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Hybrid superconducting photonic-phononic chip for quantum information processing

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The integration of qubits with long coherence times and functional quantum devices on a single chip, and thus the realization of an all-solid-state quantum computing chip, is an important goal in current experimental research on quantum information processing. Among various quantum platforms, a series of significant progresses have been made in photonic quantum chips and superconducting quantum chips, while both the number of qubits and the complexity of quantum circuits have been increasing. Although these two chip platforms have respective unique advantages and potentials, their shortcomings have been gradually revealed and need to be solved. By introducing phonon-integrated devices, it is possible to combine all unsuspended phononic, photonic, and superconducting quantum devices organically on the same chip to achieve coherent coupling among them. Here, we provide a prospect and a short review on the integrated photonic, superconducting, and hybrid quantum chips for quantum information processing.

Keywords: Photonic integrated circuits, Quantum information processing, Hybrid quantum chip, Phononic circuits, Superconducting quantum circuits

INTRODUCTION

Quantum computing has unique parallel computing advantages[1–4], and thus has significant impact on numerous fields. It has received extensive attention and huge investments both nationally and commercially. In 1994, it was proposed that by using Shor's algorithm quantum computers can efficiently factor integers, which creates a potential crisis for Rivest-Shamir-Adleman (RSA) cryptographic systems[5,6]. During the past decade, quantum computing has been applied to calculating the ground state energy[7–9] and energy spectrum of molecules[10]. With the development of a variety of quantum information processing platforms such as neutral atoms[11], ion traps[12], photonic[13,14], and superconducting integrated circuits[15,16], important experimental achievements have also been accomplished in quantum simulation[17–20], quantum metrology[21,22], quantum sensing[23], quantum chemistry[24], and quantum machine learning[25]. Because of the imperfect control and noise in quantum gates, the scale of the quantum circuits is limited in the near term that is the so-called noisy intermediate-scale quantum (NISQ) era[26,27]. Among the different systems, the realization of quantum circuits on a solid-state quantum chip is one of the most important and promising routes toward scalable quantum information processors, and has attracted researchers from a wide range of fields including mathematics, information, chemistry, materials, etc. to join in and carry out interdisciplinary research.

Although different quantum chip platforms, e.g. semiconductor, superconducting, and photonic chips, have unique advantages and potentials, each quantum chip platform also suffers from its inherent limitations, which may hinder its future development. Many challenges in the field of quantum chips need to be solved, and further exploratory research is necessary to pave the way for future solid-state quantum information processors. Photonic and superconducting integrated circuits, being two outstanding solid-state quantum chip platforms, have achieved much over the last two decades as the complexity of the circuits has dramatically increased[13–16]. To further improve the scalability and performance, hybridization of the two quantum chips as well as further combination with other potential components on a single chip have become critical for future scalable quantum processors, quantum networks, and distributed quantum computation.

PHOTONIC QUANTUM CHIPS

The quantum coherence of the electromagnetic waves at optical frequencies, on the order of 100 terahertz (10^{14} Hz), can be maintained well at room temperature because the photon thermal excitation noise in this frequency band is negligible. Photonic systems, therefore, do not need particularly complex control systems to isolate the influence of the environment. In contrast, superconducting quantum systems, which operate in the microwave frequency regime, require complex and sophisticated dilution refrigerators to provide a mK operating environment to reduce the thermal excitation[33]. Therefore, a quantum information processing platform operating at room temperature is expected to be developed in the

