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Hybrid integration methods for on-chip quantum photonics

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The goal of integrated quantum photonics is to combine components for the generation, manipulation, and detection of nonclassical light in a phase-stable and efficient platform. Solid-state quantum emitters have recently reached outstanding performance as single-photon sources. In parallel, photonic integrated circuits have been advanced to the point that thousands of components can be controlled on a chip with high efficiency and phase stability. Consequently, researchers are now beginning to combine these leading quantum emitters and photonic integrated circuit platforms to realize the best properties of each technology. In this paper, we review recent advances in integrated quantum photonics based on such hybrid systems. Although hybrid integration solves many limitations of individual platforms, it also introduces new challenges that arise from interfacing different materials. We review various issues in solid-state quantum emitters and photonic integrated circuits, the hybrid integration techniques that bridge these two systems, and methods for chip-based manipulation of photons and emitters. Finally, we discuss the remaining challenges and future prospects of on-chip quantum photonics with integrated quantum emitters.

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1. INTRODUCTION

The laws of quantum mechanics promise information processing technologies that are inherently more powerful than their classical counterparts, with examples including quantum computing [1], unconditionally secure communications [2], and quantum-enhanced precision sensing [3]. After decades of intensive theoretical and experimental efforts, the field of quantum information processing is reaching a critical stage: quantum computers and special-purpose quantum information processors may solve problems that classical computers cannot [4–6], and quantum networks can distribute entanglement over continental distances [7].

Photons are a promising system to realize quantum information processing applications due to their low noise properties, excellent modal control, and long-distance propagation [8]. These properties enable all-optical quantum technologies [9] and photonic interfaces between matter qubits [10]. By leveraging advances in photonic integrated circuits (PICs) for classical optical communications, integrated quantum photonics enables the chip-scale manipulation of quantum states of light, demonstrating orders of magnitude improvements in component density, loss, and phase stability compared to bulk-optical approaches. Such advances have enabled proof-of-principle demonstrations of quantum protocols, such as foundational tests of quantum mechanics [11], quantum simulation [12,13], and quantum machine learning [14]. Generally, such demonstrations comprise three distinct components: the generation of quantum states of light, their propagation through linear and nonlinear optical circuitry, and single-photon readout. Bringing these components together into a single integrated system could enable a new generation of quantum optical processors capable of solving practical problems in quantum chemistry [15,16] and inference [17,18].

However, fully integrating the generation, manipulation, and detection of photons is an outstanding challenge for the field due to the unique material requirements for each distinct component. For example, epitaxially grown III-V semiconductor quantum dots (QDs) are a leading approach for the near-deterministic generation of single and entangled photons in terms of purity, brightness, and indistinguishability [19–21]. However, the loss per component of III-V platforms is relatively high, and likely not at the level required for a large-scale photonic quantum technology [22]. In contrast, silicon photonics is unrivaled in terms of component density, scale, and compatibility with complementary metal–oxide–semiconductor (CMOS) electronics [23], with classical systems

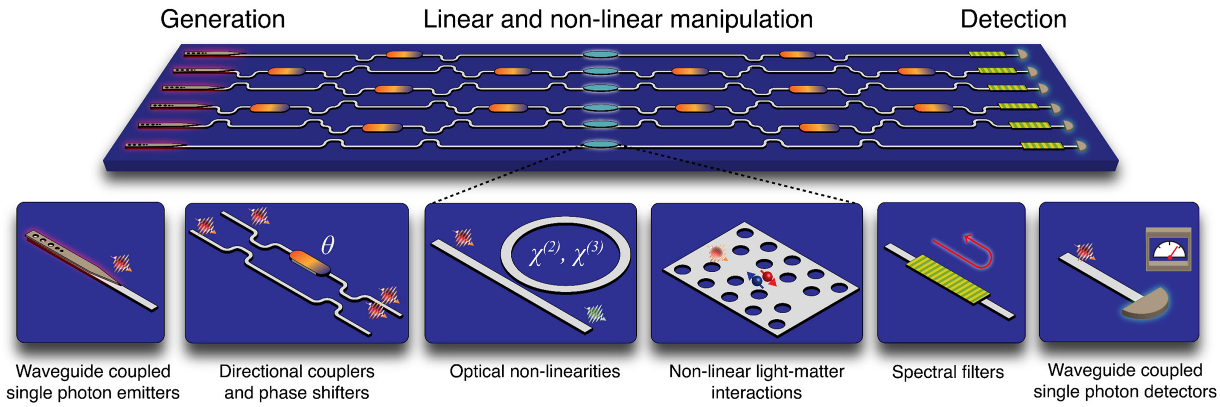

Fig. 1. Schematic of a hybrid quantum PIC consisting of different modules for the generation, linear and nonlinear manipulation, spectral filtering, and detection of nonclassical light on a single chip. These individual modules are shown in more detail in the lower row of panels. Quantum emitters generate photons and route them to low-loss photonic waveguides. The combination of directional couplers and phase shifters enable arbitrary linear operations on the photons. The use of optical nonlinearities by resonant photonics (e.g., ring-resonators) as well as atom-photon quantum interfaces expand the functionality of quantum photonics to the nonlinear regime. Lastly, spectral filtering followed by efficient on-chip single photon detectors can read out the photons without the need for lossy photon extraction from the chip.

featuring over 1000 active components [24] and integration with millions of transistors [25].

Moreover, silicon photonic-based quantum systems have demonstrated the control of >100 components [26] as well as the generation of entangled states of light [27]. However, methods to generate photons in silicon are based on spontaneous processes, such as four-wave mixing [27], or are incompatible with deterministic solid-state quantum emitters at visible or infrared wavelengths below 1 μm.

Hybrid integration approaches such as epitaxial heterogrowth [23,28], wafer bonding [29,30], and pick-and-place [31–33], provide a potential solution by incorporating disparate photonic technologies into a single integrated system that may not be otherwise compatible in a single fabrication process. In the context of quantum technologies, hybrid integration offers the tantalizing goal of bringing together quantum emitters, quantum memories, coherent linear and nonlinear operations, and single photon detection into a single quantum photonic platform, as described in Fig. 1. In this paper, we review the emerging field of hybrid integration for next-generation quantum photonic processors, including platforms for quantum emitters and PICs, as well as techniques for their hybrid integration. Additionally, we explore on-chip methods for achieving coherent control of quantum photonic systems.

2. SOLID-STATE QUANTUM EMITTERS

Solid-state quantum emitters provide an essential building block for photon-based quantum technologies, with their ability to produce single photons or entangled photon pairs in a deterministic manner [34,35]. To date, various types of solid-state quantum emitters, including QDs and atomic defects in crystals, have demonstrated single-photon emissions with high purity and indistinguishability [19,21,36], as well as the potential for room-temperature operation [37–39] and compatibility with electrically driven devices [40]. Also, their emission wavelength ranges from ultraviolet [39] to near-infrared, which includes telecom wavelengths [41–44]. New solid-state quantum emitters are continually being reported in two-dimensional (2D) materials [37,45] and perovskite nanocrystals [46], as well as in various crystal defects [38,46–48] [Fig. 2(a)].

However, the solid-state environments create several issues, such as limited light extraction efficiency, randomness of the position and frequency, and dephasing induced by interaction with charges and phonons in the quantum emitters. Initial efforts to solve these issues have focused on efficient generation of single photons by employing various micro/nanophotonic structures, including photonic crystals [43], photonic nanowires (NWs) [39,49], micropillars [50], and circular Bragg gratings [20,35] [Fig. 2(b)]. Such structures enhance the light extraction efficiency more than 80% [20] and dramatically improve the brightness of the coupled emitters by an order of magnitude. In addition, the photonic structures introduce the Purcell effect and modify the far-field pattern into Gaussian-like shape, and therefore, it is possible to improve the generation rate [51,52] and collection efficiency of single photons [20,43,53]. Furthermore, researchers are continually developing techniques for controlling the emitters' position [54–57], frequency [58–63], and dephasing [21,64], which have brought solid-state quantum emitters to the forefront of quantum light sources. Comprehensive reviews on solid-state emitters and important developments can be found in Refs. [34,65].

Beyond high-performance, engineered single-photon sources, another important issue with solid-state quantum emitters is integrating them into photonic chips that realize scalable and integrated quantum photonic systems. Recently, significant efforts have been made to realize monolithically or heterogeneously integrated quantum emitters with photonic circuits [Fig. 2(c)]. These on-chip integrated emitters serve as internal and deterministic quantum light sources for PICs.

