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Developing High-Resolution Magnetic Microscopy Applications Using NV Centers in Diamond

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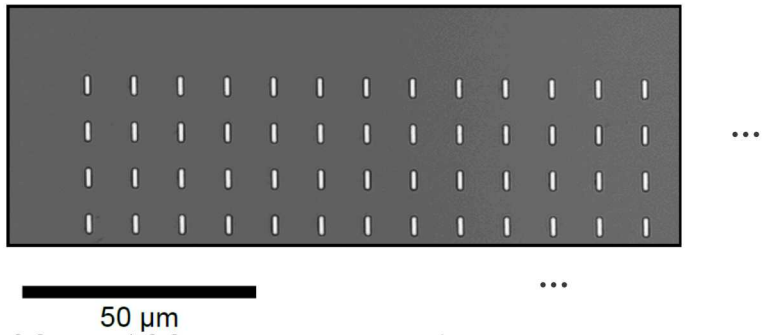
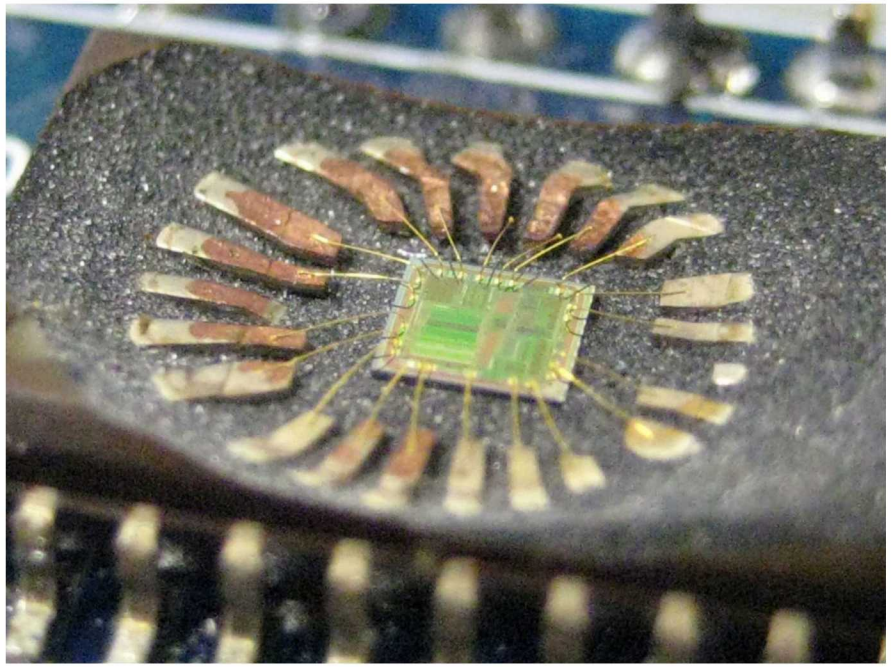
Magnetic imaging motivations

Micromagnet array

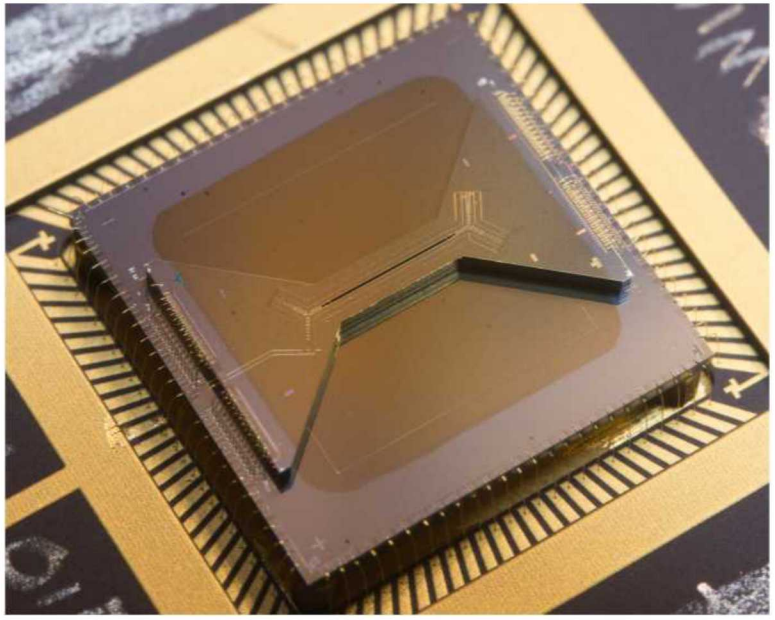


100 x 100 array of nickel micromagnets (1 x 4 µm) with 10 µm spacing

Detecting counterfeits and Trojans in electronics



Ion chip characterization for quantum computing



P. Kehayias et al., JAP 127 203904 (2020)

Magnetic microscopy wish list

As good as possible:

- Single-pixel sensitivity
- Spatial resolution
- Sample-sensor standoff distance

Also important to consider:

- Operating conditions (bias field, temperature, …)
- Field of view
- Frequency range
- $|\vec{B}|$, $\vec{B} \cdot \hat{n}$, or $\vec{B}$ measurements
- Raster-scanning or parallel readout

Magnetic microscopy wish list

As good as possible:

- Single-pixel sensitivity
- Spatial resolution
- Sample-sensor standoff distance

Our approach:
Widefield magnetic microscopy using NV centers in diamond

Also important to consider:

