SCANNING THE ISSUE

Silicon Photonics: CMOS Going Optical

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I. SILICON PHOTONICS: BRIEF INTRODUCTION

For almost 50 years, silicon microelectronics has been the engine of the modern information revolution. Complex microprocessors, dense memory circuits, and other digital and analog electronics produced by the $100 billion silicon industry mainly serve a single goal—to process more and more data faster and faster using smaller and smaller components. In this everlasting quest, the silicon industry has successfully overcome many critical issues that were initially considered to be impassible road blocks. For example, silicon materials' limitations were overcome by introducing into traditional complementary metal–oxide–semiconductor (CMOS) technology different modifications of Si-based materials including silicon-on-insulator (SOI), SiGe alloys, and strained Si. The photolithography limitation due to the diffraction limit has triggered the successful development of light sources in deep and extreme ultraviolet spectral regions as well as advances in subwavelength optical technologies. The next critical problem in the evolution of modern information systems is the physical limitation of metallic interconnects, and one of the proposed solutions is a merger of electronics and photonics into an integrated dual-functional platform—the optoelectronic integrated circuit (OEIC)—fabricated using the existing silicon infrastructure.

Recent progress in silicon compatible photonics is driving high density integration of photonic and electronic components manufactured by CMOS-based technology on the same platform.

Photonics, similarly to electronics, is also a technology of information processing, where the signal is carried by light and a basic photonic system includes a laser, a modulator, a waveguide, and a photodetector. However, in contrast to electronics where all components are integrated into a single platform and produced by the "parallel fabrication" process with billions of units fabricated simultaneously, photonics is mainly based on discrete components and serial (step-by-step) fabrication. There has been a desire for a long time now to apply the mature Si technology towards fabricating highly integrated combined photonic/electronic circuits: the optical data transmission allows much higher data rates compared to metal wires, and there are no problems associated with electromagnetic interference. Thus, such circuits could bring new functionality and be used for faster communication between circuit boards, chips on a board, and even different cores of a microprocessor. The same technology may also be useful for other areas of optical communications, including the development of integrated arrays of switches and fiber-based optoelectronic components. In addition, Si has a high thermal conductivity and a high optical damage threshold, and both these material properties are very favorable for photonic applications. Also, the relatively low cost and high quality of SOI wafers makes them an ideal platform for creating CMOS-compatible planar

Digital Object Identifier: 10.1109/JPROC.2009.2021052

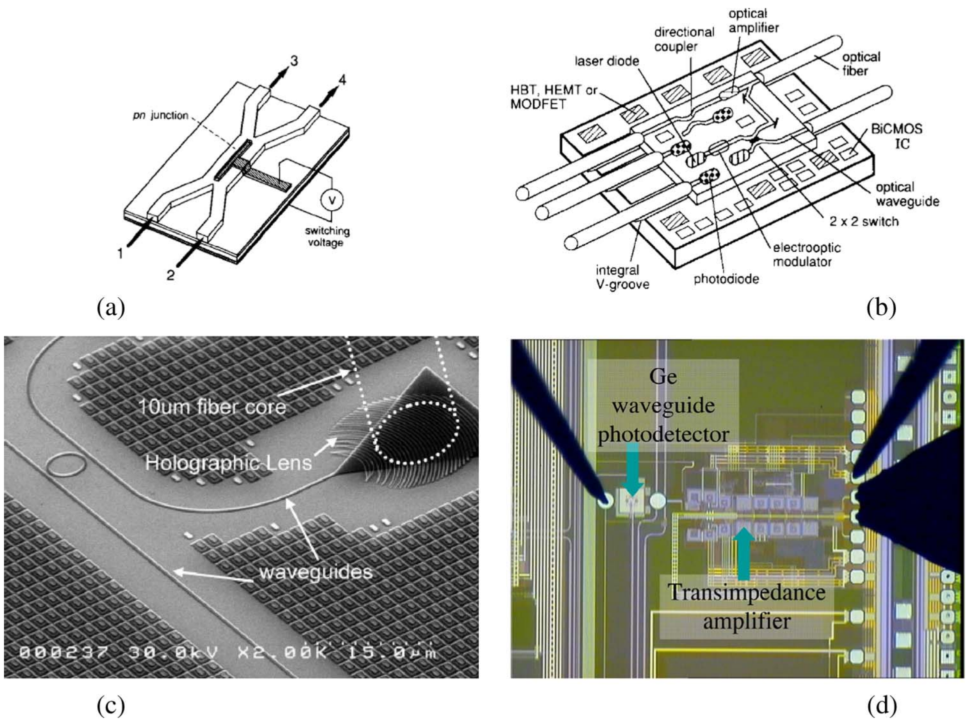

Fig. 1. ***(a) An early experimental 2 $\times$ 2 optical switch based on silicon, with (b) an associated proposal for a silicon-based OEIC "super chip" (after [2]). (c) Microscope photographs of a more modern SOI integrated-photonic test network including microring filter and fiber-to-waveguide coupler (after [3]). (d) Top view of a recently developed germanium waveguide photodiode-based receiver channel (after [4]).***

waveguide circuits. However, the most important argument for the proposed Si (probably, it would be better described as CMOS compatible) photonics industry is the lowest processing cost (per unit area) and the highest quality of Si wafers compared to any other semiconductor material. Modern Si technology represents a spectacular combination of technological sophistication and efficient economics.

