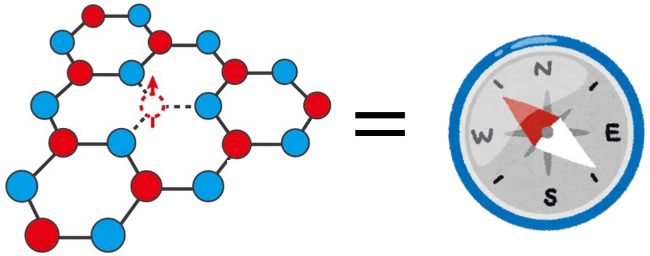
FCMN2024

2024/04/17 (Wed) 11:00 – 11:30

Talk 25min + Q&A 5min

Arrangement of Nanosized hBN Quantum Sensor Spots using Helium Ion Microscope



KS *et al.*, Appl. Phys. Lett. **122**, 244003 (2023)

Kento Sasaki

SCHOOL OF SCIENCE
THE UNIVERSITY OF TOKYO

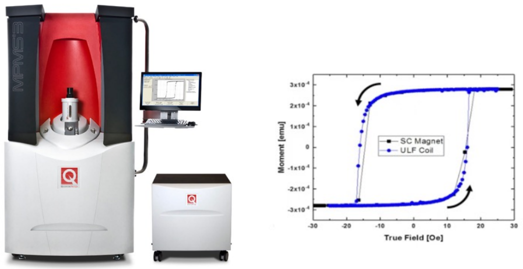
Department of Physics, The University of Tokyo

Contents

- Introduction
  - Magnetometry
  - Quantum sensor & Examples
  - hBN quantum sensor
- Principles
  - Optically detected magnetic resonance
  - Quantitative magnetometry
- Experiments
  - Creation of V_B defects
  - Creation of sensor array
  - Magnetic imaging
- Summary
- Acknowledgement

Magnetometry

Small-angle neutron scattering, muon spin rotation, etc.

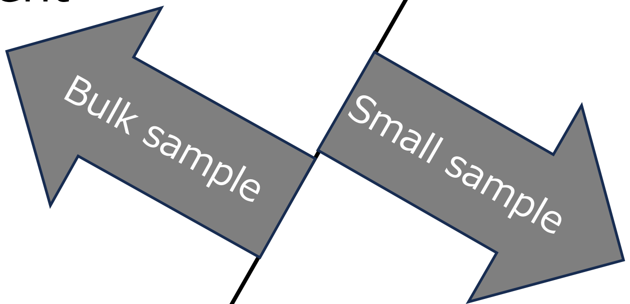


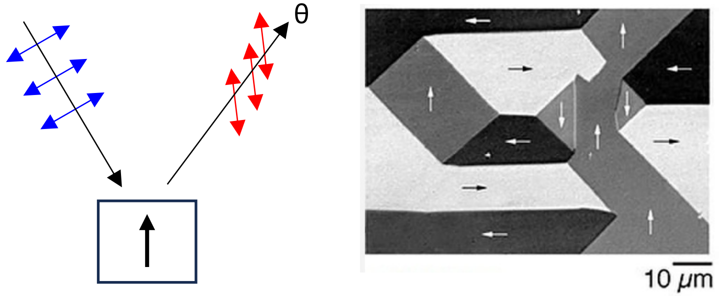
https://www.qd-japan.com/products/mpms3/

Susceptibility measurement

https://www.jeol.co.jp/products/scientific/esr/

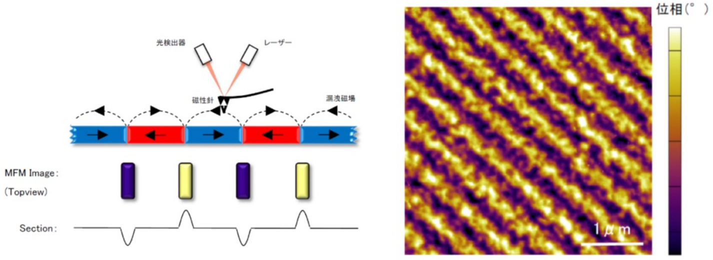
Magnetic resonance





https://www.toyo.co.jp/material/products/detail/kerr-microscope

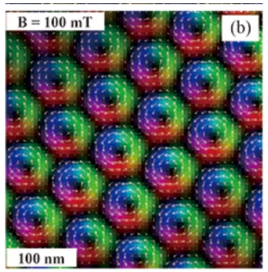
Magnetic circular dichroism



https://www.mst.or.jp/method/tabid/1373/Default.aspx

Scanning probes

(MFM,SQUID,Hall bar,GMR)



https://www.jeol.co.jp/solutions/applications/details/1094.html

Lorentz microscope

Magnetometry with new features/benefits

→ Expanding the application range of magnetometry

Difference

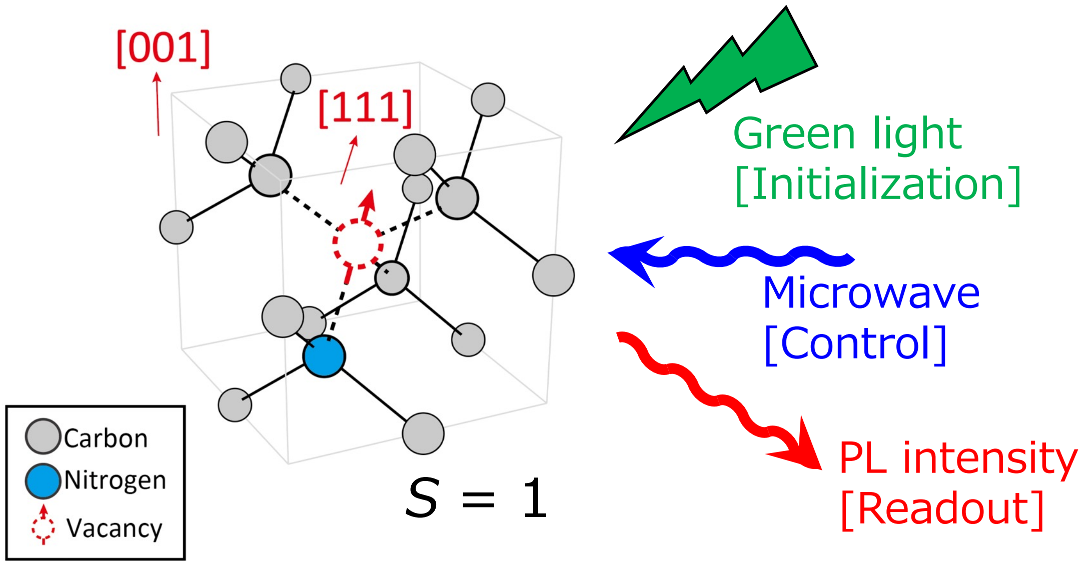
Sensitivity,

Resolution,

Measured physical quantity,

etc.

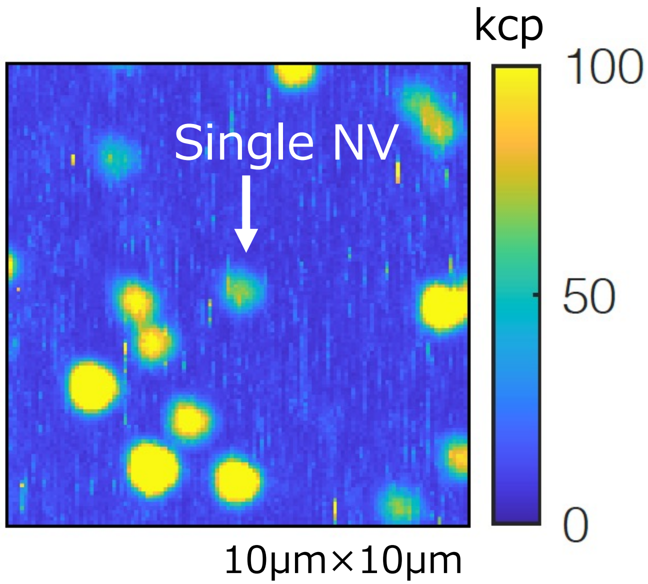
Quantum sensor: NV center in diamond (Since 2008)



Nitrogen-vacancy (NV) center

Origin of pink color

J. E. Shigley and C. M. Breeding, *Gems & Gemology* **42**, 107 (2013)



PL mapping

<u>Features</u>

- Atomic size
- Optical measurement ← More on this later
- Room temp. operation
- Quantitative (Zeeman effect)
- Temperature measurement
- Wide frequency range (DC-GHz)

etc.