- Operating conditions (bias field, temperature, …)
- Field of view
- Frequency range
- $|\vec{B}|$, $\vec{B}\cdot\hat{n}$, or $\vec{B}$ measurements
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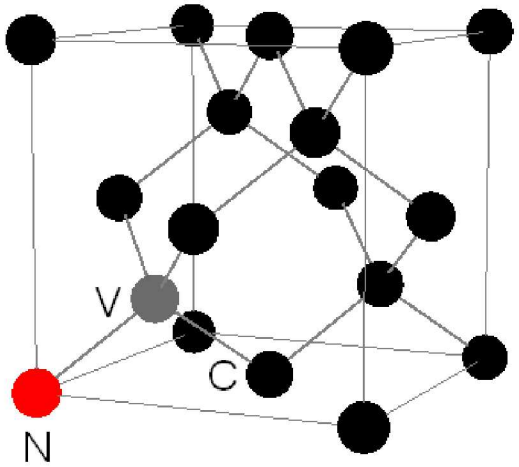
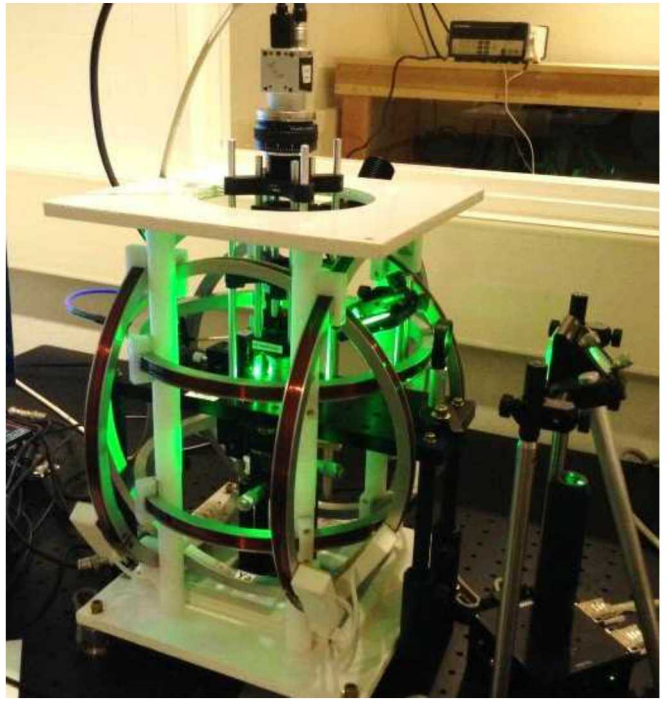


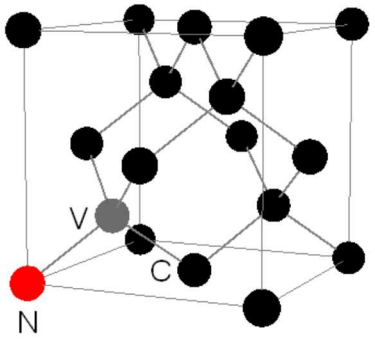


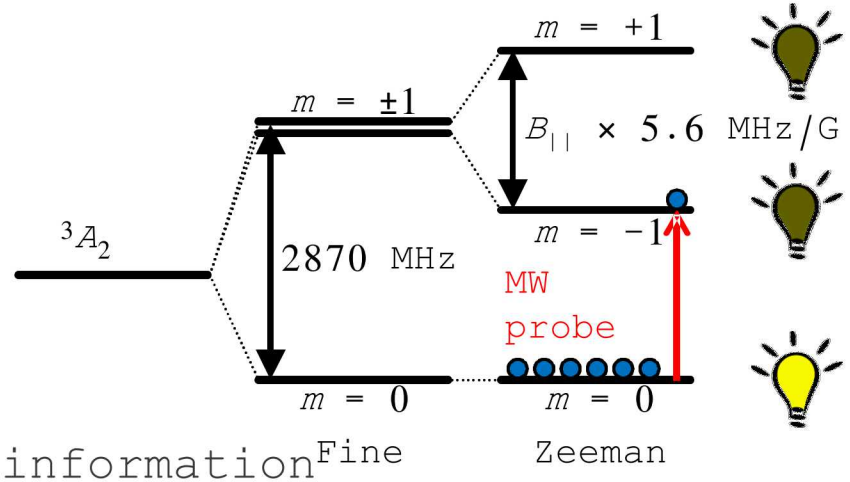
NV diamond overview

Naturally-occurring paramagnetic colo

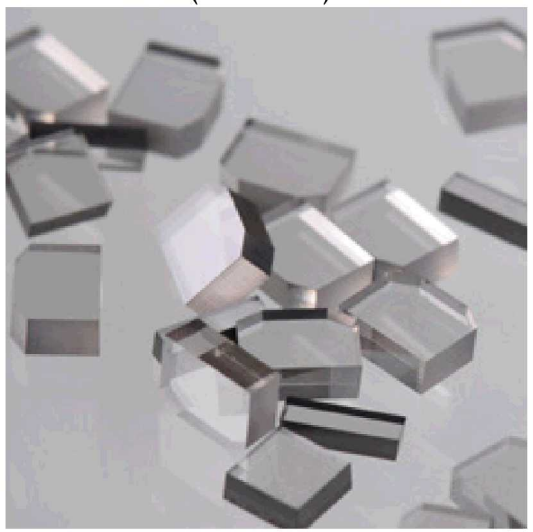
Discrete electronic states

- Magnetically-sensitive ground state
- Optical initialization & readout
- Sublevel-dependent fluorescence
- DC to GHz magnetometry for vector or scalar projection information

