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Hybrid integrated quantum photonic circuits

Ali W. Elshaari[1]✉, Wolfram Pernice[2], Kartik Srinivasan[3,4], Oliver Benson[5] and Val Zwiller[1]

Recent developments in chip-based photonic quantum circuits have radically impacted quantum information processing. However, it is challenging for monolithic photonic platforms to meet the stringent demands of most quantum applications. Hybrid platforms combining different photonic technologies in a single functional unit have great potential to overcome the limitations of monolithic photonic circuits. Our Review summarizes the progress of hybrid quantum photonics integration, discusses important design considerations, including optical connectivity and operation conditions, and highlights several successful realizations of key physical resources for building a quantum teleporter. We conclude by discussing the roadmap for realizing future advanced large-scale hybrid devices, beyond the solid-state platform, which hold great potential for quantum information applications.

Photonic quantum systems provide implementation paths for all of the essential areas of modern quantum technology, that is, quantum communication, quantum sensing, quantum computing and simulation[1]. Integrated quantum photonic circuits are a particularly desirable technology platform because they show strong potential to reach the level of component integration and performance needed for information processing, through the use of manufacturing approaches based on modern nanofabrication techniques[2]. In particular, such approaches offer: (1) functional scalability, based on the miniaturization of optical components coupled with the ability of replication and mass production[3]; (2) stability, as the circuits are built on a robust solid-state platform that minimizes deviations between adjacent optical components due to vibrations or temperature variations[4]; and (3) integrability, in that different components with complementary functionalities can be integrated in a single circuit[5].

Quantum photonic circuits consist of the following main building blocks, which underpin a number of applications: (1) single-photon sources that ideally produce one photon per excitation pulse into a desired optical mode[6]; (2) efficient and fast single-photon detectors[7]; (3) reconfigurable photonic elements that can be actively controlled, ideally conditional on intermediate measurement outcomes[8]; (4) ultralow-loss waveguiding circuits from which basic passive components such as beamsplitters, filters and delays can be created; (5) quantum memories[9] enabling photons to be stored and retrieved with high fidelity; (6) wavelength conversion elements[10] to interface dissimilar photonic components; and (7) single-photon nonlinearities[11] for photon–photon interaction and deterministic quantum gates.

The range of desired building blocks, each performing a special task, suggests that existing photonic components based on a single material system may be inadequate. For example, silicon-on-insulator platforms can provide some of the required functionalities such as photon-pair generation via spontaneous four-wave mixing, reconfigurability via thermo-optic and carrier injection effects, and moderately low optical losses, all together with the potential for complementary metal–oxide–semiconductor (CMOS) compatibility to take advantage of advanced, low-latency control electronics. However, the photon-pair generation mechanism is probabilistic, single-photon detection at wavelengths of interest (for example, 1,550 nm for low-loss propagation) requires other materials, and silicon by itself does not host a known mechanism suitable for acting as a photonic optically accessible quantum memory. Given these limitations, encountered with even the most advanced integrated photonics platforms, hybrid photonic systems leverage the strengths of different materials while avoiding their respective weaknesses, and have become a burgeoning research area in quantum photonics. In many ways, this activity parallels corresponding efforts on integrated photonics for classical applications, where notably, silicon photonics has had to confront limitations with respect to laser integration in a monolithic format (due to silicon's indirect bandgap), and heterogeneous integration with III–V semiconductor materials has been realized[12].

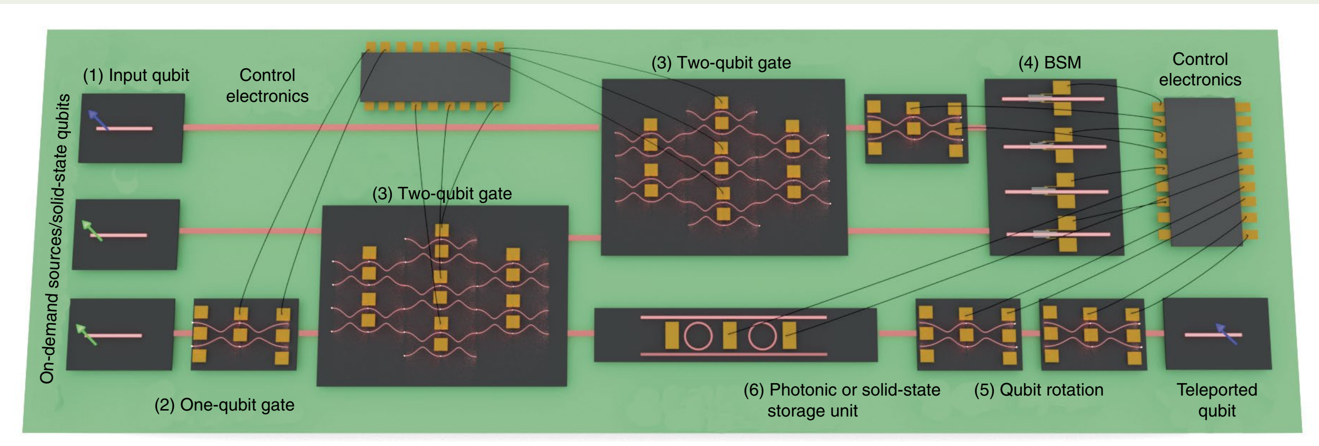
Box 1 illustrates this conceptual idea of hybrid integration for quantum photonics, where different materials with typically incompatible direct growth and fabrication technology are combined to realize a range of functionalities of value to applications in quantum information science. There are several examples of quantum devices that will require hybrid integration at some point. A node in a quantum repeater[13] needs the capability to store and manipulate quantum bits and at the same time has to transduce photons matching quantum memories to photons sent over telecom fibres. A circuit in a photonic quantum simulator[14] may have to be reconfigured based on an on-chip measurement requiring fast feedback and delay lines. The quantum teleporter illustrated in Box 1 is another example. Quantum teleportation as a resource plays a central role in quantum circuits for upscaling probabilistic quantum gates, error correction and one-way quantum computation. Realizing the quantum teleporter in Box 1 eliminates the need for post-selection through integrated quantum memories and active feed-forward, with fast conversion of quantum to classical information and vice versa. Integrating all the components of the quantum teleporter or other quantum devices of similar complexity on one chip lies outside of the scope of any current integrated photonics platforms. Different building blocks representing quantum light sources, filtering, optical delays, interference, active switching/modulation, detection and control electronics need to be combined in a modular fashion. Each of these units may be composed of heterogeneously integrated material systems, indicating how monolithic and modular hybrid integration will be required.

[1]Department of Applied Physics, KTH Royal Institute of Technology, Stockholm, Sweden. [2]Institute of Physics, University of Muenster, Muenster, Germany. [3]Microsystems and Nanotechnology Division, National Institute of Standards and Technology, Gaithersburg, MD, USA. [4]Joint Quantum Institute, NIST/University of Maryland, College Park, MD, USA. [5]Nano-Optics and IRIS Adlershof, Humboldt-Universität zu Berlin, Berlin, Germany. ✉e-mail: elshaari@kth.se

Box 1 | Hybrid quantum photonic circuits

Hybrid quantum integrated photonics is an exciting emerging field. Its conceptual idea is to combine different building blocks, which can be generally incompatible in their growth conditions and integration, in a functional circuit to perform a specific quantum task. A hybrid system that interfaces different platforms can potentially outperform its monolithic constituents or introduce an inherently missing property, for example, introducing on-demand single-photon emission or photon-pair sources in scalable and reconfigurable circuits with integrated detection and feedback. Moreover, a hybrid approach can be the natural way to integrate certain photonic elements realized in dissimilar materials, for example, semiconductor QDs, two-dimensional materials, diamond or even molecular materials. The elements can be connected by guiding structures for light, such as dielectric or plasmonic waveguides[103]. This can also require hybrid transducers converting photons into plasmons and vice versa[104]. The concept of hybrid integration is not foreign to photonic technologies — III–V lasers and silicon photonic circuits have been heterogeneously integrated using wafer bonding, nanowire bonding and transfer printing. This hybrid integration has now been embraced by quantum photonic technologies. On-demand III–V QD single-photon sources and diamond quantum memories have been integrated with a wide variety of photonic circuits, including silicon nitride, silicon on insulator and lithium niobate. There has been a tremendous progress optimizing the technology at the component level for each photonic platform, and the next steps will involve interfacing different photonic technologies either within a single circuit, or through connecting several photonic chips using photonic bonding techniques or optical fibres. Such an approach will ideally circumvent the limitations of different photonic platforms, by taking advantage of the individual attractive properties of each platform, such as high-purity single photons from QDs (qubits), fast electro-optic reconfiguration, efficient single-photon detection and all-optical quantum nonlinear processing.