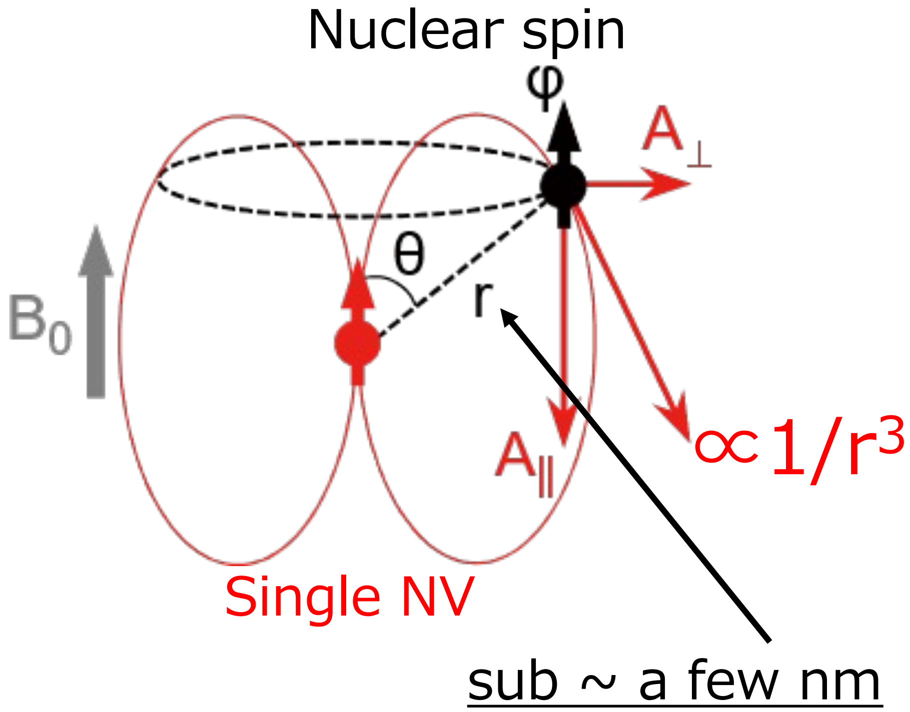
J. M. Taylor *et al.*, Nat. Phys. **4**, 810 (2008)
G. Kucsko *et al.*, Nature **500**, 54 (2013)

Examples of quantum sensing (My Ph.D works)

Nanoscale magnetic resonance using single NV centers @ RT

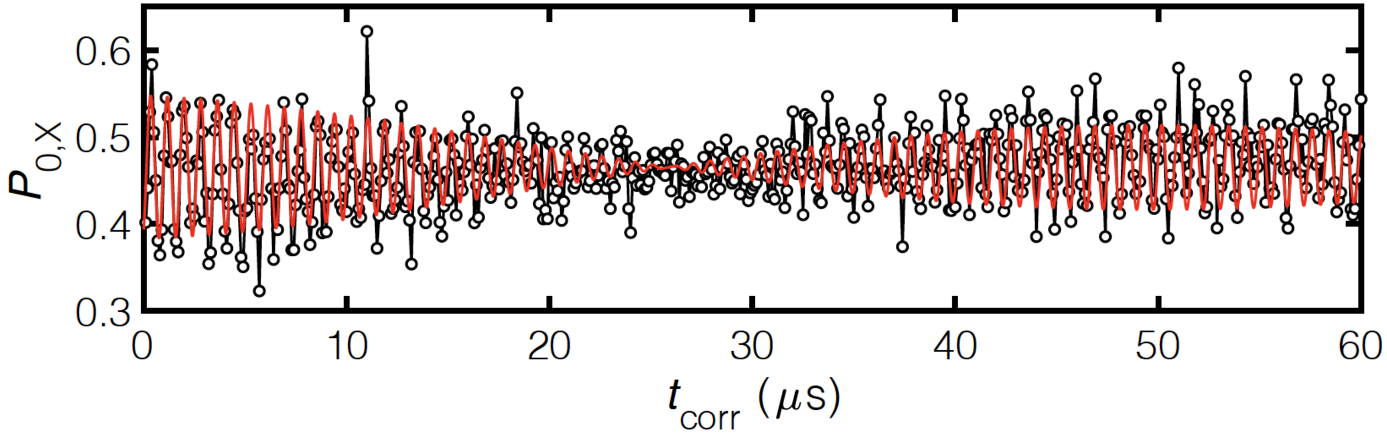
→ Combination of atomic resolution and high sensitivity

(For general imaging purpose, scanning probe technique is required)



3D Localization of single nuclear spins
(Sub-Å resolution)

KS *et al.*, Phys. Rev. B **98**, 121405 (2018)
J. Zopes *et al.*, Nat. Commun. **9**, 4678 (2018)



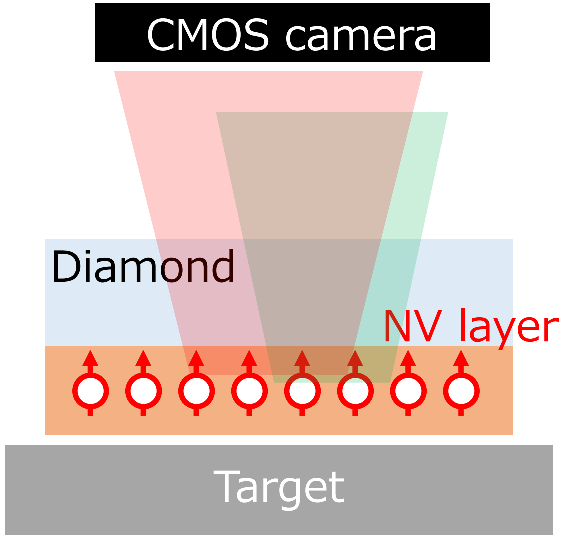
Detection of precession of single proton spin

KS *et al.*, Appl. Phys. Lett. **117**, 114002 (2020)

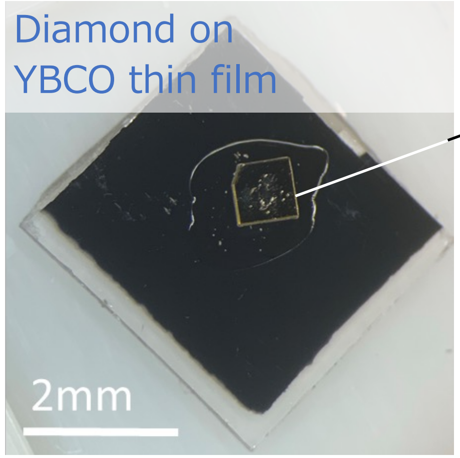
Examples of quantum sensing (Works at UTokyo)

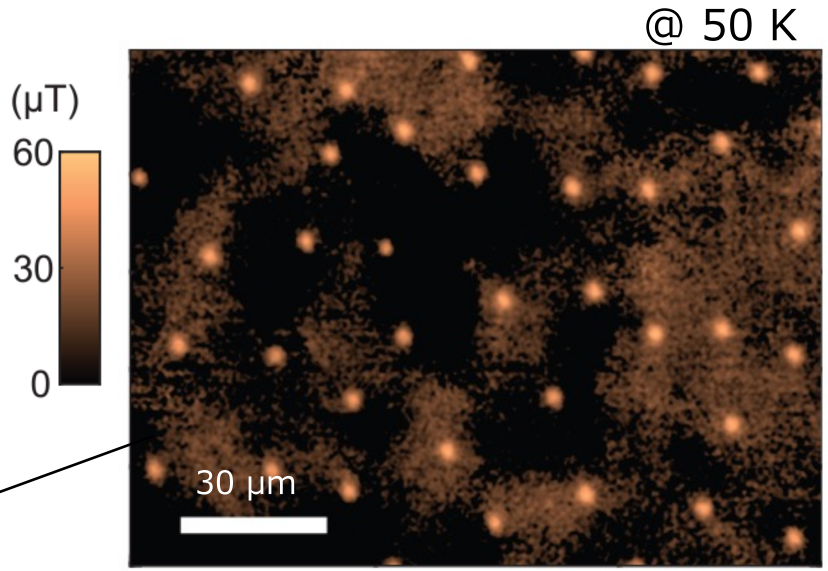
Wide-field imaging using NV ensembles @ <4K ~ RT

