value.

Indispensable, however, for local laser temperature measurements is a technique capable of delivering the data in a fast and preferentially in a continuous mode, that

Figure 9.2 Schematics of optical reflectance modulation at the mirror facet of a ridge waveguide diode laser quasi-cw square-pulse operated.

9.4 Diode laser mirror temperatures by micro-thermoreflectance

9.4.1 Motivation

In this section, further mirror temperature measurements are discussed by using the novel micro-thermoreflectance technique. On the one hand, these measurements are on laser structures different from those used in the Raman measurements discussed in Chapters 7 and 8, but on the other hand they confirm also the results of these Raman measurements and thus demonstrate the potential and many benefits of the TR technique.

9.4.2 Dependence on number of active quantum wells

What is striking in Figure 9.4 are the continuous curves in the mirror temperature increase ΔT versus drive current I_d plots recorded by TR, in contrast to the single data points of Raman measurements. The temperatures were measured in the near-field patterns of mirror facets of junction-side up mounted ridge (Al)GaInP lasers 5 μm wide with one, two, and five active quantum wells (QWs). The ΔT data are relative to ambient temperature and allow for the small heating effect of the low intensity (<1 mW) of the 457.9 nm Ar^+ probe laser line focused to a spot size of $\lesssim 1$ μm

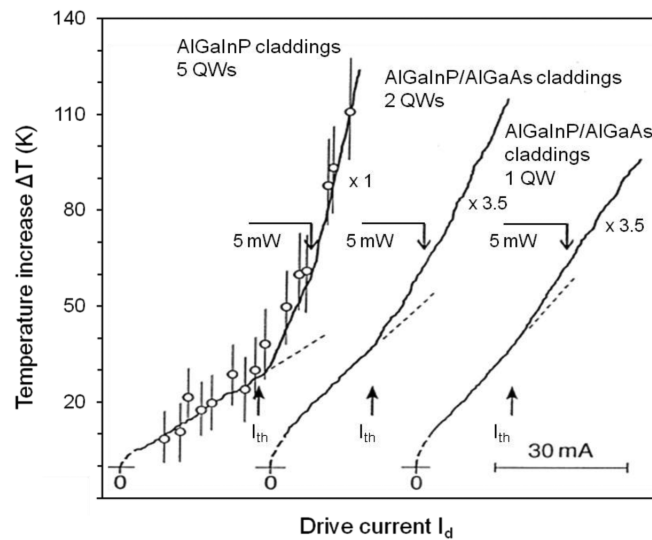


Figure 9.4 Typical temperature rise ΔT versus drive current I_d plots from thermoreflectance (TR) measurements on cleaved uncoated ridge GaInP lasers 5 μm wide with one and two active quantum wells (QWs) and mixed AlGaInP–AlGaAs claddings on the one side, and five QWs and AlGaInP claddings on the other side. The $\Delta T/I_d$ characteristic measured by using Raman spectroscopy is also shown for comparison for the 5-QW device.

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FWHM (Epperlein and Bona, 1993). To verify the temperatures derived from the TR measurements, the figure also includes Raman data obtained from the 5-QW device for comparison, which demonstrates excellent agreement between the data from the two totally different measurement techniques.

The ΔT versus I_d plots clearly show two typical regimes indicating different heating mechanisms. Below threshold current I_{th} , ΔT increases with I_d and is mainly due to Joule heating of the drive current. This is supported by the fact that the ΔT data at I_{th} agree well with the bulk temperature rises of the active p–n junction region along the cavity, as found from the comparison between P/I_d characteristics recorded under pulsed and dc conditions. However, a distinct onset in ΔT is observed at I_{th} for all three lasers, even for the SQW laser, and ΔT increases rapidly with I_d . As discussed already in Section 7.4.5.2, in this regime the Joule heating effect is superimposed by heating due to the absorption of laser radiation leading to an enhanced nonradiative carrier recombination rate in the mirror facets. The slope of the curve in this regime with respect to the dashed line of the extrapolated current heating is a sensitive measure for assessing the heating efficiency only under lasing conditions (current heating subtracted) and can be expressed by the differential temperature increase $\delta(\Delta T)/\delta P$ per laser output power unit at a reasonably low value of, say, 5 mW.

