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Imaging Fabricated Micromagnet Arrays with Nitrogen-Vacancy Centers in Diamond

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Physical Unclonable Functions (PUFs) for Hardware Security

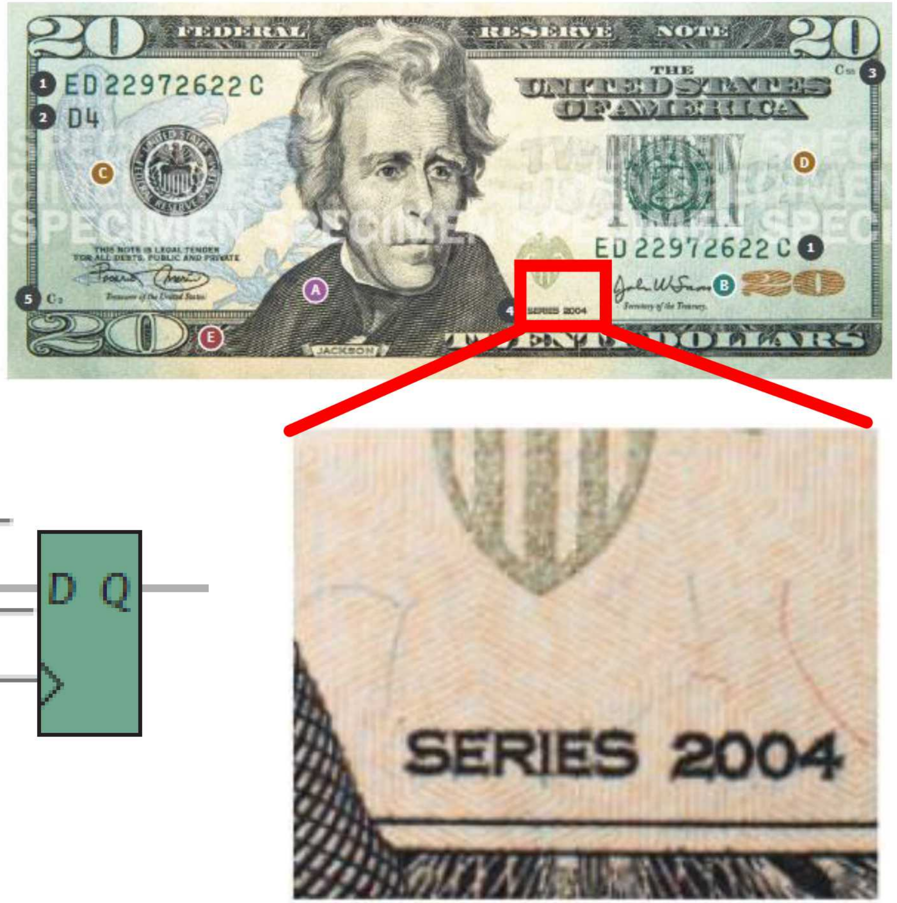
To protect against counterfeiters, tag each device or object with a unique fingerprint

Requirements:

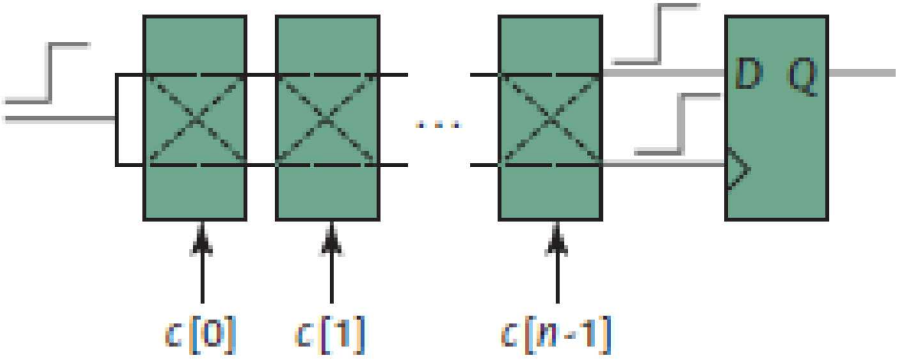
- Easy to make, hard to reproduce
- Random and unique (difficult to predict)
- Efficient to characterize, reproducible output
- Low-cost, resilient

Examples:

- Fibers in paper
- Manufacturing variations in electronics
- Ferromagnetic particles



