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Perspective

The emerging applications of silicon photonics

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ACCESSIBLE OVERVIEW Silicon photonics (SiP) has rapidly evolved from data-communication technology into a broadly enabling platform for modern physics and engineering. Its foundation on CMOS-compatible fabrication processes provides desirable scalability, cost-efficiency, and integration density, allowing light to be generated, routed, and processed on a chip with the same maturity as electronic circuits. This convergence is revolutionizing how photons can be harnessed for sensing, computation, and information processing. In particular, recent advances are propelling SiP beyond data centers into three frontiers. In LiDAR, chip-scale frequency-modulated continuous-wave systems employing optical phased arrays are delivering solid-state beam steering and coherent ranging for autonomous navigation. In quantum technologies, SiP offers a manufacturable path toward large-scale processors through heterogeneous integration of active materials such as barium titanate and superconducting detectors, enabling low-loss, high-fidelity quantum interconnects. In neuromorphic computing, SiP leverages wavelength and time-division multiplexing to perform massive parallel optical matrix operations with high energy efficiency, pointing toward ultra-fast, low-latency AI hardware. In addition, the integration of phase-changing materials and ferroelectric materials allows for multi-level programmability of neural-network synapses. This perspective discusses how SiP is changing from an application-specific solution to a general-purpose photonic platform capable of unifying communication and computation. By integrating photonics and electronics within a shared architecture, SiP stands to revolutionize the next generation of quantum-aware, perception-enabled, and energy-conscious physical systems, ushering in a new paradigm where information is processed at the speed of light.

SUMMARY

Silicon photonics (SiP) is a disruptive photonic platform offering unprecedented possibilities via advantages in photonic integration density and scalability. The technology has witnessed significant commercial success, particularly in data-center applications with co-packaged optics (CPO) and high-speed transceivers, with leading manufacturers reporting 1.6-Tbp/s interconnect performance. This perspective highlights how SiP is set to disrupt emerging verticals: light detection and ranging (LiDAR), quantum processing, and neuromorphic computing. SiP will be indispensable for autonomous systems, where silicon optical phased arrays (OPAs) deliver solid-state beam steering and coherent detection for simultaneous range and velocity determination. SiP will also enable manufacturable and scalable quantum computing through frequency-domain parallelization, modular fiber-link architectures, and complementary metal-oxide semiconductor (CMOS)-compatible platforms. SiP is also anticipated to power ultra-low-latency edge applications through wavelength-diverse all-optical processing and hybrid photonic-electronic architectures. In light of recent

developments, we present our perspective on the potential of SiP to drive the next generation of sensing, computing, and artificial intelligence systems.

INTRODUCTION

Silicon photonics (SiP)[1] began as a solution for bandwidth limitations in telecommunications. It is now poised to dominate hyper-scale data centers, where co-packaged optics (CPO) switches deliver 1.6 Tbp at markedly lower joules per bit. However, as one examines the applications demonstrated on SiP, it quickly becomes apparent that SiP sits at an inflection point of moving from a specialist technology toward a general-purpose platform for photonics. Of particular prominence would be light detection and ranging (LiDAR), quantum logic, and neuromorphic computing, three areas of pivotal importance as we witness the current unprecedented advancement in technology.[2–4] The broad relevance of SiP is further supplemented by the ongoing development in heterogeneous integration, where various functional materials (i.e., III-V, lithium niobate, barium titanate [$BaTiO_3$]) are brought into 300-mm process lines, promising "more than Moore" functionality with CMOS yield.[5]

The case for SiP as a general-purpose photonic platform can be critically attributed to its unique and unprecedented advantages in terms of integration densities and manufacturability. The fundamental reason behind the interest in photonic technologies is motivated by the power and bandwidth limitations in electronics in situations where massive parallelism is desired.[6] Surveying competing platforms, while III-V features direct bandgap for efficient light emission, small wafer sizes limit scalability and integrability. Thin-film lithium niobate confers excellent linear modulation characteristics ($V\pi < 1$ V), but its large device footprint limits on-chip integration density.[7] A compelling alternative would be the $BaTiO_3$-SiN heterogeneous platform where ultra-efficient and compact (millimeter-scale) modulation efficiencies have been routinely demonstrated ($V\pi \approx 0.2$–0.6 V·cm).[8] Looking further, electro-optic polymers fill an important niche in terms of enabling power-efficient, quasi-static control.[9] This perspective serves to examine the potential of SiP in LiDAR, quantum, and neuromorphic computing, providing an outlook and commentary on the current state and challenges.

New frontiers in SiP

Chip-scale 3D sensing

It is highly probable that SiP will feature prominently in frequency-modulated continuous-wave (FMCW) LiDAR systems where this revolutionary technique has impacted applications such as autonomous driving,[10] robotics,[11] and metrology.[12] By operating on shorter optical waves in contrast to radio detection and ranging (RADAR) systems, FMCW LiDAR will feature superior, diffraction-limited, three-dimensional sensing with higher spatial resolution and smaller apertures. SiP, as a solid-state technology, provides an appealing alternative to conventional LiDAR systems, critically eliminating all moving parts. To further elaborate, the diverse range of functionalities within the SiP component portfolio establishes a clear pathway toward solid-state, full-system, chip-scale integration,[13] where components such as lasers, photodetectors, modulators, filters, couplers, and optical phased arrays (OPAs) can all be implemented on a single chip (Figure 1B).

