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Quantum Interfaces to the Nanoscale

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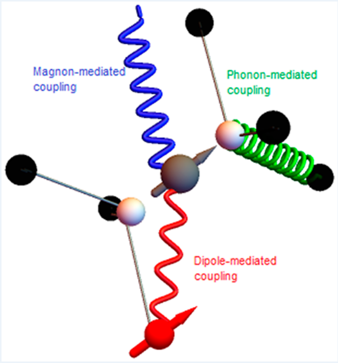
ABSTRACT: **Scalable quantum information systems would store, manipulate, and transmit quantum information locally and across a quantum network, but no single qubit technology is currently robust enough to perform all necessary tasks. Defect centers in solid-state materials have emerged as potential intermediaries between other physical manifestations of qubits, such as superconducting qubits and photonic qubits, to leverage their complementary advantages. It remains an open question, however, how to design and to control quantum interfaces to defect centers. Such interfaces would enable quantum information to be moved seamlessly between different physical systems. Understanding and constructing the required interfaces would, therefore, unlock the next big steps in quantum computing, sensing, and communications. In this Perspective, we highlight promising coupling mechanisms, including dipole-, phonon-, and magnon-mediated interactions, and discuss how contributions from nanotechnologists will be paramount in realizing quantum information processors in the near-term.**



Quantum computational nodes embedded in a high-connectivity quantum network for quantum information processing promise secure encryption, accelerated chemical and materials modeling, and quantum-enhanced sensing, among other benefits.[1−5] An ideal qubit platform must be able to process, to store, and to transmit quantum information locally and across long distances from node to node. Although many physical manifestations of qubits have been proposed, tested, and even implemented as commercial devices hosted in the cloud,[6] no single qubit technology is currently robust enough to support error-correcting codes for quantum advantage[7] and to transmit the resulting quantum information from quantum computational node to node. For instance, whereas one- and two-qubit gates can be performed quickly and with high fidelity on superconducting qubits, the physical platform leveraged by Google in their recent demonstration of quantum advantage, have low coherence times due to environmental noise, limited qubit storage capabilities, and limited implementation of deep quantum circuits.[8] In addition, because the relevant frequency scale of superconducting qubits lies within the GHz range, it can be challenging to transduce quantum information held in superconducting qubits to photonic qubits with wavelengths in the near-infrared that are suitable for low-loss and high-speed transmission through optical fibers.[9,10]

Defect centers in solid-state materials—often deemed "artificial atoms" because they can exhibit long coherence times, bright emission, and spatial localization of their electronic wave function within the angstrom scale—have been proposed as potential qubit intermediaries between other physical manifestations of qubits or as a qubit platform in their own right.[11,12] Logical qubit states can be mapped onto the nuclear spin[13−15] with MHz frequency scales or the electronic spin state in the ground-state manifold of the defect center, well-known examples of which include the nitrogen vacancy (NV) and silicon vacancy (SiV^-) centers in diamond[11,12] with GHz frequency scales. This frequency scale nicely matches those of superconducting qubits as well as microwave photons,[16] phonons of the host lattice,[17,18] and ferromagnetic magnons,[19−21] suggesting a variety of physical mechanisms for manipulating and transducing defect-center-based qubits. In addition, quantum emission of single photons from defects, even at room temperature in monolayer hexagonal boron nitride (hBN),[22−25] has been observed, paving the way for defect centers to be used for local on-chip computation and state preparation whose quantum information can be out-coupled *via* a solid-state spin−photon interface for long-distance qubit transmission. Defect centers are also expected to be scalable by leveraging the vast infrastructure and expertise of the semiconductor industry, especially for technologically mature materials such as silicon carbide. They are also expected to be highly customizable components in quantum devices due to their large chemical selection space,[26,27] where the host lattice and defect type can be permuted, and are

