PART I

INTRODUCTION

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CERAMIC INTEGRATION ACROSS LENGTH SCALES: TECHNICAL ISSUES, CHALLENGES, AND OPPORTUNITIES

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INTRODUCTION

The discovery of new and innovative materials has been known to culminate in major turning points in human history. The Bronze Age, the Iron Age, and, in our own times, the age of silicon are all considered as historical benchmarks that have transformed human civilization and have opened theretofore unforeseen possibilities for economic growth and societal impact. These progressive and defining periods in the history of humankind are marked not only by materials innovations (e.g., Damascus steel, used to make swords during 1100–1700 AD) but also, more importantly, by the transformation of new materials into goods usable for war, the arts, and commerce. The transformative impact and functional manifestation of new materials have been demonstrated in every historical era by their integration into new products, systems, assemblies, and devices.

Ceramic Integration and Joining Technologies: From Macro to Nanoscale, First Edition.
Edited by Mrityunjay Singh, Tatsuki Ohji, Rajiv Asthana, Sanjay Mathur.

INTEGRATION ISSUES IN ADVANCED TECHNOLOGY SYSTEMS

In modern times, the integration of new materials into usable products has a special relevance for the technological development and economic competitiveness of industrial societies. Current and evolving integration issues span such diverse areas as aeronautics, space, energy, nuclear power, thermoelectric (TE) power, nanoelectromechanical and microelectromechanical systems (MEMS), solid oxide fuel cells (SOFCs), multichip modules (MCMs), prosthetic devices, and many others.

MICROELECTRONICS AND NANOELECTRONICS

Integration is critically important in microelectronics at the wafer, chip, and package levels and is a means to achieving compact designs and cost reduction. Integration technology is used in the manufacture of MEMS, display devices, radio frequency (RF) components, and a number of other microelectronic components. In such applications, integration challenges are manifested in soldering, metallization, service reliability, joint degradation, vacuum seals, and other areas. Highly complex and sophisticated integration technologies are used in the construction of devices with semiconductor chips and in the development of methods to connect MEMS components.

MCMs integrate a number of unique functions into a system and consist of a group of advanced functional electronic devices that permit size reduction. MCMs combine integrated circuits (ICs) based on different materials and provide reliable low-cost integration technology to combine several ICs with a functional substrate. MCMs are designed based on thin-film multilayer structures on ceramic, silicon or metal that can offer the highest integration density per layer. They are usually built using joining and surface modification technology, such as sputtering and plating. The biggest advantage of joining is the ability to join any dissimilar materials if their surface mechanical properties, in terms of flatness, smoothness, and cleanliness, are sufficiently good.

Silicon carbide-based ceramics are increasingly being used in semiconductor switches for their lower losses and improved ability to operate at higher temperatures than silicon. Due to lower losses and higher operating temperature, a smaller heat sink can be used, thus saving on size and system cost. Integration issues in such applications center on joining SiC to other materials, such as metals. Additionally, future microprocessor technologies might increasingly utilize nanoporous organosilicate glass materials as dielectrics, and these can create integration challenges such as controlling the metal–nanoporous glass interface.

Many applications of semiconductor technology rely upon heterostructures in which the integration of dissimilar materials is realized through epitaxial growth. There is interest in creating heterostructures through joining of dissimilar materials, which permits modulation of the functional properties (e.g., electronic work functions) at the interfaces instead of through epitaxial growth. Joining can be used to create heterostructures comprising semiconductors, dielectrics, metals, or ceramics in combinations that would be difficult to achieve via epitaxial growth. In fact, wafer bonding is already being used to integrate dissimilar materials together as an alternative technique to heteroepitaxial growth. Bonding can also be used to create substrates that enable the growth of higher-quality heteroepitaxial films.