Teleportation is a central resource in quantum technology, yet realizing teleportation on-chip with active feed-forward control is still an elusive goal within monolithic approaches. We envision an exemplary hybrid quantum photonic circuit for performing teleportation of a quantum state, as shown here, consisting of on-demand single photons (1) from matter qubits that can be mapped to dual rail path coding in the photonic circuit. Reconfigurable linear-optical circuits consisting of a network of beamsplitters and phase shifters are used for qubit manipulation. An entanglement resource can be established between ancillary qubits and the target qubits by applying a sequence of a Hadamard one-qubit gate (2) and a CNOT two-qubit gate (3). Next, Bell state measurements (BSM) (4) are carried out in a chosen measurement basis to project the entangled state. After the BSM measurement, classical electrical signals from the detectors can be fed to fast and ultralow-loss electro-optic modulators based on the Pockels effect to perform rotations (5) on the teleported qubit. A qubit storage unit (6), based on either an all-photonic approach (photonic analogue of electromagnetically induced transparency, as shown in the figure) or a solid-state matter qubit with controlled capture and release times, is used to synchronize the arrival of the target qubit to the one-qubit rotation gates. Finally, the teleported on-demand single photon can be mapped back to a solid-state matter qubit. The teleporter will span several quantum photonic technologies using a modular approach: on-demand single-photon sources, which can be based on colour centres, QDs or molecules, dense passive linear optical circuits based on silicon photonics, fast reconfigurable elements exploiting the Pockels effect (aluminium nitride or lithium niobate), integrated single-photon detectors based on superconducting nanowires, and electronics for synchronization and driving of different components. In the figure, the input and teleported qubits are shown in blue arrows, the resource qubits are shown in green arrows, optical connections between different components are highlighted in pink lines and electrical contacts are shown in orange boxes.



The organization of this Review is as follows. We first describe the technical considerations that go into the design of hybrid platforms combining different components, covering selection of key resources, operation conditions, optical connectivity and large-scale integration. Next, we present several fabrication approaches for hybrid integration. Then we review the state of the art of integrating typical physical resources with specific functionalities in a hybrid manner. Next, we discuss the progress in realizing several advanced hybrid quantum devices. Finally, we provide a perspective on future directions of hybrid quantum photonic technology going beyond the solid-state platform.

Design considerations for hybrid quantum photonic integration

Building a desired hybrid integrated quantum photonic device requires a trade-off between achieving the best performance of a

Table 1 | Summary of the state of the art of monolithic photonic circuits as building blocks for a hybrid architecture

Platform		Functionality		Waveguiding properties for scaling			Interfacing with other systems	
	Single-photon generation	Solid-state qubit	Electro-optic switching	Losses	Transparency window	Refractive index contrast	Operation temperature	Coupling to optical fibres
Silica waveguides[93,94]	Probabilistic, weak χ^3	–	–	Ultralow	Visible–infrared	Weak	Room temperature	Matched
Silicon on insulator[93,95]	Probabilistic strong χ^3	–	Free carriers, introduce losses, high speed	Moderate linear loss, high two-photon absorption nonlinear loss	For wavelengths >1,000 nm	Large	Room temperature	Poor matching, efficient coupling realized with specially designed mode converters and grating couplers with back reflectors
Silicon nitride[93,96]	Probabilistic strong χ^3	–	Electrostatic devices with megahertz bandwidths possible	Low linear loss and two-photon absorption nonlinear loss	Visible–infrared	Moderate	Room temperature	Moderate matching, can be increased with apodized gratings, back reflectors, and mode converters
Lithium niobate, thin film[97,98]	Probabilistic strong χ^2	–	Pockels effect, high speed	Moderate	Visible–infrared	Moderate	Room temperature	Moderate matching
Aluminium nitride[58,99]	Probabilistic moderate χ^2	–	Pockels effect, high speed	Moderate	Ultraviolet–infrared	Moderate	Room temperature	Moderate matching
Gallium arsenide[100]	Probabilistic strong χ^2, on-demand QDs, high-performance, possibility of electrical injection	Yes, potential for deterministic quantum gates, single-photon nonlinearities, memories based on spins	Pockels effect, high speed	Moderate	For wavelengths >900 nm	Low, enhanced in suspended structures	Room temperature for probabilistic photon pair, low temperature for on-demand QD source	Poor matching, can be improved with specially designed mode converters and grating couplers
Diamond[101]	Defects, on-demand, moderate performance	Yes, good properties as a memory, potential forquantum gates	Electrostatic devices with megahertz bandwidths possible	Large	Ultraviolet–infrared	Moderate	Can be operated at room temperature, improved performance at low temperature	Poor matching, high efficiencies achieved with tapered fibre structures

'–' indicates no functionality reported for the monolithic photonic circuit.

specific element and its potential for hybrid integration. From the beginning, this requires general design considerations, which we discuss in the following.

Choice of key components. A natural starting point for selecting components for a quantum hybrid device is the monolithic platforms, owing to the already high level of potential integration. Table 1 introduces several state-of-the-art monolithic quantum photonic platforms, highlighting their advantages and disadvantages in terms of single-photon generation, potential for solid-state qubit realization, linear losses for dense integration and so on. Silicon-based photonics is the most mature photonic platform, mainly due to the advanced integration technologies borrowed directly from CMOS processes in the electronics industry. Room-temperature operation, in addition to the large index contrast, makes this platform appealing for realizing large-scale passive optical networks. However, the probabilistic nature of single-photon emission coupled with the challenges of realizing low-loss and high-speed electro-optic modulation to reconfigure quantum photonic circuits on the fly, makes it challenging to scale up circuits with high operation rates. Some of these challenges are circumvented in other quantum photonic platforms, for example, lithium niobate and aluminium nitride both offer the possibility of ultrafast optical modulation with low insertion loss based on the Pockels effect, while III–V quantum dots (QDs) and diamond colour centres offer the possibility for on-demand single-photon emission, integrated quantum memories and potential realization of deterministic quantum gates.

Diamond as a monolithic material for quantum photonics requires single-crystal thin films of about 200 nm thickness on a low-index cladding or in a suspended configuration. A suspended configuration can be achieved by bonding and ion-slicing techniques and a low-index cladding can be formed from bulk diamond substrates, though the viability of creating large-scale suspended circuits is not known. QDs, however, in suitable photonic geometries, have exhibited near-ideal single-photon emission[15,16], entangled photon-pair generation[17] and potential usage as a solid-state spin qubit[18]; however, many challenges remain. The main issue is the random nature of their positions and spread in emission wavelength, a consequence of typical QD growth mechanisms. In addition, linear losses in III–V platforms are high, as passive routing elements contain unwanted randomly positioned emitters that contribute considerably to the overall waveguide loss.

Hybrid integration can now be achieved by exploiting the remarkable individual properties that monolithic photonic platforms offer. For example, several recent efforts[19–32] have revolved around methods to integrate single quantum emitters, which provide the potential for triggered single-photon emission with no inherent multiphoton suppression/source brightness trade-off, with photonic circuits in materials that support much lower losses than those in which the emitters are natively grown/housed, and for which integration of superconducting single-photon detectors is possible. Figure 1a,b shows two representative physical resources available for hybrid quantum integration: III–V QDs[33] and superconducting detectors[34].

Operation conditions. Operating temperature is an important condition to consider when selecting components for hybrid integration; for example, many single quantum emitters and superconducting single-photon detectors require cryogenic operation at 4 K or below (see also Table 1). In addition to the potential thermal mismatch created by using dissimilar devices in a common platform, certain functions commonly used in room-temperature integrated photonics may fail. For example, optical phase control (which can translate to switching and modulation when used in appropriate geometries such as Mach–Zehnder interferometers or microring resonators) based on commonly used thermo-optic and free carrier plasma-dispersion effects in materials such as silicon nitride and silicon becomes far less efficient at cryogenic temperatures[35,36]. Several efforts are underway to understand the performance of electro-optic media at cryogenic temperatures (also for applications such as microwave-to-optical quantum-state transduction); however, a modular approach in which multichip integration is used may extend to scenarios in which chips are operated in different environments (and potentially linked by optical fibres). Figure 1c presents a recent demonstration of such a scenario, where photons from QDs operating at cryogenic temperatures were fibre-coupled to a silicon nitride nonlinear resonator operating at room temperature[10].

Another essential design feature is to consider the difficulty of on-chip hybrid integration versus the gained performance advancement. This directly leads to a key aspect in the design consideration of hybrid photonic integration: integration of different materials on one chip as opposed to coupling several devices in a modular fashion, with photonic connections, that is, optical fibres. Some photonic elements are suitable for hybrid integration, such as quantum sources and detectors; however, other components may be more easily combined on a system level such as atomic/ionic quantum devices, which can then be potentially coupled to existing fibre networks for quantum internet applications[37].

