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Future roles of solid-state quantum dot light sources

Special Collection: Hybrid and Heterogeneous Integration in Photonics: From Physics to Device Applications

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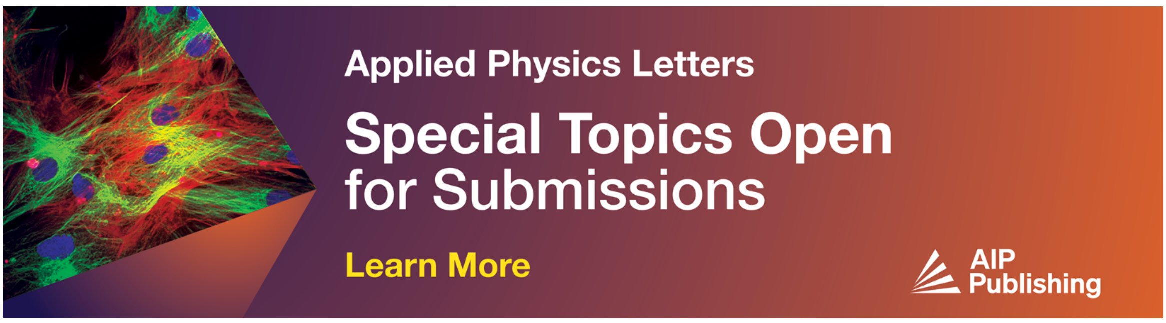

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ABSTRACT

This paper highlights the critical role of solid-state quantum dot (QD) light sources in both classical and quantum applications, with an emphasis on their integration with silicon photonics to advance future optical networks and quantum technologies. Quantum dot lasers, renowned for their low threshold currents, temperature stability, low-noise optical amplification, and enhanced coherence, are highlighted as essential components for scalable quantum systems. These features contribute to improved chip architectures, reduced module sizes, and increased channel density. The paper also explores the synergy between quantum dot lasers and silicon photonics in the generation of frequency combs, optimizing efficiency and scalability in optical networks. Furthermore, it delves into the impact of quantum dot-based single-photon sources, particularly their ability to generate entangled and polarized photons, in driving advancements across quantum technologies.

I. INTRODUCTION

The exponential growth in global data traffic, fueled by the increasing adoption of artificial intelligence (AI) and machine learning applications, has placed unprecedented demands on computing throughput, data transmission capacity, and associated overall energy efficiency within AI clusters, data centers, and across global networks. This phenomenal momentum is rapidly driving both the classical optical interconnects and revolutionary quantum technologies. Traditional electrical interconnects, which are still the backbone of short reach (< 10 m) communication, are increasingly becoming a bottleneck. These interconnects suffer from several critical limitations:

(1) their communication bandwidth inversely proportional to the length of reach, so the intrinsic signal degradation over long distances restricts the effective communication range between chips, limiting system scalability, and performance;
(2) they exhibit significant latency due to necessary equalization or/and digital signal processing to reduce errors from limited communication bandwidth stated above;
(3) charging the metal wires to send data generates excessive heat that wastes huge amount of energy and complicates thermal management within a small package volume;
(4) the physical size and sheer weight of copper cable pose new challenges in structural stability and system scale-up.

To overcome these challenges, there is a growing trend toward replacing more conventional metal wires at board and eventually chip levels with optical interlinks. Optical interconnects are known to offer several advantages, including significantly reduced latency, higher bandwidth, and lower power consumption.[1–4] Unlike electrical signals, optical signals do not suffer from resistive losses, enabling longer transmission distances without degradation. This is particularly critical as the industry moves toward higher-speed data processing and much tighter integration between computational units.[4] A promising bandwidth-scalable and energy-efficient technology enabling such a transition is the integrated wavelength division multiplexing (WDM) system, particularly the integrated dense WDM (DWDM), which allows multiple optical signals, each at a different wavelength, to be transmitted simultaneously over a single optical fiber.[5,6] This multiplexing capability drastically increases the communication bandwidth between chips, making it possible to handle the vast amounts of data generated by AI and other data-intensive applications.[7,8] Figure 1 showcases the industry first optical compute interconnect chiplet recently announced by Intel Corporation. This chiplet integrates electronic circuits and silicon photonics integrated circuits, including active building blocks like lasers and amplifiers, and is co-packaged with the CPU to leverage up to 4 terabits per second (Tbps) bidirectional data transfer rate for faster exchanges between processing units and other system-on-chips (SoCs).[8]