→ High throughput versatile imaging with μT sensitivity
(No scanning, Wide temperature/pressure range)



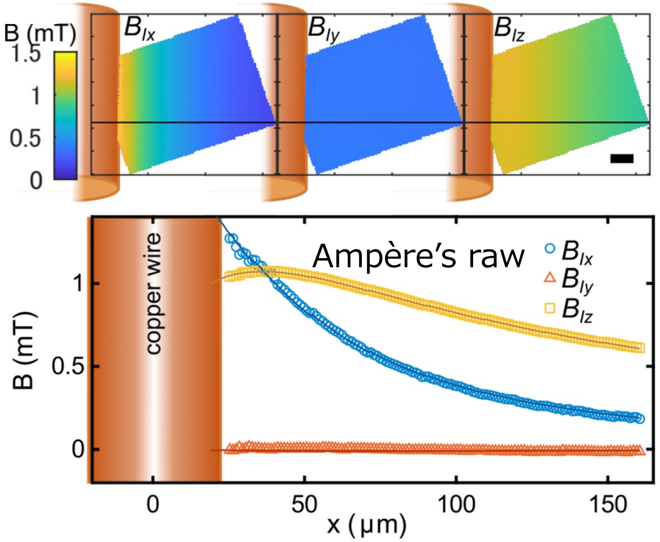
Cross-section





Quantum vortices
in superconductor thin film

N. Shunsuke *et al.*, Appl. Phys. Lett. **123**, 112603 (2023)



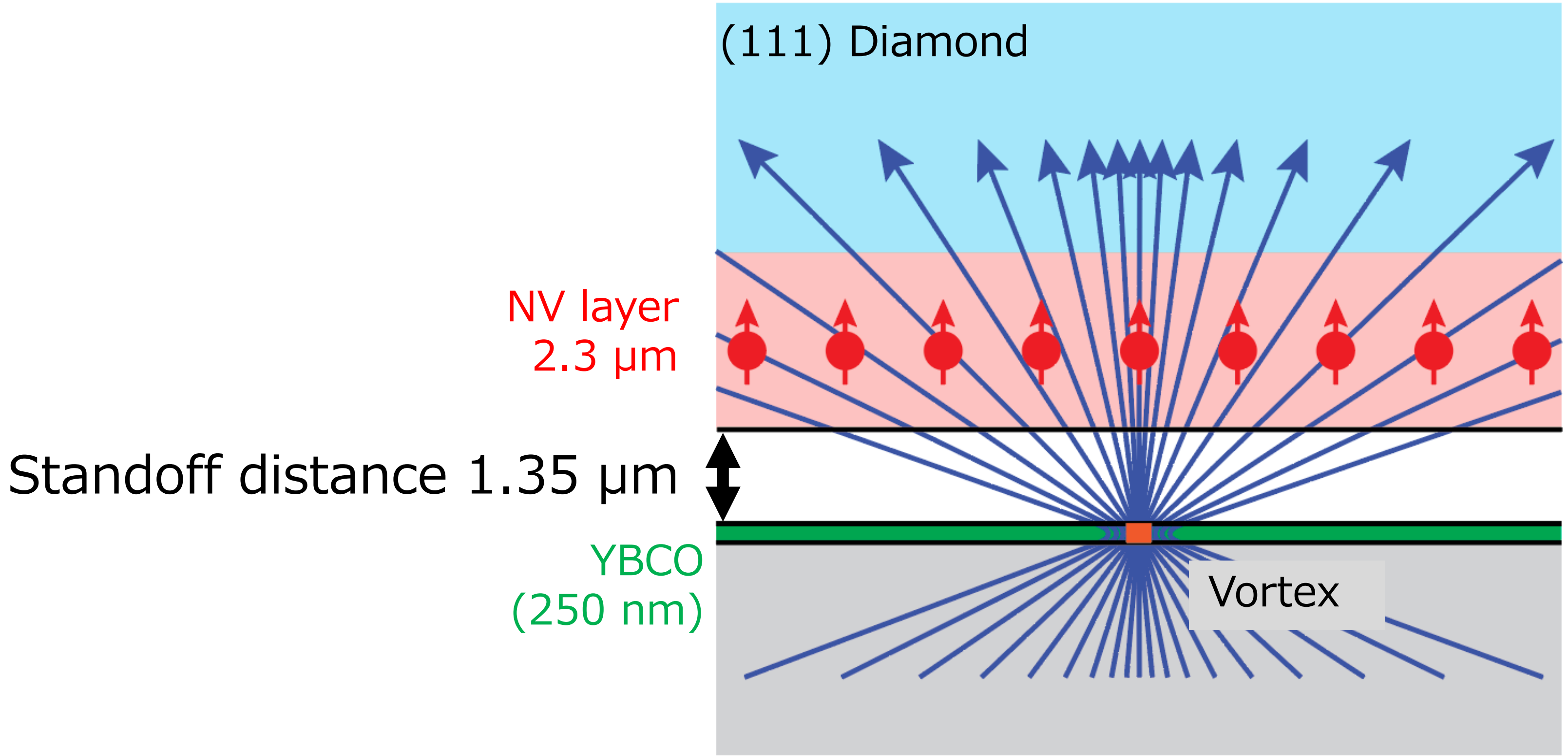
Vector magnetometry
of stray field from current

M. Tsukamoto *et al.*, Appl. Phys. Lett. **118**, 264002 (2021)

Challenge in the imaging using NV ensembles

The standoff distance is typically ~1 μm

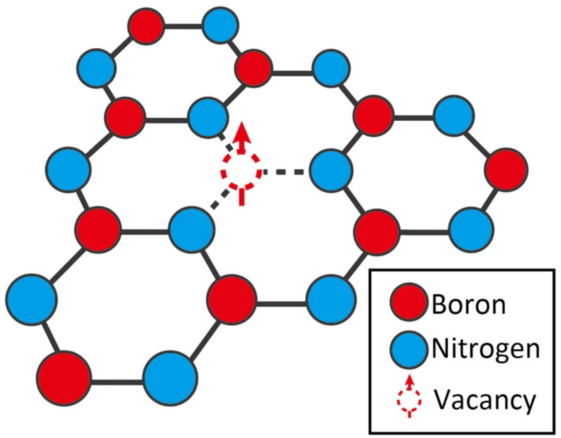
→ Limits sensitivity/spatial resolution



Cross-section

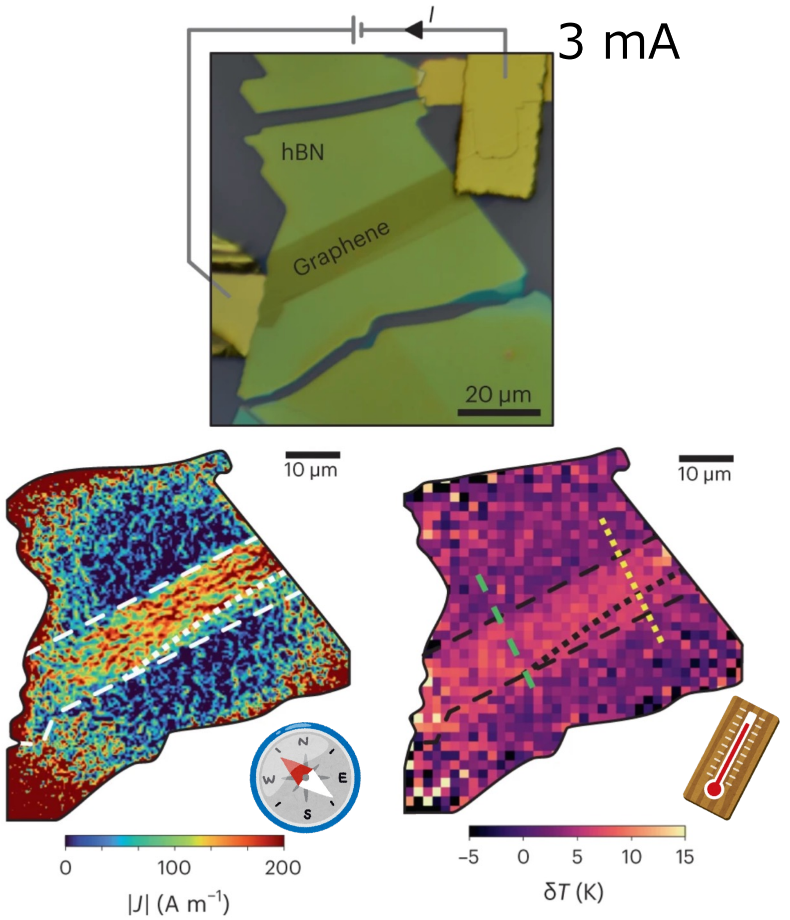
N. Shunsuke *et al.*, Appl. Phys. Lett. **123**, 112603 (2023)

hBN quantum sensor (Since 2020)



