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A bright future for silicon in quantum technologies

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ABSTRACT

Silicon is the most widely used material in microelectronic devices; integration of atomic impurities in silicon via doping during growth or ion implant is now widely used as it allows to form conventional transistors. Exploiting all the knowledge accumulated over the last 60 years in the context of the second quantum revolution that is now underway would help accelerate the commercialization of quantum technologies. Several works have already reported that silicon can be an optically active material with point-like defects emitting below the Si bandgap, both in ensemble emission and absorption in natural Si as well as in isotopically purified ^{28}Si, even under electrical pumping. Very recently, the detection of individual impurities in silicon opened the door for further exploitation of this indirect bandgap material to applications in quantum technologies, including single photon emission at near-infrared frequency, matching the telecommunication band and optical detection of individual spins. Here, we describe the current state-of-the-art and discuss the forthcoming challenges and goals toward a reliable exploitation of these solid-state quantum-emitters in the context of quantum technologies. In particular, we examine opportunities, issues, and challenges in controlling defect formation and localization, extrinsic effects, and integration of optical devices.

I. INTRODUCTION

Quantum technologies are poised to disrupt several industries, such as health, energy, and materials discovery in the next decade by revolutionizing communications (e.g., quantum cryptography), sensing (weak magnetic field and solid state memories), and computation tools (quantum computing); most analysts predict that quantum computing alone will lead to productivity gains by end-users in the form of both cost savings and revenue opportunities, around 700 billion annually.[1,2] Quantum bits, the building blocks of quantum computing, can be based on different technologies, such as photons, trapped ions, super-conductive circuits, spin and charge state in quantum dots.[3] Depending on the target application, they each have strong and weak points and are exhibiting different stages of maturity.

Among them, Si-based platforms remain highly entrancing as they can, in principle, allow linking anchored quantum bits (e.g., spin and charge state) to flying quantum bits (photons), all while working with an established and well-known material, which constitutes the backbone of the electronics industry. Remarkable advances in the field of silicon quantum computing include the demonstration of two-qubit gate fidelity above 99%,[4–6] the CMOS-based cryogenic control of quantum circuits,[7] and the fabrication of silicon qubits in a 300 mm semiconductor manufacturing facility using all-optical lithography and fully industrial processing.[8]

Despite the low temperature required, these evidence are bright examples illustrating the potential of Si-based quantum devices. This material has in fact several advantages with respect to others. To name a few, high purity and low defect density, reduced production cost, a well-developed backbone of nano-fabrication tools available "on the shelf," possibility to interface quantum devices with classical devices on the same chip, possibility to use an isotopically purified, spin-less matrix of ^{28}Si.

In the context of light emission, several solid-state light devices have been scrutinized as potential sources of flying quantum bits: semiconductor quantum dots based on III–V semiconductor compounds are bright emitters and can be epitaxially grown with alloys emitting a telecom frequency. However, they suffer from the intrinsic randomness of size, shape, and nucleation sites, leading to a broad spread of emission wavelength.[14,15] A viable alternative to quantum dots is light emitting impurities, which are point defects[16] in a semiconductor matrix combining two interesting properties: (1) uniformity of impurity species (atomic or molecule-like) and (2) ability to be easily implemented by local ion implant with ultimate spatial resolution or directly generated by fs laser pulses.[17,18]

The archetype of this latter kind of light sources is negatively charged nitrogen-vacancy (NV) pairs in diamond.[19–22] They have an optically active spin-triplet ground state, are well-isolated from the surrounding carbon lattice, and have been used in many demonstrations of early quantum devices. Nevertheless, when compared to Si, this carbon-based platform is far from optimal for scaling and integration in devices working at telecom frequency; fabrication is usually limited to small wafer sizes and remains highly expensive; doping remains very difficult and their emission is not within the near-infrared window.

Alternative quantum emitters, such as impurities in SiC, are more suitable for integration on a Si platform[22–24] as this material can be directly formed on a Si wafer. Still, in spite of its potential relevance as a material for building electronic and photonic devices, SiC is still in its infancy. A direct integration of quantum emitters in a silicon on insulator (SOI) wafer while covering the infrared telecom bands[9,25] relevant to telecommunication with optical fibers remains a more appealing solution (also in view of a spin–photon interface[10,11,12,22,26]).

A clear advantage of silicon over other solid-state platforms for applications in electronic, photonic, and quantum devices is its natural abundance: after oxygen, silicon is the most abundant element present on the Earth crust, which is composed of this element for about one third. Albeit silicon is often found in the form of silicate minerals (e.g., bound to oxygen), the chain of its purification has been boosted by a large demand for electronic devices (monocrystalline silicon) and solar panels (poli-crystalline silicon): only in 2020, the global silicon production amounted to about 8×10^6 metric tons[27] (with two thirds produced in China, followed by Russia with a production of about a 0.5×10^6 metric tons). In the same year, the request of Si-based wafers reached 12.41×10^9 square inches with an increase of about 5% with respect to 2019.

Thanks to the broad use of silicon for microelectronics, this material can be supplied in large wafers that nowadays it can reach a diameter of 17.7 in. The relevance of this semiconductor consists also in the possibility to produce a stable and high-quality insulator (stochiometric SiO_2) necessary for the fabrication of electronic devices and integrated photonic circuits. In this framework, SOI are available over 12 in. with a large choice of device thickness (from ~10 nm up to several μm) and buried oxide thickness (BOX, from ~10 nm up to several μm). The broad availability of p and n doping for bulk and SOI wafers is another crucial element placing silicon at the apex of semiconductor materials.

