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Introduction

1.1 Progress in Electronics

Development of semiconductor materials and devices has been a strong driving force for a variety of revolutionary changes and innovations in modern society. Since the invention of germanium (Ge)-based bipolar transistors in 1947–1948 [1, 2] and the subsequent success of silicon (Si)-based metal-oxide-semiconductor field effect transistors (MOSFETs) [3], semiconductor devices have given rise to a new field, *solid state electronics*. The invention of integrated circuits (ICs) made by planar technology [4, 5] triggered rapid progress in *microelectronics*. Nowadays, Si-based large scale integrated circuits (LSIs) are the key components in almost all electrical and electronic systems. Despite predictions of physical limitations, remarkable progress continues to be made in Si-based LSIs, even today [6, 7]. Solar cells and various sensors are also mainly produced using silicon.

In the meantime, compound semiconductors have established unique positions in those applications where Si devices cannot exhibit good performance because of the inherent material properties. In particular, III–V semiconductors such as gallium arsenide (GaAs) and indium phosphide (InP) have been widely employed for high-frequency devices and light-emitting devices [8, 9]. In addition to the high electron mobility and direct band structure of most III–V semiconductors, bandgap engineering and formation of heterostructures can be utilized to enhance the performance of devices based on compound semiconductors. Success in making blue and green light-emitting devices using gallium nitride (GaN) and indium gallium nitride (InGaN) was also a great milestone in the history of semiconductors [10, 11]. Thus, *optoelectronics* is one of the most important fields of development, and relies on these III–V semiconductors.

As our society continues to advance technologically, various demands for new functionalities for semiconductor devices have arisen, such as high-temperature operation and flexibility. *High-temperature electronics* is a field where wide bandgap semiconductors possess much promise [12]. Conversely, organic semiconductors and oxide semiconductors have been developed for *flexible electronics* [13].

Improvement of energy efficiency (reduction of power consumption and dissipation) is one of the most basic problems we are facing. In 2010, the world average ratio of electrical energy consumption to total energy consumption is about 20% [14], and this ratio is expected to increase rapidly in the future. Independent of the means by which electrical power is generated, power conditioning and conversion are required for cost-effective and efficient delivery to the load. It is estimated that more than 50% of all electrical power flows through some form of power conversion.

Power electronics, the concept of which was introduced by Newell in 1973 [15], involves *conversion of electric power* using power semiconductor devices and circuits. Electric power is regulated and converted so that the power can be supplied to the loads in the best form. Electric power conversion includes

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Fundamentals of Silicon Carbide Technology: Growth, Characterization, Devices, and Applications, First Edition.
Tsunenobu Kimoto and James A. Cooper.

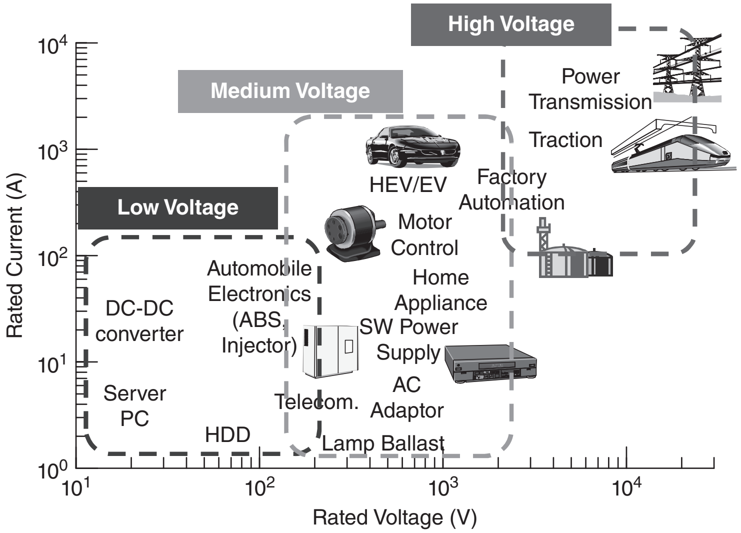


Figure 1.1 Major application areas of power devices plotted as a function of rated voltage.

