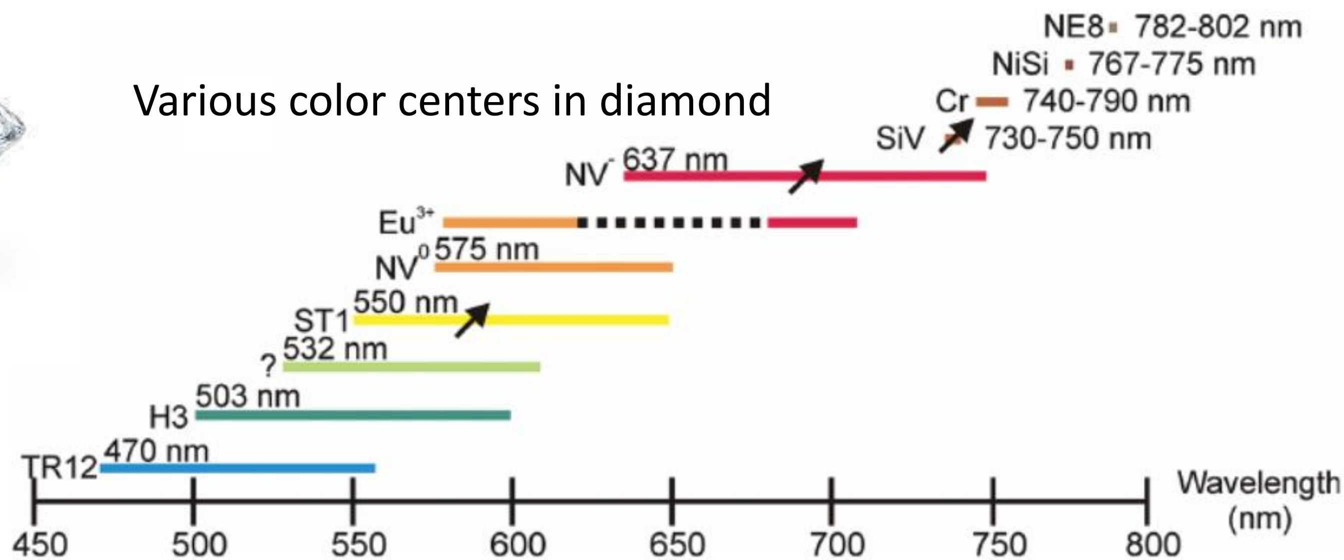
Harnessing Nitrogen Vacancy Centers in Diamond for Next-Generation Quantum Science and Technology

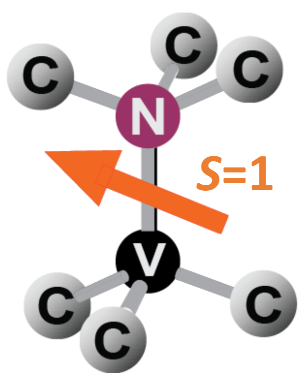
Chunhui (Rita) Du
Department of Physics
University of California, San Diego