However, the implementation of optical interconnects at the chip scale requires high-performance optical sources that can be seamlessly integrated into existing semiconductor manufacturing processes.[9] One promising approach to achieving this is through the use of quantum dot (QD) gain materials. Quantum dots, with their discrete energy levels, offer several advantages over traditional bulk and quantum well (QW) semiconductor materials.[1,2,10,11] By integrating QD material with silicon photonics, the intrinsic merits of two material systems and integration schemes are complementary and are dramatically magnified while their individual weaknesses can be conveniently eliminated or suppressed.[12]

In parallel, quantum technologies are poised to revolutionize fields, such as advanced computation, secure communication, precision sensing, and metrology. A cornerstone of these technologies is the ability to generate and manipulate quantum states of light, such as single-photon and entangled photon pairs. QDs with discrete, atom-like energy levels have emerged as an ideal platform for these applications due to their remarkable optical properties and scalability.[13,14] QDs serve as artificial atoms that can be engineered to emit single photons or entangled photon pairs on demand. When embedded in a photonic device, these emitters exhibit high brightness, stability, and tunability, making them integral to the development of quantum photonic circuits. The monolithic integration of QDs with photonic structures like waveguides, cavities, and beam splitters enables efficient photon manipulation and routing, paving the way for scalable quantum systems.

Here, we start from basics of QD material and its integration with silicon photonics and focus on QD-based optical frequency comb (OFC) sources on silicon and enabled DWDM communication systems. The transition from electrical to optical interconnects, facilitated by advances in DWDM systems and QD materials, is poised to revolutionize chip-to-chip communications. It will enable the next generation of high-performance computing systems, capable of meeting the demands of AI and other emerging technologies.[15] This shift will not only enhance the performance and scalability of AI clusters and data centers but also pave the way for more energy-efficient and compact computing systems, ensuring that the global network can continue to grow and evolve in response to future demands.[16] Unique advantages to build high-quality light sources for quantum applications are discussed in the end to showcase other promising potentials of such solid-state nanostructures.

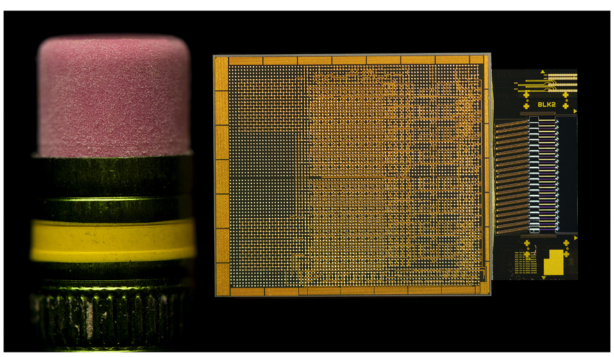

FIG. 1. First fully integrated optical compute interconnect chiplet from Intel Corporation, co-packaged with an Intel CPU and running live data.[8] (Credit: Intel Corporation).

II. ENGINEERING ADVANCED LIGHT SOURCES WITH QD LASERS

The general concept of QD was first pioneered in 1937 by Professor Herbert Fröhlich, and the first QDs were synthesized in 1979 by Professor Aleksey Yekimov from cuprous chloride (CuCl),[17] marking the debut of an ongoing era of QD development. QD material can be made from many different compounds, such as gallium arsenide (GaAs), indium arsenide (InAs), indium phosphide (InP), cadmium chalcogenides, and lead halide perovskites, and they cover a wide spectral span ranging from ultraviolet up to long-wave infrared.[18] Among these different options, InAs QD is the most adapted option for the fabrication of laser diodes in optical telecommunication. Self-organized InAs/GaAs QDs have been first observed in 1985 by Goldstein's group.[19] Conceptualized in 1982 by Arakawa's group,[20] then, after almost a decade of epitaxial development,[21–24] the first InAs/GaAs QD laser operating at room temperature, exhibiting low threshold current density and high thermal stability already, was demonstrated in 1994 by Bimberg's group,[25] while other works has also started to report the growth of QD on other substrates like InP[26,27] or silicon[28,29] for telecom application purpose. From that point onward, many efforts have been devoted to improving the epitaxial structure and bringing down the threshold current density to record-low level compared to their quantum well counterparts.[30–34]