Despite the above promising techniques for efficient generation, control, and on-chip integration of quantum emitters, combining individual techniques is very difficult and these techniques are often not compatible with each other. For example, the techniques for position and frequency control should be combined simultaneously, but they are often not compatible with integrated photonic structures. Also, the use of photonic structures places the quantum emitters near the etched surface, requiring additional efforts to control dephasing for coherent single-photon emission.

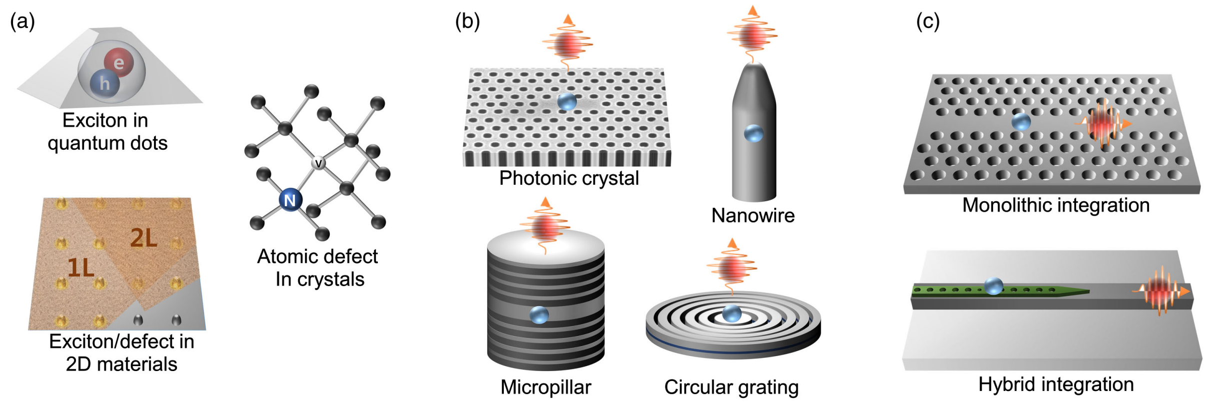

Fig. 2. (a) Various solid-state quantum emitters from single excitons in QDs, atomic defects in crystals, and exciton or defects in 2D materials; (b) quantum emitters integrated with micro/nanophotonic structures, such as photonic crystals, photonic NWs, micropillars, and circular Bragg gratings; (c) monolithic integration of the quantum emitter with an on-chip waveguide and the hybrid integration of the quantum emitter in a nanobeam (green color) on a heterogeneous photonic circuit. The blue and red spheres in (b) and (c) represent quantum emitters and single photons, respectively.

Furthermore, manipulating multiple quantum emitters in the photonic circuits poses new challenges. Therefore, achieving ideal quantum emitters that satisfy all these figures of merit still remains a challenge, but recent research efforts illuminate a new potential for the integrated quantum photonic system based on solid-state quantum emitters. We discuss platforms for PICs in Section 3 and recent key developments and issues of on-chip integrated quantum emitters in Sections 4 and 5.

3. PICs FOR QUANTUM PHOTONICS

PICs provide a compact, phase-stable, and high-bandwidth platform to transmit, manipulate, and detect light on-chip. By leveraging advances in semiconductor manufacturing for classical communication, PICs have been demonstrated with over a thousand active components in a few square millimeters [66]. Now, with many foundries offering multiproject wafer runs in a variety of material platforms, the end-user can access complex PICs in a cost-effective manner, expanding the application areas of integrated photonics. Due to these favorable properties, PICs have emerged as a promising platform with which to generate and control quantum states of light at a scale required for practical optical quantum technologies [9,23]. In the context of hybrid integration, a PIC serves as a "photonic backbone" both to route and process single photons with high fidelity and to directly engineer the quantum emitter characteristics. When designing a photonic backbone, a number of key features should be considered, including loss budget, material compatibility, wavelength compatibility, manufacturability, modulation requirements, and power budget. In the following, we examine a number of such features.

A. Material Platforms

Many material platforms exist, each with varying levels of maturity. For example, silicon photonics benefits from an advanced silicon-on-insulator (SOI) manufacturing process that enables the cointegration of photonics and CMOS electronics, enabling thousands of optoelectronic components on a single chip [26] [Fig. 3(a)]. Moreover, the high refractive index contrast between the Si core and SiO_2 cladding $\Delta n = (n_{\text{core}}^2 - n_{\text{clad}}^2)/2n_{\text{core}}^2 \approx 0.8$ enables compact componentry, which, alongside low propagation losses (as low as 2.7 dB/m [70]), enables low loss per component [23].

In the context of hybrid integration, one limitation of the SOI platform is a bandgap at ~1.1 μm, as many solid-state quantum emitters generate photons below this wavelength, causing a significant loss in an SOI chip. An approach for overcoming this limitation is to use telecom-compatible quantum emitters, such as InAs/InP QDs [41–44], defect centers in SiC [38] and GaN [47], and rare-earth-based quantum memories [71]. Moreover, the integration of these emitters into the SOI platform has been demonstrated [33]. Alternatively, one can move to a waveguide material with higher bandgap energy. For example, Si_3N_4 is transparent above 400 nm, and low-pressure chemical vapor deposition techniques onto an SiO_2 layer provides a high-quality Si_3N_4 layer with precisely controlled thickness. The moderate index contrast $\Delta n = 0.25$, alongside low surface roughness, enables waveguides with ultralow losses of 0.1 dB/m [72] (at the cost of a larger bend radius and therefore greater device footprint), which is important for on-chip delay lines [67] [Fig. 3(b)]. Recently, Si_3N_4 has been included in the SOI foundry process, enabling 3D integration [73].

In terms of emerging quantum photonic platforms, $LiNbO_3$ possesses strong electro-optic and acousto-optic properties [68,74] [Fig. 3(c)] and has a large transparency window of 350–4500 nm, making it appealing for hybrid integration. Due to the challenges in etching the material, initial efforts to develop waveguides in $LiNbO_3$ relied on titanium diffusion or proton exchange. However, the low refractive index contrast limited the scale of the devices [74]. More recently, advances in processing have enabled high-confinement nanophotonic waveguides fabricated from thin-film $LiNbO_3$-on-insulator, with losses as low as 2.7 dB/m [29] at telecom wavelengths and 6 dB/m at visible wavelengths [75]. Additionally, such waveguides have been integrated with quantum emitters [76]. AlN has also emerged as a promising platform for visible photonics [77], with a large transparency window [78] and modulation enabled by an intrinsic electro-optic [79] and piezoelectric effect [80]. Alternatively, III-V materials, such as InP, can enable the direct integration of active layers of quantum wells (QWs) or QDs during the epitaxial growth process. Therefore, III-V materials allow monolithic integration of light sources in

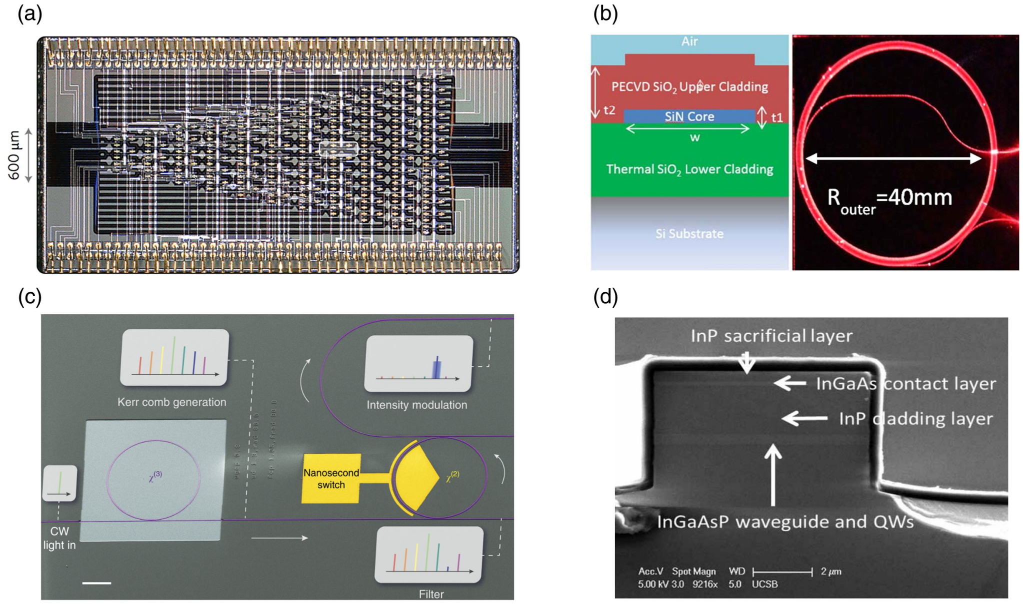

Fig. 3. (a) Optical image of a programmable Si PIC composed of 88 Mach–Zehnder interferometers, 26 input modes, 26 output modes, and 176 phase shifters; (b) cross-sectional schematic and top-view optical image of a fabricated Si_3N_4 waveguide coil (a 3 m-long spiral pattern) illuminated with a red laser; (c) SEM image of a $LiNbO_3$ photonic circuit consisting of a Kerr comb generator and an add-drop filter based on large $\chi^{(3)}$ and $\chi^{(2)}$ of $LiNbO_3$; (d) cross-sectional SEM image of the epitaxial structure of an InGaAsP waveguide, including active QWs. Images in (a)–(d) adapted with permission from Refs. [26,67–69], respectively. (a) Si/SiO_2, (b) Si_3N_4/SiO_2, (c) $LiNbO_3$, and (d) III-V compound semiconductor.

photonic platforms [69] [Fig. 3(d)]. However, compared to other materials, III-V-based PICs tend to have higher propagation loss around 2 dB/cm [81] and have a low bandgap energy that prohibits the use of visible light.

