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Quantum sensing with NV centers in diamond for light dark matter search

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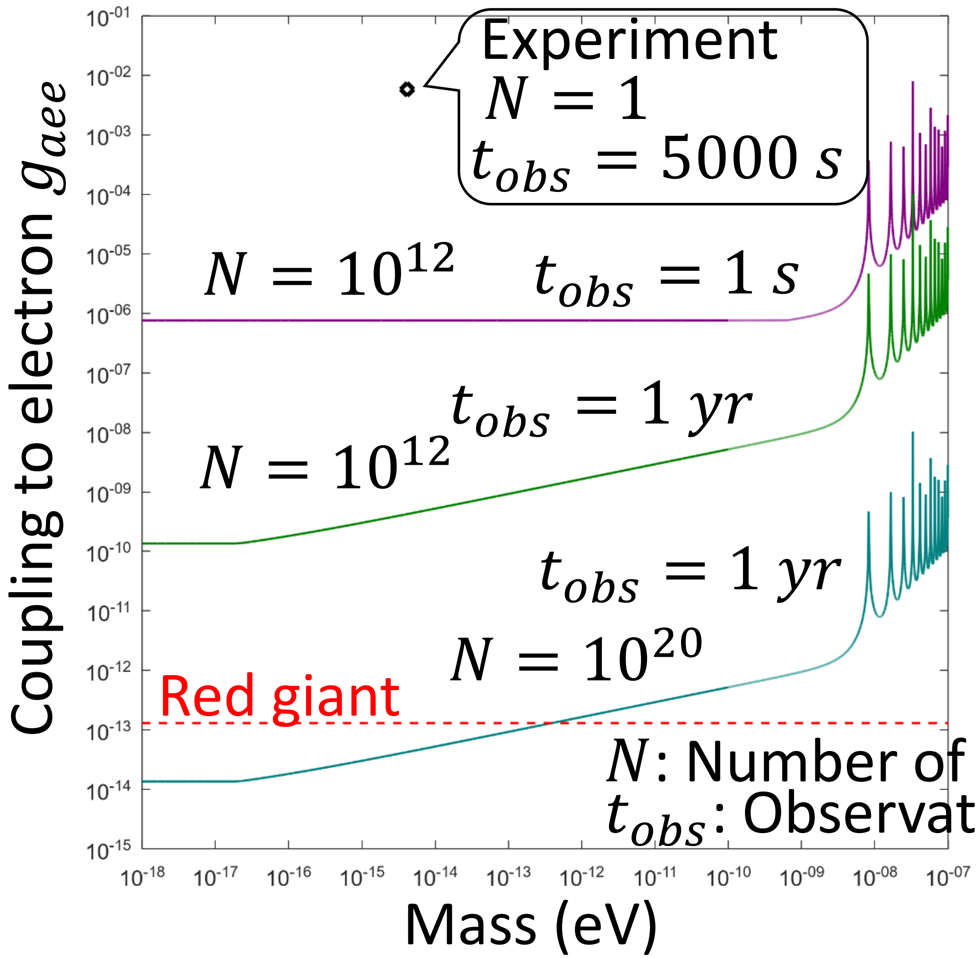
Q-LEAP

科研費 KAKENHI

Light dark matter search with nitrogen-vacancy centers in diamonds



[1] S. Chigusa, M Hazumi, E. D. Herbschleb, N. Mizuochi, and K. Nakayama, "Light dark matter search with nitrogen-vacancy centers in diamonds," arXiv:2302.12756.

$$H_{\mathrm{eff}} = \frac{g_{aee}}{m_e}\vec{\nabla} a \cdot \vec{S}_e$$

Dr. E. D. Herbschleb

12th (Yesterday) "Theory of Light Dark Matter Search with Nitrogen-Vacancy Centers in Diamonds" : K. Nakayama (Tohoku U. & QUP, KEK)

Today: NV diamond: initial experimental result

Content

1. NV center in diamond
2. Characteristics of NV centers for quantum sensor
3. How to measure?
4. Our recent researches : Light dark matter search with nitrogen-vacancy centers in diamonds