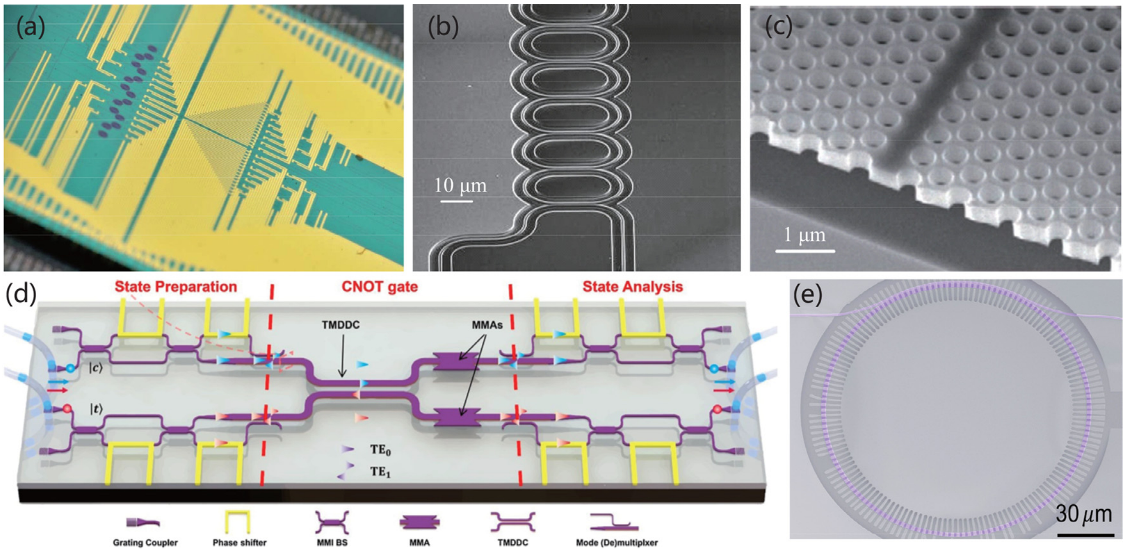

Fig. 1 | Recent progress in photonic quantum chip integration. a, A programmable large-scale integrated quantum photonic circuit to generate, control, and analyze 15 × 15 dimensional entangled states. The device fully integrates 671 photonic components with 16 identical photon-pair sources, 93 reconfigurable thermo-optical phase shifters, 122 multimode interferometers, 376 crossers, and 64 grating couplers[28]. © 2018 AAAS. **b,** Cascaded microrings for ultracompact optical buffers[29]. © 2007 Springer Nature Ltd. **c,** Highly dispersive photonic crystal waveguide for an optical delay line[30]. © 2008 Springer Nature Ltd. **d,** The multimode implementation of a 2-qubit CNOT gate with transverse mode encoding on a silicon photonic chip[31]. © 2022 American Physical Society. **e,** Periodically-poled lithium niobate microring resonators with a single-photon nonlinear anharmonicity approaching 1%[32]. © 2020 Optica Publishing Group. All images reprinted with permission.

future based on integrated photonic quantum chips for important applications such as quantum precision measurements, remote quantum networks, quantum communication, and distributed quantum computing[34].

In recent years, great progress has been made in integrating photonic quantum chips[31,35–40]. For example, based on the high scalability of the integrated chips and standard nano-fabrication processes, a large-scale integrated quantum circuit with 671 photonic components has been demonstrated[28], as shown in Fig. 1a. In such a quantum chip, a complex electric circuit is necessary to independently control the photonic components and to minimize the crosstalk. Although the integrated photonic quantum chip has the advantages of high scalability and room-temperature operation, it still faces the following two major challenges before more complex quantum information processes can be realized:

1. Lack of efficient on-chip photonic quantum memory and relay. Due to the fast propagation speed of light and the low dispersion of the low-loss optical materials required for improving the scalability of photonic quantum chips, it is difficult to achieve large optical delays on compactly integrated chips. The on-chip optical delay is currently achieved mainly by designing structures with large group-velocity dispersion, such as cascading microrings and photonic crystal structures, as depicted in Fig. 1b-c. The length of delay in these configurations is only several hundred picoseconds[29,30]. Although one-hour coherent optical storage has been demonstrated recently[41], its compatibility with other functional photonic quantum devices remains elusive.

2. Weak nonlinearities. Limited by the low intrinsic nonlinear coefficients and losses in bulky materials, single-photon-level nonlinearity can hardly be realized in current photonic quantum chips[42]. Benefiting from the large second-order nonlinear coefficient of lithium niobate and the advanced nano-fabrication processes, a single-photon nonlinear anharmonicity up to 1% has been demonstrated[32] by searchers at Yale University (Fig. 1e). However, it is still a long way to achieving strong coupling. Due to the weak photon-photon interaction, the preparation of quantum states and quantum gates at present are achieved probabilistically by post-selection, which reduces the success rates of operations and thus hinders the further extension of photonic quantum information processors. As depicted in Fig. 1d, without post-selection the CNOT gate can only succeed with a probability of 1/9[31]. To enhance the photon-photon interaction, high-power lasers are desired, however, this may also introduce noise and affect the fidelity of quantum information processing.

