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Silicon Carbide

From Abrasives to Quantum Photonics

Traditionally used for abrasives, LEDs and transistors, the material may enable scalable quantum and nonlinear photonics through direct integration of solid-state qubits into photonic circuits.





Remarkably, by creating a defect in a crystalline material (for example, by removing or substituting an atom), one can produce some of the best quantum memories in the world.

The 2000s were a simpler time for integrated photonics, when a handful of material platforms dominated research and industrial applications. The past decade, however, has seen an explosion of new photonics materials: GaP, Ta₂O₅, SiC, AlN, LiNbO₃, diamond and others. The enthusiasm for new materials stems in part from the high-level of technological know-how the integrated photonics community has developed—which has built the confidence to take advantage of exotic platforms with the best intrinsic properties for a given application.

At the same time, the applications of integrated photonics also have become more numerous, introducing new technical challenges and material requirements of their own. One material rising to those challenges is silicon carbide (SiC)—a substance traditionally used for abrasives, LEDs and transistors, but that is emerging as an enabling platform for scalable quantum and nonlinear photonics. This

feature looks at the prospects and challenges for SiC in the quantum realm.

Spin-based quantum photonics

It is remarkable that, by creating a defect in a crystalline material (for example, by removing or substituting an atom), one can produce some of the best quantum memories in the world. The atomic defect supports the existence of localized electronic states deep within the crystal band gap. These states are shielded from the environment by the “semiconductor vacuum,” which, in theory, is perfectly periodic. Thus, as with a trapped atom in an actual vacuum, electronic states in the semiconductor vacuum are well protected from quantum decoherence.

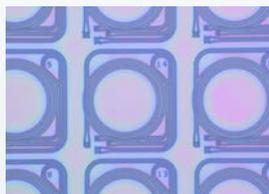
The class of crystal defects most interesting for quantum photonics is so-called color centers, the electronic structure of which allows them not only to store quantum information, but also to broadcast it in the form of a photon. Since an optical photon

Silicon carbide at a glance

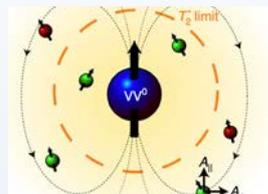
Known for exceptional durability in demanding electrical, mechanical and radiation environments, silicon carbide (SiC) is finding new applications in integrated photonics. Combining a wide optical transparency window, high refractive index, and strong second- and third-order nonlinearities, SiC also hosts numerous color centers promising for applications in quantum photonics.



Heteroepitaxy substrate



Integrated photonics



Quantum registers



MEMS devices



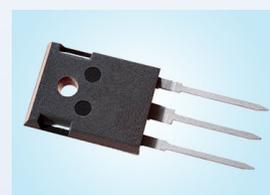
Abrasives



Fake diamonds



Heating elements



Power electronics

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is the ideal carrier of quantum information, color centers would seem to be perfect candidates for quantum communication applications that require a memory component to function efficiently.

Why are such memory components necessary for quantum communications? After all, transmitting internet traffic across the floor of the Atlantic Ocean requires not memory, but only a chain of fiber amplifiers that periodically boost the optical signal. Quantum states, however, cannot be amplified due to the no-cloning theorem; indeed, if they could be, quantum communications would have no security advantages over classical protocols.

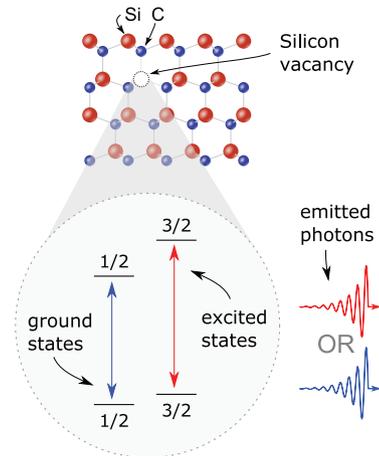
Consequently, to mitigate the loss of quantum information in a fiber and to extend the reach of quantum signals, more advanced schemes—quantum repeaters—are necessary, and quantum memories, which can substantially improve such a repeater’s efficiency, become essential. Color centers have emerged as a central enabling technology for this requirement. In one recent breakthrough, researchers at Harvard University used a color center embedded in a diamond nanophotonic device to implement basic quantum-repeater functionality and thereby demonstrate memory-enhanced quantum communication.