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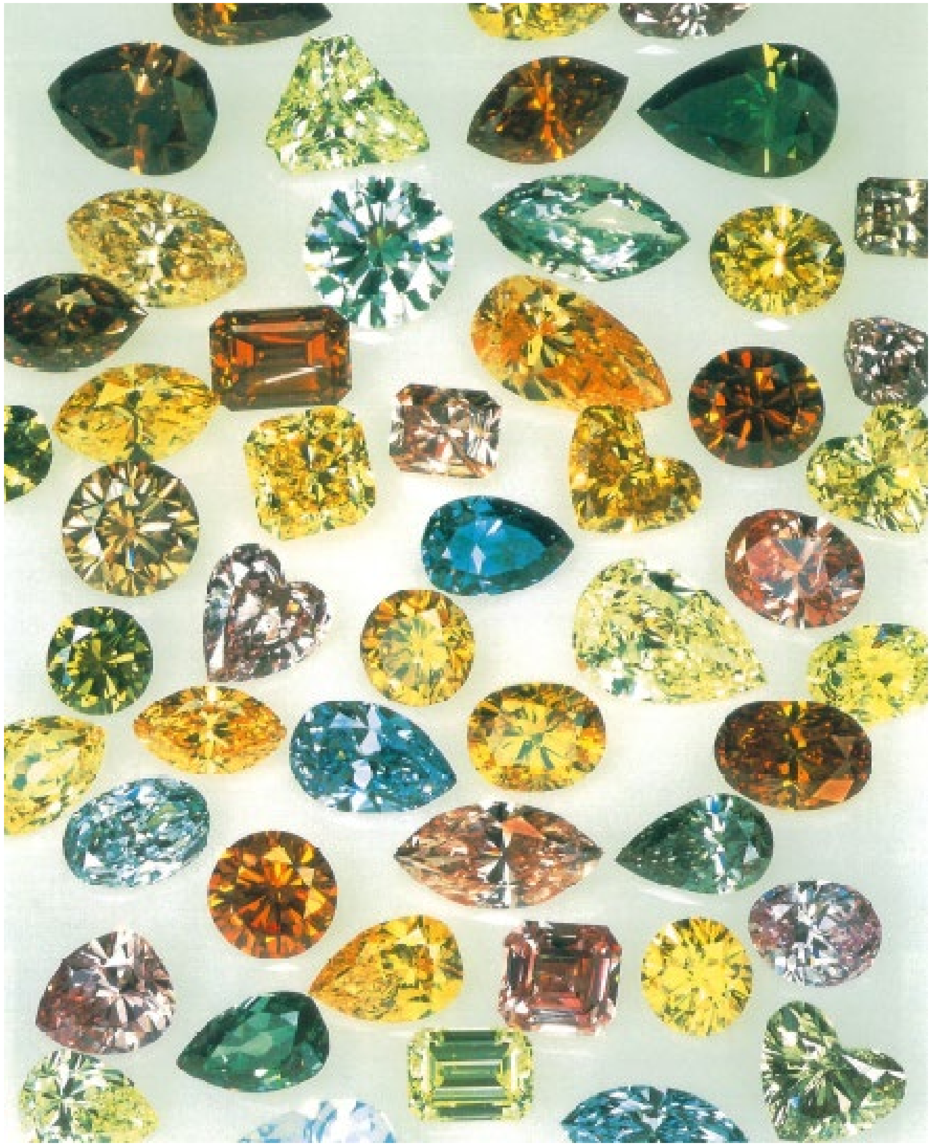
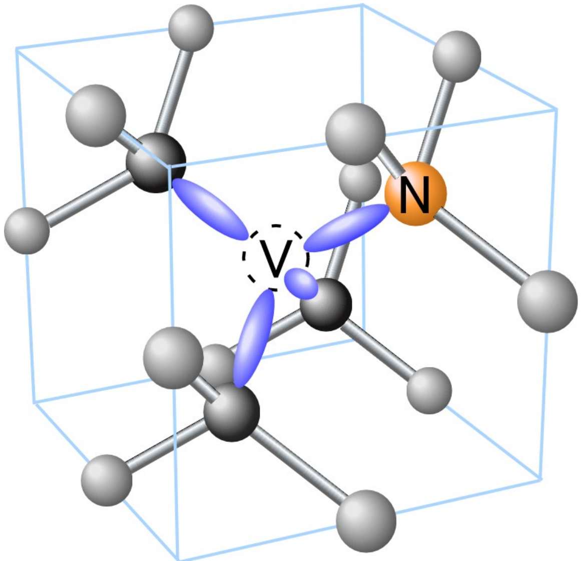
NV center in diamond



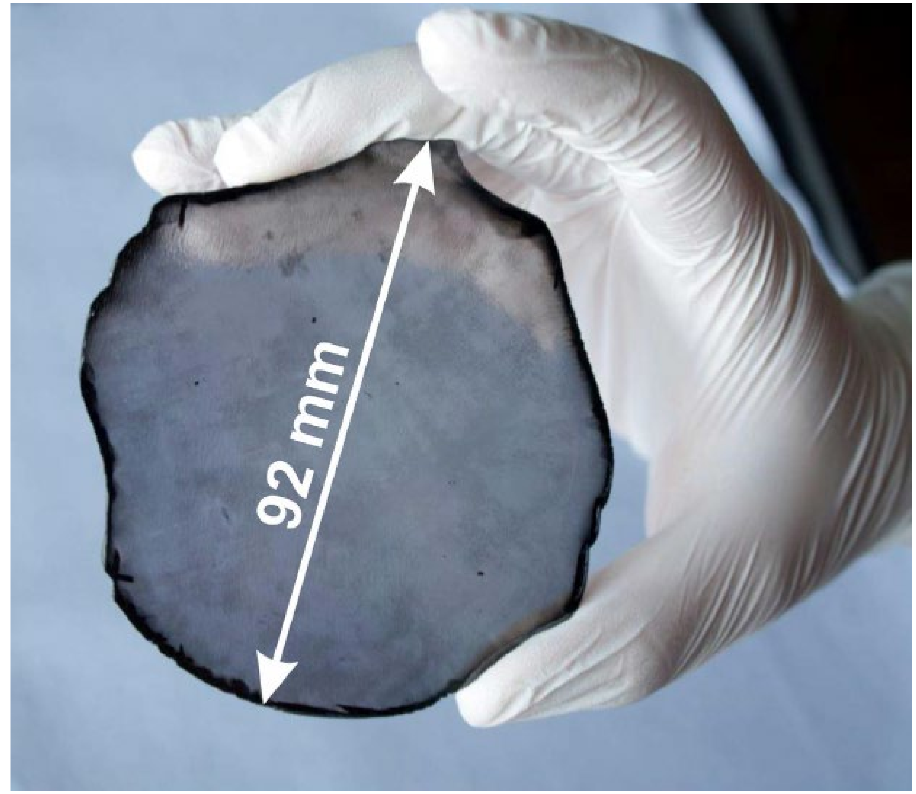
Impurities/defects cause Colors!