Nanotechnology has revolutionized device concepts by offering a range of functionalities available in the nanometer range. To achieve these functionalities, however, nanostructures need to be integrated in electronic, photonic, optoelectronic, and sensing systems and devices. Controlled synthesis and self-assembly of functionally and morphologically distinct nanostructures and their integration into manufacturable devices such as field-effect transistors (FETs) and gas sensors or biosensors demand new design paradigms to overcome such challenges as coupling different forces (e.g., mechanical–electrical), interfaces (e.g., metal–semiconductor), and interactions (e.g., biological–nonbiological components) in integrated systems. In addition, the novel functionalities in hybrid materials such as polymer–ceramic nanocomposites are also based on a molecular-level integration of nanoscopic ceramic particles in polymer matrices, which demands better understanding of interfacial phenomena and integration (synthetic) pathways.

ENERGY

Integration of advanced ceramics plays a critical role in all aspects of energy production, storage, distribution, conservation, and efficiency. Among the alternative energy systems, fuel cell technology is particularly important. Advanced ceramics (e.g., yttria-stabilized zirconia, lanthanum strontium manganese oxide, and Ni–YSZ cermet) play a key role in various components of SOFCs. Ceramic or metal interconnects and sealing components are needed for system integration.

TE devices with high energy-conversion efficiencies and with the capability for prolonged operation are needed for various applications. Electrical and thermal properties of novel electrode materials and interfaces, as well as joint durability, need to be evaluated and optimized. Thermal expansion mismatch coupled with high temperature at the hot shoe-leg joint makes a robust design and the development of integration technologies critical. At each interface in a TE device, the composition, operating temperatures, and thermal mismatch issues are different, and these could become particularly important in segmented legs with multiple interfaces. Integration issues are also important in micro-TE power generators based on ceramic catalyst combustors that employ integration of a thermopile of thin-film metals and thick-film ceramics on dielectric membranes. Another illustration of integration in the energy sector is the development of MEMS-based fuel injectors for use in gas turbine engines.

AERONAUTICS AND GROUND TRANSPORTATION

Many advanced ceramics and ceramic matrix composites (CMCs) have been developed for applications in thermal structures, exhaust nozzles, turbopump blades, combustor liners, radiant burners, heat exchangers, and a number of other applications that involve extremely harsh conditions. For example, carbon–carbon composites containing SiC

(C/C–SiC) show promise for lightweight automotive and aerospace applications. In the automotive industry, C/C–SiC brake disks are already being used in some car models in Europe. Carbon–silicon carbide (C/SiC) composites are being developed for hypersonic thermal structures and advanced propulsion components. Similarly, SiC/SiC composites are being developed for applications in combustor liners, exhaust nozzles, reentry thermal protection systems, hot gas filters, and high-pressure heat exchangers, as well as components for nuclear reactors. Integration issues are important when developing components based on such materials. Mechanical joining and attachment technologies, brazing, and diffusion bonding have emerged as key technologies for integrating CMCs for a number of such applications.

INTEGRATION ACROSS DOMAINS AND LENGTH SCALES

Next, we present a brief overview of key issues in ceramic integration science and technology across length scales and technical fields to set the stage for more focused discussions in subsequent chapters. We summarize the main points of each chapter as presented by their authors to give the reader a bird's-eye view before reading the chapters.

SCIENCE AND TECHNOLOGY FOR MACROSCALE INTEGRATION

In Chapter 2, Janczak-Rusch presents the state of the art of the brazing of ceramics and their composites. The chapter focuses on methods to overcome poor wettability, relieve stresses, and improve joint reliability by designing and developing brazing filler alloys with tailored properties. The author discusses a number of interesting systems: Si_3N_4–TiN, mullite–mullite, and SiC fiber-reinforced glass. An approach for holistic joint investigation is recommended that combines experimental testing, fractography, and microstructural study with numerical simulation to understand and optimize joint behavior and performance.

