A CMOS-integrated quantum sensor based on nitrogen-vacancy centres

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The nitrogen–vacancy (NV) centre in diamond can be used as a solid-state quantum sensor with applications in magnetometry, electrometry, thermometry and chemical sensing. However, to deliver practical applications, existing NV-based sensing techniques, which are based on bulky and discrete instruments for spin control and detection, must be replaced by more compact designs. Here we show that NV-based quantum sensing can be integrated with complementary metal–oxide–semiconductor (CMOS) technology to create a compact and scalable platform. Using standard CMOS technology, we integrate the essential components for NV control and measurement—microwave generator, optical filter and photodetector—in a 200 μm × 200 μm footprint. With this platform we demonstrate quantum magnetometry with a sensitivity of 32.1 μT Hz\(^{-1/2}\) and simultaneous thermometry.

Quantum metrology based on solid-state spins has demonstrated impressive sensing capabilities for various environmental physical quantities. In particular, the NV centre in diamond has emerged as a leading room-temperature quantum sensor for temperature\textsuperscript{1–4}, strain\textsuperscript{5–7}, electric fields\textsuperscript{8–10} and magnetic fields\textsuperscript{11–14}, including for atomic species\textsuperscript{15–25}. The capabilities of NV-based quantum metrology are based on its long spin coherence time\textsuperscript{26} and its efficient optical interface for spin polarization and probing. NV-based quantum metrology is based on optically detected magnetic resonance (ODMR)\textsuperscript{28}, involving an energy shift \(\gamma B\) on the NV ground-state spin triplet \(|m_z=0, \pm 1\rangle\), where \(B\) is the magnetic field component along the NV symmetry axis. The spin transition frequencies, \(\nu\), between sublevels \(|0\rangle\) and \(|\pm 1\rangle\), are given by

\[
\nu = \frac{D_{g0} - \beta g \Delta T}{2} \pm \frac{\gamma \nu B_z}{2}
\]

where \(D_{g0} = 2.87\) GHz is the room-temperature natural ground-state splitting between sublevels \(|0\rangle\) and \(|\pm 1\rangle\), \(\gamma\) is the electronic gyromagnetic ratio \((28\) GHz T\(^{-1}\)), \(\beta = 74\) kHz K\(^{-1}\) (ref. \textsuperscript{26}) and \(\Delta T\) is the temperature shift from room temperature. Measuring \(\nu\) gives \(B\) and \(\Delta T\) in their difference and sum, respectively. In addition, measuring \(B\) for at least three of the four possible NV orientations in diamond (inset, Fig. 1a) quantifies all components of \(B\) for vector magnetometry\textsuperscript{11–14}.

The NV ground-state transitions \(\nu\) are measured by ODMR under green laser excitation, as illustrated in Fig. 2a. The spin magnetic sublevel \(|0\rangle\) has a bright cycling transition, where it emits red fluorescence. By contrast, the \(|\pm 1\rangle\) can undergo an intersystem crossing into a metastable, dark spin-singlet state, from where it decays back into the \(|0\rangle\) sublevel. This has two consequences: optical spin polarization into sublevel \(|0\rangle\) and lower average fluorescence of the \(|\pm 1\rangle\) spin populations. The microwave field moves spin population between \(|0\rangle\) and \(|\pm 1\rangle\). Sweeping the applied microwave frequency leads to the ODMR spectra in Fig. 2b, from which \(\nu\) are determined.

On-chip microwave generation and delivery

In our chip-scale NV magnetometer, the ground-state spin transitions are driven by the on-chip generated microwave fields. Figure 3a shows the circuitry for on-chip microwave generation and delivery. This circuitry is composed of a phase-locked loop (PLL),...
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Fig. 1 | CMOS-integrated quantum sensing architecture. a, A green pump laser excites an NV ensemble in the diamond slab. Microwave fields generated on-chip manipulate NV electron spins through an on-chip inductor, leading to ODMR. A metal/dielectric grating absorbs the green pump beam and transmits the NV spin-dependent fluorescence to the on-chip photodiode. Inset: NV atomic structure. b, c, Top-view micrographs of the fabricated CMOS chip without (b) and with (c) the diamond slab. Scale bars, 200 μm.