Within the active region of a QD laser, due to the spatial separation between dots and the three-dimensional confinement, carriers can populate the same energy level despite their nature of Fermion. Consequently, temperature dependence of the peak gain and threshold current are reduced.[2,35] As a results, QD lasers have been reported to exhibit high optical gain,[36] high output power,[37] and high temperature continuous-wave (CW) operation.[38,39] In addition, the discrete density of states resulting from the three-dimensional confinement are high around the edges of the bandgap compared to quantum wells. When charge carriers are injected, they occupy these narrow energy ranges with high density, increasing the gain and lowering the threshold current density.[40] The discrete nature of the energy levels and the wide separation also improve the temperature stability since higher temperatures are needed to cause energy transitions. Furthermore, the threshold can be further reduced by using narrower designs since the reduced carrier diffusion can minimize surface recombination. Many other amazing properties have also been unveiled successively in the following decades, such as low relative intensity noise (RIN) level,[41] ultra-fast gain recovery time,[42] high third-order nonlinear susceptibility,[43] high overall immunity to the dislocations due to short diffusion length, and exceptional resistance against external reflections.[2,44,45] All these fascinating features naturally lead to the idea of replacing QW sources with QD lasers. Moreover, due to the inhomogeneous broadening caused by dot size dispersion, QD lasers often exhibit a wide gain spectrum,[46,47] which can be exploited for wide-span tunable lasers and optical frequency comb (OFC) generation through passive mode-locking. A first experimental work in 2007 has demonstrated the potential of QD Fabry–Pérot (FP) laser as multi-wavelength source with low noise floor for WDM systems.[48]

Around the same period, Moore's Law was beginning to fail and left very little room for the computational performance of single-core central processing unit (CPU) due to the physical limitation.[49] Subsequently, multi-core architecture has been forcibly introduced into the market and has become the standard up until the current days. However, such architecture has inadvertently complexified the intra- and inter-chip interconnects, hence resulting highly multi-threaded configurations to access code and data stored in off-die memory, thus, high-bandwidth and low-latency interconnects are required.[49] Nevertheless, due to Ohm's Law, processor cores and high-capacity memory have to be closely stacked to ensure high performance and high energy efficiency, which also unavoidably leads to more serious heating problem. In addition, the energy consumption increases exponentially when accessing farther cache level or main memory, as studies have shown.[50] To this end, replacing current electrical interconnects with photonic ones is the optimal solution, for the obvious reason that photonic interconnect dissipates little propagation loss and much larger intrinsic bandwidth, subsequently several orders of magnitude lower power over long reach compared to electrical interconnect,[5] thanks to the intrinsic low-loss of optical guides (fibers and waveguides). In addition, unlike electrical wires, by incorporating DWDM system, including advanced modulation and digital signal processing technologies, a single optical guide can carry practically unlimited number of channels, meaning that deploying photonic interconnects will significantly reduce the electrical layout complexity. It was envisioned that future architecture would co-package electronic integrated circuits (EICs) and photonic integrated circuits (PICs) interconnected with optical fibers/waveguides.[49,51,52] To achieve such perspective, silicon photonics comes under the spotlight as one of the most advantageous options, thanks to their compatibility with commercially available advanced complementary metal-oxide semiconductor (CMOS) foundries for unprecedented integration density, fabrication precision, and their optical transparency over a wide wavelength span. Due to the indirect bandgap structure, the most efficient way to "light up" silicon PICs is either to package laser diodes off-die and in close vicinity or to integrate them on-die. While off-die option is a simple and low-cost option, it is not helpful to scale up production. The on-die option, on the other hand, is by far the more appealing one as industries is shifting toward 2.5D and 3D co-packaging, where EICs and PICs will be stacked to improve yield, enhance compactness, and elevate channel density and data volume.[3,5]

In addition to the conventional process of flip–chip bonding the fabricated diode laser chip onto silicon wafer, there are two types of integration to accommodate laser diodes onto silicon wafer: heterogeneous integration, where the laser epitaxial structure is grown on a native III–V substrate is wafer-bonded on Si,[53–56] and monolithic integration (heteroepitaxial integration), where the laser epitaxial structure is directly grown on Si through epitaxy.[57–60] The former through direct wafer bonding is a proven scalable and reliable technique which has been commercialized by Intel to produce millions of heterogeneous QW lasers on their silicon photonic product. Thus, it is straightforward to explore QD version heterogeneous light source for large-volume commercial deployment.[61,62] Enormous breakthroughs and continuous progress are also realized on monolithically integrating QD lasers on large-scale Si wafers.[63,64] Both approaches are propelling QD lasers to manifest as a superior candidate for next-generation on-chip light source on silicon thanks to their fascinating traits. Figure 2 summarizes the outstanding benefits of QDs for silicon photonics.