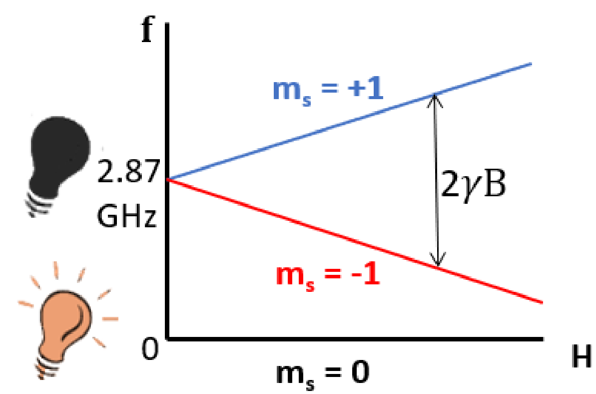
Introduction to NV centers in diamond



I. Aharonovich et al., *Adv. Opt. Mater.* **2**, 911 (2014)

Nitrogen vacancy (NV) center in diamond

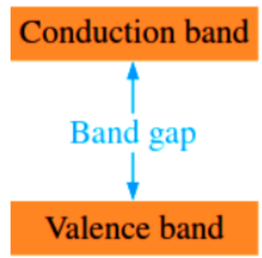


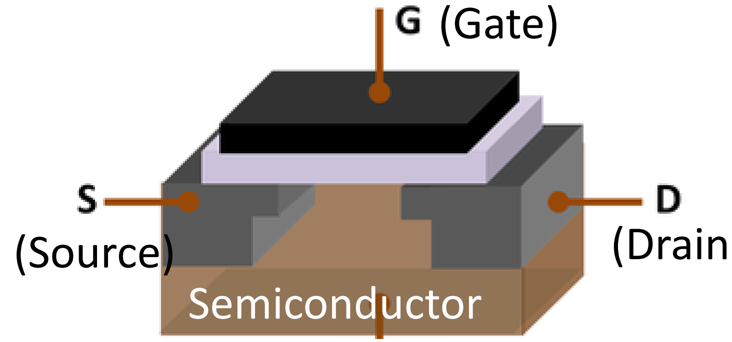


Conventional computing

- Conventional computing use binary codes i.e. bits 0 or 1 to represent information.