Another way color centers can benefit quantum technologies is through generation of more complex photonic states beyond single photons. By using the color-center quantum memory, it is possible to generate trains of entangled photons (such as so-called cluster states) that can be used for robust computing and communication protocols. So far, cluster states have been demonstrated only in quantum dots—but color-center quantum memory could also be used to generate such entangled-photon trains.

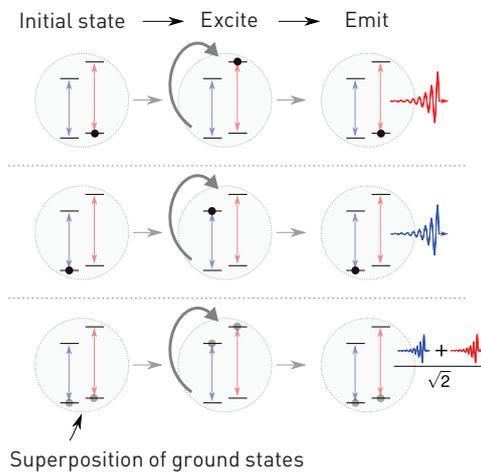
SiC: Leveraging the semiconductor industry

Most groundbreaking work with color centers has so far been done in diamond, specifically the nitrogen–vacancy (NV) and silicon–vacancy (SiV) color centers. These color centers are based on defects in the diamond crystal lattice, in which two carbon atoms are replaced in the crystal lattice are replaced by a nitrogen atom and a lattice vacancy

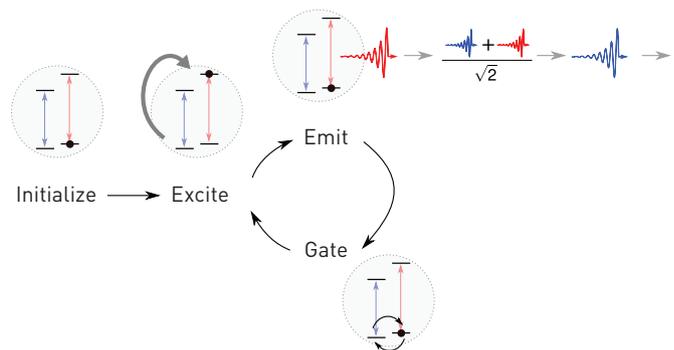
Color centers for generating chains of entangled photons