III. QD LASERS FOR OPTICAL FREQUENCY COMB GENERATION

Recently, QD multi-wavelength light sources emerge as a particularly attractive key building block to combine QD material with Si photonics and mutually benefit each other. In addition to employing single-wavelength laser array,[65] multi-wavelength emission from a single QD laser, i.e., OFC, offers advantages in compactness, simple control, and energy efficiency. Compared with conventional QW lasers, QD lasers exhibit numerous properties that make them particularly suited for OFC formation, including ultrafast carrier dynamics, ultrabroad bandwidth, and high nonlinear susceptibility.[43] These low-noise QD-based frequency comb lasers allow for independent utilization of comb lines in coherent applications, unlike QW counterparts, which have large radio frequency (RF) linewidths unsuitable for such uses. Upon locking QD gain medium, comb laser configuration is another key design parameter. After the previously mentioned first experimental work,[48] comb lasers have been proposed for system applications instead of FP lasers, for the reasons that

- the free-spectral range (FSR), or mode spacing, is strictly identical and stabilized through the entire span;
- comb laser provide much wider, flat-top spectrum;
- comb laser exhibits lower intensity noise level compared to FP laser.

These properties are essential to establish stable DWDM channels throughout a single photonic interconnect. Here, thanks to the high third-order nonlinear susceptibility, the wide gain envelope, and the large gain, QD comb lasers offer better performance like high modal power, large number of exploitable modes, and low RIN floor.[6,66] Moreover, thanks to its optical feedback tolerance due to small linewidth enhancement factor (α_H-factor) and symmetric gain profile, QD comb lasers can maintain high performance even under large amount of external reflection[67,68] and potentially requires no optical isolation.[69] In addition, QD laser device is capable of operating on both ground- and excited-state, which can be employed for multi-band transmission, further expanding the transmission capacity from a single source.[70,71]

Recent exciting progresses of QD-based OFC on both heterogeneous[72,73] and monolithic[74–76] integration platforms on silicon clearly show it a promising solution for low-cost, energy-efficient, and large-scale silicon photonic integrated circuits (PICs). Figure 3 shows spectra of such QD-on-Si OFC sources with channel spacing around 60 GHz at room temperature on (a) heterogeneous and (b) monolithic platforms. Under proper biases on gain and saturable absorption (SA) sections, stable mode-locking and high comb line extinction ratio are obtained at first or higher-order harmonics, depending on the number and location of SA section. QD are known for their tolerance of optical feedback for designing PICs integrating a QD comb laser with other components on the same chip. Experimental results showed error-free operations for -18.5 dB on-chip optical feedback,[67] indicating high tolerance for optical feedback.

QD lasers have significant gain-induced Kerr nonlinearity due to their fast gain medium and enhanced carrier confinement. Although they typically have low α_H-factors, which is beneficial for feedback