B. Low-Loss Cryogenic Modulation

A key consideration for PICs for hybrid integration of quantum emitters is low-loss modulation at emitter-compatible cryogenic temperatures (<10 K). A variety of modulation techniques exist, each with varying figures of merit (e.g., bandwidth, loss, extinction ratio, power consumption), which may be suited to different quantum applications. For example, fast modulation is critical for wave-packet engineering [82] and demultiplexing many single photons from a single quantum emitter [83], while quasi-static phase tuning [84] can be used to "trim" waveguides for high-fidelity linear optical operations [85]. Regardless of the particular protocol, modulator loss is generally a key consideration for quantum photonic applications to reduce errors and enable large-scale operation.

Materials with appreciable $\chi^{(2)}$ coefficients, such as $LiNbO_3$ [86] and AlN [77,86,87], enable switching via the Pockels effect, which is, in principle, not limited by cryogenic temperatures. Meanwhile, materials without an appreciable $\chi^{(2)}$ coefficient, such as Si or Si_3N_4, must rely on effects such as the plasma-dispersion effect [88], microelectromechanical effects [89], or thermo-optic effects [90]. Plasma-dispersion modulators, which rely on fast injection or depletion of carriers on fast time scales, have been demonstrated in Si microdisks at cryogenic temperatures [91], but the introduction of carriers causes loss. Thermo-optic Si_3N_4 modulators have been demonstrated at cryogenic temperatures [92]; however, the thermo-optic coefficient dn/dT of both Si_3N_4 and SiO_2 decreases by an order of magnitude.

An alternative approach is to integrate materials possessing a strong Pockels effect with a non-electro-optically active material via hybrid integration. Organic polymers [93], $LiNbO_3$ [94], and electroactive oxides [95] have all been incorporated into Si. Notably, barium titanate possesses an exceptionally strong Pockels coefficient of 1000 pm/V at room temperature [96], and its integration with both Si and Si_3N_4 has been demonstrated at cryogenic temperatures, maintaining a Pockels coefficient of 200 pm/V [97] (compared with $LiNbO_3$ of 30 pm/V at room temperature) and a modulation bandwidth of 30 GHz with negligible loss.

C. On-Chip Detection of Photons

Photonic quantum information processing requires efficient readout of the state of the photons. Since the photons propagate along the waveguide in photonic circuits, to detect them it is necessary to extract on-chip propagating photons and couple them into an objective lens or a fiber. To minimize the coupling loss, various methods have been proposed, such as grating-assisted coupling, evanescent coupling, tapered waveguides, and end-fire coupling with a lensed fiber [98]. Although several schemes exist for efficient free-space and fiber coupling, the coupling efficiency largely depends on fiber-waveguide mode matching, alignment, and wavelength.

To mitigate coupling loss, the most desirable way for detecting propagating photons in a chip is to integrate the detectors in the same device. Single-photon detectors based on superconducting NWs are of great interest for this purpose because they can be fabricated on the photonic circuits directly and offer a fully integrated on-chip quantum photonic device, as shown in Fig. 4(a) [99,100]. Additionally, superconducting NW-based detectors outperform other detectors in terms of single-photon detection characteristics, such as high efficiencies of over 90%, fast response times below 3 ps [101], and high operation rates of over 100 MHz [102] in a broad

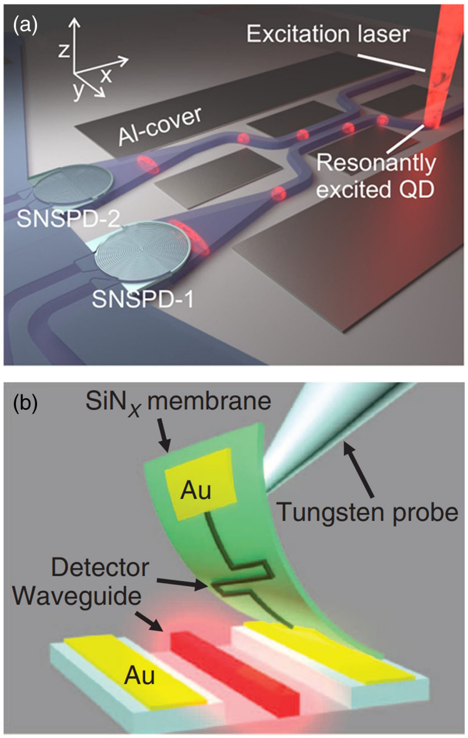

Fig. 4. (a) Schematic description of the on-chip detection of photons using an integrated superconducting NW detector; (b) integration of a single-photon detector using a pick-and-place technique. Images in (a)–(b) adapted with permission from Refs. [99,107].

spectral range, including the telecom wavelengths [103]. Such detectors have been directly integrated onto waveguide materials such as Si_3N_4 [104], AlN [105], and Si [106]. Furthermore, it is also possible to postintegrate separately fabricated detectors into the photonic circuits. For example, Fig. 4(b) demonstrates the hybrid integration of the superconducting NW detector on a photonic waveguide using the pick-and-place technique [107]. Recently, the integration of on-chip spectrometers has been demonstrated, and the efficient integrated detectors showed that the system works at a single-photon level in a broadband spectrum [108].

While significant progress has been made on individual PIC components, the challenge is to integrate them all within a single quantum photonic system. Breakthroughs in hybrid integration of PICs for quantum photonics will benefit from a two-step approach: advances in PIC technology will open up new opportunities for hybrid integration, and fully understanding the unique requirements of quantum technologies will help direct PIC research.

4. HYBRID INTEGRATION TECHNOLOGY

PICs can efficiently manipulate and route light across the chip. To perform quantum information processing tasks, however, quantum light sources are required. These photons can be externally generated outside the chip and brought to it with various coupling techniques, or internally generated using the nonlinearity of the waveguide materials [109]. However, these approaches are currently falling short of the demanding efficiency requirements for complex quantum information processors [24]. A promising alternative is to integrate bright quantum emitters onto PICs directly. This could be beneficial for many aspects of the system, such as improving efficiency, scalability, stability, and controllability. However, creating a hybrid platform between the quantum emitter and the photonic circuit with efficient and deterministic coupling is a challenging task, and certain criteria must be considered. In this section, we review multiple techniques for hybrid integration and their ability to maintain high crystal quality and efficient optical coupling between the platforms, as well as their potential for scalability. The current state-of-the-art for hybrid integration of the quantum emitters onto photonic circuits is summarized in Table 1.

A. Random Dispersion

Quantum emitters in the form of nanoparticles, such as colloidal QDs or diamond nanoparticles, can be simply integrated with photonic structures by dispersing them onto the photonic platforms [116,117] [Fig. 5(a)]. Since the quantum emitters in the nanoparticles are not hosted in a bulky dielectric medium, they can efficiently emit single photons without the problem of total internal reflection, a major issue for quantum emitters in a bulk medium. However, the nanoparticles themselves possess a large surface area, which often leads to optical instability, such as blinking or bleaching, due to the significant influence of the surface states and enhanced Auger process [118]. Therefore, additional surface treatment or environmental control may be required.

Besides, the simple dispersion method does not precisely control the position of the emitters, but instead randomly places them near the photonic structures (e.g., waveguides or cavity structures). This fact limits the use of the random dispersion method for quantum photonic applications where the deterministic coupling of multiple quantum emitters with high coupling efficiency is crucial. To improve the coupling efficiency, it is possible to selectively disperse the nanoparticles using lithography-based masking [119] or tip manipulation of the particles in an atomic force microscope [120]. Therefore, with proper surface encapsulation and precise positioning techniques, this method could be an easy way to prototype and realize hybrid platforms.

