The creation of affordable high speed optical communications using standard semiconductor manufacturing technology is a principal aim of silicon photonics research. This would involve replacing copper connections with optical fibres or waveguides, and electrons with photons. With applications such as telecommunications and information processing, light detection, spectroscopy, holography and robotics, silicon photonics has the potential to revolutionise electronic-only systems.

Providing an overview of the physics, technology and device operation of photonic devices using exclusively silicon and related alloys, the book includes:

- Basic Properties of Silicon
- Quantum Wells, Wires, Dots and Superlattices
- Absorption Processes in Semiconductors
- Light Emitters in Silicon
- Photodetectors, Photodiodes and Phototransistors
- Raman Lasers including Raman Scattering
- Guided Lightwaves
- Planar Waveguide Devices
- Fabrication Techniques and Material Systems

Silicon Photonics: Fundamentals and Devices outlines the basic principles of operation of devices, the structures of the devices, and offers an insight into state-of-the-art and future developments.
Silicon Photonics
Dedication

PKB
To Chitrani (wife), Rikmantra (son), and Kaberi (sister)

MJD
To Meena (wife), and Arif, Imran, and Tariq (sons)
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Series Preface

Wiley Series in Materials for Electronic and Optoelectronic Applications

This book series is devoted to the rapidly developing class of materials used for electronic and optoelectronic applications. It is designed to provide much-needed information on the fundamental scientific principles of these materials, together with how these are employed in technological applications. The books are aimed at (postgraduate) students, researchers and technologists, engaged in research, development and the study of materials in electronics and photonics, and industrial scientists developing new materials, devices and circuits for the electronic, optoelectronic and communications industries.

The development of new electronic and optoelectronic materials depends not only on materials engineering at a practical level, but also on a clear understanding of the properties of materials, and the fundamental science behind these properties. It is the properties of a material that eventually determine its usefulness in an application. The series therefore also includes such titles as electrical conduction in solids, optical properties, thermal properties and so on, all with applications and examples of materials in electronics and optoelectronics. The characterization of materials is also covered within the series in as much as it is impossible to develop new materials without the proper characterization of their structure and properties. Structure–property relationships have always been fundamentally and intrinsically important to materials science and engineering.

Materials science is well known for being one of the most interdisciplinary sciences. It is the interdisciplinary aspect of materials science that has led to many exciting discoveries, new materials and new applications. It is not unusual to find scientists with a chemical engineering background working on materials projects with applications in electronics. In selecting titles for the series, we have tried to maintain the interdisciplinary aspect of the field, and hence its excitement to researchers in this field.

Arthur Willoughby
Peter Capper
Safa Kasap
Preface

Semiconductor research made a giant leap forward with the invention of the transistor in 1947. Since then, a great many researchers engaged in the study of fundamental physical processes of semiconductors: mostly silicon (Si) or germanium (Ge), their growth technology, and device fabrication methods. Initially the emphasis was on the study of electronic processes with a view to optimizing the device’s performance. Some efforts were made to study optical processes in semiconductors, primarily to understand the band structure of the materials. The idea to use semiconductors and their junctions for optoelectronic systems applications was not well defined in the early stages of the development of semiconductor technology.

The next decade (i.e., the 1950s) saw the emergence of Si as the leading electronic material. In fact, silicon is the material par excellence. The decade starting from 1960 marked the dominance of Si in electronics, thanks to the development of planar technology, and, later on, integrated circuits. This dominance of Si is still in force today; almost more than 95% of all electronic circuits are now grown on a Si platform. This dominance is expected to continue following the trend over the last few decades where the number of transistors in a chip doubles about every 18 months and the size of the individual transistors is shrinking at the same pace. The length of the channel in a field effect transistor has shrunk to a few tens of nanometers, and the downsizing is expected to continue in the near foreseeable future.

Coming back to photonics, the subject of semiconductor optoelectronics owes its origin to the announcement of semiconductor lasers almost simultaneously by four groups in 1962. The proposal to use optical fiber as a communication medium came in 1966. The semiconductor laser was soon vastly improved by using heterojunctions grown by liquid phase epitaxy (LPE), molecular beam epitaxy (MBE), or metal–organic vapor phase epitaxy (MOVPE). These developments led to remarkable progress in the area of optoelectronics or photonics, in which optical communications, among many other applications, form an ever-growing industry.

