Silicon Photonics

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Guest Editor

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Silicon, well established as an electronics platform, was first seriously explored as an optical waveguide platform in 1987 by Soref and Bennett. Light at fiber-optic communication wavelengths can pass through crystalline silicon with very high transmission. Silicon waveguides can be made by etching into the thin crystalline silicon layer on a silicon-on-insulator wafer. Because of the high refractive index of silicon compared to the surrounding oxide, these waveguides can bend with radii less than five micrometers and make compact splitters/combiners, filters, and polarization elements. High-speed optical modulators can be made by rapidly changing free electron and hole densities in the silicon in the optical path, and photodetectors can be made by epitaxially growing germanium on the silicon, both using electrically connected p-n junctions. The only element missing to complete an optical integration platform is an integrated light source, rendered very difficult because of the indirect bandgap of silicon and germanium. While to date, no practical electrically pumped light emitter has been deployed based on silicon itself, multiple hybrid and heterogeneous solutions have been reported.

This month's special issue provides a state-of-the-art overview of the field of silicon photonics, which is making a significant impact on fiber-optic communications and spreading to new areas such as sensors and deep learning.

Initially, silicon photonics was a solution looking for a problem. III-V materials, such as InP and GaAs, were usually a better solution, offering integrated lasers and more efficient modulators. This changed as the continuing demand for fiber-optic transmission capacity resulted in higher speeds and advanced modulation formats, such as pulse amplitude modulation and quadrature phase-shift keying. These formats require complex, linear, and high-speed transmitters and receivers. The leveraging of existing high-yield manufacturing and dense packaging of silicon electronics to silicon optics finally made economic sense.

Today, 30 years later, silicon photonic-integrated circuits are making a dramatic impact on fiber-optic communications. They are widely deployed, from transoceanic to rack-to-rack links. Silicon photonics has significantly changed the cost structure and supply chain of fiber-optic transceivers. There have been more than 1 000 000 publications on silicon photonics. Silicon photonics is finding its way into other areas, as well, such as sensors, including optical coherence tomography and LiDAR, and deep learning computation. With the growth of the market size, the supply chain is becoming more mature and more complete, with a growing number of commercial actors for prototyping, manufacturing, design automation, testing, and packaging.

This special issue starts with an introductory paper by the team of Graham Reed at the University of Southampton presenting a brief history of the field of silicon photonics. The paper encompasses a discussion of the key devices, with a focus on the key performance milestones that were instrumental in demonstrating the potential of silicon photonics.

The primary component of silicon photonics is the silicon otpical waveguide. Daoxin Dai of Zhejiang University reviews advanced passive devices in silicon photonics, such as on-chip polarization-handling devices, mode converters/(de)multiplexers, microring-resonator optical filters/switches, all taking advantage of the high index contrast, and asymmetric silicon-based waveguide structures.

Building on the improvements in high-resolution lithography for silicon, one can create artificial dielectrics, periodic structures in silicon photonics with periods substantially smaller than a wavelength of light in the material. Robert Halir of the University of Malaga and collaborators discuss the theory and applications of these subwavelength structures.

Active devices in silicon are key to silicon photonic's success. Jeremy Witzens of RWTH-Aachen reviews optical modulators in silicon. This has become a very rich topic, including Mach-Zehnder modulators and ring modulators. The tradeoffs in design to achieve high speed with minimal drive voltage and insertion loss are studied.

Takashi Asano and Susumu Noda of Kyoto University review the history of 2-D photonic crystal slabs based on silicon photonics. In particular, the paper focuses on ultrasmall cavities with ultrahigh-quality factor, and their applications as add/drop filters and Raman lasers. Also ways to establish strong coupling between distant nanocavities are discussed.

Kangmei Li and Amy Foster of Johns Hopkins University discuss nonlinear optics in silicon photonics. Because of the tight optical confinement, very compact nonlinear devices can be made in silicon photonics. Applications include the generation of octave-spanning optical frequency combs for making precise clocks.