NV center

The atomic structure was identified by ESR in 1977.

J. H. N. Loubser & J. A. van Wyk, Diamond Res., p. 11, 1977



Synthetic Diamond (CVD, HPHT) Commercially available (4-10 mm□, http://www.e6.com/)

Hetero-epi, CVD, single crystal

Scientific reports 7:44462 (2017) doi:10.1038/srep44462

The diamond will lose its value as gem stones, but its excellent characters is interested by scientists.

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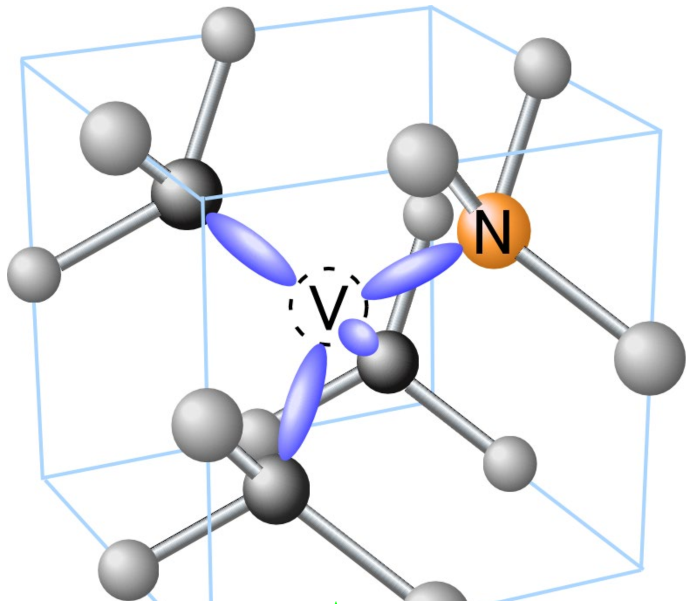
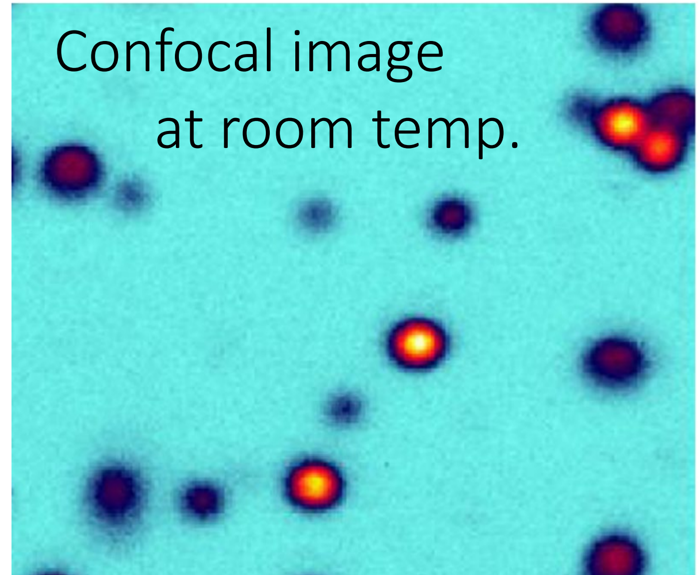
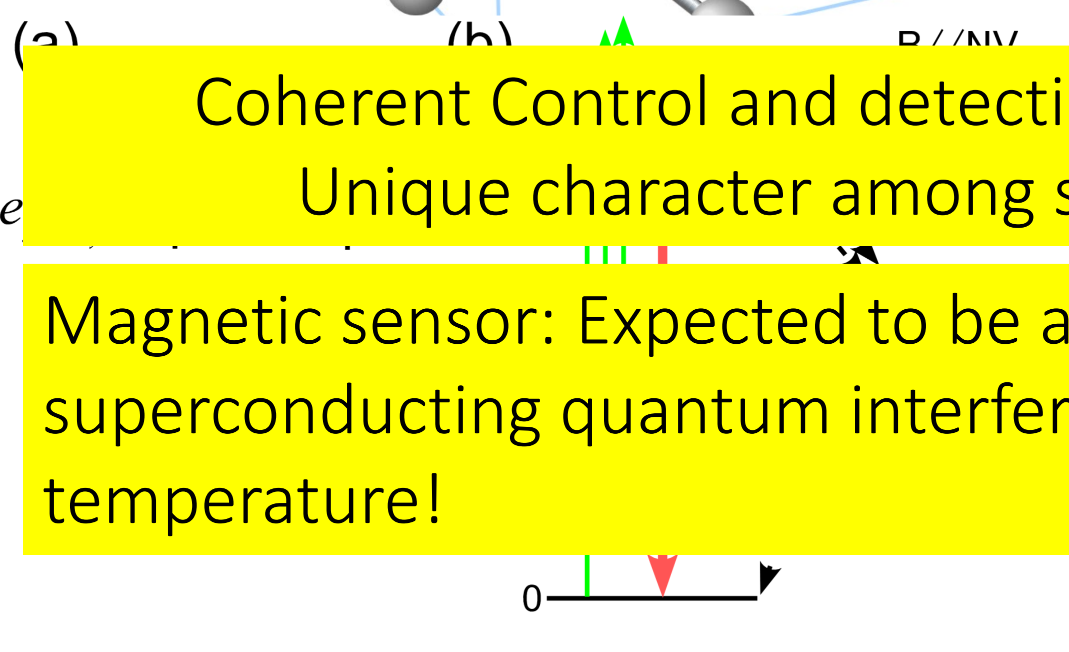
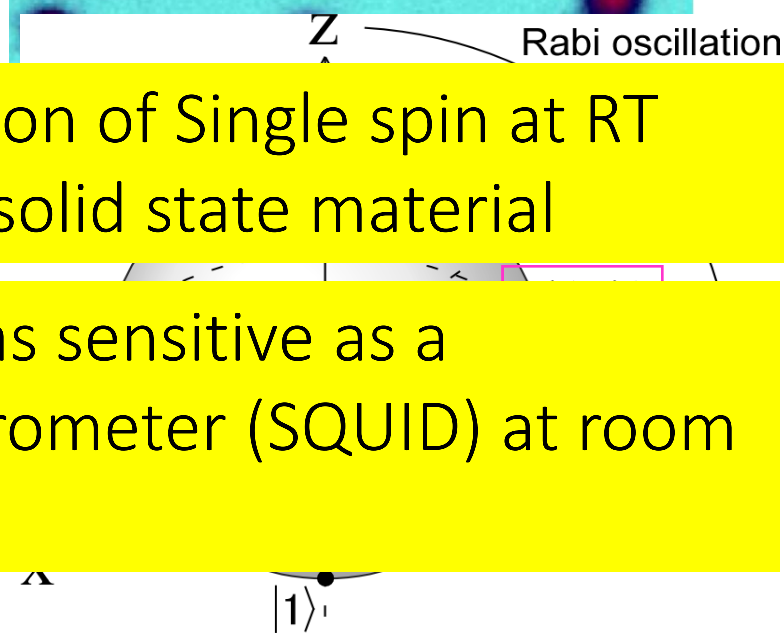
NV center in diamond