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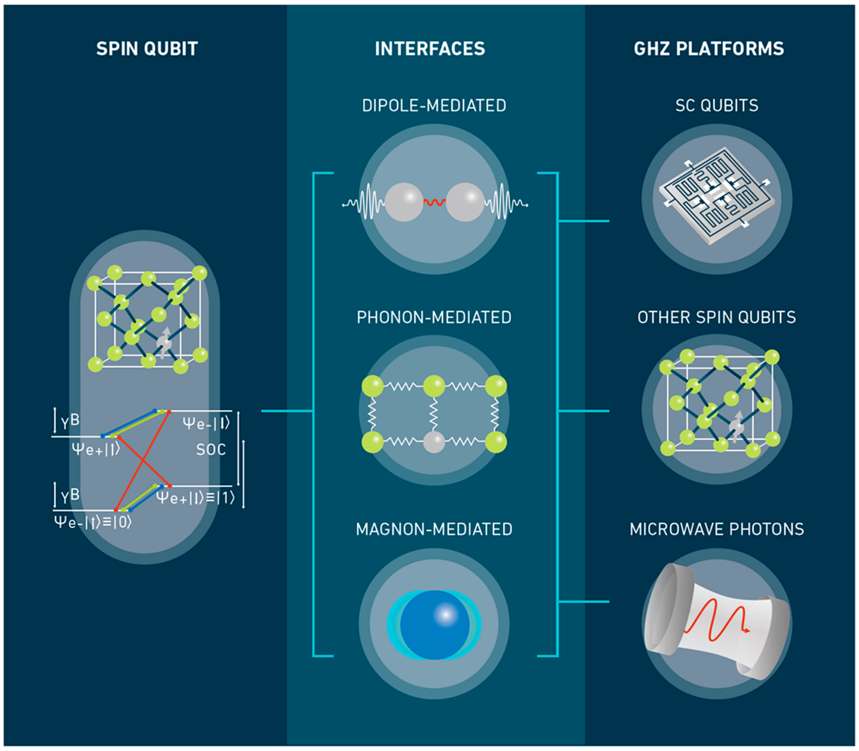

Figure 1. Spin qubits are capable of coupling to key GHz quantum systems, such as superconducting qubits, other spin qubits, and microwave photons *via* dipole-mediated (red), phonon-mediated (green), and magnon-mediated (blue) interactions. Such functionality unifies their complementary strengths of quantum information processing, storage, and transmission into one composite platform. The level structure of the silicon vacancy in diamond with transitions corresponding to each of the discussed interfaces is shown as an example, where the levels are split by spin−orbit coupling and Zeeman shifts by external magnetic field *B*. SC: superconducting.

tunable due to external strain, electric, and magnetic fields, as well as engineered electromagnetic environments.[28−37]

Although the potential impact of defect emitters on developing quantum information processors in the near-term is evident, it remains an open question how best to design and to control quantum interfaces to defect centers from other GHz platforms. In this Perspective, we first highlight promising physical mechanisms and device architectures for coupling defects to other qubit platforms *via* dipole-, phonon-, and magnon-mediated interactions, all graphically depicted in Figure 1. We focus specifically on quantum interfaces between superconducting qubits, other defect-based spin qubits, and photons because these three complementary platforms enable effective processing, storage, and transmission of quantum information, respectively. We then point out gaps in the theoretical and experimental literature and conclude by arguing that the contributions toward quantum interfaces from the burgeoning community of quantum nanotechnologists will be paramount in realizing a near-term quantum information processor.

COUPLING MECHANISMS AND QUANTUM INTERFACES

We describe physical coupling mechanisms to defect centers that can be used as quantum interfaces between other physical manifestations of qubits, such as superconducting qubits, other defect centers, and photonic qubits. We focus on—roughly in order of decreasing theoretical and experimental maturity—dipole-, phonon-, and magnon-mediated interactions. Each of these three physical coupling mechanisms is associated with unique advantages and disadvantages, and we suggest near- and long-term routes for further research and development of practical quantum interfaces.

Dipole-Mediated. The theoretical basis of local dipole-mediated interactions between defect emitters, most relevant for quantum interfaces between two defect qubits, has largely been adapted from decades of research in the atomic, molecular, and optical (AMO) physics community. We take care to differentiate between two distinct types: transition dipole coupling and permanent dipole coupling. In transition dipole coupling, two qubits are coupled *via* the transition dipole moments of an electric- or magnetic-dipole-allowed transition in each emitter, resulting in a composite qubit system whose eigenstates are not simply product states of the constituent emitters.[38−40] Transition dipole coupling is especially useful for entangling the constituent qubits of the composite system, effectively resulting in a multiqubit gate,[38,39] and producing entangled photon pairs upon emission from an excited state,[40] as shown in Figure 2c. Transition dipole coupling is often seen in the context of Rydberg atoms,[41] which are highly excited atoms with an electron with a large principal quantum number n such that they behave as highly polarizable Bohr atoms. In permanent dipole coupling, the electric or magnetic field of one emitter induces a Stark or Zeeman shift of the levels of another polarizable emitter to implement, for instance, controlled-phase gates based on detuned or resonant emitter−photon interactions.[42] The dipole moments can be electric or magnetic in nature—although electric dipole coupling is generally stronger, magnetic dipole coupling is especially relevant for controlling defect-center-based spin qubits.[43−45]

