THE JEWEL IN THE DETECTOR

Diamonds, one of the hardest materials on Earth, are so strong that they can protect fragile quantum states that would otherwise survive only in a vacuum or at ultra-cold temperatures. Engineers are mastering the art of growing diamonds with special properties and detecting their quantum spins — opening up a range of sensing applications in the life sciences and elsewhere.

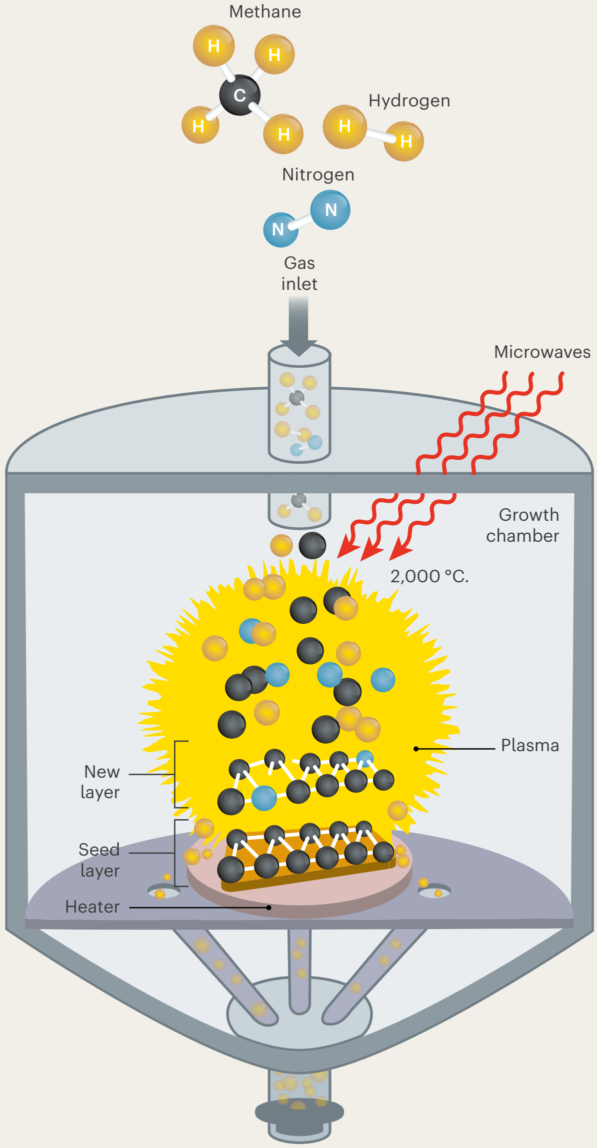
By **Neil Savage***; infographic by* **Mohamed Ashour**

GROWING DIAMONDS

Engineers can synthesize diamonds in several ways, but chemical vapour deposition[1,2] is usually the method of choice for fabricating the single-crystal films needed for sensors.

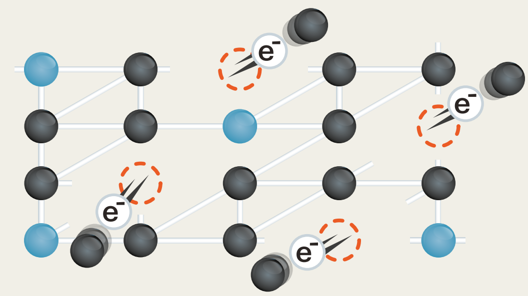
1. Laying down layers

A mix of methane, hydrogen and nitrogen gas is superheated, using a heat source such as microwaves, to form a plasma. Carbon atoms from the methane, as well as the occasional nitrogen atom, settle out of the plasma onto a heated seed layer that prompts the growth of a diamond crystal film. Hydrogen modulates the process.



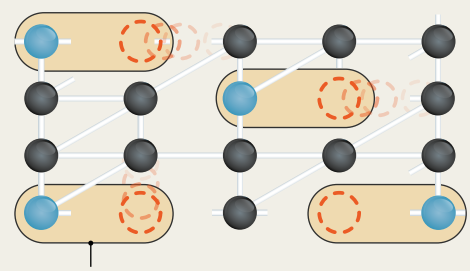
2. Bombardment

The diamond film is then hit with an electron beam, which kicks some carbon atoms out of the crystal to create empty spaces. These vacancies are distributed randomly among the carbon and nitrogen atoms in the crystal.