Unfortunately, silicon, the most widely used material in electronics, does not find the same niche in optoelectronics. The indirect nature of its band gap prevents the realization of efficient light-emitting diodes (LEDs) or laser diodes; the absence of linear electro-optic effect stands in the way of achieving high-speed modulators using Si-based materials; and, in addition, the band gap of Si does not match the standard wavelengths of 1.3 μm or 1.55 μm in present fiber-optic telecommunications systems. If, however, the problems could be solved, the integration of electronic and photonic devices on Si platform will be possible with all the benefits of Si technology that include low cost, high packing density, compact size, and high reliability. This dream had been cherished by many people over the last four decades, with little relative successes compared to silicon electronics.
Currently, there is one niche area in optoelectronics in which Si finds its place. This is the planar lightwave circuits (PLCs) used in optical fiber communications. These include primitive devices like planar waveguides with silica-on-Si (SOS), silicon-on-insulator (SOI), directional couplers, Y-junctions, as well as more complex passive circuits like arrayed waveguide gratings, add-drop multiplexers and hybrid lightwave circuits embodying light sources, light detectors, multiplexers and demultiplexers, and various other components. These circuits rely on standard microelectronics technology and are therefore cheap and reliable. The Si-based PLC came into usage during the mid-1980s.

Yet, the main challenge to realize sources and modulators could not be overcome. The motivation for Si photonics came from the IC industry itself in the form of interconnect bottleneck. Electrical connectors in integrated circuits introduce larger time delays than the gate delay, and multilayered interconnections need insulators in between. Optical interconnects can solve both these problems.

There appeared several novel concepts and demonstrations of light emission from Si which include porous Si, Si nanocrystals, and erbium-doped Si. But the true solution is yet to be found. However, in view of the importance of the issue, almost all important players in the integrated circuits manufacturing business have started extensive research in silicon or group IV photonics. Governments of countries with major research investments such as the United States, Canada, Japan, countries of the European Union, China, India, and Brazil are providing substantial funds to find useful solutions. And the Institute of Electrical and Electronic Engineers (IEEE) is now holding an annual conference titled “Group IV Photonics.”

A number of review articles and at least two books on this subject have appeared. One book on silicon photonics by Reed and Knights is the first textbook in the subject. It emphasizes the waveguiding and modulation properties of Si-based structures, and briefly discusses their light emission properties. The volume on silicon photonics edited by Pavesi and Lockwood is a compilation of articles written by experts, and the chapters are excellent source of references for both new and experienced researchers in the field.

The need for a textbook dealing first with the fundamental aspects of silicon and then covering the application areas was articulated by the present authors as early as 2001, when Professor Basu made his first visit to McMaster University at the invitation of Professor Deen. Initially, the composition of the book was not clearly defined because, in some areas, there were very few published reports, for example on sources and modulators, and their performance was far below that of III–V semiconductor counterparts. The contents evolved to become better defined during Professor Basu’s subsequent visits to McMaster University and in close collaborations with Professor Deen. It was decided then to cover the basic optoelectronic processes in bulk and quantum nanostructures, sources, detectors, modulators, wave propagation in guided structures, and components for dense wavelength division multiplexing (DWDM) optical communications systems. And a chapter on growth and fabrication was also planned. The present text covers all these topics.

This book is an outcome of nearly a decade’s efforts by the authors. Care has been exercised to include the latest developments in the field as much as possible. However, since the field is growing and evolving at a rapid pace, it has not been possible to do justice to all the recent developments. The book is primarily a text with the targeted audience of senior undergraduates, graduate students, practicing engineers and technologists, and beginners in
the field, for whom introduction to basic principles and overall development in the field are more important. Interested readers may find a vast amount of contemporary literature once they get acquainted with the subject to help develop their understanding of the subject a number of examples within each chapter and also problems at the end of each chapter have been included.

