Diamond for Quantum Computing

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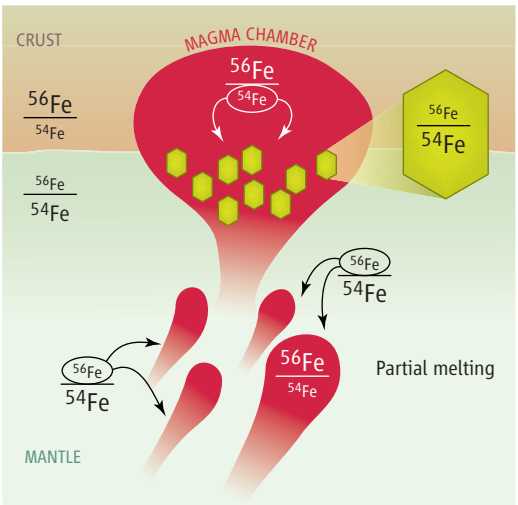

Fates of iron isotopes. Schematic of Fe-isotope fractionation during magmatic processes. During partial melting in the mantle, the heavy Fe isotopes preferentially enter the melt, resulting in high $^{56}Fe/^{54}Fe$ in melts and the crust, and low $^{56}Fe/^{54}Fe$ in the depleted mantle (the latter does not differ much from that of the bulk silicate Earth, for mass-balance reasons). Likewise, light Fe isotopes preferentially enter olivine during fractional crystallization, resulting in low $^{56}Fe/^{54}Fe$ in the crystals and increasingly higher $^{56}Fe/^{54}Fe$ in the remaining melt. Fractional crystallization of magnetite has the opposite effect, however (*15*).

processes, when other metal ions do not? There is no definitive answer to this question yet. However, in contrast to Li and Mg, Fe occurs in two different oxidation states in basalts (Fe^{2+} and Fe^{3+}). Only Fe^{2+} fits into the olivine structure, whereas Fe^{3+} preferentially stays in the melt. Potentially, this different partitioning of Fe species leads to measurable fractionation of their isotopes. Future experimental studies may provide the answer to this question, and also resolve whether this isotope fractionation occurs as an equilibrium or kinetic process.

In addition, because olivine is the most abundant mineral in the upper mantle and is the major host for Fe, we can speculate that Fe-isotope fractionation during melting in the mantle must occur as well. Indeed, the direction of isotope fractionation between olivine and melt during fractional crystallization agrees with that earlier predicted to occur during partial melting (*8*–*10*); that is, olivine and mantle rocks are isotopically lighter than basalt.

These findings of magmatic Fe-isotope fractionation open new possibilities for studying magmatic processes on Earth and other planets. Future studies may link the small differences we are observing in the Fe-isotope composition of materials from different planets—for example, the apparently heavier Fe-isotope compositions of lunar and terrestrial basalts compared to those from the planets Mars and Vesta (*3*, *8*, *9*)—to their respective conditions during planetary differentiation.

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APPLIED PHYSICS

Diamond for Quantum Computing

Optically active defects in diamonds are promising candidates for the building blocks of quantum computers.

Steven Prawer and Andrew D. Greentree

For the technologist seeking to build devices that take advantage of the quantum mechanical properties of coherence and entanglement, diamond looks to be the ideal material. Single-crystal diamond has long held allure as a gemstone, and its extreme electrical, optical, and mechanical properties have already found applications such as heat spreaders, optical windows, electrodes for electrochemistry, high-energy particle detectors, dosimeters, and biosensors. But it is in the quantum realm that diamond truly stands apart, its optical properties tailor-made for the fabrication of the building blocks of new quantum technologies. The optical centers in diamond offer access to isolated quantum systems that can be controlled at room temperature.

A color center is an impurity or defect in a crystal and is responsible for the colors of emeralds and rubies. The color center most used in diamond is the negatively charged nitrogen vacancy (NV) center. These optically active centers, consisting of a substitutional nitrogen atom next to a missing carbon atom (see the figure, left panel), are so bright that they can be detected individually with conventional microscopy. Because the ground state shines more brightly than the excited state, the state of the NV center can be read out. Resonant microwave pulses allow full quantum control of the state of the center.

These properties have enabled the construction of the most basic building block of a quantum processor, the quantum bit or qubit that is operable at room temperature. This is revolutionary in terms of solid-state quantum computing, where the usual temperature scales being discussed are fractions of a kelvin. The time required to manipulate the state of the qubit is brief (tens of nanoseconds), and the measured room-temperature decoherence rate is measured to be 0.35 ms (*1*), meaning that some 10^4 operations can be performed before decoherence takes over and the state is lost. Demonstrations of multiqubit couplings (albeit in a nonscalable design) (*1*–*3*) show promise for building small quantum memories and other few-qubit protocols.