A key subsystem in SiP-based FMCW LiDAR is the integrated OPA, which coherently distributes a single optical input across an on-chip antenna array.[13] By individually controlling the amplitude and phase of each emitter, OPAs enable beamforming and steering without mechanical components. The general goals for these OPAs are to achieve small beam divergences by utilizing large aperture sizes, wide beam-steering fields of view (FOVs), and low electrical and optical power consumption. For instance, quasi-1D OPAs[14–16] typically constitute a splitter-tree distribution network that feeds an array of long integrated grating-based antennas[17] (Figure 1C). Within these architectures, beam steering is achieved by wavelength tuning, and steering in the array dimension is accomplished by phase tuning of each antenna via integrated modulators. Another example are true-2D OPAs, which comprise a distribution network leading to a 2D array of small integrated grating-based antennas.[18,19] In this design, bidimensional beam steering is achieved electro-optically by controlling the phase of each antenna element, with the tradeoffs generally among antenna spacing, FOVs, and optical efficiencies. Other instances include arrayed-waveguide-grating-based OPAs for pure-wavelength-based 2D steering,[20] sparse non-uniform OPAs for grating-lobe suppression,[21] star-coupler-based OPAs for multi-beam operation,[22] and other OPA-adjacent architectures such as focal-plane arrays.[2] Notably, OPA systems have found applications beyond LiDAR, encroaching into free-space optical communications,[15] augmented-reality displays,[23] biophotonic optical tweezers,[24] and 3D printers.[25]

The current autonomous vision landscape comprises several competing technologies where camera-based systems dominate commercially. Like FMCW LiDAR, coherent RADAR also enables the simultaneous determination of range and velocity, albeit by utilizing significantly longer wavelengths.[26] On the other hand, time-of-flight (ToF) LiDAR operates by emitting energetic optical pulses where the range is determined through the measured round-trip time. ToF LiDAR is experiencing growing market prominence as the economies of scale from the prevalent adoption of the advanced driver-assurance system (ADAS) drives costs down.[10] As a nascent technology, it would be realistic to admit the technical hurdles that remains for SiP FMCW LiDAR. However, as described in the following paragraph, SiP FMCW LiDAR will offer particular advantages over its contemporaries that will prove to be invaluable in the long run.[15] The heterodyne principles on which FMCW LiDAR are based necessitate precise linear frequency sweeps that map round-trip delays into a stationary beat note via the chirp slope. In addition, the range resolution and maximum distance of LiDAR are fundamentally limited by the linewidth of the driving laser.[16] These requirements imply that integrating spectrally pure lasers with ultra-fast linear-chirp capability is among the foremost requirements. However, this goal is hindered by the limited modulation mechanisms in conventional SiP platforms (thermo-optic and carrier-injection/depletion effects), which necessitate additional linearization feedback and

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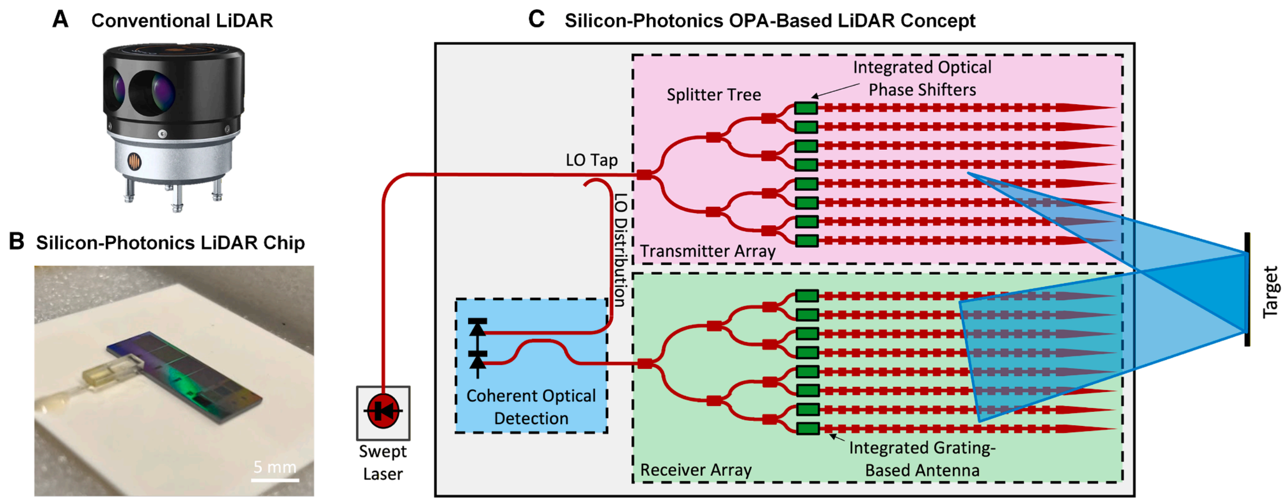

Figure 1. SiP for LiDAR applications

(A and B) Photograph of (A) a conventional mechanical LiDAR sensor with rotating components versus (B) a SiP-based solid-state LiDAR sensor demonstrating compact integration.

(C) Conceptual diagram of a typical SiP OPA-based FMCW LiDAR system, illustrating the TX/RX OPAs, FMCW laser source, and coherent detection circuitry.

digital signal processing.[9] The heterogeneous integration of Pockels materials such as lithium niobate, lithium tantalate, or $BaTiO_3$ presents an exciting strategy to enable ultra-fast and linear phase control. $BaTiO_3$ could be instrumental in large-scale, compact OPAs where the energetic cost scales with $1/2 \times CV^2$—the exemplary electro-optic coefficient of $BaTiO_3$ allows smaller system footprint and lower V_π.[8] Furthermore, electro-optic polymers and liquid crystals can be excellent for low-frequency phase control, where stable and highly efficient operation have been demonstrated.[9,27] Alternatively, it may be interesting to consider that the external implementation of electro-optic components could prove to be superior, avoiding the complex nonlinearities of the laser cavity. Chip-scale optoelectronic integration remains a universal challenge for SiP technologies, particularly in FMCW LiDAR systems. A viable SiP FMCW system requires substantial electronic infrastructure for beam steering, chirp generation, coherent detection, low-noise laser current injection, and laser-frequency stabilization.[19] To date, several promising proofs of concepts have been demonstrated: flip-chip-integrated application-specific integrated circuits (ASICs) for OPA beam steering and FMCW LiDAR sensing,[16] monolithically integrated CMOS for OPA beam steering,[19] 3D-integrated CMOS for OPA beam steering,[13] and FMCW LiDAR sensing.[14] These demonstrations establish promising approaches toward fully integrated SiP FMCW LiDAR modules.