Optical connections. Different elements on a photonic integrated hybrid platform or even on different chips are connected in a modular approach with light. A first concern in this respect are optical losses as light propagates from one material to the next (Table 1 compares different material platforms). Fortunately, integrated photonic circuits benefit from a robust and low-loss solution: adiabatic tapers in which light is evanescently coupled from one waveguide in the first material to another waveguide in the second material, as shown in Fig. 1d. Such evanescent coupling can be both spectrally broadband and highly efficient — in principle, near-unity efficiency can be achieved, and >98% efficiency has been demonstrated experimentally[38]. As an example, low-loss coupling between gallium arsenide and silicon nitride waveguides can be achieved despite their dissimilar material refractive indices (n = 3.5 and n = 2.0, respectively). This is possible because the phase velocity of light travelling in a waveguide depends not just on the refractive index of the core medium but also on that of the cladding layers and the fraction of the field residing in each. As a result, properly designed adiabatic tapers not only increase mode overlap but also enable matching of waveguide phase velocities. Besides evanescent coupling, we note that interlayer grating couplers for transferring light between different waveguiding layers have also been explored[39].

Considering the integration complexity for realizing a quantum teleporter, it seems likely that multichip integration will also be needed. Realizing low-loss optical connections between different chips is a recognized challenge in integrated photonics — typical approaches include micro-optics and direct facet-to-facet coupling. Recent work on three-dimensional printing of photonic structures delivers important possibilities for novel ways to combine and interface photonic circuits as shown in Fig. 1e, as well as the potential for automated assembly of photonic multichip systems[40]. Encouraging results using photonic wire bonding suggest that evanescent coupling techniques via adiabatic tapers[41], as described above, can enable coupling between several monolithic circuits. Moreover, other possibilities might include direct printing of free-form optics[42] onto waveguide facets and gratings to perform the needed beam-shaping between different guiding materials with dissimilar mode profiles. In addition, complex microscale optical systems comprising mirrors and lenses can be used for routing of photons and enhancing the collection efficiency from quantum light sources, with the possibility to match the emission to pre-existing fibre optical networks.

Large-scale integration. To harness the true potential of the quantum phenomena on a large scale, photonic systems, at least substantial portions, need to be compatible with foundry-based fabrication[2]. The last two columns in Table 1 provide important aspects to be considered. Silicon photonics delivers a very promising route for scaling using advanced CMOS processing techniques. It has been shown that 16 photon-pair sources can be simultaneously pumped to produce a multidimensional entangled state (Fig. 1f)[43]. Quantum and classical photonic circuits share the same challenges with respect to scaling, both on inter- and intrachip levels. While in classical photonic circuits inherent circuit losses and chip-to-chip coupling losses are less detrimental due to the possibility of signal amplification, quantum circuits are more sensitive to losses (no-cloning theorem), which places more stringent requirements on the performance of different elements. Luckily, quantum photonic technology can benefit from the tremendous progress in the classical photonic research that is constantly pushing for scalable systems through optimizing large-scale integration of passive and active circuits[12], implementing efficient chip–chip[44] and chip–fibre couplers[45], and packaging[46]. The upcoming challenge for hybrid quantum photonic circuits is to implement the hybrid techniques, discussed in the following section, while maintaining the required tolerances for specific quantum applications coupled with large-scale implementations. This will impose stringent requirements on the design and fabrication criteria, to move from proof-of-concept demonstrations of few quantum devices to full large-scale multichip systems, while maintaining the compatibility of the integrated materials.

The design of hybrid quantum photonic systems so far has relied mainly on the knowledge of key physical features of the individual components, with design considerations spanning a small parameter space. As the complexity of the systems increases — aiming for tens and hundreds of qubits, covering a large bandwidth range, spanning several optical coding approaches (that is, spatial or modal), combining materials with different refractive indices and

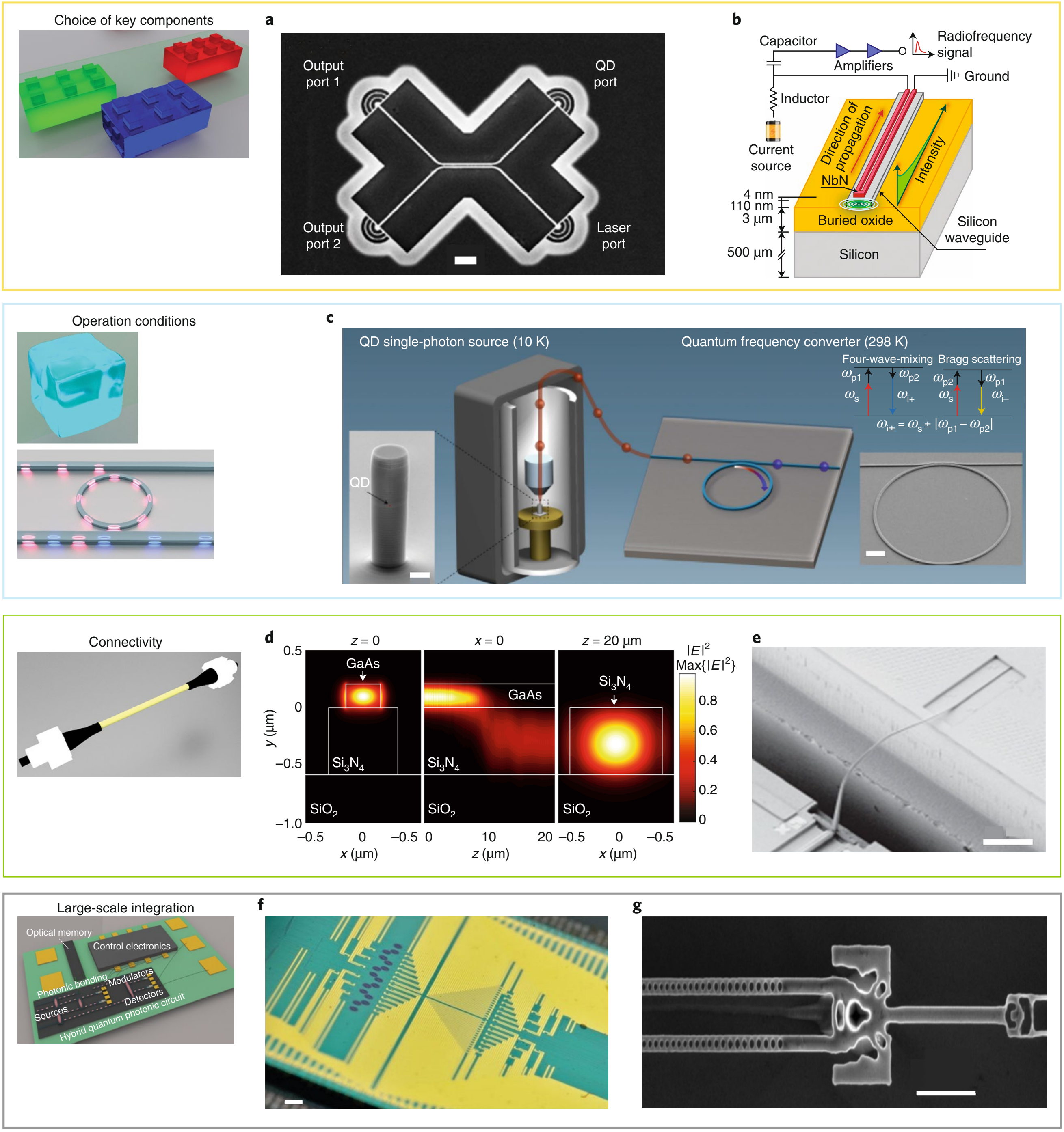


Fig. 1 | Design considerations of hybrid quantum photonic circuits. a,**b**, Key choice of component. The left artistic image shows different 'toy' key building blocks. **a**, Deterministic single-photon sources from III–V QDs integrated in a waveguide with 50/50 beamsplitter[33] (scale bar, 2 μm). **b**, Travelling-wave single-photon detector evanescently coupled to silicon waveguide[34]. **c**, Operation conditions. The left artistic images show the contrast of operating temperatures, cryogenic versus room temperature. Quantum frequency conversion in a hybrid system interfacing III–V quantum emitters (left inset; scale bar, 1 μm) operating at cryogenic temperatures and nonlinear silicon nitride resonator operating at room temperature[10] (right inset; scale bar, 10 μm). ω_{p1} and ω_{p2} are the pump photons, ω_s is the signal photon, while ω_{i+} and ω_{i-} are the idler photons. **d**,**e**, Connectivity. The left artistic image symbolically describes connectivity with an optical fibre. **d**, Adiabatic coupling between different materials comprising a hybrid quantum photonic circuit, in this case gallium arsenide and silicon nitride[19]. The colour bar represents the square of the electric field E. **e**, Photonic wire bonding between different types of photonic chips, in this case, an InP laser chip and silicon photonic chip[41] (scale bar, 35 μm). **f**,**g**, Large-scale integration. The left artistic image shows a large-scale hybrid circuit. **f**, Multidimensional path entanglement in silicon photonics, through simultaneous pumping of 16 photon-pair sources[43] (scale bar, 1 mm). **g**, Inversely designed quantum photonic circuit, symmetric along the left edge, to entangle two quantum emitters (scale bar, 2 μm)[48]. Panels adapted with permission from: **a**, ref. [33]; **b**, ref. [24]; **d**, ref. [19]; **g**, ref. [48], under a Creative Commons licence (https://creativecommons.org/licenses/by/4.0/); **c**, ref. [10], OSA; **e**, ref. [41], OSA; **f**, ref. [43], AAAS.