Coherent Control and detection of Single spin at RT
Unique character among solid state material

Magnetic sensor: Expected to be as sensitive as a superconducting quantum interferometer (SQUID) at room temperature!

Characteristics of NV center for sensing

Magnetic field sensitivity : η

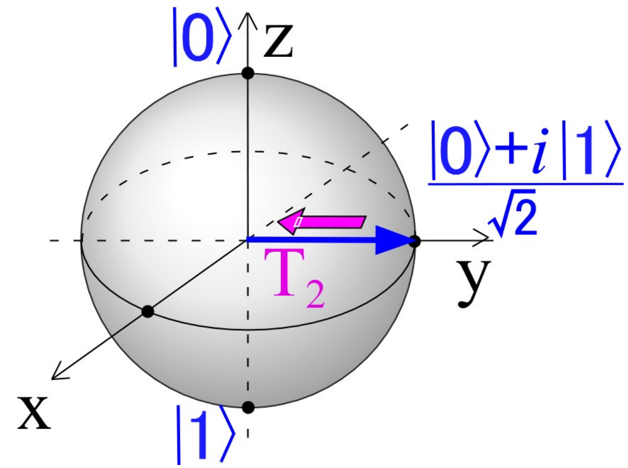
$$\eta \propto \frac{1}{\sqrt{n_{NV} T_2}}$$

n_{NV} : The number of NV

Superposition state

$$|\Psi\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$$

Coherence time (T_2) :



Long T_2 : Longest T_2 among solid state electron spins at RT.

Sensing of magnetic field, electric field, temperature, pressure, pH

Why can we enhance sensitivity and spatial resolution?

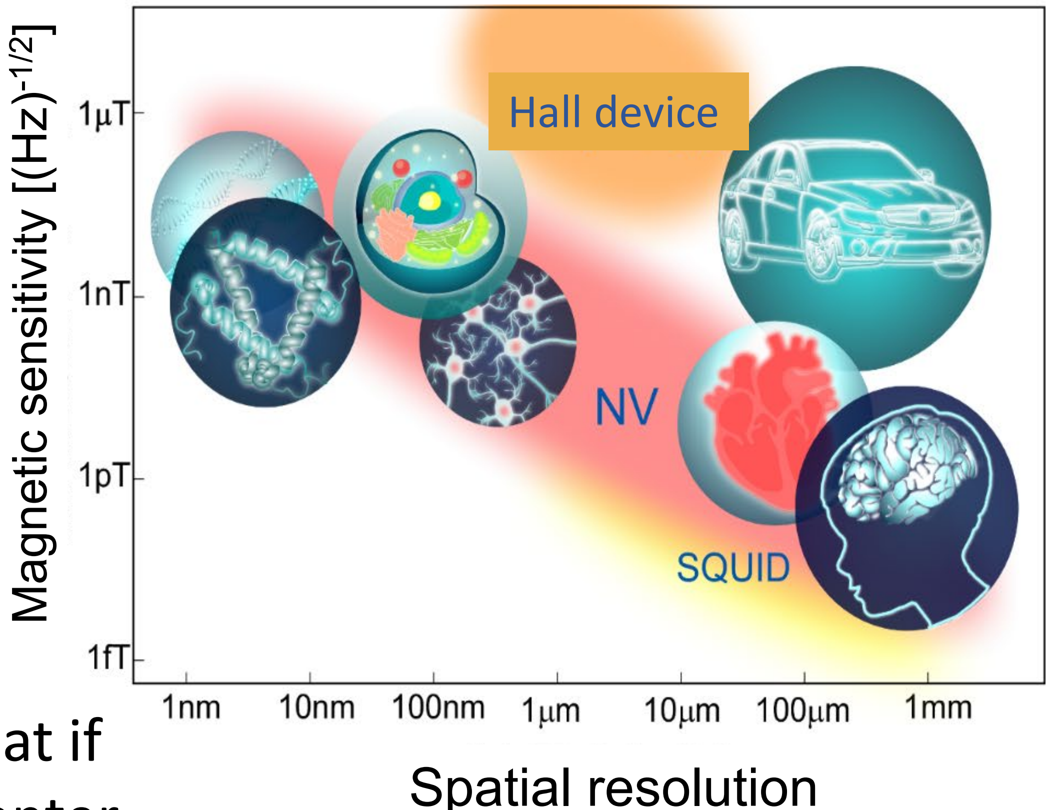
Sensitivity (η)