Fig. 2 | NV energy level diagram and ODMR spectra. a, NV energy level diagram: the green optical pump (green arrow) excites NV electrons from $^1A_2$ to $^1E$. NV centres then emit red fluorescence by radiative decay (red arrow). The intersystem crossing rate (black dashed arrow) depends on the NV spin states, resulting in spin-dependent fluorescence. b, Top: for $B = 0$, the ODMR spectrum shows one fluorescence dip for $\nu = D_{zz}$. Bottom: for an external magnetic field $B_{ext}$, this resonance splits into two Zeeman-shifted spin transitions (black curve), whose difference (mean) gives $D_i/2\Delta T$. The grey curves show ODMR for the other three possible NV orientations.

The PLL control voltage $V_{ctrl}$ varies from 0 to 5 V. The entire PLL is closed with off-chip components to enhance the stability and decrease the phase noise of the signal. Further details are provided in the Methods.

The microwave fields are delivered to the NV ensemble through the loop inductor (Fig. 3a) implemented on the topmost copper layer (Metal 9, see Methods for details) with a thickness of 3.4 μm. To efficiently deliver the microwave field, the loop inductor and a pair of shunt capacitors ($C_1$ and $C_2$ in Fig. 3a) form a resonating load for the current driver. $C_1$ and $C_2$ are MOS variable capacitors with capacitance ranging from 312 fF to 1.4 pF. By electrically tuning them via $V_{ctrl}$, the load resonates near $D_{zz}$. This current driver fed by the output of the ring VCO produces oscillating current in the inductor at the VCO microwave frequency. To improve the performance of this inductor for advanced NV sensing protocols, we need to increase the applied microwave field amplitude. The amplitude is enhanced by a factor $Q$ of the driver d.c. bias current ($I_{bias}$, $\approx$ 5 mA from a 2.5 V power supply), where $Q$ (~15) is the quality factor of the inductor. In addition, we use a three-turn loop to multiply the microwave field strength. Overall, we have 25× enhanced microwave field strength compared to a non-resonant single-turn loop (as plotted in Fig. 3b). With an outer diameter of 236 μm, the loop exhibits an inductance of ~3 nH. In addition, the aforementioned sensing protocols also require highly uniform microwave fields over the excitation volume. To achieve this, three capacitive parasitic loops are inserted to tailor the radius of these loops so that their opposite induced field homogenizes the overall generated field. Another degree of freedom is provided by the capacitive gaps in the parasitic loops. This controls the amount of current flowing in these loops. We thus optimized these two parameters (the parasitic loop radius and the capacitive gap) for the three parasitic loops to achieve >95% uniformity. Detailed dimensions of the microwave launcher and loop inductor are provided in the Methods and Supplementary Fig. 1, respectively. The spectral purity (phase noise) of the microwave is ~90 dBc/Hz at an offset frequency (also the FM modulation frequency $f_m$) of 1.5 kHz.

On-chip spin readout

The NV spin transitions are detected using an on-chip photodetector. The green laser pump beam is filtered by a CMOS-compatible periodic metal–dielectric structure (Fig. 4a) in the Metal 8 interconnect layer. Specifically, incident light couples to the surface plasmon polariton at the metal–dielectric interface, where the green pump
On-chip ODMR detection and quantum sensing

We detect NV-ODMR with a lock-in technique. The green laser beam continuously excites the NV ensemble, and the frequency-modulated (FM) microwave fields \( f_m = 1.5 \text{ kHz}, \) modulation depth of 6 MHz drive the NV electron spin transition. The spin-dependent fluorescence produces photocurrent within the on-chip photodiode (Fig. 4b). We read out the modulated photocurrent with the voltage drop across a 50 \( \Omega \) resistor at \( f_m \) with 1 s integration time, which corresponds to an equivalent noise bandwidth of 0.078 Hz considering the filter roll-off of 24 dB/dec^(-1) with a Stanford Research Systems lock-in amplifier (SR865A). The use of the lock-in amplifier rejects the d.c. current offset of the photodiode, which is caused by the unmodulated green laser, and avoids the low-frequency flicker noise accordingly.