This cost-driven approach is challenged by several fundamental and technical problems. First, Si is an indirect bandgap semiconductor, and basic physics suggests that Si-based light emitters and electrooptical modulators should be extremely inefficient. Secondly, assuming that a silicon laser can be developed, the heat generated by an array of lasers on a chip is going to be very high, and it will require additional cooling systems. To avoid optical losses, the proposed massive optical connections should have very precise alignment. Also, their dimensions are limited by the desired operating wavelength, which is around 1.3–1.6 μm. In addition, Si photodetectors are not sensitive in this spectral region, and Ge photodetectors should monolithically be incorporated into the proposed photonic systems. Since Si and Ge have 4.2% lattice mismatch, this task is far from being a simple one.

Despite the fact that Si photonics was envisaged a long time ago [1], only recently have advances in the development of CMOS-based photonic systems promised commercial development of such systems on a large scale (see Fig. 1). This Special Issue presents a set of review papers addressing major challenges and summarizing recent progress in the several subfields of Si-based photonics.

II. PHOTONIC DEVICES ON A CHIP

The first paper, on "Device Requirements for Optical Interconnects to Silicon Chips," by Miller, examines the demands of interconnects to and on silicon chips. It compares electrical and optical interconnects and projects the requirements for optoelectronic and optical devices integrated into future high-performance silicon chips. According to the author, the necessity of a low interconnect energy imposes strict limits on the energy of the optical output devices—as low as $\sim$10 fJ/bit. Other critically important parameters are femtofarad photodetector capacitances, very compact wavelength splitters, and dense waveguides. The paper emphasizes that future photonic devices would need to work at least at the on-chip clock rate, which scales to 14.3 GHz on the International Technology Roadmap for Semiconductors; for connections to optical fibers, the higher off-chip clock rates (which scale to 67.5 GHz) would likely be required. In terms of the discussed energy targets, silicon ring resonators look promising, although precise tuning of their very sharp resonances and tuning power dissipation are significant issues. Electroabsorption modulators should also be able to reach the energy targets, possibly even without resonators, though very compact integrated device structures would be required. Considering laser integration, only the most aggressive concepts (e.g., quantum dot nanocavity lasers) appear to be viable.

The second paper, on "On-Chip Optical Interconnect," by Ohashi *et al.*, is focused on the architecture and devices of a bonded photonic structure incorporated into a chip. The fabricated optical layer contains Si nanophotodiodes for optical detectors, which are coupled with silicon–nitride waveguides using surface-plasmon antennas. The output signals from the photodiodes are sent electrically to the transimpedance-amplifier circuitries on the Si chip and trigger the operation at a frequency of 5 GHz. In this design, the electrooptical modulator consumes the most power and requires a large footprint on a chip. The paper concludes that the developed flip-chip bonded structure is a cost-effective approach to reduce the power consumed by the on-chip optical interconnects.

The third paper, on "Recent Progress in High Speed Silicon-Based Optical Modulators," by Marris-Morini *et al.*, is focused on the evolution of silicon optical modulators and provides an analysis of high-performance devices integrated into optical waveguides. Among other possibilities, devices utilizing the carrier depletion effect in Si and SiGe/Si are considered in great detail. Theoretical analysis of the SiGe device speed has pointed out an intrinsic frequency limitation at ~16 GHz, which is due to the time required for the carriers to escape out of the SiGe wells. A new all-silicon structure is considered with the anticipated maximum intrinsic frequency close to ~100 GHz. A large phase modulation efficiency, low optical loss, and large cutoff frequency are obtained by optimizing simultaneously the optical and electrical characteristics. Recent experimental results on a high-speed and low-loss silicon optical modulator using an asymmetric Mach–Zehnder interferometer based on a p-doped slit embedded in the intrinsic region of a lateral pin diode integrated in a SOI waveguide are presented, and an insertion loss of 5 dB with a −3 dB bandwidth of 15 GHz is demonstrated.

