APL Photonics

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Cite as: APL Photonics **5**, 020402 (2020); https://doi.org/10.1063/5.0002005
Submitted: 21 January 2020 . Accepted: 24 January 2020 . Published Online: 21 February 2020

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APL Photonics EDITORIAL scitation.org/journal/app

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Submitted: 21 January 2020 • Accepted: 24 January 2020 •
Published Online: 21 February 2020

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https://doi.org/10.1063/5.0002005

INTRODUCTION

Photonic devices have found wide applications covering but not limited to high-speed telecommunications, datacenters, sensing, photovoltaics, quantum information processing, and bio-photonics. To achieve breakthrough yet balanced performance, photonic integration is often needed and has attracted intense research interest from both industry and academia. Silicon photonics is booming and gradually accepted by industry, as it enables high yield and low cost integration by leveraging the standard complementary metal-oxide semiconductor (CMOS) manufacturing capabilities developed in microelectronics foundries. In the past two decades, silicon photonics has thus emerged as a mature technology, allowing for multiple optical functions to be integrated onto the same chip-based platform. Relatively fast electro-optic modulators, high-speed SiGe photodetectors, ultra-low loss silicon waveguides, couplers, and demultiplexers are now available. However, full-scale integration of silicon photonics in most applications is often impossible due to the lack of light sources, while the performance of typical modulators and detectors remains limited. In parallel, new materials are emerging, which provide complementary properties to silicon, thereby offering unlimited possibilities to improve the device performance as well as to implement novel functions.

When it comes to light emission, silicon turns out to be intrinsically limited. In particular, its indirect bandgap results in a poor radiative efficiency that has precluded the realization of monolithic bright light sources in silicon. Even though some strategies have been recently investigated to improve these properties, such as engineering defects and strain in Si or exploiting nanostructures to increase carrier confinement hence radiative efficiency, the heterogeneous integration of III–V materials onto silicon has provided a more reliable path toward the realization of efficient LED and laser devices. This might represent the first example of successful hybrid material integration in photonics.

TECHNOLOGICAL DEVELOPMENTS

In the last two decades, several technological advances have allowed material integration to be considered as a viable pathway toward the realization of advanced photonic integrated circuits. The first one has been the development of bonding technologies that enable the heterogeneous integration of various materials onto silicon, through dye to wafer bonding or even at the wafer-scale.[1] This has been mostly driven by the realization of lasers and light sources onto silicon, which was pioneered in the 2000s by the CEA-Leti and IMEC in Europe[2,3] and by Intel and J. Bowers's group in the U.S.[4,5] Advances in the design of these lasers as well as their integration on a chip have now enabled very compact light sources[6] to exhibit improved performance, such as direct high-speed modulation, low power consumption,[7] and laser wavelength tunability,[8] while efficiently feeding a photonic integrated circuit.[9] This successful bonding technology now starts being applied to other functionalities, such as nonlinear optical devices. The integration of a nonlinear function, whether it be a light source or an all-optical signal processing device, onto a semiconductor substrate improves the device stability and heat dissipation while multiplying the degrees of freedom for achieving efficient device design.

The second technological advance has been the recent availability of thin film materials that can be easily integrated on silicon or glass substrates, a prominent example being $LiNbO_3$ thin films on an insulator.[10] The latter allow for tightly light confining geometries so as to realize a variety of miniaturized and energy efficient photonic devices that harness the optical properties of $LiNbO_3$. In particular, its high nonlinear $\chi^{(2)}$ response lends itself to efficient and high-speed (>100 GHz) electro-optic modulators,[11,12] spectrometers,[13] or wideband electro-optic frequency combs.[14] In addition, the advent of 2D materials has given a new breath to hybrid photonics, as these new materials can be relatively easily integrated onto planar silicon photonic platforms, while bringing fundamentally new properties. Besides the use of graphene since the late 2010s, several kinds of monolayer materials, including transition metal dichalcogenides such as WSe_2 or MoS_2, have emerged, offering new properties that can advantageously complement silicon photonics.[15,16] These have led to the creation of light-emitting devices,[17] ultra-fast and sensitive photodetectors, highly compact electro-optic modulators,[18,19] broadband optoelectronic devices,[20] and nonlinear signal processing devices.[21,22]

On a different front, advances in the deposition/growth of high quality materials onto silicon (such as Si_3N_4 or Si_xGe_{1-x}) by CVD or epitaxy have increased the number of functionalities that can be integrated onto silicon, such as high efficiency photodetectors, high speed modulators, octave-spanning optical frequency combs,[23,24] or supercontinuum light sources. Yet, some issues remain for some of these materials, in terms of the full CMOS compatibility of the associated process, due to the high temperature requirement for their growth and/or annealing or the management of strain in the deposited layer. The inclusion of optically active rare-earth impurities on chip-based silicon-oxide materials also remains an active research field for light emission or amplification. Alternative works continue to explore the direct growth of lattice mismatched materials, such as III–V quantum dots, onto silicon with some successful demonstration of monolithic laser diodes,[25] while new oxide materials have been envisaged to expand the silicon device functionality[26] or serve as an intermediate buffer to epitaxy III–V semiconductors onto silicon.[27]