optical mode profiles, and hosting quantum sources of different nature (that is, deterministic or on-demand) — more sophisticated design approaches can greatly boost the overall system performance. Inverse design can potentially aid the realization of complex hybrid photonic systems. Computer-aided design has been successfully implemented for a wide variety of novel applications spanning linear and nonlinear photonics[47]. Computer-aided inverse design has been used to realize compact diamond photonic chips that can entangle two quantum emitters coupled to nanobeam cavities, as shown in Fig. 1g[48]. The technique allows for satisfying several design goals in parallel in a single device. This approach can also be applied to a hybrid scenario and may drastically reduce the footprint of future hybrid photonic devices to address large arrays of quantum sources and memories, to build compact nonlinear devices — as shown recently with passive Kerr-based isolator[49] — and even to interface different photonic systems in a modular fashion.

Fabrication approaches for hybrid quantum photonic integrated circuits

We now discuss three important approaches for hybrid integration, highlighting their advantages and technological challenges: (1) wafer bonding, (2) transfer printing and (3) pick and place. In the wafer-bonding technique, shown in Fig. 2a, a substrate containing quantum sources or memories can be bonded to another photonic material. The technique has been successfully used to perform chip-scale bonding of III–V epitaxially grown QD sources to silicon nitride photonic circuits as shown in Fig. 2b, and of 4H-SiC containing single-photon-emitting colour centres to silicon dioxide on silicon wafer[50]. After the bonding takes place, the sacrificial layer is removed to reveal the photonic circuit layer, for example, through mechanical grinding, chemical mechanical polishing or chemical etching[19,50]. In the III–V–silicon example, the bonding was realized using low-temperature, plasma-activated direct bonding[19,20]. Then the sacrificial layers were chemically etched to realize a thin layer of high-quality gallium arsenide, containing indium arsenide/gallium arsenide QDs, which was evanescently coupled to the silicon photonics layers. This method holds great potential for large-scale integration of silicon and III–V photonics, and has been already adapted for classical photonics applications to integrate lasers with silicon photonics[51], as shown in Fig. 2c. It provides a scalable, top-down heterogeneous approach that can be extended to incorporate active and passive photonic circuit elements with precise and repeatable, sub-50 nm alignment defined strictly by lithography. However, one main challenge is the random nature of the distribution of QDs, both spectrally and spatially. While various location techniques can be used to determine the relevant spatial and spectral information for the QDs[20], their random locations and spread in emission properties places design constraints on photonic circuits. We note that transfer of large-scale semiconductor membranes can also be realized through epitaxial lift-off techniques[52] in which the device layer of interest is released from its original host substrate through selective under-etching and then transferred to the target host substrate[53].

The second method is transfer printing, which alleviates the position uncertainty while sacrificing some of the scaling capabilities. Using this method, shown in Fig. 2d, an array of suspended quantum devices realized in one chip can be transferred using a rubber stamp to another target photonic circuit chip. In the process, a rubber stamp made from polydimethylsiloxane (PDMS) can be first patterned and then placed on top of the suspended structure to be transferred using a high-precision positioning system. As the rubber stamp is quickly peeled off the surface, it can carry the suspended structures, which are then bonded to the target chip through van der Waals forces. Using this technique, indium arsenide/gallium arsenide QD structures with one-dimensional cavities were transferred to silicon-based waveguides, as shown in Fig. 2e[31]. Transfer stamps were also used to integrate two-dimensional materials to silicon nitride waveguides[54], as shown in Fig. 2f, with great potential to realize arrays of single-photon sources using chemical vapour deposition growth, which can be electrically pumped and tuned through the quantum-confined Stark effect. Moreover, a similar technique was used to couple gallium selenide crystals to dielectric waveguides[55], providing a means to incorporate robust and on-demand single-photon sources to pre-existing circuits. Despite the promise of transfer printing, there are still challenges to confine one, and only one, quantum emitter to the transferred structure; without this, spectral filtering to isolate the target quantum emitter is needed, limiting the possibility of in-plane excitation, which is crucial for large-scale circuits.

Pick-and-place technology offers comparable scaling potential to transfer printing, with wider versatility with respect to the type of device that can be transferred. The method uses nanomanipulation performed either under an optical microscope[23], which can be combined with an atomic force microscope[56], or under a scanning electron microscope[25], with a nanomanipulator to pick and place certain quantum photonic elements such as sources or detectors, as shown in Fig. 2g. The desired element is attached to the nanomanipulator tip through van der Waals forces, which can be large enough to detach the desired photonic device from the parent substrate[23], or through the aid of a focused ion beam[25]. The method was used to address previous challenges regarding the randomness in quantum emitter spectral properties and position — site-controlled indium phosphide nanowires containing single indium arsenide phosphide QDs were deterministically integrated in silicon nitride photonic circuits, both butt coupled[21,23] as shown in Fig. 2h[23] and encapsulated[22]. The pick-and-place technique was also used to transfer a range of other photonic components, including suspended indium arsenide/indium phosphide QD structures as shown in Fig. 2i[25] and superconducting nanowire single-photon detectors (SNSPDs) fabricated on a silicon nitride membrane to an aluminium nitride waveguide[57]. Finally, we note that an important advantage of the pick-and-place and transfer-printing techniques over the wafer-bonding technique is that pre-screening of the structures to be transferred can be done, to ensure that only high-performing structures are integrated.

Hybrid integration of key physical resources in integrated quantum photonics circuits

Based on selected monolithic components and utilizing the fabrication techniques as described in the previous two sections, several key physical resources for integrated quantum devices have been realized. Using the highly challenging goal of the quantum teleporter proposed in Box 1 as a guideline, we now introduce several examples of hybrid integration of key physical quantum elements that would be required not only for quantum teleportation but also for other devices such as quantum repeaters or quantum simulators.

Hybrid integration of quantum sources. Starting points for any quantum photonic chip are single-photon sources. For integrated quantum photonics, they primarily rely on two different processes. The first one is probabilistic and relies on second- and third-order nonlinearities such as spontaneous parametric downconversion[58] and four-wave-mixing[59] to probabilistically generate photon pairs. Spontaneous parametric downconversion is an excellent resource for generating indistinguishable photons. Heralding, that is, detection of one of the photons in a pair, can be utilized to generate a single-photon state probabilistically. The second process is on-demand using optically active transitions in single quantum emitters. An ideal on-demand single-photon source produces one (and only one) photon per excitation pulse into a desired collection channel (for example, an optical fibre), all generated photons are identical and the source repetition rate is gigahertz or higher. Since photon