SiP FMCW LiDAR uniquely facilitates the synergistic combination of coherent optics with CMOS-class manufacturability and cutting-edge performance.[14] Relative to current perception technologies, SiP FMCW LiDAR confers distinct technical advantages. Coherent Doppler detection facilitates the simultaneous single-shot measurement of the phase and velocity point cloud at millimeter- to centimeter-scale resolution.[16] By exploiting the principles of coherent detection, SiP FMCW LiDAR is inherently resilient to ambient light interference. In addition, the wavelength region of 1.55 μm is eye-safe, which permits higher average power within eye-safety limits.[15] This critically leverages the time-bandwidth product for improved signal processing gain. Shot-noise limited detection will further reduce susceptibility to crosstalk between adjacent optical channels. Furthermore, the shorter operating wavelengths in contrast to millimeter-wave FMCW LiDAR will enable significantly higher range and velocity resolution.

Currently, SiP FMCW LiDAR occupies a modest fraction of the autonomous-vision market. In spite of this, we anticipate significant adoption of these systems as AI agents transit from the virtual space into physical embodiments via autonomous robotics.[28] The proliferation of physical agents will inevitably require vision sensors that possess the following features that can uniquely be attained via SiP FMCW systems: compact, energetically efficient, operate at eye-safe wavelength for human-proximate deployment, possess ability for simultaneous range and velocity determination with high precision, and resilient against multi-agent interference.[11] Addressing the latter is especially imperative for scalable autonomous deployment where systems must operate reliably despite electromagnetic crosstalk from adjacent units. To that effect, we propose the implementation of a waveform-provisioning policy that incorporates FMCW-parameter diversity and wavelength channelization. This will provide each physical agent with a unique perception signature that will serve to reduce the probability of inter-system interference. It can be concluded that SiP FMCW LiDAR is poised to serve as the primary perception modality for these agents. Moving forward, we anticipate that the primary demand for SiP FMCW LiDAR will be driven by autonomous physical agents, which will in turn reduce manufacturing costs, subsequently enabling broader market penetration. Nevertheless, SiP FMCW LiDAR should be regarded as a complementary technology rather than a replacement for the incumbent.[26]

Scalable photonic qubits

The fundamental goal of quantum computing is to solve problems that are intractable for classical computers. For example, in quantum chemistry, predicting binding energies and excited states requires computational resources that scale exponentially on classical platforms. The advantages of SiP quantum computing are 3-fold: foundry-scale manufacturability, frequency parallelization, and high-fidelity chip-to-chip connectivity.[3] Together, these raise the possibility of building modular, fiber-linked architectures that will potentially enable scaling into million-qubit systems. Current approaches in SiP split along two main paradigms: all-photonic, measurement-based linear optical quantum computing, and spin-photon architecture that integrates stationary-matter qubits to photonics.[3,29,30] Notably, PsiQuantum has recently reported the ultra-low-loss heterogeneous $BaTiO_3$-*SiN* wafer-scale photonic quantum computing platform, comprising SiN waveguides, heterogeneous $BaTiO_3$-*SiN* highly efficient phase shifters, and superconducting nanowire single-photon detectors (SNSPDs) demonstrating the possibility of fault-tolerant quantum computing, predicated upon SiP. In further detail, 99.98% ± 0.01% state preparation and measurement fidelity, 99.50% ± 0.25% Hong-Ou-Mandel visibility, and 99.72% ± 0.04% chip-to-chip interconnect fidelity have been reported.[3] From a platform perspective, the electro-optic effect of $BaTiO_3$ persists at cryogenic temperatures, enabling the phase shifters to be operated in conjunction with the SNSPDs on the same chip, reducing the footprint of the photonic quantum system. These seminal results represent substantial progress toward the goal of quantum-advantage-utility-scale quantum processors. At the same time, the broader quantum-photonics community have placed distinct bets to attain quantum scalability. For instance, deterministic emitters to reduce multiplexing overhead and continuous-variable and Gottesman-Kitaev-Preskill (GKP) encodings to reduce hardware requirements.[31]

As opposed to the photonic-centered approaches mentioned above, T-center photonic quantum computing leverages on the spin-photon interaction.[29] The long electron and nuclear spin lifetimes within silicon will enable memory-rich, modular processors where spins can be stored locally on chip, and photons are used to interconnect various quantum memory nodes. The challenge, however, lies in deterministic defect placement, spectral homogeneity across large arrays, and cavity-enhanced spin-photon coupling.

Recent advances in key enabling technologies are addressing challenges in SiP quantum computing. Inspired by classical wavelength-division multiplexing (WDM), multi-frequency quantum computing has emerged as a particularly promising approach in SiP. By utilizing silicon microresonators, single-qubit gates across 34 distinct frequency bins (21 GHz) have been demonstrated.[30] Furthermore, the integration of phase-change materials (PCMs), particularly antimony selenide (Sb_2Se_3), enables ultra-low-loss reconfigurable quantum circuits.[32] This will address large interferometric meshes and frequency-bin circuits where static reconfigurability dominates. Furthermore, theoretical studies have suggested that quantum nonlinear regimes, while thought to require prohibitive Q-factors, could be reduced by orders of magnitude via non-classical driving protocols.[33] This will increase the ease of access to quantum nonlinear regimes, facilitating the deterministic entangling of gates, unconditional few-photon-state preparation, and quantum non-demolition measurements in SiP. The quantum SiP component ecosystem is further supplemented by the heterogeneous integration of III-V optical materials and SNSPDs.[4,34] This thriving field provides encouragement toward the ultimate goal of SiP-based, quantum-utility-scale processors.