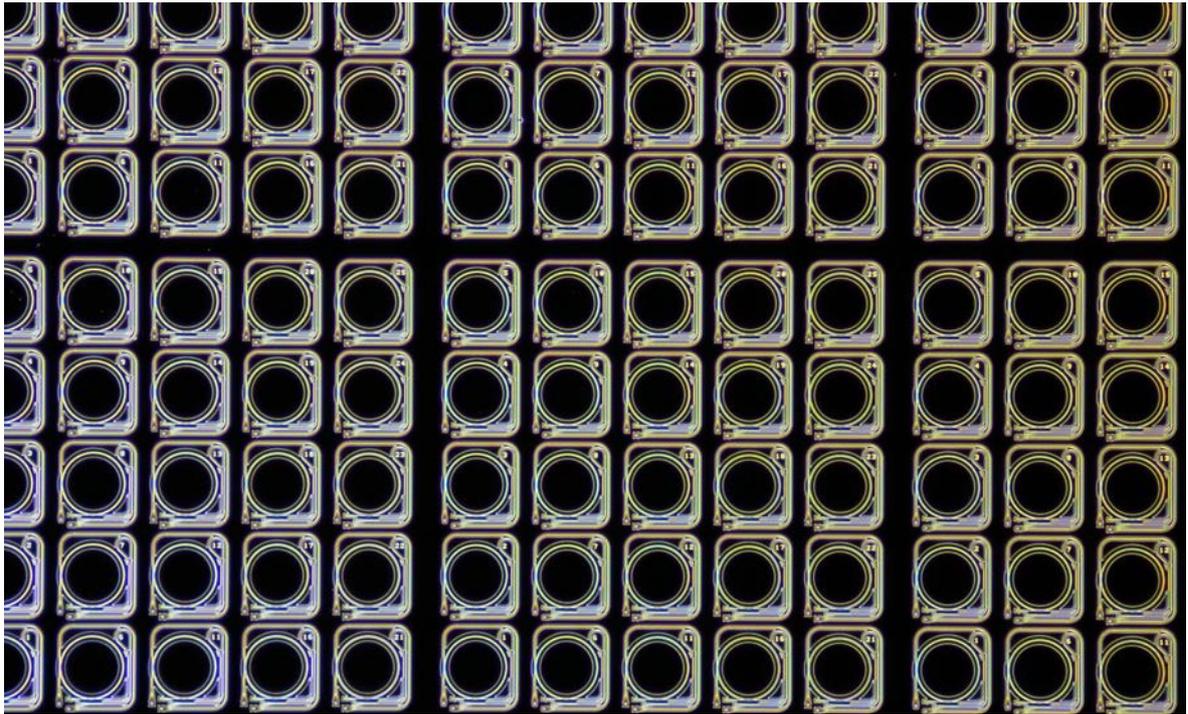
The silicon vacancy (V_{Si}) in SiC is a color center with spin $3/2$ that emits photons of different colors depending on V_{Si} 's ground state.



If prepared in the $1/2$ ($3/2$) ground state, upon excitation with an above-resonant laser, the V_{Si} will emit a blue (red) photon. If the ground state is prepared in a quantum superposition, the photon will be a superposition of red and blue.



By repeatedly exciting the color center while applying a ground state gate after each emission, a variety of chains of entangled photons, such as cluster states, can be generated.



Microscale photonic devices created on SiC platform. Each device is roughly 100 μm on a side. Courtesy of D.M. Lukin

(for NV centers) or a silicon atom and a vacancy (for SiV centers). SiC is relatively new to the field, but has some similarities to diamond. (Indeed, interestingly, replacing every other carbon atom in a diamond crystal with a silicon atom actually results in a crystal of SiC, in the material's cubic polytype.)

Like diamond, SiC hosts color centers that are promising for quantum photonic technologies. Unlike diamond, however, SiC wafer production is backed by a multibillion dollar semiconductor industry. Companies such as Cree, Inc., are expanding their SiC growth capabilities to meet the increasing demand for efficient, high-power semiconductor devices for applications such as electric cars. Consequently, a six-inch wafer of high-purity SiC can be purchased for the same price as a 5×5-mm chip of diamond, a nearly thousand-fold price difference per chip area.

Decades of investment and research into optimized bulk crystal growth—reducing contamination, defects, dislocations and other issues—as well as advanced homoepitaxial chemical vapor deposition (CVD) of SiC layers has enabled an unprecedented purity and control. In 2019, building on those developments, researchers at the University of Chicago demonstrated that commercial, wafer-scale SiC *p-i-n* junctions host spectrally tunable color centers with excellent optical and spin

properties. That demonstration has paved the way toward scalable color-center technologies.

From bulk crystal to thin films

Although wafers of high-purity SiC have been commercially available for decades, the integrated-photonics community had not been able to take advantage of this intrinsically high-transparency semiconductor—though not for lack of trying. To create integrated photonics in a new material, a thin layer of the material must be isolated on a low-index substrate, so that waveguides and resonators can be patterned on the thin layer to confine light and control its propagation. The longstanding challenge for SiC was finding a suitable method for fabricating a thin film from a high-quality bulk wafer.