Carbon–carbon composites have found use in a number of demanding applications, such as in the nose cones of rockets and missiles and in aircraft brakes. One emerging application of C/C is in components used in nuclear reactors. For example, C/C is used as a plasma-facing material because it can mitigate heat flux owing to its plasma tolerance. Even under off-normal plasma events, vapor shielding can protect C/C from erosion at high power fluxes. Owing to the absence of melting and to their excellent resistance to thermal shock and thermal fatigue, C/C targets have demonstrated proven compatibility with plasma conditions, particularly at low densities. These materials perform well under pulsed high heat fluxes and have a low neutron absorption cross-section. Besides, they retain mechanical strength at elevated temperatures and have a low atomic number, which induces low power losses in the plasma. Integration issues for these materials are important both for the next generation of thermonuclear fusion reactors and for fission-reactor components. In both cases, extreme thermomechanical stresses on the joined component must be taken into account, together with material modification related to the presence of neutrons. Joining and integration issues of C/C and CMCs for the nuclear industry, with a focus on brazing technology, are reviewed by Ferraris et al. in Chapter 3. C/C joining is revisited in a later chapter for thermal management applications.

Brazing is a low-cost and industrially proven technology to reliably integrate ceramics in components. Brazing of ceramics demands use of ultrapure atmospheres or cover fluxes in order to suppress the adhesion-limiting effects of atmospheric contaminants. This usually adds to the processing cost and slows production. In Chapter 4, Weil et al. describe an air brazing method that has emerged for joining ceramics. The method was originally developed by the authors to produce oxidation-resistant hermetic joints for use in SOFCs and in oxygen and hydrogen concentrators. The key to developing a successful filler metal composition for air brazing is to identify a metal oxide wetting agent that is mutually soluble in a molten noble metal solvent. For example, near-eutectic Ag–CuO filler metal compositions are promising in joining ceramics such as YSZ, ferrites, alumina, and magnesia. Ternary additions can further improve the filler wettability, raise the use temperature, and increase the joint strength. The authors discuss process mechanisms, braze metallurgy, and performance of air brazed joints in a number of systems.

Among advanced ceramics, silicon carbide is particularly interesting owing to its potential for use in high-temperature, structural applications. It has high strength, creep resistance, corrosion resistance, and high-temperature capability. However, limitations that are in part geometry inherent in hot pressing and chemical vapor deposition (CVD), as well as difficulty in machining have restricted the wider use of SiC. One cost-effective solution for fabricating complex-shaped SiC components is through the joining of simple-shaped ceramics. In Chapter 5, Halbig and Singh discuss joining of SiC for a lean direct ceramic injector proposed for use in jet engines by NASA. Techniques for bonding the SiC laminates of the injector to one another and to Kovar tubes are enabling technologies for developing such injectors. For bonding SiC laminates, diffusion bonding has been proposed; for attaching Kovar tubes, brazing has been proposed. The authors describe the technical challenges to be overcome in diffusion bonding and brazing, such as nonuniformity of bond formation, chemical incompatibility, and residual stresses. In an earlier development, silicate glass was used as the bonding layer between the SiC laminates. However, difficulty in achieving a uniform glass layer, with the resulting lack of hermeticity, prompted diffusion bonding using titanium foils and physical vapor deposited (PVD) Ti coatings. Process optimization was conducted to obtain diffusion bonds that were uniform, chemically stable, and crack free. The authors present the outcomes of studies on microstructure, phase analysis, nondestructive evaluation, and tensile pull tests.

Advanced C/C composites composed of carbon fiber-reinforced carbon matrix are fabricated using either resin infiltration and pyrolysis or chemical vapor infiltration (CVI) approaches. A wide variety of C/C composites have been developed using different types of carbon fibers, fiber weave patterns, fiber coatings, carbon matrices, and fabrication technologies. The fibers make the composite stronger, tougher, and thermal shock resistant and make it highly conductive when high-conductivity C fibers with the basal planes of carbon oriented parallel to the fiber axis are used. These high-conductivity fibers can rapidly spread heat in the direction of the fiber. For integration in components, C/C needs to be joined to other materials. Joining and integration of C/C composite to metals, especially for thermal management applications, is reviewed in Chapter 6 by Singh and Asthana. In particular, they present research in vacuum brazing of C/C composites to titanium and copper-clad molybdenum for thermal management. Technical issues such as wettability and thermomechanical compatibility of joined materials are addressed, and the role of joining atmosphere, filler chemistry, surface roughness, and residual stresses is discussed together with joint microstructure, mechanical properties, and broader joint design issues.

