QUANTUM OPTICS

Diamond defects cooperate via light

Silicon-vacancy centers in diamond show single-photon switching and superradiance

By **Ronald Hanson**

Quantum light–matter interfaces operating at optical wavelengths are key to emerging applications in quantum information processing such as distributed quantum computing and secure quantum communication (*1*). In the past decade, such interfaces have been successfully implemented across platforms ranging from trapped atoms and ions to quantum dots to defect centers in diamond. On the other hand, integrating and optically coupling several optical emitters within a single device has proven to be a more demanding goal. On page 847 of this issue, Sipahigil *et al.* (*2*) report on an all-diamond nanophotonics platform that enables efficient coupling of quantum emitters to on-chip cavities and waveguides. These results could pave the way for large on-chip quantum networks and novel quantum science experiments.

So far, most of the work with defect centers in diamond has been on the nitrogen-vacancy (NV) center. Its intrinsic spin-photon quantum interface—similar to that of trapped ions (*3*)—has been used to create quantum-entangled states of widely separated spins (*4*), which has enabled, for example, teleportation between separate diamonds (*5*). One drawback of the NV center is the broadness of its emission spectrum. For quantum information applications, photons must be coherent, and only 3% of the emission from NV centers is coherent—a major reason that entangling rates of distant spins have been low. Many efforts are ongoing to enhance this fraction through coupling to optically confined modes in cavities (*6*).

Unlike the NV center, the silicon-vacancy (SiV) center (*7*) emits roughly half of its photons coherently and, in the absence of a cavity, is more efficient as a single-photon source than the NV center. The SiV center also couples much more strongly to confined optical modes than the NV center does, making it the emitter of choice for Sipahigil *et al.* to realize the basic ingredients of an on-chip optical quantum network.

The reliable optical coupling of single defects to solid-state optical structures has been hindered by two major challenges. The emitter and the optical mode need to overlap spatially with accuracy much better than the optical wavelength within the structure, a requirement hampered by the limited accuracy of nanofabrication and placement of single emitters. Sipahigil *et al.* combine state-of-the-art nanofabrication (*8*) with Si ion implantation at specific locations within the diamond nanostructures. The positioning uncertainty of this implanting is ~40 nm, well below the SiV optical wavelength of ~300 nm within diamond. Converting implanted Si ions to SiV centers is not efficient (a few percent), precluding a fully deterministic fabrication procedure. Nonetheless, many SiVs could achieve efficient coupling of a single SiV center to a nanobeam cavity, as evidenced by an observed cooperativity near unity. These capabilities were exploited to create a device in which a single photon can open an optical transmission channel.

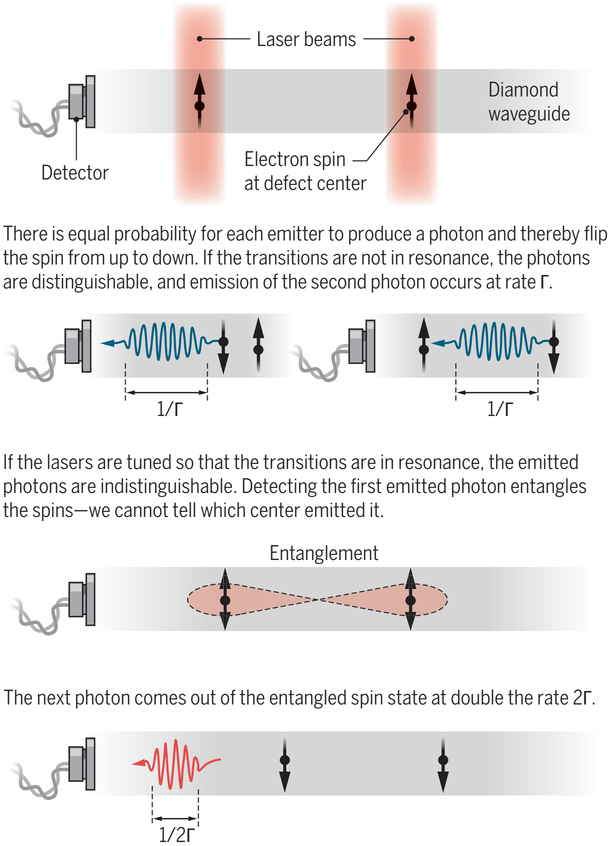
Another challenge toward integrated devices is the large inhomogeneous spread of emitter line widths within nanostructures caused by enhanced strain and uncontrolled surface charge. Most applications will require the photons to be indistinguishable (and therefore have the same wavelength). NV centers in separate bulk diamonds have been efficiently tuned onto resonance using local electric fields (*4*, *5*). SiV centers are less sensitive to electric fields because they are internally more symmetric than their NV-center cousin, which results in less spectral diffusion but also inhibits electrical tuning to compensate strain.