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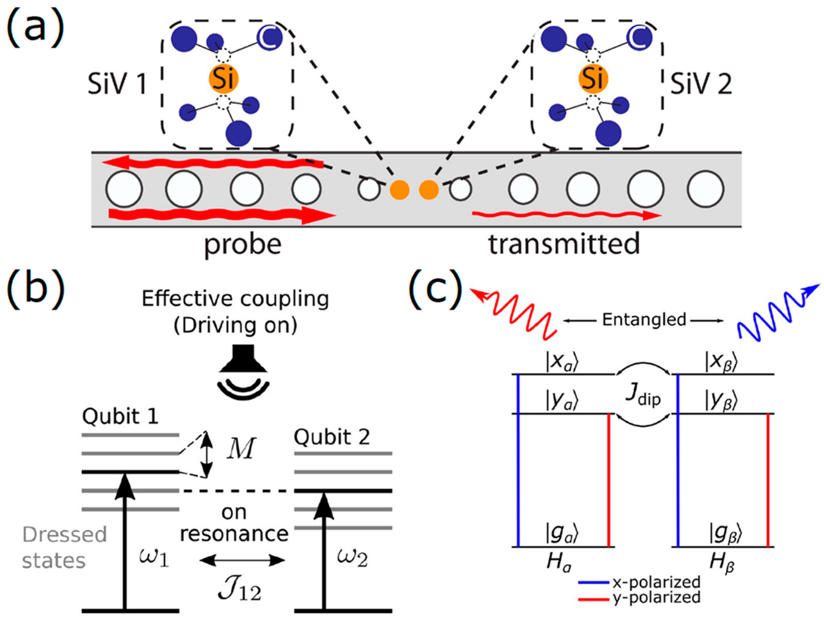

Figure 2. (a) Pair of silicon vacancy (SiV^-) defects are embedded in a diamond photonic nanocavity, where cavity photons mediate spin−spin dipolar interactions.[46] Reprinted with permission from ref 46. Copyright 2018 AAAS. (b) Acoustic modulation selectively tunes different qubits to be simultaneously on resonance.[18] Reprinted with permission from ref 18. Copyright 2020 American Physical Society. (c) Spin qubits are coupled *via* a local transition dipole interaction, which enables the generation of entangled photon pairs.[40] Reprinted with permission from ref 40. Copyright 2020 American Physical Society.

From an experimental perspective, the realization of dipole coupling in atoms and trapped ions differs drastically from defect centers in solid-state materials. Careful engineering of optical or ion traps is needed to keep atoms or ions fixed in place,[47] as local dipole-mediated coupling is strongly dependent on the qubit−qubit distance. In contrast, defect-center-based qubits are fixed within their crystal host matrix, enabling more stable coupling with comparatively minimal engineering. Local dipole-mediated interactions as the physical basis for quantum interfaces between defect centers and other platforms is especially relevant in light of recent experimental demonstrations of deterministic atomic patterning on defects in two-dimensional materials, such as graphene and transition metal dichalcogenides, with scanning transmission electron microscopy (STEM) and scanning tunneling microscopy (STM).[48,49]

Although the fundamental theoretical description of local dipole-mediated interactions between defect centers is relatively straightforward and can be realized in a stable manner given their fixed geometries, in practice, these interactions are not necessarily optimal for quantum information processing applications. Without mechanisms to control the dipole coupling, local dipole-mediated interactions are always "on", limiting coherence times of quantum states stored in defects. Another challenge with local dipole-mediated coupling is that because the strength of the interaction is highly distance-dependent and decays *via* an inverse power law $1/r^3$ with increasing defect−defect distance r, the connectivity of qubits with others is limited by their physical proximity. However, quantum algorithms often require the fewest resources and, thus, can be implemented with the highest fidelity for qubits with full connectivity.[50] The goal, then, is to be able to turn interactions "on" and "off" between defect centers quickly and with arbitrary connectivity over large length scales. One potential solution is to use external fields with large spatial gradients to tune defects into resonance with each other. To this end, magnetic fields with spatial gradients as high as ∼10 mT/nm, with the intention of exerting differential Zeeman shifts of approximately 300 MHz/nm on defect center-based spin qubits, have been realized.[51−53] Another method is to use dynamic acoustic control to tune qubits into resonance selectively for efficient dipole-mediated defect−defect interactions. For instance, our group recently developed a theoretical framework demonstrating that dipole-mediated defect−defect interactions can be activated by applying an oscillating strain field that enables efficient parametric interactions between defects that are spectrally mismatched, perhaps due to local variations in strain,[18] as shown in Figure 2b. This interaction enables a two-qubit gate and can realize pairwise coupling between emitters within a larger network of spin qubits with high speed.

The goal, then, is to be able to turn interactions "on" and "off" between defect centers quickly and with arbitrary connectivity over large length scales.