Most of the chapters of the book were written during the periods when Professor Basu (PKB) visited McMaster University and in collaboration with Professor Deen. Professor Basu acknowledges the support, hospitality, and very congenial academic and non-academic atmosphere created by Professor Deen and his team, Dr. Ognian Marinov, Dr. Nikhil R. Das, and Mrs. Saswati Das, during his stay in Hamilton. In addition, PKB’s students and colleagues, Dr. (Mrs.) Sumitra Ghosh, Dr. (Mrs.) Bratati Mukhopadhyay, Dr. (Mrs.) Gopa Sen, and Dr. Abhijit Biswas, merit special mention for their help in drawing figures, making available a number of papers, and providing useful collaboration. PKB also acknowledges partial financial support from the Department of Science and Technology, Government of India, through project No. SR/S2/CMP-34/2006, as well as from the University Grants Commission through the UGC–Basic Scientific Research Faculty Fellowship Programme. Finally, he records his indebtedness to his late father Jitendranath, late mother Amita, wife Chitrani, son Rikmantra, and sister Kaberi for their encouragement and for giving him complete freedom to pursue academic work without caring for household duties.

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MJD
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1

Introduction to Silicon Photonics

1.1 Introduction

Silicon is the material par excellence. It is the most widely studied material in the history of civilization. In fact, the present-day information age has dawned with an electronics revolution brought about by the maturity of silicon-based microelectronics.

The growth of the silicon industry follows the now-famous Moore’s law, which states that the number of transistors in an integrated circuit chip doubles every 12 months (since revised to every 18 months). However, during the last few years there has been indication of the decline of Moore’s law. There are doubts whether in future silicon-based integrated circuits (ICs) will deliver the same advantages and functionalities as shown today.

The weakest point of silicon is that proper light emitters and modulators cannot be realized by using it due to the indirect nature of its band gap. On the other hand, there is a steady increase in the area of photonics, in the form of optical communication and networking, optical information processing, and consumer electronics based on light. Present-day photonics relies on compound semiconductors and their alloys. Although discrete devices using these materials show very good performance, when it comes to integration of these devices, preferably on the same substrate, the levels of integration and performance are far below what has already been achieved in electronic integration. It is natural to expect that monolithic optoelectronic integrated circuits (OEICs) will provide the same advantages, that is, low cost due to batch fabrication, high functionality, scaling for denser integration, and so on, as provided by silicon ICs.

If, however, it is possible to grow OEICs on silicon and integrate with electronic ICs by using the same production facilities, the benefits to be accrued need no further elaboration. Si-based systems will then be used in all fields of electronics, computers, and communication. This is the dream cherished by many workers over the last few decades, though that dream is yet to materialize. In spite of this, Si-based photonics remained an active area of research and over the last 10–15 years some significant milestones have been achieved.
Another important area of application of silicon photonics is in the very large-scale integrated (VLSI) circuit itself. The complexity of present-day ICs has reached such a high level that the interconnects within it are formed on a number of levels. At present the number is six, but within a few years it will be doubled. The metallic interconnects, mainly Cu, provide delay due to resistor–capacitor (RC) time constants, which far exceed the transit time delay associated with the individual transistors. If the increase in speed is to be maintained at the same rate for the next-generation ICs, the interconnect bottleneck must be properly addressed. Optics is believed to be the right solution to the problem.

In the present chapter, we shall give an overview of the developments in silicon electronics, the present status, and the problems faced to achieve the goals discussed in this section. We first give a very short history of the development of silicon-based microelectronics, the present status, and the international roadmap for future development. The two most important areas in which presence of silicon is needed, that is, communication and interconnect in chips, will then be described, giving the reader an idea of the present scenario and the problems faced. In this connection, the alternative to monolithic integration, that is, the hybrid integration technology, followed at present and the related problems will be pointed out. Finally, the scope of the present book will be outlined.

A number of text, research monographs, and reviews have already appeared dealing with silicon photonics. The reader is referred to such sources, all of which contain a large number of useful references [1–13].

1.2 VLSI: Past, Present, and Future Roadmap

The announcement of the first point contact transistor on December 23, 1947, marks the birth of the electronics era. Although the material used in this device and its improved version, the junction transistor, was Ge, it was soon felt that single-crystal silicon would be a better alternative. The first silicon bipolar transistor came in 1954. The concept of the IC was first explored in 1958, and its working was demonstrated by using discrete components. A few months later, an IC using planar technology was developed. The bipolar transistor technology was developed earlier and was applied to the first IC memory in the 1960s. Although bipolar transistors are the fastest at the individual circuit level, their large power dissipation and very low integration level (≈10^4 circuits per chip), compared to today’s VLSI standard, do not promote their use.