B. Epitaxial Growth of Heterostructures

Optically stable single-photon emission with high single-photon purity and indistinguishability can be generated from quantum emitters embedded in a high crystalline bulk medium, which can be achieved from epitaxially grown QDs or defects in a diamond film. Using the epitaxial growth technique, growing quantum materials directly on a photonic platform can provide hybrid heterostructures for both emitters and photonic circuits in a single wafer. For example, hybrid heterostructures of III-V compound semiconductors on a Si wafer, which are particularly important for realizing many optoelectronic applications [23,28], can be achieved using the epitaxial growth method [Fig. 5(b)]. However, growing such heterostructures is not always favorable, the crystal quality often being sacrificed due to the formation of antiphase boundaries and large mismatches in the materials' lattice constants, thermal coefficients, and charge polarity. To maintain crystal quality, a buffer layer needs to be inserted between the heterostructures, and therefore, the quantum emitters require a few hundred nanometer separations from the boundary, which reduces the coupling efficiency with the photonic circuits [121]. Although the epitaxial growth of quantum materials on photonic circuits is still

Table 1. Comparative Summary of Representative Demonstrations with Integrated Quantum Emitters on a Photonic Chip

Integration Method	Emitter	Photonic Chip	Coupled Emitters[a]	Coupling Efficiency (%)[b]	Alignment	$g^{(2)}(0)$	Indistinguishability	Detection	Demonstration[c]
Wafer bonding	QDs	Si_3N_4	1 (gas-tuning)	72	e-beam lithography	0.13 (with correction)	—	fiber-coupled	weak coupling [29] (microring resonator)
Wafer bonding	QDs	Si_3N_4	1	3	e-beam lithography	0.11	89 (At $\tau = 0$)	fiber-coupled	postselection using *in situ* lithography [110]
Wafer bonding	QDs	SiON	20 (Stark tuning)	8	random	0.23	54 (At $\tau = 0$)	fiber-coupled	on-chip HOM [62]
Transfer printing	QDs	GaAs	2	63	optical microscopy	0.23	—	free space (grating coupler)	weak coupling [111] (nanobeam cavity)
Transfer printing	QDs	SOI	1 (temp. tuning)	70	optical microscopy	0.3	—	free space (grating coupler)	weak coupling [112] (nanobeam cavity)
Transfer printing	WSe_2	$LiNbO_3$	1	0.7	optical microscopy	—	—	fiber-coupled	waveguide coupling [113]
Microprobe	QDs	SOI	1	15	SEM	0.25	—	free space (grating coupler)	on-chip HBT [33]
Microprobe	QDs	SOI	1 (Stark tuning)	—	SEM	0.12	—	free space (grating coupler)	large-frequency tuning [63]
Microprobe	QDs	SOI	1 (temp. tuning)	—	SEM	0.25	—	free space (grating coupler)	on-chip frequency filtering [114]
Microprobe	QDs	$LiNbO_3$	1	—	SEM	0.08	—	free space (grating coupler)	on-chip HBT [76]
Microprobe	defect	Si_3N_4	1	—	optical microscopy	0.07 (free space) 0.17 (on-chip)	—	fiber-coupled	on-chip integration of quantum memory [32]
Microprobe	QDs	Si_3N_4	1 (strain tuning)	1	optical microscopy	0.1	—	fiber-coupled	on-chip frequency tuning of emitters and ring-resonator [115]

[a]The coupled emitters denote the number of studied or controlled emitters. The tuning mechanism is shown in parentheses.
[b]The coupling efficiency is determined between the quantum emitters and the waveguide.
[c]HBT represents Hanbury Brown and Twiss interference experiments.

challenging, several new approaches, such as selective area growth and defect trapping, are being developed [122,123]. Therefore, this method still has strong potential for future on-chip hybrid quantum photonic devices.

C. Wafer Bonding

Another well-known method for integrating dissimilar material platforms is the wafer-to-wafer bonding technique [124]. Since each material is grown separately using its own optimized equipment and conditions, this method can maintain high crystal quality for both compounds and provide various material options that are more limited in the monolithic epitaxial growth technique. The wafer-bonding technique is also useful to couple the emission of quantum emitters to the photonic circuits with a precisely controlled short distance between two platforms. For example, the bonding process flips a III-V wafer including the emitters near the top surface and bonds the wafer to a target photonic wafer, as shown in Fig. 5(c). Therefore, the high-quality top surfaces of both wafers can be interfaced by a thin bonding layer, typically less than 5 nm [124]. With these hybrid heterostructures, we can configure complicated electronic and photonic structures using micro/nanolithography techniques [29]. Figure 6(a) shows a QD wafer orthogonally bonded to the side of an SiON photonic circuit [30], and Fig. 6(b) shows a tapered GaAs waveguide on an Si_3N_4 waveguide after the wafer bonding process of two wafers [29]. One remaining problem for this technique is the random position and frequency of the emitters. Since the wafer-bonding method integrates two platforms on a wafer scale, without precise control of the lateral position and frequency of the individual emitters, the actual coupling efficiency and yield remain low. However, recently developed techniques for site-controlled emitters [54–57], *in situ* lithography [110,126,127], and local frequency tuning [29,58,63] may provide possible solutions for these issues. Figure 6(c) shows that the position of the quantum emitters in the bonded wafer is predefined by cathodoluminescence in scanning electron microscopy (SEM), and the device is fabricated by the *in situ* electron beam lithography technique.

D. Pick-and-Place

In the wafer-bonding technique, the independent growth of the materials for the quantum emitters and photonic platform preserves the crystal quality and provides hybrid heterostructures at the wafer-scale. However, one limitation of this method is the reliance on a random coupling between the emitters and photonic chips. To overcome this problem, a number of groups have suggested a pick-and-place method that transfers small-scale quantum devices one by one instead of implementing wafer-scale integration. This single-device transfer method allows the emitters to be precharacterized before assembly [31,32], and therefore it is possible to selectively integrate desired emitters at a specific position of

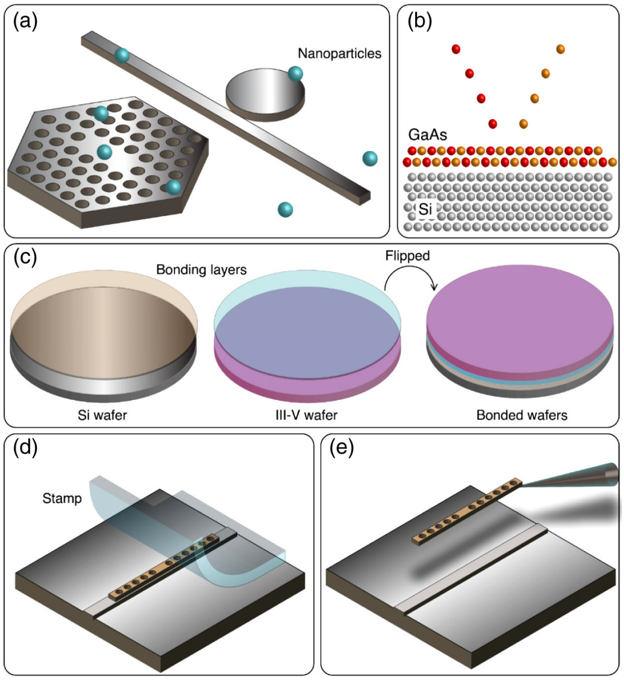

Fig. 5. Schematics of various hybrid integration methods for the quantum emitters on the photonic platforms. (a) Randomly dispersed nanoparticles in the vicinity of photonic structures, such as a microdisk or a photonic crystal cavity; (b) the epitaxial growth technique can be used to deposit layers such as GaAs on a Si substrate with a buffer layer (not shown); (c) wafer-bonding technique to form a heterostructure of a III-V layer on a Si substrate; (d) pick-and-place process by transfer printing a nanobeam containing quantum emitters on a waveguide, using a rubber stamp; (e) pick-and-place process using a microprobe that places a nanobeam on a waveguide. Quantum emitters are embedded in the nanostructure.

the photonic circuits. Another important feature of the pick-and-place method is that users are free to choose not only the materials but also the dimension and design of the device structures for the emitters and photonic circuits, which is limited for the preintegrated wafers in the wafer-bonding method. Therefore, the two independently designed platforms can have more flexibility and functionality for controlling the emitters and photons on a chip. For example, the hybrid system can include more complicated structures such as photonic crystal cavities or frequency tuners for increasing light–matter interaction strength [128]. Also, the pick-and-place technique can integrate various types of quantum materials, such as one-dimensional (1D) vertical NWs [125,129] and 2D van der Waals materials [113,130,131] that host the quantum emitters inside. This technique has also been successfully exploited to realize the integration of single-photon detectors on a photonic circuit [107].