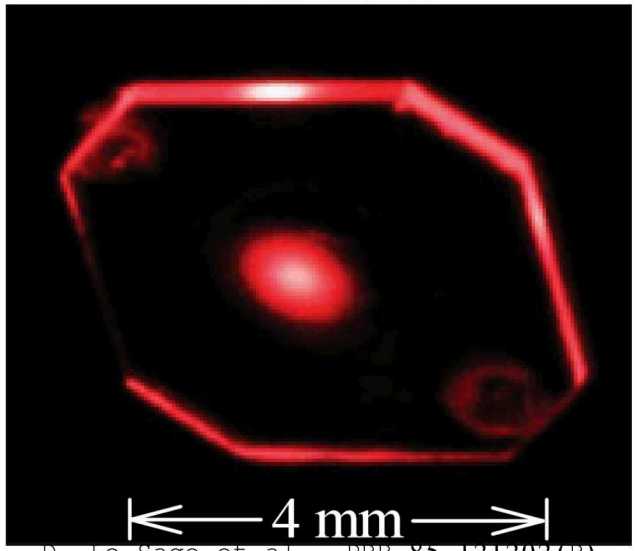




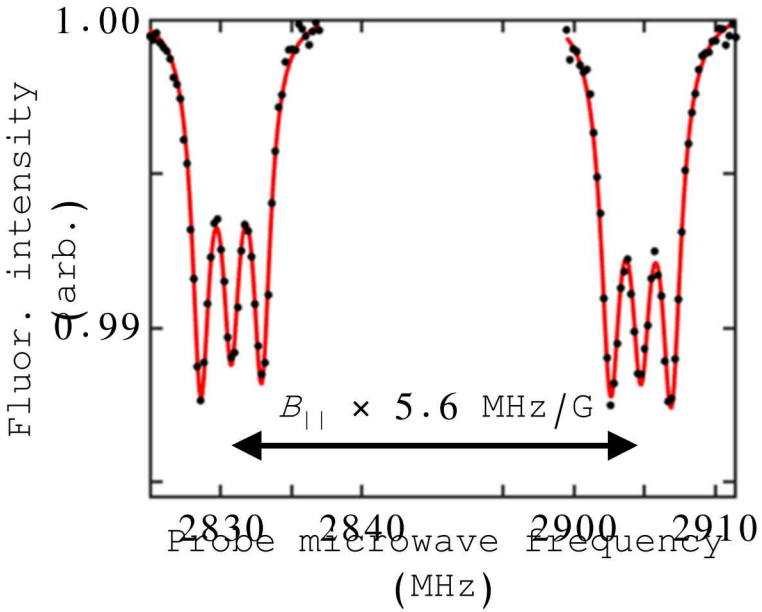
Synthetic diamond chips (few mm)



NV fluorescence under laser illumination



D. Le Sage et al., PRB 85 121202(R) (2012)



NVs are good for high-res magnetic imaging

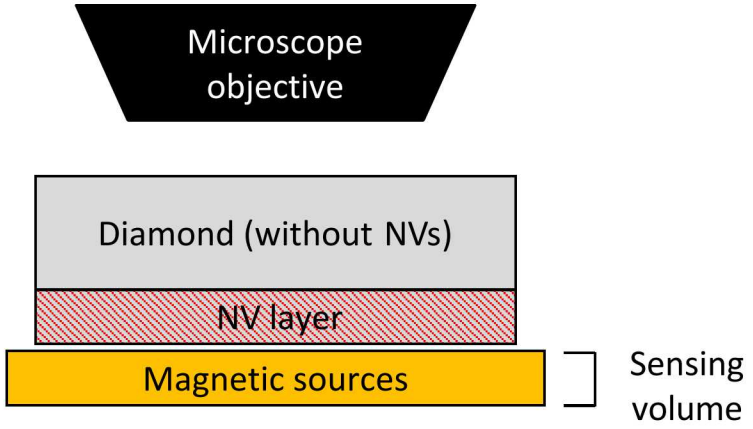
Small sensor-target separation

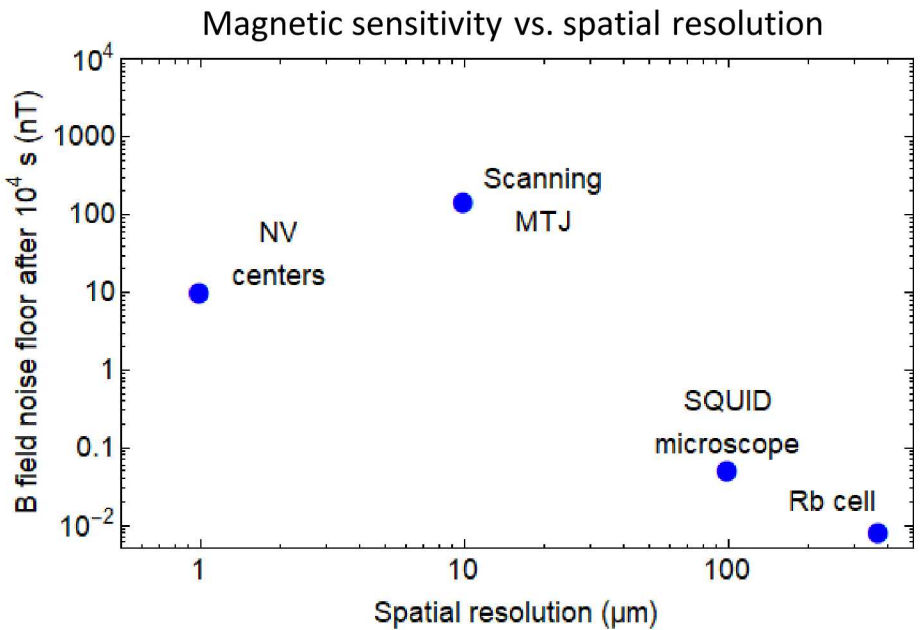
High magnetic moment sensitivity

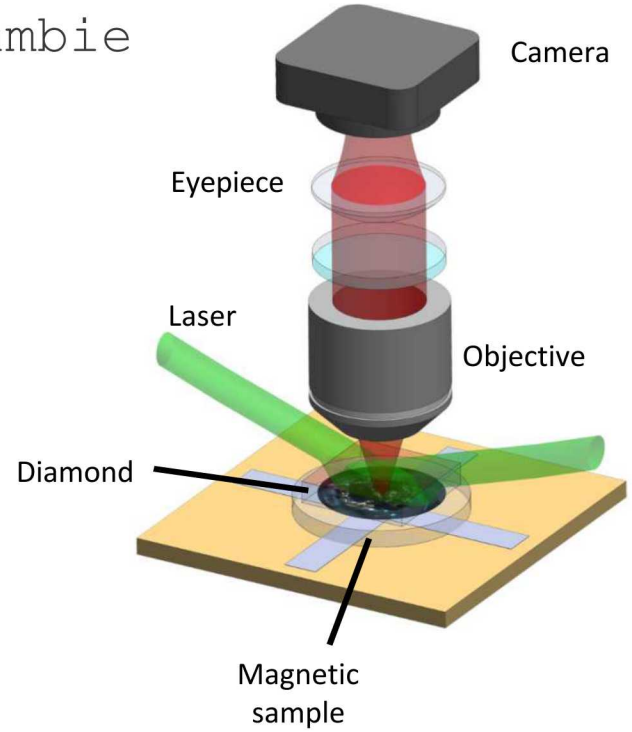
Few-mm FOV, micron-scale spatial resolution