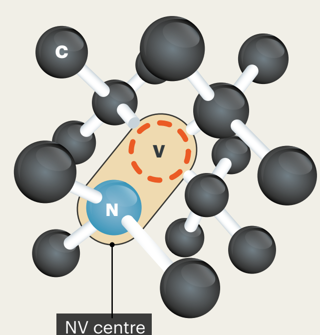
3. Annealing

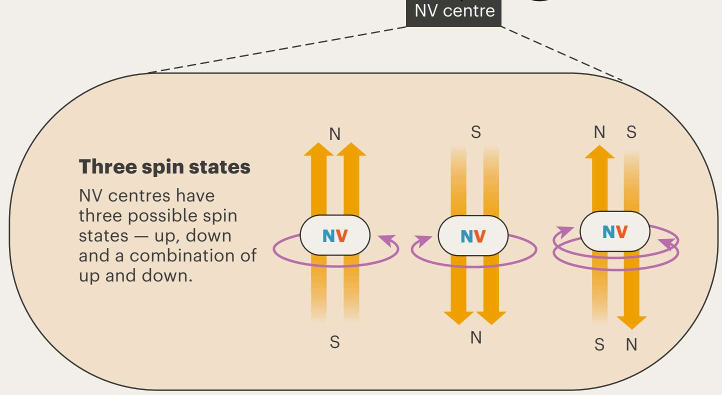
Heating the diamond above 700 °C energizes the atoms, causing the vacancies (dashed red circles) to move around. Many of them settle next to nitrogen atoms to form nitrogen-vacancy (NV) centres.



4. Centres of excellence

The nitrogen atom, vacancy and the carbon atoms immediately around them form an 'artificial atom', which has its own quantum property, known as spin. Spin can be pictured as a set of magnets, with north and south poles. The arrangement of these magnets provides the spin state.





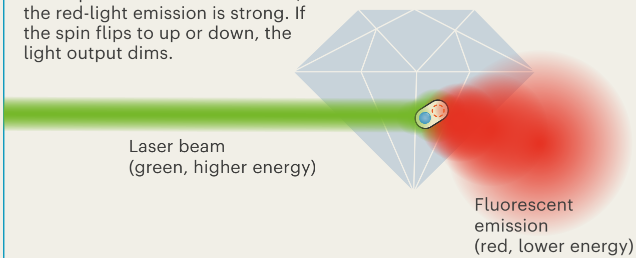
Watch an animation at nature.com/collections/quantum-diamond-sensors-outline

A NEW SPIN ON FLUORESCENCE

NV centres fluoresce red when green light is used to excite them. Measuring how much red light is emitted reveals the state of the spin; combined with microwaves and magnetic fields, this method is called optically detected magnetic resonance[3], and can be used for diagnostics or imaging.

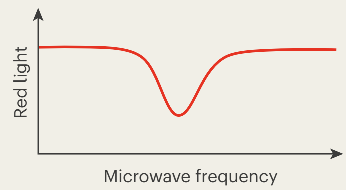
Dimmer switch

For a spin in a combination state, the red-light emission is strong. If the spin flips to up or down, the light output dims.



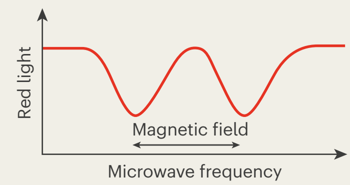
Microwaves

Tuning an emitter through microwave frequencies will find one that flips the spin to up or down, causing the intensity of red-light fluorescence to dip.



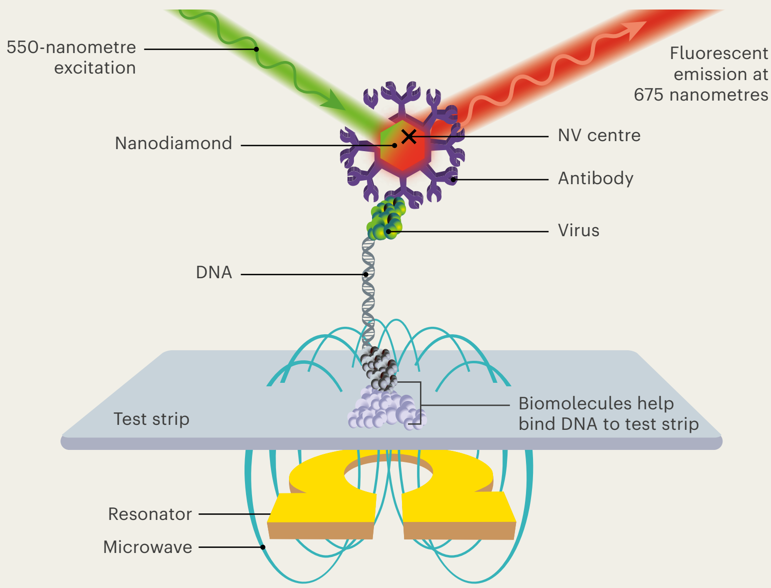
Magnetic field

With a magnetic field present, two frequencies cause dips in light intensity. The difference between those dips reveals the strength of the field.