A fundamental requirement for brazing of ceramics using liquid filler is the wettability of solids by liquids. For example, integration of ceramics to metals by brazing requires that molten braze spread on and cover the surfaces to be bonded. Thus, braze composition and joining conditions are designed to facilitate spreading, often with the aid of chemically active additives that favorably modify the surfaces to be bonded. Study of brazing thus represents a confluence of classical surface science, adhesion phenomena, high-temperature chemistry, phase equilibria, and metallurgy, among other disciplines. In Chapter 7, Pervertailo and Loginova examine physicochemical regularities of wetting and contact phenomena in carbon–metal systems under vacuum as well as under high pressure. Such phenomena include, among others, dissolution, adsorption, and reaction, all of which are critical for braze performance.

For example, the authors show that "nonreactive" Ni–C melts contain clusters of weakly deformed tetrahedra and octahedra of Ni atoms, elongated carbon chains, and closed carbon fragments. Carbon chains penetrate the nickel matrix and uniformly distribute throughout the melt. The atomic spacing in chains is similar to that in planar graphite networks, meaning that covalent bonds between carbon atoms in molten Ni are partially retained. As the melt composition approaches the eutectic, the size and number of clusters of weakly deformed tetrahedra and octahedra are increased. These clusters serve as precursors to the adsorbed species and thus influence the wetting behavior in nonreactive high-temperature systems.

INTEGRATION ISSUES IN ENERGY GENERATION AND DEVICE FABRICATION

The next nine chapters focus on integration issues in energy generation and device fabrication.

For several decades, there has been a push toward miniaturization of microelectronic components. However, such miniaturization has been less successful with inductive components. In Chapter 8, Matz reviews the progress made in the design, fabrication, and performance of magnetically coupled inductors using NiZnCu and MnZn ferrite multilayers. In particular, he focuses on low-temperature cofiring technology used to produce mixed dielectric–ferrite multilayered inductors. Magnetic losses are lower in magnetic ceramics than in amorphous magnetic metals, and this has promoted the use of ferrite and dielectric ceramics in multilayer boards. Low-temperature cofiring of dielectric and ferrite ceramic layers in multilayer boards is desirable because magnetic flux leakage is high and electric insulation is low between the turns of a coil when the turns are immediately surrounded by ferrite. Currently, there is strong interest in cofired ceramics, and the push is to reduce inductor line and space widths to low values ($<100\,\mu$m) by printing methods. However, the challenge to fabricating a ferrite core around a dielectric board lies in both the technology and the thermal expansion mismatch of the materials. Magnetic permeability is sensitive to the mechanical stress that occurs in multilayer structures due to expansion mismatch. This has inhibited the development of a useful cofiring technology for dielectric and ferrite tapes, even though the ferrites are amenable to low-temperature sintering. Matz's results support the conclusion that integrated ceramic transformers with mixed dielectric–ferrite multilayers will be feasible once a few steps in design and technology development have been perfected and the challenges related to cost-efficient sintering and shaping, in combination with low-dielectric multilayer boards, have been overcome.

TE power generated from vast amounts of waste heat emitted by automobiles and factories promises to revolutionize the energy landscape. TE materials such as oxide compounds can convert waste heat into electrical energy without using moving parts such as turbines and without producing carbon dioxide gas, radioactive substances, or other regulated emissions. To achieve realistic TE power generation, a high TE figure of merit and chemical stability are required. In Chapter 9, Funahashi et al. discuss the TE properties at high temperature of a number of oxide compounds mainly based on Co with layered structure, such as Co-349 and BC-222. The temperature dependencies of electrical resistivity, Seebeck coefficient, thermal conductivity, thermal expansion, three-point bend strength, and fracture toughness are presented together with X-ray phase analysis and scanning electron micrographs (SEMs) of microstructures. The authors conclude that even though the layered oxides Co-349 and BC-222 have good TE conversion efficiency, it is currently insufficient for widespread application. New materials possessing higher figures of merit even at low temperatures are necessary, and the authors make suggestions about possible materials and approaches to designing and synthesizing such materials.