Successful exploitation of this material for quantum technologies requires high purity to ensure minimal noise from the environment and facilitate the deterministic creation and study individual light emitters. To this end, the purity of electronic grade silicon can reach 99.999 999 9% ("ninety-nines"), leaving a concentration of impurities of about $\rho_I \sim 5 \times 10^{13}\,\mathrm{cm}^{-3}$ and rendering it one of the purest materials available. For instance, in a SOI of 220 nm (that is the typical thickness used for the fabrication of integrated photonic circuits at telecom frequency), the concentration of uncontrolled impurities can be as low as $\sigma_I \sim 10\,\mu\mathrm{m}^{-2}$ to be compared with $\sigma_{Si} \sim 10^{10}\,\mu\mathrm{m}^{-2}$ Si atoms in the same area. Provided that these emitters are typically formed by two or more impurities within a cell volume (e.g., C-pairs, Fig. 1), assuming a stochastic model[28–30] the diads density should be less than $\rho_{I-I}^2 \times V_{Si} \sim 4 \times 10^5\,\mathrm{cm}^{-3}$ (where V_{Si} is the volume of the unit cell of the Si crystal $\sim 1.6 \times 10^{-22}\,\mathrm{cm}^{-3}$) and that for a 220 nm thick SOI translates in $\sigma_{I-I} \sim 10^{-7}\,\mu\mathrm{m}^{-2}$.

It thus appears that electronic-grade silicon, in principle, could constitute a rather clean environment for applications in quantum optics that, in contrast with III–V or SiC, overcomes any problem related to alloy disorder. However, we also note that this estimation may be a lower bound for the number of emitting impurities in pristine samples,[31] given the existence of several unavoidable and uncontrolled issues, such as the presence of interfaces between the SOI and the underlying BOX, impurities at the wafer top surface and impurities introduced during the SOI fabrication (e.g., via oxygen implant for SIMOX or proton implant for Smart-Cut[32,33]).

II. STATE-OF-THE-ART OF QUANTUM EMITTERS IN SILICON

Micro- and nano-architectures based on silicon drove the electronic revolution in the 60s, as a result, the vast majority of classical electronic devices are built on a Si-based platform. Photonic devices based on Si are also a well-established technology.[36] This is possible thanks to the versatility of this material for carrier transport and to its transparency for light propagation in the near-infrared frequency range.

Unfortunately, the indirect nature of its energy bandgap does not allow for efficient photoluminescence emission. However, light emission below bandgap can be recovered by exploiting extrinsic and intrinsic impurities associated with rare-earth atoms, carbon, oxygen, and hydrogen impurities as well as self-interstitial, to name a few[9,22,34,37,38] (Figs. 1–3).

These emitters are commonly known as radiation-damage centers as they are usually created via high-energy electron irradiation or directly by ion implant. They can be created in bulk Si as well as in silicon on insulator (SOI), another attractive platform for the fabrication of electronic and photonic devices (such as integrated photonic circuits). Most of these emitters are well known, with most studies having focused on ways of eliminating them in order to achieve high purity silicon. The list of light emitting centers in silicon is extremely long.[39] Here, we limit the description to the few ones that have been recently scrutinized for applications in quantum optics and spintronics. In Fig. 1(a) we represent, from the second to the fifth panel, respectively: the C center composed of one interstitial oxygen and an interstitial-carbon,[40,41] the G-center composed of two carbons atoms, one interstitial and one substitutional bound to a self-interstitial,[42,43] the W-center composed of clusters of three self-interstitials,[44] and the T center composed of two substitutional carbon atoms with one of the two linked to a hydrogen interstitial.[45]

Despite of being discovered long ago, very little is known for many of the silicon impurities. As an example, a clear picture of the microscopic structure, electronic properties, fine and hyperfine interaction of the light emitting G-center has been addressed by first-principles calculations only very recently[34] (Fig. 2). A similar