Anti-counterfeitting fibers in a banknote



Arbiter PUF with switchable delay lines and D-type flip-flop

T. Bauer and J. Hamlet, IEEE Security & Privacy 12 6 97-101 (2014)
T. McGrath et al., Appl. Phys. Rev. 6 011303 (2019)

Micromagnet PUFs

Encode a unique fingerprint with random ferromagnetic states

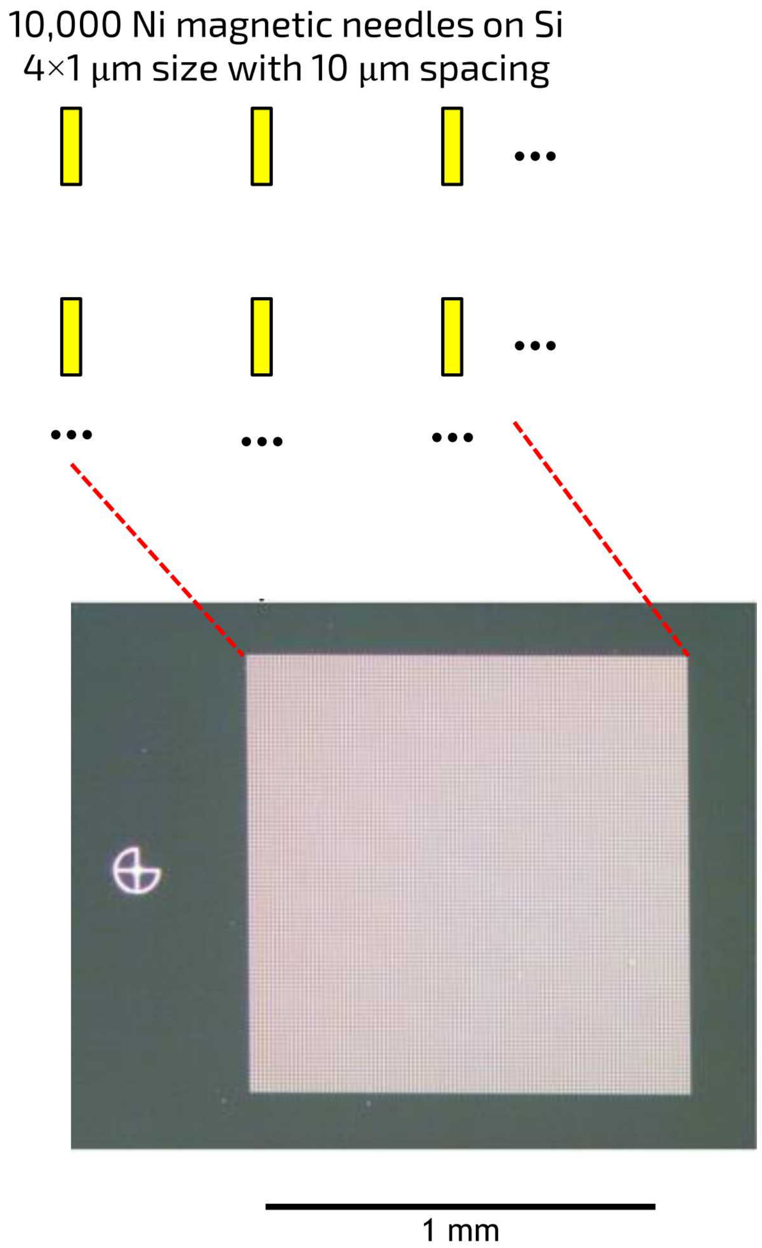
- Individual magnetic states are hard to control but easy to randomize
- Two allowable magnetic states (along y axis); convert to {0,1} bit string
- Resistant to temperature and external B fields

Drawbacks:

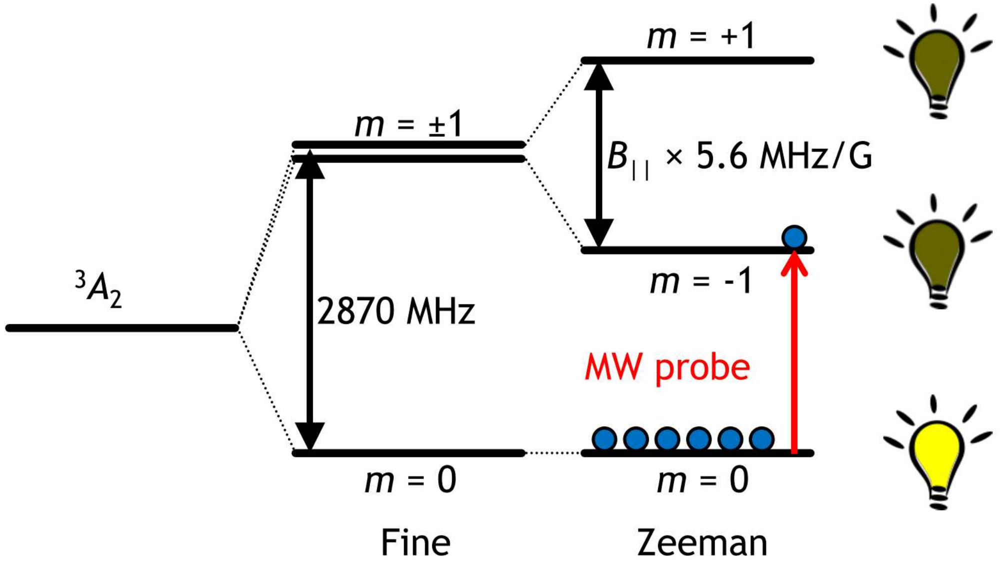
- Needs high-resolution magnetic imaging to measure each magnetic state
- Reading out the micromagnet states with a scanning-tip magnetometer can be time-consuming

Solution:

- Optical magnetic state readout with a widefield NV magnetic microscopy setup



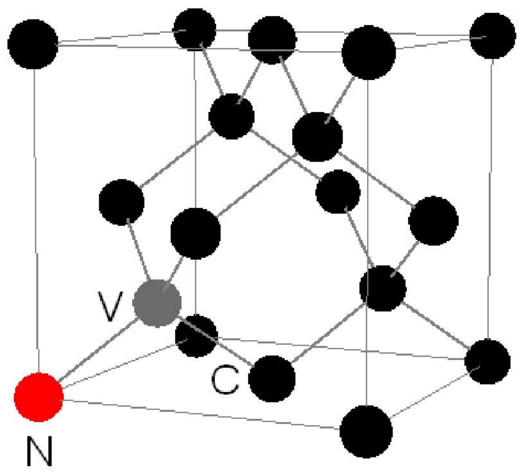
NV diamond overview



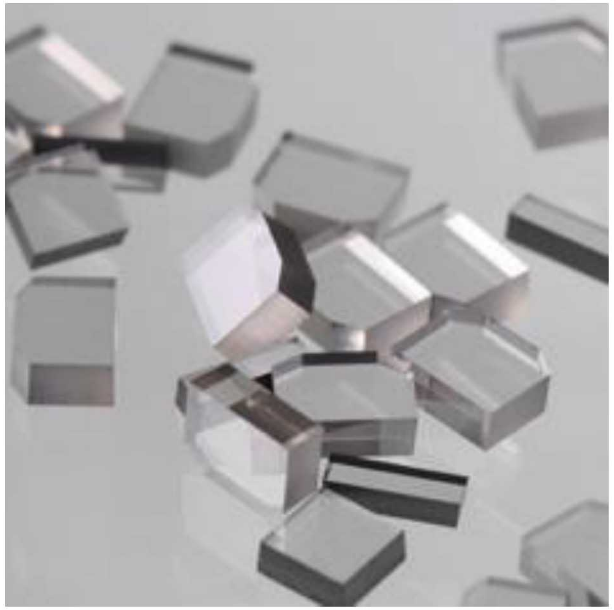
Naturally-occurring paramagnetic color centers