SOFC reactors based on ceramics have high efficiency and have the ability to operate in the intermediate temperature range. Power densities in excess of 2 kW/L are possible in auxiliary power units and small generators by improving materials, accumulating small parts, and assembly into high-performance modules. In Chapter 10, Fujishiro et al. discuss integration technologies for SOFCs and other electrochemical reactors, particularly tubular SOFCs with submillimeter diameters when they are accumulated into cubes. The authors show that hundreds of submillimeter SOFC tubes can be precisely mounted in porous electrodes in small volumes of one cubic centimeter. The authors fabricated and tested such microtubular SOFCs and demonstrated their excellent power densities of 1–3 W/cm^3. The authors show how novel ceramic fabrication processes can integrate SOFCs into prototype modules of microhoneycomb cell stacks with a cell integration density of 250 multilayered tubes per cubic centimeter in porous electrode cubes. The authors also discuss a new concept of a nanoscale electrocatalytic reactor for NOx decomposition based on NiO and YSZ. Electrochemically formed nanograins of Ni surrounded by nanopores, in a NiO/YSZ interface of the electrode, can lead to a remarkable improvement in efficiency.

In chemical microsystems including sensors, functional materials such as oxides need to be integrated into the silicon technology. However, functional materials cannot always be obtained by the standard *complementary metal oxide semiconductor* (CMOS) technology; for such cases, transducer materials are obtained separately and are implanted onto microsystems. Recent research has focused on chemical routes,such as precipitation methods, to produce high-quality powders, as opposed to thin films that require the use of vacuum systems. In Chapter 11, Shin et al. present their research on the synthesis of platinum–alumina catalyst pastes from powders and how these pastes are utilized in microsensors and other devices. Sensors were also fabricated by dispensing the pre-treated ceramic materials onto the microdevice using microprinting technology. The deposition of functional films, either by screen printing or by the more sophisticated drop-deposition techniques, such as ink-jet systems, was performed after combining the functional material with organic carriers. The authors demonstrate that such a dispensing technique can be successfully employed for the preparation of a ceramic catalyst combustor with nanoparticles for gas-sensing applications.

Optoelectronic devices, such as photodiodes, solar cells, light-emitting diodes (LEDs), and laser diodes, are fundamental to a wide variety of high-technology systems. Generally, optoelectronic devices are composed of discrete elements that perform different functions; these elements interface with one another via fiber connections. Unfortunately, lack of efficient coupling often results in optical losses and high costs. Integration of monolithic components can eliminate problems inherent in device coupling, such as mechanical movement, thus reducing the packaging cost and size. Effective integration demands that each component should function as if it were discrete. Incorporation of nanomaterials into nanophotonic and optoelectronic devices permits this to be achieved, and it increases the range of functionalities for applications such as light generation, displays, modulation, sensing, imaging, and communications. Innovative nanodevices have been developed using combinations of nanostructures that can be embedded in hybrid architectures for "on-chip" integration of components. Such devices require integration of functional materials and components using methods developed for chip-scale integration at the range of micrometers to nanometers, including monolithic integration, hybrid integration, layer-by-layer assembly, and directed assemblies. In Chapter 12, Erdem and Demir describe the state-of-the-art and innovative integration approaches that are being perfected for cutting-edge optoelectronics and nanophotonics.

