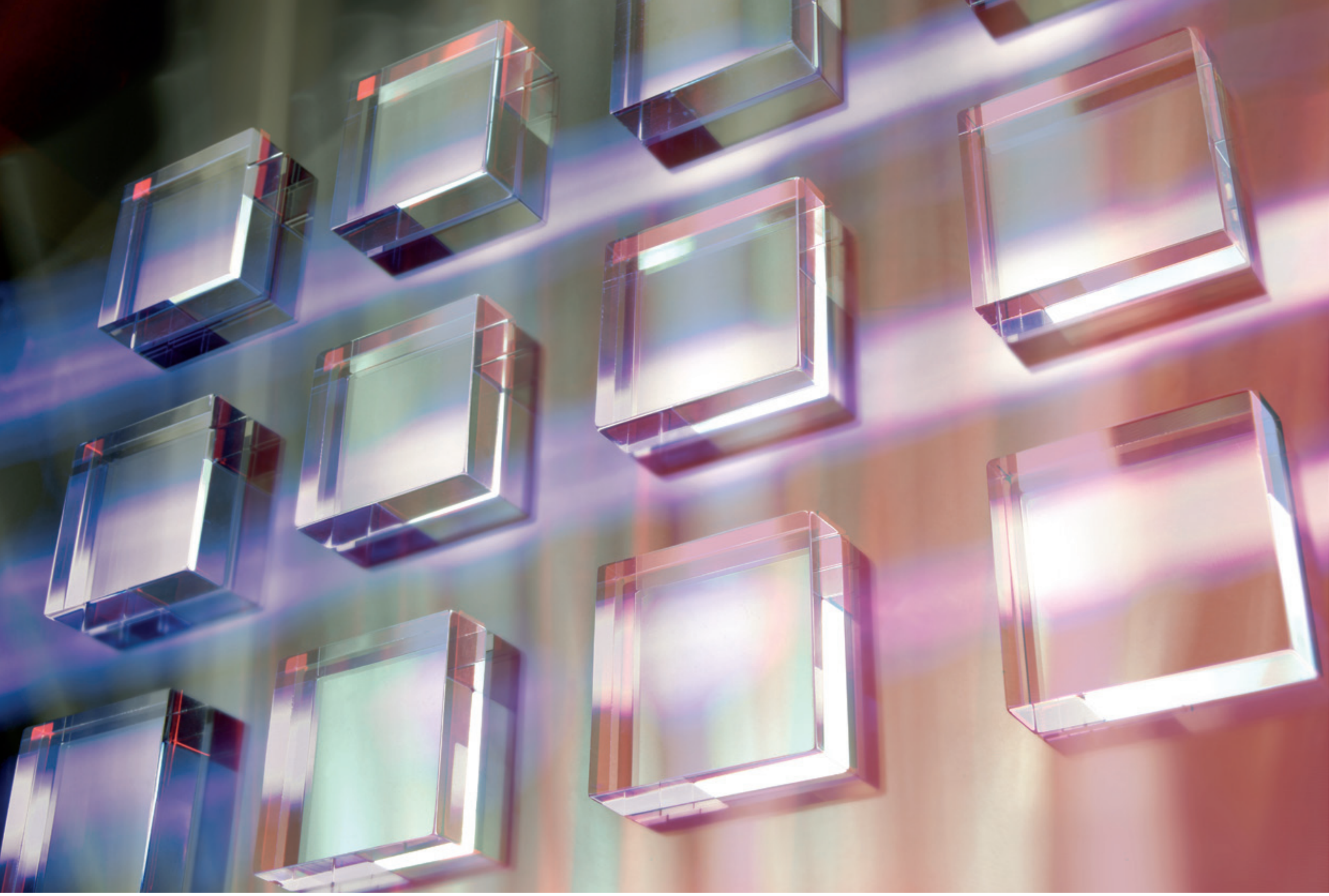


The company Element Six produces pure diamonds with flaws at less than one part per billion.

ELEMENT SIX

FLAWED TO PERFECTION

Ultra-pure synthetic diamonds offer advances in fields from quantum computing to cancer diagnostics.