Discrete electronic states

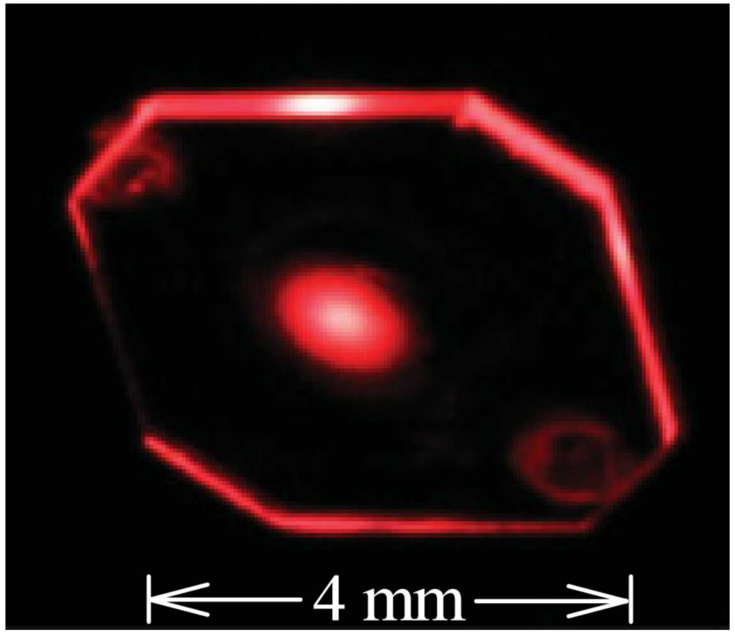
- Magnetically-sensitive ground state
- Optical initialization & readout
- Sublevel-dependent fluorescence
- DC to GHz magnetometry



Synthetic diamond chips (few mm)



NV fluorescence under illumination



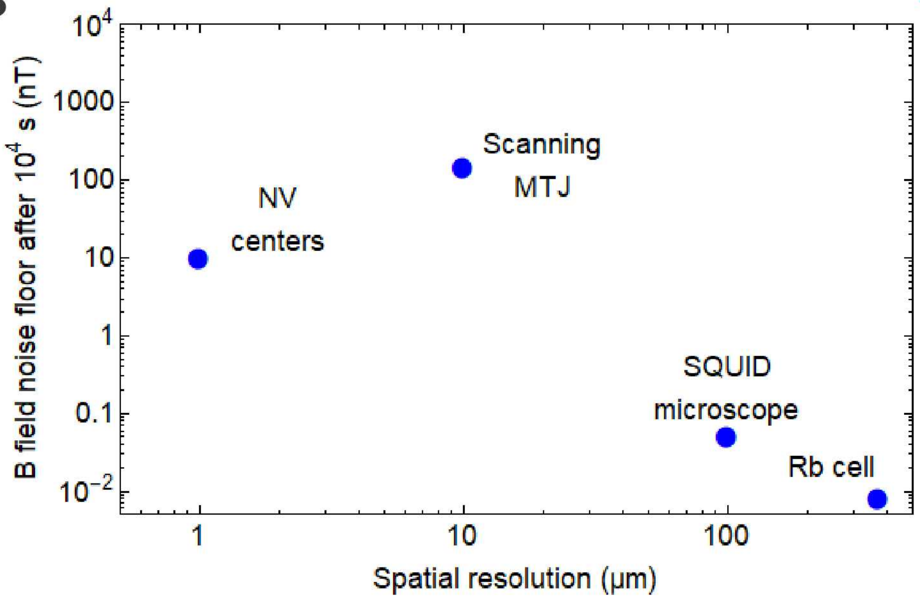
D. Le Sage et al., PRB 85 121202(R) (2012)
R. Schirhagl et al., Ann. Rev. Phys. Chem. 65 83-105 (2014)

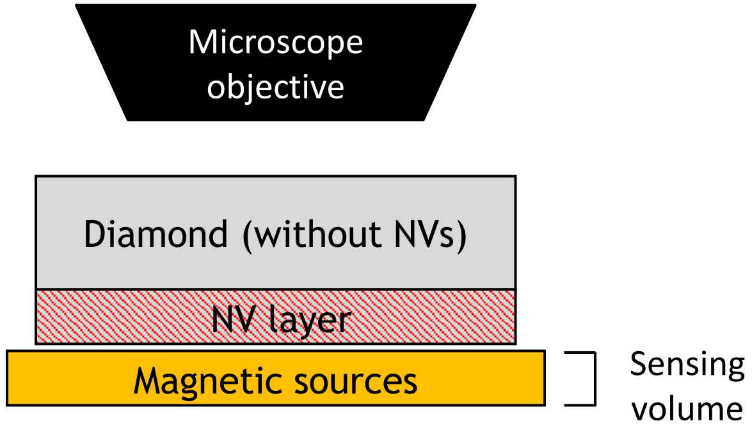
NVs are good for high-res magnetic imaging