The most notable example of bulk-to-thin-film transformation is, of course, silicon-on-insulator (SOI), the workhorse platform for integrated photonics. Among the technologies for producing SOI, the process marketed as SmartCut, pioneered in the late 1990s by Michel Bruel of CEA-Leti in Grenoble, France, has taken the lead. In SmartCut, hydrogen ions are implanted into a bulk crystal and form an H⁺-rich layer below the surface. With high-temperature annealing, the H⁺ layer vaporizes to produce

Like diamond, SiC hosts color centers promising for quantum photonic technologies. Unlike diamond, SiC wafer production is backed by a multibillion dollar semiconductor industry.

H₂ bubbles, inducing the cracking and separation of a thin film from the bulk crystal. This results in a perfectly monocrystalline film of extremely uniform thickness. A variety of sensitive experiments have shown that SOI prepared via SmartCut is, in material quality, practically indistinguishable from bulk silicon, and the technique has enjoyed incredible success in the silicon world.

SmartCut technology has also been applied to SiC. Surprisingly, however, SiC-on-insulator (SiCOI) films prepared this way displayed significantly reduced material quality relative to bulk material, including a high optical absorption of around 5 dB/cm. So great an optical loss would clearly make the material unsuitable for high-performance integrated photonics.

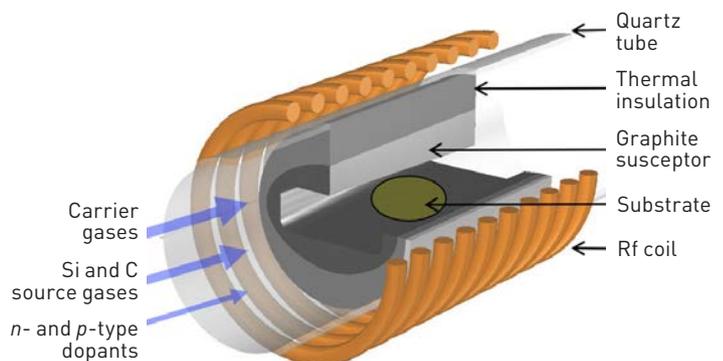
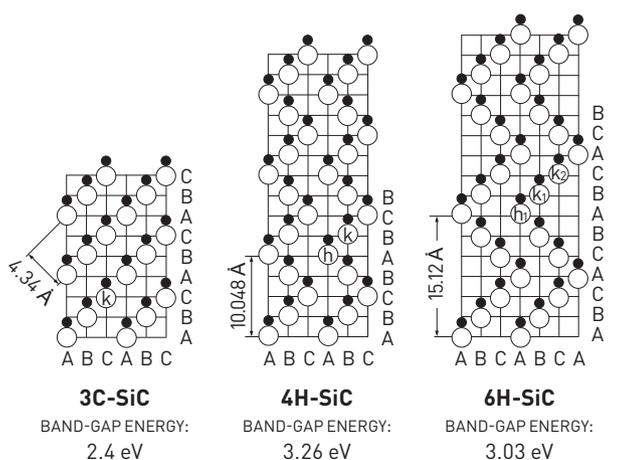
What went wrong? Perhaps the key issue for SiC with SmartCut is melting temperature. Bulk silicon melts at a relatively low temperature of 1400 °C and softens at even lower temperatures; as a result, the crystal lattice damage induced by implanting hydrogen ions is almost fully repaired during the annealing process. In contrast, SiC does not melt at

all, but sublimates to gas at an extreme temperature of 2700 °C, at which any substrate used for the SiC thin film would be destroyed. Consequently, it is believed that in SiC created with SmartCut, the large optical absorption is inevitable, as the damage induced by the hydrogen implantation is virtually permanent and cannot be repaired.