Extension of lifetime under severe operating conditions is fundamentally important for gas turbines to achieve high efficiencies and low energy consumption. The current operating temperatures of 1500°C have been achieved mainly from development of air cooling and thermal barrier coating (TBC) technologies. TBCs of YSZ together with bond coats of MCrAlY (where M is Ni, Co, etc.) are the most common coating material for turbine blades. However, significant thermal stress during prolonged severe heat cycles causes cracking and fatal delamination. The coatings are deposited using plasma spray, electron-beam PVD, or CVD. Conventional CVD combined with laser heating can accelerate chemical reactions to deposit films. In Chapter 13, Goto describes work on integrating laser technology and conventional CVD to achieve dramatic acceleration of coating deposition on turbine blades.

Metal interconnects are essential for microelectronic device integration. Early ICs frequently failed at interconnections, chiefly by electromigration. The electron wind force and the triple points in the grain structures of interconnections were discovered to lead to such failure. However, with progression toward very large scale integration (VLSI), the scaling laws for interconnect failure subsumed additional factors such as multiple driving forces, multiple diffusion paths, and stress-induced migration. It is noteworthy that, with new failure mechanisms coming into play, the underlying physics changes, and the corresponding stochastic processes, such as the statistical distribution of failure time, are also modulated. In Chapter 14, Tan and Hou present experiments and models to describe how the changing physics of electromigration and stress migration affect the failure probability of interconnections in microelectronic circuits.

Miniaturization of microelectronic components continues to be a major driving force for innovation in industry. Miniaturization of microwave systems relies on thin-film ferroelectrics because of their ability to produce tunable RF and microwave circuits with a broad range of tunability. This enables the designer to meet the stringent frequency and power requirements of wireless communications systems. Tunable circuits can compensate for the effects of aging and temperature excursions in RF circuits. The ferroelectric material barium strontium titanate (BST) exhibits an electric field-dependent dielectric constant. This allows capacitors with BST as the dielectric to have adjustable capacitances. BST is tunable and has high dielectric constant, high power handling capability, and ease of integration with other thin-film devices. In Chapter 15, Kumar et al. present a critical review of BST's material properties and address issues relevant to its integration, such as interdiffusion in the substrate layers and formation of voids and hillocks. Platinum is the preferred electrode material for BST because it is nonreactive to BST and forms an interface possessing favorable electrical properties. Integrating Pt, however, is challenging because of poor adhesion, difficulty in dry etching, and diffusion in the BST–Pt layers. The authors' research suggests that thin films of nanocrystalline diamond can be used as an efficient diffusion barrier layer between BST and Pt.

Ceramic films and coatings for advanced applications can be deposited using a number of techniques, including the newly developed aerosol deposition (AD) method in which submicrometer oxide and nonoxide ceramic particles are accelerated by gas flow up to 100–500 m/s followed by impact on a substrate. A thick, dense, uniform, and hard ceramic coating can form at room temperature without additional energy consumption for melting of ceramic powders as is required in thermal spray processes. The process is simple, energy-effective, and relatively inexpensive, and it can be done under low vacuum. AD can reduce the fabrication steps in the manufacture of electronic devices such as MEMS, RF components, and optoelectronic devices. It is particularly useful for integrating "on-demand" microscale parts. In Chapter 16, Akedo presents the mechanisms and features of AD and its applications to a number of devices.

INTEGRATION ISSUES AT THE NANOSCALE AND IN BIOLOGICAL SYSTEMS

The last group of eight chapters deals with integration issues at nanoscale and in biological systems and devices.

In Chapter 17, Masuda and Koumoto discuss nanointegration and liquid-phase patterning of ceramic thin films and particle assemblies. Micropatterning is attractive for photonic crystals, solar cells, and molecular sensors, among others. The authors describe the procedures used to fabricate nanopatterns and micropatterns of ceramic thin films such as TiO_2, Fe_3O_4, and ZnO, and colloidal crystals using environment-friendly solution chemistry approaches. They show that micropatterns of randomly deposited nanoparticles can be created using capillary, gravitational, and electrostatic forces. In fact, many kinds of patterning techniques have been developed to prepare patterns of thin films, for example, photolithography, microcontact printing, wet etching, and ink-jet printing. However, etching or "liftoff" is required in many such methods, which impairs the performance and increases waste and energy consumption. The deposition of thin films only on desired areas of a substrate is thus required for the pattering of ceramic thin films, and solution synthesis approaches enable this to be readily accomplished.