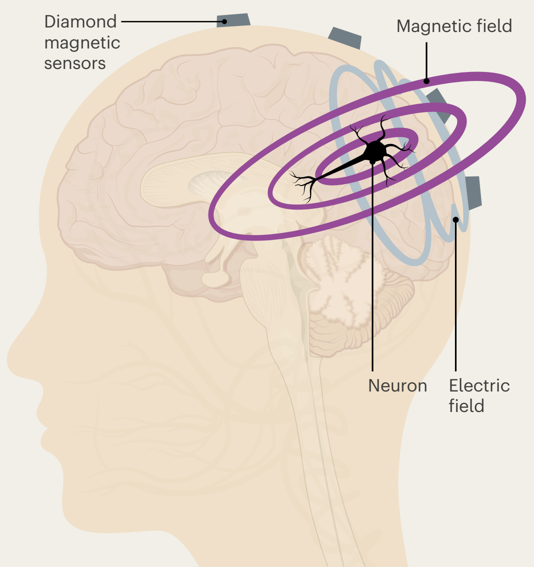
Capturing virus particles

The fluorescent properties of quantum diamonds could be used for ultrasensitive diagnostic tests. In a blood sample, nanodiamonds studded with antibodies could be used to capture a virus. This would then attach to DNA that sticks to a test strip over a microwave resonator. Microwaves would change the spin in the captive diamonds, enhancing their fluorescent signal and making the technique 100,000 times more sensitive than other methods[4].



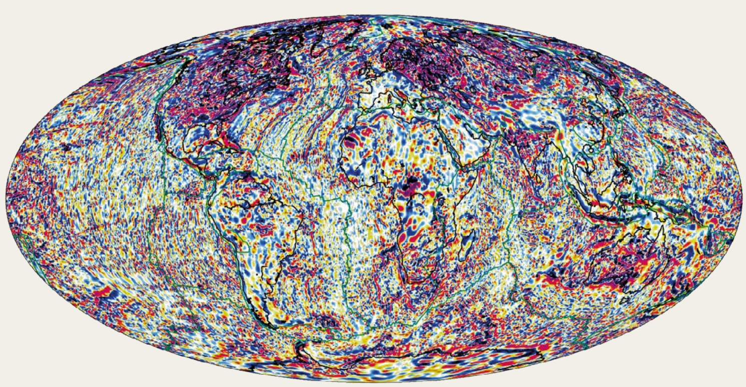
Peering into the brain

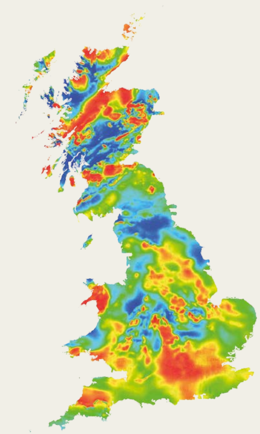
Electrical activity by neurons in the brain produces magnetic fields that penetrate the skull. Detecting these rather than the electrical fields creates clearer images of brain activity. Sensors using NV diamonds[5] could replace superconducting devices, which can read magnetic fields but require cryogenic temperatures.



FINDING YOUR WAY

GPS helps people to navigate, but the satellites can be vulnerable to solar flares or intentional jamming. Because Earth's magnetic field varies in strength and direction around the globe, measuring it provides another way of determining position. Magnetometers based on NV centres could take readings of magnetic fields and pinpoint their whereabouts, potentially with an accuracy of 50 metres. The reading could be compared with existing maps of magnetic anomalies to find locations, with the accuracy depending on the resolution of the map.





Colour-coded maps show localized variations in Earth's magnetic field.

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References: 1. Chakraborty, T. *et al. Phys. Rev. Mater.* **3**, 065205 (2019). 2. Edmonds, A. M. *et al*. Preprint at http://arxiv.org/abs/2004.01746 (2020). 3. Frellsen, L. F. & Ahmadi, S. *Quant. Views* **2**, 10 (2018). 4. Miller, B. S. *et al. Nature* **587**, 588–593 (2020). 5. Dale, M. W. & Morley, G. W. Preprint at http://arxiv.org/abs/1705.01994 (2017).