BY ELIZABETH GIBNEY

The 'magic Russian diamond', as some researchers have come to call it, was just 2 millimetres square, very clear and of a quality any jeweller would be happy to set in an expensive ring. Jörg Wrachtrup, a physicist at the University of Stuttgart in Germany, had spent much of 2005 looking for something just like it; his group finally found it by trawling through journals from the Russian Academy of Sciences, reading descriptions of the physical properties of such rare gems. But Wrachtrup wasn't interested in this diamond's beauty: what intrigued him was that the stone was very pure and perfectly flawed.

Inside the Russian gem, the regular diamond lattice of carbon atoms was interrupted on rare occasions by a nitrogen atom, with a neighbouring carbon atom also missing. Within each such hole, an extra electron could become trapped (see 'A useful hole'). Such impurities are not in themselves unusual. But Wrachtrup and others had theorized that, in some specific cases, electrons in these holes could prove the perfect medium for storing information for quantum computing — an effort to vastly speed up computing calculations by exploiting the fuzzy world of quantum mechanics. Unlike other candidates for such information storage, these defects in diamond should do their job at room temperature. To test the idea, Wrachtrup's lab split the diamond and sent half of it to Mikhail Lukin, a physicist at Harvard University in Cambridge, Massachusetts. By the end of 2006, both groups had shown that the Russian stone proved the theory correct[1,2]. "This diamond showed behaviour we had never seen before," says Wrachtrup.

Since then, the field has exploded. In 2005, just a handful of groups worldwide were working on the quantum possibilities of diamond; there are now about 75 in on the action. The Russian diamond has been cut up and divided between teams. Despite much searching, no other natural gems quite like it have been found. So researchers have turned their attention to making synthetic versions that are even better.

As more teams have entered into the game, so have ideas for potential applications. The same properties that make diamonds useful for storing quantum information also make them ideal for sensing magnetic fields with incredible precision, which could be used to eavesdrop on the processes in living cells in real time. Tiny sensors could provide cellular-level imaging with one billion billion times more sensitivity than conventional magnetic resonance imaging (MRI), allowing investigators to map electrical activity in neurons or watch a cell's reaction to a drug.

"We're really solving problems we haven't been able to solve before," says Wrachtrup.

GROWN FROM SCRATCH

Diamond lovers are familiar with impurities for their ability to give the stones exotic hues: nitrogen can lend a yellow tone; boron turns them blue. What excites physicists is the 'spin' of the electrons trapped in such defects. That quantum property can be either up, down or somewhere in between — all at the same time. Such fuzziness is required for the basic unit of quantum computing, called quantum bits, or qubits. Unlike conventional computer bits that are either on or off, a qubit must have the capacity to exist in multiple states simultaneously, allowing a computer to perform parallel calculations.

Quantum properties such as spin are delicate, and are easily influenced by any outside interference. Diamond makes a great candidate for qubits because its rigid crystal structure helps to isolate and protect trapped electrons' fragile quantum states from random perturbations. The spin can, however, be manipulated by microwaves and read out using lasers.

Natural stones usually contain flaws at a level of about one-in-a-thousand atoms, which is much too many to make them useful for information storage: the defects are so close together that they interfere with each other, meaning that electrons cannot reliably hold any given spin state for long. By contrast, the Russian diamond contains fewer than one nitrogen atom per billion carbon atoms.

Back in 2005, Wrachtrup's tests showed that electrons in the Russian diamond could maintain a defined spin state for almost a millisecond; the only other set-ups able to maintain a spin state for this long were those that were super-cooled to near absolute zero and maintained under a high vacuum. Diamond allows scientists to change and read the quantum state of a single electron at room temperature using everyday lab equipment. "That was a bit of a game changer," says David Awschalom, a physicist at the University of Chicago in Illinois, who was one of the first investigators to work on quantum-grade diamonds.

Makers of synthetic quantum-grade diamonds try to achieve at least the same level of purity as that of the Russian diamond. Unlike stones made for jewellery or industrial cutting, these diamonds aren't grown by putting a lump of carbon under high temperature and pressure. Instead, gases such as methane and hydrogen are heated into a plasma, so that carbon atoms can be deposited onto a template layer by layer.