The boom of silicon photonics at the international level has led to new initiatives such as multi-project wafer (MPW) services. Major European foundries such as IMEC or CEA-Leti offer photonic device prototyping service for academia and industry where chips are fabricated as per the layouts supplied by customers. AIM photonics in the U.S. is an industry driven public–private partnership that provides access to state-of-the-art manufacturing of photonic integrated circuits. AMF in Singapore has offered MPW and customer design services to a wide range of academic and industrial users. Similarly, silicon photonic foundries have grown rapidly in Japan, Australia, and China. While these initiatives started with silicon photonics, the services have expanded toward the use of other materials than silicon such as Si_3N_4 (Pix4life[28]), III–V, glass, or even hybrid versions of these. These services also now enable device applications targeting wavelength windows outside the telecom band, for instance, the mid-IR range [through MIRPHAB (Mid InfraRed PHotonics devices fABrication for chemical sensing and spectroscopic applications)] or the visible (PIX4Life).

Besides expanding the device functionality by adding new materials, hybrid photonics also aims to take advantage of the mature silicon photonic technology to harness the properties of light at the micro- and nano-scale and thus enhance the interaction between light and the "hybridized" material. The resulting low loss waveguide and high Q factor microring resonators in silicon and silicon nitride ($Q \sim 10^7$) can be combined with other materials transferred onto their surface.[22,29] Slot waveguides increase the interaction of light in a tightly confined space that can be filled with another material with adequate properties.[30] Bound states in the continuum, topological photonics, and non-reciprocal photonics are just a few nanophotonics illustration examples of the new concepts that help to better confine or guide light in chip-based platforms and could help increase the interaction with a material other than the silicon host material.

Coupling strategies to vertically transfer light adiabatically between different layers are now available and mature, leading to efficient and functional multilayer chips that make the most of the material combination, as in recently demonstrated $LiNBO_3/Si_3N_4$ architectures[31] or energy efficient high-speed $LiNbO_3$/Si hybrid modulators.[12,32] In the laser area, this has led to bright light sources that exploit III–V as a gain medium and a mature and high quality silicon optical cavity underneath. Light evanescently couples from the structured passive layer to the upper active one across its multiple round-trips in the cavity.[8] More generally, the integration of a gain medium with a long high quality resonator made in a passive low loss circuit could enable the realization of more advanced light sources such as pulsed lasers on a chip.[33]

NEW FUNCTIONS AND APPLICATIONS OFFERED BY HYBRID MATERIAL INTEGRATION

In addition to the early realization of light sources and efficient detectors, new functions and applications have arisen from the hybrid combination of silicon with the novel materials that have become available for integrated optics. We give a few examples of these new functionalities below.

Tunable/reconfigurable optics

One missing functionality of silicon photonics has been the lack of reconfigurability of the fabricated chip. The device operation is typically set at the design stage, which limits the flexibility of the resulting circuit. The direct integration of metal based microheaters has been successfully implemented to address this issue, but it remains cumbersome and difficult to operate in practice. To overcome this limitation, materials with phase change properties, such as GeSbTe or VO_2, have been explored.[34–36] Their properties can be widely tuned optically, thermally, or electrically, providing a new path toward the realization of circuits with on-demand functionalities as well as some non-volatile reconfigurable properties, or flexible metasurfaces. Graphene and 2D materials, in general, have also been widely used so as to provide a way to tune or reconfigure the photonic devices underneath, whether it be a passive device[37] or a frequency comb source.[38]

All-optical information processing devices and broadband light sources

Several nonlinear material candidates are investigated as alternatives to silicon with the aim to eventually integrate them onto silicon photonic platforms. The nonlinear optical response of suitable materials can lead to the creation of optical devices such as all-optical switches or parametric amplifiers that can directly control light signals with other light signals. These can be much faster than their optoelectronic counterparts. Perhaps more importantly, these nonlinear properties can enable completely new functions such as the generation of frequency combs[39] or supercontinuum[40] for high-data rate transmission applications. A wide range of nonlinear devices can be realized for information processing using light control signals. Eventually the co-integration of these functions with microelectronic circuits could lead to the development of advanced optoelectronic systems, following the 2015 successful demonstration example of inter-chip optical interconnect via silicon photonic/microelectronic co-integration using CMOS processes.[41]