Cavity photons can be used to overcome the limitation set by distance-dependent dipole coupling and to underlie quantum interfaces between defects and superconducting qubits, other defects, and photons,[54] an example of which is shown in Figure 2a. In cavity photon-mediated interactions,[46] defects are embedded in a cavity that concentrates the local electromagnetic field, enhancing and delocalizing the dipole-mediated coupling between the defects *via* the photon modes of the cavity.[55] The cavity photons can then be coupled to other qubit platforms to realize a quantum interface between defects. Because the qubits interact through the photon modes that are delocalized through the cavity, cavity photon-mediated

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interactions relax spatial constraints imposed by local dipole-mediated interactions, a well-known phenomenon in the field of polaritonic chemistry, where the chemical activity of molecules can be modulated and molecule−molecule interactions can be delocalized over arbitrary distances.[53] Coupling superconducting qubits to solid-state spin defects *via* cavity photons has been extensively explored[56−59] and is discussed in detail in ref 60. Cavity photon-mediated dipolar interactions in the optical domain have been demonstrated more recently in SiV^-,[46] although inhomogeneous broadening and decoherence introduced by the solid-state environment remain challenges and, similarly to purely local dipole-mediated interactions, can be improved by selective tuning of defect centers.

Phonon-Mediated. Researchers working with defect centers can also uniquely take advantage of vibrational modes of the host crystal, acoustic phonons that lie in the GHz range, as a long-distance coupling mechanism between qubits. Just as with cavity photon-mediated interactions, phonons are delocalized and can couple arbitrarily separated qubits. As a result, phonons have been envisioned as universal quantum transducers among several solid-state qubit platforms,[10,32] especially relevant for realizing defect−defect and superconducting qubit−defect quantum interfaces and paving the path toward fault-tolerant quantum computers with concatenated cat codes.[61]

We first discuss phonon-mediated defect−defect interactions. All phonon-mediated interactions with defects require the defect state to be susceptible to local strain. Notable recent theoretical proposals and experimental realizations of phonon-mediated defect−defect quantum interfaces are rooted in the SiV^- in the diamond system,[32,35] which has particularly high strain susceptibility due to its high symmetry within the lattice. In these studies, separated SiV^- defect centers are coupled *via* the phonon modes of a quasi-one-dimensional diamond waveguide designed to enhance phonon−defect interactions. The quantum states encoded in long-lived electronic spin states are converted into propagating phonons that are then teleported onto a distant defect center. To enable tunable coupling between arbitrarily separated defect centers, researchers have explored applying spatially inhomogeneous external fields, including strain[63] and magnetic fields.[64] Finally, rather than tuning the defect centers into resonance, one could also tune the energies of the phonon mode intermediaries by coupling them to cavities, as we demonstrated in ref 65: the cavity−phonon coupling can tune the effective frequency of the phonon polaritons and could lead to increased selectivity.

> Phonons have been envisioned as universal quantum transducers among several solid-state qubit platforms

Acoustic phonons can also be used to couple defect centers with superconducting qubits.[17,62] Recent work has proposed an architecture for a phononic bus to serve as a coherent interface between a superconducting quantum processor, defect center-based spin memory, and photonic quantum network.[17] The superconducting qubit−defect interaction is mediated by phonons with an acoustic bus connected by piezoelectric transducers. The authors use realistic experimental parameters for the superconducting qubits, which offer high-fidelity and high-speed state initialization and quantum logic gates, and the SiV^- defect center in diamond, which offers long coherence times, long-range connectivity, straightforward scalability to large qubit numbers, and high readout fidelity over 99.9%. The SiV^- defect center is coupled to a ^{13}C nuclear spin qubit to enable outcoupling to an optical fiber for transmission in a quantum network. We estimate maximum quantum state transfer with fidelity exceeding 99% with a bandwidth in the MHz range.

Despite exciting early success in the field of spin−phonon coupling, challenges remain with controlling undesirable thermal population of phonons that may lead to noisy quantum interfaces.[10] To overcome thermal noise, further research is needed to increase spin−phonon coupling rates by, for example, leveraging spin states of electronic excited states rather than ground states of defect orbitals, exploring the strain susceptibility of defect hyperfine couplings, or computationally discovering new defects with stronger spin−spin or spin−orbit coupling to minimize deleterious effects to their spin coherence.[60] In addition, discovery of piezoelectric materials and improved fabrication techniques are required to improve Q factors of next-generation phononic cavities.