$$\eta \propto \frac{1}{\sqrt{n_{NV} T_2}}$$

n_{NV} : Number of NV

Not only T_2 but also the number of NV also contributes to the sensitivity.

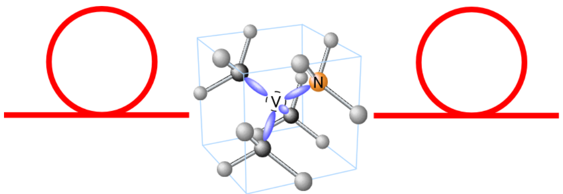
The trade-off relationship is that if the concentration of the NV center increases, T_2 becomes shorter. If the concentration keeps constant and n_{NV} increases, the spatial resolution decreases.



Mizuochi, OYO BUTSURI, 87, 251-261(2018).

Expected applications

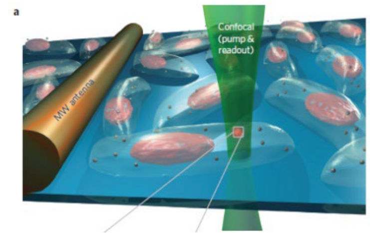
Quantum Cryptography



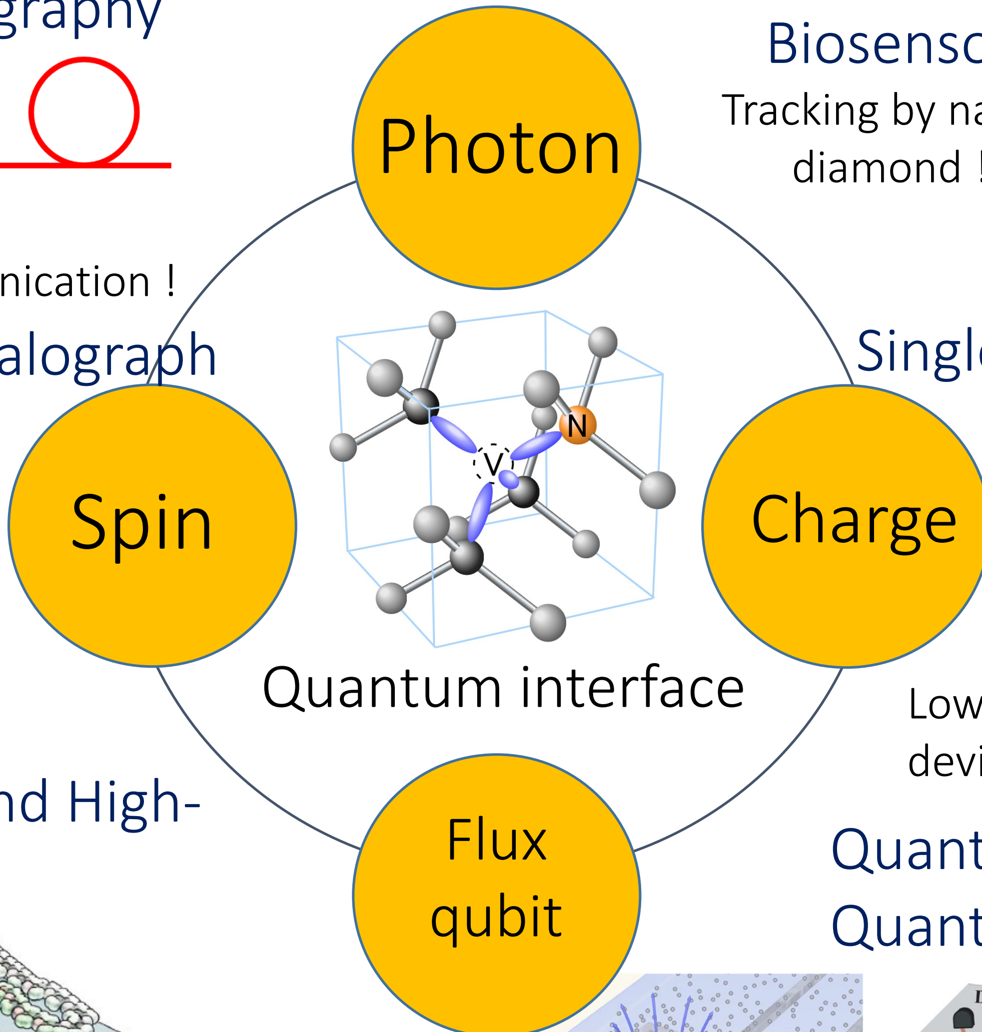
Unbreakable communication !

Biosensor

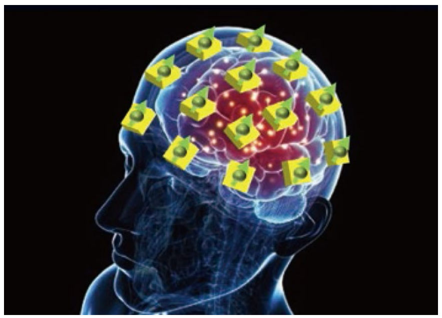
Tracking by nano-diamond !