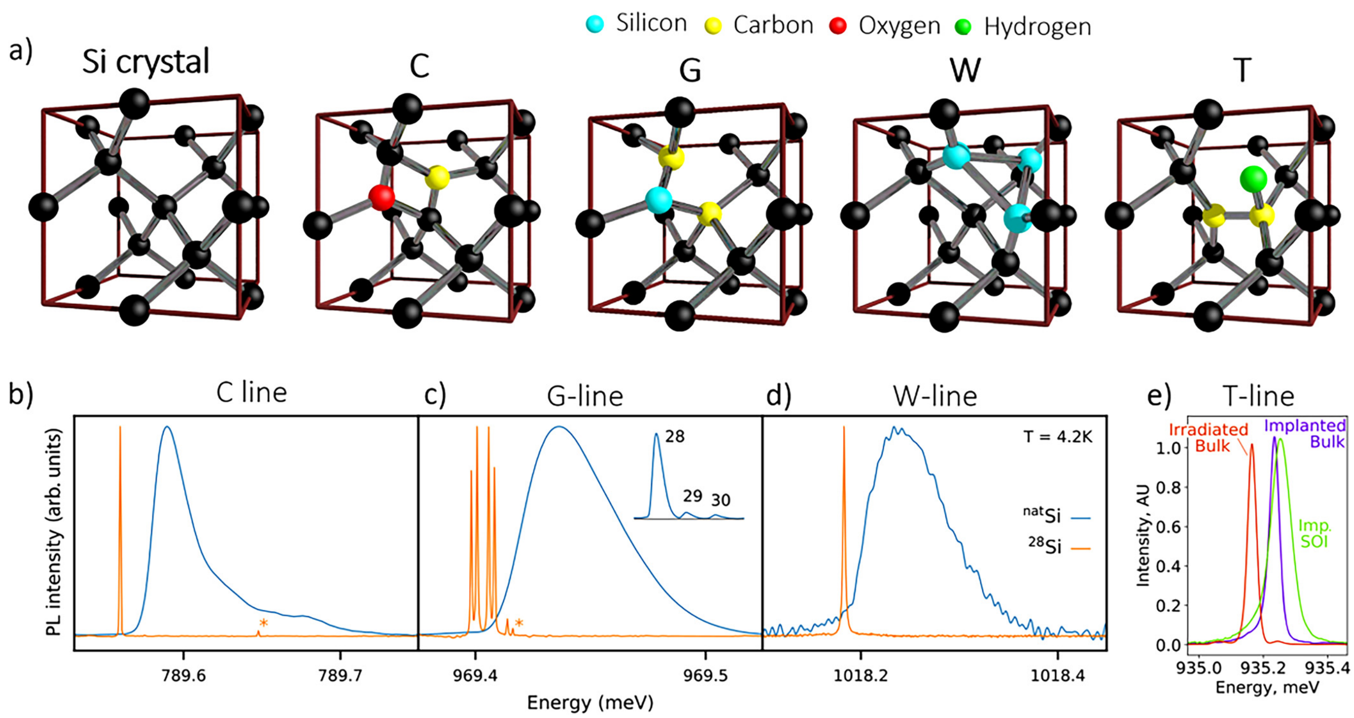

FIG. 1. (a) From the left to the right panel: crystalline structure of Si, C-center, G-center, W-center, and T-center. Reproduced from the Ph.D. thesis of Dr. A. Kurkjian with permission from Prof. S. Simmons and M. Thewalt.[12] (b)–(d) Photoluminescence intensity of the zero-phonon line of C, G, and W centers in bulk Si (blue line) and isotopically purified bulk ^{28}Si (orange line). Reproduced with permission from Chartrand *et al.*, Phys. Rev. B **98**, 195201 (2018). Copyright 2018 American Physical Society. (e) Photoluminescence intensity of the zero-phonon line of T centers in bulk Si irradiated with electrons (red line), bulk Si implanted with protons (purple line), and silicon on insulator (SOI) implanted with protons (green line). MacQuarrie *et al.*, New J. Phys. **23**, 103008 (2021). Copyright 2021 Authors(s), licensed under a Creative Commons Attribution (CC BY) license.

theoretical analysis has been reported for the T-center.[46] Density functional theory calculations for the G-center provide an energy difference between the transitions $^1A' \leftrightarrow ^1 A''$ and $^1A' \leftrightarrow ^3 A''$ of, respectively, 985 and 678 meV. The first transition is not far to what is conventionally observed in photoluminescence experiments.[38,47] From the experimental point of view, a direct measurement of the recombination lifetime of an ensemble of G-centers was reported only in 2018.[38] Generally speaking, this points to a deep gap in the knowledge of these emitters that leave room for improvements and potential exploitation.

Beyond applications of the ensemble emission (e.g., for lasing[47] and LED[48,49]), one can envision quantum light sources in bulk Si and SOI[31,35,50–52] (Fig. 3). The associated transitions match very well the telecommunication windows (Figs. 1 and 3): *O band* (G-center, SD-2, SD-5), *E band* (SD-1, SD-2), *L band* (C-center) and exhibit promising properties as flying quantum bits: a recombination lifetime in the range of 4–40 ns, a quantum efficiency larger than 50%,[50] a Debye–Waller factor of 2%–40% at ~10 K[35] [Fig. 3(b)], well-defined polarization axes, accounting for single emission dipole, resilience to thermal cycles, thermal stability, non-blinking emission intensity, and a brightness exceeding 10^5 counts per second at the detector[31] (using a superconducting nanowire single-photon detector, detection efficiency of about 90%) limited to about 2% by total internal reflection owing to the relatively large refractive index of Si (~3.5).

Clear anti-bunching in the second order, intensity correlation function has been independently reported by three different groups for the G-center,[31,35,50,51] the W-center,[52] and also for a new set of unknown impurities likely related to carbon[35] [Fig. 3(c)]. The smallest reported value for $g^2(0)$ is of 0.07 ± 0.04[31] (likely limited by the presence of spurious emission within the detection spot and by intrinsic dark counts of the detector) underlying the high quality of these emitters.

These important achievements were obtained using commercial SOI wafers and are the irrefutable proof of the atomic-like density-of-states of this class of emitters. *De facto* they open the route to the implementation of quantum optical devices in a Si-based, device-friendly environment.

III. FUTURE CHALLENGES FOR ALL-SILICON, QUANTUM INTEGRATED PHOTONIC CIRCUITS AT TELECOM FREQUENCY

A. Extrinsic effects

In spite of a rather small extension of the electronic wavefunction of light-emitting impurities at low temperature (e.g., about