AC–DC, DC–AC, DC–DC (voltage conversion), and AC–AC (voltage or frequency conversion) [16]. The efficiency of power conversion is typically 85–95% using currently available technology, which is not high enough, because approximately 10% of the electric power is lost as heat at every power conversion. In AC–DC and DC–AC conversions, which are very common, the efficiency becomes as low as about $(0.9)^2 \approx 0.8$.

In general, the efficiency of power electronics is limited by the performance of semiconductor devices, capacitors, inductors, and packaging. In particular, power semiconductor devices have attracted increasing attention as key components which limit the performance and size of power converters. As shown in Figure 1.1, the major applications of power devices include power supplies, motor control, telecommunications, heating, robotics, electric/hybrid vehicles, traction, lighting ballasts, and electric power transmission. Development of high-voltage and low-loss power devices is also essential for construction of future smart grids.

Realization of high-performance power devices will lead not only to enormous energy saving but also to conservation of fossil fuels and reduced environmental pollution. At present, Si is the most commonly used semiconductor for power devices. The performance of Si power switching devices has been significantly improved through development of power MOSFETs and IGBTs (insulated gate bipolar transistors) [17, 18]. Progress in Si LSI technology and in advanced simulation technology has had great impact on the development of Si power devices in recent decades. However, now that Si power device technology is relatively mature, it is not easy to achieve innovative breakthroughs using this technology. *Silicon carbide* (SiC) is an old but emerging semiconductor, which is promising for advanced power devices because it has superior physical properties. SiC devices are also promising for high-temperature and radiation-resistant operation. GaN is also attractive as a material for power devices, and the intrinsic potential of GaN is very similar to that of SiC (since they have almost the same bandgap and critical electric field strength). At present, however, growth and device-fabrication technologies for SiC are more advanced, and SiC power devices exhibit better performance and reliability. GaN-based lateral switching devices processed on heteroepitaxial GaN on Si show some promise for relatively low-voltage (100–300 V) applications. When the GaN technology becomes more mature, especially when large-diameter bulk growth is readily achieved, both SiC and GaN power devices will be widely employed, depending on the performance and cost. For high-voltage bipolar device applications, however, SiC should be inherently superior because SiC has an indirect band structure, leading to an inherently long carrier lifetime.

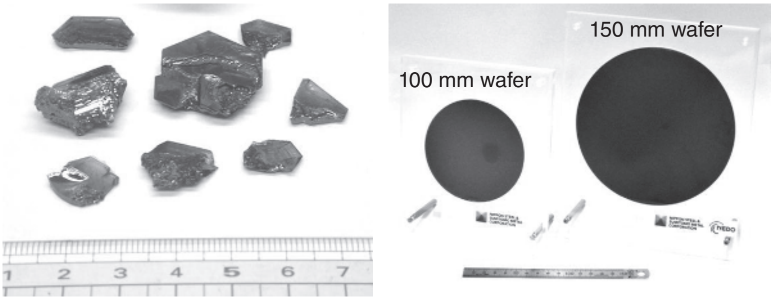
1.2 Features and Brief History of Silicon Carbide

Silicon carbide (SiC) is a IV–IV compound material with unique physical and chemical properties. The strong chemical bonding between Si and C atoms gives this material very high hardness, chemical inertness, and high thermal conductivity [19]. As a semiconductor, SiC exhibits a wide bandgap, high critical electric field strength, and high saturation drift velocity. Both n- and p-type control across a wide doping range is relatively easy in SiC; this makes SiC exceptional among wide bandgap semiconductors. The ability of SiC to form silicon dioxide (SiO_2) as a native oxide is an important advantage for device fabrication. Because of these properties, SiC is a promising semiconductor for high-power and high-temperature electronics [20–22]; subsequent chapters will describe in detail the fundamentals of SiC technologies, its properties, growth, characterization, device fabrication, and device characteristics.