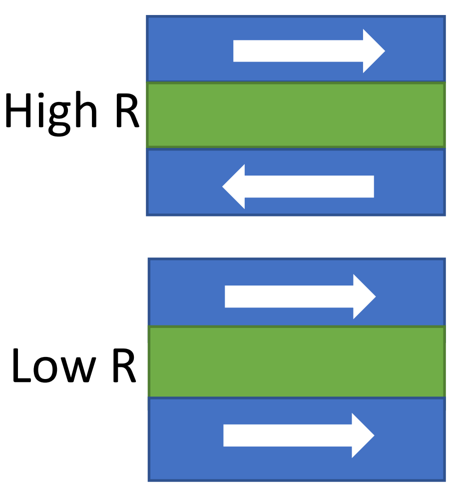
- **Transistor**



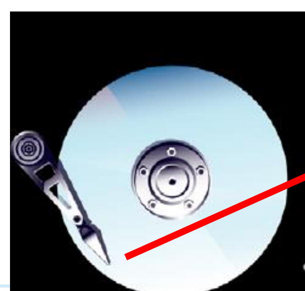


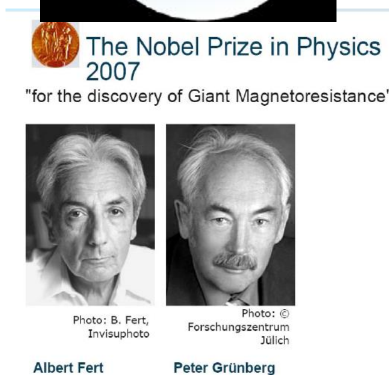
- **Spin-based devices**

Spin-dependent resistance

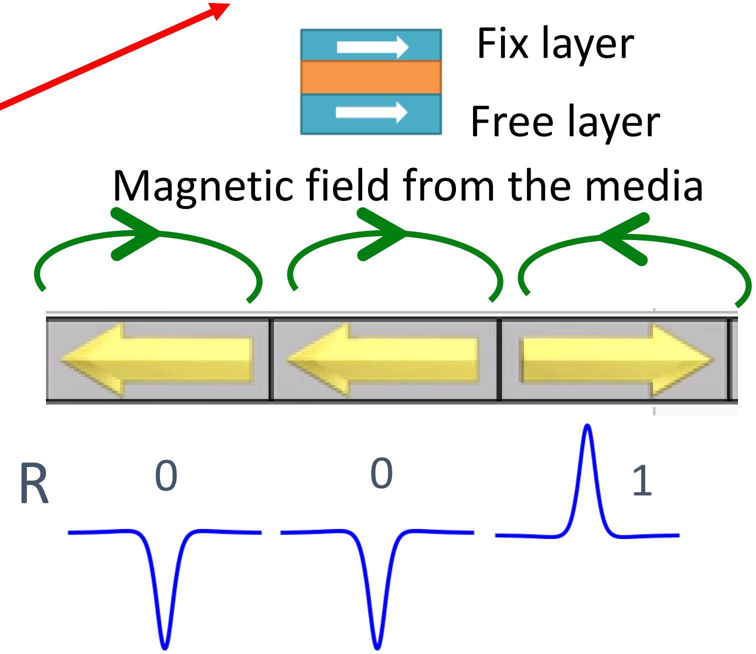


Hard drive

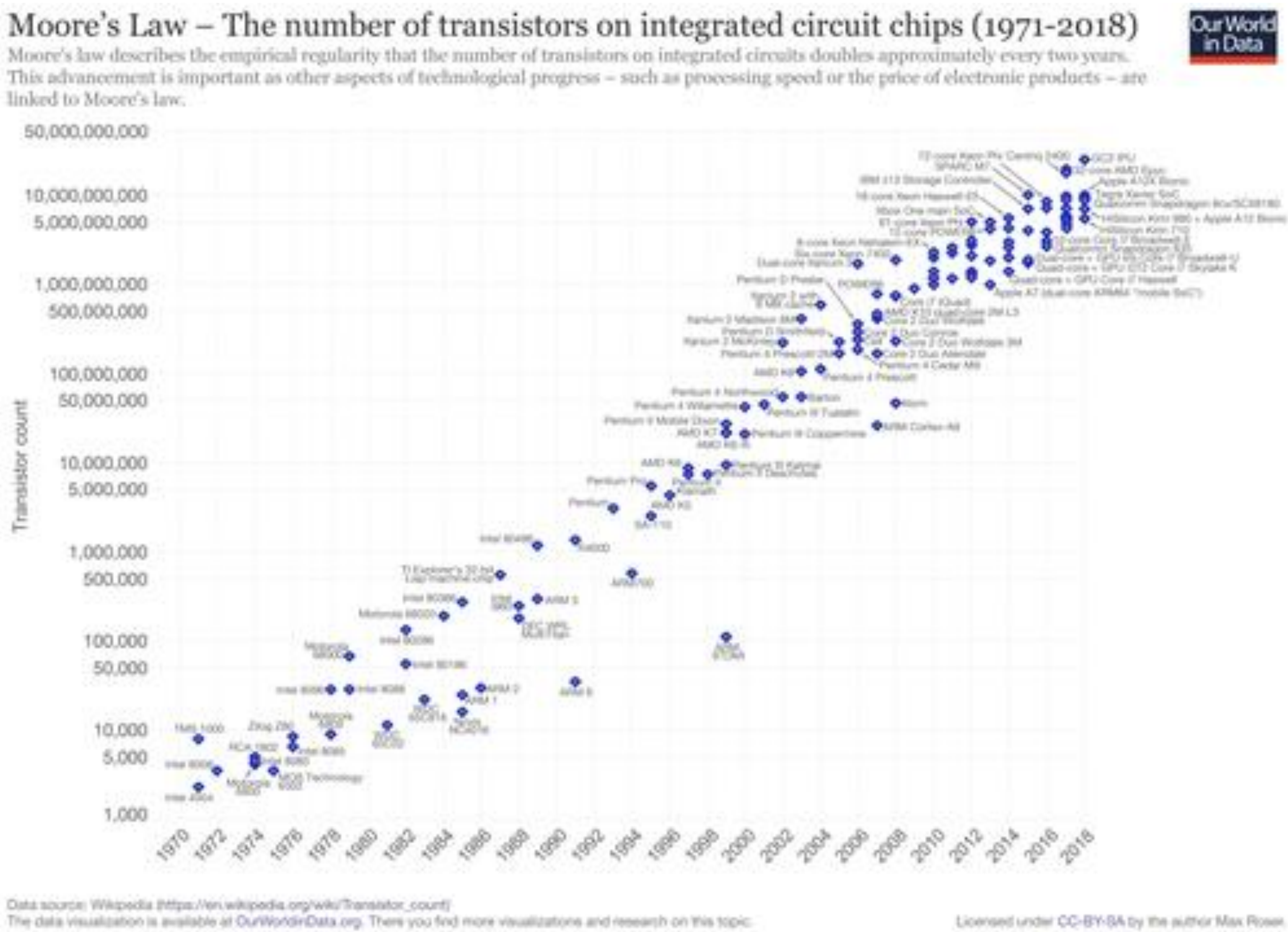




GMR Read Sensor



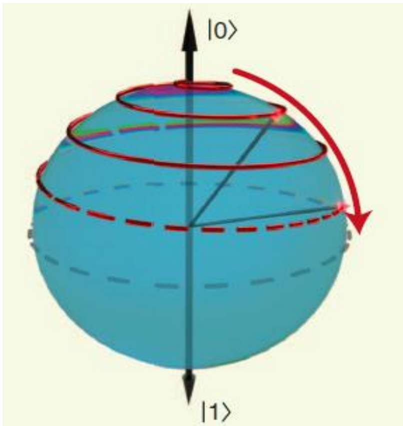
Moore's law



- Moore's law is the observation that the number of transistors in a dense integrated circuit (IC) doubles about every two years.