Despite the high application potential of nonlinear optics for Datacom and all-optical information processing, no nonlinear material candidate has emerged as a clear choice to complement silicon photonics so far, the latter being plagued by high nonlinear losses at telecom wavelengths. Wide bandgap semiconductors such as GaInP,[42] GaP,[43] AlGaAs,[44,45] or SiC have been investigated successfully, showing record high performance for parametric amplification or supercontinuum generation in compact waveguides. These start being integrated onto silicon using the bonding techniques that were developed for III–V/Si light sources. The resulting GaP,[46,47] GaInP,[48] SiC,[49] or AlGaAs[50,51] on oxide platforms offer more opportunities for dispersion engineering at the core of the device efficiency while providing more tightly confining waveguide geometries. Polymer materials with strong nonlinearities have been successfully integrated onto silicon nanophotonic devices.[30] Chalcogenide compounds[52] or glass materials such as Si_xN_y or Hydex[53] have also been advantageously exploited for chip-based nonlinear optics. Although their relatively weak nonlinearity precludes the realization of compact devices, their ultra-low loss has led to the creation of integrated and wideband frequency combs based on high Q microresonators. New optical functions relying on hybrid photonics also directly benefit from the combined response of several materials with a complementary second and third-order nonlinear response, as for AlN/SiN[54] hybrid geometries. In this context, the use of $LiNBO_3$ on insulator waveguides has provided a way to reach a record 2 octave spanning supercontinuum, through harnessing both the $LiNBO_3$ second- and third-order nonlinearity.[55] Some materials deposited onto silicon chips such as Si ultra-rich silicon nitride (Si_7N_3) have been specifically engineered for exhibiting the right combination of nonlinear properties and demonstrated promising results.[56,57] Finally, new materials, such as the so-called epsilon-near-zero materials, continue to emerge with relevant nonlinear properties that form the basis of new research directions.[58,59]

Quantum optics

Silicon photonics and material nonlinearities have also been applied to quantum optics. For instance, non-classical light sources of correlated photon pairs or entangled photons have been achieved in chip-based platforms. The brightness can be increased by the use of high Q microring resonators or photonic crystals. In addition, the device compactness allows for several of these sources to be integrated on one platform so as to provide a solution for their non-deterministic emission. Other materials, such as wide bandgap semiconductors, have demonstrated improved performance devices, thanks to their lower nonlinear loss. In this context, hybrid photonics could thus be advantageously exploited.[49]

Access to other wavelength range: Mid-IR and visible/UV

The technology of photonic integrated circuits tends to migrate toward applications in new wavelength ranges with the help of hybrid material integration. The mid-IR range, where many molecules and biomolecules have a strong fingerprint, exhibits a strong potential for applications in biodetection, as relevant for defense, security, and environmental sensing.[60] While quantum cascade lasers have enabled the realization of efficient light sources in this wavelength range, nonlinear optics in SiGe or chalcogenide platforms could provide light sources with a much broader spectrum.[61,62] These could increase the reliability of the detection systems while allowing multiple molecules to be detected in parallel.

On the other end of the spectrum, an increased number of functionalities exploit the combination of silicon with materials that exhibit a broad transparency window, down to the visible or the UV, such as diamond, AlN, GaP, SiN, or $LiNBO_3$.[63] These could be useful for LIFI applications.

Photonic hybrid integrated circuits

In many different fields, thanks to the integration of several devices relying on different materials, more advanced functions become available or completely new opportunities. For instance, the co-integration of laser or amplifier diodes and high Q microresonators could lead to significant improvements in the operation, stability, and performance of frequency comb sources.[64] In Ref. 65, the monolithic integration of a comb source with an electrically controlled add-drop filter and an intensity modulator, all being made in $LiNbO_3$, gives a relevant example of advanced functionalities that can be achieved for data communications through integrating multiple functions on a chip. A compact and high-precision optical frequency synthesizer has been recently demonstrated by combining integrated optoelectronic devices (on separate chips) so as to provide a tunable III–V/Si laser and two frequency combs made in SiO_2 and Si_3N_4, respectively.[66]

Quantum network applications could make the most of the integration of various sources, multiplexers, and detectors onto the same platform. In the field of optical computing, various strategies have been recently proposed based on either reservoir computing or neural photonic networks. Chip-based programmable nanophotonic processors[67] could be created by combining both passive and low-loss integrated optical circuits with nonlinear functions to emulate the neuron response.[68]

In conclusion, efforts have been pursued that tend to integrate a higher number of new materials onto silicon photonic chips for high performance devices as well as completely new functionalities. While the whole field might have started with the integration of III–V onto silicon for the realization of light-emitting devices, the number of functions and materials envisaged has widely expanded and now largely overcomes the sole issue related to light sources. New functions/applications have arisen along the way as hybrid photonics technologies continue to develop. Elegant solutions at both the design and fabrication level have been found, creating new opportunities for advanced hybrid devices and circuits. APL Photonics is the perfect channel to communicate on these new and exciting developments, and the editorial team looks forward to receiving your contributions that continuously unravel how innovative ways to harness hybrid photonics allows us to go far beyond silicon photonics.

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