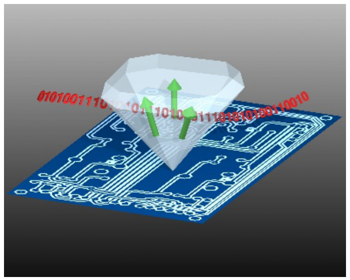
(Nat. Nanotech. 2012)



Magneto-encephalograph

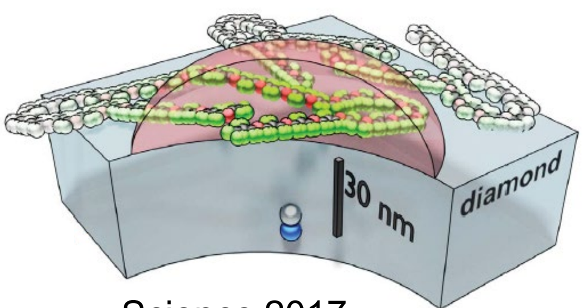


Single electron device



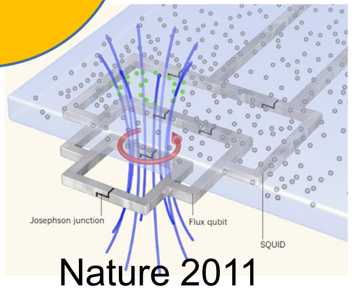
Low energy consumption device

High-sensitive and High-resolution NMR



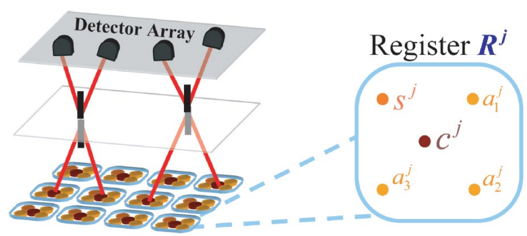
Science 2017

Ex. NMR of single protein



Nature 2011

Quantum computer, Quantum simulator



Jiang,et al, PRA 2008

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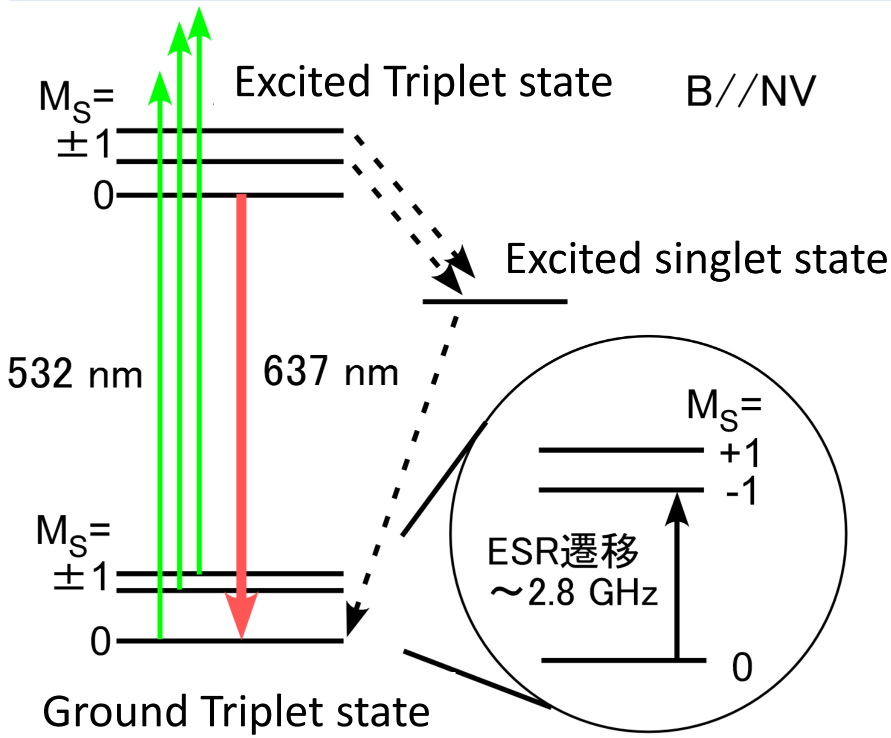
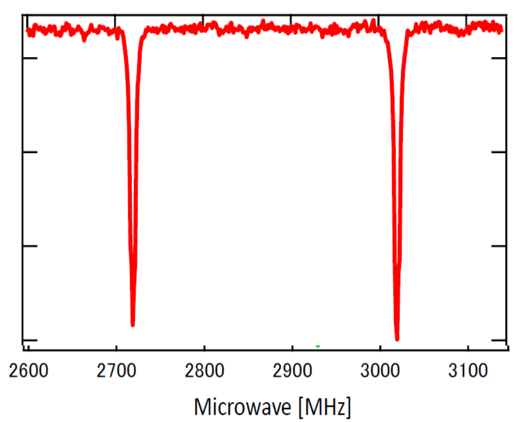
Measurement method : Optically detected magnetic resonance (ODMR)





1: Initialization （To M_S = 0）: Laser excitation (532 nm) and spin selective deactivation due to SOC.