The temperatures in Figure 9.4 are linearly proportional to the number of QWs (see also Figure 7.29) up to two, whereas the dependence is superlinear up to five QWs (cf. Figure 4.7). The latter can be accounted for by the use of AlGaInP cladding layers in the 5-QW device, which have a higher electrical and thermal resistivity than the mixed AlGaInP–AlGaAs claddings used in the SQW and DQW devices (cf. Sections 4.4.2.2 and 7.4.6.3) and therefore a higher heating power.

In terms of a simplified picture, the QW number dependence of the mirror temperature can be understood by taking into account, first, that each QW may act as a possible heating source fed by any possible nonradiative recombination of the injected carriers, and, second, that the individual heating sources in lasers with more than one QW are cumulative in their effect. See also the discussion in Section 1.3.4.3 on the dependence of the threshold current on the number of QWs involving different loss mechanisms such as free-carrier absorption leading to an increased optical loss coefficient α_i and thus higher internal heating.

9.4.3 Dependence on heat spreader

Figure 9.5 shows ΔT versus I plots of 980 nm compressively-strained InGaAs/AlGaAs GRIN-SCH SQW ridge uncoated lasers 5 μm wide recorded under different conditions. First, the dependence on the use of a thick Au heat spreader (HS) layer on top of the p-contact (Figure 9.5b) is shown in (A) and (B) of Figure 9.5a. The graphs clearly show a decrease in the temperature for devices with the HS lined up with the mirror edge (B), in contrast to devices with the HS recessed (A) by $\sim 20 \mu\text{m}$ (Figure 9.5b). The averaged drop in temperature is by a factor of two measured at the 60 mW mark of the three devices in each group. This difference can be understood from the fact that the temperature decreases exponentially

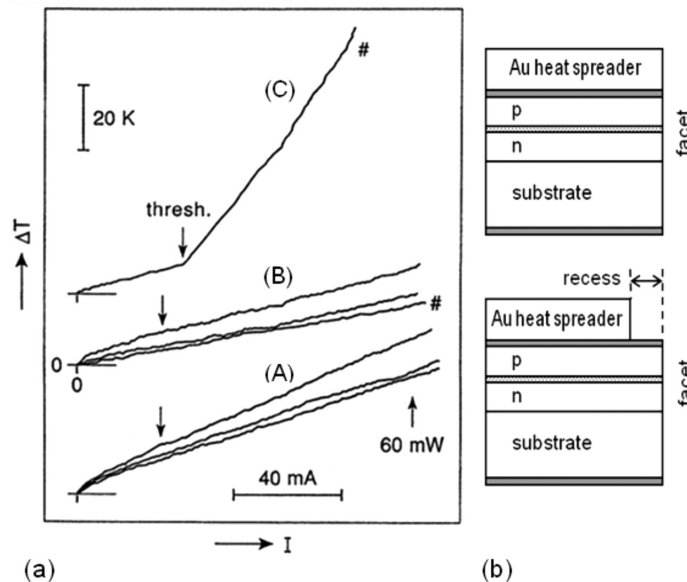


Figure 9.5 Maximum temperature rise ΔT versus drive current I plots measured by TR on uncoated mirrors of 5 μm ridge InGaAs/AlGaAs SQW lasers depending on a heat spreader (HS) on top of the structure (b). (a): (A) HS $\cong$ 20 μm recessed; (B) HS lined up with mirror edge; (C) after COMD of device marked # in comparison to as-grown device in (B).

from the mirror surface toward the laser cavity, which will be discussed in detail in Section 9.6 below.

The second effect deals with the emergence of the kink at I_{th} in the $\Delta T/I$ characteristic after a COMD event occurred. The characteristics of as-grown lasers in (A) and (B) of the figure show no kink at threshold and thus are dominated by the Joule heating of the drive current. However, after COMD occurred a distinct kink at threshold appeared, as demonstrated by the characteristic marked # in (B) for the as-grown facet and (C) for the facet after COMD. This demonstrates in a distinct manner the superposition of laser radiation heating caused by surface absorption effects as argued already on many occasions in the text, in particular in Sections 7.4.6.1 and 8.2.3.1.

9.4.4 Dependence on mirror treatment and coating

A similar topic has been discussed in Section 7.4.6.2 on ridge (Al)GaAs lasers 7 μm wide in a ΔT versus P dependence representation by using Raman spectroscopy for measuring the mirror temperature rises ΔT . Here, we discuss ΔT versus I measurements on (Al)GaAs devices 10 μm wide with similar mirror treatments and coatings achieved, however, using the TR technique (Epperlein, 1993). The objective is to quantify the mirror surface quality/heating efficiency by the slope of signal rise at threshold relative to the current-heating signal slope below threshold.