Magnon-Mediated. Magnons are quantized spin oscillations of magnetic solids that lie in the GHz range for ferro- and ferrimagnets and in the THz range for antiferromagnets.[66,67] In this Perspective, we focus on the former due to the ease of addressability with an external magnetic field. Although theoretical and experimental explorations of magnon-mediated qubit−qubit interfaces are nascent relative to dipole- and phonon-mediated coupling mechanisms, such interactions possess great promise for both defect−defect and superconducting qubit−defect interfaces.[68,69] Although there has yet to be a demonstration of a direct magnon-mediated superconducting qubit−defect interface, several studies have demonstrated strong coupling between microwave cavity photons and magnon modes of a magnetic nanoparticle in a variety of geometries and material systems.[70−77] In Figure 4c, we see that these magnon-generated microwave cavity photons can then be coupled to superconducting qubits[78] to enable single-shot single-magnon detection,[79] which is advantageous over direct spin qubit−microwave coupling without magnon mediation due to the latter's lower coupling rates.[29]

Completing the transduction chain between defect centers and superconducting qubits therefore requires demonstration of magnon−defect center coupling, as explored theoretically in refs 19−21. In our work in refs 20 and 21, we consider a spherical nanoparticle of ferrimagnetic yttrium iron garnet (YIG) that can sustain antenna-like magnon resonances in analogy with optical or infrared plasmonic nanoantennas.[78] This nanomagnonic cavity can reduce the size of the magnetic field from the millimeter scale, typical for experiments coupling magnons to macroscopic microwave cavities, down to the nanoscale to enable stronger coupling. We predict magnon−defect center coupling rates of $g \sim 1$ MHz for magnetic-dipole-allowed transitions of a SiV^- defect center placed a few nanometers away from the surface of the sphere, well within the strong coupling regime given the low loss of YIG. In addition, the magnitude of the vacuum magnetic field of the sphere varies strongly on the length scale of the defect emitter, analogous to the strong electric field gradients near the surface of plasmonic nanoparticles. By coupling these inhomogeneous fields with a description of the SiV^- beyond the magnetic point dipole approximation in ref 21, we show nonzero coupling of $\sim$10 kHz between the spatially varying vacuum magnetic field and the logical $|0\rangle$ and $|1\rangle$ states corresponding to the lowest

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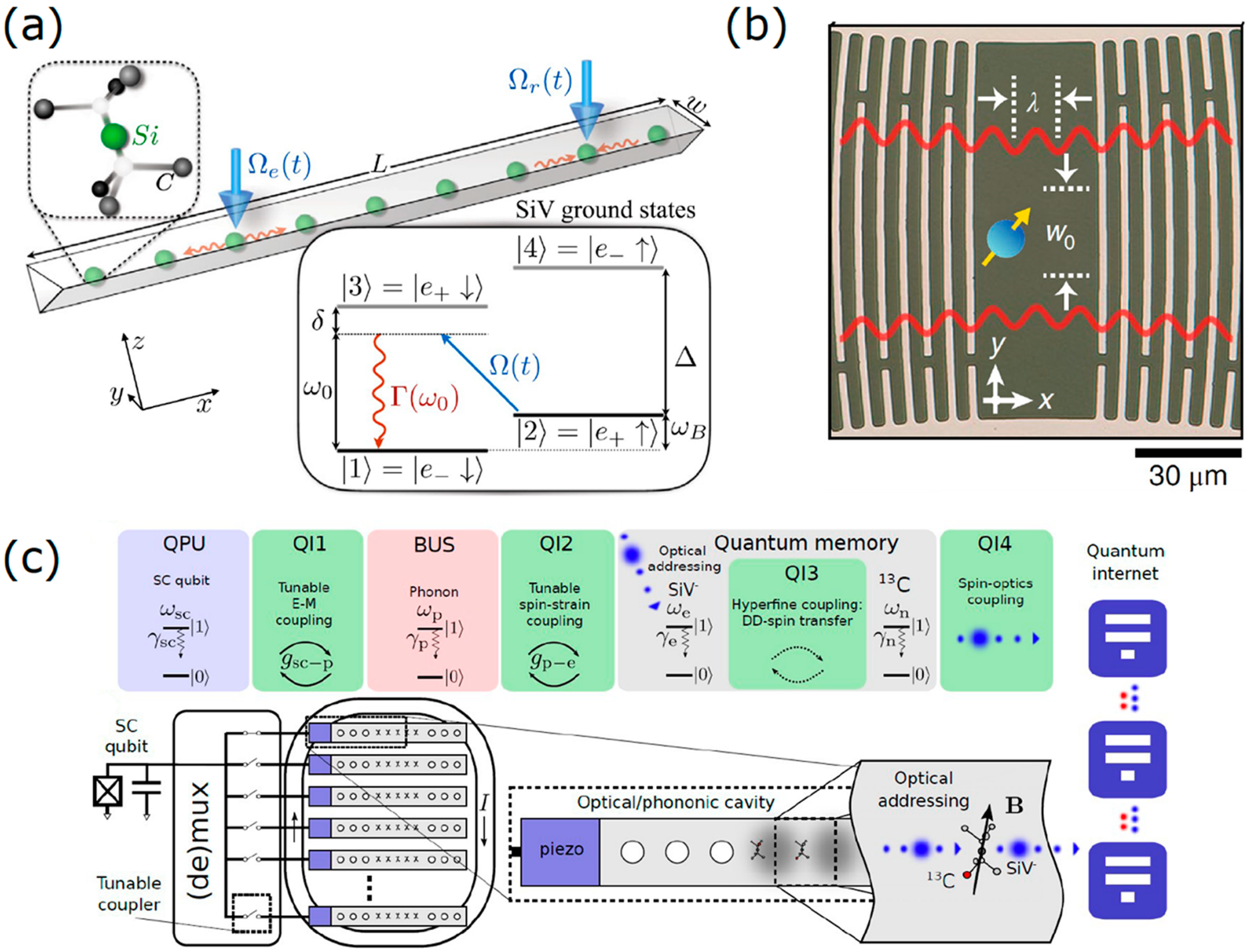