Boron vacancy (V_B) defect

A. Gottscholl *et al.*, Nat. Mater. **19**, 540 (2020)



A. J. Healey *et al.*, Nat. Phys. 19, 87 (2023)

Visualization of current & joule heating of 4-nm thick graphite @ RT

P. Kumar *et al.*, Phys. Rev. Applied **18**, L061002 (2022)
M. Huang *et al.*, Nat. Commun. **13**, 5369 (2022)
Review: S. Vaidya *et al.*, ADV PHYS-X **8**, 2206049 (2023)

Difference with NV centers

- van der Waals crystal (2D material)
- Single vacancy (not complex defects)

This presentation

- Principles of quantum sensing
- Creation of V_B defects
- Magnetic imaging using sensor array

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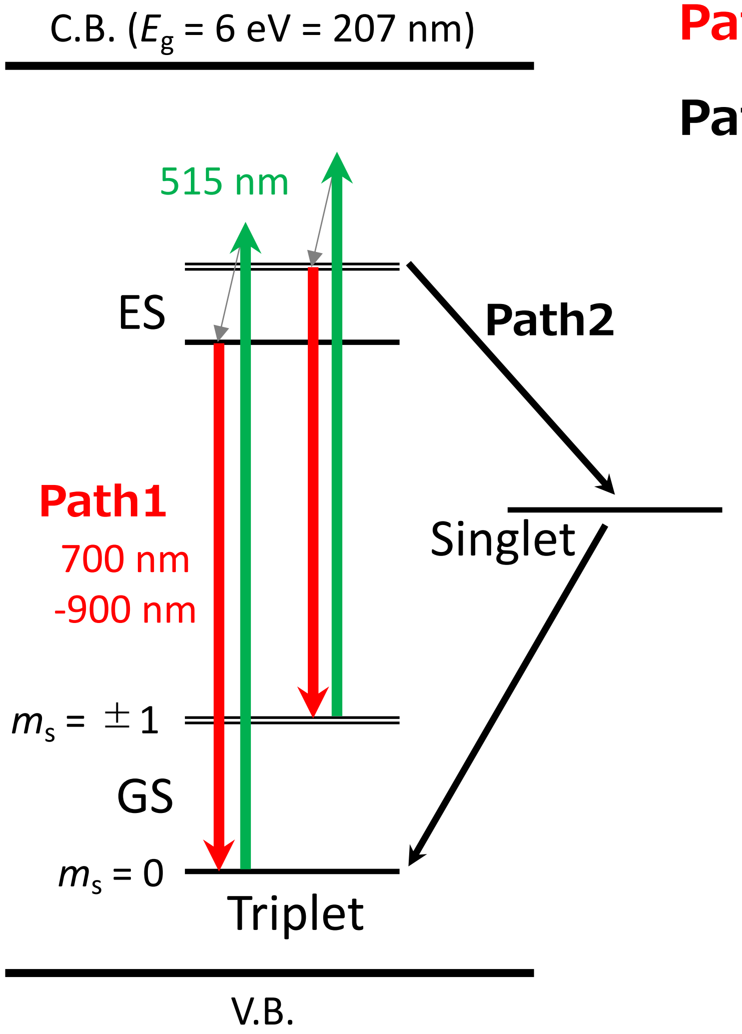
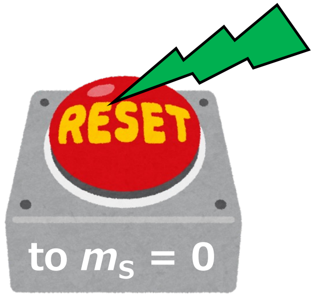
Optical transition



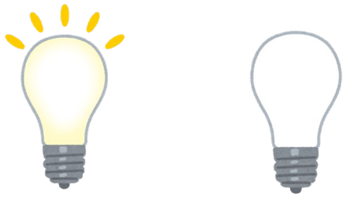
Path1: Radiative (PL), spin does not change

Path2: Non-radiative, spin selective ($m_S = \pm 1 \rightarrow m_S = 0$)

✓ Continuous excitation polarizes the sensor to m_S = 0 state
→ **Initialization**