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10 μm wide ridge (Al)GaAs SQW lasers. Cleaved mirrors.

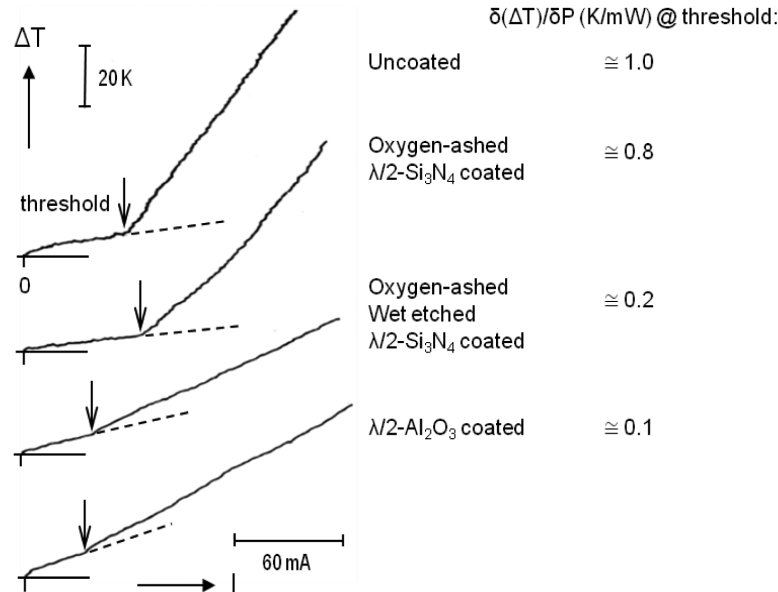


Figure 9.6 TR facet temperature rises ΔT measured on (Al)GaAs SQW lasers 10 μm wide with different mirror treatments and coatings. Differential temperature increases per power unit at threshold are listed for the various mirror technologies to compare the respective mirror surface qualities/heating efficiencies.

Figure 9.6 shows the graphs for (i) uncoated, (ii) oxygen-ashed, $\lambda/2$ - Al_2O_3 -coated, (iii) oxygen-ashed, wet-etched, $\lambda/2$ - Si_3N_4 -coated, and (iv) $\lambda/2$ - Al_2O_3 -coated mirrors with the differential temperature increases $\delta(\Delta T)/\delta P \cong 1.0, 0.8, 0.2$, and 0.1 K/mW, respectively.

What is remarkable is the reduction of heating due to optical power absorption by a factor of 4 due to the removal of the damage layer after an oxygen-ashing treatment by a wet etch. In addition, measurements on mirrors with the same surface treatment prior to coating showed no significant difference in ΔT between $\lambda/2$ - Al_2O_3 and $\lambda/2$ - Si_3N_4 passivation layers.

Finally, the signal of the slightly convex characteristics near the zero-point $I \gtrsim 0$ can be ascribed to electroreflectance caused by a surface potential modulated by the pulsed carrier injection during the TR measurement. This interpretation is in agreement with results from electric field-induced Raman scattering (EFIRS) measurements (Beeck *et al.*, 1989) on the band bending of laser mirror surfaces.

9.4.5 Bent-waveguide nonabsorbing mirror

A nonabsorbing mirror (NAM) structure based on a bent-waveguide concept has been discussed in Section 4.3.4 to enhance the optical strength of the laser facet.

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In this approach, the optical beam is decoupled from the active waveguide layer into the nonabsorbing cladding layer with a higher bandgap energy (Gfeller *et al.*, 1992a, 1992b). As described previously, the bent-waveguide structure in the mirror regions of ridge (Al)GaAs lasers 3.5 μm wide is formed by overgrowing a wet-etched channel 1 μm deep with 22° sloped sidewalls in the n^+ -doped (100) GaAs substrate. Exact wafer orientation is necessary to obtain symmetrical growth conditions on both channel slopes.

To assess the effectiveness of the NAMs with respect to a reduction of optical absorption, the rise of mirror temperatures ΔT of lasers with dry-etched (CL_2 reactive ion etching) and $\lambda/2$ - Al_2O_3 -coated mirrors has been measured for the first time for progressive NAM section lengths x in the range $-1 < x < 16 \mu\text{m}$ by spatially resolved ($\lesssim 1 \mu\text{m}$) TR.