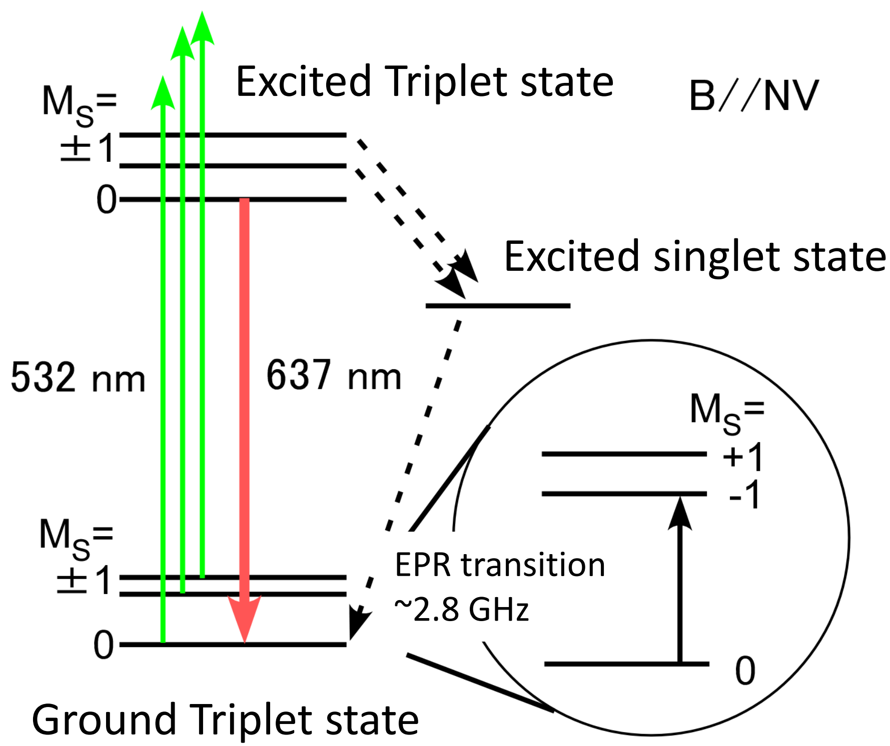
2: Magnetic resonance (To M_S=-1)

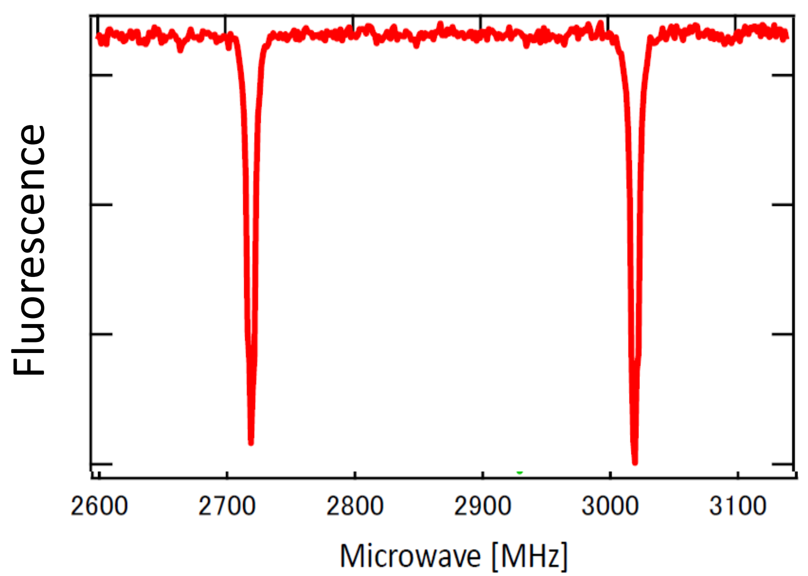
Microwave irradiation to Zero-field splitting (dipolar-dipolar interaction) = 2.87 GHz

3: Optical detection:

Laser excitation (532 nm) and <u>detection of change of fluorescence</u>.

How to sense the magnetic field?





ODMR spectrum of NV center

The resonance freq. of the ODMR signal shifts depending on the magnitude of the magnetic field. The magnetic field: from the shift of the resonant freq.!

The narrower the line width, the smaller the shift can be detected. Namely, the sensitivity improves! (The longer T_2, the narrower the line width!)

Magnetic field, temperature, electric field, and pressure can be measured!

Spin Hamiltonian

Zeeman

Spin-spin interaction (dipolar int.)

$$H_{gs} \cong \mu_B g_e \mathbf{S}\cdot\mathbf{B} + hD_{gs}\left[S_z^{\ 2} - \frac{1}{3}S(S+1)\right] - d_{gs}^{\ \perp}\left[E_x\left(S_xS_y + S_yS_x\right) + E_y\left(S_x^{\ 2} - S_y^{\ 2}\right)\right]$$

Magnetic field

Temperature

Stress

Electric field

Demonstrated high sensitivity (room temperature)

Temperature (single)

5 mK/$\sqrt{Hz}$

Neumann, et al,. Nano Lett. 2013

Stress

0.6 MPa/$\sqrt{Hz}$

Doherty, et al., PRL 2014.

Electric field (single)

202 V/cm$\sqrt{Hz}$

Dolde, et al., Nat. Phys. 2011.