Quantum computing and quantum information processing

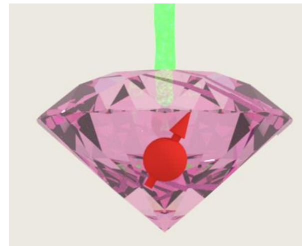
- Quantum memory



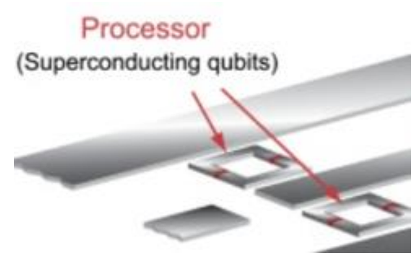
$$|\Psi\rangle = \alpha_0|0\rangle + \alpha_1|1\rangle$$

D. D. Awschalom *et al., Science* **339**, 1174 (2013)

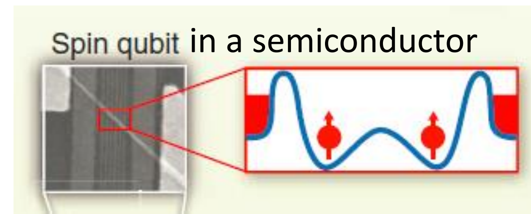
- Various qubit



Color centers



C. Grèzes et al., C. R. Phys. 17, 693 (2016)



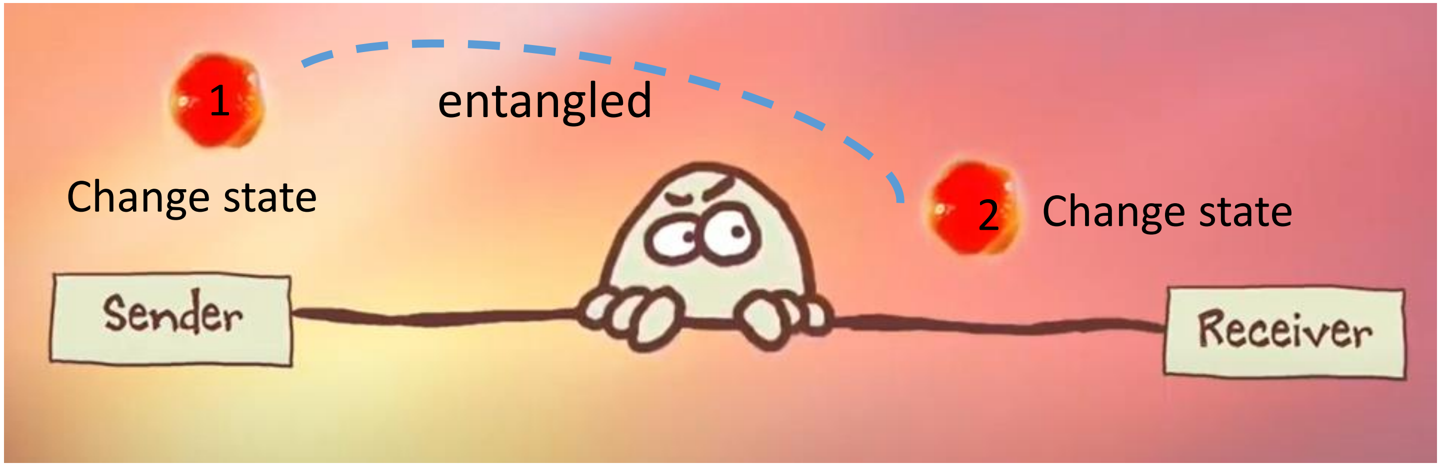
D. D. Awschalom *et al., Science* **339**, 1174 (2013)