Some academic labs can make such diamonds themselves, but the major hub for research into this type of diamond production is the UK-based labs of the company Element Six, which has been synthesizing diamond — originally for cutting and drilling — for more than 50 years. Its business is booming. In July 2013, the company opened a £20-million (US$32.9-million) Global Innovation Centre in Harwell near Oxford, UK, to research and develop better diamond-production schemes for new applications. It now sells a few hundred off-the-shelf pure diamonds for quantum research each year, and its production of custom diamonds for specific projects has doubled annually since 2007, totalling 1,500 so far. In the lab where the custom diamonds are grown, a dozen machines hum away, teeming with feeding tubes that bring in the basic ingredients.

Element Six now sells an ultra-pure diamond with impurities lower than one part per billion, into which scientists can implant desired defects. Those cost about $1,000 each. For their custom diamonds, the company works with researchers to put flaws in precise layers and to control the levels of different carbon isotopes, which can also affect a diamond's properties. "Building it atom by atom gives you the ability to control impurities," says Geoff Scarsbrook, research and development operations manager at Element Six. The company provides these diamonds to researchers at no cost with the aim of developing intellectual property rights and opening promising new markets. "We are prepared to take quite a long view," says Scarsbrook.

That they have a long outlook is just as well. Producing a single qubit is one thing, but producing a functional quantum computer with many cooperating qubits is quite another — as researchers working with other materials have discovered. Since the mid-1990s, a few systems have emerged as the leading candidates for qubits, including ions trapped by an electromagnetic field and superconducting circuits, which must be super-cooled. Scientists working with these systems still struggle to deal with interference and to hook multiple qubits up into usable systems. So far, the world's best all-purpose quantum 'computers' are toy models comprising little more than a dozen qubits that can do small tasks such as factoring the number 15 (with one stand-out exception of a controversial, specialized type of quantum system, see *Nature* **498,** 286–288; 2013).

Diamonds show substantial potential, however, and some gems can now keep qubits protected from interference for long enough to do something useful, says Ronald Hanson, a nanoscientist at Delft University of Technology in the Netherlands. In 2012, for example, Lukin's team reported[3] achieving a lifetime for a diamond qubit of more than one second, on a par with what has been achieved in trapped atoms and about 10,000 times better than in superconducting circuits. To do this, his team used the trapped electrons' spin only as a messenger. To actually hold information they used the quantum-spin properties of the neighbouring impurities — such as a nitrogen atom or a carbon-13 isotope — which are about 1,000 times less sensitive to interference than the spins of electrons are. A trick to control the electrons' spin when they are not acting as a messenger can theoretically extend the qubit's lifetime by up to a minute.

QUANTUM BITS AND PIECES

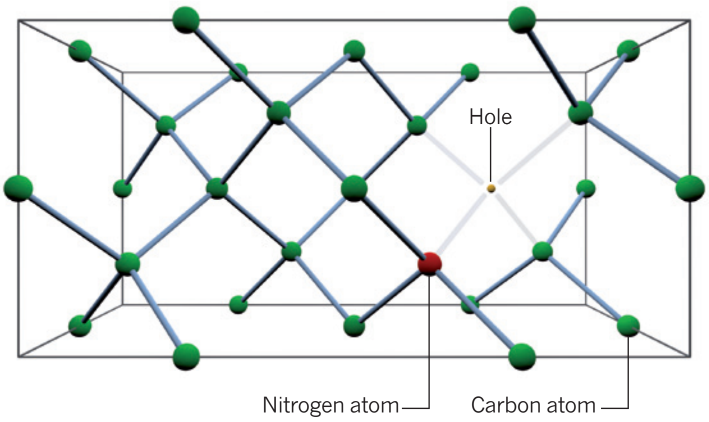
But connecting up the qubits — which involves 'entangling' their states so that they can work together to perform calculations — is a greater challenge. Wrachtrup's approach is to carefully position diamond defects about 20 nanometres apart in an array, so that the trapped electrons are close enough to entangle. Yet manufacturers have a hard time fabricating diamonds with such precisely placed defects. And the proximity of the imperfections means that the spin of each electron must be precisely controlled if the quantum states are to survive — something that is ever more difficult to achieve as the systems scale up in size.