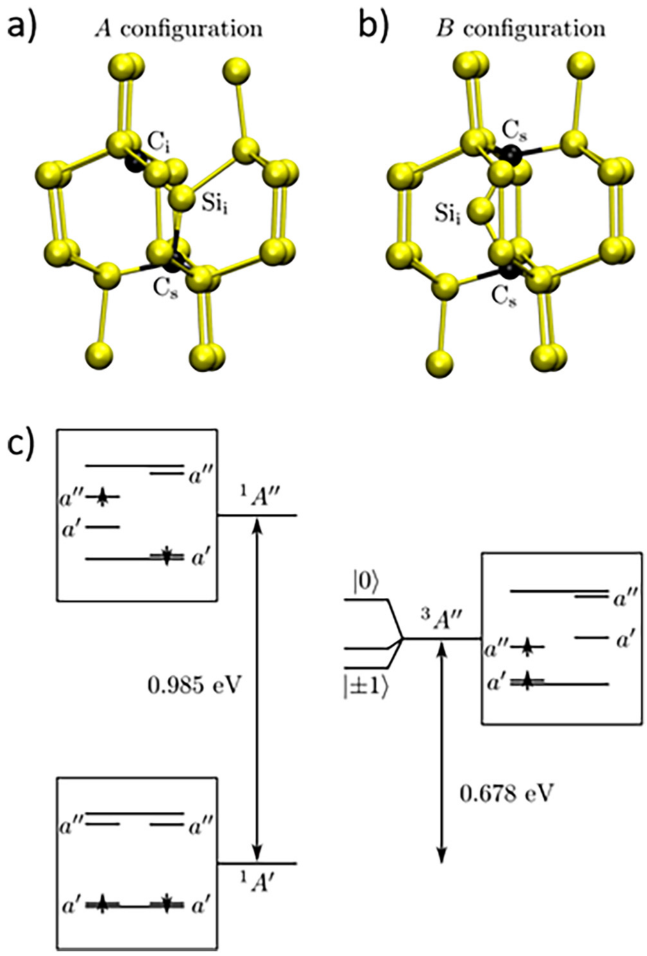

FIG. 2. (a) Structure of the A form of the G-center: C_iSi_i–C_i. (b) Structure of the B form of the G-center: C_s–Si_i–C_s. (c) Electronic levels of the G-center, B configuration. Reproduced with permission from Udvarhelyi *et al.*, Phys. Rev. Lett. **127**, 196402 (2021). Copyright 2021 American Physical Society.

1.6 Å for the light emitting G-center at 10 K[38]) that should limit the impact of nearby impurities and extrinsic effects, the associated emission is clearly sensitive to the surrounding environment[53] (Figs. 4 and 5). The control of these perturbations is crucial for exploiting these impurities for quantum light emission and spin–photon interface, enhancing their coherence in view of the fabrication of arrays of identical defects emitting mutually indistinguishable single photons and scaling this approach to a large number of quantum bits.

1. Spectral diffusion

One of the relevant mechanisms affecting the coherence of individual, strongly-confined emitters are random fluctuations of the charged environment leading to a quantum-confined Stark effect (spectral diffusion). This inhomogeneous broadening, measured in the line shape of individual quantum light sources, springs from the integration of the signal over relatively long time intervals (e.g., a few seconds) resulting in the pileup of many photons emitted at slightly different energies due to fast changes of the surrounding charged environment.[54] Thus, line shape and broadening measurements provide a first assessment of the quantum-confined Stark effect and of the quality of the semiconductor matrix surrounding an emitter in terms of amount and distance of the perturbing charges.[55–57]

Very recently, ensemble measurements were performed on T-centers exploiting a newly-developed spin-dependent spectroscopic technique.[13] Whereas in isotopically purified ^{28}Si and bulk Si irradiated with electrons the impact of spectral diffusion affects the linewidth [Fig. 4(a)] with a broadening lower than μeV, the SOI counterpart that underwent ion implant, provides a value that can be between one and two order of magnitudes larger [Fig. 4(b)]. These results confirm that also for T-centers integrated in a flat SOI without any top-down etching (i) the ion implant increases the overall defectivity and the associated impact on the spectral diffusion (e.g., as shown for NV centers in diamonds[58,59]) and (ii) that the presence of interfaces close to the emitters increases electric and magnetic field noises.[57,60,61]

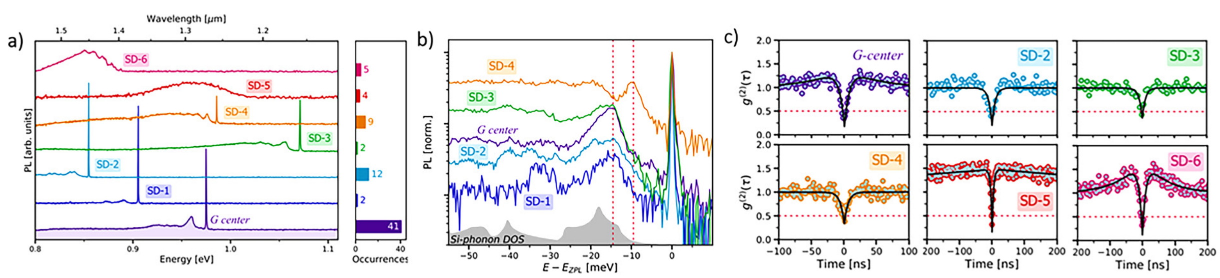

FIG. 3. (a) Photoluminescence spectrum of individual impurities in C-implanted SOI wafer (C implant at 36 keV, fluence 5×10^{13} cm^{-2}cm). The right inset displays the number of emitters associated with each kind of impurity detected in an area of about 600 μm^2. (b) Photoluminescence spectra normalized to the zero phonon line peak and shifted in energy to the zero phonon line energy for impurities G, SD-1, -2, -3, and -4. The dotted, vertical lines highlight the position of the first phonon replica, whereas the shaded highlight the phonon density of states of the Si matrix hosting the impurities. (c) Second order autocorrelation function [$g^2(\tau)$] of six individual impurities in SOI. The horizontal, dashed lines highlight $g^2(\tau) = 0.5$, below which the emission can be ascribed to an individual two-level system. Reproduced with permission from Durand *et al.*, Phys. Rev. Lett. **126**, 083602 (2021). Copyright 2021 American Physical Society.