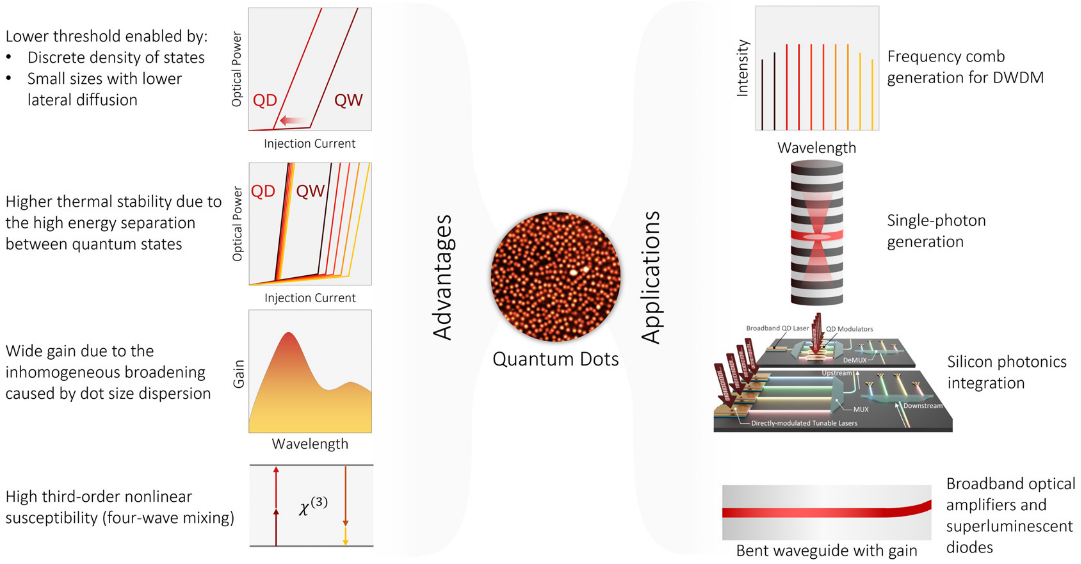

FIG. 2. Overview of the benefit of quantum dots for silicon photonics.

immunity, this reduces the Kerr effect. Recent studies have shown that the α_H-factor in QD comb lasers can be significantly increased by adjusting the SA reverse voltage. This variation is mainly due to carrier-induced refractive index changes, with a slight decrease in differential gain. These adjustments allow tuning of the Kerr nonlinearity and consequently the group velocity dispersion (GVD), enabling the tuning of the frequency modulation comb bandwidth by a factor of two by altering the SA bias. Therefore, an optimal α_H-factor for a desirable OFC specification and feedback tolerance needs to be engineered. On the other hand, the self-injection-locking technique allows the phase noise of each line to be narrowed down to a few kHz, which meets the requirement of advanced format modulation, that is, 16-QAM and 32-QAM, for tens Tbit/s and beyond coherent optical networking systems.

IV. QD LASERS-POWERED DWDM INTERCONNECT AND BEYOND

In a recent demonstration of an integrated DWDM transmission experiment using coherent data encoding,[9] only two matching QD comb lasers were employed as carrier and local oscillator, of which the optical spectra are presented in Fig. 4. In this demonstration, 26 comb lines were used for dual polarization 56 GBaud data transmission over 10 km of standard single-mode fiber (SSMF). Five lines were bulk modulated simultaneously, providing two aggressor channels on each side to avoid saturation of the employed fiber amplifier. Using 26 lines encoded with 56 Gbaud DP-32QAM, a record-setting aggregate data rate of 12.1 Tb/s is achieved by two QD comb lasers in a comb-to-comb configuration. The low frequency drift of the lasers allowed the local oscillator to remain aligned to the carrier throughout the transmission capacity testing. These advancements highlight the significant progress in QD silicon technology, showcasing its potential for high-speed data transmission applications.

The primary goal of investigating QD-based OFC is to explore their potential as light sources for DWDM and pair them with highly integrated silicon photonics. Silicon photonics offers unprecedented integration density and fabrication precision, making a high-Q resonator-based DWDM architecture on silicon an ideal choice. Cascaded compact high-Q resonators, such as microring resonator arrays, are natural components for WDM (de)multiplexing. Modulation speeds

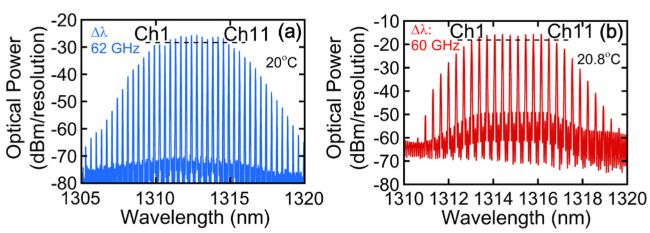

FIG. 3. Optical spectra of (a) a heterogeneously integrated external-cavity quantum dot comb laser on silicon with mode spacing $\Delta\lambda = 62$ GHz and (b) a monolithically integrated quantum dot comb laser on silicon with mode spacing $\Delta\lambda = 60$ GHz.

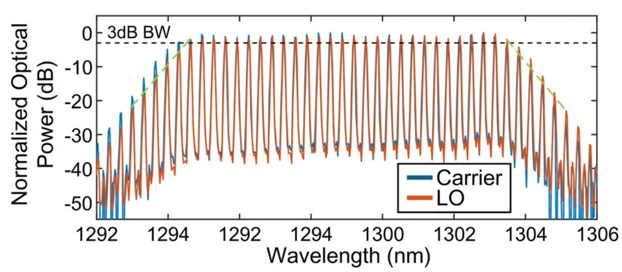

FIG. 4. Optical spectra of two matching but independent QD comb lasers grown on silicon, employed for 10 km transmission based on comb-to-comb configuration, with one deployed as carrier and the other as local oscillator.[9]

exceeding 300 Gb/s (direct detection) have been demonstrated on a single silicon microring modulator with a 7.5 μm radius.[77] A comb laser-powered, microring resonator-based solution is significantly more compact–potentially thousands of times smaller–than an array of single-wavelength sources powering Mach–Zehnder interferometer (MZI) modulator arrays, which then require dedicated WDM components like arrayed waveguide gratings.