From a broader perspective, quantum computing can be classified into four categories: atom,[35] ion,[36] superconducting,[37] and photonic systems.[3,38] In the near term, it is our opinion that superconducting circuits are poised to demonstrate utility-scale processors. Superconductor-based quantum computing have demonstrated below-threshold surface-code memories on production-level hardware with ~1.1-μm code cycles and real-time decoding.[39] This is combined with nanosecond-scale gates and millisecond-class coherence. Nonetheless, challenges such as cryogenic-induced correlated errors and the limited connectivity will hinder large-scale implementation.[3] SiP can overcome these limitations by serving as a quantum interconnect. More interestingly, advances in meta-optics will also provide an additional modality of interconnection (Figure 2). It is, however, our opinion that the inherent advantages of SiP in terms of manufacturing and networking will position it as the *de facto* platform for large-scale quantum processors in the long run. The 300-mm wafer-scale demonstration of GKP states in *SiN* with photon-number-resolving detectors has demonstrated scalability of a primary fault-tolerant component.[31] Fusion-based quantum computing has indicated fault tolerance that trades squeezing against loss.[3] Leveraging the modularity of SiP and fiber networks, single-photon detectors can be operated at cryogenic temperatures independently of the remaining room-temperature components.[40] Recent progress offers strong optimism for the long-term feasibility of SiP-based quantum computing. However, further developments are necessitated, particularly in addressing end-to-end loss budgets, on-chip GKP implementation, fusion-resource generation, SNSPD integration, and photonic interconnects.

Computing at light speed

Demands for computing bandwidths have highlighted the limitations of classical von Neumann architectures due to the separation of memory and computation.[41] Recent demonstrations have indicated that SiP can alleviate these issues significantly.[42,43] However, SiP neuromorphic computing is unlikely to constitute a like-for-like replacement to electronic accelerators; rather, we view it as complementary. Driven by wavelength parallelism and in-memory processing, the platform offers unprecedented gains in computational efficiencies, which will facilitate all-optical matrix-vector multiplications that form the backbone of all neural networks.[42] In essence, it can be seen that the natural role of photonic neuromorphic processors lies in relieving memory movement and bottlenecks associated with analog linear algebra and not as a substitute for trillion-parameter training.

By employing a diffractive-interference hybrid design, the Taichi chiplet (Figure 3A) has achieved an energy efficiency of 160 TOPS/W, representing an order-of-magnitude improvement compared to conventional processors.[4] These results are achieved through the application of distributed computing that supports millions of neurons while maintaining coherent optical processing. The architecture implements photonic reconfigurability through electronics, where linear compute is

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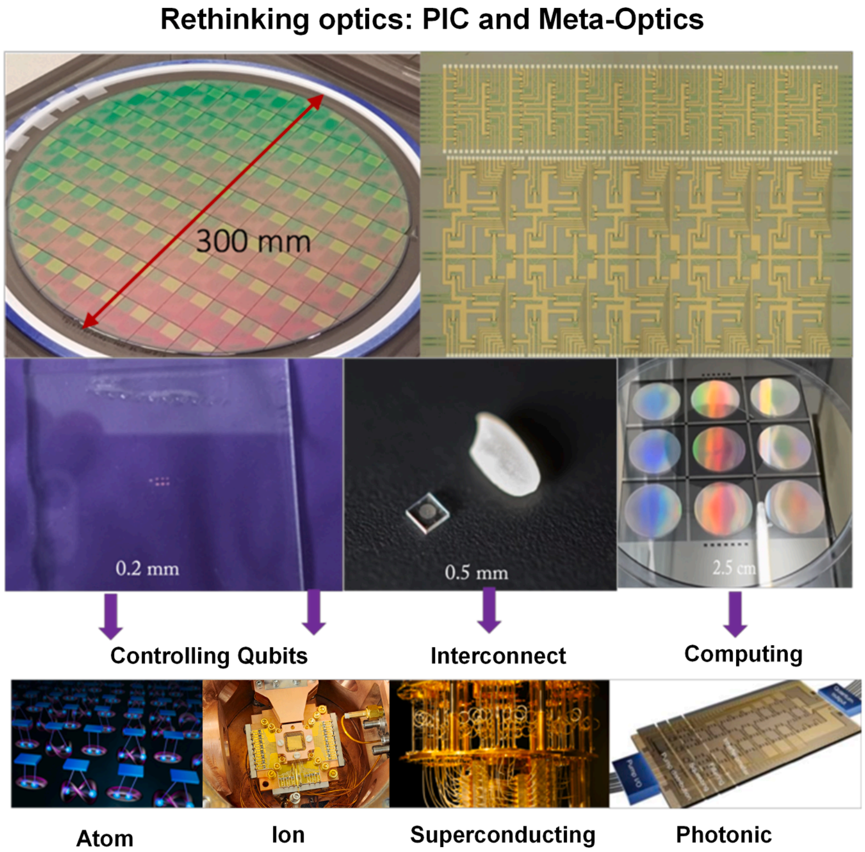

Figure 2. SiP for quantum computing
Engineered semiconductor optics is expected to play an increasingly important role in scaling up quantum information-processing systems. SiP and meta-optics (developed by A.M.'s group) will play an ever-growing role in multiple aspects of quantum information processing: qubit control, interconnect, and compute. The bottom row indicates the atom (credit: Sampson Wilcox/RLE), ion (credit: Y. Colombe/NIST), superconducting (reproduced from Castelvecchi.[37]), and photonic-based quantum computing platforms (reproduced from Xanadu[38]).

distributed through multiple interferometric paths. Specifically, this demonstration highlights the niche of SiP in terms of bandwidth and latency.