Sipahigil *et al.* solved this problem by using Raman photons instead of resonant photons. The emitters are virtually excited with a Raman laser beam that is far detuned from the optical transition, and the resulting spontaneous emission is of a photon whose wavelength can be tuned by varying the Raman laser's wavelength. Because the emitters are embedded in a waveguide structure, this process is relatively efficient, resulting in a tuning range of tens of linewidths, comparable to the variation observed for SiV centers.

With this nanophotonics platform in hand, Sipahigil *et al.* demonstrate a novel two-photon correlation effect that results from two SiV centers within a single waveguide being made to emit indistinguishable Raman photons. The key idea is that when a single photon is detected, there is no way of determining which of the two SiV centers emitted that photon. In case both SiV centers were initially prepared in the bright state so that they could both be the source of

Superradiance in diamond

Silicon-vacancy defects in a one-dimensional diamond waveguide possess an electronic spin. Excitation of the defect with laser light leads to emission of a photon. The rate of photon emission depends on quantum entanglement.



There is equal probability for each emitter to produce a photon and thereby flip the spin from up to down. If the transitions are not in resonance, the photons are distinguishable, and emission of the second photon occurs at rate Γ.

If the lasers are tuned so that the transitions are in resonance, the emitted photons are indistinguishable. Detecting the first emitted photon entangles the spins—we cannot tell which center emitted it.

The next photon comes out of the entangled spin state at double the rate 2Γ.

GRAPHIC: C. BICKEL/*SCIENCE*

QuTech and Kavli Institute of Nanoscience Delft, Delft University of Technology, P.O. Box 5046, 2600 GA Delft, Netherlands. Email: r.hanson@tudelft.nl

the photon, quantum theory dictates that the detected photon—in retrospect—came out of a superposition of both SiV centers having emitted it. This leaves those centers in a specific entangled state that is superradiant: A second Raman photon will be emitted at a rate twice that of a single SiV center because of the coherent phase relation between the emitters. In this ideal scenario, entanglement between the two SiV centers is thus heralded by the detection of the first Raman photon.

The experiment of Sipahigil *et al.* shows a crucial step toward such on-chip heralded entanglement. Careful tuning of the Raman photon energies results in a distinctive feature in the two-photon intensity correlation measurements; the antibunching dip that is characteristic of single emitters completely vanishes once the emitted photons are made indistinguishable. Control experiments convincingly demonstrate that this feature is indeed caused by the formation of a superradiant state (see the figure). With future improvements in the initialization of the spin and charge state of SiV centers and longer spin coherence times, this procedure could yield rapid high-fidelity entanglement across the on-chip network.

Although these experiments show much potential, more research is needed to turn it into a truly scalable platform. First, if the yield of Si to SiV conversion could be increased, tens of defects could be coupled within a single integrated device. Second, the coherence time of the emitters—tens of nanoseconds for SiV centers at 4 K and limited by stimulated phonon transitions—must be improved by many orders of magnitude. One approach may be to operate at even lower temperatures, where the relevant phonon occupation is diminished (*9*). Another approach could be to apply the same platform to other defect centers. For instance, although the NV center is more susceptible to charge fluctuations, NV spin coherence times above tens of milliseconds are now routinely observed. If these challenges can be met, the result could be a versatile and powerful platform that marries fast optically mediated entanglement between long-lived quantum systems, opening the door to a new generation of quantum optics experiments and large-scale quantum information processing devices. ■

REFERENCES

1. H. J. Kimble, *Nature* **453**, 1023 (2008).
2. A. Sipahigil *et al.*, *Science* **354**, 847 (2016).
3. C. Monroe, J. Kim, *Science* **339**, 1164 (2013).
4. B. Hensen *et al.*, *Nature* **526**, 682 (2015).
5. W. Pfaff *et al.*, *Science* **345**, 532 (2014).
6. M. Lončar, A. Faraon, *Mater. Res. Soc. Bull.* **38**, 144 (2013).
7. G. Burkard, *Physics* **7**, 131 (2014).
8. M. J. Burek *et al.*, *Nat. Commun.* **5**, 5718 (2014).
9. K. D. Jahnke *et al.*, *New J. Phys.* **17**, 043011 (2015).