In the first decade of the twenty-first century, controlled manipulation of nanomaterials progressed to the point where construction and characterization of proof-of-concept nanodevices became feasible. 1-D nanostructures such as nanowires and nanotubes came to be used as building blocks in prototype components such as interconnects, gas sensors, biosensors, photodetectors, lithium-ion batteries, and TE generators. The next key challenge is the scale-up to the production of large-scale components that integrate functional nanostructures in devices. In Chapter 18, Mathur and coworkers review the progress in controlled growth of 1-D nanostructures, structure–property relationships, fabrication of nanowire-based FET, and higher-level integration of nanowires into complex nanodevice architectures. They present both conceptual and prototypical progress in harvesting nanomaterials for use in devices. The authors discuss technical challenges to scale-up, including fabricating better electrical contacts with nanowires, developing and interfacing low-cost nanowire-based electronic components, and meeting the industrial standards for precision and reliability. The authors also make recommendations to solve such challenges and point out the importance of reliability issues that accompany the integration of nanostructures into a conventional device and the necessity of systematic investigations in this regard.

Diamond-like carbon (DLC) has a number of attractive properties, such as high Young's modulus, high hardness, chemical inertness, and hydrophobicity. DLC films are proposed to be used to build microscale and nanoscale architectures possessing resistance to degradation in humid and harsh environments. In Chapter 19, Li and Chua highlight the potential of DLC films versus Si-based materials in nanostructure design. They discuss the synthesis and physical properties of DLC, its potential for use in micromechanical and nanomechanical devices, and fabrication technology such as focused ion beam (FIB) and FIB-assisted CVD to design and build DLC architectures. The authors also highlight the technical challenges in DLC film design and fabrication, such as film etching and the optimization of nanoarchitecture design. Owing to their biocompatibility, nanostructured DLC films can be used in biosensors and nanofluidic systems for single-molecular sensing and detection. The authors suggest that combining bottom-up and top-down approaches will enable sophisticated nanoarchitectures with enhanced performance to be created for DLC-based devices. The theme of nanointegration based on thin-film growth is further discussed in a later chapter by Jin et al.

In special cases, high-performance nanoscale devices demand highly oriented and ordered arrays of nanostructures to be created in order for their anisotropic properties to be profitably harvested or for the areal density of discrete elements (e.g., transistors) of the device to be increased. Highly oriented, 1-D nanowire structures permit enhanced areal density to be achieved, together with electrical and optical properties that can be tailored. Thus, low-dimensional nanowire structures serve as an ideal platform to probe properties that may be inaccessible in large devices. In Chapter 20, Pliszka et al. present synthesis, properties, and applications of vertically aligned ceramic nanowires made from oxides, carbides, and nitrides.

In Chapter 21, Jin et al. discuss advances in nanointegration based on thin-film growth with 2-D and 3-D ordered nanostructures of nanoparticles and nanowires. Ordered nanostructures in thin films can form either spontaneously (e.g., by long-range elastic interactions) or by nucleation and growth on prepatterned templates. The authors discuss both approaches: strain-induced self-organization to develop ordered surface nanostructures, such as ripples and islands, and ordered nanowires on prepatterned surfaces that could yield defect-free nanostructures for use in optoelectronic devices such as nanowire-based FETs. Such applications demand integration of functional nanostructures into progressively larger assemblies that are needed in practical devices. Currently, nanointegration can be done using lithography, nanoimprint lithography, and thin-film growth. The authors focus on nanointegration based on thin-film technology, which is readily adaptable to industrial practices because it is widely used in the semiconductor industry. It is conceivable that thin-film-based nanointegration will play a key role in developing next-generation nanostructured devices for optoelectronic and biomedical applications.