SUPERCONDUCTING QUANTUM CHIPS

Although a strictly cryogenic environment is required, the development of quantum information processing based on programmable solid-state superconducting quantum chips is much more advanced compared to photonic quantum chips. Due to the strong and lossless Josephson nonlinearity and the high flexibility of the macroscopic superconducting circuits, many different types of superconducting qubits such as charge qubits, phase qubits, flux qubits, and their evolved structures have greatly enriched the Hamiltonians that can be designed and the corresponding quantum information processing capabilities[45]. Benefiting from the continued development of nano-fabrication techniques, materials, and designability, researchers already have the capability to precisely design large-scale integrated superconducting quantum circuits.

In the past decades, coherence times, gate operation fidelity, and information readout speed of superconducting qubits have been significantly improved. The coherence times of superconducting qubits have been able to exceed 100 microseconds by properly designing the superconducting circuits to reduce the dissipation into the environmental electromagnetic modes[15]. In addition, the fidelity of single-qubit gates has already exceeded 99.9%, and a variety of different two-qubit gate schemes have been proposed and experimentally demonstrated, with the best fidelity exceeding 99%[45]. Last, based on charge measurement, flux measurement, and the dispersive readout techniques, fast and high-fidelity readout of qubit states has also been achieved[46,47]. With these developments, the research groups from Google and University of Science and Technology of China (USTC)

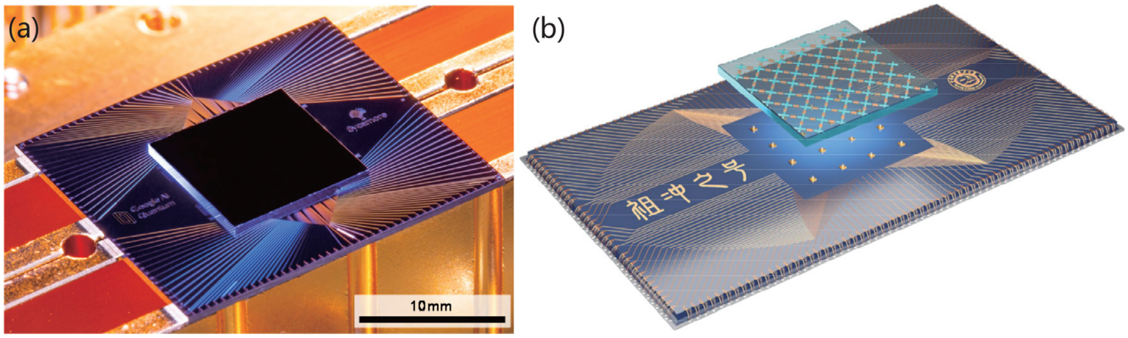

Fig. 2 | Recent superconducting processors. a, Programmable solid-state superconducting processor with 53 qubits and 86 couplers realized by Google[43]. © 2019 Springer Nature Ltd. **b,** Programmable solid-state superconducting processor with 66 qubits and 110 couplers by USTC[44]. © 2021 American Physical Society. All images reprinted with permission.

have prepared 53-qubit and 66-qubit superconducting circuits on chips in 2019 and 2021, respectively, and verified the quantum advantage[43,44,48], as shown in Fig. 2. Alternatively, by exploiting the large Hilbert space of microwave modes, bosonic quantum error correction codes[49–52] and fault-tolerant quantum gate operations[53,54] have been demonstrated with superconducting circuits.

With a further increase in the number of superconducting qubits on a single chip in the future, it is foreseeable that the extension of superconducting quantum chips will face some limitations:

1. The size of superconducting devices. Since the wavelength of microwaves is on the order of centimeters, and the size of the superconducting resonators on the superconducting quantum chip will be limited, which makes the high integration degree of the system difficult. Additionally, in highly integrated superconducting quantum chips, how to route and suppress microwave crosstalk will be another challenge.

2. The connection over a long distance. Since superconducting quantum chips operate in the microwave band, while the microwave transmission loss and environmental thermal excitation are large at room temperature, it is difficult to transmit quantum information over long distances based on microwaves. Therefore, it is a pressing challenge to develop new chip technologies to efficiently convert quantum information carried by microwaves to telecom wavelengths for quantum networks and distributed quantum information processing.