Figure 5a shows the lock-in signal for the ODMR experiment under zero external magnetic field applied. This spectrum corresponds to the derivative of the ODMR spectrum shown in Fig. 2b. Next, we align a permanent magnet (6.27 mT) to split the spin transitions of the four NV orientations. Figure 5b plots the ODMR spectrum, which exhibits the expected eight spin transitions (Fig. 2b). The use of the corresponding four NV ensembles enables vector magnetometry. In particular, we note the spin transitions at \( \nu_\perp = 2.8303 \text{ GHz} \) and \( \nu_\perp = 2.9330 \text{ GHz} \) of the NV ensemble.

Monitoring the lock-in signal \( V \) at \( \nu_\perp \) and \( \nu_\parallel \) enables independent measurements of the magnetic field and temperature, as described above. Specifically, the sum of the lock-in signal change \( \Delta V \) at \( \nu_\perp \) is proportional to \( \Delta T \), while the difference provides \( \Delta B_z \):

\[
\Delta T = \frac{1}{2\mu_T} \left( \left. \frac{\Delta V}{dV/df} \right|_{\nu_\parallel} - \left. \frac{\Delta V}{dV/df} \right|_{\nu_\perp} \right) \tag{2}
\]

\[
\Delta B_z = \frac{1}{2\gamma_e} \left( \left. \frac{\Delta V}{dV/df} \right|_{\nu_\parallel} - \left. \frac{\Delta V}{dV/df} \right|_{\nu_\perp} \right) \tag{3}
\]

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**Fig. 3 | On-chip CMOS microwave generation and inductor characteristics.** a, Schematic of the microwave generation circuitry. b, High-frequency electromagnetic fields simulations for the on-chip inductor. The magnetic field amplitude is plotted as a function of distance from the inductor centre (dashed line in a). The resonant multi-turn loop inductor (blue) produces 25x higher amplitude compared to the non-resonant single turn inductor (red) at the same d.c. current. Insertion of the parasitic capacitive loops yields a microwave uniformity of 95% over 50 \( \mu \text{m}. \) c, Optical micrograph of the CMOS chip (right) and photograph of the printed circuit board for testing (left).
Figure 5c plots the detected $\Delta B_z$ induced by an electromagnet (blue) and the measured centre frequency shift (red). The plotted centre frequency could be converted to a temperature after $\beta_f$ calibration.

The magnetic field sensitivity is given by the following relation:

$$S = \frac{\sigma_{B_z}}{\sqrt{\text{ENBW}}}$$

where $\sigma_{B_z}$ is the noise in $\Delta B_z$, measurements and ENBW is the equivalent noise bandwidth of the lock-in detector. In our measurement, ENBW = $5/(64\tau)$ with a time constant $\tau$ of 1 s, accounting for the 24 dB oct$^{-1}$ of the lock-in amplifier filter rolloff. By measuring $\sigma_{B_z}$ of 6.3 $\mu$T from the modulated spin-dependent fluorescence (inset, Fig.5c), we determine a d.c. magnetic field sensitivity of 32.1 $\mu$T Hz$^{-1/2}$, which includes an additional $\sqrt{2}$ factor of the $\nu_\perp$ and $\nu_\parallel$ signal average. This d.c. magnetic field sensitivity is limited by the noise detected in the ENBW at $f_m = 1.5$ kHz. Figure 5d plots the noise spectral density measured at $\nu_\perp$ (no temperature compensation) using the lock-in amplifier, where the noise floor is ~35 nV Hz$^{-1/2}$. This noise is then converted to the magnetic field sensitivity with the slope at $\nu_\perp$ and $\gamma_\perp$ (plotted in the right y-axis in Fig. 5d).

The achieved magnetic field sensitivity is orders of magnitude worse than the best d.c. sensitivities reported: 290 and 28 pT Hz$^{-1/2}$ for vector$^{27}$ and scalar$^{41}$ magnetometry, respectively, to the best of our knowledge. Our sensitivity is mainly limited by the green laser intensity noise (see Methods for detailed noise estimation). However, this performance can be improved by (1) including metal gratings in multiple CMOS metal layers based on the wavelength-dependent Talbot effect$^{42}$ and (2) fabricating a resonant grating$^{43}$ in diamond. These also attenuate the green laser and consequently reduce the laser intensity noise by several orders of magnitude. In addition, using a diamond waveguide geometry$^{27}$—possibly with a higher NV density$^{44}$ (~10 ppm)—should increase the signal-to-noise ratio by orders of magnitude. Moreover, dynamical decoupling sequences$^{28,35}$ can improve the sensitivity by a few orders of magnitude for measuring magnetic fields at frequencies above the NV decoherence rate.