The control of conductivity in the surface of a semiconductor by an external electric field was proposed in the early 1930s. Attempts for conductivity modulation during the early part of the 1950s were not very successful. The first metal oxide semiconductor field effect transistor (MOSFET) using SiO_2 as the gate insulator on silicon substrate was fabricated in the 1960s. The complementary MOS (CMOS) transistor was fabricated in 1963, and its advantage of lower power consumption was firmly established. The one-transistor dynamic random-access memory (DRAM) cell was announced in 1968, and the first microprocessor was marketed in 1971 [14].

The advantages of silicon as an electronic material are too many to recount here. Silicon is available in nature abundantly. It can be purified to a very high level. Native oxide silica is a very good insulator, is stable, and can withstand a large field across it; and above all, the interface charge between silica and silicon can be reduced to a minimal level. SiO_2 can be easily patterned by photolithography [15].
Although bipolar transistors are faster than MOSFETs at the individual level, the low power consumption in CMOS, adaptability to planar processing, reduced size of the transistor, and larger packing density and ease of fabrication with reduced number of masks have made the CMOS technology on silicon substrate the sole technology followed by industries [16]. Figure 1.1 illustrates the developments of VLSIs over the last three decades and the technology roadmap for the coming decade [17].

At the rate shown in Figure 1.1, there were 1 billion transistors on a single die before 2007. With increasing numbers of transistors per die, the minimum feature size, or roughly the channel length in a single transistor, was around 70 nm in 2008. For almost the past 30 years, the feature size in IC lithography has been reduced at a rate of $0.7 \times \sqrt[3]{C_2}$ every three years. It is predicted that the feature size will reach 35 nm in 2014.

1.3 The Interconnect Problem in VLSI

On-chip interconnect is nothing but electrical wiring. According to the International Technology Roadmap for Semiconductors (ITRS), an interconnect is electrical wiring that distributes clock and other signals, and provides power and ground to and among the various circuits or systems functions on a chip.

The process devoted to metallization and interconnect involves deposition of metals, interlevel dielectrics deposition, and etching steps. A typical interconnect structure is shown in Figure 1.2.

The earlier approach was aluminum deposition and dry-etch definition. Currently, copper wires are introduced. The global wires connect different functional units, distributing clock signals and power among them. The length of the global wires scales down with chip size. On the other hand, local wires connect the gates, sources, and drains of close MOSFETs of the same functional units and their length scales with gate size.

Although the downscaling of transistor increases the speed, the same is not true for the downsizing of interconnect. In earlier ICs in use around the 1980s, the delay in interconnects was propagation limited, that is, it was limited by the time of propagation of the electromagnetic waves associated to SiO$_2$, rather than the RC time constant, which was $\sim 1$ ps. It is predicted that for 35 nm technology generation, the interconnect response time of 0.1 mm copper line with a low-k dielectric ($k = 2$) will be about 250 ps, about two orders of magnitude higher, and will account for delays related to the RC time constant of the wire.
The second issue with interconnect is power consumption. With scaling of transistors, the power consumption by the interconnect exceeds that by a transistor. For example, for 1.0 μm devices, the switching energies in the transistor and 1 mm long interconnect were, respectively, 300 and 400 fJ. The predicted values for 35 nm technology are 0.1 and 3 fJ, respectively, indicating that the ratio between dissipation in the interconnect and in the transistor is about 30.

Figure 1.3 shows a trend of interconnect propagation delay for 1 cm length with feature size and year for aluminum metal and silica insulators, copper and low-k dielectrics, and projected optical waveguide technology. It indicates that Al-based technology has reached the performance limit at 0.55 μm; the reduced resistance due to Cu and reduced capacitance due to low-k dielectric ensure a performance improvement limit up to 0.18 μm technology.

![Figure 1.2 Schematic view of electrical interconnect in very large-scale integrated (VLSI) circuit.](image)

![Figure 1.3 Variation of interconnects propagation delay with year and feature size for Al–SiO$_2$, Cu–low-k dielectric, and projected optical interconnects technology.](image)
The optical interconnect using silicon microphotonics technology offers a potential solution to the RC time delay associated with traditional metal interconnects. Using photons as bits of information, instead of electrons, a speedier performance of the devices is expected. Use of photons also solves the power dissipation problem. Photons propagate in transparent media with less heat dissipation and almost no cross-talk. Unlike electrical current beams, light beams can cross one another without using any insulator. The multilevel interconnection scheme shown in Figure 1.2 is not needed when light beams are used for interconnects within the chip.