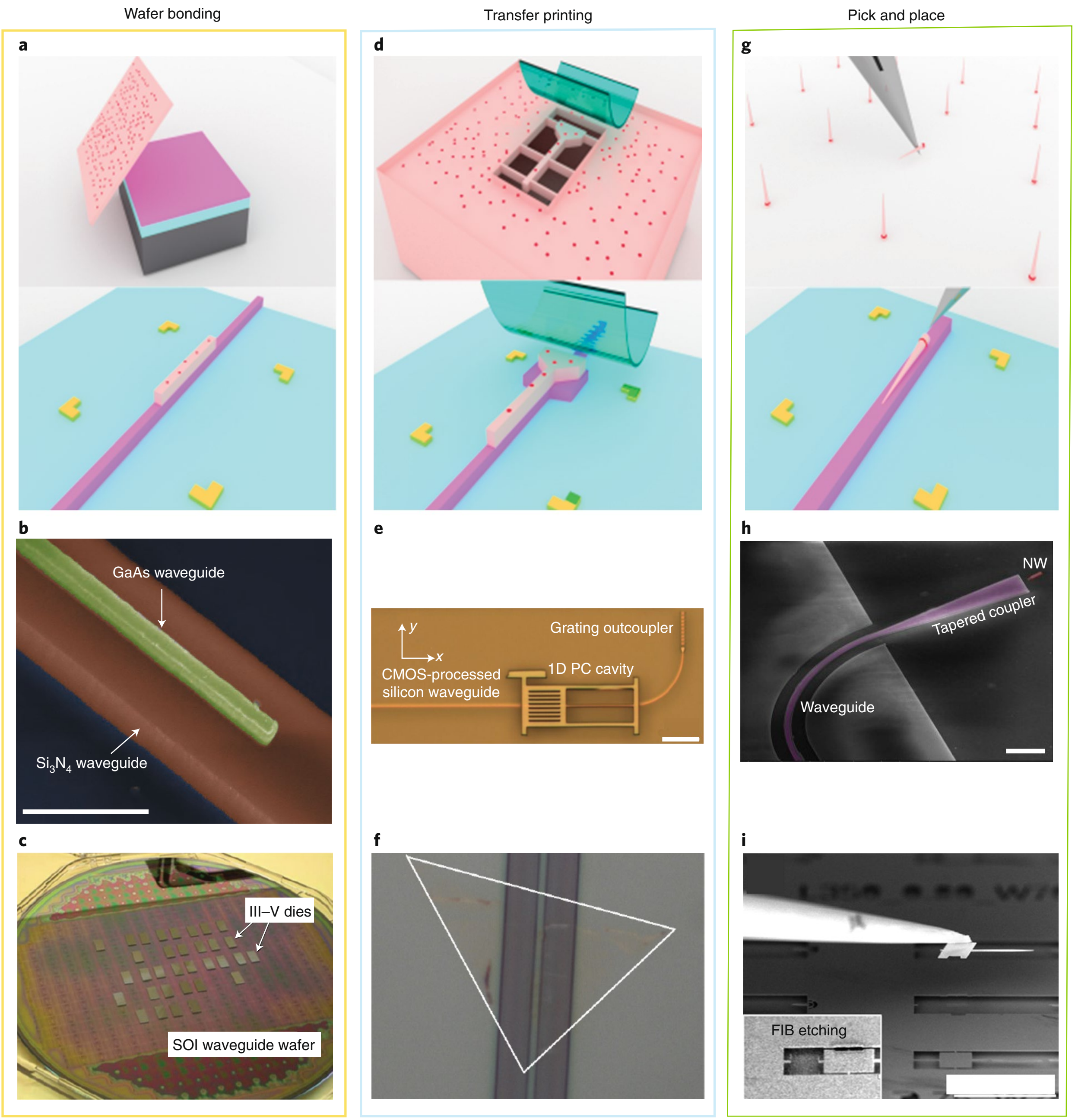


Fig. 2 | Hybrid quantum photonic integration approaches. **a**, Wafer-bonding approach to combine different materials. **b**, Wafer-bonding of a gallium arsenide nanobeam with QDs to silicon nitride waveguides: single photons from the QD are adiabatically coupled to the silicon nitride waveguide[19] (scale bar, 500 nm). **c**, Bonding of a silicon-on-insulator (SOI) wafer with III–V dies[51]. **d**, Transfer-printing approach for hybrid integration. **e**, Transfer printing of a QD photonic crystal (PC) cavity to a silicon waveguide[31] (scale bar, 5 μm). **f**, Transfer printing of a two-dimensional material (WSe_2) to a silicon nitride waveguide: single photons emitted from the monolayer are coupled to a silicon-based photonic circuit[54]. The flake is highlighted by the white triangle. **g**, Pick-and-place technique using a nanomanipulator. **h**, Pick-and-place integration of a indium phosphide nanowire (NW) QD to a silicon nitride waveguide fabricated on a piezoelectric crystal for strain tuning of the quantum source and the circuit[23] (scale bar, 2 μm). **i**, Hybrid integration of indium arsenide/indium phosphide QDs to silicon photonic waveguide using pick-and-place technique[25] (scale bar, 20 μm). The inset shows focused ion beam (FIB) etching of a QD structure. Panels adapted with permission from: **b**, ref. [19]; **f**, ref. [54], under a Creative Commons licence (https://creativecommons.org/licenses/by/4.0/); **c**, ref. [51], IEEE; **e**, ref. [31], APS; **h**, ref. [23], American Chemical Society; **i**, ref. [25], American Chemical Society.

antibunching from atoms was first observed[60], it has been known that isolated single quantum emitters can form such a source, as there is no fundamental trade-off between brightness and multi-photon probability in the emission process. Several candidates have been investigated in pursuit of such a source, including colour centres in diamond[61] and silicon carbide[62], III–V QDs[63], carbon nanotubes[64], single molecules[65], ions and neutral atoms[60,66], and defects in two-dimensional materials[67]. In QDs, a cascaded decay can be exploited to generate photon pairs, even in an entangled state[68].

Remarkably, the list of available single-photon sources reduces drastically if we consider only emitters that can be monolithically integrated in planar photonic circuits. In addition, monolithic integration is not an option for some quantum sources due to the challenge of confining light within the material. For a comprehensive