The pick-and-place technique requires detaching the quantum emitter devices from the original wafer and releasing them onto prepatterned photonic circuits. A transfer printing method shown in Fig. 5(d) is one well-known example of the pick-and-place technique that uses an adhesive and transparent rubber stamp made of a material such as polydimethylsiloxane. Since the pick-and-place method assembles two prefabricated structures, high alignment accuracy is a crucial requirement for achieving high coupling efficiency of the integrated emitters with the photonic chip. The use of transparent stamps enables the user to monitor the alignment in real time with an optical microscope [see Fig. 6(d)], and additional alignment markers can increase the alignment accuracy [111,112]. In this case, the alignment accuracy is limited by the optical diffraction limit of around a few hundred nanometers for visible light. Another experimental challenge of this technique is the limited ability to reposition the emitters, since the adhesion between the integrated structures is much stronger than their adhesion to the stamp. Therefore, the stamp cannot pick up the

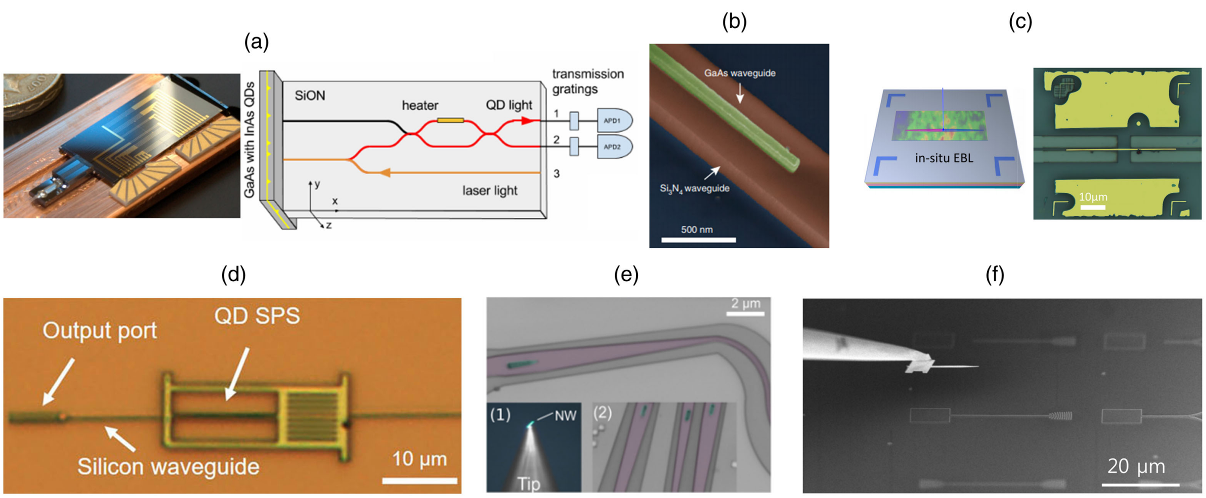

Fig. 6. Experimental demonstrations of hybrid integration of quantum emitters with photonic circuits using different integration techniques. (a) Optical image and schematics of integrated InAs QDs on a SiON photonic chip made by the orthogonal wafer-bonding method; (b) GaAs nanobeam on an Si_3N_4 waveguide by electron beam lithography from a wafer-bonded GaAs/Si_3N_4 heterostructure; (c) left panel shows a schematic of *in situ* electron beam lithography of a GaAs nanobeam aligned to a preselected QD. The right panel shows an optical microscopy image of fabricated devices (GaAs and Si_3N_4 colored in yellow and green, respectively); (d) optical image of integrated InAs QDs (QDs) on a Si waveguide using a transfer printing method; (e) optical image of the transferred single NW-QDs on a Si_3N_4 waveguide using a microtip, with insets showing (1) picked NWs on a tip and (2) integrated NWs on waveguides; (f) SEM image of an integrated InP nanobeam on an Si waveguide beam splitter using a microprobe. Images in (a)–(f) adapted with permission from Refs. [29,30,33,110,112,125], respectively. (a) Wafer bonding (orthogonal direction); (b) wafer bonding (vertical direction); (c) wafer-bonding (*in situ* lithography); (d) transfer printing; (e) microprobe (optical microscope); and (f) microprobe (electron microscope).

emitters again. Also, the stamping process may induce force over a large area, causing unwanted damage to the photonic circuit, such as physical damage on the photonic structures or detachment of the deposited metal electrodes. Introducing a carefully designed microstamp may avoid these problems [132] and could be used for highly integrated and fragile platforms.

Another effective technique for the pick-and-place method is using a sharp microprobe [33,115,125,129,133] [Fig. 5(e)]. A few micrometer or submicrometer-sized probe tips can pick up quantum emitters and transfer them onto the target position in either an optical [see Fig. 6(e)] or an electron microscope system [see Fig. 6(f)]. In particular, the latter environment significantly improves the alignment accuracy over the transfer printing method. Additionally, the probe tip allows us to move the emitter position even after integration for better alignment accuracy. Furthermore, the sharp probe tip can pick up fragile single NWs grown along the vertical direction [125,129] [Fig. 6(e)]. Even though handling quantum devices one by one with the pick-and-place technique relies on a sophisticated process for the precise control of single devices, it provides the highest accuracy and controllability. Additionally, the process is compatible with various materials and structures. Further efforts for simplifying and automating the process may enable scalable and rapid fabrication of on-chip quantum photonic platforms with multiple deterministically integrated emitters.

5. ON-CHIP CONTROL OF QUANTUM EMITTERS AND PHOTONS

Along with the efficient integration of quantum emitters with photonic circuits, controlling the quantum emitters so they are identical to each other is essential to meet the criteria for quantum operation based on multiple indistinguishable single photons. Furthermore, to establish efficient quantum operation on a chip, the photonic circuits should route, modulate, and detect the generated photons with minimal loss. In this section, we introduce the promising techniques for on-chip control of the emitters and photons, as well as recent demonstrations of on-chip quantum operation.

A. Coherent Control of Quantum Emitters

Two-photon interference based on the Hong–Ou–Mandel (HOM) interferometer is the primary mechanism for achieving measurement-based quantum interaction with photons [134]. The successful interference relies on highly coherent and indistinguishable single photons, which requires a sufficiently long coherence time (τ_2) compared to the spontaneous decay time τ_1, that is $\tau_2 \approx 2\tau_1$. However, the existence of phonon interactions and charge fluctuations in the solid-state environment causes timing and spectral jitters as well as pure dephasing, and thus the emitters have a broad emission linewidth compared to their intrinsic linewidth limited by the lifetime [135]. Such linewidth broadening becomes worse with an above-band excitation scheme that creates more interaction with phonons and charges in solid-state systems. In the case of InAs QDs, the linewidth is typically over a few tens of micro electron volts with the above-band excitation at a low temperature of 4 K, while their radiative decay time is as short as 1 ns, corresponding to a sub-micro electron volt homogeneous linewidth [136]. Therefore, the coherence time of the emitters will be an order of magnitude shorter than the radiative decay time [43,137].

Together with phonon interaction, the fluctuating charge environment in the vicinity of the quantum emitters is another source of dephasing [138]. To stabilize the charge environment, surface passivation by adding a capping layer [136] or filling the charge trap with electrostatic field control [139] have been suggested.

Recently, a number of groups have reported near transform-limited linewidths based on resonant [19,21] and quasi-resonant [140] methods. Figure 7(a) shows the indistinguishable visibility of QDs' different excitation schemes: above-band [43,137], quasi-resonant [19,140–142], resonant [19,21,50,143–145], and two-photon resonant excitations [20,35]. We note that high indistinguishability does not sacrifice the brightness in the quantum emitters. Instead, the degree of indistinguishability strongly depends on the excitation scheme, while the brightness is mostly determined by the photonic structures. This is in contrast to the heralded single photons from nonlinear processes having an inherent trade-off between brightness and indistinguishability [146].

In addition to highly indistinguishable single photons, driving quantum emitters with a resonant laser enables a coherent control of two-level systems, which act as a stationary qubit. Therefore, controlling the quantum states of the emitters in a coherent manner is essential for quantum information processing [147]. Vacuum Rabi oscillation [148] and Mollow triplet [149] as signatures of resonant atom–photon interactions have been demonstrated from coherently driven quantum emitters.