Ongoing efforts to enhance integration density, operational flexibility, and energy efficiency have produced remarkable architectural diversity. Mach-Zehnder interferometer meshes implement unitary transformation through singular-value decomposition, facilitating precision at the expense of larger footprints.[42] Conversely, compact microring-based arrays can leverage the parallelism derived from WDM strategies, increasing integration density. More specifically, such systems have indicated computation densities exceeding 34 $TOPS/mm^2$.[46] Similar to quantum processors, PCMs are commonly implemented in SiP-based photonic neuromorphic circuits to eliminate static power consumption, offering multi-level programmability.[45] Notably, non-volatile ferroelectric memory based on $BaTiO_3$ offers an attractive alternative to PCMs, enabling pure phase memory through ferroelectric domain manipulation that alters the refractive index without inducing absorption.[47] In spite of the above, it would be important to point out that constraints in wavelength diffraction result in significantly lower weight density compared to CMOS memories. Consequently, current approaches employ time-division multiplexing (TDM) and WDM,[6] where parameters are electronically streamed and high-bandwidth multiply-accumulate operations are executed in photonic domains.

All-optical neuromorphic circuits (Figure 3C), in principle, represent the optimal architecture from an energy-efficiency standpoint. Hybrid methods have yielded nanosecond-level compute loops,[43] but full-optical stacks could promise identical levels of latency with significantly lower per-layer conversion overhead. This is, however, predicated upon the reduction in nonlinear power threshold. The development of photonic neurons with stronger nonlinear response remains the central challenge in photonic neuromorphic computing.[48] The energetic advantage of all-optical neuromorphic circuits depends on several prerequisites: low-threshold, cascadable optical nonlinearities (i.e., InP spiking neurons), loss-tolerant fanout (i.e., loss penalty per layer), and variability budgets (i.e., fabrication-induced phase variation, PCM cell uniformity). To that effect, all-optical neuromorphic circuits might represent a long-horizon target.

Research in this field has expanded to dynamic, time-encoded computing models, particularly spiking and reservoir paradigms. The former, inspired by biological neurons that encode information through temporal spike patterns, benefits from the intrinsic temporal resolution of SiP (Figure 3D).[45] Furthermore, the option to integrate these SiP neuromorphic circuits with the existing optical communication infrastructure positions this technology uniquely for edge-computing applications, where ultra-low-latency decision, autonomous navigation, and real-time signal processing are warranted.[49] Recent demonstrations of photonic reservoir computing for telecommunication highlight this synergy, where nonlinear equalization is performed directly in the optical domain.[50]

The most viable path forward for SiP neuromorphic computing might not involve the pursuit of all-optical systems. Rather, the judicious electronic-SiP co-design can leverage the complementary strengths. Photonics can be used for high-bandwidth linear operations, while electronics remain crucial for signal regeneration, memory storage, and complex control logic.[44] The integration of $BaTiO_3$ for highly efficient phase modulation and memory can reduce aggregate photonic system loss and energetic requirements.[8] 3D integration technologies offer a clear path for the monolithic integration of SiP with electronics.[13]

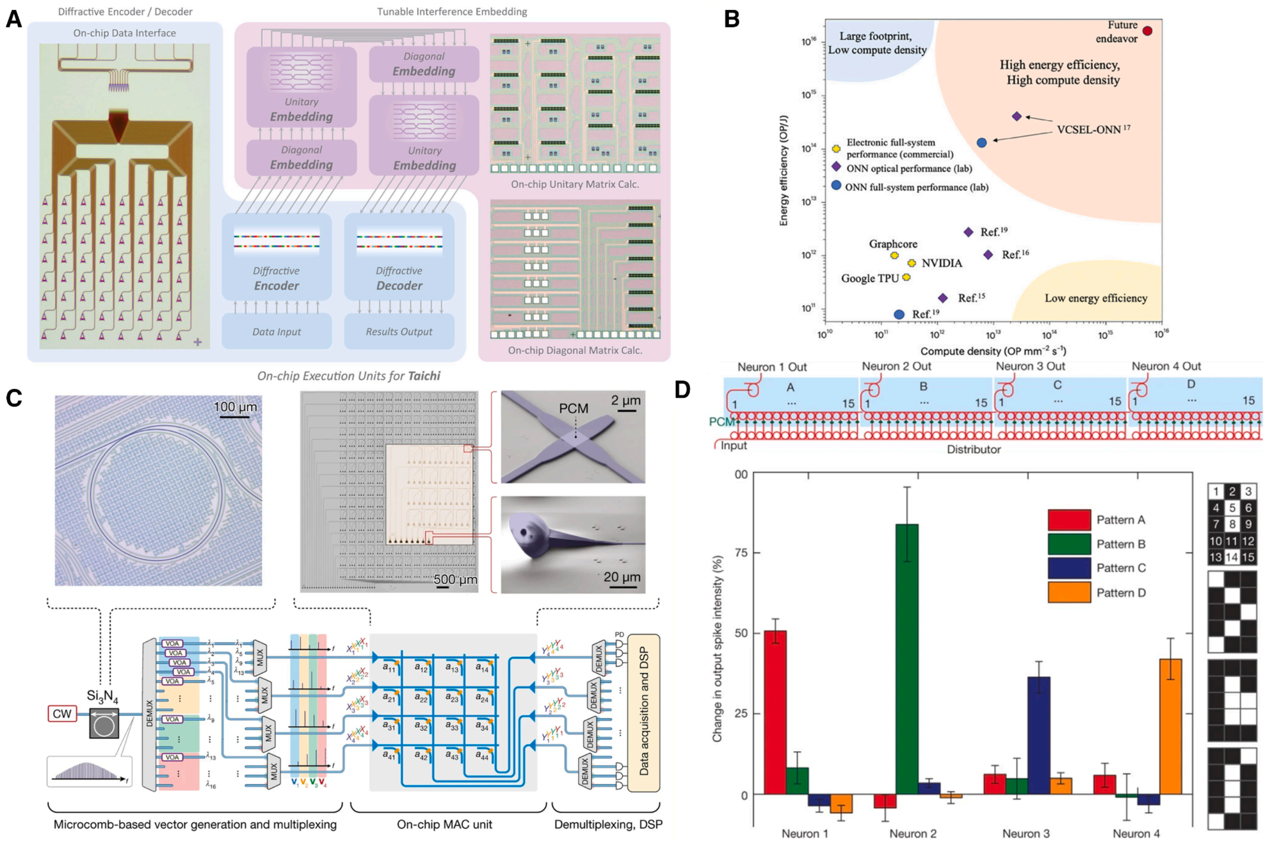

Figure 3. SiP for neuromorphic computing

(A) Schematic of the Taichi photonic chiplet showing diffractive-interference hybrid architecture achieving 160-TOPS/W efficiency. Reproduced with permission from Xu et al.[4]