Figure 9.7 shows the schematics of the NAM structure and, for illustration, the $\Delta T/I$ characteristics at three typical positions $x = -1, 5$, and 15 μm with high, low, and high temperatures measured for example at 30 mW for each device, respectively. This temperature behavior is also clearly reflected in the differential temperature increase at threshold, which is lowest for a device with a NAM section length $x = 5 \mu\text{m}$. The characteristics can be accounted for by the properties of the conventional mirror at $x = -1 \mu\text{m}$, a NAM with a beam fully in the nonabsorbing cladding at $x = 5 \mu\text{m}$, and a NAM with a partially recoupled beam into the absorbing waveguide at $x = 15 \mu\text{m}$, respectively.

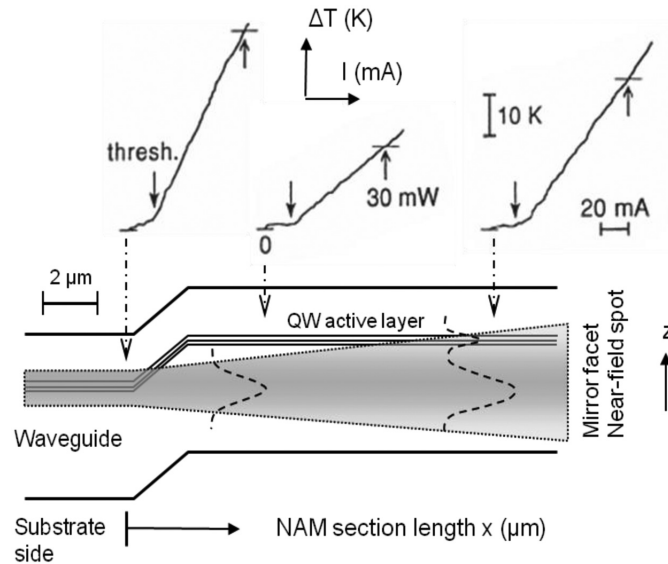


Figure 9.7 Scheme of a bent-waveguide nonabsorbing mirror (NAM) structure of dry-etched, coated (Al)GaAs lasers. Schematic side view of the beam propagation in the structure. Selected temperature ΔT versus current I characteristics recorded on mirror facets at different NAM section lengths $x = -1, 5$, and 15 μm . Scale valid along cavity in x direction.

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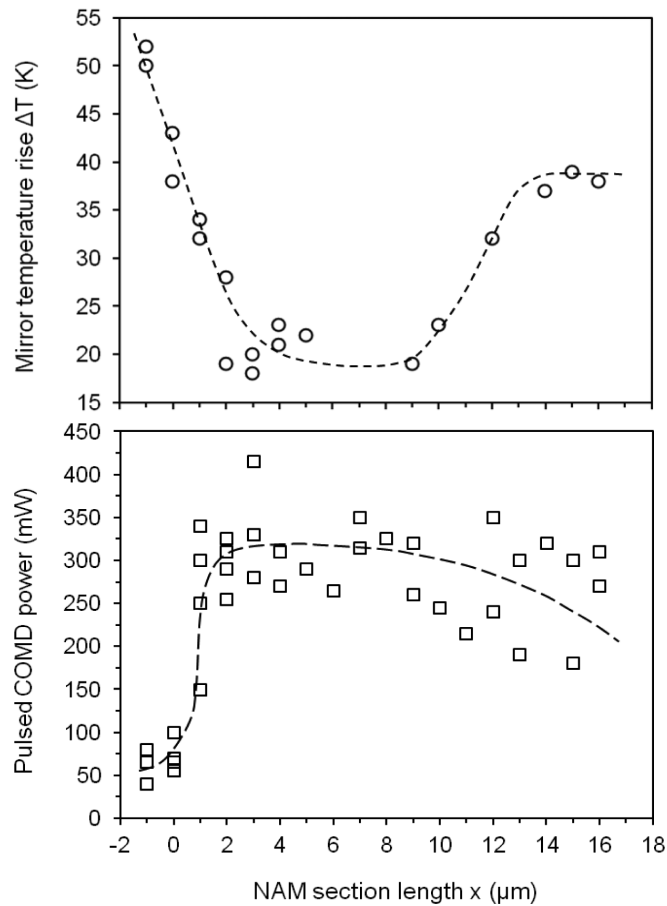


Figure 9.8 Experimental mirror temperature increases ΔT at 30 mW quasi-cw power (top) and pulsed COMD power levels (bottom) for etched and passivation-coated mirrors of (Al)GaAs lasers $5\ \mu\text{m}$ wide as a function of progressive nonabsorbing mirror (NAM) section length x . (Adapted in modified form from Gfeller *et al.*, 1992a.) Dashed lines are guides to the eye.