The physical and chemical stability of SiC, however, has made crystal growth of SiC extremely difficult, and severely hampered development of SiC semiconductor devices and their electronic applications. The existence of various SiC structures with different stacking sequences (otherwise known as polytypism) [23] has also hampered growth of electronic-grade SiC crystals. SiC polytypes such as 3C-, 4H-, and 6H-SiC, are described in Section 2.1.

1.2.1 Early History

SiC itself is rare in nature, and synthesis of a compound material containing silicon–carbon bonds was first reported by Berzelius in 1824 [24]. Acheson invented a process for the synthesis of SiC from silica, carbon, and some additives (e.g., salt) in 1892 [25]. This process (*Acheson process*) provided volume production of SiC powders used for cutting, grinding, and polishing, which was the first industrial application of SiC. In the Acheson process, ingots which contain small single crystalline SiC platelets (mainly 6H-SiC) can be obtained as a by-product (Figure 1.2a). Although these SiC platelets are not pure, they were used for some basic studies on the physical and chemical properties of SiC. One of the highlights of this work was the first discovery of electroluminescence (emission of yellow light) from SiC by Round in 1907 [26]. In the meantime, Moissan discovered natural SiC and investigated this material as a mineral [27]. This is why SiC is named “Moissanite” in mineralogy or in the field of gem stones.



(a) (b)

Figure 1.2 (a) SiC platelets (mainly 6H-SiC) obtained as a by-product in the Acheson process. (b) 4H-SiC wafers with 100 and 150 mm in diameter.

Lely successfully grew relatively pure SiC crystals by a sublimation technique (*Lely method*) in 1955 [28]. The crystals obtained are mostly 6H-SiC, but inclusions of foreign polytypes are often observed. Owing to the relatively high crystal quality of the Lely platelets, the first wave of research into SiC as a semiconductor emerged in the 1960s. During this period, the main target applications for semiconductor SiC were the development of high-temperature devices and blue light-emitting diodes [29, 30]. Shockley participated in an international conference on SiC, and emphasized the promise of SiC for high-temperature electronics [30]. Important academic studies on optical properties of SiC were extensively performed by Choyke [31]. However, because of the small size of Lely platelets and unsteady material supply, research and development of SiC semiconductors slowed down in the late 1970s, and the technology remained immature. Conversely, polycrystalline SiC technology was developed, and SiC-based ceramics, heating elements, passive components, and thermistors were commercialized.

1.2.2 Innovations in SiC Crystal Growth

In 1978–1981, Tairov and Tsvetkov invented a reproducible method for SiC boule growth [32, 33]. They introduced a 6H-SiC seed into a sublimation growth furnace, and designed an appropriate temperature gradient to control mass transport from the SiC source onto the seed crystal, based on thermodynamic and kinetic considerations. This growth process is called the *modified Lely method* or *seeded sublimation method*. Several groups followed and further developed the growth process to obtain SiC boules with a larger diameter and a reduced density of extended defects. Davis and Carter significantly refined this method [34]. The first commercialization of SiC (6H-SiC) wafers occurred in 1991 [35]. Through continuous efforts, reasonably high-quality SiC wafers, 100–150 mm in diameter, are commercially available from several vendors at present (Figure 1.2b). The availability of single crystalline wafers has driven rapid development of SiC-based electronic devices.

Concerning epitaxial growth of SiC, liquid phase epitaxy (LPE) of 6H-SiC on Lely platelets was investigated in the 1980s, in research targeting blue light-emitting diodes [36, 37]. Heteroepitaxial growth of 3C-SiC on a Si substrate by chemical vapor deposition (CVD) was developed [38, 39] in the early 1980s, but the performance of electronic devices (Schottky barrier diodes (SBDs), pn diodes, MOSFETs) was far below that expected. This result can be attributed to a high density of stacking faults and dislocations, which are generated because of large mismatches in the lattice constants and thermal expansion coefficients. Therefore, a few groups started CVD growth of 3C-SiC on 6H-SiC{0001} (Lely or Acheson platelets). Although the quality of 3C-SiC was much improved, it was still not satisfactory.