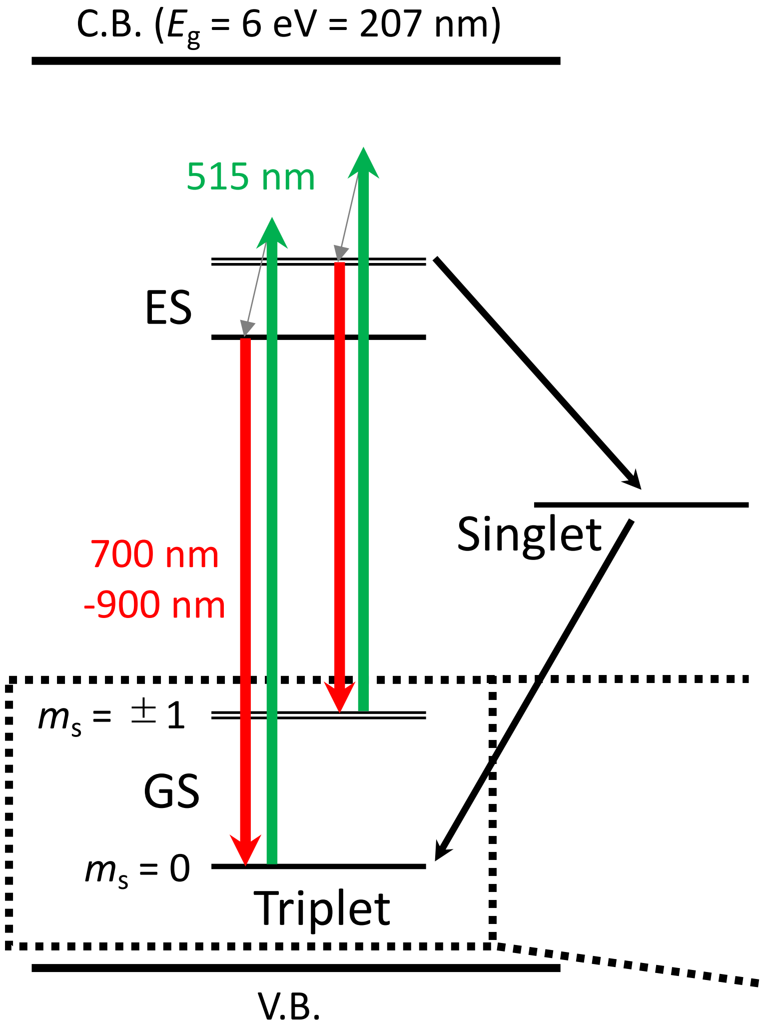


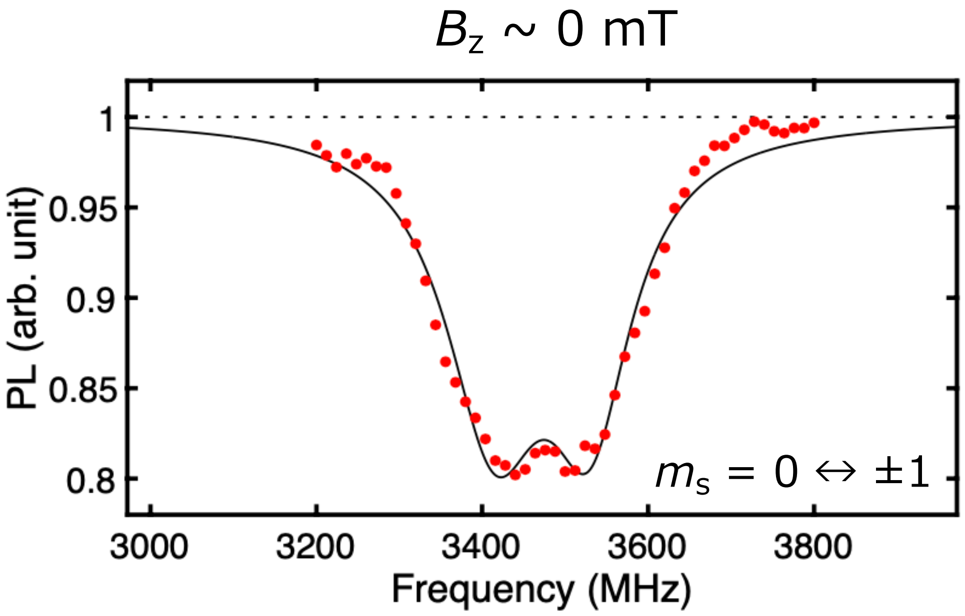
✓ $m_S = \pm 1$ state has less intensity due to the non-radiative transition
→ **Readout**

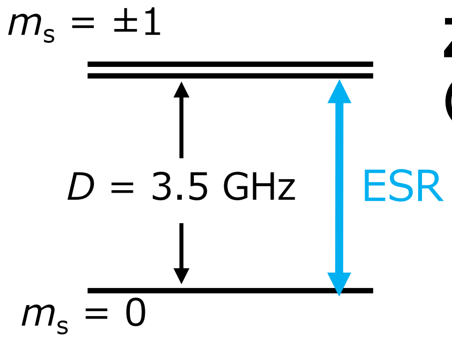


$m_S = 0$　　$m_S = \pm 1$

Optically detected magnetic resonance (ODMR)







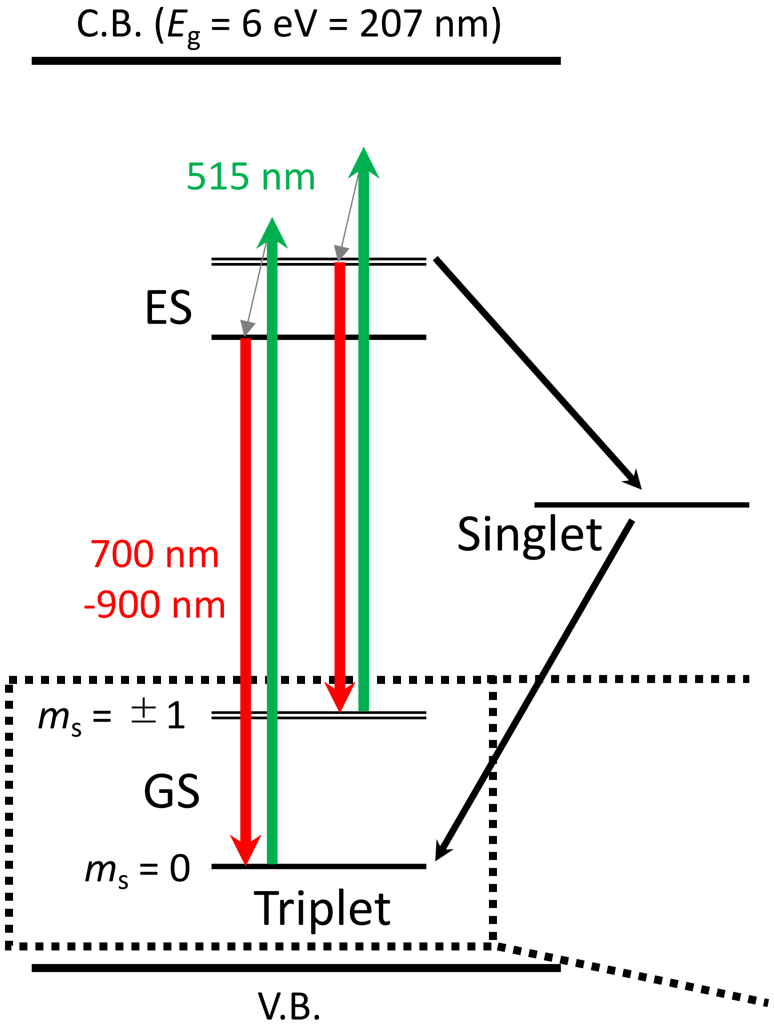
Zero-field splitting
(dipole interaction)

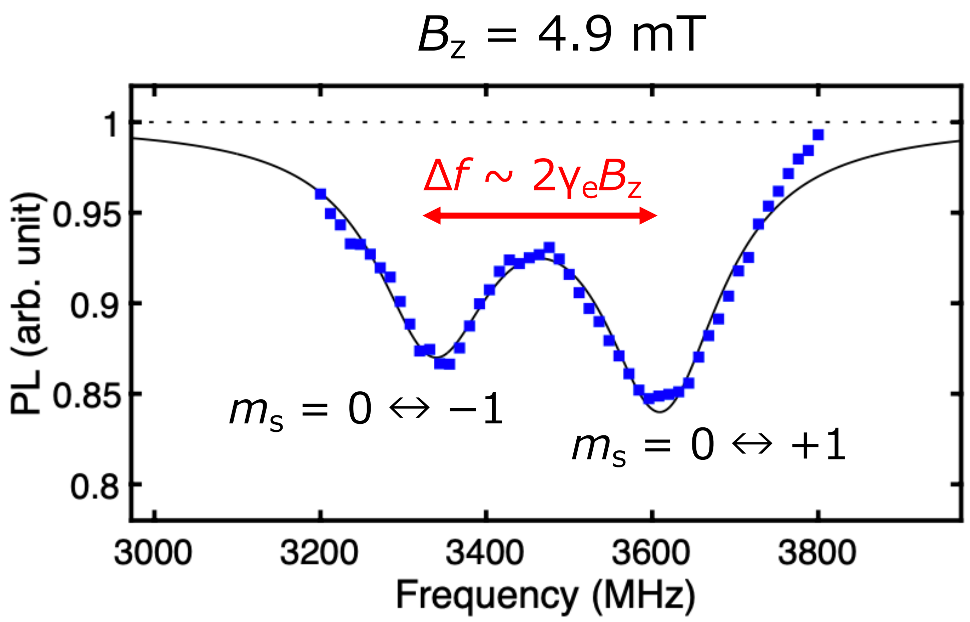
$$\hat{H} = D\hat{S}_z^2$$

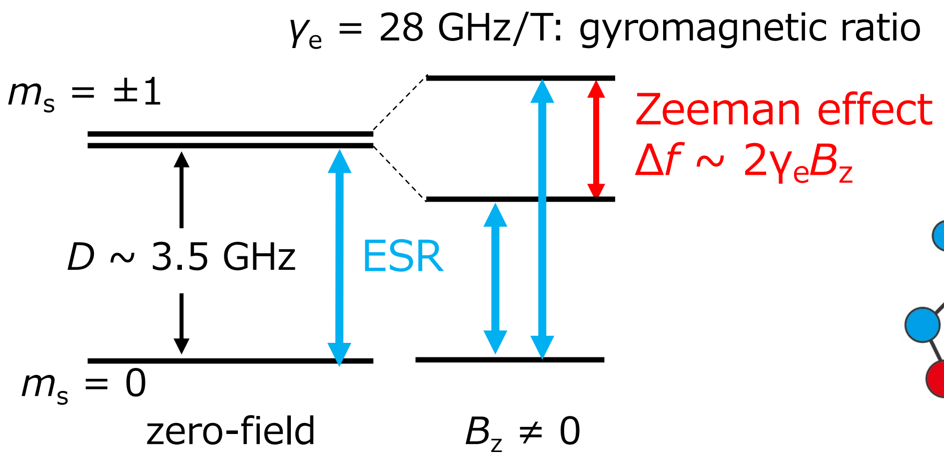
$dD/dT = -623$ kHz/K

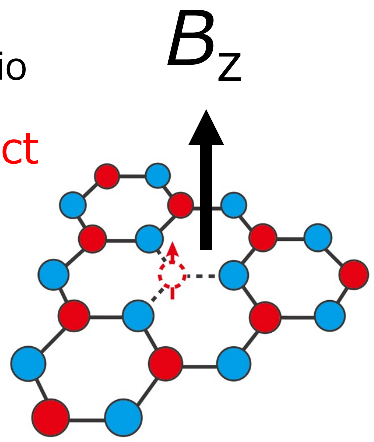
A. Gottscholl et al., Nat. Commun. **12**, 4480 (2021)

Quantitative magnetometry









Quantitative estimation of magnetic field from resonant freq.