Scaling of electronic device density using bottom-up approaches offers the potential for low-cost, high-density integration of nanoscale devices. Using such approaches, functional nanostructures can be assembled from chemically synthesized nanoscale building blocks in a manner similar to the complex architecture of biological systems such as proteins and biomolecules. Considerable progress has been achieved in synthesizing 1-D nanowires with controlled composition, structure, size, morphology, and electrical and optical properties. A high surface-to-volume ratio, the benefits of quantum confinement, and low-cost synthesis are the major drivers for developing prototypes of functional nanowire devices such as p–n junction diodes, lasers, and photovoltaics. Successful integration of nanowires requires reproducible interfaces, interconnections, and the transfer of nanowires from the mother substrate to the device platform, which remain as major challenges in the large-scale production of nanodevices. In Chapter 22, Sarkar and Islam review the common approaches to controllably aligning and interfacing nanowires with bulk photonic devices and circuits, and they address the challenges and issues in obtaining mass manufacture and reproducible integration of nanowires. The authors propose that formation of "nanobridges" and "nanocolonnades" can create robust contacts to nanowires with low contact resistance on production scales.

Printable electronics extensively utilize nanotechnology to expedite manufacture and to save energy in producing microelectronic interconnects. In particular, piezo printhead-type ink-jet printing technology offers substantial manufacturing advantages in providing promising products for tomorrow, namely, flexibility of produced components, less waste material in manufacturing, environmentally friendly production, and lower-cost products. In Chapter 23, Caglar et al. discuss issues concerned with demonstrating the integration of nanomaterials-assisted ink-jet printing in electronic manufacturing for mass production. Process challenges in designing and patterning printable structures, printing process optimization, and sintering or curing of conductive or dielectric nanomaterials using laser sintering, a process that is faster than conventional furnace sintering, have been discussed. Ink-jet printing technology offers additive on-demand material deposition on substrates. It is possible to print very precise structures without the need for a mask-and-etching process. Line/space widths of $50\,\mu m/50\,\mu m$ are possible and further reductions are feasible. The process minimizes wasted material and, therefore, manufacturing cost and is suitable for integration into a product development value chain.

Perhaps nowhere is the power of integration revealed as remarkably as in the biointegration of prosthetic devices, in which an inorganic substance (ceramic) is integrated with an organic, living tissue. The bonding between living tissue and implanted devices is usually aided by bioceramic coatings. Since the 1970s, biocompatible ceramics have played an increasingly important role in repairing living tissues and organs and in promoting the regeneration of cells. In the last chapter of the volume, Kawashita et al. introduce ceramics for a number of biological applications, including bone repair and artificial joints, and discuss bioactive ceramics, bioceramic–polymer composites, bioactive cements, and bioactive inorganic–organic hybrids. They also discuss the requirements for artificial materials to form apatite—a major bone ingredient—and the role of functional groups that promote apatite nucleation in the joint. In many such applications, long-term stability of biointegrated prosthetic devices and sensors is needed. Conversely, detachability of biomodules for flexibility in repair or to accommodate add-on features could also be a consideration. Thus, integration issues could center on somewhat conflicting requirements. Other developments include bio-MEMS devices such as the lab-on-a-chip (LOC) module that can consolidate all the complicated laboratory procedures onto a single chip for specific biomedical applications, and ink-jet bioprinting technology for manufacturing 2-D and 3-D patterns of immobilized hormones to direct cell behavior. Integration of complex designs at the micrometer and nanometer scales is the basis of these emerging technologies.

The collective state-of-the-art knowledge about integration gathered from diverse fields and presented in these 24 chapters represents the diversity and unity of integration science and technology. Emerging applications of new materials with engineering performance far superior to the current generation of materials will require new developments in integration technology to manufacture devices, components, assemblies, and systems based on materials and structural features at multiple-length scales. The following chapters develop these themes for a variety of advanced and emerging materials.