(B) Performance comparison of photonic neuromorphic processors versus electronic counterparts, demonstrating superior energy efficiency and computational density. Reproduced with permission from Li et al.[44]

(C) Integrated photonic tensor core based on PCM crossbar arrays enabling parallel convolutional processing. Reproduced with permission from Feldmann et al.[43]

(D) All-optical spiking neural-network implementation with PCM-based synaptic weights for in-memory computing. Reproduced with permission from Feldmann et al.[45]

Two fundamental constraints will shape the practical scaling of SiP neuromorphic systems. First, photonic synaptic density in SiP is ultimately bounded by wavelength-scale devices and bend radii. It is important to note that WDM/TDM mitigates but does not address the fundamental limitation. In addition, development in scalable multi-material integration processes must be attained before *in situ* updates across large arrays become routine. Significant progress in these multi-material optoelectronic platforms makes photonic-electronic weight virtualization the pragmatic strategy for the continued scaling of these systems.

The unique advantage of SiP neuromorphic circuits can be derived from edge-processing (i.e., front-end perception),[49] targeting applications that focus on latency rather than parameter count. We believe that SiP neuromorphic circuits will establish a foothold in low-latency edge inference performing bandwidth-heavy linear subroutines where large-scale training will remain electronic-centric for the foreseeable future.

DISCUSSION

This perspective highlights the transition of SiP as a general-purpose photonic platform for the generation, manipulation, and detection of light at scale. We expect that SiP will be the primary photonic platform that drives applications across FMCW LiDAR, quantum processing, and neuromorphic computing. The key challenges confronting these applications are common, extending to the broader ecosystem: scalable integration of an electrically pumped coherent light source, process uniformity across large-scale photonic circuits, high-density optoelectronic integration, and heterogeneous integration. The latter is of significant importance, as discussed in this perspective, where recent breakthroughs in SiP applications are driven by heterogeneous integration where the native functionalities offered by conventional SiP might be insufficient (i.e., lack of monolithic electrically pumped lasers and Pockels effect). We believe that further development and democratization of heterogeneous processes will be pivotal toward the growth of SiP as a general-purpose photonic platform. Furthermore, the most ideal system architectures will be optoelectronic, leveraging the bandwidth of photonics and the strengths of electronics in terms of memory and logic. As such, the development of an advanced silicon photonic-electronic framework will be imperative. Investments in hardening SiP processes, standardized and deterministic heterogeneous integration, and advanced optoelectronic frameworks will yield multiplicative returns, accelerating the development of SiP LiDAR, quantum processors, and neuromorphic computing.

In our view, the path forward requires a shift from development in application-specific silos toward standardization in components, processes, and electronic-photonic integration. Critically, this will create a cohesive SiP ecosystem where fundamental aspects of developments are consolidated, de-risking otherwise costly developments and processes that would be difficult to justify for a single photonic application.

Furthermore, the functional synergies between the applications highlighted in this perspective can potentially enable systems that exhibit novel capabilities. OPAs can be integrated within defect- and ion-based quantum systems to function as free-space quantum interconnects, facilitating precise beam delivery. Embedding SiP neuromorphic circuits within LiDAR will enable low-latency perception to decision for edge-autonomous robotic systems. The integration of SiP neuromorphic circuits with quantum processors can potentially provide autonomous, energetically efficient, ultra-low-latency classical control that will be able to keep pace with quantum state evolution and error accumulation.

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AUTHOR CONTRIBUTIONS

J.X.B.S., W.J., Q.W., A.M., J.N., and J.H. came up with the overall direction of the perspective and revised the overall article. L.R., Y.Z.T., A.G.C., and V.H.N.T. drafted, reviewed, and revised the manuscript on their respective parts (L.R., introduction, summary, and scalable photonic qubits; Y.Z.T., discussion, chip-scale 3D sensing, and figures; A.G.C., scalable photonic qubits, computing at light speed, and figures; V.H.N.T., chip-scale 3D sensing, computing at light speed, and references). S.T., L.M.-M., and H.W. reviewed and revised the chip-scale 3D sensing section. Y.S. and X.L. reviewed and revised the scalable photonic qubits section. Z.X., S.H.C., and J.Q.L. reviewed and revised the computing at light speed section. Y.S. reviewed and revised the references.

DECLARATION OF INTERESTS

The authors declare no competing interests.