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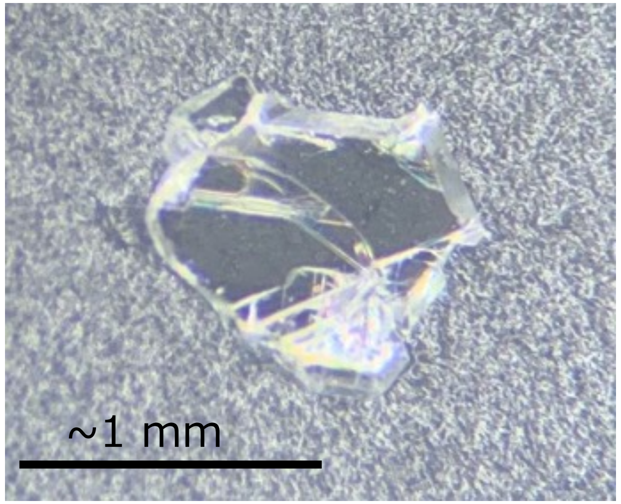
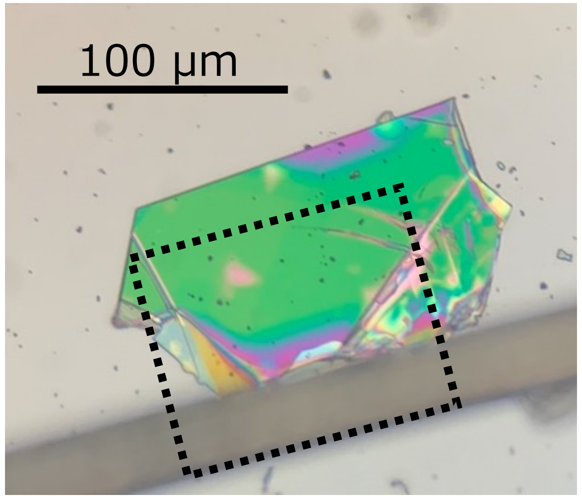
Conventional method: Creation of V_B defects



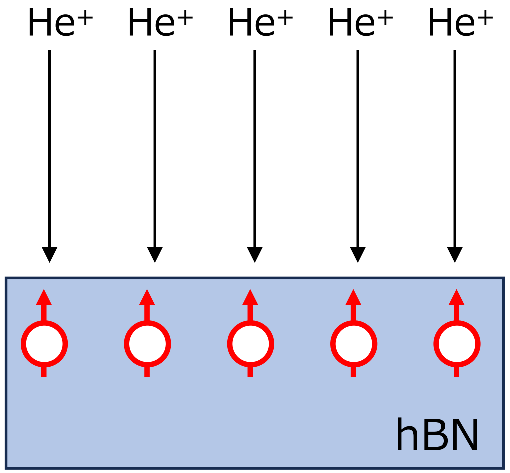
hBN single crystal (Bulk)

Cleave

with scotch tapes

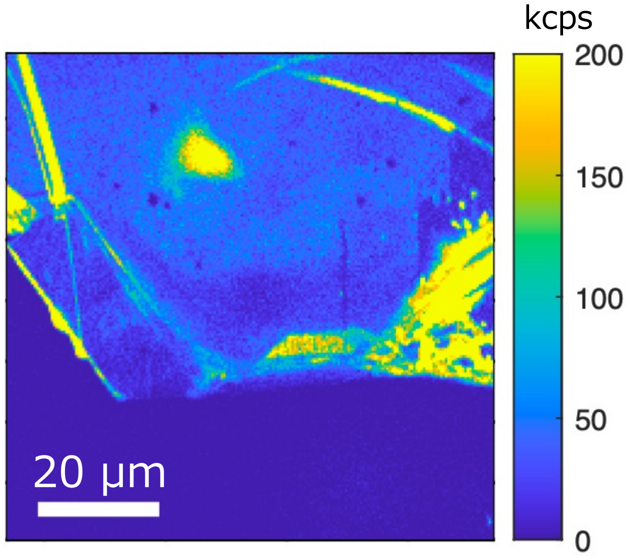


Flake (Thickness~100nm)



Ion implantation (He, 30 keV, 10^{15} cm^{-2})

N.-J. Guo *et al.*, ACS Omega **7**, 1733 (2022)

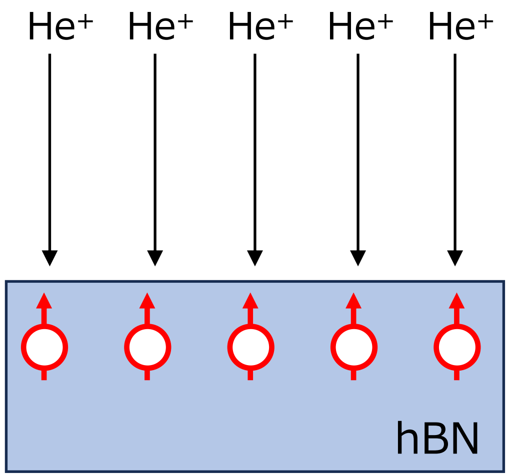


PL map @ Laser 13 µW

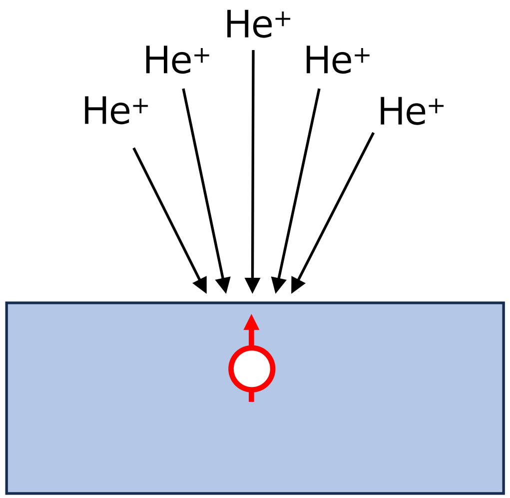
KS *et al.*, Appl. Phys. Lett. **122**, 244003 (2023)

This work: Arranging sensors with HIM

Conventional method:
Neutron or Ion irradiation



This work:
Focused He ion beam



Helium ion microscope (HIM)

