SENSORS

Silicon integration for quantum sensing

CMOS technology can be used to miniaturize quantum-sensing technology based on nitrogen-vacancy centres in diamond.

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Quantum sensing[1] leverages fundamental principles such as quantum coherence and superposition to measure a range of physical properties, from electric currents to strain, at a level of sensitivity that is often beyond classical measurement systems. In many cases, this sensing can also be performed on the microscopic scale, which is inaccessible to traditional techniques. Governments and companies are investing heavily in quantum technologies through programmes such as the European Union's €1 billion Quantum Flagship[2], and quantum sensing has been identified as the quantum technology with some of the earliest potential commercial applications.

One the most intensively studied quantum-sensing technologies is based on a point defect system in diamond known as the nitrogen–vacancy (NV) centre[3], which comprises a single nitrogen atom adjacent to a carbon crystal vacancy. The unpaired electrons associated with the NV centre have a net spin of 1, which can be controlled and measured using a technique known as optically detected magnetic resonance. Optically detected magnetic resonance uses a microwave a.c. magnetic field to resonantly drive spin transitions in the NV defect, with the resultant spin population monitored via photoluminescence. In this configuration, a pump laser excites the NV centre, and subsequent relaxation via emission of photons provides a spin-dependent signal that allows spin readout[4,5]. Individual NV centre electron spins can be used as quantum bits (qubits) for quantum computing or communication applications, though their application as quantum sensors is currently generating the greatest excitement.

Unlike many other quantum systems, which can typically only function at cryogenic temperatures of the order of 1 K or less, NV diamond sensors can operate all the way up to room temperature, where they can be used to probe properties such as magnetic field or temperature under ambient conditions. This is because their spin coherence times remain long, even at elevated temperatures. Magnetic field sensitivities down to the picotesla level have recently been demonstrated using ensembles of NV centres at room temperature[6]. Furthermore, NV centres can be used in very small structures, such as diamond nanocrystals, meaning they can be used to sense physical properties with very high spatial resolution, down to the nanoscale[7]. Such NV-containing nanodiamonds have even been inserted into and used to probe living human cells[8].

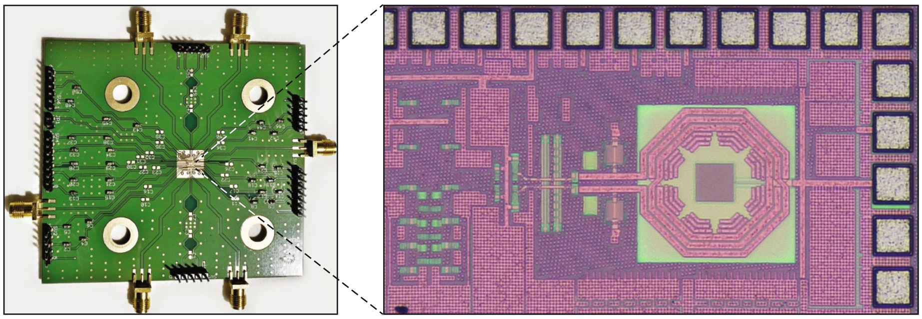

Fig. 1 | CMOS-integrated nitrogen–vacancy quantum sensor. CMOS technology could help take diamond NV sensing from the lab to commercial prototypes. Optical micrograph of the CMOS chip (right) and the printed circuit board (left). Figure reproduced from ref. [10], Springer Nature Ltd.

While the sensitivity of NV-based sensors has advanced significantly over the past decade or so, particularly in regards to magnetometry[9], most systems are relatively large. They are also assembled from discrete components, including a laser and optics to provide the pump signal, a microwave loop antenna to drive spin resonance, and a separate optical system for light collection and detection. Such systems are appropriate for proof-of-principle demonstrations in the laboratory, but ultimately, if quantum sensors are to become affordable and employed in portable applications or large-scale sensor networks, a greater level of system integration will be required.

Writing in *Nature Electronics*, Ruonan Han, Dirk Englund and colleagues at MIT now report a device that integrates almost all of the components required for NV diamond spin control and sensing in one monolithic silicon complementary metal–oxide–semiconductor (CMOS) chip that is around 1 mm in size[10]. This silicon chip is bonded directly to a diamond chip of similar dimensions, which contains the NV centres used for the quantum sensing. The CMOS chip incorporates a custom-designed microwave antenna, including integrated CMOS circuitry to drive it, with an optical filter to reject the pump laser, and an integrated silicon photodetector array. The only external components used in the demonstration are the pump laser and focusing optics. However, these could potentially be integrated in the future by employing a chip-scale laser diode or CMOS-compatible waveguided delivery of the optical pump beam[10].

The researchers used CMOS technology to design and integrate all of the microwave generation circuitry, including a voltage-controlled ring oscillator, with a loop inductor antenna to deliver an optimized microwave a.c. magnetic field to the NV spin ensemble (Fig. 1). On the same chip, they designed and configured a CMOS-compatible optical filter, composed of a microscale grid that is used to block the pump beam and transmit the fluorescence signal from the NV spins to the integrated silicon photodetector array. This detector array was segmented to minimize eddy current effects from the stray microwave field.

Despite the impressive design and system integration, the sensitivity of the resulting magnetometer, 32 μT $\mathrm{Hz}^{-1/2}$, is still lower than that of state-of-the-art NV sensors, which have achieved sensitivity values of 28 pT $\mathrm{Hz}^{-1/2}$ (ref. [11]). In this respect, the device must be considered an embryonic prototype, demonstrating that CMOS integration is possible. Potential improvements to the system design include: the incorporation of gratings in multiple CMOS metal layers or a resonant grating in the diamond to improve filtering of the fluorescence signal; the use of higher NV-centre densities; and dynamical decoupling sequences to improve quantum coherence[10].

Though the microsystem developed by Han and colleagues will require considerable improvements to take it to the level of sensitivity needed for practical applications, their platform has arguably the highest level of integration and miniaturization of any quantum-sensing system reported to date. It thus opens a path to more ubiquitous and commercially viable sensing arrays in the future. ❐

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https://doi.org/10.1038/s41928-019-0278-2

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