REFERENCES

1. Sia, J.X.B., Li, X., Wang, J., Wang, W., Qiao, Z., Guo, X., Chen, J., Zhang, X., Yang, K., Zhang, H., et al. (2022). Wafer-scale demonstration of low-loss (∼0.43 db/cm), high-bandwidth (>38 ghz), silicon photonics platform operating at the c-band. IEEE Photon. J. *14*, 1–8.
2. Zhang, X., Kwon, K., Henriksson, J., Luo, J., and Wu, M.C. (2022). A large-scale microelectromechanical-systems-based silicon photonics LiDAR. Nature *603*, 253–258.
3. PsiQuantum team (2025). A manufacturable platform for photonic quantum computing. Nature *641*, 876–883.
4. Xu, Z., Zhou, T., Ma, M., Deng, C., Dai, Q., and Fang, L. (2024). Large-scale photonic chiplet taichi empowers 160-TOPS/W artificial general intelligence. Science *384*, 202–209.
5. Shekhar, S., Bogaerts, W., Chrostowski, L., Bowers, J.E., Hochberg, M., Soref, R., and Shastri, B.J. (2024). Roadmapping the next generation of silicon photonics. Nat. Commun. *15*, 751.
6. Daudlin, S., Rizzo, A., Lee, S., Khilwani, D., Ou, C., Wang, S., Novick, A., Gopal, V., Cullen, M., Parsons, R., et al. (2025). Three-dimensional photonic integration for ultra-low-energy, high-bandwidth interchip data links. Nat. Photonics *19*, 502–509.
7. Hu, Y., Zhu, D., Lu, S., Zhu, X., Song, Y., Renaud, D., Assumpcao, D., Cheng, R., Xin, C.J., Yeh, M., et al. (2025). Integrated electro-optics on thin-film lithium niobate. Nat. Rev. Phys. *7*, 237–254.
8. Demkov, A.A., and Posadas, A.B. (2024). Ferroelectric batio3 for electro-optic modulators in si photonics. IEEE J. Sel. Top. Quantum Electron. *30*, 1–13.
9. Taghavi, I., Moridsadat, M., Tofini, A., Raza, S., Jaeger, N.A.F., Chrostowski, L., Shastri, B.J., and Shekhar, S. (2022). Polymer modulators in silicon photonics: review and projections. Nanophotonics *11*, 3855–3871.
10. Li, Y., and Ibanez-Guzman, J. (2020). Lidar for autonomous driving: The principles, challenges, and trends for automotive lidar and perception systems. IEEE Signal Process. Mag. *37*, 50–61.
11. Perez-Grau, F.J., Martinez-de Dios, J.R., Paneque, J.L., Acevedo, J.J., Torres-González, A., Viguria, A., Astorga, J.R., and Ollero, A. (2021). Introducing autonomous aerial robots in industrial manufacturing. J. Manuf. Syst. *60*, 312–324.
12. Trocha, P., Karpov, M., Ganin, D., Pfeiffer, M.H.P., Kordts, A., Wolf, S., Krockenberger, J., Marin-Palomo, P., Weimann, C., Randel, S., et al. (2018). Ultrafast optical ranging using microresonator soliton frequency combs. Science *359*, 887–891.
13. Ranno, L., Sia, J.X.B., Dao, K.P., and Hu, J. (2023). Multi-material heterogeneous integration on a 3-d photonic-cmos platform. Opt. Mater. Express *13*, 2711.
14. Bhargava, P., Kim, T., Poulton, C.V., Notaros, J., Yaacobi, A., Timurdogan, E., Baiocco, C., Fahrenkopf, N., Kruger, S., Ngai, T., et al. (2019). Fully integrated coherent LiDAR in 3D-integrated silicon photonics/65nm CMOS. In 2019 Symposium on VLSI Circuits (IEEE), pp. C262–C263.
15. Poulton, C.V., Byrd, M.J., Russo, P., Timurdogan, E., Khandaker, M., Vermeulen, D., and Watts, M.R. (2019). Long-range LiDAR and free-space data communication with high-performance optical phased arrays. IEEE J. Sel. Top. Quantum Electron. *25*, 1–8.
16. Poulton, C.V., Byrd, M.J., Russo, P., Moss, B., Shatrovoy, O., Khandaker, M., and Watts, M.R. (2022). Coherent LiDAR with an 8,192-element optical phased array and driving laser. IEEE J. Sel. Top. Quantum Electron. *28*, 1–8.
17. Garcia Coleto, A., Notaros, M., and Notaros, J. (2024). Visible-light uniform and unidirectional grating-based antennas for integrated optical phased arrays. Opt. Express *32*, 46447–46466.
18. Fatemi, R., Khachaturian, A., and Hajimiri, A. (2019). A nonuniform sparse 2-D large-FOV optical phased array with a low-power PWM drive. IEEE J. Solid-State Circuits *54*, 1200–1215.
19. Chung, S., Abediasl, H., and Hashemi, H. (2018). A monolithically integrated large-scale optical phased array in silicon-on-insulator CMOS. IEEE J. Solid-State Circuits *53*, 275–296.
20. Liu, Y., Zhang, C., DeSantis, D.M., Hu, D., Meissner, T., Notaros, J., and Klamkin, J. (2025). High-resolution arrayed waveguide grating-assisted passive optical phased array for 2D beam steering. Opt. Express *33*, 7714–7722.