In addition to offering superior integration and bandwidth density, the nonlinearity dependent on cavity intensity and the relatively weak individual comb lines—drawbacks associated with silicon microring resonators and QD comb lasers, respectively,—actually complement each other well. The signal strength after the microring modulator bank can be enhanced by an on-chip optical amplifier, which can be easily integrated heterogeneously alongside the QD comb laser on the same chip.

Moreover, such a DWDM system is less complex and less power-hungry in terms of control. The channel spacing of a QD comb laser remains constant despite inevitable spectral shifts under different bias and environmental conditions. This spectral shift, occurring as a group, simplifies the process of tracking and matching individual microring resonances. Additionally, if the comb laser is integrated with the microrings on the same chip, global environmental temperature variations tend to impact both the laser and the modulators similarly. Once the comb line-microring resonance is established initially, wide-range tuning of the microrings is unnecessary, thereby simplifying control and reducing power consumption.

This technology is attracting increasing interest, not only from leading academic groups but also from industrial players, like Hewlett Packard Enterprise, Ayar Labs, Intel, Quinessence, Ranovus, etc., who are investing in it for future large-scale deployment. However, QD-based OFCs are not limited to excelling in micro-resonator-based architectures. They remain an attractive choice for MZI modulator-based direct detection and coherent architectures as well.

Beyond datacom optical interconnect applications, primarily in the O-band, QD-based laser sources could also play a significant role in lidar, sensing, computing, quantum, and metrology applications, similar to other Si_3N_4, $LiNbO_3$, or III-V Kerr OFCs.[78–80] The direct multi-wavelength emission from QD comb lasers is likely to surpass other approaches in terms of footprint, power consumption, and more. Ongoing innovations in physics, research, and engineering will continue to advance QD epitaxy on various substrates,[81–83] expand spectral coverage, refine laser design and fabrication, and enable dispersion engineering and other novel designs. These improvements will enhance both single- and multi-wavelength QD sources, making them more competitive and versatile for an expanding array of emerging applications.

Furthermore, QD superluminescent light-emitting diodes (QD-SLEDs) and quantum dot semiconductor optical amplifiers (QD-SOAs) are highly attractive technologies for advanced photonic systems, leveraging the unique properties of QDs, such as high efficiency, broad spectral bandwidth, and thermal stability. QD-SLEDs combine the high brightness of lasers with the broad spectral width of LEDs, making them ideal for applications like optical coherence tomography (OCT), fiber optic sensing, and WDM systems due to their low coherence and high power.[84] Recent studies using quantum well dots (QWD) demonstrated that ground-state optical gain remains unsaturated at high injection currents, facilitating broadband emission and high output power. Another breakthrough involved developing a multiple InAs/GaAs QD-layer structure with a large inhomogeneous dot size distribution. This innovation, combined with a tilted stripe waveguide structure and specifically designed facet coatings, enabled independent control of cavity mirror losses for ground- state (GS) and excited-state (ES1 and ES2) emissions, achieving a minimal spectral dip of only 1.3 dB.[85] Furthermore, substantial progress has been made in transitioning QD SLEDs from native to silicon substrates, exemplified by the realization of electrically pumped continuous-wave InAs QD SLEDs monolithically grown on silicon. These devices demonstrated a maximum 3 dB bandwidth of 103 nm centered at the O-band and a maximum single-facet output power of 3.8 mW at room temperature.[86] Last but not least, QD-SOAs, on the other hand, provide low-noise, broadband optical signal amplification, critical for extending transmission distances in optical communication, supporting WDM architectures, and amplifying quantum signals without degradation. Both devices benefit from QD's tunable and temperature-stable properties and are key to enabling compact, energy-efficient, and scalable integration with silicon photonics.