The paper on a "Cascaded Microresonator-Based Matrix Switch for Silicon On-Chip Optical Interconnection" by Poon *et al.* reviews developments in cascaded microresonator-based matrix switches for silicon photonic interconnection networks with the focus on two-dimensionally cascaded microring resonator-based electrooptic switches coupled to a waveguide cross-grid on a silicon chip. It presents details of the microring resonator-based cross-grid switch design for high-data-rate signal transmission. The proof-of-concept experiments demonstrated a single cross-grid switch element and a 2×2 matrix switch array, with ~1 ns-speed switch on/off times and 5-Gbit/s data transmission rate without significant waveform distortion.

The paper on "High Performance Quantum Dot Lasers and Integrated Optoelectronics on Si" by Mi *et al.* provides a review of the recent developments of self-organized In(Ga)As/Ga(Al)As quantum dot lasers grown directly on Si and their on-chip integration with Si waveguides and quantum-well electroabsorption modulators. A novel dislocation reduction technique with the incorporation of self-organized In(Ga,Al)As quantum dots as highly effective three-dimensional dislocation filters has recently been developed to overcome the issues associated with the Si and III–V materials' incompatibility. With the use of this technique, quantum dot lasers grown directly on Si exhibit a relatively low threshold current ($J_{th} = 900$ A/cm^2) and very high temperature stability. Integrated quantum dot lasers and quantum-well electroabsorption modulators with a coupling coefficient of more than 20% and a modulation depth of ~100% at a reverse bias of 5 V are demonstrated. The monolithic integration of quantum dot lasers with both amorphous and crystalline Si waveguides fabricated using plasma-enhanced chemical-vapor deposition and membrane transfer are described. The paper concludes that further improvement in the device performance can be achieved by using low defect density buffer layers on Si (e.g., relaxed and graded SiGe layers, etc.) and quantum dot dislocation filters.

III. SILICON-BASED PHOTONIC MATERIALS

The paper on "Silicon Nanocrystals as an Enabling Material for Silicon Photonics" by Yuan *et al.* considers the limitations of silicon as a photonic material and suggests several strategies to overcome these problems. The paper emphases the continuous effort on optical gain in Si nanocrystals (Si-ncs) and to their sensitization effect on Er ions with the goal to achieve light amplification at 1.55 μm. The paper also considers non-linear optical effects in Si nanocrystals that could be used for development of fast all-optical switches.

The paper on the "Photonic Properties of Er-doped Crystalline Silicon" by Vinh *et al.* reviews the photonic properties of Er-doped crystalline silicon (c-Si). It emphasizes that in addition to the predictable optical properties, specifically the desirable 1.55 μm wavelength of emission, Er ions in a semiconductor host can be excited not only by a direct absorption of energy into the 4f-electron core but also indirectly, by energy transfer from the host. The paper considers critical issues of Si:Er materials science such as the low solubility of Er in c-Si and the multiplicity of centers that Er forms in the Si host. It clearly explains the main problem: the long radiative lifetime (milliseconds) of the first Si:Er excited state requires a large concentration of Er to maximize the emission intensity, which is precluded by the low solid-state solubility of Er in c-Si. The paper presents details of the complex physics of Si:Er excitation and recombination mechanisms, including multistage excitation and deexcitation, luminescence thermal quenching, back transfer process of excitation reversal, and Auger-type energy transfer to free carriers. It considers prospects of optical gain in Si:Er and concludes that despite more than 30 years of active research, the fundamental problems associated with the thermal quenching of emission and the low optical activity of the Er dopants incorporated into bulk c-Si remain unsolved. The paper presents a new direction in this field—Si/Si:Er multilayers with nanometer dimensions and shows that this Si-based nanomaterial can be used for light emitters and amplifiers at a wavelength of 1.55 μm.

The paper on "Silicon-Germanium Nanostructures for Light Emitters and On-Chip Optical Interconnects" by Tsybeskov and Lockwood reviews the physical and light-emitting properties of epitaxially grown Si/SiGe quantum wells and Si/SiGe cluster multilayers. These nanostructures emit light in the important communications wavelength region of 1.2–1.6 μm. Until recently, the major roadblocks for practical applications of these nanostructures were strong thermal quenching of the luminescence quantum efficiency and a long carrier radiative lifetime. The paper emphasizes the latest progress in the understanding of the physics of carrier recombination in Si/SiGe nanostructures and suggests a new route toward Si/SiGe-based light emitters for on-chip optical interconnects.