Further discussion of the use of light waves for chip-to-chip or board-to-board connections will follow in Section 1.6.

1.4 The Long-Haul Optical Communication Link

Fiber-optic communication links have spread today over the whole globe like a spider’s net. A still larger number of links is being added. Today’s fiber-optic links employ dense wavelength division multiplexing (DWDM), in which huge amounts of data carried by hundreds of carrier wavelengths, each modulated at a high bit rate (≈10 Gb/s or more), are transmitted by a single strand of a fiber. In Section 1.4.1, we shall first discuss the basic link, and the components used [18]. In Section 1.4.2, the materials used to grow the devices and the methods of integration of the devices will be pointed out.

1.4.1 Basic Link and Components

Figure 1.4 shows a block schematic of the WDM communication link. Voice, picture, or computer data, in digital format, are impressed on each laser emitting at a particular wavelength (e.g., $\lambda_1$). Either the laser may be directly modulated, or an external modulator may be used to impress the signal on the laser beam. A multiplexer combines the modulated signals coming from the bank of lasers, and the combination is transmitted by an optical fiber. After traversing a distance of a few hundred kilometers, the signal becomes attenuated.

![Figure 1.4 Schematic diagram of a WDM point-to-point communication link.](image-url)
and the digital pulses considerably spread due to material dispersion of the fiber. The combined signal is then regenerated by a regenerator (not shown in Figure 1.4). A photodetector first converts the weak and distorted optical signal into a stream of electrical pulses. These pulses are then reshaped and retimed by a decision circuit. The cleaned electrical pulses are then converted to optical pulses by a laser, and the stream of pulses propagates through another long section of the fiber. At present, a number of optical amplifiers are inserted at regular intervals in the link to boost up the intensity of optical signals, adding noise at the same time. A repeater or regenerator, which includes a detector, a laser, and different electronic circuits as described in this chapter, is then employed to reshape the pulses.

The transmitter and receiver units of the link need additional sub-units. The basic device in the transmitter, that is, the laser, is to be properly biased by a driver and the light output power should be accurately controlled by a monitor circuit. An optical amplifier, usually a semiconductor optical amplifier (SOA), may boost the laser power up. A variable optical attenuator (VOA) is sometimes necessary to reduce or control the intensity. In the receiver unit, the optical signal is detected by a photodetector. The weak electrical signal is then amplified first by a low-noise preamplifier and then by power amplifiers. Further processing systems are needed before these signals are converted back to the original format, at which time they are transmitted. The bottom part of Figure 1.5 indicates the occurrence of various devices in the order they appear in an optical link. Further discussion of Figure 1.5 will be made in connection with the integration of devices, which is discussed in Section 1.4.2.

The present-day communication links work around 1.55 μm, the wavelength at which optical fibers have minimum attenuation. The optical amplifiers, the Er-doped fiber amplifiers (EDFAs), also work around this wavelength. Earlier systems used a 1.3 μm.

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**Figure 1.5** Level of device integration in commercially available products. Reproduced with permission from [2] Copyright (2004) Springer Science + Business Media
transmission window of the fiber, at which the material dispersion of the fiber is minimum. The DWDM system employs hundreds of wavelengths, separated approximately from each other by about 100 GHz (0.8 nm), covering both the 1.3 and 1.55 μm windows.

The requirement that all the optoelectronic and electronic components must work at the two wavelengths completely rules out the use of silicon-based active devices in the telecommunications network, since the cutoff wavelength of Si is about 1.1 μm. The materials of choice are quaternary alloy InGaAsP and ternary alloy InGaAs grown on InP substrate.

### 1.4.2 Materials and Integration

There are many differences between today’s microelectronics and photonics industries. While silicon is the only material in the former, a variety of materials are used in photonics. InP substrate is used for source and detector development, silica as the fiber material, different semiconductors and even insulators like LiNbO₃ for modulators, an Si platform for passive lightwave circuits used in DWDM, and Si-based ICs for driver and controller circuits. No single material or single technology is leading the market. The production technology is still primitive, and the level of integration is far below the level achieved in microelectronics.