Magnetic sensor sensitivity using the NV center

Ensemble (RT)
B_{AC}=~ 9 pT $Hz^{-1/2}$

PRX 2015

Ensemble (RT)
B_{DC}=~ 15 pT $Hz^{-1/2}$

PNAS 2017

Spatial resolution：50 μm × 50 μm × 0.5 mm

Single (RT)
B_{AC}=9.1 nT $Hz^{-1/2}$

Nature Commun. 2019

Single (RT)
B_{DC} = 10 nT $Hz^{-1/2}$

Nature Commun. 2019

Magnetic field sensitivity (Minimum detactable B)： η

$$\eta \propto \frac{1}{C\sqrt{n_{NV}\,\tau\,T_2}}$$

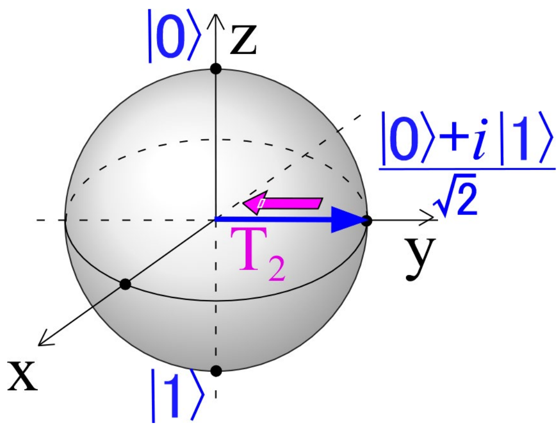
C ： readout contrast

n_N ： The number of NV

τ ： Measurement time

Phase measurement

We can obtain information such as magnetic field from the phase of coherence!



Coherence is generated by 90 degree pulse. After that, when the magnetic field from the outside changes, the coherence begins to rotate in the xy plane when viewed in the rotating coordinate system. Information on the magnetic field from the outside can be obtained from the phase.

Magnetic field sensitivity (Minimum detactable B) : η

$$\eta \propto \frac{1}{C\sqrt{n_{NV}\,\tau\,T_2}}$$

C : readout contrast

n_{NV}: The number of NV

τ : Measurement time

L. M. Pham, et. al., Phys. Rev. B **86**, 121202 (2012)

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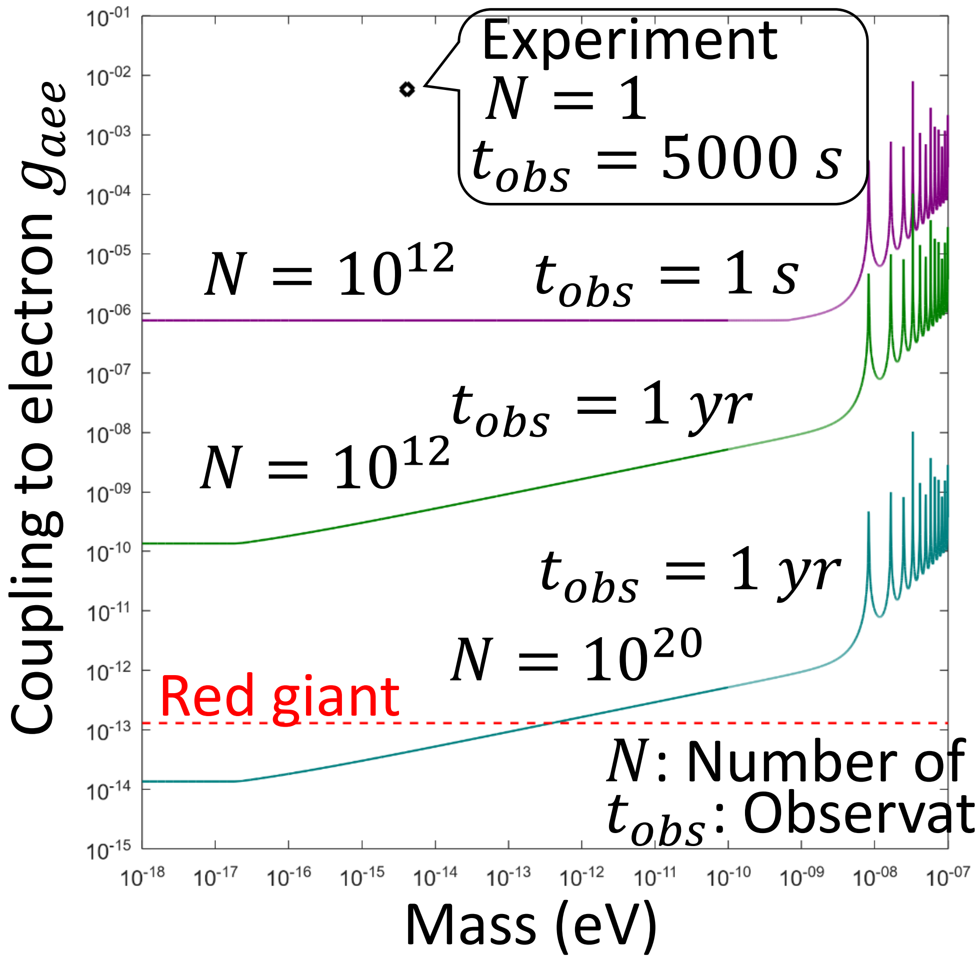
Light dark matter search with nitrogen-vacancy centers in diamonds



N: Number of NV centers
t_{obs}: Observation time

[1] S. Chigusa, M Hazumi, E. D. Herbschleb, N. Mizuochi, and K. Nakayama, “Light dark matter search with nitrogen-vacancy centers in diamonds,” arXiv:2302.12756.

$$H_{\mathrm{eff}} = \frac{g_{aee}}{m_e} \vec{\nabla} a \cdot \vec{S}_e$$

NV diamond: initial experimental result

We analyzed the advantages and limitations and demonstrated using NV center.

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