Figure 3. (a) One-dimensional arrays of silicon vacancy (SiV) centers are selectively coupled to each other *via* phononic excitations Γ and optical pumps Ω.[32] Reprinted with permission from ref 32. Copyright 2018 American Physical Society. (b) Surface acoustic waves (red) are generated *via* an AlN interdigital transducer (IDT) to drive a defect spin in silicon carbide.[62] Reprinted with permission from ref 62. Copyright 2019 Springer Nature. (c) Coupling scheme developed to use a phononic bus as in panel (a) to couple superconducting qubits to spin qubits.[17] Reprinted with permission from ref 17. Copyright 2020 The Authors.

spin states of the ground state manifold, where the transition between them is typically forbidden by magnetic dipole selection rules. Finally, with respect to a magnon-mediated defect−defect interface, in ref 20, we show that two defects placed on opposite sides of the nanomagnonic YIG sphere experience a magnon-mediated coupling over 1000 times stronger than simple magnetic dipole coupling, as depicted in Figure 4b.[80]

Recently, researchers have begun to realize magnon−defect coupling interactions experimentally by utilizing NV$^-$ centers for nanoscale detection of magnons.[81,82] Although this measurement was centered on measuring increased spin relaxation rates in the presence of magnons, which is indicative of a weak coupling, this research only utilized micrometer YIG disks. As such, future experimental work using smaller nanomagnonic cavities can expect to observe increased confinement and stronger coupling to defect spins.

Despite these developments in our understanding of magnon-mediated quantum interfaces, much remains to be explored. From a theoretical perspective, further investigation of the unique advantages of magnon-mediated interactions *versus* other delocalized interactions, including the previously described cavity photon-mediated and phonon-mediated interactions, is warranted. For instance, interactions of localized magnons among themselves[83] and with microwave cavities[84,85] could result in nonreciprocal cavity responses[85] and magnon-mediated nonreciprocal defect-spin networks. In addition, magnons can exhibit strong nonlinearities,[86] which are difficult to achieve in weakly self-interacting cavity photons and phonons without inducing overwhelming inhomogeneous broadening. From an engineering perspective, given how notoriously difficult YIG is to fabricate without drastically increasing the damping,[87] realization of many such schemes will require either leaps in fabrication capabilities or exploration of novel magnetic materials with low losses. A prime candidate is the low-loss organic ferrimagnet vanadium tetracyanoethylene (V[TCNE]$_x$),[19] which can be grown more easily on substrates than can YIG. Inspired by studies in the field of plasmonics, where plasmonic surfaces and plasmonic dimers have been shown to support fields with much larger electric field gradients and magnitudes, respectively, we also expect optimization of the geometry of magnonic cavities to be fruitful. For instance, Fukami *et al.* recently predicted that spatial guiding of magnon modes using ferromagnetic bar and