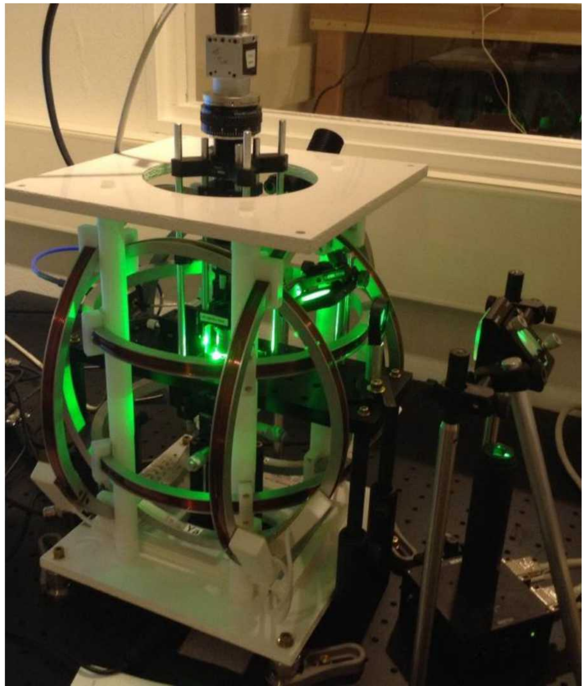
Advantages:
- Small sensor-target separation
- High magnetic moment sensitivity (~ 1E-15 J/T in 1 s)
- Few-mm FOV, micron spatial resolution
- Overlay optical and magnetic images
- Parallel acquisition (no sensor scanning)
- Works at ambient conditions

Example applications:
- Condensed-matter physics
- Biomagnetism
- Paleomagnetism

Magnetic sensitivity vs. spatial resolution







E. V. Levine et al., Nanophotonics doi:10.1515/nanoph-2019-0209 (2019)

Fabrication, measurement, and analysis

Micromagnet fabrication

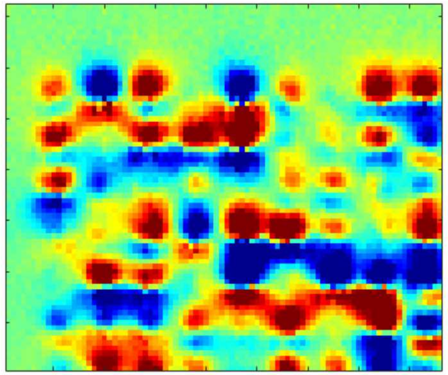
- e-beam lithography on resist, develop, Ni deposition, liftoff