Another approach explored for producing thin films of SiC has been heteroepitaxy, the growth of SiC on a different material substrate. The polytype 3C-SiC grows readily on silicon and offers a convenient, wafer-scale approach to thin-film SiC. However, the lattice mismatch between SiC and silicon leads to a high density of crystal lattice imperfections in the SiC. This low material quality degrades not only the properties of color centers, but also those of classical photonic circuits.

Toward better thin-film quality

In 2019, research groups at Kyoto University and Stanford University independently introduced a “grinding and polishing” approach—which essentially



Left: SiC exists in hundreds of polytypes (unique crystal structures), the three most common being 3C (cubic) and 4H and 6H (stacked layers). Of these, 4H-SiC has become the polytype of choice for the industry and has thus been best-developed. Right: One challenge in growing SiC is ensuring that the right polytype is obtained. The high temperature required for SiC growth also imposes challenges for designing reactors to create the bulk material. The horizontal hot-wall chemical vapor deposition (CVD) reactor, developed at Linköping University, Sweden, enabled unprecedented high-purity growth of homoepitaxial SiC layers.

Courtesy of Jawad Ul-Hassan

The grinding-and-polishing technique with SiC has enabled demonstration of some essential components for integrated quantum photonics with color centers.

relies on brute force—to create the elusive high-quality thin-film SiC. The method consists of bonding SiC onto a carrier wafer, grinding the wafer to a thickness of several micrometers, and then polishing it to obtain a smooth surface. Although the method is not immediately scalable due to the thickness nonuniformity introduced in the process, the resulting SiCOI retains the pristine material quality of bulk SiC wafer.

The grinding-and-polishing technique has enabled demonstration of some essential components for integrated quantum photonics with color centers. These have included the integration of single color centers into high-quality nanophotonic cavities and waveguides, with propagation losses below 0.1 dB/cm. Low-loss waveguides are essential to the vision of scalable photonics not only to connect quantum nodes across the chip with high efficiency, but also to take advantage of

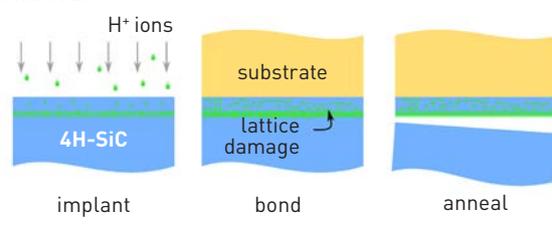
the intrinsic second- and third-order optical nonlinearities of SiC: high-quality nanophotonic cavities can be engineered to translate the frequency of a photon while otherwise preserving its quantum state. The emitted photons from color centers could then be translated directly on-chip into the telecommunications band, for more efficient routing via existing fiber networks.

Refining the process to enable wafer-scale production is an important next step. Here, the history of the semiconductor industry again provides reason for optimism. Before the SmartCut approach came to dominate the SOI industry, other competing methods to produce SOI had been developed. Among them is bonded and etched-back silicon-on-insulator (BESOI). This method proceeds similarly to the grinding-and-polishing method for SiC, with one crucial difference: an additional epitaxy is performed before bonding. One can then take advantage of selective chemical etching after grinding to eliminate the nonuniformity introduced in the grinding step.

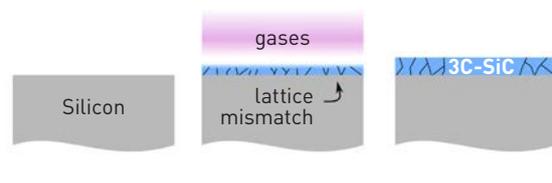
A similar approach could potentially allow high-purity SiCOI to be fabricated on the wafer scale. While one of the most chemically inert materials, SiC is nonetheless susceptible to doping-selective photoelectrochemical etching. This opens the door for an analog of BESOI to be implemented in SiC, thereby adding SiC to an expanding list of commercially available new thin-film materials (like the recently developed lithium niobate on insulator).