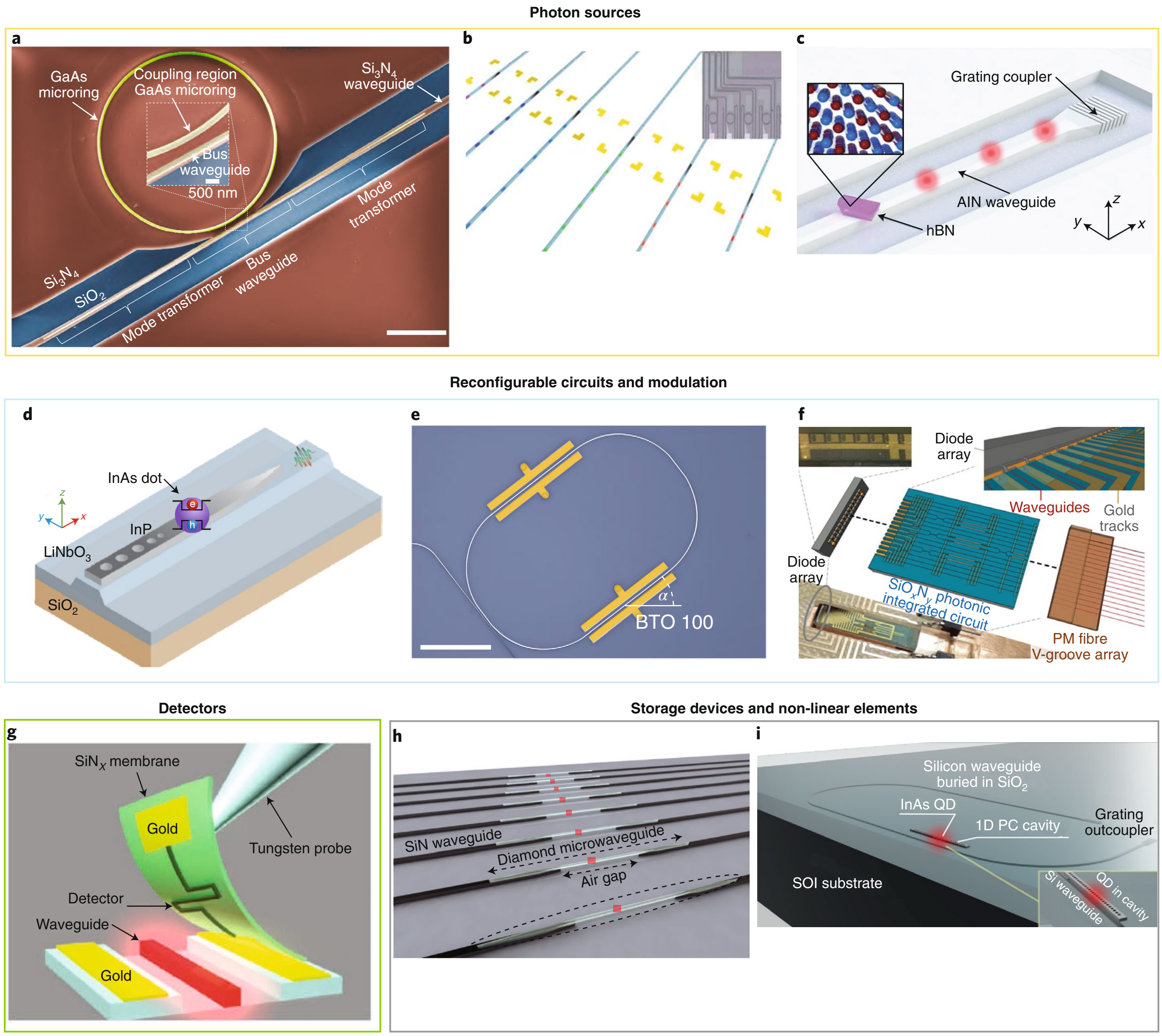


Fig. 3 | Hybrid integration of key quantum photonic resources. a, Wafer bonding of a gallium arsenide ring resonator with QDs to silicon nitride waveguides[19] (scale bar, 10 μm). **b**, Encapsulation of multiple nanowire QD single-photon sources in silicon nitride waveguides[21]. **c**, Coupling a hexagonal boron nitride (hBN) single-photon emitter with an aluminium nitride waveguide using exfoliation and stamping[72]. **d**, Hybrid integration of telecom QDs to lithium niobate waveguide[24]. **e**, Hybrid integration of barium titanate (BTO) electro-optic modulator to silicon photonics platform[77] (scale bar, 50 μm). α is the relative angle between the racetrack resonator and the BTO <100> pseudo-cubic crystalline direction. **f**, Interfacing III–V QD chip with configurable silicon nitride photonic circuit[79]. Emitted photons are then coupled to an array of polarization-maintaining (PM) optical fibres. **g**, Hybrid integration of SNSPDs fabricated on silicon nitride membranes on aluminium nitride photonic waveguides using a pick-and-place technique[57]. **h**, Pick-and-place hybrid integration of long-lived diamond quantum memories on silicon nitride waveguides[27]. **i**, Strong coupling of QDs in a gallium arsenide nanobeam PC cavity to a silicon waveguide[31]. Panels adapted with permission from: **a**, ref. [19]; **b**, ref. [21]; **g**, ref. [57], under a Creative Commons licence (https://creativecommons.org/licenses/by/4.0/); **c**, ref. [72], Wiley; **d**, ref. [24], AIP; **e**, ref. [77], Springer Nature Ltd; **f**, ref. [79], AIP; **h**, ref. [27], under a Creative Commons licence (https://creativecommons.org/licenses/by/3.0/); **i**, ref. [31], APS.

review of solid-state single-photon sources and a comparison of their different properties, we refer the reader to ref. [69].

In Fig. 3a–c, we illustrate three examples of hybrid integration of single-photon emitters in photonic light-guiding elements. In Fig. 3a, we show a III–V QD in a gallium arsenide waveguide taper attached to the top of a silicon nitride waveguide by wafer bonding. This enables the transfer of optical power from the top layer to the bottom layer. The same technology was employed to fabricate QDs in gallium arsenide ring resonators coupled to silicon nitride waveguides to explore the weak coupling regime for radiative lifetime enhancement. A fourfold reduction in the emission lifetime, Purcell enhancement, collected from the silicon nitride waveguide was observed experimentally[19]. This result is important for more complex circuits containing several quantum emitters, to reduce the effects of dephasing due to interaction of the quantum emitters with the environment, and boost the photons' indistinguishability[70]. QDs in cavities were also integrated in silicon circuits using the transfer-printing technique[31]. To enable more control over the selection of the quantum emitters, the pick-and-place technique was used to encapsulate single nanowire QDs in a silicon nitride waveguide[22]. Furthermore, simultaneous deterministic integration of multiple quantum sources in addition to filtering and multiplexing was recently realized using the same approach[21], as shown in Fig. 3b. In this way, several photons could be launched and routed on an integrated chip[21]. To take advantage of the existing technology in the telecommunication window, it is desirable to realize on-demand single-photon sources at telecom wavelengths in silicon photonic circuits. Single-photon emission at telecom wavelengths was realized in silicon photonic crystals through hybrid integration with erbium-doped yttrium orthosilicate crystals, leading to emission rate enhancement of a factor of more than 650 (ref. [71]).

The field of hybrid integration of quantum sources is rapidly growing, both with respect to the types of material incorporated and the method of integration. Through selective under-etching and the chip-transfer technique, gallium phosphide membranes were used to form photonic circuits on diamond substrates[53]. In addition to addressing and collecting the emission of nitrogen vacancy centres through the gallium phosphide waveguiding layer, gallium phosphide introduces a second-order nonlinearity that can potentially enable fast electro-optic switching and wavelength conversion[53]. A common challenge of the previously discussed single-photon sources used in hybrid integration is the need for operation at cryogenic temperature to preserve the sub-Poissonian statistics and indistinguishability. However, recently, defects in hexagonal boron nitride as room-temperature single-photon sources were integrated into aluminium nitride waveguides using exfoliation and stamping, as shown in Fig. 3c. This demonstrates the interesting potential of defects in two-dimensional materials in general as bright single-photon sources[72], albeit without photon indistinguishability yet reported. For additional examples of integration of quantum sources, we refer the reader to ref. [73].

Hybrid circuit reconfiguration elements. Dynamic circuit reconfiguration is an important resource shared between classical and quantum applications. Rapid changes in the optical properties of an integrated device on the order of the time-of-flight timescale are essential for feed-forward operations to perform rotations on the qubit for linear optics quantum computation or teleportation[8]. Furthermore, for probabilistic single-photon sources, spatial and temporal multiplexing schemes can increase determinism of single-photon emission[74]. Figure 3d–f depicts a route towards a reconfigurable hybrid photonic chip. Starting with an integrated photon source, Fig. 3d shows an indium arsenide/indium phosphide QD emitting at telecom wavelengths, which was transferred deterministically, with nanoscale precision, to lithium niobate photonic circuits. With its large nonlinearity, lithium niobate opens the door for fast electro-optic control of single photons from on-demand single-photon sources[24]. Fast electro-optical modulation on-chip with ultralow insertion loss is very challenging to achieve in silicon. This has motivated recent efforts to enhance effective nonlinearities and study fast and low-loss electro-optic switching in aluminium nitride[75] and lithium niobate on insulator[76]. Yet, it is still desirable to have the same capabilities in platforms lacking inherent second-order nonlinearity, such as silicon photonics with its advanced integration techniques and industrial potential. Hybrid integration techniques were used to integrate large-Pockels-effect materials such as barium titanate[77] as shown in Fig. 3e, and lithium niobate[78], achieving 50 Gbit s^{-1} and 100 Gbit s^{-1} on-chip modulation, respectively. The developed fabrication processes can also be applied to other low-loss materials with no electro-optics modulation capabilities such as silicon nitride, allowing the connection of a reconfigurable circuit with fast electro-optics modulation to multiple III–V quantum emitters via direct chip–chip coupling. Such coupling of many emitters to a reconfigurable silicon nitride chip is shown in Fig. 3f[79]. Finally, one may also envision coupling to many superconducting single-photon detectors, discussed in the next section, thus incorporating all the essential elements for qubit generation, fast manipulation and detection on a single chip.

Single-photon detectors in hybrid circuits. Efficient single-photon detectors that can be seamlessly integrated with active and passive elements are key resources for nearly any quantum circuit, and in particular for a quantum teleporter. While many semiconductor-based technologies have been explored, SNSPDs have proven to provide superior performances with respect to detection efficiency, time jitter and dark noise[80,81]. Waveguide coupled SNSPDs deliver high on-chip detection efficiency (>90%), low dark count rate (<1 Hz) and high timing resolution (<20 ps)[34]. SNSPDs are prepared from thin superconducting films. Several superconducting materials, such as tungsten silicide, molybdenum silicide and niobium titanium nitride, can be deposited at room temperature on a wide range of substrates, facilitating hybrid integration with photonic circuits. Recently, hybrid integration of SNSPDs was realized, as shown in Fig. 3g[57]. The reported process delivers 100% yield, which paves the way for advanced integration of multiple sources and detectors on chip. Going forward, the combination of SNSPDs with complex, dynamically reconfigurable photonic architectures for active feedback operations will also require interfaces with external electronic circuitry that harness their superior performances.

Hybrid storage devices and nonlinear elements. A quantum memory for high-fidelity storage and retrieval of photonic qubits is central in many quantum information applications. An ideal memory should have several features: 100% capture and release efficiency from/to specific optical mode, on-demand readout with storage times longer than the time needed to establish on-chip entanglement or reconfigure the photonic circuit, gigahertz bandwidth, operation at telecom wavelength for transmission through a fibre network, negligible added noise per storage, and robustness combined with ease of use and integration with other dense photonic circuits. At present, there are several approaches under investigation, including coupling rubidium atoms to photonic structures, atomic frequency combs, long-lived spin states in diamond, or rare-earth ions in crystals. Hybrid integration is needed to incorporate such memories in large-scale quantum photonic systems. Hybrid integration of long-lived nitrogen-vacancy-centre quantum memories to silicon nitride waveguides was recently demonstrated using pick-and-place techniques[27], as shown in Fig. 3h. The result is particularly interesting since several quantum information systems, such as quantum computers and repeaters, require long-lived quantum memories that can be controlled individually[27], and spin states in nitrogen vacancy centres can reach coherence times on the order of seconds[82].