A more detailed $\Delta T/x$ dependence is plotted in Figure 9.8, which can be divided into three distinct regions.

In the region $-1 < x < 2\ \mu\text{m}$ (transition from conventional mirror to sloped waveguide section) the temperature measured at 30 mW optical output power falls sharply from typically 50 to 20 K.

In the range $2 < x < 10\ \mu\text{m}$ (optical beam propagating fully in nonabsorbing cladding), the temperature remains at this low level of 20 K, and increases again for $x > 10\ \mu\text{m}$ (partial beam recoupling into the absorbing waveguide leads to increased heating; recoupling is evidenced by monitoring the optical near-field patterns, see Figure 4.5).

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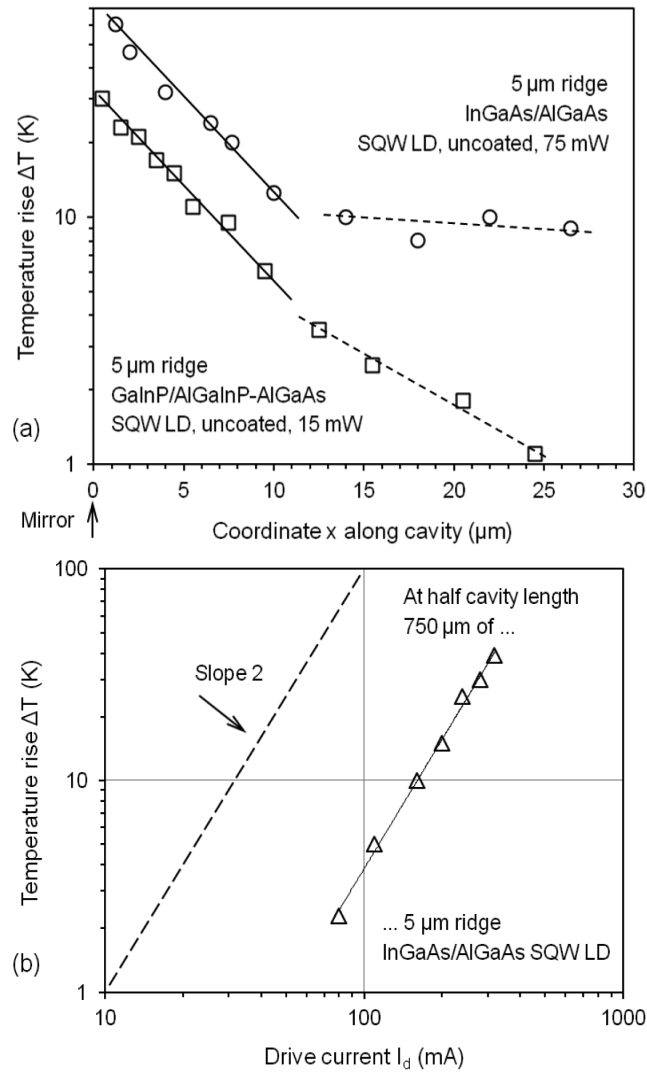


Figure 9.15 Cavity temperatures measured by spatially resolved EL for an InGaAs/AlGaAs and GaInP/AlGaInP-AlGaAs SQW laser. (a) Log of temperature rise ΔT versus coordinate x along cavity plots show for both lasers the same steep exponential decay of ΔT with a characteristic length of $\sim 6 \mu\text{m}$ (1/e point) followed by a much slower but different decay toward the bulk of the cavity. (b) Temperature rises ΔT taken as a function of drive current I_d near the center of the cavity are proportional to the square of I_d in line with the expected Joule heating power of the drive current.

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is strongly proportional to the Joule heating of the drive current given by I_d^2 , which is illustrated in the figure. The temperature rise in the cavity center of a 5 μm ridge uncoated InGaAs/AlGaAs laser is $\Delta T \sim 40$ K at 300 mA (150 mW).