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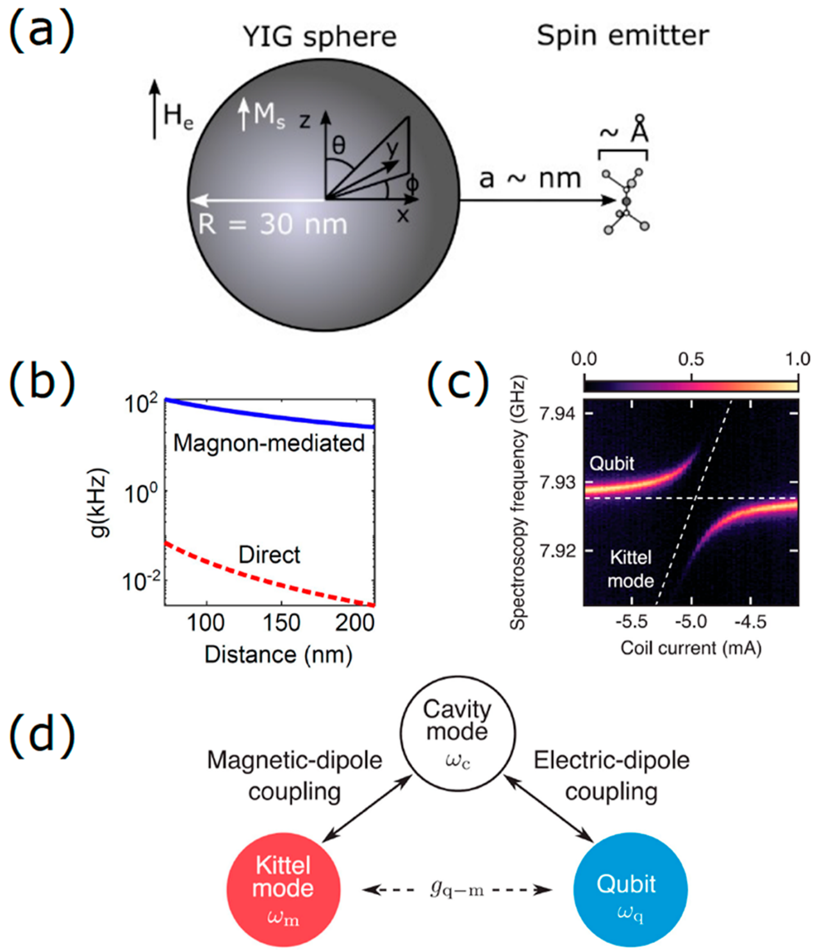

Figure 4. (a) Silicon vacancy (SiV) defect center coupled to a magnonic mode of the yttrium iron garnet (YIG) nanosphere. (b) Magnon-mediated spin−spin coupling rate g is enhanced by 3 orders of magnitude over the strength of local dipole couplings.[20] (a,b) Reprinted with permission from ref 20. Copyright 2020 American Physical Society. (c) Level anticrossing indicative of strong coupling enables single-magnon detection using superconducting qubits. (d) Strong magnetic−dipole coupling between the Kittel magnon mode and microwave cavity photons enables an effective coupling g_{q-m} between magnon mode and superconducting qubits, seen in panel (c).[79] Reprinted with permission from ref 79. Copyright 2020 AAAS.

waveguide structures dramatically improves the range of spin−spin coupling interactions to more than 2 μm.[88] Finally, coupling of host lattice magnons, which can be driven by ultrafast pulses or phonons,[89,90] may offer similar selectivity over arbitrarily long distances, as with host lattice phonon-mediated quantum interfaces.

APPLICATIONS OF QUANTUM INTERFACES TO SPINS

The recent improvements to quantum interfaces discussed in the last section could make hybrid spin platforms suitable for applications that are being actively pursued by the quantum community today. Although the complementary set of advantages enabled by these hybrid systems could be useful toward realizing many present applications, in this Perspective, we focus on two pressing research endeavors: coherent microwave-to-optical conversion and long-lived quantum memories for superconducting qubits. Realizing effective solutions for both will pave the way toward scalable quantum computation.

One of the key qubit architectures that have been proposed for developing future quantum computers is superconducting qubits. This platform has many favorable characteristics, such as low gate times, easy access to single-qubit and two-qubit interactions, and on-chip architectures that permit intuitive scalability to larger Hilbert spaces. However, these systems suffer from coherence times that are relatively low (~100 μs) compared to the defect spin qubits we have discussed, where coherence times range from ~20 ms for the SiV^- to seconds for nuclear spin qubits. The comparatively low coherence times of superconducting qubits is one of the primary challenges preventing implementation of large-scale, high-fidelity quantum algorithms, and although these coherence times have improved dramatically in the past decades, it has become a challenge to find paths toward improving them further.