Overlay optical and magnetic images

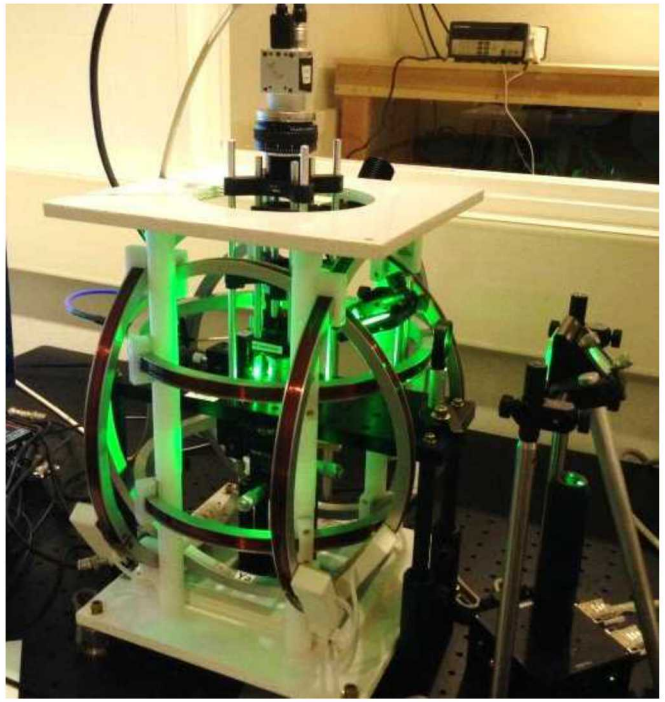
No sensor scanning, works at ambie







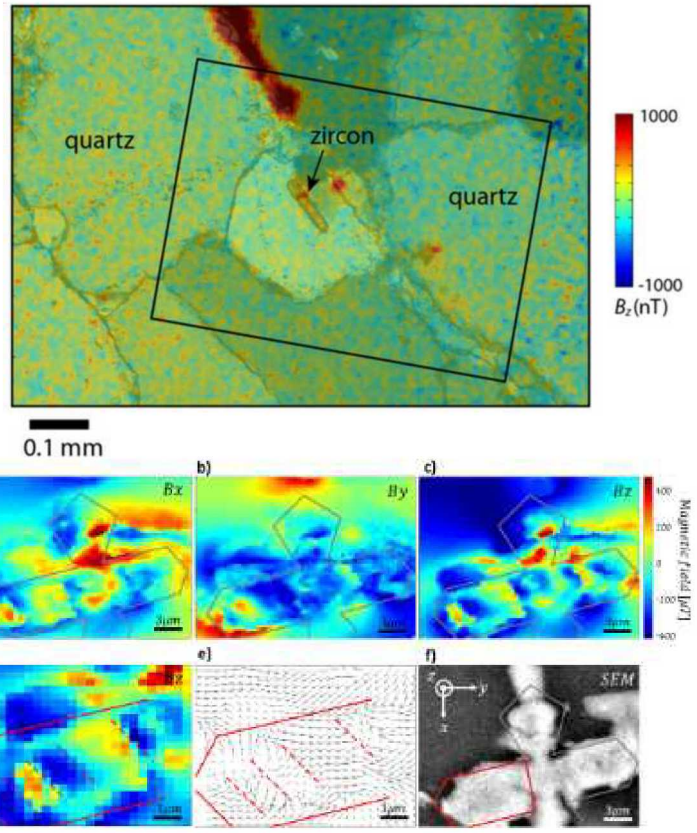
D. R. Glenn et al., Geochem. Geophys. Geosyst. 18, 8 (2017)