9.7 Diode laser facet temperature – two-dimensional mapping

9.7.1 Motivation

Knowledge of the two-dimensional temperature distribution on a laser facet can give useful information about local hot spots, the quality of facet passivation treatment and reflectivity coating layers, the bond between coatings and the semiconductor surface, and can contribute to the optimization of the vertical structure to achieve the goal of lowest possible absolute operating temperatures and temperature gradients.

The first ever mirror temperature map of an operating diode laser was obtained by the author (Epperlein, 1990) and reported in subsequent papers (Epperlein and Martin, 1992; Epperlein, 1993, 1997).

9.7.2 Experimental concept

Temperature maps have been obtained by raster scanning the focus spot of the low-power probe laser across the mirror surface of the quasi-cw square-pulse power-modulated diode laser (see Section 9.1.2). The high spatial resolution (~ 0.8 μm FWHM optical spot size) two-dimensional scanner with two orthogonally mounted high-precision (0.1 μm mechanical step size) stepping motor-driven translation stages, discussed in Section 7.1.2 and Figure 7.2, was employed in this application. The $\Delta R/R$ signal was detected as a function of location and, after conversion to temperature, a ΔT map was generated.

9.7.3 First temperature maps ever

A contour map of a typical temperature rise (relative to 300 K) distribution on an as-cleaved and uncoated mirror of a 15 μm wide ridge and 750 μm long InGaAs/AlGaAs GRIN-SCH SQW laser, quasi-cw square-pulse operated at a power $P = 40$ mW, is displayed in Figure 9.16.

The scanned area is 35 $\mu\text{m} \times 15$ μm with the first scan aligned along the active layer approximately 0.5 μm (residual thickness, see Section 2.3) away from the lower edge of the etched ridge profile. Note that the scale in the y direction is smaller than that in the z direction.

There are two striking features: first, a very localized hot spot with a strong temperature rise $\Delta T \sim 60$ K within the near-field pattern just below the ridge characterized by the dense 2 K equidistant contour lines; and, second, a much lower temperature regime characterized by the wider contour lines indicating a slower decay of temperature. This regime is in the GaAs substrate as indicated by the arrow

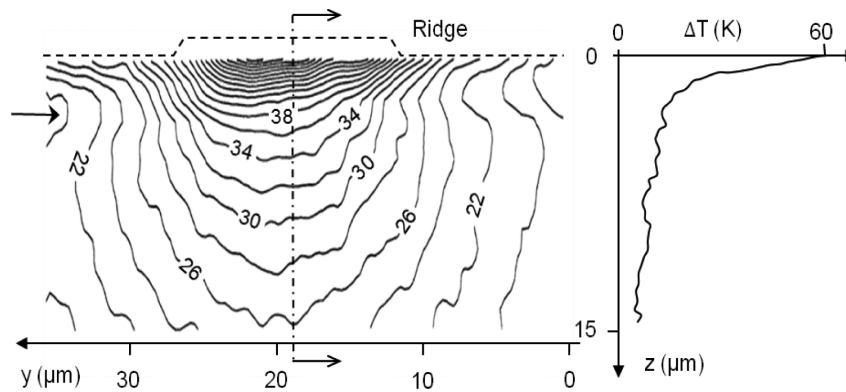


Figure 9.16 Contour map of the temperature rise ΔT distribution recorded by scanning TR on a cleaved uncoated mirror facet of an (Al)GaAs diode laser 15 μm wide operated at 40 mW quasi-cw. The scan was not exactly parallel in the horizontal y direction, which caused a slight displacement in the z direction of the contour indents on both sides due to the epitaxial layer/substrate interface (see arrow) with different thermal conductivities in both regions. The effect of the latter is demonstrated by the different widths of the isothermal contour lines and the different slopes of the two sections in the ΔT versus z line scan. Note that the scale in the y direction is smaller than that in the z direction.

marking the boundary line between the epitaxial (mainly) AlGaAs layers and the GaAs substrate. The ratio of the temperature decay strength in the GaAs and AlGaAs is fully consistent with the thermal conductivity that is about 5–6 times larger in GaAs than in AlGaAs. The two different temperature zones are also clearly demonstrated in the line scan shown in the figure. The contour map exhibits particularly well the epilayer/substrate interface with the indent of the isothermal lines becoming more pronounced in the horizontal y direction and the bending of the contour lines away from the heat source due to the strong heat-spreading effect of the top p-metallization.