The interfaces we detail in this Perspective suggest a different approach toward improving the fidelity of quantum circuits implemented on superconducting qubits. Rather than work to improve the intrinsic coherence times of SC qubits, we can use these interfaces to transduce quantum information from idle superconducting qubits onto spin qubits. By distributing the processing and storage capabilities across superconducting qubits and defect spin qubits, which have comparative advantages in these domains, this approach seeks to improve the gate depth that quantum circuits can run before the quantum information decoheres. An example of such an

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Table 1. Relevant Parameters of Various Published Results[a]

demonstrated couplings	exp/theo	coupling rate, g (MHz)	cooperativity (C)	temperature	length scale (μm)
spin−spin[46] (2018)	exp	7.3	23	85 mK	1
μwave photon−dipole[95] (2019)	exp	5600	38	60 mK	1
SC qubit−phonon[96] (2018)	exp	1.2	4	7 mK	1
spin−phonon−spin[32] (2018)	theo	1.2	25	1 K	10
spin−phonon[17] (2020)	theo	0.5	40	10 mK	10
spin−magnon[20] (2020)	theo	1	16	1 mK	0.07
spin−magnon[19] (2020)	theo	0.01	15	100 mK	0.03
μwave photon−magnon[75] (2019)	exp	171	160	1.5 K	100
SC qubit−magnon[84] (2015)	exp	10	115	10 mK	500

[a]Experimental ("exp") and theoretical ("theo"), showcasing different coupling mechanisms. The cooperativity $C = \frac{4g^2}{\kappa\gamma}$ is a common measure of the coupling strength, where κ and γ are characteristic decay rates of the composite system. $C > 1$ is indicative of the strong coupling regime, a bare requisite for implementing efficient quantum interfaces.

implementation is laid out in Figure 3c, and similar procedures are expected to be implemented with magnonic interfaces.

As Figure 3c suggests, transduction to a spin quantum memory can then enable out-coupling of quantum information to optical photons and effectively connect superconducting and spin qubits to long-range photonic networks. Viewed in its composite, coupling microwave photons to spin qubits also acts as a functional transduction mechanism for realizing microwave-to-optical conversion schemes. This is a capability that has garnered immense interest in recent years, with physical implementations that span optomechanical, electro-optic, and magneto-optic systems.[91−93] Indeed, there has already been a scheme used implementing a dipolar interface to spins,[94] but the efficiency of this transduction is limited by the relatively weak microwave−spin coupling. As such, we believe that further study into improving these interfaces will grant access to an efficient transduction mechanism that doubles as a quantum memory, which will be critical for realizing large-scale quantum computers, where each chip of qubits will act as nodes in a larger entangled quantum system connected by photonic qubits.

CONCLUSION

In this Perspective, we discuss several leading mechanisms for coupling defect-center-based spin qubits to other qubit platforms, specifically superconducting qubits, other defect centers, and photons. These interactions form the basis of quantum interfaces needed to leverage the complementary advantages of each of these qubit platforms to engineer a quantum information processor capable of processing, storing, and transmitting qubits. In Table 1, we bring attention to several recent experimental and theoretical results aimed at utilizing these coupling mechanisms for coupling various key GHz platforms. We also show a set of relevant parameters that characterize the applicability of these results toward realizing an efficient quantum interface. It remains challenging to activate local dipole-mediated quantum interfaces selectively because the dipole-mediated interaction is strictly dependent on both the relative orientation of and distance between qubits, which are fixed in solid-state systems. Cavity photon-mediated dipole coupling can overcome these limitations, but they are limited to interfacing between certain states of qubits due to dipole selection rules, and the issue of tuning qubits into resonance with each other on-demand for fast entanglement or state transfer remains. Phonon-mediated quantum interfaces, a unique coupling mechanism available only in solid-state materials, in sharp contrast to dipole-mediated interactions originally explored in AMO systems, can couple qubits over arbitrary distances as long as the qubit states exhibit strain susceptibility. Spatially inhomogeneous fields and fast acoustic driving can selectively tune qubits in resonance for efficient phonon mediation of quantum information. However, much progress at the nanoscale is needed to engineer effective coupling, such as further design of phononic cavities, materials development, and fabrication of piezoelectric materials, as well the uncovering of novel mechanisms to enhance phonon-mediated interactions. Magnon-mediated interactions are an exciting, more recently explored method of coupling defect-center-based spin qubits with other qubits, especially to superconducting qubits, by offering higher coupling rates than are possible *via* microwave photon-mediated interactions. We specifically consider nanomagnonic cavities, magnetic analogues of plasmonic particles that can concentrate magnetic fields to nanoscopic volumes and enable strong magnon−spin and spin−spin coupling. We believe nanomagnonic systems are especially fertile ground for nanotechnologists, given the need for translation of quantum optical theory and development of nanofabrication methods for low-loss magnetic materials to realize nanomagnonic devices with unique capabilities, including nonreciprocal coupling and strong nonlinearities. Finally, we note that although we focus on defect centers in this Perspective, much of our discussion could equally be applied to molecular qubits, a more recently proposed and exciting new qubit platform.[97−99] In conclusion, development of quantum interfaces to defect centers at the nanoscale promises discoveries of fascinating phenomena and is critical for the realization of a quantum information processor.

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Notes

The authors declare no competing financial interest.

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