Besides memories, another key element is a quantum logic element. A strong nonlinearity at the single-photon level would enable logic operations with a smaller overhead for both classical and quantum-information technology. Strong coupling of III–V QDs in a one-dimensional cavity coupled to a silicon waveguide to achieve quantum nonlinearity was recently demonstrated[31] and is shown in Fig. 3i. The work highlights an important missing ingredient in silicon-based photonics that for now can only be realized using hybrid integration. Such nonlinear elements can enable important quantum information tasks such as controlled coherent coupling and entanglement of distinguishable systems[83], and promise to reduce the overhead requirements for on-chip quantum computing.

Finally, nonlinearity — more in classical sense — is required to establish quantum frequency conversion of light at the single-photon

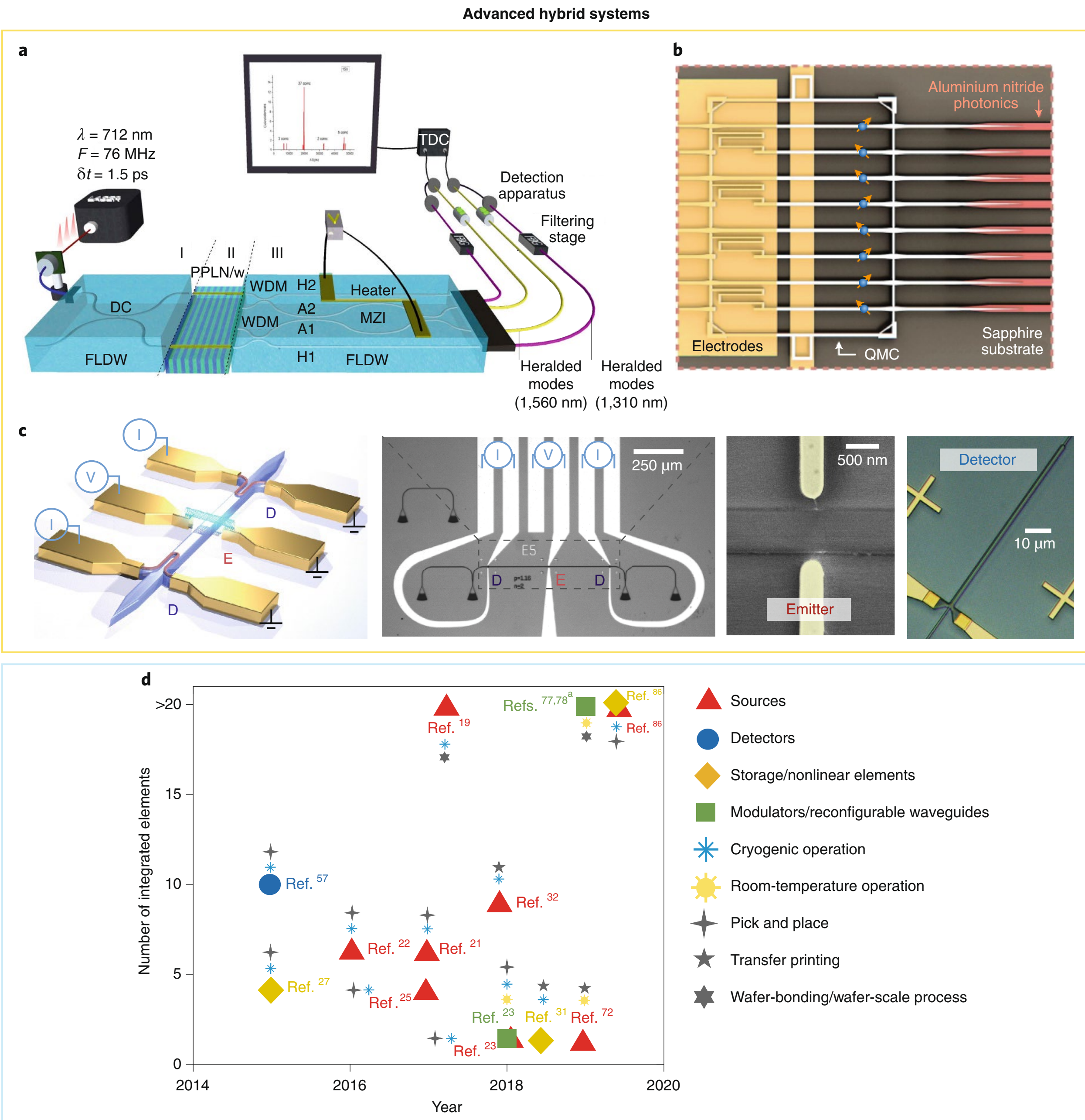


Fig. 4 | Advanced hybrid systems. a, Hybrid system consisting of nonlinear lithium niobate waveguides and femtosecond-laser-direct-written waveguides to generate two-photon states[85]. The hybrid circuit consists of three blocks: I, for splitting the pump laser using a directional coupler; II, for simultanouse pumping of two periodically poled lithium niobate waveguides (PPLN/w); III, for state engineering using a reconfigurable Mach–Zehnder interferometer (MZI). λ, laser wavelength, δt, laser pulse duration; F, laser repetition frequency; TDC, time-to-digital converter; WDM, wavelength division multiplexer; DC, 50/50 coupler; FLDW, femtosecond laser direct-write; H1/2 outer waveguide modes; A1/2, inner waveguide modes. **b**, Hybrid integration of near-indistinguishable 72 artificial atoms, germanium-vacancy and silicon-vacancy colour centres in diamond, to an aluminium nitride photonic integrated circuit[86]. Groups of eight artificial atoms are integrated in quantum microchiplets (QMC). **c**, A proof-of-concept integrated quantum link at telecom wavelength consisting of electrically triggered carbon nanotube single-photon sources, silicon nitride nanowaveguide and superconducting single-photon detectors, all fabricated on a single chip[26]. The superconducting single-photon detectors and the carbon-nanotube emitter are denoted by D and E, respectively. **d**, Number of key physical resources realized versus demonstration year, with additional information regarding the operation temperature and the method of integration used. [a]No specific number of devices is presented, but the fabrication is done on a wafer scale, so the main limitation is the device size (3-mm-long Mach–Zehnder modulator). Panels adapted with permission from: **a**, ref. [85], under a Creative Commons licence (https://creativecommons.org/licenses/by/4.0/); **b**, ref. [86]; **c**, ref. [26], Springer Nature Ltd.

level with negligible added noise. Such a conversion is needed to interface photonic components operating at different wavelengths, such as integrated quantum memories on the one hand and photons travelling in fibres in the telecom band on the other hand. It can also be exploited to compensate the mismatch of the emission wavelength of several quantum emitters[84], for example, QDs. Wavelength conversion of on-demand photons was recently realized in a modular chip–chip-level hybrid system[10]. Quantum light from a QD was