9.7.4 Independent temperature line scans perpendicular to the active layer

A high-precision temperature line scan perpendicular to the near-field pattern of an E2-passivated (see Section 4.2.2.1), Al_2O_3 -coated front mirror ($R = 0.1$) of a compressively-strained InGaAs/AlGaAs GRIN-SCH SQW single-mode high-power diode laser with a ridge 4 μm wide is shown in Figure 9.17. The temperature measurements were recorded at an output power of 110 mW for two separate runs and with a spatial resolution of 0.8 μm FWHM.

The figure shows the hot spot area within the near-field pattern with a spot size of ~ 2 μm FWHM in the vertical direction, which is $\sim 3 \times$ higher than the effective extension of the near field. The decay of the temperature toward the substrate side is divided into the two zones comprising the epitaxial layers and the substrate as demonstrated in an impressive manner by the $\log \Delta T$ versus z coordinate graph of

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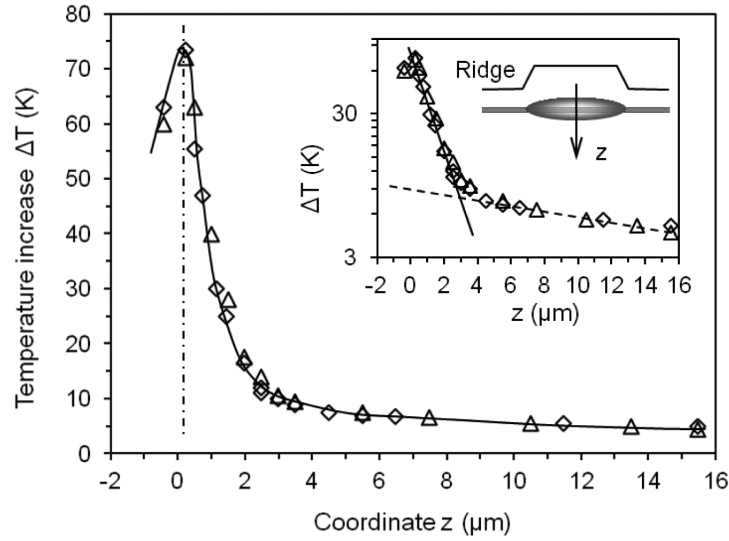


Figure 9.17 Temperature line scan ΔT versus z direction perpendicular across the near-field spot center of an InGaAs/AlGaAs SQW laser $4\ \mu\text{m}$ wide at high power of 110 mW cw toward the GaAs substrate in two separate scans. The log ΔT versus z graph in the inset shows an exponential decay of ΔT in both epitaxial and substrate areas in agreement with the respective thermal conductivities in these areas.

the inset confirming, for the first time, exponential decay in both areas. The slope ratio of the two experimental log curves is in excellent agreement with the ratio of the relevant thermal conductivities in the two regions confirming the result obtained in the section above.

9.7.5 Temperature modeling

The experimental ΔT map can be compared to heat flow calculations. From a theoretical point of view, the temperature distribution in the laser can be obtained by solving the three-dimensional heat equation in the device. For simplicity, however, we can neglect any variation of heat production that may occur along the laser structure. Therefore, we can limit the calculations to a cross-section of the laser where a solution of the two-dimensional heat equation must be found:

$$-\text{div}(k \times \text{grad}(T)) = Q + h + (T_{\text{ext}} - T) \quad (9.4)$$

where k is the heat conduction coefficient, Q the heat source, h the convective heat transfer coefficient, and T_{ext} the external temperature. We further neglect particular thermal effects at the mirror including laser radiation absorption and nonradiative recombination effects and any convective heat transfer ($h = 0$) and external temperature ($T_{\text{ext}} = 0$) in the numerical computation process. The heat flow calculations