When a single atom deexcites, it emits a single photon, and these photons can be used for a number of applications including quantum metrology, imaging, and ultrasecure communications using quantum key distribution (QKD). The NV centers in diamond mimic these single atoms, displaying photostable

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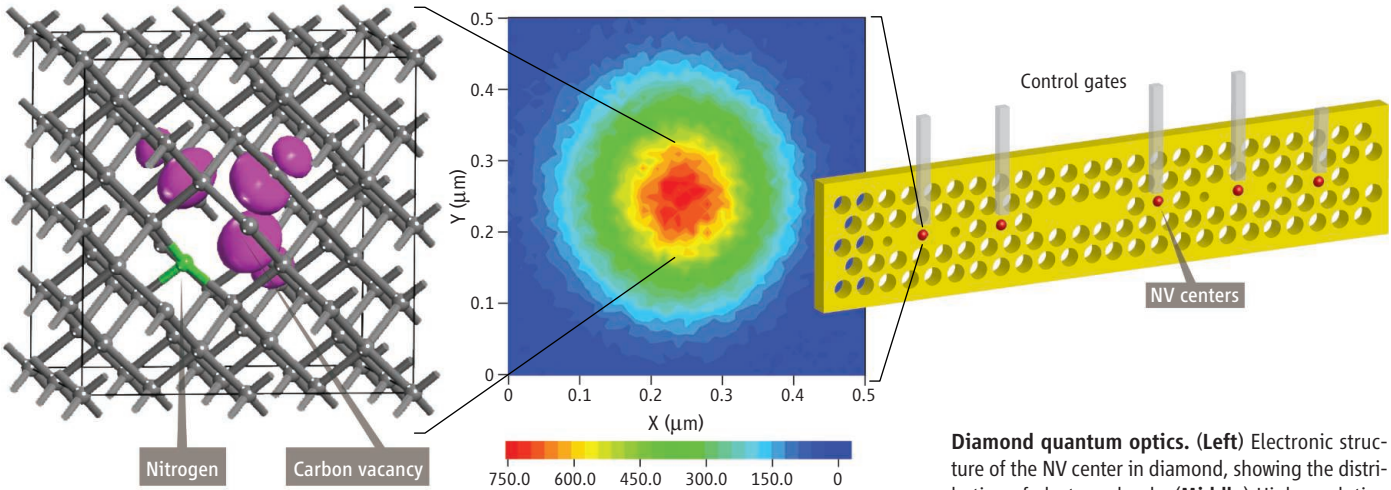

Diamond quantum optics. (**Left**) Electronic structure of the NV center in diamond, showing the distribution of electron clouds. (**Middle**) High-resolution confocal image of a single NV center. The signal-to-background ratio is in excess of 50:1. (**Right**) Schematic of a photon module consisting of NV centers in an array of photonic band-gap cavities. Tuning of each NV center to the cavity resonance is achieved via control gates [adapted from *16*].

single-photon emission (*4*); this property has led to the first commercially available, fiber-coupled, single-photon source units (*5*). Promising results have also been obtained with nickel-related centers in diamond (*6*). These are particularly suited to ground-to-satellite secure communications because of their longer wavelength. There are many other optical centers in diamond, and the race to find the "best" center is on.

Given these demonstrations of quantum-state readout, coherent manipulation, and quantum storage, why have devices not moved beyond single-photon sources? In part, the toolkit required to engineer diamond devices is in its infancy. The well-established techniques for silicon cannot be directly applied to diamond because of its hardness and chemical inertness. One approach to solving these issues is to grow chemical vapor–deposited diamond onto etchable substrates to leave behind the required structure (*7*). Another is to use a combination of ion implantation to graphitize the diamond (making it etchable) and then use a focused ion beam, laser ablation, or other milling methods to sculpt features into diamond (*8*).

The other challenge is to effectively couple light from the diamond to other solid-state photonic structures. Strong coupling enhances photon collection efficiency and provides a mechanism to control and tune the optical transitions (*9*). Optical coupling is also essential for scalability because it allows for long-range coupling between qubits (*10*). Considerable progress has been made in techniques for fabricating thin, single-crystal diamond membranes (*8*), whispering-gallery mode resonators (*11*), and photonic band-gap microcavities (*12*). However, the quality factor is still very far from what is required for scalable devices. Still, there seems to be no reason to believe that fabrication techniques will not rapidly improve in the near future if existing tools are optimized. Although the ground states are well protected from environmental decoherence, the excited states are not. All demonstrations of coherent optical coupling have so far used cryogenic operating conditions (*13*, *14*). Scalability may therefore preclude room-temperature operation of a diamond quantum computer.

One problem with using diamond is the lack of a reliable supply of materials that are perfect enough for quantum technologies. Progress has been made in the manufacture of single diamond crystals by chemical vapor deposition techniques. The background concentrations of nitrogen and boron (potential sources of decoherence) have been reduced to less than one part per billion (*15*), with dislocation densities far lower than that of natural diamond. The availability of material of such purity and perfection will enable practical quantum devices.

At present, fabrication of single qubits is very difficult. How then can we seriously propose building a large-scale qubit device, where every element is identical? One idea (championed by Ray Beausoleil of Hewlett Packard) is to follow strategies used when solid-state devices were not as perfect as they are now—that is, to incorporate a defect-tolerance approach. Diamond can incorporate defect-tolerant methodologies because the color centers can be individually characterized optically. The approach would be to make a large number of generic atom-cavity systems and expect that most will fail as qubits. When one is identified as functional, it is used as a component in the overall quantum computer. This approach builds scalability into the design at the outset and should lead to larger arrays of operational qubits.

Opinions of the viability of quantum computing have fluctuated between outlandish optimism and outlandish pessimism. Given what we know now about the challenges of scaling up quantum processors, it appears unlikely that we will see a large-scale quantum computer in the next 10 years. But the beauty of diamond for quantum information processing is that there are applications based on coherent quantum mechanics in few-qubit devices right now. These include entangled-state microscopy, teleportation, and quantum games. With ready access to genuine multiparticle entanglement, it is clear that new applications will also be found. Applications at the few-qubit level are necessary to build a commercial pathway between today's demonstrations and massively entangled quantum computers. Diamond therefore seems ideal as a bridge because of its bright single centers and the rapidly emerging nanofabrication toolkit.

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