In 1987, Matsunami *et al.* discovered that high-quality 6H-SiC can be homoepitaxially grown by CVD at relatively low growth temperature, when a several degree off-angle is introduced into the 6H-SiC{0001} substrates ("*step-controlled epitaxy*") [40]. Davis *et al.* also reported homoepitaxial growth of 6H-SiC on off-axis substrates [41]. Homoepitaxial growth of 6H-SiC on off-axis 6H-SiC{0001} became a standard technique in the SiC community because it yielded high purity, good doping control, and uniformity. In 1993, a high mobility of over 700 $\mathrm{cm^2\ V^{-1}\ s^{-1}}$ was first reported for 4H-SiC grown using this technique [42]. The combination of this result, the other superior physical properties of SiC, the commercial release of 4H-SiC wafers, and demonstration of excellent 4H-SiC devices made 4H-SiC the preferred choice for electronic device fabrication in the mid 1990s. In the meantime, the doping control was drastically improved by exploiting the "*site-competition*" concept proposed by Larkin *et al.* [43]. A *hot-wall CVD* reactor was proposed by Kordina *et al.* [44], and this reactor design is currently the standard, because it allows superior control of temperature distribution, has a much longer susceptor life, and better growth efficiency.

Since high-quality 4H- and 6H-SiC epitaxial layers (both n- and p-types) can be obtained, physical properties and defects of SiC have been extensively investigated in the University of Pittsburgh, the University of Erlangen-Nürnberg, Linköping University, Kyoto University, Ioffe Physical Technical Institute, Purdue University, the Naval Research Laboratory, the State University of New York at Stony Brook, Carnegie Mellon University, AIST, and so on.

1.2.3 Promise and Demonstration of SiC Power Devices

The outstanding potential of SiC-based power devices was suggested in 1989 by Baliga [45], and a systematic theoretical analysis of the performance was published in 1993 by the same group [46]. These papers have inspired and motivated scientists and engineers in this field.

As a result of the progress in homoepitaxial growth technology described above, lightly-doped hexagonal SiC epitaxial layers with reasonable quality became available in the early 1990s. Matus *et al.* reported a 1 kV 6H-SiC pn diode and its rectification operation up to 600 °C [47]. Urushidani *et al.* in 1993 demonstrated a 1 kV 6H-SiC SBD with a low specific on-resistance and 400 °C rectification [48]. In 1994, the on-resistance of high-voltage SiC SBDs was significantly reduced by using 4H-SiC [49]. After structure and process optimization, the first SiC SBD products were released in 2001 [50]. One of the typical applications of SiC SBDs was as fast diodes employed in a power-factor-correction circuit of switching-mode power supplies. Because of the negligibly small reverse recovery of SiC SBDs, the switching loss can be dramatically reduced and the switching frequency can be increased, leading to the downsizing of passive components. SiC SBDs are currently employed in a broad spectrum of applications, such as industrial motor control, photovoltaic converters, air conditioners, elevators, and traction (subway). In research and development, the maximum blocking voltage of SiC diodes exceeded 20 kV [51, 52].

In conjunction with development of high-voltage SiC diodes, fabrication of vertical SiC switching devices started in the early 1990s. In 1993, a vertical trench MOSFET of 6H-SiC was demonstrated by Palmour *et al.* [53]. Palmour and coworkers also extensively developed 4H-SiC trench MOSFETs, thyristors, and bipolar junction transistors (BJTs), as important steps toward high-power electronics [54]. In 1996 and 1997, the first planar double-implanted metal-oxide-semiconductor field effect transistor (DIMOSFET) of 4H-SiC with a blocking voltage of 760 V and low on-resistance was reported by Purdue University [55]. This group demonstrated a 1.4 kV–15 mΩ cm^2 4H-SiC trench MOSFET with a number of innovative design features in 1998 [56]. To avoid problems at the SiC MOS interface, vertical junction field effect transistors (JFETs) were also developed [57], leading to the commercialization of 4H-SiC power JFETs in the mid 2000s [50]. After steady improvement of MOS channel mobility and oxide reliability, 4H-SiC power DIMOSFETs have also been commercially available since 2010 [35, 58]. Figure 1.3 shows a picture of a 100 mm wafer after processing of SiC power MOSFETs. However, these