- **NV spin host the longest spin lifetime among room temperature solid state spin qubit**

Quantum network: multiple qubits and entanglement

Quantum communications

Secure quantum communication: Safe from hackers



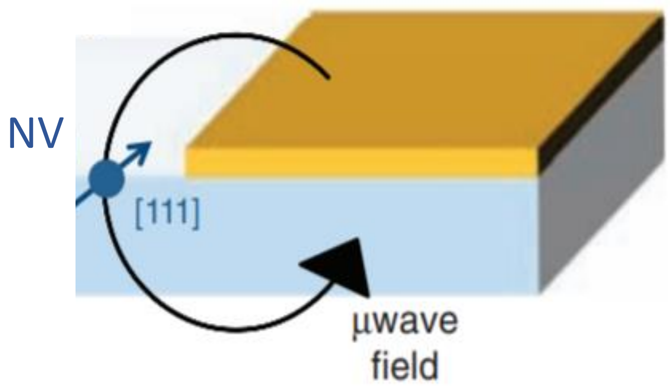
Quantum computation with NV centers

What is a good spin qubit?

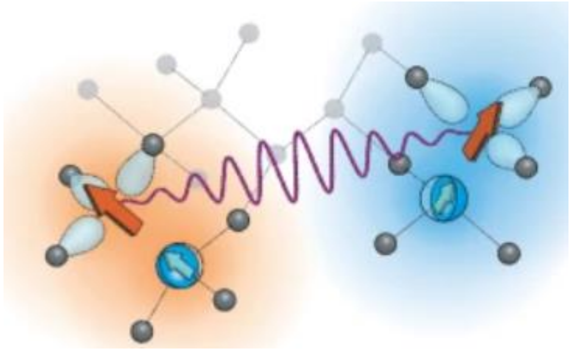
- Long lifetime
- Work at ambient condition
- Scalable

The applications to quantum computing is limited by the scalability of NVs

- NV spin is typically driven by GHz frequency dispersive MW field
- Direct entanglement of NV spins over 30 nm is challenging



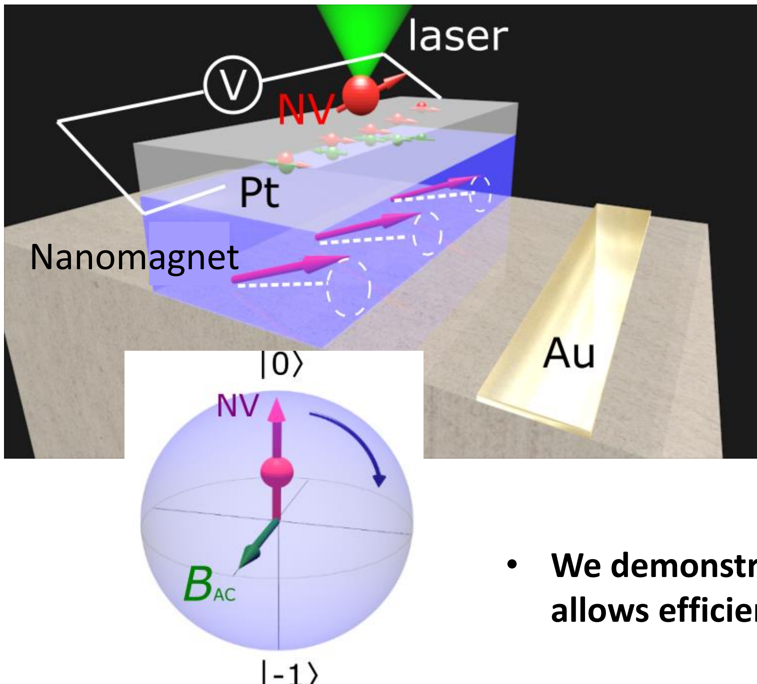
G. D. Fuchs *et al.*, *Science* **326**, 1520 (2009)