IV. NEW DIRECTIONS IN CMOS-COMPATIBLE PHOTONICS

The paper on "Silicon Organic Hybrid Technology—A Platform for Practical Nonlinear Optics" by Leuthold *et al.* considers a relatively new approach toward cost-effective and efficient modulators for silicon photonics. This hybrid technology enables modulation at bit rates beyond 100 Gbit/s and relies on the well-established CMOS-compatible processing technology for fabricating SOI waveguides, while an organic cladding layer adds the required nonlinearity. Two key device prototypes are exemplarily discussed in detail. The first device demonstrates demultiplexing of a 120 Gbit/s signal by means of four-wave mixing in a slot-waveguide that has been filled with a highly nonlinear organic material. The second device is a 100 Gbit/s/1 V electrooptic modulator based on a slow-light SOI photonic crystal covered with a nonlinear organic material. The paper concludes that the silicon organic hybrid approach provides the highest nonlinearities, beyond 100 000 $(\text{W-km})^{-1}$. Theoretical calculations show that the same technology is capable of producing silicon electrooptical modulators with a speed beyond 100 Gbit/s at an operating voltage of $\sim$1 V.

The paper on "Negative Index Materials with Gain Media for Fast Optical Modulation" by Bratkovsky discusses the physics and device applications of negative refractive index behavior, which is observed in artificial structures known as metamaterials (MMs). The MMs are periodic structures supporting backward optical waves with generally antiparallel phase and group velocities. Metal-dielectric MMs and systems are of special interest to CMOS-compatible nanophotonics due to a high dielectric contrast and proposed applications in dense integrated optical systems. The paper considers various ways of combining metallic materials for a negative dielectric constant and a gain medium to compensate for optical losses. It shows that Si-compatible subwavelength optical components with the use of the MMs could be fabricated using traditional CMOS methods.

V. SILICON PHOTONIC SYSTEMS

The paper on "Si Photonics and Fiber to The Home" by Wada *et al.* considers technical details of the optical fiber-to-the-home (FTTH) approach. Mass production in terms of CMOS technology is a prerequisite for Si photonics to provide a cost-effective solution, and FTTH should meet this requirement. The paper describes a design of the FTTH chip architecture with wavelength-division multiplexing based on ring-resonator demultiplexers and multiplexers. The paper concludes that the grand challenge for this application is monolithic integration of Ge photodetectors and modulators into the FTTH chip.

The last paper of this Special Issue, on "Computing Microsystems Based on Silicon Photonic Interconnects" by Krishnamoorthy *et al.*, presents a design of a microsystem that utilizes silicon photonic interconnects to enable a highly compact supercomputer-scale system. It describes and justifies single node and multimode systems interconnected with wavelength-routed optical links and analyzes their benefits versus electrically connected systems. The paper considers the constituent optical components and system requirements and provides an overview of the critical technologies needed to fulfill this proposal. The paper analyzes the power dissipation of a photonic link, suggests a roadmap to lower the energy-per-bit of silicon photonic interconnects, and identifies the challenges that will be faced by future Si photonics device and circuit designers.

VI. OUTLOOK

This Special Issue presents review papers summarizing the truly global effort in the development of Si photonics, which one day, most likely, will join the growing family of CMOS-based technologies (CMOS, Bi-CMOS, RF-CMOS, etc.), possibly, we suggest, under the name "Opto-CMOS." Based on the impressive progress and strong support of this technology worldwide, one can anticipate that it will happen and will happen soon. We hope that this

Special Issue will help to disseminate and promote a better understanding of the advances and roadblocks of this effort as well as delineate the outstanding progress that has been made in recent years. More importantly, we hope that our work will stimulate even wider interest in silicon photonics and trigger new directions in this fascinating research area, as well as encourage important and necessary technological developments. ■

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David J. Lockwood received the Ph.D. degree in physics from Canterbury University, New Zealand, in 1969, the D.Sc. degree from Edinburgh University, U.K., in 1978, and the D.Sc. degree from Canterbury University, U.K., in 2000.

His doctoral work focused on the electronic, optical, and magnetic properties of solids. He carried out postdoctoral work in physical chemistry at Waterloo University, Canada (1970–1971) and was a Research Fellow at Edinburgh University (1972–1978) before joining the National Research Council of Canada in 1978, where he is presently a Principal Research Officer. At NRC, his research has centered on the optical properties of low dimensional materials and recently has focused on Group IV and III–V semiconductor quantum dots and transition-metal magnetic nanostructures. He has made seminal contributions to our understanding of the optical properties of silicon nanostructures and is internationally recognized for his expertise in silicon photonics. He has published more than 500 scientific articles in journals and books, has received six U.S. patents, and edited a definitive and frequently cited book on *Light Emission in Silicon* (Boston, MA: Academic, 1997). He coedited the standard reference book on *Silicon Photonics* (Berlin, Germany: Springer-Verlag, 2004). He has played a significant role in organizing a large number of international conferences and symposia and served for four years on a NATO Science Committee promoting international scientific research on the physics of low-dimensional semiconductors. He is a member of the editorial boards of six physics journals as well as the Founding Editor of the book series *Nanostructure Science and Technology*.

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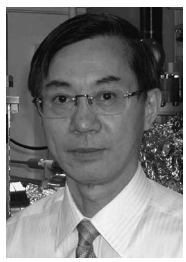

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