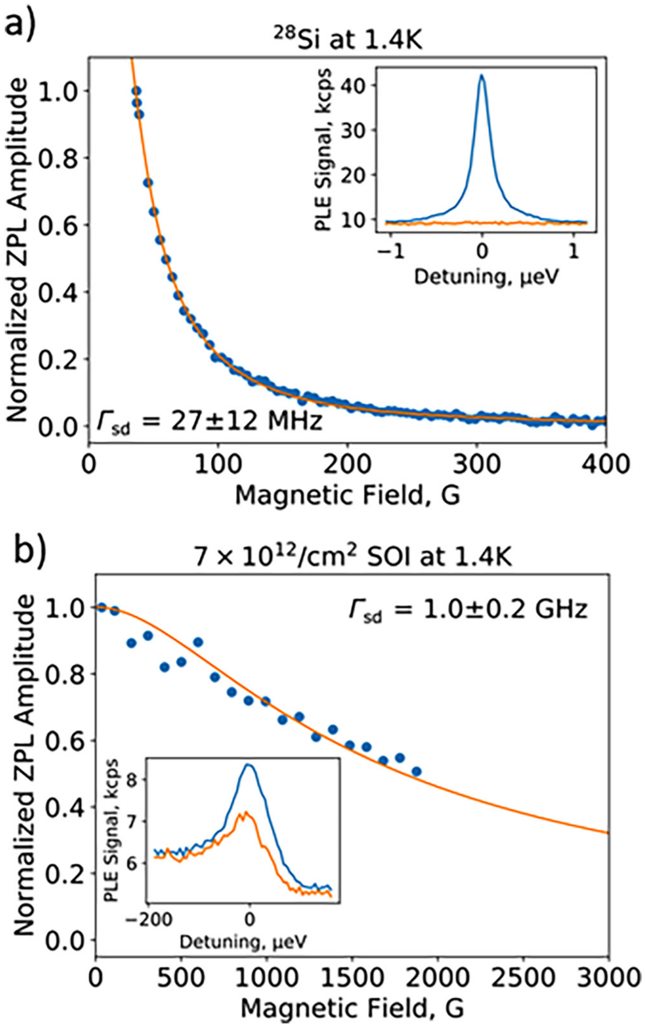

FIG. 4. (a) Zero phonon line intensity of an ensemble of T-centers as a function of the applied magnetic field at 1.4 K, for bulk ^{28}Si. The inset show the zero phonon line at B = 36 G (blue) and 450 G (orange). (b) Zero phonon line intensity of an ensemble of T-centers as a function of the applied magnetic field at 1.4 K, for SOI implanted respectively at 7×10^{12} cm^{-2}. The insets show the zero phonon line at B = 36 G (blue) and 2000 G (orange). MacQuarrie *et al.*, New J. Phys. **23**, 103008 (2021). Copyright 2021 Authors(s), licensed under a Creative Commons Attribution (CC BY) license.

Although an extensive characterization and comprehension of the impact of spectral diffusion on the electro-optical properties of individual impurities in Si is still missing, these early results strongly suggest that ion implantation adds some disorder to the crystalline matrix and that the presence of interfaces is detrimental. *Ad hoc* strategies should be devised in order to address this issue. A viable solution could be improving the high-temperature annealing process that typically follows the ion implant step (e.g., for the creation of G-centers[38,62]). However, there are limits to the thermal processing that can be used for integrating these emitters in a photonic device. (1) The BOX of SOI is high-quality, thermal SiO_2 but cannot be exposed to very large temperatures (after lithography and etching): annealing above 900 °C promotes intermixing between Si and SiO_2, potentially damaging the whole photonic device.[63] (2) Solid state dewetting, that is, a shape instability that thin films undergo when annealed even well below their melting temperature,[64,65] is another relevant issue that can have a detrimental impact on a tiny device implemented in a SOI substrate. (3) Owing to the rather large mobility of impurities and interstitial in silicon, high temperature annealing may destroy the light emitters and thus is not viable.

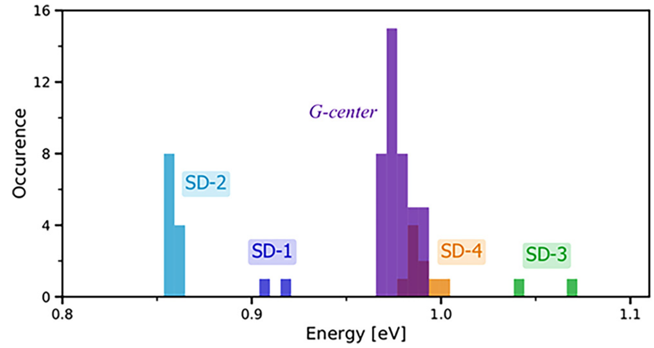

FIG. 5. Statistics of the zero phonon line emission from individual quantum emitters measured in a carbon implanted SOI (see also Fig. 1). Reproduced with permission from Durand *et al.*, Phys. Rev. Lett. **126**, 083602 (2021). Copyright 2021 American Physical Society.