**Figure 4** | On-chip detection of NV spin-dependent fluorescence. **a.** CMOS-compatible optical pump beam filter: the periodic metal–dielectric grating absorbs the green laser light. Inset: finite-difference time-domain (FDTD) calculation of the optical intensity map inside the structure for green (top) and red (bottom) light. The incident light polarization is perpendicular to the grating line. **b.** Photodiode geometry: the photodiode area is divided into four sub-areas, isolated by shallow trenches to reduce the eddy current (yellow loops) losses. Inset: cross-section along the dashed line in the main panel.

**Figure 5** | On-chip detection of ODMR and NV-based quantum magnetometry. **a.** FM lock-in signal of NV spin-dependent fluorescence at zero external magnetic field (in addition to $B \approx 100 \mu$T of Earth’s magnetic field). **b.** FM lock-in signal with a permanent magnet ($B_0 = 6.27$ mT): $B_z$ is the magnetic field along the NV axis with the spin transition at $\nu_\parallel$. The linewidth of the ODMR is 7 MHz. Slopes $dV/d\nu$ at $\nu_\perp = 2.8303$ GHz and $\nu_\parallel = 2.9330$ GHz are 42.969 nV MHz$^{-1}$ and 42.450 nV MHz$^{-1}$, respectively. **c.** On-chip magnetometry (blue) and temperature effect (red) separation: lock-in signals at $\nu_\perp$ are observed while switching the polarity of the external electromagnet with a period of 26 min. Inset: histogram of measured magnetic field $B_z$ with a s.d. of 6.3 $\mu$T. This uncertainty corresponds to a magnetic field sensitivity of 32.1 $\mu$T Hz$^{-1/2}$. After calibration of $\beta$, the plotted centre frequency (red) could be converted to a temperature. Measurement is conducted with a time constant of 1 s. **d.** Noise spectral density monitored at $\nu_\perp$. 

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Eddy current analysis. For a square photodiode with a side length $L$, the eddy current power $P_{\text{eddy}}$ is quadratically proportional to the change in magnetic flux $\Delta \Phi / dt$:

$$P_{\text{eddy}} \propto \frac{\Delta \Phi}{dt} \frac{(\Delta \Phi / dt)^2}{R} \propto \frac{L^2 (\Delta \Phi / dt)^2}{L} \propto \frac{L^2 |dB/dt|^2}{\Delta \Phi / dt},$$

where $t$ is the time, $R$ is the resistance and $B$ is the magnetic field generated by the loop inductor in Metal 9. By dividing the photodiode active area into N x N sub-areas, the eddy current is reduced by $N^2 \times (k/(N) \times L^2 = 1/N$.

Noise estimation. In our experiment, the measurement noise ($38$ nV Hz$^{-1/2}$ at $f_s = 1.5$ kHz) primarily derives from the green laser intensity noise due to the limited performance of the optical filters. This laser intensity noise is orders of magnitude larger than other noise sources: (1) the NV red fluorescence shot noise is $R_\beta = 9 pV Hz^{-1/2}$, (2) the thermal noise of the photodiode is orders of magnitude larger than other noise sources: (1) the NV red fluorescence shot noise is $R_\beta = 9 pV Hz^{-1/2}$, (2) the thermal noise of the photodiode is orders of magnitude larger than the shot noise, and (3) the laser intensity noise is orders of magnitude larger than the shot noise.

Data availability. The data that support the plots within this paper and other findings of this study are available from the corresponding author upon reasonable request.

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Author contributions

D.R.E. and R.H. initially conceived the diamond–CMOS integration. M.I.I. conceived the idea of stacking the microwave inductor, plasmonic filter and photodiode in a 3D architecture. M.I.I., C.F. and D.K. contributed to chip specifications, design and the experiment. M.I.I. constructed the CMOS chip prototype. D.K. performed FDTD simulations for the optical design and the diamond transfer on the CMOS chip. C.F. prepared the control software for the experiment. C.F. and D.K. constructed the optical set-up and etched the CMOS passivation layers. All authors contributed to discussion of the experimental results and writing of the manuscript.

Competing interests

The chip-scale spin control and detection scheme in this work has been filed in a United States provisional patent application (62/623151).

Additional information

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