In a truly monolithic IC, all components, that is, electronic circuits, light sources, photodetectors, modulators, waveguides, multiplexers, and so on, are grown on the same piece of semiconductor substrate. Since good sources and modulators have not yet been realized using silicon, and since efficient silicon photodetectors do not exist at 1.55 μm, monolithic integration on a silicon platform is at present ruled out. It is possible, in principle, to use InP substrate for integration. However, the small wafer size, high cost, and other factors limiting the manufacturability have hindered progress in this direction.

Hybrid integration, in which disparate parts are assembled onto one common platform, has been pursued for quite some time. In common hybrid optical components, III–V compound light sources and detectors are attached onto silicon on insulator (SOI), silica, or polymer platforms. These components are commercially available. Figure 1.5 gives examples of discrete components in package, hybrid integration, and monolithic integration. The order of the devices on the axis agrees with the order of appearance of the devices in an optical link. As mentioned already, monolithic integration is almost exclusively on an InP platform; however, photodetectors and transimpedance amplifiers (TIAs) have been grown on silicon.

The main interest in hybrid technologies lies in the combination of III–V semiconductor laser diodes with Si integrated circuits for optical fiber communication or optical interconnects. For this purpose, GaAs or InP is grown on Si and then processed, or, alternatively, laser devices are detached from their substrate by an epitaxial liftoff process and then bonded to Si substrate.

For growth of GaAs and InP on Si, the large lattice mismatch (4% for GaAs and 8% for InP), different thermal expansion coefficients, and fast diffusion of Si as impurities all create difficulties in maintaining low defect densities in compounds for laser production. Although several new techniques have been developed to overcome these difficulties, it is too early to predict the long-term success of the techniques.

In the epitaxial liftoff technique, wet chemical etching is performed and then the III–V heterostructure is floated off and transferred to a planar Si substrate. The bonding occurs due
to the van der Waals force. In the wafer fusion process, the two materials (of high quality) are brought into intimate contact under hydrogen ambient at around 450 °C. Under uniform direct pressure, the substrates form robust chemical bonds. One of the substrates, for example compound semiconductor, is selectively etched and photonic devices grown onto it are integrated with silicon electronic circuits. Once again, it is difficult to predict how far these technologies will be successful in commercial production.

It appears, therefore, that the most satisfactory solution to the above-mentioned problems would be achieved when all the optoelectronic and photonic components could be grown on a single substrate, for which silicon seems to be the best choice. The extensive experience in Si fabrication and processing could then be put to maximum use. Unfortunately, however, the lack of suitable emitter and especially a laser based on Si, as well as of a fast modulator, stands in the way of achieving the coveted goal.

1.5 Data Network

While long-haul optical communication systems work at 1.55 μm, to exploit the minimum attenuation in the fiber, local area networks span smaller distance and area. In this case, working at other wavelengths, at the cost of higher attenuation of signals, may be of advantage due to the availability of cheap components. A possible system employs GaAs-based lasers at around 800 nm, at which wavelength Si photodetectors and other electronic circuits would offer a low-cost solution. If, in addition, Si emitters are available, further reduction in cost is highly expected.

A large part of data communication network is anchored to servers and desktop computers that utilize Si devices. The large potential volume of the market and the competition with copper cables will necessitate more use of inexpensive optical fibers. Si-based photonic components will offer the cheapest solution to the network.

1.6 Conclusions

From the discussions in the above sections, the following points emerge:

- The interconnect problem within a chip is taking an alarming shape. Optical interconnect based on silicon technology may offer a viable solution.
- The long-haul optical communication link employs at present a number of different devices (viz., lasers, modulators, power monitor and control, amplifiers, photodetectors, photoreceivers, multiplexers, demultiplexers, filters and other passive lightwave circuits, and active network components like wavelength converters, etc.). Apart from passive components, most of the active components are fabricated on the InP platform. A truly monolithic OEIC on silicon may offer all the advantages of integration including cost reduction.
- Si-based photonic devices may offer lower cost in the sector of data networks covering shorter distances.
- Si microphotonics seem to be an attractive solution for next-generation optical interconnects for chip-to-chip or board-to-board interconnects.
- Discrete silicon photonic devices like light-emitting diodes (LEDs) and lasers are in demand for consumer electronics, display, and mobile communication, and as mid-infrared or THz emitters.