The main obstacle to the use of resonant excitation is a strong laser background scattered from the solid-state chip. Since the resonant scattered laser cannot be filtered out from the single photons using a spectral filter, it is necessary to employ other techniques for separating two resonant signals. For example, a cross-polarization technique using a polarizing beam splitter combined with linear polarizers can selectively eliminate the laser background [150]. With an on-chip device, the nanophotonic waveguide can also act as a polarization filter [99,140,151–153]. Aligning the laser polarization direction along the waveguide direction prohibits the laser propagation in the waveguide [99]. Additionally, the large distance between the excitation and collection spots on the waveguide reduces the scattered laser signal further, as shown in Fig. 7(b). Employing a two-photon resonant excitation method can also provide an alternative solution when the scattered laser light is unavoidable [20,35,64,154].

B. Generation of Multiple Indistinguishable Single Photons

Having coherent single photons from a single quantum emitter enables us to scale up to multiple indistinguishable single photon emitters on a chip. This is particularly important for large-scale photonic quantum simulators, such as boson samplers [155] and large-scale entangled photonic cluster states [156]. The most convenient way to produce multiple indistinguishable single photons is by parametric downconversion in nonlinear media. However, this process is intrinsically probabilistic, and multiphoton events are inevitable as the brightness is increased. Therefore, the system becomes significantly inefficient with scale.

A bright single quantum emitter combined with a temporal-to-spatial demultiplexing technique is one possible way to achieve multiple single photons in a deterministic manner [Fig. 8(a)].

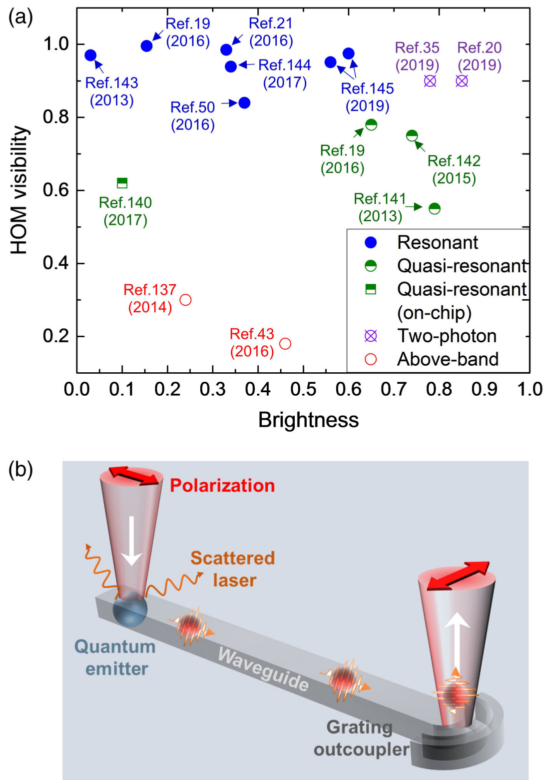

Fig. 7. (a) Comparison of the brightness and HOM interference visibility from quantum emitters driven with various excitation schemes: above-band (empty red circles), quasi-resonant (half-filled green circles), quasi-resonant on-chip (green half-filled squares), resonant (filled blue circles), and two-photon resonant (crossed purple circle) excitations. Brightness is determined at the first lens or fiber. For the resonant excitation, we consider 50% loss from the polarization optics, essential for suppressing the scattered laser, and therefore the maximum brightness is limited to 0.5 for unpolarized single photons. Ref. [145] used linearly polarized single photons to circumvent the limitation of the resonant excitation. Quasi-resonant indicates that laser energy is lower than the wetting layer bandgap. (b) Schematic of resonant excitation of on-chip integrated quantum emitters in a nanophotonic waveguide that separates the single photons from the resonant excitation laser.

Multiple delay lines and beam splitters can spatially distribute the temporal array of single photons to multiple channels of the photonic circuit [144,157]. The advantage of this method is that the system only needs one bright single-photon source with high purity and indistinguishability. For the deterministic distribution of the photons in each channel, electro-optic routing devices can be incorporated instead of passive beam splitters [157,159]. However, since the degree of the indistinguishability decreases with the temporal separation between the photons [160], ultrafast electro-optic switches would be required to obtain maximum indistinguishability between photons. Furthermore, the technique requires a few tens of nanoseconds' long delay lines for compensating for the time interval between photons on a photonic circuit, but integrating such long delay lines with fast routers is a challenging task on a chip.

Instead, integrating multiple quantum emitters can offer a solution. The main challenge of incorporating multiple quantum emitters in a single chip is the frequency randomness of the quantum emitters, which limits quantum interference between photons from individual emitters. To eliminate this frequency mismatch between emitters, various local frequency tuning methods have been introduced. For example, Figure 8(b) shows QDs integrated into multiple channels of an SiON photonic circuit using wafer bonding. The emission frequency of the integrated quantum emitters can be tuned independently by applied electric fields. Similar approaches have also been demonstrated in the InAs QD–Si waveguide hybrid system [Fig. 8(c)] [63]. Another method of frequency tuning is by applying a local strain on the emitters. Within a hybrid system, the strain tuning can be achieved by integrating the emitters on miniaturized piezoelectric actuator chips so that the platform can induce a local strain to individual emitters in an array [Fig. 8(d)] [58–60].

On-chip-integrated quantum emitters with matched frequency can provide not only multiple indistinguishable single photons, but also an outstanding platform to study many-body quantum physics. For example, multiple quantum emitters coupled to the same optical mode form entangled superposition states known as Dicke states, leading to collective behaviors of the coupled emitters [161]. In particular, integrating the emitters into a 1D waveguide can realize long-range interactions between the emitters [162]. For example, Fig. 8(e) shows two far-separated quantum emitters coupled to a photonic crystal waveguide with a local frequency tuner. The collective effect of the resonantly coupled emitters leads to superradiant emission by an enhanced radiative decay rate. To date, various solid-state quantum systems have demonstrated such interaction on a chip [59,158,163], and recently, superradiance has been achieved with three quantum emitters in a waveguide with a local strain tuning method [59].

Along with the frequency control, the positional control of the emitters is another important factor for generating quantum emitter arrays with high coupling efficiency between the emitters and photonic circuits. Depending on the types of emitters, various experimental approaches have demonstrated deterministic positional control of the emitters. For instance, the position of semiconductor QDs can be controlled by employing prepatterned substrates [57], a buried stressor technique [164], or three-dimensional (3D) nanostructures such as pyramidal structures [54]. Growing vertical NWs also enables the placing of the single QD in the middle of the NW so the user can easily specify the position of the QDs during the growth process [165]. This NW structure is particularly useful for hybrid integration because the NWs can control the position and number of QDs and be easily transferred into a photonic circuit with high coupling efficiency [115,125]. In the case of defects in crystals, ion-implantation [55,166] or laser-writing [167] techniques enable the control of the position and density of the defects by changing the dose value. Atomically thin 2D materials are also of great interest as arrayed single-photon sources with their flexibility and tunability. For example, positioning quantum emitters with 2D materials can be achieved by transferring the material on nanopatterned substrates, which induce a local strain that can form strain-induced quantum emitters at deterministic positions [60,113,131].

These successful demonstrations of local controls of quantum emitters' frequency and position on a chip show the potential of PICs with integrated multiple, identical, quantum emitters, generating multiple indistinguishable single photons. Therefore, the remaining challenge lies in combining individually developed techniques in a single chip.