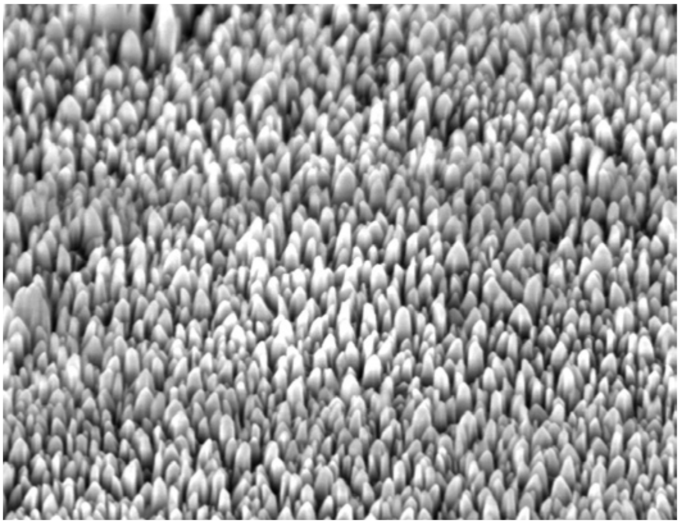
In an alternative approach, Hanson's team last year reported connecting up diamond qubits that are 3 metres apart by using flying intermediaries: photons that entangle with the electron spins and with each other[4]. That could prove particularly useful for a quantum network used to exchange information over long distances. But for Hanson's system to work, the qubits have to entangle in a much shorter time than the qubit lifetime. That means entanglement should happen many times a second; so far, Hanson and his collaborators have only succeeded in producing entanglement once every 10 minutes.

Physicists including Hanson, Lukin and Dirk Englund, an electronic

A USEFUL HOLE

The regular lattice of carbon atoms in a diamond crystal can be interrupted by a nitrogen atom sitting next to a missing carbon. Electrons trapped in the resulting hole can carry quantum information.





Nanometre-scale pillars etched from diamond can be used as magnetic probes.

LUOZHOU L /ENGLUND GROUP/MIT

engineer at the Massachusetts Institute of Technology in Cambridge, are trying to improve the entanglement rate by building tiny cavities and mirrors into thin films of diamond — this helps to bounce photons around and gives them more opportunities to interact with the electron qubits. Hanson thinks that this should make it possible to reduce entanglement times to fractions of a second. Teams are working on the best way to do this — some methods require thin films of diamond no more than a few hundred nanometres thick, laboriously ground from larger pieces. “It’s very tedious to do,” says Wrachtrup. “It’s almost a work of art.”

So far, the most sophisticated quantum-computing systems made of diamond — achieved separately by two different groups[5,6] — involve four entangled qubits. Scaling up to more than about ten will require a concerted engineering effort, says Wrachtrup. But diamond remains a viable option for quantum computing, with its greatest selling point being its ability to hold quantum information for long periods of time, at room temperature and without a vacuum. “It’s really that combination that shows promise,” says Hanson.

TINY MAGNETS

While researchers continue to battle with quantum computing, other applications for diamond could come to fruition more quickly. Some of the first researchers to explore the quantum properties of diamond realized that the way in which delicate spin states can be affected by their environment could be put to good use. The electrons’ spins have a magnetic moment, which makes them act like tiny bar magnets that are sensitive to other nearby magnetic fields.

Sensing techniques such as MRI make use of a similar phenomenon — the spin inherent in hydrogen atoms — to spy inside the human body. But these require millions of atoms to get a signal. And for the greatest precision, the machines need to be cooled to very low temperatures. Diamond probes can be small enough and close enough to their target to pick up a signal from a single atom, at room temperature — the magnetic field of the atom affects the electrons’ spin, which can be read with a laser.

Sensors that use large numbers of diamond defects to measure relatively large magnetic fields are already in development. At small scales there have been proof-of-principle studies, including work measuring spins in a drop of oil just 5 cubic nanometres in size[7] and even in a single molecule[8]. In 2011, a team led by Lloyd Hollenberg at the University of Melbourne in Australia put nanodiamonds into living cells, allowing scientists to study tiny magnetic changes within them[9]. Wrachtrup says that a diamond-based probe should eventually be able to image the structure of a complex molecule such as a protein, monitor activity in the brain or track the action of a drug in a cell — all without altering the living system being observed.