Carl Zeiss ORION Plus @ AIST SCR
Resolution < 1 nm

Advantage: Uniform

Further challenge:
Optical resolution > standoff

Advantage: Sensor arrangement with high precision

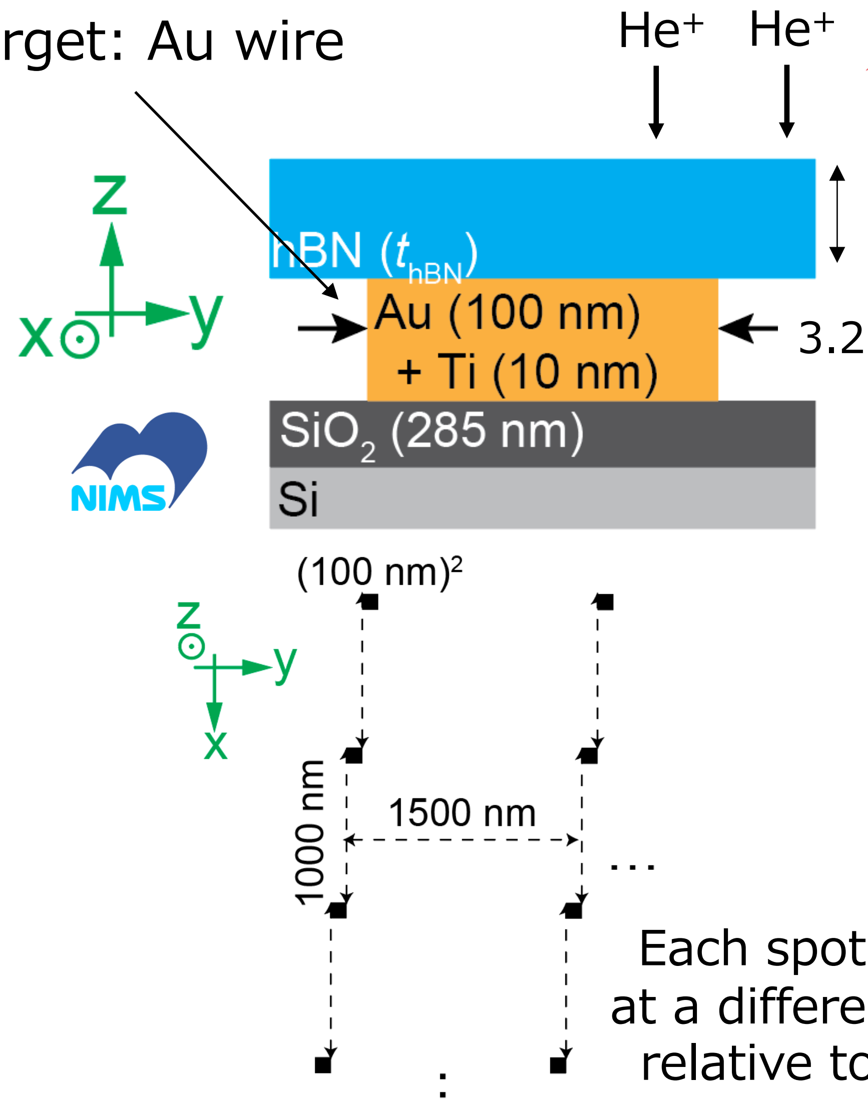
Not straight forward for 2D wide field imaging

→ We arrange special array for high resolution imaging

KS *et al.*, Appl. Phys. Lett. **122**, 244003 (2023)

Proof of principle: Creation of sensor array

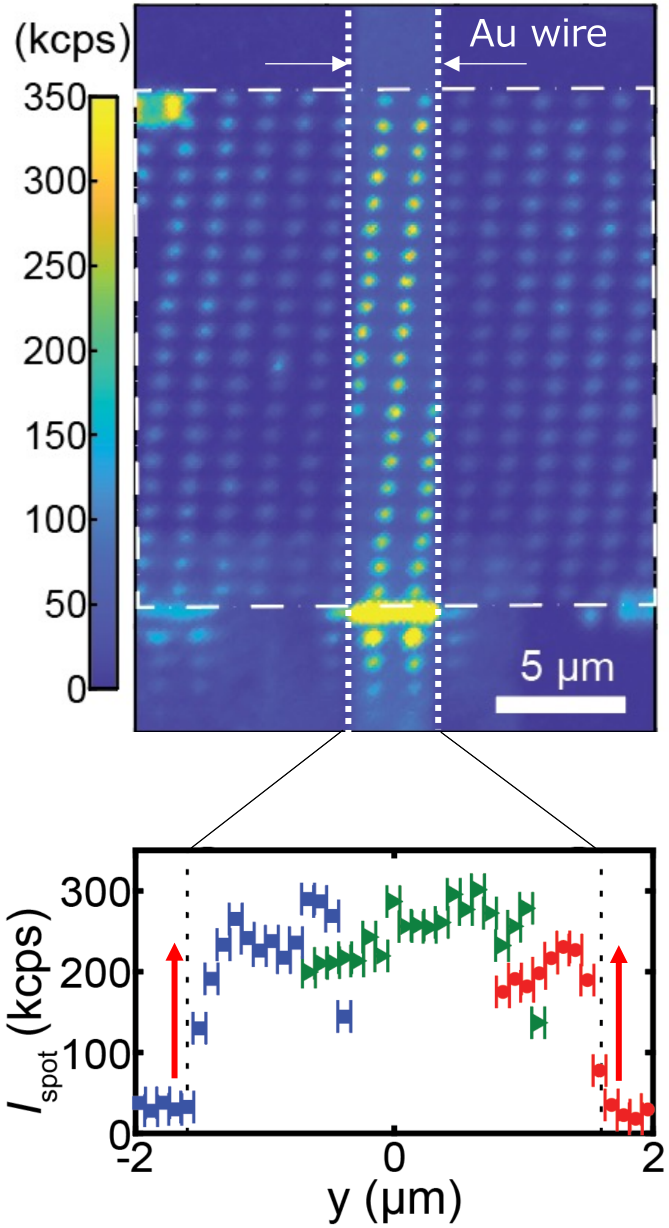
Target: Au wire



Each spot is placed at a different position relative to the wire

Irradiation pattern

(30 keV, 10^{15} cm^{-2})