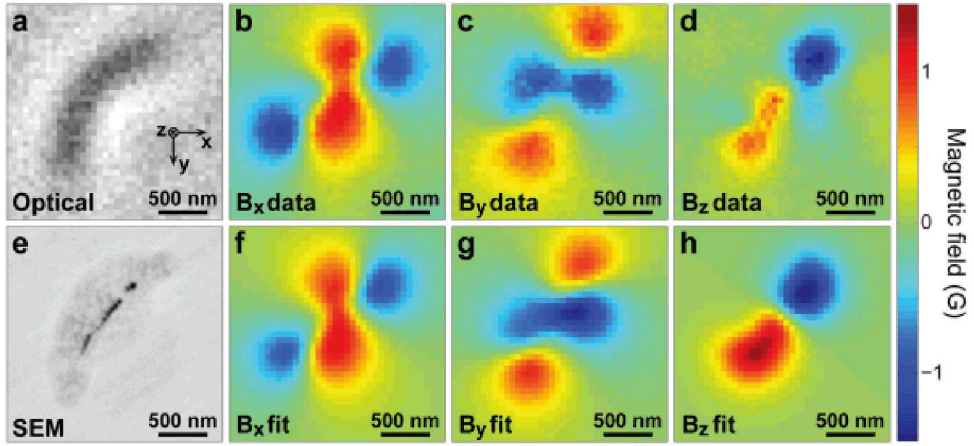
Widefield NV magnetic microscopy setup

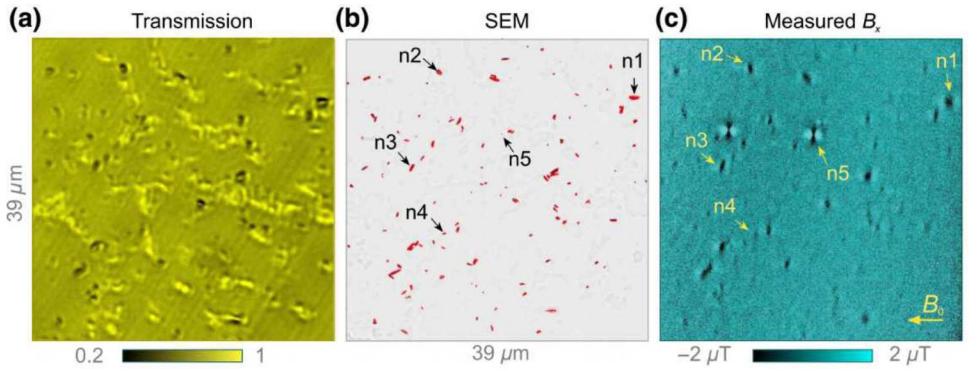
NV magnetic imaging highlights

Geomagnetism

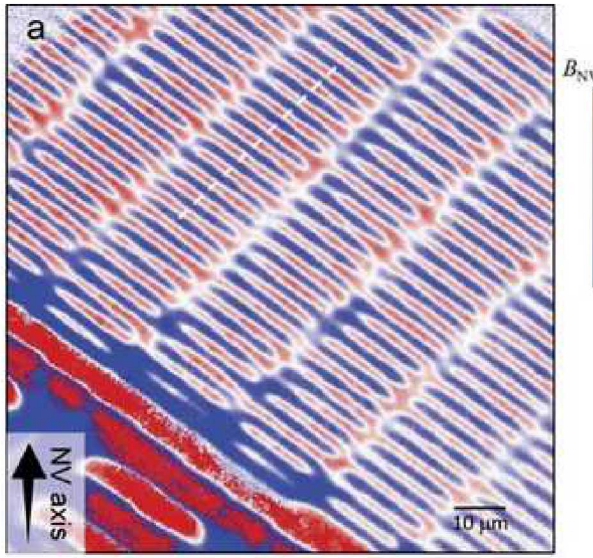


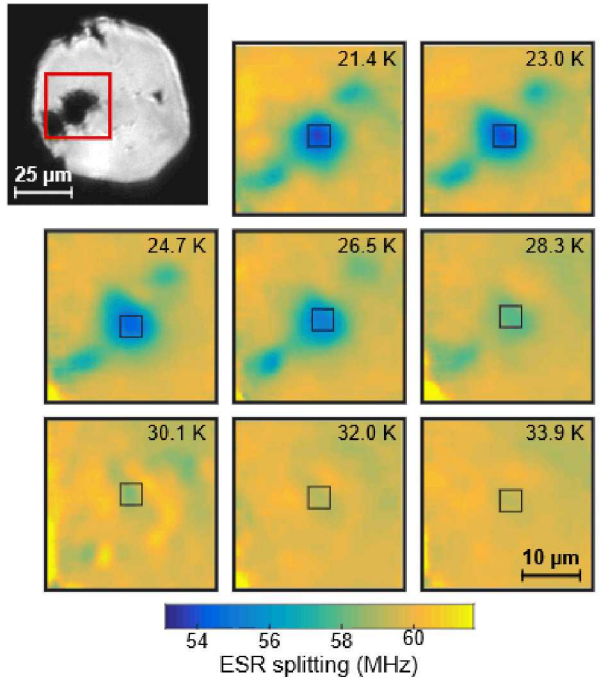
Biomagnetism





Condensed-matter physics





B. P. Weiss et al., Geology 46 5, 427-430 (2018)
E. Farchi et al., Spin 07 03 1740015 (2017)
D. Le Sage et al., Nature 496, 486-489 (2013)
I. Fescenko et al., Phys. Rev. Applied 11 034029 (2019)
D. A. Simpson et al., Sci. Rep. 6 22797 (2016)
M. Lesik et al., Science 366 6471 (2019)

Application #1: micromagnet array PUFs

To protect against counterfeiters, tag each object with a unique fingerprint

Requirements for PUFs:

- Easy to make, hard to reproduce individual ones
- Random and unique (difficult to predict)
- Efficient to characterize, reproducible output
- Low-cost, resilient

Examples:

- Fibers in paper
- Manufacturing variations in electronics
- Our work: fabricated micromagnets

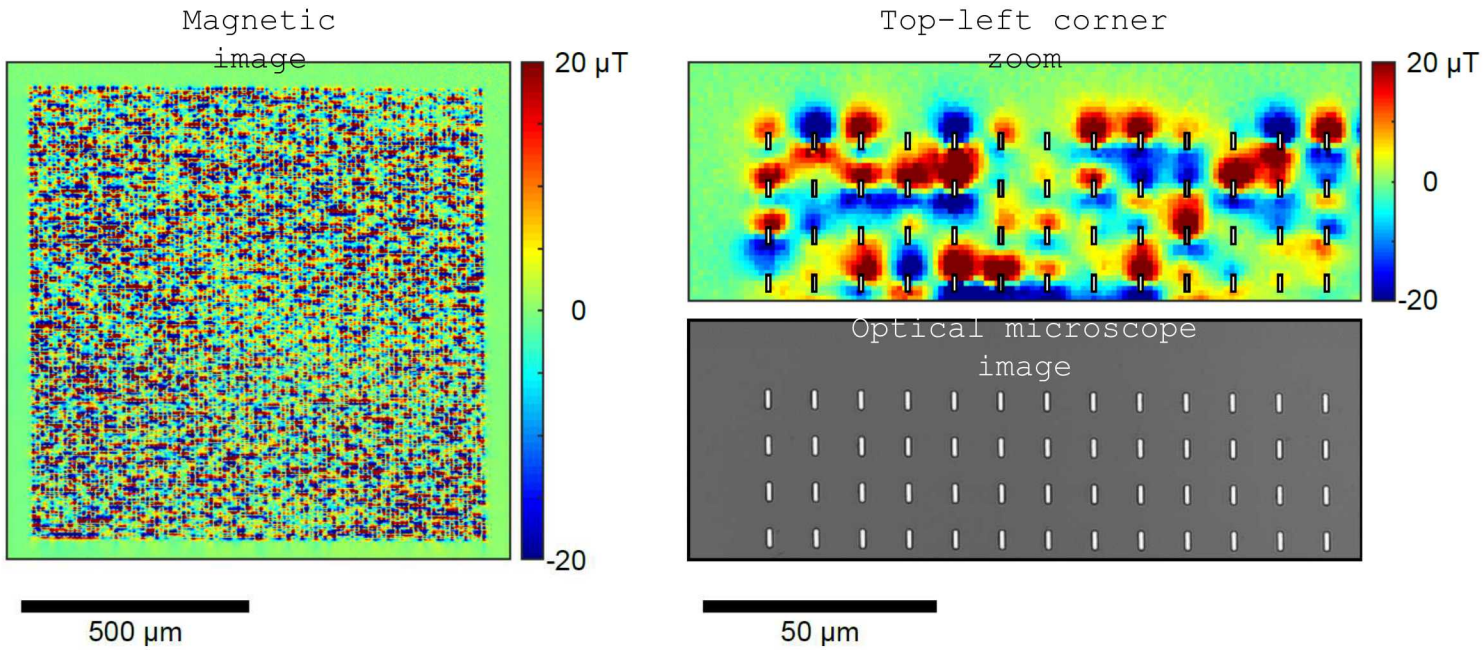
Anti-counterfeiting fibers in a banknote