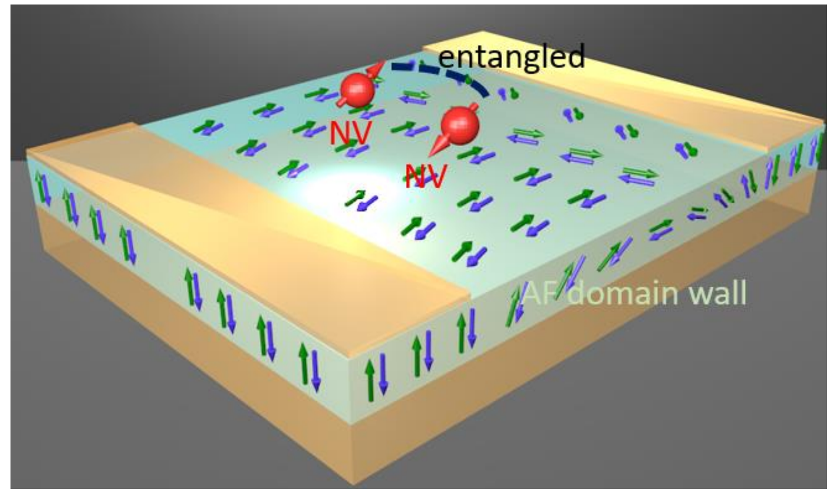
F. Dolde *et al.*, *Nat. Phys.* **9**, 139 (2013)

Room temperature quantum computing using NV spin quantum bit

Electrical and coherent control of single NV spin



Entanglement of distant NV spin mediated by solid state materials

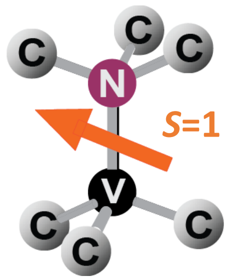


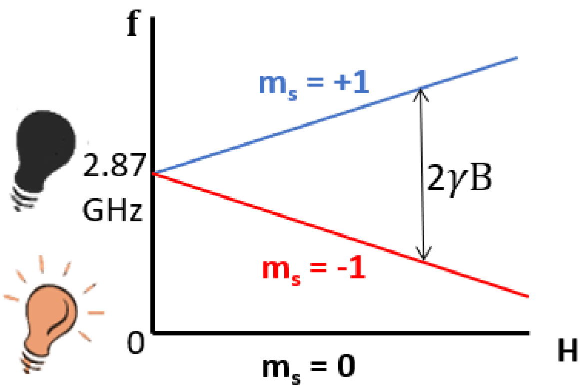
- **We demonstrates a hybrid NV/nanomagnet hybrid quantum device that allows efficient control of NV spin rotation electrically**
- **The demonstrated coupling between the NV spin and spin waves points to the possibility to establish long range entanglement between distant NV qubits.**

X. Wang et al., *npj Quantum Inf.* **6**, 78 (2020) (in collaboration with Prof. Fullerton's group)

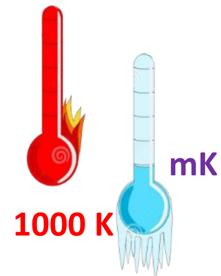
Quantum sensing using NV centers

Nitrogen vacancy (NV) center in diamond





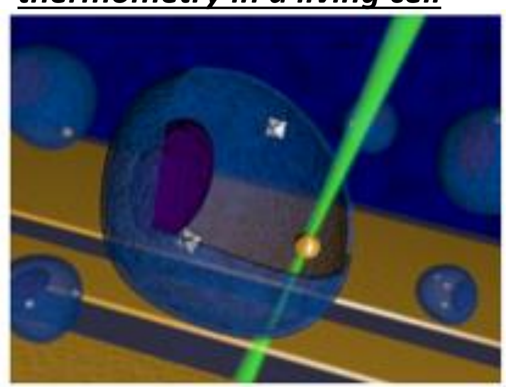
- Magnetic field sensitivity ~10 nT
- Temperature sensitivity ~10 mK
- Nanometer spatial resolution
- Broad range of working temperature and conditions