Measurement details

- 20 minute acquisition, 1 μm/pixel, 4x4 mm diamond chip with a 4 μm NV layer

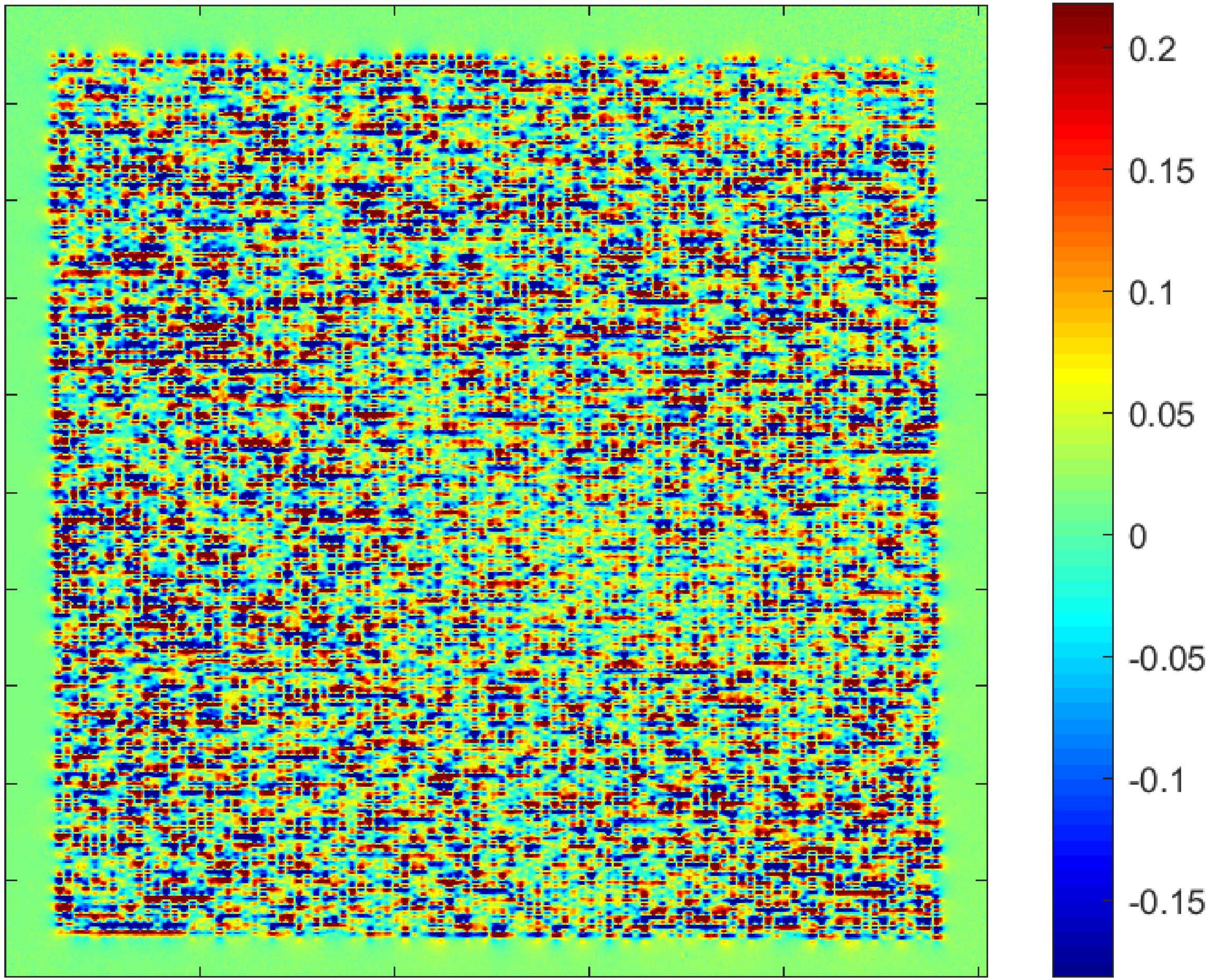
Analysis

- Orient array to be square, horizontal line cuts, peak detection



Bit string:
1, 0, 1, 0, 0, 1, 0, 1, 1, …

NV magnetic map of
10,000 micromagnets
(1x1 mm area)



Detailed characterization

Micromagnet ferromagnetism / coercivity

- Despite measuring in a ±1.5 mT bias field, the micromagnet states are unaffected

Randomness

- In first attempt, micromagnet bit string passes all NIST randomness tests (except one)