Lukin’s group has also made use of nanodiamond probes to take temperature readings inside a cell to within a few hundredths of a degree[10], by monitoring the response of trapped electrons’ sensitive spin to the expansion and contraction of a diamond lattice as it heats and cools. Nanodiamond probes should be able to detect changes of a few thousandths of a degree, and could be used to infer biological processes such as tumour metabolism.

However, making nanometre-sized ultra-pure diamonds for tiny probes is a real headache: the deposition method used by everyone, including Element Six, produces gems that cannot be separated from their template base. Most of the proof-of-principle work on nanodiamond probes has therefore been done using relatively impure diamonds, made through high pressure and temperature compression. This limits their sensitivity.

Englund’s team has come up with a better means of production, which is now being commercialized by Diamond Nanotechnologies in Boston, Massachusetts, a company Englund set up with a former postdoc. They paint gold palladium dots over pure diamond and then etch away the bits of surface left exposed, producing a series of gold-topped diamond posts that his team calls ‘nano-grass’. These can be mowed, and the gold tops easily removed, to produce individual, minuscule diamond pillars. When made in this way, the electrons trapped in the diamond defects hold their spin for 100 times longer than those in conventional nanodiamonds[11]. The firm is using these pillars to build a prototype magnetic field sensor that is sensitive enough to detect the field from just a few electrons.

DIAMOND DOUBLES

Researchers will need production improvements such as these if they want to squeeze all the promise out of diamonds. But there is still a long way to go to perfect precision doping of defects and the production of large thin films and complex diamond structures.

Fulfilling specifications like these is routine for many semiconductor materials, including silicon. So Awschalom’s group is exploring whether it might be possible to reproduce the seemingly unique properties of diamond in such materials. In 2011, his group showed that silicon carbide — a relatively cheap semiconductor that has for decades been manufactured in large, thin films for use in electronics — can host defects in which bound electrons exhibit the same quantum quirks as in diamond[12]. His group has made silicon carbide qubits. But these lack the main advantage of diamond qubits: so far, the lifetime of trapped electron spin states in silicon carbide at room temperature is 20 times shorter than in diamond — too short for most practical applications.

Awschalom’s group is among a number attempting various tricks to boost silicon carbide qubit lifetime, including purifying the isotopic composition of the material. And the team is collaborating with theorist and former colleague Chris Van de Walle at the University of California, Santa Barbara, to predict which defects in other crystalline materials — including gallium nitride, which is used in light-emitting diodes — might match diamond’s properties. “It’s definitely an extremely promising new direction,” says Englund. “There could be many we just don’t know about.”

But for most researchers, diamonds remain the material of choice. With their extreme purity and controllable spin states, synthetic stones now outshine any natural gem. Even so, the original magic Russian diamond continues to prove its worth. “We still have pieces in the lab, and once in a while we use them,” says Wrachtrup. “They’re still among the best we have.” ■

Elizabeth Gibney *is a reporter for* Nature *in London.*

1. Nizovtsev, A. P. *et al. Opt. Spectrosc.* **99,** 233–244 (2005).
2. Childress, L. *et al. Science* **314,** 281–285 (2006).
3. Maurer, P. C. *et al. Science* **336,** 1283–1286 (2012).
4. Bernien, H. *et al. Nature* **497,** 86–90 (2013).
5. Robledo, L. *et al. Nature* **477,** 574–578 (2011).
6. Dolde, F. et al. Preprint at http://arxiv.org/abs/1309.4430 (2013).
7. Staudacher, T. *et al. Science* **339,** 561–563 (2013).
8. Sushkov, A. O. *et al.* Preprint at http://arxiv.org/abs/1311.1801 (2013).
9. McGuinness, L. P. *et al. Nature Nanotechnol.* **6,** 358–363 (2011).
10. Kucsko, G. *et al. Nature* **500,** 54–58 (2013).
11. Trusheim, M. E. *et al. Nano Lett.* **14,** 32–36 (2014).
12. Koehl, W. F., Buckley, B. B., Heremans, F. J., Calusine, G. & Awschalom, D. D. *Nature* **479,** 84–87 (2011).