HYBRID QUANTUM CHIPS

Given the respective advantages and core challenges of the integrated photonic quantum chips and the superconducting quantum chips, the organic combination of the two systems can give full play to their own advantages and solve some of their problems at the same time. However, the huge gap in frequency between optical waves and microwaves makes it difficult to interact with each other directly. Introducing high-frequency phonons in the GHz frequency band as a medium is a feasible method. On the one hand, the wavelength of the high-frequency phonons is on the order of several hundred nanometers, which is comparable to the wavelength of optical waves. On the other hand, the high-frequency phonons match the operating frequency of superconducting microwave devices, i.e., the operating band of 5–10 GHz for superconducting qubits. Importantly, phonons feature both the high integration level of photonic devices and the long coherence times of superconducting devices[59], therefore, phononic devices provide additional options for solid-state quantum computing chips.

Research on quantum chips based on high-frequency phonons is still at the initial stage, and there are few related studies. Most of the current research efforts are dedicated to the study of acoustic devices at sub-GHz, MHz, or even lower frequencies. The phononic modes with such low frequencies will suffer the large thermal excitation even when working in dilution refrigerators. Besides, the existing integrated phonon devices constrain the acoustic mode field mainly based on acoustic energy-band control techniques, suspended waveguide structures, bulk acoustic wave structures, and surface acoustic wave structures, as shown in Fig. 3a-c. The fabrication processes of acoustic energy-band structures and suspended waveguide structures are complicated, and these devices are vulnerable to external impacts and may be fragile. In addition, the bulk or surface waves are limited to the weak lateral constraint on the acoustic field, which prevents bent phononic circuits. Therefore, acoustic structures based on these principles can hardly achieve an effective three-dimensional confinement of the acoustic field. Consequently, it is difficult to construct complex acoustic functional devices to enhance acoustic-matter interactions such as those in superconducting or photonic quantum chips.

To overcome this challenge, an extensible architecture of phononic integrated circuits has been proposed and demonstrated[58,65,66], where phonons could be effectively confined in unsuspended microstructures based on high-acoustic-index-contrast. For example, integrated acoustic microring resonant cavities[58,65], acoustic mode converters[67], and the electric control of phonons have been proposed and demonstrated[68]. Such an architecture provides a possible solution to hybrid quantum chips that monolithically integrate phononic, photonic, and superconducting devices. It has the following advantages:

1. The dielectric waveguide allows the simultaneous confinement of both phonons and photons, and thus the phonon-photon interaction can be enhanced by exploiting the photon-elastic effect. It has been demonstrated that the coupling strength between phonons and photons can be improved by more than two orders of magnitude compared to other device architectures[69–71]. Moreover, by further reducing the propagation loss of the phononic waveguide and improving the transduction efficiency of the transducer in the acousto-optic waveguide, a nanowatt pump power is expected for a complete optical mode conversion[71]. Therefore, it is possible to achieve efficient optical-microwave quantum frequency conversion[72]. This frequency conversion can solve the problem of the long-distance connection between superconducting quantum processors, and bring the lossless Josephson nonlinearity[73] to photonic circuits.

2. Ultrahigh quality phononic modes are allowed in unsuspended microring structures, since the radiation loss to the substrate can be greatly suppressed by choosing an appropriate radius[74]. A high quality factor of up to 3×10^4 for the 5 GHz phononic mode has been realized recently[66], and the propagation loss of the phononic modes can be further decreased