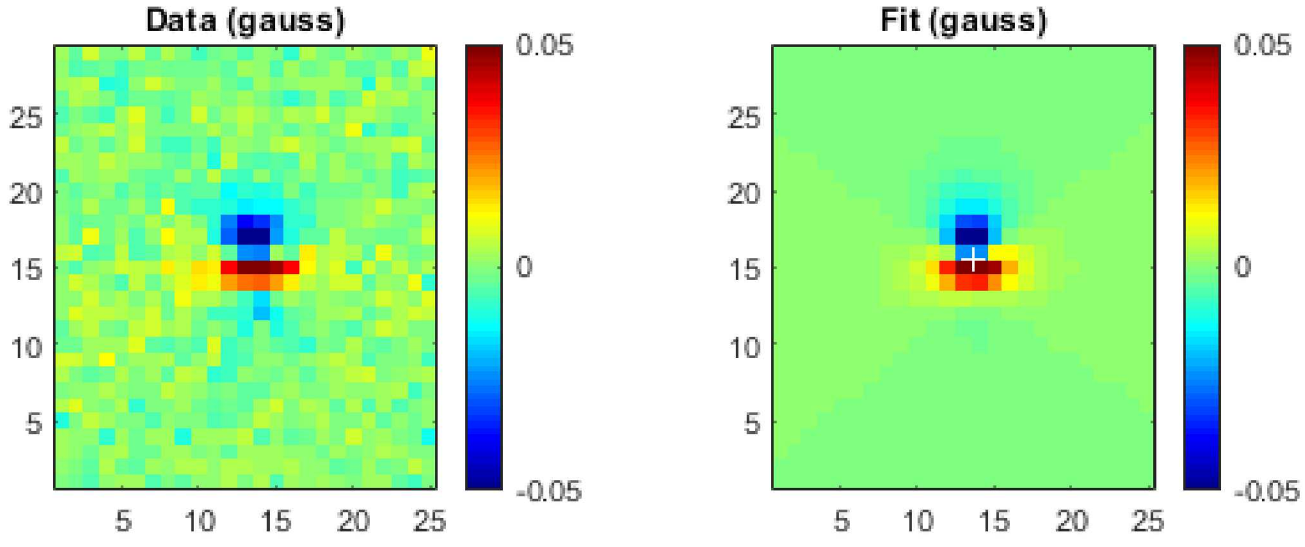
Standoff distance and minimum spacing

- ~2 μm best-case standoff distance
- 5-6 μm micromagnet spacing should be possible

Sensitivity and SNR

- Roughly 20 μT field strength and 5 μT noise floor after 1 s

Example 1x0.25 μm micromagnet
1.8 μm standoff, 6.3E-15 J/T moment, 1 μm/pixel



NIST SP 800-22 (2010)

Next steps

Further optimize fabrication and measurement parameters

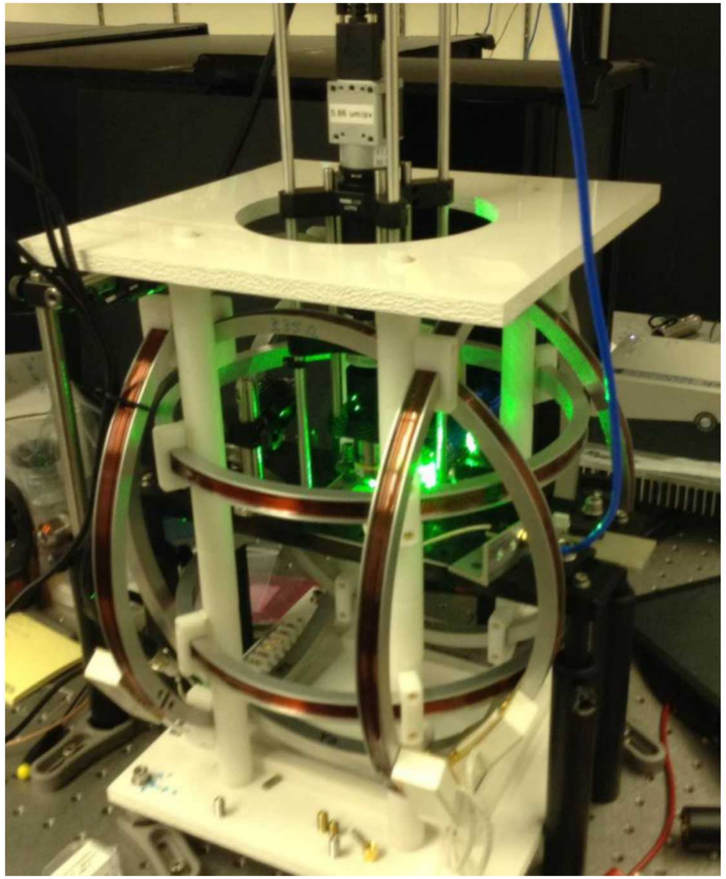
- Controls: micromagnet dimensions & spacing, NV layer thickness
- Tradeoffs: standoff distance, magnetic field strength, magnetic moment, magnetic sensitivity

Wipe a micromagnet array to reset all the states

- Thermal demag, alternating field demag

Verify resilience to heating, external fields, and aging

Outlook & Acknowledgements



Micromagnet arrays are useful as PUFs
- NV magnetic microscopy enables parallel wide-field readout
- SNR is sufficiently good for readout in minutes
- Further validation and optimization are ongoing

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Collaborators: Acosta group (University of New Mexico)

Poster session: Wednesday afternoon (2:30-5:30), Rio Pavilion 8-11

DT-01. Super-Resolution Magnetic Microscopy using Nitrogen-Vacancy Centers in Diamond. *N. Mosavian*[1], B.A. Richards[1], P. Kehayias[2] and V.M. Acosta[1] *1. Center for High Technology Materials and Department of Physics and Astronomy, University of New Mexico, Albuquerque, NM, United States; 2. Sandia National Labs, Albuquerque, NM, United States*