Three SiC thin-film fabrication methods

SmartCut



Heteroepitaxial SiC



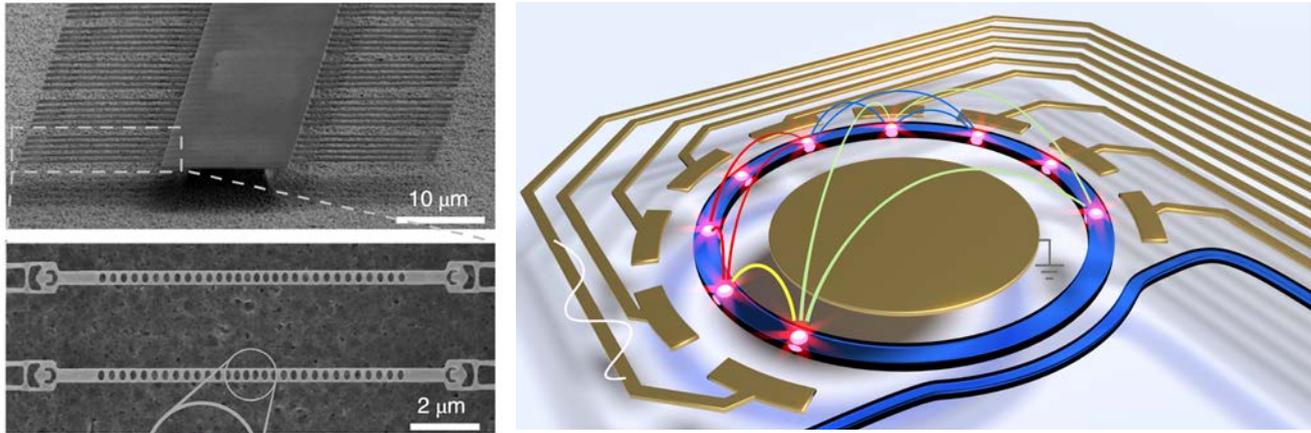
"Grind and polish" SiC



SiC in quantum photonics and beyond

Although the demonstration of a high-quality thin-film SiC platform has been an important step, many challenges remain. One is demonstrating narrow linewidth and spectrally tunable color centers, which will enable the controllable generation of on-chip color-center entanglement through photon interference. If this challenge can be overcome, SiC may become a platform of choice for combining state-of-the-art classical photonics with spin-based quantum technologies.

Applications for commercially available SiCOI would likely extend well beyond quantum photonics, however. The material's high refractive index (2.6) and large band gap (3.2 eV) make SiC an attractive



Left: SiC photonics with integrated single color centers. Embedding a color center in a nanophotonic resonator (inset) enables more efficient extraction of light, which translates to brighter single-photon sources and higher rates of entanglement generation. Right: A critical next step for spin-based integrated quantum photonics is to make multiple color centers “talk” to each other on the same chip. One approach for realizing this is to embed multiple color centers into a single resonator and independently tune each with electric fields.

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platform for strong-confinement nonlinear photonics in the visible spectrum. In the telecommunications band, optical frequency combs with low on-chip power requirements have already been demonstrated on SiCOI. Furthermore, active devices can be manufactured via planar semiconductor junctions or through the introduction of a graphene monolayer, which readily grows on the surface of 4H-SiC.

Aside from photonics, SiC could also emerge as a top contender for realizing micro- and nanomechanical devices that push the limits of current capabilities. Owing to its superior mechanical properties, SiCOI may be employed for fabrication of next-generation mechanical resonators.

Meanwhile, SiCOI has the advantage of full compatibility with standard CMOS fabrication, which means that foundries can immediately apply their infrastructure to SiC devices without fear of contamination of the facilities or the need to re-design the fabrication flow. The development of high-quality SiC photonics is thus an example of how industrial investment into a technology can be crucial for expanding emerging fields of research. Without decades of material development in the semiconductor industry, the advances in SiC for classical and quantum photonics would not have been realized. Existing industrial infrastructure, when examined from a fresh perspective, can enable rather than hinder innovation. **OPN**

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