Room-Temperature Quantum Sensing in CMOS: On-Chip Detection of Electronic Spin States in Diamond Color Centers for Magnetometry

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Outline

• Introduction

• CMOS-Based Quantum Magnetometer
  – System Architecture
  – Microwave Signal Generation
  – Optical Excitation Filtering
  – Optical Fluorescence Readout

• Experimental Data
  – Measurement Results Using Layer of Nano-Diamonds
  – Measurement Results Using Bulk Diamond

• Conclusion
Nitrogen Vacancy (NV) in Diamond Magnetometer

Nitrogen vacancy center in diamond

Optically detected magnetic resonance (ODMR)

- Gyromagnetic ratio \( \gamma = 2g\mu/h = 2.8 \text{ MHz/Gauss} \)
Nitrogen Vacancy (NV) in Diamond Magnetometer

- Sensitivity $\propto \frac{1}{\text{SNR}} \propto \frac{1}{\sqrt{N}}$  
  – Where N is number of NVs


0.29 nT/√Hz

Ensemble of NVs  
Nitrogen Vacancy (NV) in Diamond Magnetometer

- Nano-tesla sensitivity
- Nanometer spatial resolution
- Vector field measurements
- Ambient conditions (room temperature)

Magnetic structure imaging

Bacteria magnetic imaging
NV Magnetometer System Components

- Signal generator
- Photodetector
- Microwave antenna
- Optical filters
- Green Laser
- CMOS integrated NV magnetometer (TSMC 65nm LP process)
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CMOS Based Quantum Magnetometer

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Microwave Signal Generation

- 2.87 GHz microwave signal generation
  - 2.6 GHz - 3.1 GHz for optically detected magnetic resonance (ODMR) measurements
- 10 Gauss field strength at 2.87 GHz with 95% homogeneity
  - To increase the contrast
  - To drive the NVs with equal strength for spin control pulsed sequences (Echo, Ramsey, ..)
Microwave Signal Generation

Microwave Coil

160 mA is required to get 10 Gauss for 200 µm diameter coil

\[ B_z = B_0 \frac{1}{\pi \sqrt{Q}} \left( E(k) \frac{1 - \alpha^2 - \beta^2}{Q - 4\alpha} + K(k) \right) \]

\[ \alpha = \frac{r}{a}, \quad \beta = \frac{z}{a}, \quad k = \frac{4\alpha}{Q}, \quad r^2 = x^2 + y^2 \text{ and } Q = (1 + a)^2 + \beta^2 \]

https://tiggerntatie.github.io/emagnet/offaxis/iloopoffaxis.htm

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Slide 9
Microwave Signal Generation

Microwave Coil

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Microwave Signal Generation

Microwave Coil

EM simulated performance

Single loop inductor
Inductor with capacitive loop
Inductor with inductive loop

Magnetic field (Gauss)

Distance from inductor center

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Microwave Signal Generation

- **10 Gauss** with **95%** uniformity
  - **6 mA** DC current in the driver
  - **25x** field strength more than simple non-resonant loop

- **2.6 GHz-3.1 GHz** Microwave frequency sweep
Optical Spin Readout

- Optical filter is required for green light rejection
- Photodiode is used to detect red fluorescence
Optical Excitation Filtering

Plasmonic Filter

Filter 3D structure

Filter cross section

- Measured isolation is 10 dB

Green light (532 nm)

Red light (700 nm)

FDTD simulated performance
Optical Fluorescence Readout

P+ N-well Photo-diode

- Measured responsivity is 0.23 A/W

- $P_{Eddy} \propto \frac{EMF^2}{R} \propto \left(\frac{d\phi}{dt}\right)^2 \alpha \frac{L^4 (dB/dt)^2}{L} \propto L^3 \left(\frac{dB}{dt}\right)^2 \propto L^3$

- $2\times2$ diode $\rightarrow P_{Eddy} \propto 4 \times \left(\frac{L}{2}\right)^3 \left(\frac{dB}{dt}\right)^2 \propto \frac{L^3}{2}$

- Cuts the losses in anode and cathode

- $n\times n$ diode $\rightarrow P_{Eddy} \propto \frac{L^3}{n}$
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Passivation Layer Removal

• Background fluorescence is emitted from the passivation (silicon nitrite) layer

• Reactive ion etching (RIE) for passivation layer removal
Nano-Diamonds Deposition

- Deposition of diamond nano-crystals solution

Before deposition

After deposition & evaporation
Nano-Diamonds Measurement Results

- **Sensitivity:** $\eta_{\text{CW}} = \frac{1}{\gamma} \frac{\sigma \Delta v}{C} \sqrt{t} = 74 \mu \text{T}/\sqrt{\text{Hz}}$

where $\gamma = \frac{g e B}{\hbar} = 2.8 \text{ MHz/Gauss}$, $\sigma \equiv \text{Std. dev.}$, $\Delta v \equiv \text{Linewidth}$, $C \equiv \text{Contrast}$, $t \equiv \text{Integration Time}$
• **Sensitivity:** $\eta_{CW} = \frac{1}{\gamma m} \sigma \sqrt{t} = 2.5 \mu T/\sqrt{\text{Hz}}$

where $\gamma = \frac{eH_B}{h} = 2.8 \text{ MHz/Gauss}$, $\sigma \equiv \text{Std. dev.}$, $m \equiv \text{Slope of FM signal}$, $t \equiv \text{Integration Time}$
Bulk Diamond Measurement Results

- FWHM = 5 µV
- $D_{2s} = 2.87$ GHz
- $B = 0$

Graph showing lock-in signal vs frequency.
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## Performance Summary

<table>
<thead>
<tr>
<th>Technology</th>
<th>Vector meas.</th>
<th>Optical isolation</th>
<th>Sensing area</th>
<th>Form factor</th>
<th>Sensitivity</th>
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</thead>
<tbody>
<tr>
<td>This work (Nano-diamonds)</td>
<td>No</td>
<td>10 dB</td>
<td>50 μm × 50 μm</td>
<td>~ 1 mm³ **</td>
<td>73 ( \frac{\mu T}{\sqrt{Hz}} )</td>
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<td>65nm CMOS</td>
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<tr>
<td>This work (Bulk Diamond)</td>
<td>Yes</td>
<td>20 dB</td>
<td>50 μm × 50 μm</td>
<td>~ 1 mm³ **</td>
<td>2.5 ( \frac{\mu T}{\sqrt{Hz}} )</td>
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<td>65nm CMOS</td>
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<tr>
<td>Nature physics (2015) *</td>
<td>Yes</td>
<td>&gt;60 dB</td>
<td>1 mm × 1 mm</td>
<td>~ 1 m³</td>
<td>0.29 ( \frac{nT}{\sqrt{Hz}} )</td>
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<tr>
<td>Discrete devices</td>
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** Does not include LASER
Conclusion

• Combines the advantages of CMOS and NV center in diamond in a small form factor
• Couples tightly the CMOS components with NV qubits
• Offers on-chip spin state readout
  • Easy integration of control logic
  • Less IOs
  • Closed-loop feedback between spin-manipulation and readout
• Enables compact and scalable advanced quantum systems.