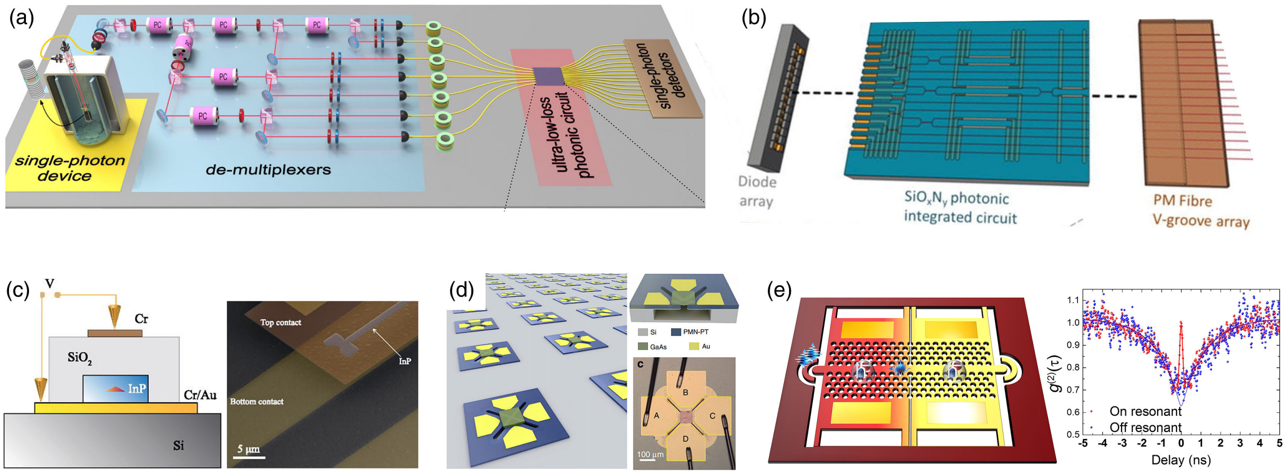

Fig. 8. (a) Schematic of the experimental setup for a boson sampler using a temporal-to-spatial demultiplexing technique with a single QD; (b) independently tunable multiple QD device integrated with an SiON photonic chip; (c) illustration and SEM image of the InAs QD integrated with an Si substrate with a Stark tuning structure; (d) microelectromechanical systems for anisotropic strain engineering of QD-based single-photon sources; (e) on-resonant two QDs in a photonic crystal waveguide with local heaters. The right panel shows superradiant emission as a result of the quantum interaction between two emitters coupled to a single optical mode of the waveguide. Images in (a)–(e) adapted with permission from Refs. [58,62,63,157,158], respectively.

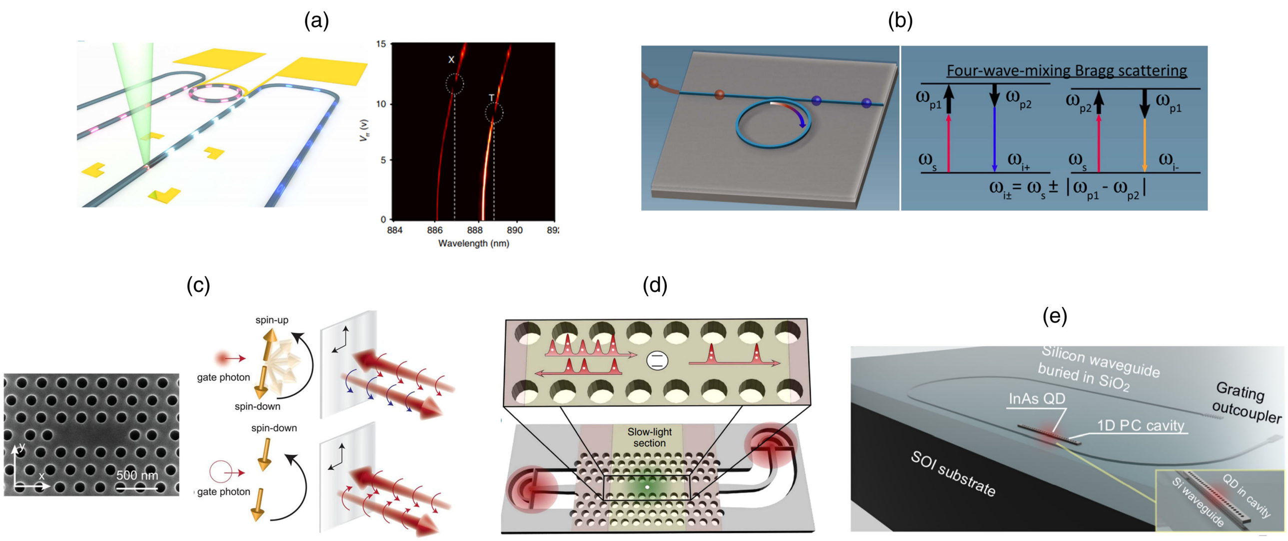

Fig. 9. (a) Frequency sorter based on a frequency tunable add-drop filter [129]; (b) frequency converter using the four-wave mixing Bragg scattering process; (c) schematic image of a single-photon switch and transistor based on a single QD in a photonic crystal cavity. The schematic shows that a gate photon controls the state of the spin, and then the spin determines the polarization of the signal field. (d) Schematic image of controlled waveguide transmission with the coupled quantum emitter, showing a strong optical nonlinearity at a single-photon level; (e) demonstration of strong coupling between the QD and the nanobeam high Q cavity on an Si waveguide. Images in (a)–(e) adapted with permission from Refs. [129,171,172,173,174], respectively. (e) Strong light-matter interaction in hybrid system.

C. On-Chip Manipulation of Photons

In the absence of direct photon–photon interaction, requiring strong Kerr nonlinearity, efficient quantum information processing can be realized with quantum light sources, linear optical components, and detection and fast feedforward [168]. Using well-developed bulk or fiber optics such as mirrors, beam splitters, wave plates, and polarizers, we can easily manipulate the quantum state of photons to encode and decode the quantum information into the path, polarization, and time bin of the photons. Realizing such optical components in PICs provides a promising solution for demonstrating a scalable and integrated quantum photonic system. Recent advances in PICs, as introduced in Section 3, can highly integrate waveguides, beam splitters, phase shifters, and delay lines in a single chip. Combining these components can form tunable Mach–Zehnder interferometers, playing a key role in reconfigurable PICs [28].

The use of quantum emitters as quantum light sources requires additional photonic components to spectrally filter single-photon emission from unwanted background emissions, including the scattered laser [169,170]. Such frequency sorters have been demonstrated by using nanophotonic structures in hybrid systems [114,129]. Figure 9(a) shows on-chip integrated quantum emitters and a microring, acting as an add-drop filter. To match the frequency of quantum emitters to a narrow spectral line of the add-drop filter, either the quantum emitters or the resonant mode of the add-drop filter can be independently tuned using local heating, strain, or electric field.

The components based on enhanced optical nonlinearity using integrated nanophotonic structures can add more functionality to PICs. The frequency conversion of photons is one representative example and is very useful for quantum emitters. Although frequency-tuning techniques have already been introduced above, the achievable tuning range from controlling the emitter typically remains below 10 nm. In contrast, the frequency conversion using $\chi^{(2)}$ or $\chi^{(3)}$ nonlinearity in the nanophotonic structures such as a ring resonator acts on photons and offers a much wider tuning range from a few tens of nanometers up to a few hundred nanometeres. Figure 9(b) shows a waveguide-coupled resonator that converts the emission frequency of the quantum emitters using four-wave mixing Bragg scattering [171]. Yet, the technique shows a conversion efficiency of 12%, and therefore further development to improve the conversion efficiency without sacrificing purity and indistinguishability of single photons will be required. The fact that the frequency converter can match the emission frequency in a wide spectral range without local control of the emitters may open a new possibility of hybrid devices involving different types of quantum emitters, such as InAs QDs with near-infrared emission and defects in diamonds with visible emission in a chip. Such hybrid architecture will be very interesting because the system can provide efficient sources of photonic and spin qubits in the same chip, acting as quantum channels and memories, respectively.

Having a deterministic source of indistinguishable single photons realizes efficient nonuniversal quantum computation with linear interferometers [157,175]. However, even with the deterministic photon sources, the major challenge with linear optics is that entangling operations such as the generation of Bell states or cluster states is probabilistic. To overcome this limitation, various optical schemes, including additional optical elements, have been suggested. For example, fast low-loss switching can be used to turn these probabilistic operations into near-deterministic ones via multiplexing [176]. Therefore, the important challenge that realizes such deterministic quantum gates in photonic circuits still remains for linear optical quantum computing on a chip.

D. Quantum Interface between Photons and Stationary Qubits

In the previous sections, we introduced on-chip generation and control of photons in PICs. Although photons provide an excellent carrier for quantum information, the storage time and deterministic interactions between photons are absent unless coupled to nonlinear matter. Integrated quantum emitters in PICs can provide not only single-photon qubits but also stationary qubits storing and mediating photonic qubits. Therefore, incorporating quantum-specific components, such as quantum memories and quantum gates, as well as coherent nonlinear optical elements based on stationary qubits, enable a wider range of photonic quantum information processing schemes [177] (Table 2) and new opportunities for exploiting quantum optics. For example, solid-state quantum emitters with a ground-state spin can mediate photon–photon interactions and store the information for a long time [180]. Recent advances in atomic defects in diamond have realized a coherent spin of over 1 s [181], and various new solid-state spins are emerging from several wide-bandgap semiconductors, such as SiC [182] and hBN [183].