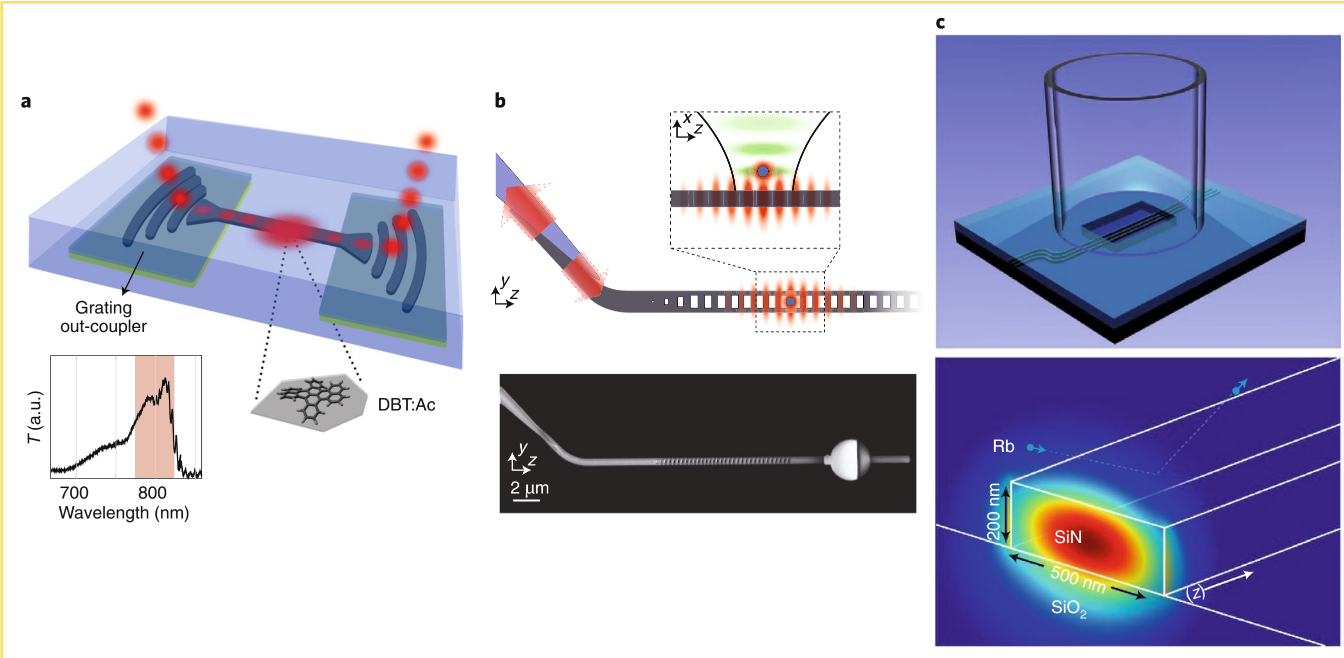


Fig. 5 | Beyond hybrid integration of monolithic resources. **a**, Hybrid integration of a DBT:Ac (dibenzoterrylene embedded in a rigid matrix of crystalline anthracene Ac) molecule single-photon source to a silicon nitride waveguide[29]. The inset shows the transmission *T* of the grating coupler around the DBT fluorescence window (red-shaded area). **b**, Nonlinear phase gate in a hybrid atomic-photonic system[102]. **c**, Hybrid atomic cladding photonic waveguide demonstrating light–matter interaction at room temperature[91]. Panels adapted with permission from: **a**, ref. [29], American Chemical Society; **b**, ref. [93], Springer Nature Ltd; **c**, ref. [91], under a Creative Commons licence (https://creativecommons.org/licenses/by/4.0/).

coupled to a silicon nitride integrated nonlinear resonator and single photons were converted with 12% efficiency within the near-infrared band, while maintaining sub-Poissonian statistics with limited added noise.

Towards hybrid quantum photonic devices

Using the first steps of hybrid integration of several key components as described in the previous section, the first hybrid quantum photonic devices emerged. Figure 4 shows three examples. The first one (Fig. 4a) is a photon-number state generator[85], where two different fabrication techniques, that is, nonlinear waveguides on lithium niobate for efficient photon-pair generation and femtosecond-laser-direct-written waveguides on glass for photon manipulation, were combined. Through real-time device manipulation capabilities, a variety of path-coded heralded two-photon states were produced, ranging from product to entangled states. A larger-scale hybrid integration of single-photon sources was demonstrated by coupling near-indistinguishable artificial atoms (defect centres in diamond) to aluminium nitride photonic circuits, as shown in Fig. 4b[86]. In these so-called quantum microchiplets, 72 germanium- and silicon-vacancy colour centres were transferred on aluminium nitride photonic waveguides, all operating with close to lifetime-limited bandwidth, with the ability to frequency tune. The authors relied on a pick-and-place approach to transfer pre-screened chiplets from the source chip to the target photonic circuit chip with a theoretical coupling efficiency to the waveguides of 98% — the reported quantum sources transfer success rate was 90%. The use of piezoelectric controllers for the manipulation offers outstanding accuracy of transfer with a placement mean error of 38 nm and s.d. of ±16 nm, corresponding to a drop in coupling efficiency of 10%. The systematic approach for transfer can be also adapted for the assembly of other large-scale circuits containing QDs, rare-earth dopants and colour centres, with the ability to co-integrate CMOS electronics in a modular fashion for an additional degree of control of the quantum sources or the photonic circuits[86]. The realized building blocks, combined with phase stable modulators and interferometers, will become an important ingredient in modular quantum and multiplexed quantum repeaters[86]. Finally, Fig. 4c shows a proof-of-concept device, where three key quantum components were combined on a single chip: single-photon generation with electrical triggering, routing and detection. In the work[26], semiconducting single-walled carbon nanotubes were incorporated onto silicon nitride waveguides using dielectrophoresis, allowing for scalable and site-selective placement of quantum emitters.

All these devices are still not on the level of the complexity required for implementing the teleporter that we introduced in the beginning of this Review. However, there has been considerable progress, in particular with respect to the integration of different kinds of on-demand single-photon sources and photonic circuits. With the additional integration of detectors, which has been achieved as well (Fig. 4c), a hybrid quantum photonic simulator[87] with up to 100 qubits is within reach. As a summary of the level of integration and appropriateness for real applications, we plot in Fig. 4d the number of hybrid integrated components versus the demonstration year.

Outlook and perspective

Many components and methods to achieve a high level of hybrid integration in quantum photonic circuits already exist, though substantial effort is required to move from the single-/few-component level thus far shown to the completely functional modules and systems envisioned for our teleporter in the beginning of this Review. Without the quantum memory, our exemplary teleporting circuit consists of classical photonic elements complemented with a vast resource of photon sources and a huge array of high-efficiency detectors. A true advance in scalability would certainly be to go from the existing level of few photons to several hundreds of photons in the circuit. Concerning the number of qubits, photonic quantum simulation may then compete with what is possible today with trapped cold atoms in optical lattices. Also, probabilistic linear optical quantum gates including teleportation to enhance their efficiency could be implemented. It is unrealistic to achieve this without a high level of integration on one ultralow-loss and reconfigurable chip.

One major hurdle is, however, that superconducting detectors (and most quantum-emitter based sources/qubits) integrated on such a platform need cryogenic temperatures, whereas the classical circuit prefers room temperature. Optical links between a room-temperature chip and cryogenic detectors would, however, be cumbersome and a source of loss. Since superconductivity inevitably requires a low temperature, the only way is to further develop a low-loss and configurable cryogenic photonic circuitry. Another hurdle, when using the most promising resource of indistinguishable and/or entangled photons, that is, photon-pair sources, is the non-probabilistic pair generation, although multiplexing[88] can improve the heralding probability. Here again, an integration of many pair sources, detectors, fast switches and delay lines on one chip would be a viable path for scaling up.

On a more technological side, quantum elements on integrated chips are often initialized, manipulated or read out by additional optical or microwave control pulses. Often, for example, for initializing the spin state in quantum dots, polarized pump light has to be provided perpendicularly to the substrate plane, which is typically done by free space beams. A further level of integration would thus require going to a third dimension. Also, with the tremendous advancement of superconducting qubits for quantum computation[89], coherent transducers between the microwave domain and optical domain become very important for connecting photonic and superconducting qubits. Optical or microwave control pulses applied to a cryogenic hybrid chip require careful heat management. The same holds if several hybrid chips operating at different temperatures (millikelvin for storage, kelvin for quantum control, room temperature for electronics) have to be combined and optically or electronically connected in compact modular form.

Hybrid photonic integration offers exciting new possibilities for material integration as highlighted above, with potential as a viable path for quantum optical information processing, provided that it can address or circumvent some of the major challenges it faces, such as large scaling, optical losses, matching of different photonic elements and near-deterministic generation of the photon as a flying qubit, to highlight a few. In the future, one can envision many more levels of hybrid integration. One direction is not only to include different, mainly monolithic, components on one chip but also to combine different physical systems.

An example is a platform using single organic molecules embedded in host crystals. At low temperatures, such molecules represent nearly perfect two-level systems. In a hybrid approach, molecules (dibenzoterrylene molecules embedded in a matrix crystal of anthracene) were coupled to silicon nitride[29] (Fig. 5a) and titanium oxide[30] waveguides, opening the possibilities for coherent all-optical control of the emission, all on-chip. However, due to the required very low operation temperature (<2 K), the limited stability of the host crystal at room temperature and the lack of more than two stable electronic states, molecules may be more appropriate for fundamental light–matter studies rather than for a near-future quantum technology.

Another exciting approach could combine the long coherence times and strong interactions offered by ions or atoms with photonic integrated circuits. Such a new level of hybrid integration would also provide a route towards a quantum storage element with long coherence times. A quantum storage element is at present among the most difficult challenges, and even a less sophisticated yet integrated element that is capable of storing a faint light pulse for milliseconds would still be very useful as a delay line or for synchronization, even in a purely classical application.

Delay and eventually storage of photons from integrated photon sources in alkali gas cells has been demonstrated[90]. A full integration of such an approach is still missing, although there is an existing technology of micro-integrated gas cells[91] or gas-filled microstructured fibres[92] for applications such as magnetometry. In this sense, one may also envision a merging of photonic chips and atom chips. Figure 5b,c shows the first steps in this direction. Strong coupling between a single cold atom and nanoscale-photonic crystal cavity (Fig. 5b) enabled phase control of the atom conditional on the presence of a photon and vice versa[93]. At room temperature, strong light–matter interaction was achieved between rubidium in a micro glass cell integrated with silicon nitride photonic waveguides[91] (Fig. 5c).

After all, quantum photonic hybrid integration is at large a very advanced engineering task. This approach, which is striving for the utmost quantum performance will, however, be very valuable for future integrated photonics as a whole.

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Competing interests

The authors declare no competing interests.

Additional information

Correspondence should be addressed to A.W.E.