V. QUANTUM DOTS FOR QUANTUM TECHNOLOGIES

Quantum technologies are expected to revolutionize a wide range of applications that can make use of the unique advantages offered by quantum mechanical phenomena, such as entanglement and superposition.[13] These applications include quantum key distribution (QKD) and quantum computing. Of the several platforms used in quantum applications, quantum optics is one of the most promising approaches to generate and process qubits. Optical qubits are encoded in one of the quantum states of the photon. To be able to process the qubit, it is imperative that a single photon is transmitted and received. The generation of a single photon has been demonstrated in different ways, including from color centers and isolated atoms or molecules (two-level systems).[14,87,88] A quantum dot can be considered as an artificial atom. If properly isolated, the quantum dot can be optically or electrically excited to emit a single photon.[13,89–91]

Single-photon emission from semiconductor quantum dots, including InAs, GaAs, InGaAs, and GaN, has been reported over the past few decades.[92–95] These types of QDs cover a wide spectral range, allowing for their use in many applications, depending on the required wavelength. The highest purity achieved to date of these single-photon sources varies based on the material system. For the near infrared and telecommunication wavelengths, which relay on GaAs/AlGaAs and InAs/InP material systems, $g^{(2)}(0)$ values below 10^{-3} have been achieved, whereas the values are typically above 10^{-2} for the visible and ultraviolet range.[96] To ensure having high purity, proper QD isolation is needed. Furthermore, it can be improved by relying on two-photon excitation since it lowers the probability of re-excitation.[96,97] These techniques lower the multi-photon noise. To improve the performance of single-photon emission even further, a single dot can be placed within a cavity. This can be a pair of distributed Bragg reflectors (DBRs) or a photonic crystal.[13] The Purcell effect enhances the spontaneous emission of the quantum dot due to the resonance in the cavity. The cavity also helps in photon extraction in the desired direction, improving the extraction efficiency and brightness. Moreover, the use of semiconductor QDs allows integration in photonic integrated circuits. Given the maturity of the growth of semiconductor QDs, as well as semiconductor processing, QD single-photon sources can potentially enable integrated quantum systems spanning the entire optical spectrum. Several recent review articles cover the challenges of the use of QDs in quantum networks and provide a perspective on their potential.[98,99] Finally, let us also stress that squeezing typically requires nonlinear optical interactions, and the strong exciton–photon coupling in QDs particularly within photonic cavities or waveguides can facilitate these interactions effectively. Theoretical studies have demonstrated the potential for generating quadrature-squeezed photons from a single QD, emphasizing the role of exciton–phonon coupling in quadrature squeezing and providing valuable insight into the fundamental interactions within QDs.[100,101] Furthermore, QD lasers have shown promise for producing broadband amplitude-squeezed light. Experimental results have reported efficient amplitude squeezing across a wide frequency range, achieved with electrically driven QD lasers operating at room temperature.[102] Additionally, QDs can be seamlessly integrated into photonic circuits on silicon platforms, enabling scalable squeezed light sources for advanced quantum photonics applications.

VI. SUMMARY

This perspective paper highlights QD nanostructures as a transformative innovation for versatile applications, in particular, a complementary addition to silicon photonics. These nanostructures enable energy-efficient light sources that can be seamlessly integrated with silicon and represent an optimal solution for achieving efficient frequency combs. QD lasers have become indispensable for enhancing coherence and stability due to their operation at lower threshold currents and reduced sensitivity to temperature fluctuations. This inherent stability is particularly advantageous for quantum systems requiring consistent and precise photon emission. Moreover, QD lasers can be integrated onto silicon-based platforms, ensuring compatibility with existing semiconductor manufacturing processes. In the realm of quantum integrated technologies, QDs have been pivotal, particularly following the observation of the Purcell effect and the demonstration of the first single-mode single-photon source. They are central to advancing protocols for quantum communication and quantum computing. This integration capability is critical for building scalable quantum systems that interact seamlessly with classical computing hardware. These advancements position QD technologies as a cornerstone for bridging the gap between classical and quantum domains, paving the way for scalable, energy-efficient, and highly stable classical and quantum systems essential for the next generation of information technologies.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Heming Huang: Conceptualization (equal); Writing – original draft (equal); Writing – review & editing (equal). **Omar Alkhazragi:** Conceptualization (equal); Writing – original draft (equal); Writing – review & editing (equal). **Di Liang:** Conceptualization (equal); Writing – original draft (equal); Writing – review & editing (equal). **Frédéric Grillot:** Conceptualization (equal); Writing – original draft (equal); Writing – review & editing (equal).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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