Silicon nitride waveguides add an additional degree of freedom to silicon waveguides. There are two papers on silicon nitride waveguide platforms. Dan Blumenthal of the University of California Santa Barbara along with a team from Lionix International reviews the state of the art of silicon nitride waveguide platforms, with their capabilities complimentary to those of silicon-on-insulator platforms, amongst others with respect to the loss levels and the power handling properties. Even if these platforms do only allow for passive functionalities so far, they offer appealing performance features that give them a competitive advantage in a range of applications where low loss or high power is key attributes. Wesley Sacher from the California Institute of Technology and his colleagues from the University of Toronto discuss multilayer platforms using silicon nitride and silicon waveguides. This technology allows 3-D photonic circuits to be created.

As mentioned, the missing component in silicon photonics to complete an optical transceiver is a native, integrated laser. An alternative approach to an on-chip laser is to use heterogenous integration and there are two papers on this important topic. Tin Komljenovic and colleagues from the University of California Santa Barbara focus on oxide bonding of III-V semiconductors and magnetooptic materials, while Owen Marshall from Ghent University—imec and collaborators focus on other material combinations (a.o. PZT, BTO, and graphene) as well as hetero-epitaxial growth of III-V semiconductors.

One of the biggest challenges in silicon photonics is coupling the very small optical mode in silicon wire waveguides to the much larger optical mode of single-mode fibers in an efficient manner. Diedrik Vermeulen and Christopher Poulton of Analog Photonics discuss in detail the various approaches reported and deployed in industry in today.

Regarding applications of silicon photonics, Thierry Pinguet *et al.* of Luxtera discuss the factors that are at stake to bring a low-cost, low-power, high-performance, and high volume optical transceiver to market. Key in this has been to emulate the approaches of the microelectronics industry with respect to design, wafer-level manufacturing, wafer-level testing, and assembly. Also, the pros and cons of monolithic and hybrid electronics/photonics integration are discussed.

Silicon photonics is especially suited for advanced modulation format transmitters and coherent reception, because of the large number of required integrated optical components. Coherent communications is widely deployed in long-haul and metro networks and is moving to shorter reaches. This area is covered by Christopher Doerr and Long Chen of Acacia Communications, focusing on industry deployments today and tomorrow.

Jean-Marc Fedeli and Sergio Nicoletti of CEA-LETI review the state of the art in silicon-based mid-IR-integrated photonics. They discuss the waveguide platforms as well as the options to integrate mid-IR light sources in such platforms. The route toward applications in the field of chemical sensing, IR spectroscopy and imaging, and free-space communications is also covered.

Silicon photonic devices are usually fabricated in large foundries that serve multiple customers. Silicon photonics takes advantage of these open-access silicon electronics foundries, and this ecosystem and its evolution are discussed in detail by Abdul Rahim and colleagues from Ghent University and imec.

In conclusion, silicon photonics is currently significantly impacting the fiber-optic transceiver industry, allowing the relentless trend of smaller footprint and lower cost-per-transmitted-bit to continue. Its weakness of not having a native laser is overcome by its high-yield processes, low-cost wafers, and ability to copackage with electronics. It is no longer just replacing existing optical transceiver technologies but enabling new applications of optics. It is also spreading to other areas, including sensors and deep learning. As these higher volume applications become more prevalent, silicon photonics progress will likely continue, as the higher volumes encourage silicon foundries to devote more resources to its development. ■

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Roel Baets (Fellow, IEEE) received the M.Sc. degree in electrical engineering from Ghent University (UGent), Ghent, Belgium, in 1980, the second M.Sc. degree from Stanford University, Stanford, CA, USA, in 1981, and the Ph.D. degree from UGent in 1984.

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Dr. Baets is a Fellow of the European Optical Society and the Optical Society of America (OSA). He is also a member of the Royal Flemish Academy of Belgium for Sciences and the Arts. He was a recipient of the 2011 MOC Award and the 2018 PIC-International Lifetime Achievement Award. He is the Director-at-Large in the Board of Directors of the OSA. He is an ERC Grantee of the European Research Council.