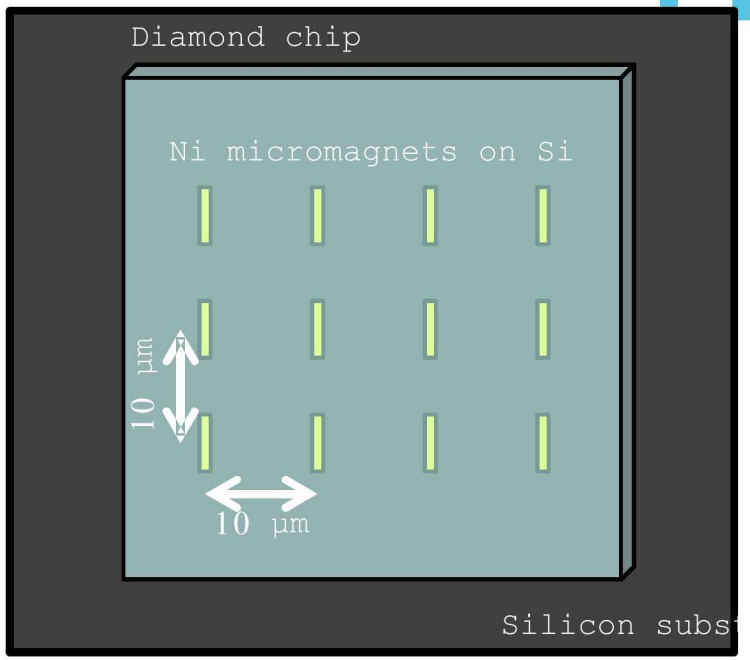
T. Bauer and J. Hamlet, IEEE Security & Privacy 12 6 97-101 (2014)

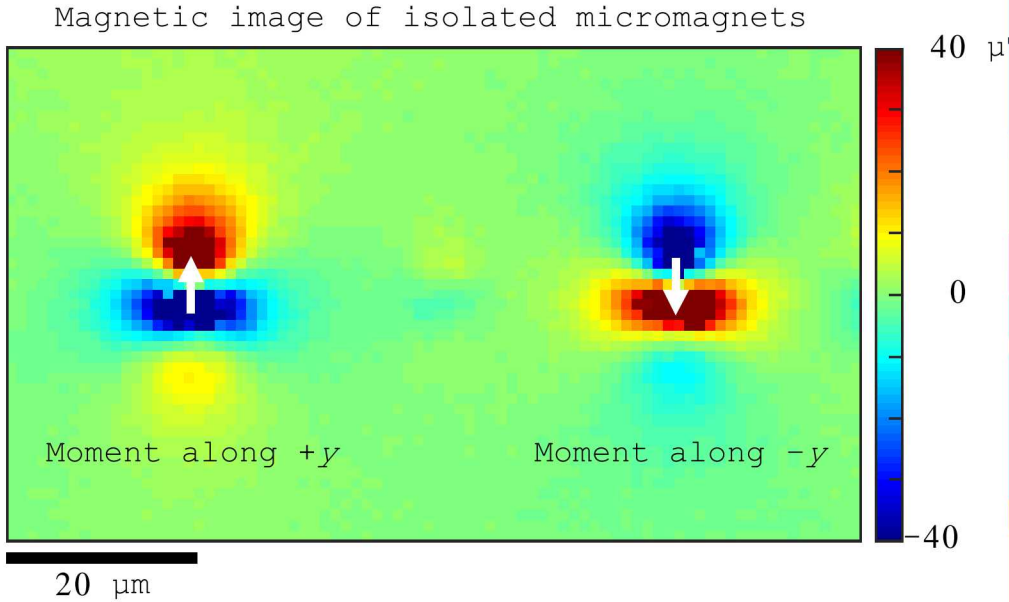
Application #1: micromagnet array PUFs

Use a micromagnet array as a PUF

- Each magnet has a random (uncontrollable) magnetization
- Measure each micromagnet, generate a binary $\{0,1\}$ for each
- Benefits: PUF is unpowered, compact, CMOS-compatible, stable over geological timescales, and can be hidden under a thin opaque layer







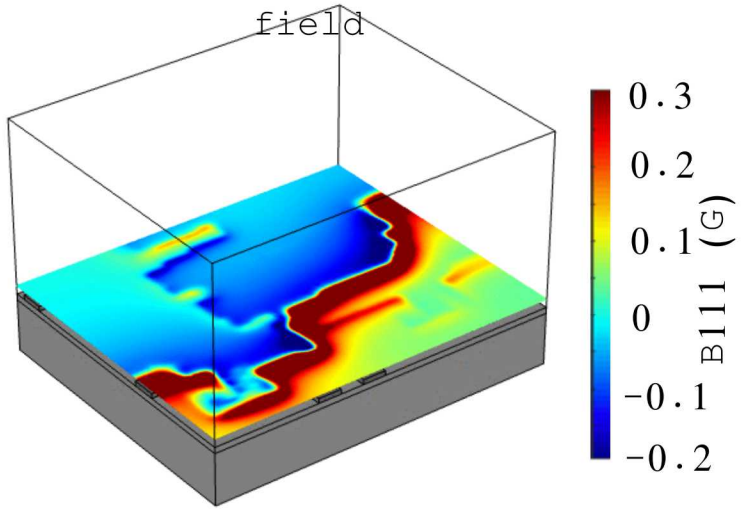
P. Kehayias et al., JAP 127 203904 (2020)