A well-established approach to circumvent the issues of spectral diffusion is a resonant-excitation scheme. This method exploit a sharp laser tuned at the same energy of the zero-phonon line exciting only the associated optical transition. This technique seems a necessary step to fully exploit the potential of these quantum emitters that brings also another relevant advantage: the resonant Rayleigh scattering from an individual two level system inherits the coherence of the laser while preserving the anti-bunching character of a quantum emitter.[66] Remarkably, the two-photon indistinguishability of a coherently driven quantum emitter can be tuned adjusting the laser coherence. In addition to a resonant pumping, more sophisticated excitation schemes include the presence of an additional, non-resonant, low-energy laser to control the presence of a charge in a quantum emitter[67] that is very important beyond the issue of spectral diffusion (e.g., in order to switch from A to B form in a G-center, Fig. 2).

2. Hyperfine interactions

A second relevant perturbation to the electro-optical performances of these emitters can spring from hyperfine interactions between the nuclear and electron spins that may reduce photon and spin coherence. This phenomenon is ascribed to nuclear spins that in silicon is mostly associated with the presence of ^{29}Si (with a nuclear spin of 1/2) that fluctuate in time. The use of ^{28}Si (a zero isospin matrix, erasing any hyperfine interaction) provides unprecedented sharp lines (less than 1 μeV) measured in the ensemble of

C-, G-, and W-centers[9] [Figs. 1(b)–1(d)]. In silicon, the same phenomenology has been deeply studied[54,68–73] in view of the exploitation of the long spin coherence of electronic and nuclear spins for atomic-scale electronic devices based on individual dopants.[74,75]

In the framework of light emitting impurities, ^{28}Si has been successfully exploited to show a spin–photon interface exploiting an ensemble of T-centers:[10,11] [Fig. 4(a)], the T-center in ^{28}Si provides a direct access to nuclear and electron spin degrees of freedom with a lifetime in the range of seconds and milliseconds, respectively. A potential drawback of this emitter is its relatively long recombination lifetime that is about 0.9 μs.

These important achievements directly point to the possibility of using ^{28}Si as a quantum material[76,77] and build quantum devices for highly coherent single photons, spin-photon entangled states, and much more. However, a major step in this direction will require the fabrication of photonic devices (e.g., to create a cavity to accelerate the spontaneous emission rate and inject and extract the photoluminescence) exploiting a ^{28}SOI platform. This calls into play the production of this material that is the most abundant stable isotope of Si (being about the 92% of the total Si composition) but requires a long process to reach a high level of purity rendering it, for the moment, highly expensive: centrifugation of SiF_4 to purify $^{28}SiF_4$ followed by conversion in enriched silane gas $^{28}SiH_4$ (direct centrifugation of silane is not possible owing to its low molecular mass). Other approaches to produce this material, such as mass separation, ion exchange, and laser technology, are less efficient in reaching high level of purity and are more expensive with respect to centrifugation.

Epitaxial growth of layers of ^{28}SOI was shown using $^{28}SiH_4$ produced by Isonics Corporation in USA in collaboration with the Voltaix company between 1998 and 2005, reaching a purity better than 99.9%.[78,79] A 5 kg boule of purified ^{28}Si has been produced within the Avogadro project in Berlin in 2005.[80] More recently, chemical vapor deposition of ^{28}Si (with a purity of 99.992%) atop a thinned SOI of 300 mm diameter was shown by CEA laboratory in France for the fabrication of CMOS-based quantum bits with a pre-industrial protocol.[81–83] This accounts for the presence of a well-established community ready to tackle this activity with advanced fabrication protocols.

The narrow photoluminescence lines observed in ensembles of light emitters in bulk ^{28}Si[9–11] suggests that the actual level of purity of this material (impurities can be less than 800 ppm[83]) can be used for quantum technologies with light emitters. From spectroscopic measurements on the ensemble,[9] comparing the emission from natural Si and purified ^{28}Si, the signatures of isotopes 29 and 30 are clearly absent in the latter case. It is actually interesting to note that, for C and G-lines involving C impurities, the impact the ^{13}C isotope (composing the emitter itself) on the photoluminescence signal can be detected, being about two order of magnitude lower than that associated with the ^{12}C isotope and providing a spectral shift of 0.1 μeV or less.[9] Thus, in spite of this small impact, a better control of the spin-state of these impurities will also pass through the precise control of the isotopic composition of the implanted species.

3. Local strain

The results in ^{28}SOI discussed in Sec. III A 2 demonstrate that there is sufficient interest and efforts already underway toward the engineering of quantum emitters. Recent reports showed that a local implant of Si ions in a ^{28}SOI allows one to isolate individual W-centers acting as single photon emitters with a $g^2(0) \simeq 0.12$ without any background or dark counts correction.[52] In spite of the importance of this result, at the individual emitter level, there are relatively large spectral shifts from a W-center to the other (of about 1 meV). The same kind of effect was also reported for G-centers and other single photon sources in conventional SOI (Fig. 5), pointing to additional, unwanted effects damaging the potential indistinguishability of photons emitted by different sources and, in the end, the scalability of this approach.

Although a direct link to the potential source of these shift is still missing, different local strain experienced by each emitter is certainly a realistic hypothesis.[53,84] It was in fact already reported that splittings and shifts of the zero phonon line of C- and G-centers in silicon can be ascribed to local strain[85,86] in analogy to other systems.[87,88]

There are several well-known approaches that could be used to tune several quantum bits to the same energy. Relaxing the strain by high temperature annealing may be hard to implement, given the high mobility of the interstitials composing these quantum emitters. A viable solution could be the application *operando* of a local and irreversible strain by local crystallization of metal oxides (e.g., SiO_2, TiO_2, and HfO_2). This was efficiently exploited in III–V quantum dots showing superradiant emission from three independent sources integrated in a waveguide.[89] Alternatively, dynamic and reversible tuning of the emission could be obtained by applying a local, static electric field through an electric contact resulting in a controlled Stark-shift (e.g., in a MOS-like configuration).