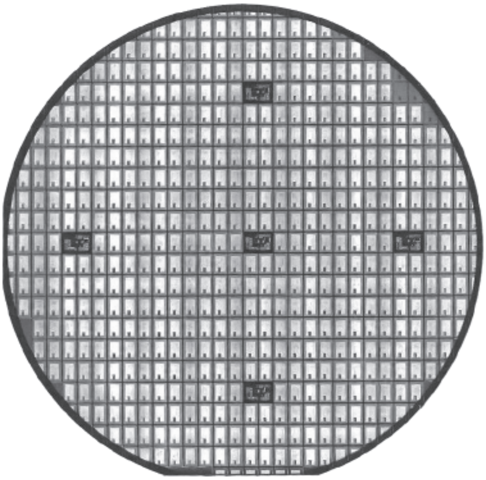


Figure 1.3 100 mm 4H-SiC wafer after processing of power MOSFETs. Reproduced by courtesy of T. Nakamura (Rohm).

SiC power switching devices require further improvement in performance and cost reduction. The market is slowly growing as these devices become more cost-effective. As far as ultrahigh-voltage switching devices are concerned, 12–21 kV thyristors, IGBTs, and BJTs have been demonstrated [59–62].

1.3 Outline of This Book

As a result of the rapid progress in SiC growth and device technologies in the last decade, some SiC power devices are now in commercial production. The major benefits of SiC devices include lower power dissipation, smaller size, and simplified cooling units of power converters. A number of academic studies on the materials science and device physics of SiC have been carried out, adding substantially to the scientific knowledge in this area. In this book, fundamental physics, present understanding, and unaddressed issues in SiC technology are summarized.

The outline of the chapters is as follows:

Chapter 2 describes the unique crystal structures and physical properties of SiC, and compares SiC with Si and other semiconductors.
Chapter 3 focuses on bulk growth of SiC for wafer production. The basic principles and technology development for sublimation growth are explained.
Chapter 4 gives the basics of homoepitaxial growth of hexagonal SiC by CVD. Doping control and defects in SiC epitaxial layers are presented.
Chapter 5 is devoted to techniques used to characterize the electrical and optical properties of SiC. Detection of various defects in SiC and the nature of these defects are also described.
Chapter 6 discusses device processing technologies, such as ion implantation, etching, MOS interface, and metallization. Both fundamental issues and practical considerations are given.
Chapter 7 describes the basic physics of power diodes, especially SBDs and pin diodes, and gives examples of SiC-based diodes and their performance.
Chapter 8 explains the structure, design, and performance of unipolar power switching devices, such as MOSFETs and JFETs. The oxide/SiC issues are also addressed.
Chapter 9 deals with bipolar power switching devices, such as BJTs, IGBTs, and thyristors.
Chapter 10 describes basic issues in the optimization of power devices, including design of blocking voltage, edge termination. A performance comparison of various Si, SiC, and GaN devices is also given.
Chapter 11 introduces applications of SiC devices in power systems. Basic circuits and operation of power conversion, motor drive, inverter, DC–DC converter, power supply are described.
Chapter 12 focuses on specialized SiC devices other than power devices. The devices include high-frequency devices, high-temperature devices, and sensors.

In a book this size it is difficult to completely cover the entire field of SiC materials and devices. The authors have tried to focus on the fundamental science and the state-of-the-art technology. For example, the description of solution growth of SiC boules, the heteroepitaxial growth of 3C-SiC, the theoretical study on defects in SiC, and latest device development is not very extensive. For additional detail, please see the related books [63–69], review papers, and conference proceedings.

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