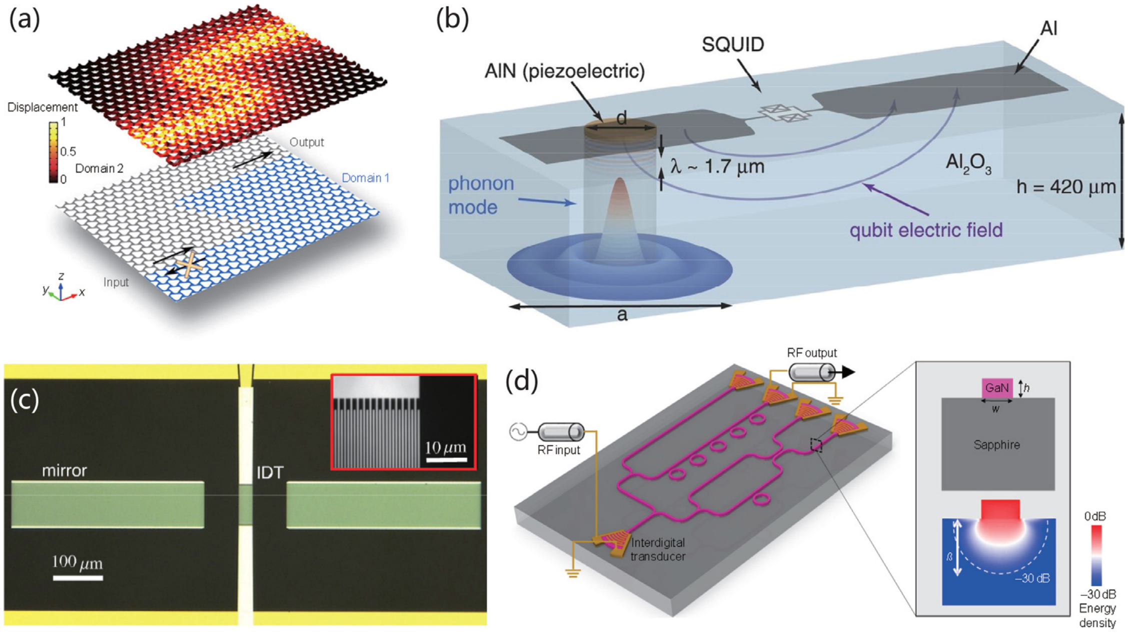

Fig. 3 | Integrated phononic devices. a, Topologically protected elastic waves in phononic metamaterials[55]. © 2015 Springer Nature Ltd. **b,** Bulk acoustic resonator for quantum acoustics[56]. ©2017 AAAS. **c,** Surface-acoustic-wave resonator on quartz with $Q_i \geq 4.0\times10^4$ at 4.4 GHz[57]. ©2016 American Physical Society. **d,** Phononic integrated circuits based on high-acoustic-index-contrast phononic waveguides[58]. © 2019 Springer Nature Ltd. All images reprinted with permission.

by improving the nano-fabrication processes. Eventually, the quality factor of the phononic modes could be limited by the material absorption, which is expected to exceed 10^6 for high-quality single-crystal materials. For instance, an ultrahigh quality factor of around 10^{10} has been demonstrated for a suspended silicon phononic nanocavity[59]. Therefore, the phononic modes may provide compact multi-mode quantum memories for optical signals as well as logical qubits for bosonic quantum error correction codes[52].

3. Since the propagation speed of the acoustic wave is five orders of magnitude slower than that of the electromagnetic wave, the wavelength of the phonon and the corresponding size of integrated phononic devices could also be orders of magnitude smaller than those of microwave devices at the same working frequency. Therefore, by replacing the microwave resonators and waveguides with their phononic counterparts, hybrid superconducting-phononic circuits will have a higher degree of integration. For example, the crosstalk between two phononic waveguides is

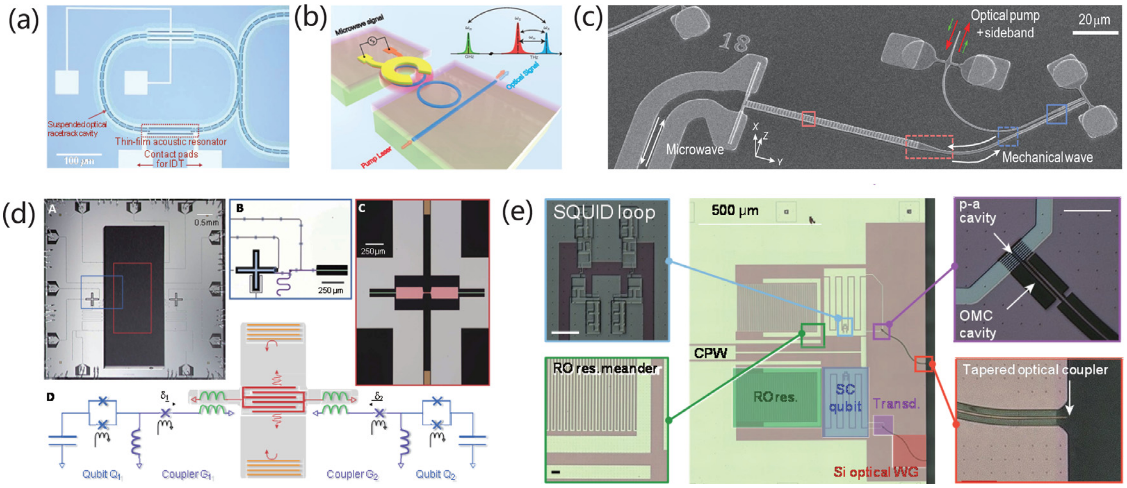

Fig. 4 | Hybrid quantum chips. a-c, Microwave-optical converter implemented by GHz piezo-optomechanics without superconducting qubits, where surface acoustic wave[60], © 2019 Optica Publishing Group bulk acoustic resonator[61], © 2021 American Physical Society and unsuspended phonon waveguide[62] © 2020 Springer Nature Ltd. are adopted respectively. **d,** Quantum state transfer and remote qubit entanglement achieved by using surface acoustic wave phonons[63]. © 2019 AAAS. **e,** Superconducting qubit to optical photon transduction realized in a hybrid superconducting-photonic-phononic chip[64]. © 2020 Springer Nature Ltd. All images reprinted with permission.