21. Hutchison, D.N., Sun, J., Doylend, J.K., Kumar, R., Heck, J., Kim, W., Phare, C.T., Feshali, A., and Rong, H. (2016). High-resolution aliasing-free optical beam steering. Optica *3*, 887–890.
22. DeSantis, D.M., Mazur, B.M., Notaros, M., and Notaros, J. (2024). Multi-beam solid-state LiDAR using star-coupler-based optical phased arrays. Opt. Express *32*, 36656–36673.
23. Notaros, J., Raval, M., Notaros, M., and Watts, M.R. (2019). Integrated-phased-array-based visible-light near-eye holographic projector. In 2019 Conference on Lasers and Electro-Optics (CLEO) (IEEE), pp. 1–2.
24. Sneh, T., Corsetti, S., Notaros, M., Kikkeri, K., Voldman, J., and Notaros, J. (2024). Optical tweezing of microparticles and cells using silicon-photonics-based optical phased arrays. Nat. Commun. *15*, 8493.
25. Corsetti, S., Notaros, M., Sneh, T., Stafford, A., Page, Z.A., and Notaros, J. (2024). Silicon-photonics-enabled chip-based 3d printer. Light Sci. Appl. *13*, 132.
26. Zhang, Y., Carballo, A., Yang, H., and Takeda, K. (2023). Perception and sensing for autonomous vehicles under adverse weather conditions: A survey. ISPRS J. Photogrammetry Remote Sens. *196*, 146–177.
27. Yang, Y., Forbes, A., and Cao, L. (2023). A review of liquid crystal spatial light modulators: devices and applications. Opto-Electronic Science *2*, 230026.
28. Roriz, R., Cabral, J., and Gomes, T. (2022). Automotive lidar technology: A survey. IEEE trans. Intell. Transp. Syst. *23*, 6282–6297.
29. Higginbottom, D., DeAbreu, A., Bowness, C., Alizadeh, A., Chartrand, C., Brunelle, N., MacQuarrie, E., Lee-Hone, N., Ruether, M., Kazemi, M., et al. (2023). Integrated silicon t centres for quantum technologies. In Quantum Computing, Communication, and Simulation III vol. 12446 of *SPIE Proceedings*, p. 124460T.
30. Henry, A., Fioretto, D.A., Procopio, L.M., Monfray, S., Boeuf, F., Vivien, L., Cassan, E., Alonzo-Ramos, C., Bencheikh, K., Zaquine, I., and Belabas, N. (2024). Parallelization of frequency domain quantum gates: manipulation and distribution of frequency-entangled photon pairs generated by a 21 GHz silicon microresonator. Adv. Photonics *6*, 036003.
31. Larsen, M.V., Bourassa, J.E., Kocsis, S., Tasker, J.F., Chadwick, R.S., González-Arciniegas, C., Hastrup, J., Lopetegui-González, C.E., Miatto, F.M., Motamedi, A., et al. (2025). Integrated photonic source of gottesman–kitaev–preskill qubits. Nature *642*, 587–591.
32. Fang, Z., Mills, B., Chen, R., Zhang, J., Xu, P., Hu, J., and Majumdar, A. (2024). Arbitrary programming of racetrack resonators using low-loss phase-change material Sb 2Se 3. Nano Lett. *24*, 97–103.
33. Lingenfelter, A., Roberts, D., and Clerk, A.A. (2021). Unconditional fock state generation using arbitrarily weak photonic nonlinearities. Sci. Adv. *7*, eabj1916.
34. Davanco, M., Liu, J., Sapienza, L., Zhang, C.Z., De Miranda Cardoso, J.V., Verma, V., Mirin, R., Nam, S.W., Liu, L., and Srinivasan, K. (2017). Heterogeneous integration for on-chip quantum photonic circuits with single quantum dot devices. Nat. Commun. *8*, 889.
35. J. Chu (2022). Vibrating atoms make robust qubits, physicists find. https://news.mit.edu/2022/vibrating-atoms-qubits-0126.
36. IonQ (2018). Ion-based commercial quantum computer is a first. https://physicsworld.com/a/ion-based-commercial-quantum-computer-is-a-first/.
37. Castelvecchi, D. (2023). Google's quantum computer hits key milestone by reducing errors. Nature. https://doi.org/10.1038/d41586-023-00536-w.
38. Xanadu (2025). Integrated quantum photonics. https://strawberryfields.ai/photonics/hardware/details.html.
39. Google Quantum AI and Collaborators (2025). Quantum error correction below the surface code threshold. Nature *638*, 920–926.
40. de Cea, M., Wollman, E.E., Atabaki, A.H., Gray, D.J., Shaw, M.D., and Ram, R.J. (2020). Photonic readout of superconducting nanowire single photon counting detectors. Sci. Rep. *10*, 9470.
41. Jones, N. (2018). How to stop data centres from gobbling up the world's electricity. Nature *561*, 163–166.
42. Shastri, B.J., Tait, A.N., Ferreira de Lima, T., Pernice, W.H.P., Bhaskaran, H., Wright, C.D., and Prucnal, P.R. (2021). Photonics for artificial intelligence and neuromorphic computing. Nat. Photonics *15*, 102–114.
43. Feldmann, J., Youngblood, N., Karpov, M., Gehring, H., Li, X., Stappers, M., Le Gallo, M., Fu, X., Lukashchuk, A., Raja, A.S., et al. (2021). Parallel convolutional processing using an integrated photonic tensor core. Nature *589*, 52–58.
44. Li, R., Gong, Y., Huang, H., Zhou, Y., Mao, S., Wei, Z., and Zhang, Z. (2025). Photonics for neuromorphic computing: Fundamentals, devices, and opportunities. Adv. Mater. *37*, 2312825.
45. Feldmann, J., Youngblood, N., Wright, C.D., Bhaskaran, H., and Pernice, W.H.P. (2019). All-optical spiking neurosynaptic networks with self-learning capabilities. Nature *569*, 208–214.
46. Meng, X., Shi, N., Zhang, G., Li, J., Jin, Y., Sun, S., Shen, Y., Li, W., Zhu, N., and Li, M. (2025). High-integrated photonic tensor core utilizing high-dimensional lightwave and microwave multidomain multiplexing. Light Sci. Appl. *14*, 27.
47. Peng, Y., Liu, X., Luo, G., Zhang, F., Sun, T., Li, H., Cheng, Y., and Peng, Y. (2025). Flexible batio3 ferroelectric nonvolatile memory for neuromorphic computation. ACS Appl. Mater. Interfaces *17*, 18571–18581.
48. Xu, X., Han, W., Tan, M., Sun, Y., Li, Y., Wu, J., Morandotti, R., Mitchell, A., Xu, K., and Moss, D.J. (2023). Neuromorphic computing based on wavelength-division multiplexing. IEEE J. Sel. Top. Quantum Electron. *29*, 1–12.
49. Brunner, D., Shastri, B.J., Qadasi, M.A.A., Ballani, H., Barbay, S., Biasi, S., Bienstman, P., Bilodeau, S., Bogaerts, W., Böhm, F., et al. (2025). Roadmap on neuromorphic photonics. Preprint at arXiv. https://doi.org/10.48550/arXiv.2501.07917.
50. Wang, D., Nie, Y., Hu, G., Tsang, H.K., and Huang, C. (2024). Ultrafast silicon photonic reservoir computing engine delivering over 200 tops. Nat. Commun. *15*, 10841.