10.1126/science.aak9836

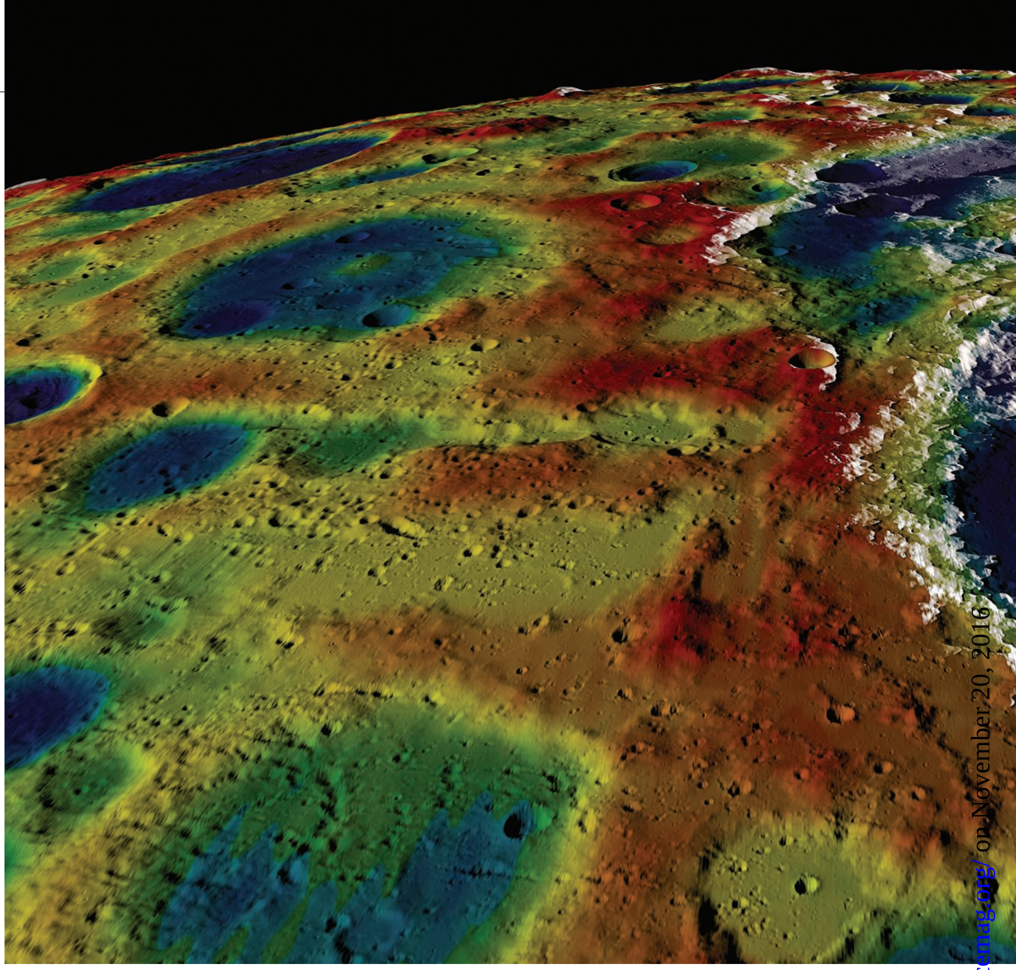


ILLUSTRATION: NASA'S SCIENTIFIC VISUALIZATION STUDIO

GEOPHYSICS

Revealing the dynamics of a large impact

Drilling into the Chicxulub crater provides constraints on how it formed

By **Penny Barton**

Steady as a rock. We all know what to expect of rock. Rocks deform infinitesimally slowly. Earth scientists get excited at the prospect of "rapid" plate movements that average the same speed at which our fingernails grow. Humans don't make much impact on rocks, except at the most puny of scales. Sometimes nature does experiments for us that we could never do for ourselves: When a large meteorite hits the planet, interactions occur that are far outside our normal experience. The outer surface is deformed with a force and strain rate that we cannot begin to reproduce; rocks flow like fluid, very fast and on a huge scale. On page 878 of this issue, Morgan *et al.* (*1*) present results from a drilling expedition into the Chicxulub crater that reveal how the formation of peak rings in large impact craters occurs. Numerical simulations of the impact model the time scale of events: a rim of mountains, higher than the Himalayas, adjacent to a void 25 km deep and about 70 km wide, forming and collapsing within the first three minutes; the central fluidized peak rising and collapsing in minutes 3 to 4; and a shakedown period in minutes 5 to 10, leaving a shallow crater at the surface, an intensely deformed impact zone extending through the thickness of the Earth's crust and beyond, and the world changed forever.

We see widespread evidence of meteorite impact on the rocky planets in our solar system—generally, those without active

Department of Earth Sciences and Homerton College, University of Cambridge, Cambridge CB2 3EQ UK. Email: pb29@cam.ac.uk

Diamond defects cooperate via light

Ronald Hanson (November 17, 2016)

Science **354** (6314), 835-836. [doi: 10.1126/science.aak9836]

Editor's Summary

This copy is for your personal, non-commercial use only.

Article Tools Visit the online version of this article to access the personalization and article tools:
http://science.sciencemag.org/content/354/6314/835

Permissions Obtain information about reproducing this article:
http://www.sciencemag.org/about/permissions.dtl