Application #2: counterfeit electronics probe

Passively interrogate IC behavior and find counterfeits & Trojans

Commercial 555 timer die

Simulated B field



LED image

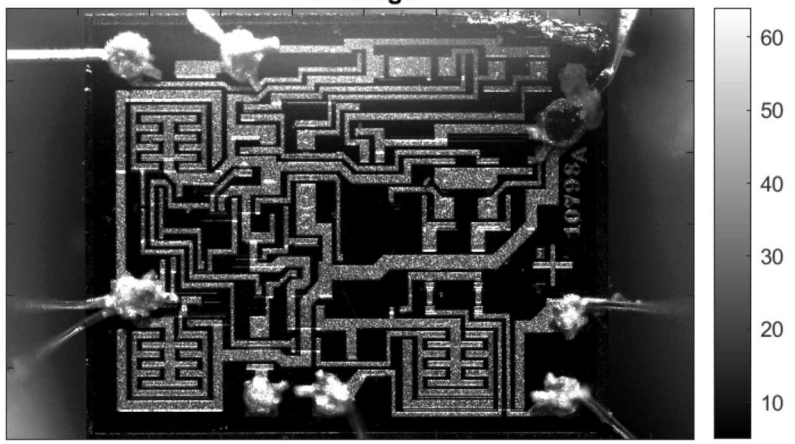
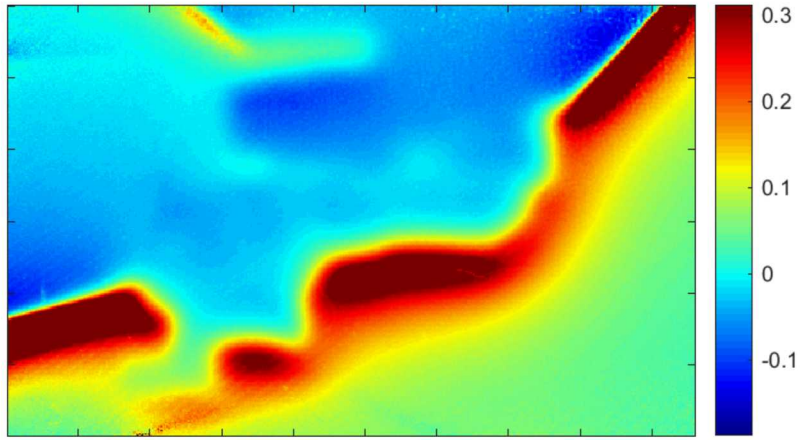


Image dimensions: 1.31 x 2.09 mm

Output current on B_{111} (gauss)



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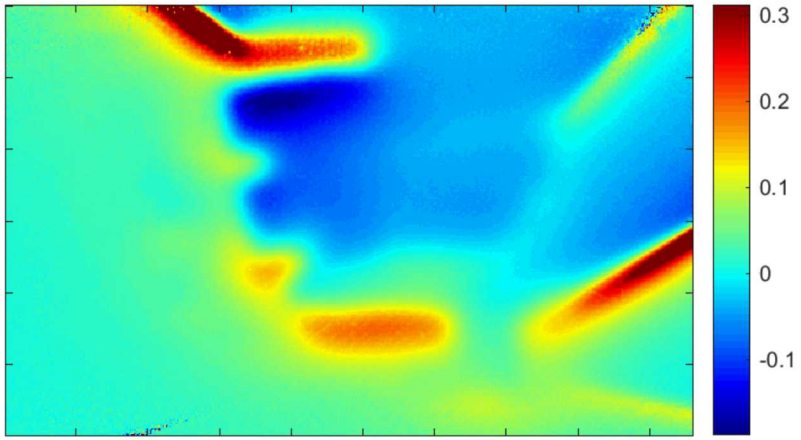
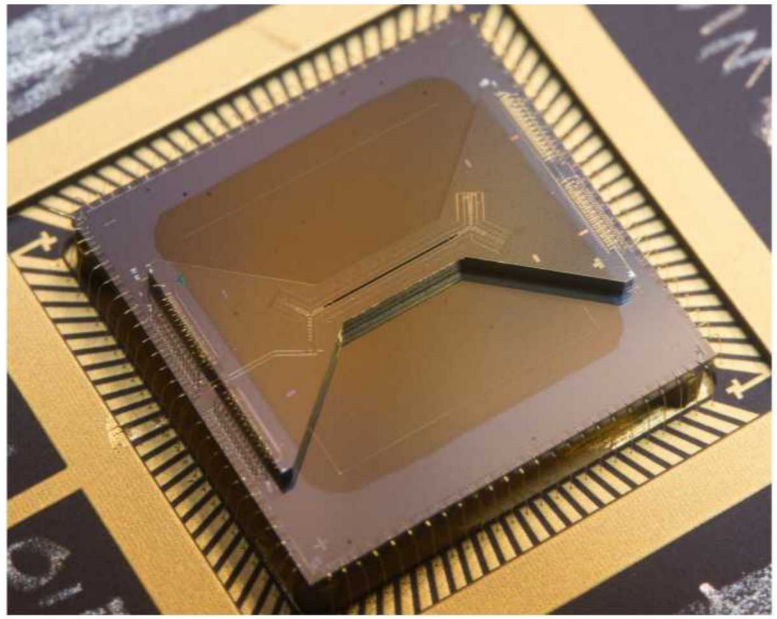


Application #3: ion chip characterization

Characterize ion chips over a wide frequency range
- DC magnetic gradients
- RF trapping potential (10-100 MHz)
- Microwave chip traps (few GHz)

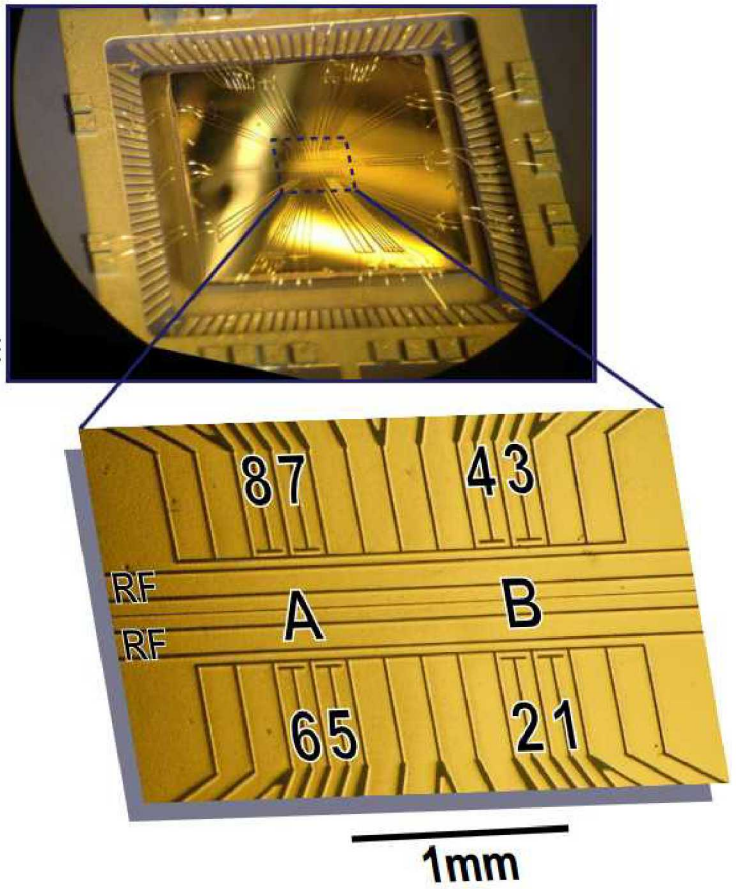
Validate FEM calculation & manufacturing