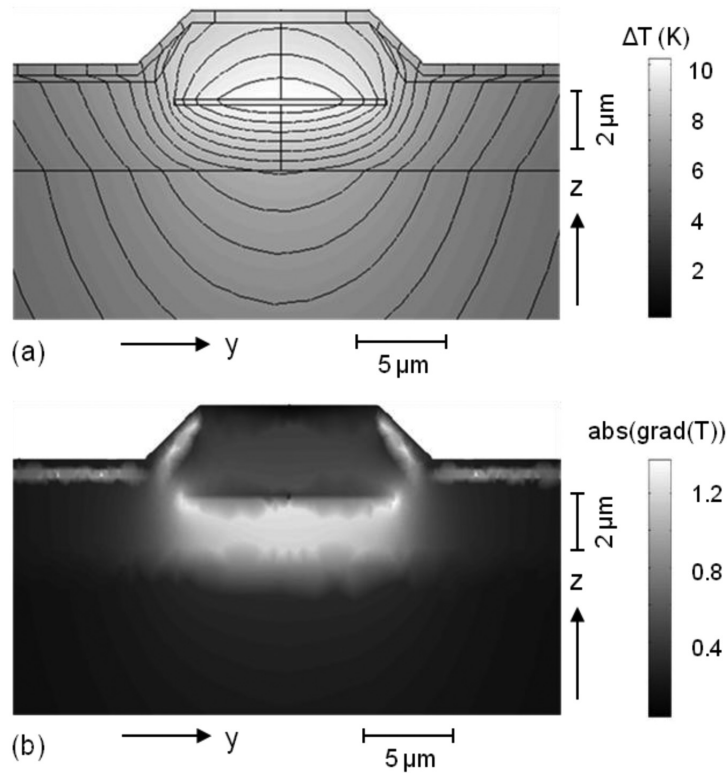


Figure 9.19 Numerical computation of the temperature map $\Delta T(y, z)$ of the laser used in Figure 9.16 by considering only the different thermal conductivities of the various layers in the vertical laser structure. The modeling does not consider mirror heating effects due to laser radiation absorption and nonradiative recombination. (a) Contrast and contour image in good qualitative agreement with experimental temperature map of Figure 9.16. (b) First temperature gradient map of a diode laser mirror with strong gradients below the active layer as heat source toward the epitaxial layer/substrate interface, and along the silicon nitride layer.

9.7.5.2 Modeling results and discussion

Figure 9.19a shows the calculated mirror temperature map $\Delta T(y, z)$ of the laser used in Section 9.7.3 in excellent qualitative agreement with the experimental contour plot of Figure 9.16. In particular, the contrast and contour images show the hot spot area with its highest temperatures at the heat source of the active layer and with a steep temperature decay in the epitaxial region toward the substrate side due to a lower thermal conductivity in the epitaxial $\text{Al}_{0.35}\text{Ga}_{0.65}\text{As}$ layers than in the GaAs substrate. The wider contour lines towards the p-contact indicate the strong heat spreading effect of the metallization.

The maximum temperature of $\Delta T \sim 10$ K is in agreement with the cavity temperature measured toward the center of the cavity caused mainly by the distribution of the different thermal conductivities in the structure. The difference between

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maximum ΔT values of the calculated map (Figure 9.19a) and the experimental map (Figure 9.16) is due to laser radiation absorption and nonradiative recombination effects at the facet not taken into account in the numerical computation. The ratio of six between both values is in reasonable agreement with temperature measurements made from the mirror edge along the laser cavity (Figure 9.15).

Finally, Figure 9.19b exhibits for the first time a calculated temperature gradient map across the mirror facet. There are two striking areas where the gradients are highest. One is, as expected, below the active layer to the boundary with the substrate, whereas the other is in the dielectric Si_3N_4 layer along the lower edges of the ridge profile, but most importantly also along both ridge slope sides.

Considering the different thermal expansion coefficients of $\sim 14 \times 10^{-6} \text{ K}^{-1}$, $\sim 3 \times 10^{-6} \text{ K}^{-1}$ (Suganuma *et al.*, 1985) and $\sim 5.5 \times 10^{-6} \text{ K}^{-1}$ (Ioffe Physico-Technical Institute, 2001) for the dominating Au in the p-contact, Si_3N_4 , and $\text{Al}_{0.35}\text{Ga}_{0.65}\text{As}$, respectively, these areas are potential sources for the formation of high thermal stress fields leading to high local stress amplitudes. The latter may trigger the formation of detrimental structural defects and cracks in the materials and may cause problems in the adhesion of the nitride and metallization layers.

These thermal stress fields superpose the intrinsic mechanical stress fields (see Section 8.2), caused by the deposition of the dielectric nitride and p-metallization layers at temperatures of $\sim 120^\circ\text{C}$ on ridge waveguide structures. As discussed in Section 8.2, local mechanical stress fields, which may now be enhanced through the superposition of both stress fields, are responsible for the formation and migration of defects (see Figures 8.8 and 8.9) resulting in an even stronger negative effect on diode laser performance and reliability.

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DLE: B, C, D, E, F, G, H, L, M, O, Q, R, S, T, U, W

DLR: A, C, D, E, F, L, O, R, S

DLD: A, D, E, L, M, P, R, S, T

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