negligible when their separation is only 1 μm. Additionally, since acoustic waves cannot propagate in the vacuum, the crosstalk between phononic devices and electrodes is greatly suppressed. Therefore, by using integrated phononic devices instead of microwave devices, it would be possible to suppress the crosstalk between microwave devices and thus further improve the integration degree of superconducting quantum chips[56,75,76].

4. Functional phononic circuits promise the signal routing, filtrating, and processing on the chip, and thus minimize the light-induced noise on superconducting circuits[77] by separating the photonic and electrical components. This architecture has great potential for high-performance hybridized quantum circuits.

Although it is technically extremely difficult to realize the above quantum chip architecture for the co-integration of high-performance photonic, phononic, and superconducting circuits, a lot of experimental efforts have been spent on related hybrid circuits. Hybrid photonic-phononic, photonic-superconducting, and superconducting-phononic devices have been studied separately, in pursuit of optomechanical systems[78], coherent optical-microwave conversion[72], and quantum control of mechanical oscillators[56], respectively. Recently, a full hybridization involving all three systems is studied, and the high-efficiency conversion between optical and microwave photons that is mediated by phonons has been demonstrated without superconducting qubits[60–62,64,72], as shown in Fig. 4a-c. In addition, the potential of phonons in superconducting circuits is revealed in the demonstration of quantum state transfer and remote superconducting qubit entanglement based on surface acoustic wave phonons[63], where the phononic channel is 2-millimeter-long, corresponding to a 500 ns delay line. Finally, by using an intermediary nanomechanical resonator that converts the electrical excitation of the qubit into a single phonon by means of a piezoelectric interaction and subsequently converts the phonon to an optical photon by means of radiation pressure, superconducting qubit-to-optical photon transduction has been demonstrated in a hybrid quantum chip[64], as shown in Fig. 4e. However, the suspended phononic and photonic structures used in this work might hinder the further extension of the system.

CONCLUSION & OUTLOOK

Individual photonic, phononic, and superconducting quantum chips have particular advantages for quantum information processing, however, they also encounter their own problems in their further development. By integrating different quantum systems together, one can take advantage of their respective strengths. It is difficult but promising to integrate all three aforementioned systems on-chip organically, and we envision the following potential challenges in the near future:

First, the efficient packaging of the hybrid quantum circuits. The main difficulty will come from the realization of efficient fiber-to-chip coupling, which is critical for potential applications. The coupling loss not only limits the achievable conversion efficiency between optical and microwave signals, but also gives rise to the leakage of pump light in the cryostat, which might limit the environmental temperature and induce noise excitation to the superconducting devices.

Second, the material-limited device performances. The imperfection of nano-fabrication processes and the absorption loss of materials might exacerbate the propagation losses of the phononic and photonic waveguides, and thus limit the performance of hybrid devices. Therefore, appropriate materials with excellent intrinsic optical and acoustic properties are desired for an extensible architecture of hybrid quantum circuits. In addition, the compatibility between distinct dielectric and superconducting materials is also important for the fabrication and design of devices.

Third, the eventual scalability of the system is still limited. On the one hand, the footprints of both the photonic and phononic devices are limited by the wavelength of their carrier, and thus the number of quantum devices on a single chip is limited. Therefore, extending the hybrid quantum circuit to higher-frequency phonons and photons is appealing. On the other hand, the mK temperature represents a limiting factor for the applications of hybrid quantum circuits. Although the volume and refrigerating capacity of the dilution refrigerator may currently be a limiting factor for the extension of the system, we are optimistic that cheaper and more compact cryostats will be available commercially because of the promising future of superconducting quantum technologies.

In conclusion, with the encouraging and remarkable developments in recent years, it is undoubtable that hybrid integrated quantum chips will have significant contributions to all aspects of modern quantum technologies ranging from distributed quantum computation, quantum networks, quantum communication to fundamental physics research, such as quantum acoustics.

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