Test an ion chip before installing it in the expe



Sandia high-optical-access ion chip

Ion chip with 3.2 GHz near-field microwave gates



P. Maunz, SAND2016-0796R
D. P. L. Aude Craik et al., PRA 95 022337 (2017)

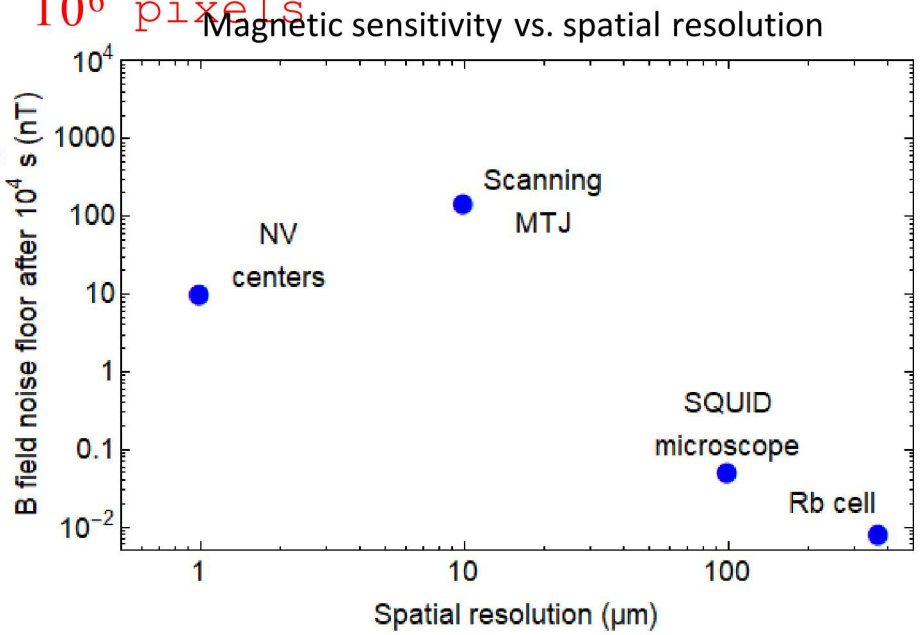
Summary

As good as possible:

- Single-pixel sensitivity — Few μT after 1 s in a 1 μm pixel
- Spatial resolution — Few microns
- Sample-sensor standoff distance — As close as ~10 nm

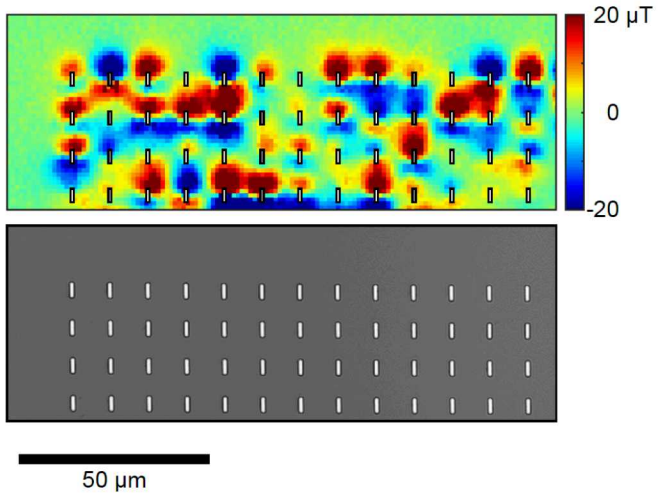
Also important to consider:

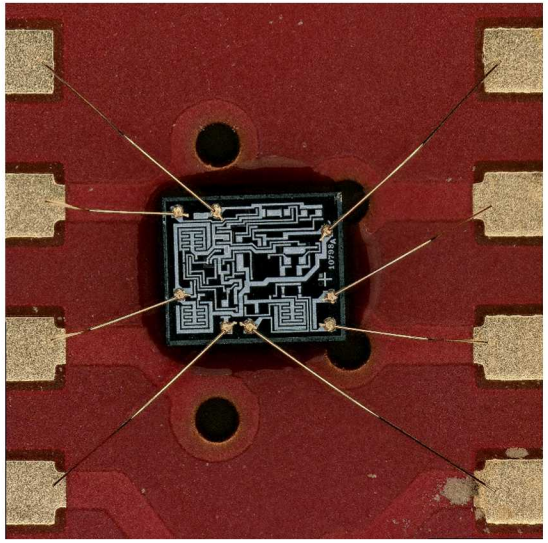
- Operating conditions — Ambient conditions, arbitrary B_0
- Field of view — ~0.1 to few mm, 10^6 pixels
- Frequency range — DC to 100 GHz
- $|\vec{B}|$, $\vec{B}\cdot\hat{n}$, or $\vec{B}$ measurements — Vector or proje
- Raster-scanning or parallel readout — Parallel

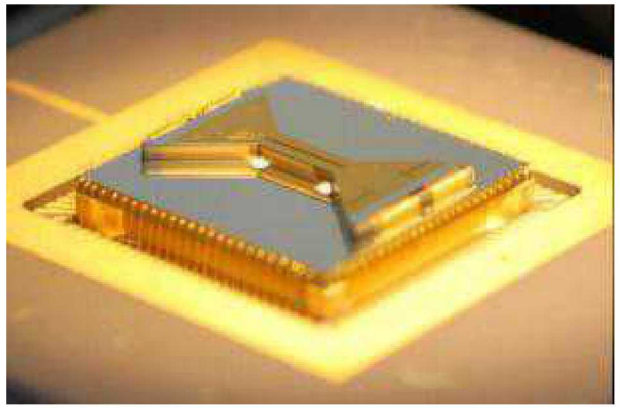


Summary

NV magnetic imaging enables new insights and directions for related fields







Ongoing investigations into alternative optically-active defects:

- SiV, SnV, PbV, ST1, ..., SiC polymorphs, ...

Collaborators:

- Micromagnet PUFs: Ezra Bussmann, Tzu-Ming Lu, Andy Mounce
- IC magnetic imaging: Ray Haltli, Edlyn Levine, Tzu-Ming Lu, Andy Mounce, Denise Tibetts, Darlene Udoni
- Ion chip traps: Susan Clark, Ray Haltli, Melissa Revelle