B. Deterministic fabrication of individual quantum emitters

Deterministic fabrication of the impurities with ∼nm lateral resolution is one of the necessary steps for the controlled fabrication of this class of emitters. Examples of this kind have been widely reported for NV centers in diamonds exploiting a pierced atomic force microscope tip[90–92] or a mass-filtered focused ion beam.[93,94] Both methods were successful in creating an individual emitter within a photonic crystal microcavity.[95,96] Single ion implanters are also well-established and widely used techniques that could fulfill this task as it was already shown for phosphorous in Si[97,98] and rare-earth in yttrium–aluminum–garnet.[99]

In spite of the advanced level of these nano-fabrication techniques, these methods are based on phenomena that are intrinsically stochastic and may have a relatively low yield in the generation of single emitters. Moreover, the above-mentioned examples make use of relatively low energy ions limiting the ion range straggling allowing to place the ions with a precision of the order of a few tens of nm.

When complex impurities in silicon are concerned, one has to face a severe challenge: they are composed of several impurities eventually of different nature (e.g., two C and one Si for the G-center), which calls into play the need of placing them within the same unit cell potentially rendering the overall generation yield very low. As an example, we plotted the simulated ion range for C ions implanted in a 220 nm thick SOI in Fig. 6. Ideally, in order to

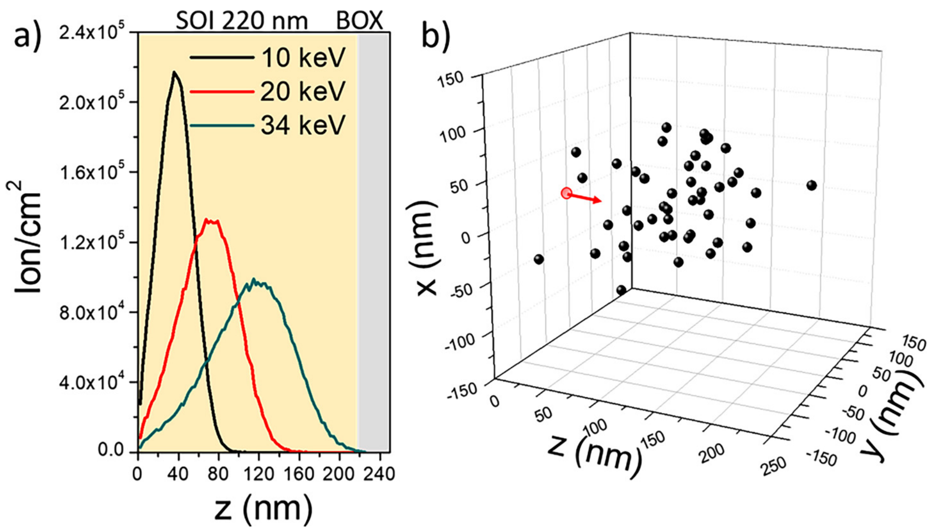

FIG. 6. (a) SRIM simulations of carbon ion range as a function of depth z for implant in a 220 nm thick SOI at 10, 20, and 34 keV. The profiles are obtained integrating over 10^5 ions. The shaded areas highlight the SOI and the BOX underneath. (b) 3D representation of 50 carbon ions implanted in Si at 34 keV. The red dot highlights the point of impact and the arrow the direction of the impinging ions.

couple the photoluminescence emission in a photonic circuit (e.g., a waveguide or a ring resonator), the implant energy should be large enough to produce the defect at its center. This can be obtained with an ion energy of about 34 keV. However, at this energy, the profile of the implant is relatively large, featuring a full width at half maximum of about 110 nm [Fig. 6(a)]. Representing the simulated ion position of 50 carbon ions implanted in Si at 34 keV, it appears that a similar spread is also present in the lateral direction. In order to limit these issues, possible strategies could include the use of thinner SOI allowing for lower implant energy at the center of the slab or *ad hoc* engineering of the photonic modes to work with the impurities implanted at the SOI surface.