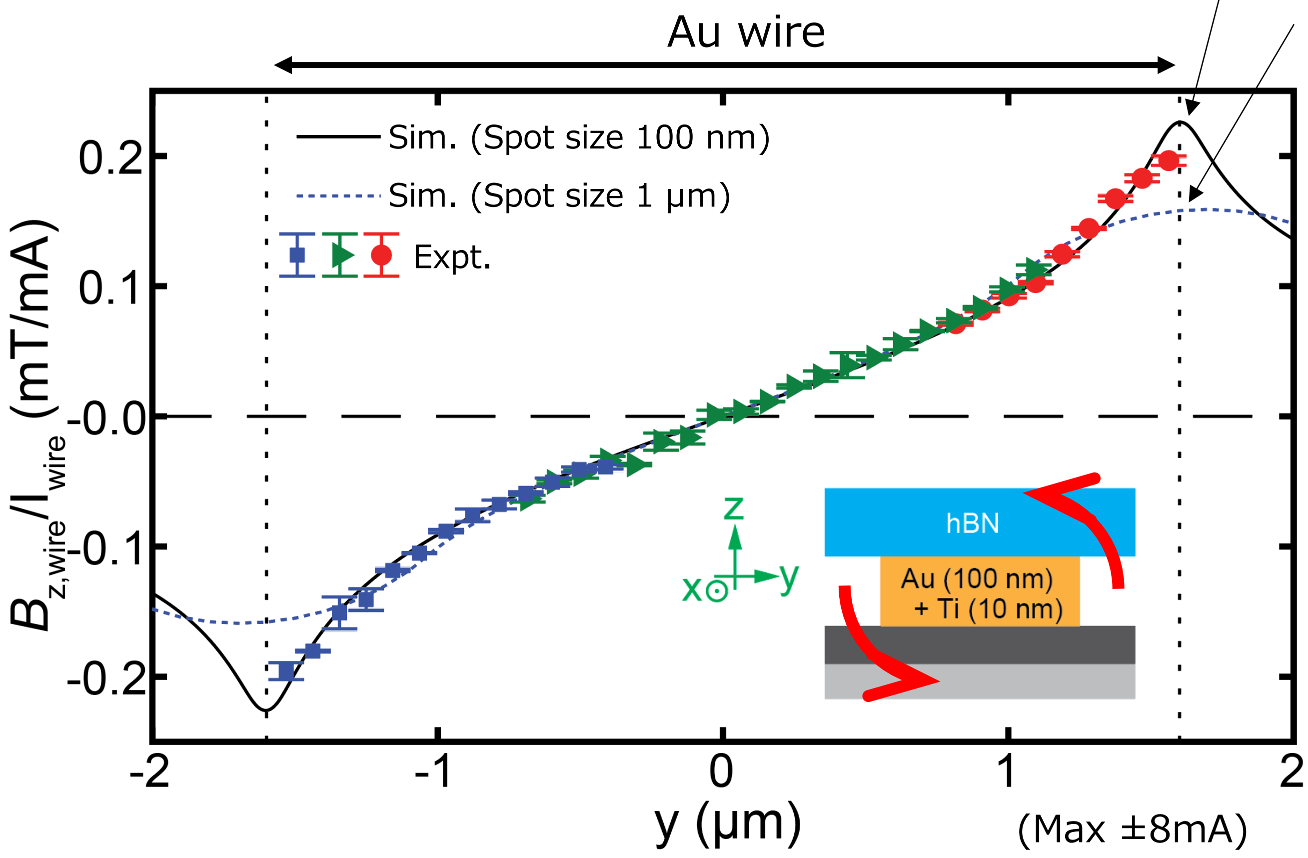


Steep rise

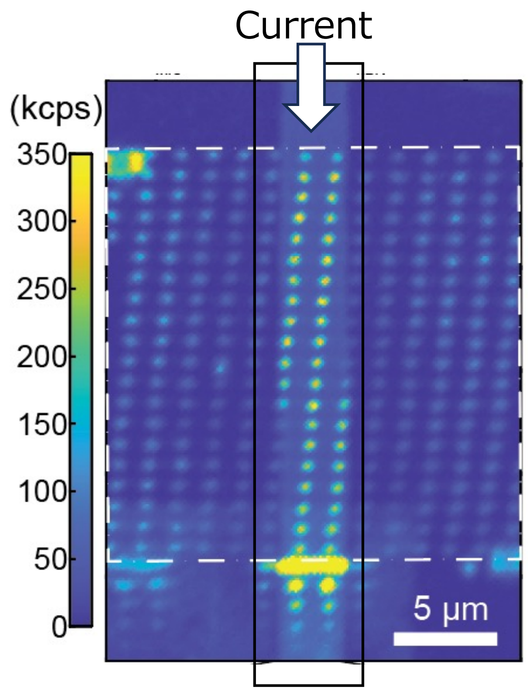
Magnetic imaging with sensor array

Present situation

Typical resolution (1 μm)



(Max ±8mA)



Sensitivity: 73.6 μT/$Hz^{0.5}$ (430 μA/$Hz^{0.5}$)

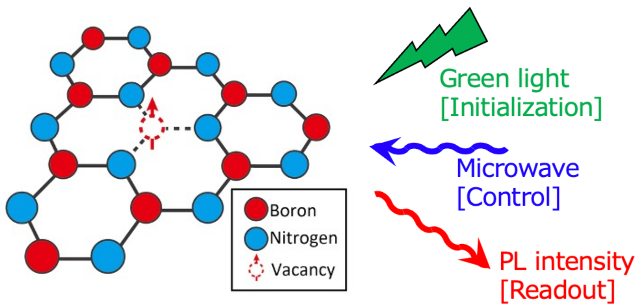
Quantitative, high spatial resolution (1D) magnetic field imaging

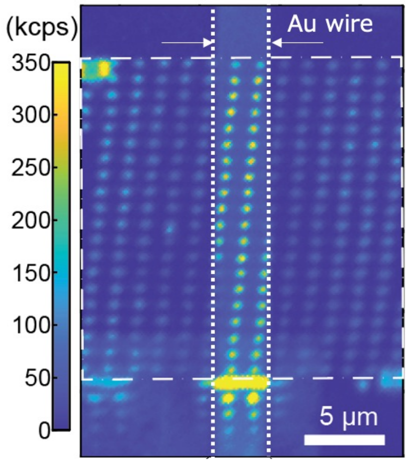
Summary

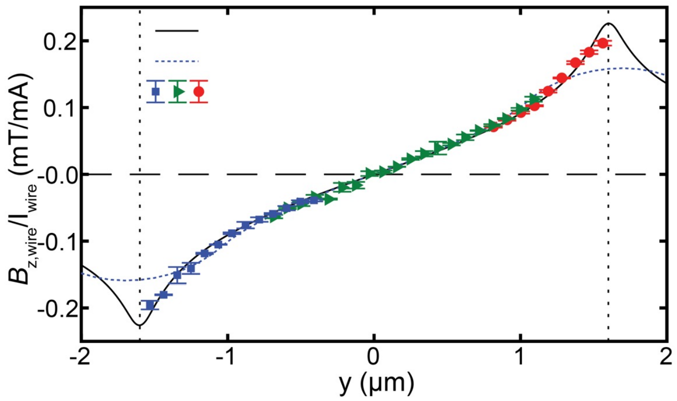
- Some color centers can be used as quantum sensor for magnetometry & thermometry
- V_B^- defects are nano-sized and quantitative magnetic field sensors
- Sensor arrangement at targeted position using helium ion microscope
- Proof-of-principle by visualizing stray field of current

- Outlook:
  Visualize current/magnetization/temperature of small or symmetric target

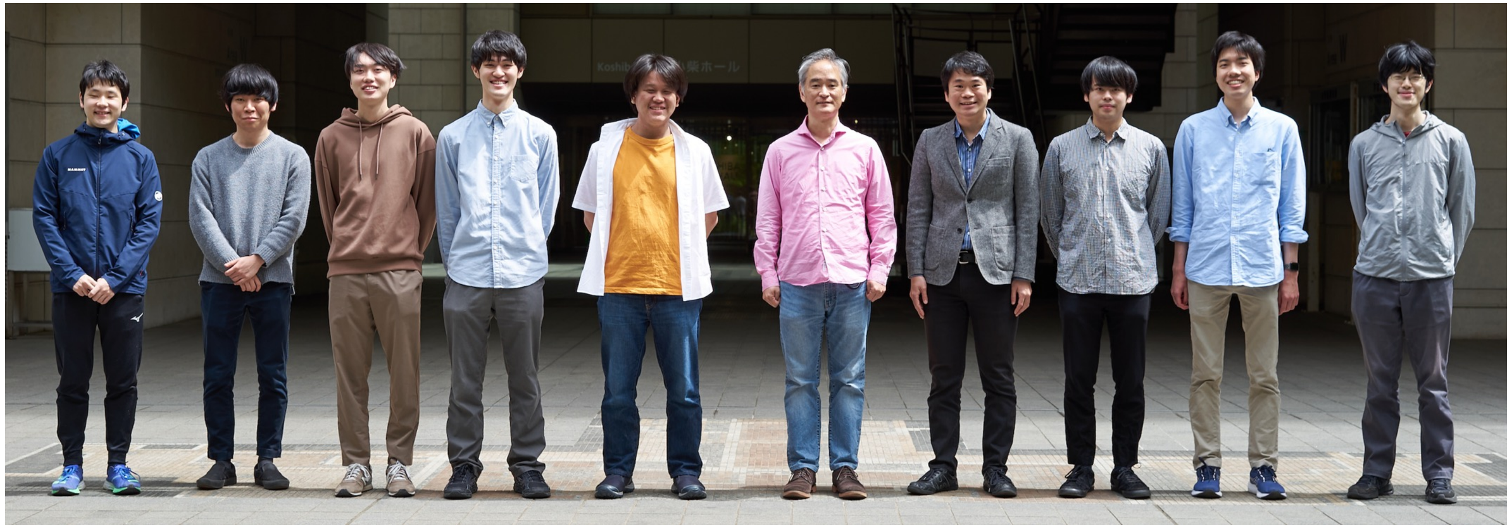
  Ex.) Edge current, Micro/Nano wire, vdW magnetic and superconducting materials, moiré junction devices







Acknowledgement



Group photo (2023)

Staff:
- K. Kobayashi (PI)
- K. Sasaki

D3: K. Ogawa
M. Tsukamoto

D2: Y. Nakamura
S. Nishimura

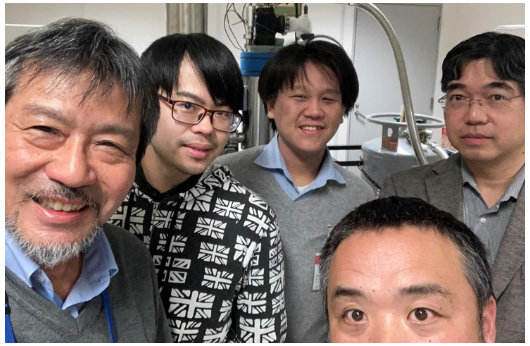
D1: H. Gu
K. Yamamoto

M2: T. Kobayashi
R. Suda

M1: R. Harada

Collaborators (about the topics in this presentation)

NIMS : T. Taniguchi, K. Watanabe, T. Iwasaki, T. Tsuji
AIST : S. Ogawa, Y. Morita, H. Watanabe
TUT : S. Nakaharai
Tokyo Tech. : M. Hatano, T. Iwasaki
Keio : K. M. Itoh, J. Ishi Hayase
Riken : E. Abe



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