Quantum entanglement between photons and quantum emitters is the most important requirement to realize quantum interface and has been demonstrated from various quantum emitters [147,172,184]. Employing low-loss photonic cavities or waveguides tailor light–matter interaction and realize an efficient quantum interface with high cooperativity $C = 2g^2/\kappa\gamma$. (κ and γ represent the decay loss rates of cavity photons and quantum emitters, respectively, and g is the coupling constant between emitter and photon). High cooperativity C over 100 has been demonstrated from QDs strongly coupled in a microcavity [185]. In the context of cavity quantum electrodynamics (QED), the emitter–photon interface controls the state of the stationary qubits such as spins via the polarization state of photons, and vice versa. Recent work has demonstrated the conditional phase shift of photons [178], and strong photon–photon interaction [172] mediated by the strongly coupled cavity-quantum emitter systems. Recent theoretical work also indicates that dynamically switchable cavities can form deterministic photon–photon gates with high fidelity [186].

Employing the quantum interface based on the cavity-quantum emitter coupled system can realize fascinating photonic quantum components such as single-photon transistors and photon number filters. Figure 9(c) shows an experimental demonstration of a single-photon switch using the spin of a charged QD in a photonic crystal cavity. The result demonstrates that a gate photon controls the relative phase of reflected photons via coupled solid-state spins in a cavity and shows the potential for single-photon nonlinearity in a compact chip. Photon blockade is another example of strong nonlinearity at a single-photon level. The strongly coupled cavity-quantum emitter system creates anharmonic ladder states that can alter the photon statistics from coherent to sub-Poissonian or super-Poissonian light sources and be used as photon number filters [179].

Along with the high Q cavity, 1D nanophotonic waveguides can also mediate an efficient emitter–photon interface, based on waveguide QED [187]. The slow-light mode in the waveguide plays an important role in the waveguide QED, which has a principle similar to the cavity QED. Since the waveguides use propagation modes instead of localized modes, as in the cavity, multiple quantum emitters at different positions can couple simultaneously to the waveguide and interact via real and virtual photons, enabling long-range connectivity [162]. The nanophotonic waveguides provide a particularly attractive platform since they can have high coupling efficiency (β) between propagating photons and coupled emitter [188] and be naturally incorporated in PICs. Also, they have a wider spectral coupling window compared to high Q cavities. These facts have attracted much attention for realizing strong optical nonlinearity at the single-photon level in a waveguide [173,189]. Figure 9(d) describes a schematic description of single-photon nonlinear optics using single QDs coupled to a photonic crystal waveguide. The emitter–waveguide coupled system modifies the transmission of photons with the coupled quantum emitter in the waveguide [173].

Therefore, the light–matter interaction with the integrated emitters enables a vast range of practical applications, such as quantum repeaters [190], quantum logic gates [178], photon–photon gates [191], single-photon transistors [172], and photon number filters [192] in integrated photonic circuits. The studies

Table 2. Representative Demonstrations of Quantum Took Kits for Integrated Quantum Photonic System

Quantum Functional Component	Role	Basic Principle	Related Work
Quantum memory	Store information in a photonic circuit	Long coherence time of spin	[32]
Spin-photon quantum interface	Control a spin (photon) state with a photon (spin)	Quantum entanglement between spins and photons	[147,178]
Photon-photon gate	Conditional photon switch	Strong optical nonlinear response mediated by emitters	[172]
Integrated quantum node	Large scale system involving multi-emitter coupling	Cooperative behavior of emitters mediated by photons	[59,158,163]
Photon number filter	Modification of photon statistics	Photon blockade in anharmonic ladder systems	[179]

show the potential capability of integrated quantum emitters as a source of both photonic and stationary qubits and a mediator of spin-photon interfaces on a chip. However, although the experimental results serve as valuable proof-of-principle, such results have demonstrated the interaction of the quantum emitters with an attenuated laser. Therefore, the quantum gate with true single photon sources is still a challenging task. Besides, most demonstrations remain nonuniversal quantum gates, while the deterministic generation of universal quantum gates such as controlled-NOT and $\sqrt{\text{SWAP}}$ will be required to generate photonic cluster states and on-chip photonic quantum computations [193,194].

So far, most demonstrations of on-chip quantum interfaces have been performed on monolithically integrated platforms, which limit the number and function of the quantum elements and thus increase the difficulty for further development. The hybrid integration methods will provide a solution for scalable, integrated quantum photonic systems by the postassembly of independently optimized emitters, cavities, and photonic circuits in a single chip. Recently, on-chip strong light–matter interaction in a hybrid system has been demonstrated with combined quantum emitters, high Q cavity, and photonic waveguide, as shown in Figure 9(e). Developing such hybrid systems combining bright sources and interfaces will enable deterministic and efficient quantum gates operating with single photons.

6. REMAINING HURDLES AND OUTLOOK

In this review, we have presented recent advances in integrated quantum photonic systems that generate and manipulate quantum light and establish spin-photon interaction in a single chip. Solid-state quantum emitters now demonstrate high generation rates, purities, and indistinguishability of single photons with controlled position and frequency as well as spin with long coherence times. Meanwhile, PIC can manipulate photons in various degrees of freedom using combined couplers, phase shifters, and linear/nonlinear components on a chip. Recent approaches for the hybrid integration of solid-state quantum emitters with photonic circuits have shown a possible solution for the long-standing issue of lack of deterministic quantum light sources in the PICs. Also, integrating the quantum emitters in PICs provides many quantum functional components on a chip, and therefore it adds more functionality and flexibility for on-chip photonic quantum information processing.

However, despite this progress, realizing practical on-chip quantum photonic devices with integrated quantum emitters still faces many challenges. The principal obstacle is the need to generate multiple indistinguishable single photons from independently controlled quantum emitters. Although the number of quantum emitters that can be simultaneously controlled on a chip is increasing using the approaches introduced in Section 4, those emitters still lack long coherence times [59], and therefore, extending the scale of the system while preserving indistinguishability is a great challenge that lies ahead in the field of the solid-state quantum emitter.

Another challenge is realizing efficient on-chip quantum interaction. We reviewed the possible mechanisms for such quantum interactions in Section 5, which included two-photon interference using linear optics, atom-mediated nonlinear photon–photon interaction in cavities, and photon-mediated atom–atom interaction in waveguides. However, the interference visibility, single dipole cooperativity, and entanglement fidelity need to be further improved for a large-scale quantum system. To meet the performance criteria for deterministic quantum information processing with photons, higher efficiency, scalability, stability, and controllability of the emitter and photons are required. Satisfying all these conditions may be implausible within a single material. However, hybrid integration approaches may pave the way by combining efficient single-photon sources, coherent spins, and high-quality nanophotonic structures, as well as spectral and spatial control of the emitters and the photons.

For applications, an electrically driven system at room temperature is of great interest. Given the well-developed technology of semiconductor device manufacturing, electrically driven single-photon devices have been successfully demonstrated from various quantum emitters at room temperature [39,195,196]. Although those devices can efficiently generate single photons, the results have a lack of indistinguishability of the single photons. To avoid significant spectral/timing jitters and dephasing induced by electrical excitation at the above bands, integrating a miniaturized tunable laser on the same chip has been suggested as a possible solution since it operates the system electrically but excites the quantum emitters optically at a resonant frequency [197,198]. For room-temperature operation, phonon interaction is unavoidable and broadens the emission linewidth, limiting indistinguishability. Therefore, achieving coherent single photons will be inherently difficult at high temperatures, and it requires phonon decoupling not to lose coherence properties. Recently, phonon decoupling in a low-dimensional system such as defects in 2D hBN has been reported, leading to a Fourier transform-limited linewidth at room temperature [199], and new quantum emitters such as perovskites have also been investigated toward room-temperature coherent emission [46].

Although it remains experimentally difficult to realize large-scale quantum photonic devices, the field of integrated quantum photonics is rising with developing quantum photonic technological capability, and it will provide a promising platform for various chip-scale quantum optics applications such as boson sampling [175] and quantum chemistry [13] and also for large-scale photonic quantum processors, enabling photonic cluster state quantum computing [156] and optical quantum networks [18,200]. Such integrated quantum photonic circuits can also interface with electronic microprocessors that can realize quantum-enhanced processing [25]. While quantum simulators and noisy intermediate-scale quantum processors are now becoming feasible [6,201], it is necessary to perform heuristic benchmarking on various problem classes. Large-scale systems with efficiently coupled spins and photons on a chip present a promising path to such applications.

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