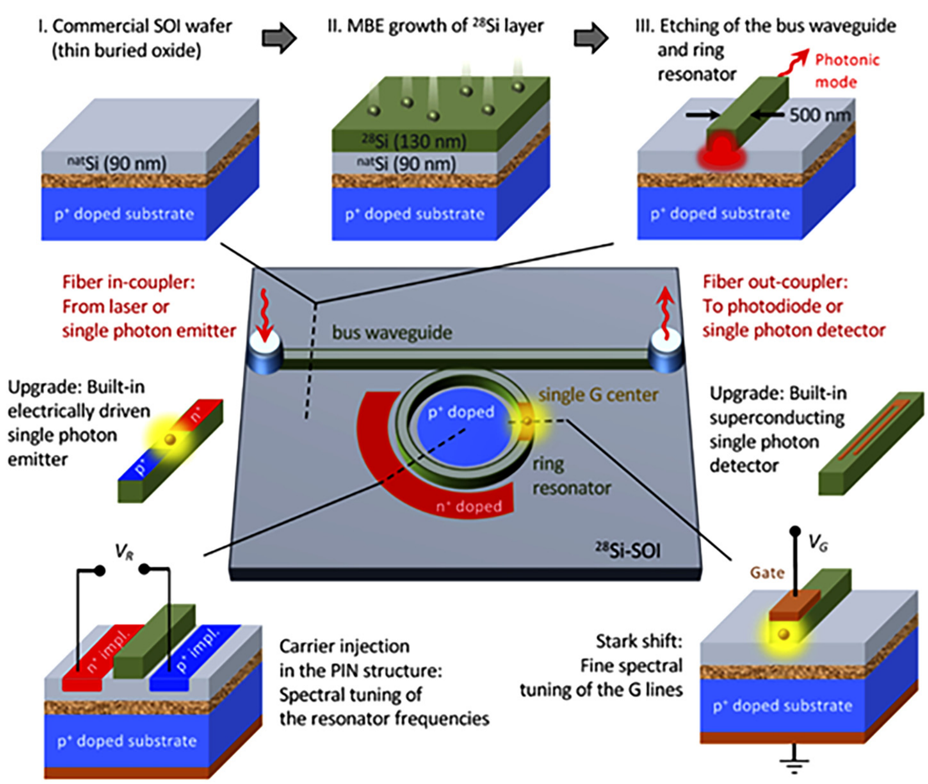

FIG. 7. Scheme of ^{28}SOI integrated photonic circuits and electronic devices for scalable quantum circuits based on individual emitting impurities. Reprinted with permission from Hollenbach *et al.*, Optics Express **28**, 26111 (2020). Copyright 2020 The Optical Society.

An attractive alternative to localized ion implant is an all-optical fabrication of individual quantum emitters. A direct control of their activation has been demonstrated in diamonds[17] and SiC[18] with fs-laser pulses: by *in situ* and *operando* monitoring the photoluminescence emission after individual laser pulses, the fabrication yield can be very close to unity. This will entail the preliminary ion implant of the impurities followed by laser activation.

C. Integration in opto-electronic devices

The last aspect we consider for the scaling of this approach for quantum technologies is the integration of impurities in photonic circuits and electronic devices[100] (Fig. 7). Electrical injection of carriers in ensembles of G-centers has been already shown exploiting a light emitting p–n junction[48,49] and their integration in a high finesse cavity has been proposed.[101,102] However, from power dependent photoluminescence experiments, unwanted absorption was shown, pointing to residual defects that spoils the emission. Other reports of integration of G-centers ensembles in photonic devices demonstrated that luminescence was activated (likely at the interface between Si and air) through the top-down etching[47,103] that, in principle, may complicate the isolation of individual emitters.

The aforementioned results were obtained in SOI samples undergoing implant with large doses. For lower doses, as low as $10^{13}\,\mathrm{cm}^2$, coupling of individual G-centers in a waveguide was reported with clear anti-bunching ($g^2 < 0.5$), a lifetime compatible with that found in the ensemble (∼8 ns) and with a very limited spread of the zero-phonon-line between different emitters (1279 ± 1 nm).[51] This promising results suggest that we stand at a turning point for quantum devices in Si: all the tools developed for silicon based integrated photonic circuits could be exploited to manipulate single photons. A pictorial representation of these tools is displayed in Fig. 7 from Ref. 31 that traces a road-map for the future development of integrated photonic circuits embedding quantum emitters in ^{28}SOI. Following the growth of ^{28}SOI on conventional SOI and implant of emitting impurities, top-down etching will be used to define photonic devices such as waveguides, resonators, logic gates, modulators, and light couplers. Finally, direct single photon detectors using superconductive wires (e.g., as already shown in other systems[104,105]) will be the last step to fully operate quantum bits of light on a Si-based chip toward scaling.

IV. CONCLUSION

In conclusion, several recent works with individual impurities in silicon have underlined their potential as quantum emitters and opened the door to intense investigations of this material for quantum devices. Although those efforts are still at an early stage, and silicon still lags behind other quantum bit technologies, important theoretical and experimental evidence are rapidly emerging, pointing to new insight, improved devices, and performances in the near future. The broad availability of Si and its crystal quality, the possibility to purify a ^{28}Si matrix, and the strength of nanofabrication of electronic and photonic devices are key elements that can rapidly accelerate the development toward commercial quantum devices.

The possibility for defects in silicon to outperform current solutions, such as III–V-based single photon sources or spin quantum bits in NV-centers, will largely depend on the performances and scalability of this approach. To this end, there are many challenges that must be addressed in the next years. Mandatory spatial addressability of individual emitters (that should be placed with high precision within optical and electronic devices) is just one of the steps that is still missing. The control of the fluctuating electric and magnetic environment will be also a crucial step to improve the coherence of photon and spin degrees of freedom. Evidence of slight differences between nominally identical emitters point to uncontrolled extrinsic effects, likely related to residual strain, that will potentially harm the scalability of this approach. The control of these perturbations that are not yet fully understood is a prerequisite for the fabrication of competitive quantum devices.

Quantum devices in silicon exploiting spin of individual impurities and charge state of quantum dots provide a well-established platform for quantum bit manipulation in a device-friendly environment. The very low temperature required by these platforms (tens of mK) could also be convenient for the manipulation of the light emitters addressed in this Perspective. The detrimental effects of phonon-interactions on the Debye–Waller factor, spoiling the coherence of the emitted photons, suggest the need for much lower operating temperature channeling all the recombination in the zero-phonon line. Merging the electronic control of spin and charge states of light-emitting impurities at telecom frequency may be the next step toward a full exploitation of anchored and flying quantum bits for quantum computation and quantum information protocols in silicon.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

DATA AVAILABILITY

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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