Quantum sensing under high pressure

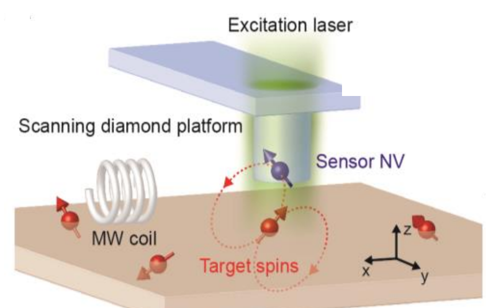
S. Hsieh et al., *Science* **366**, 1349 (2019)

Nanometer-scale thermometry in a living cell



G. Kucsko et al., *Nature* **500**, 54 (2013)

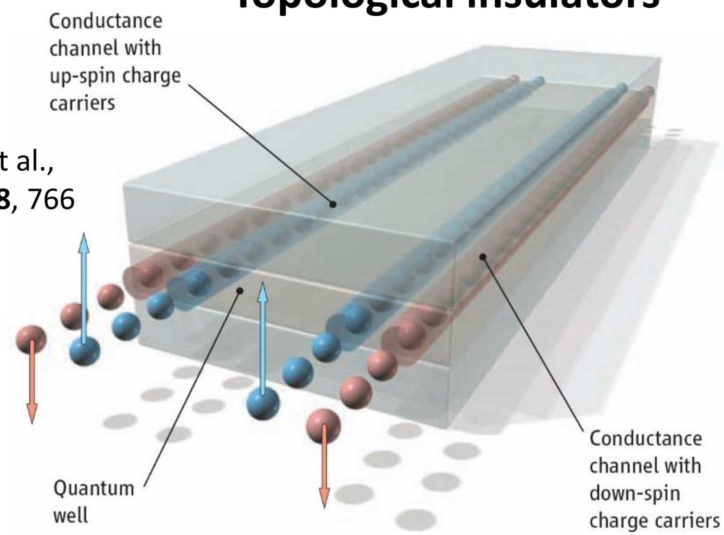
Image of a single electron spin and ensembles of nuclei spin



Yacoby Group, *Nature Phys.* **9**, 215 (2013)

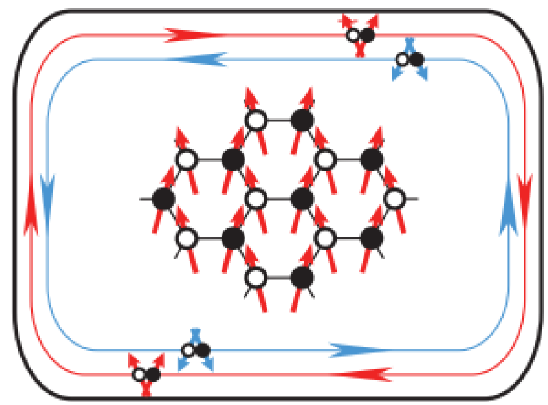
Quantum sensing of quantum materials

Topological insulators



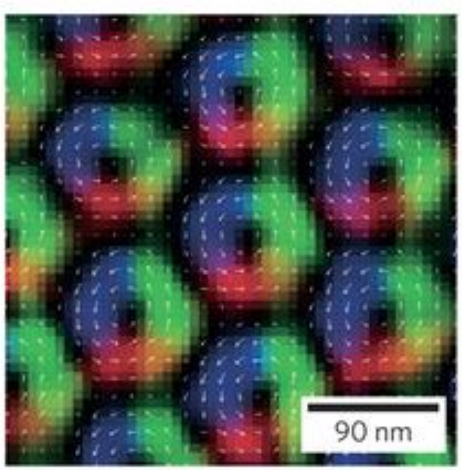
M. König et al., *Science* **318**, 766 (2007)

Canted antiferromagnetic state in graphene



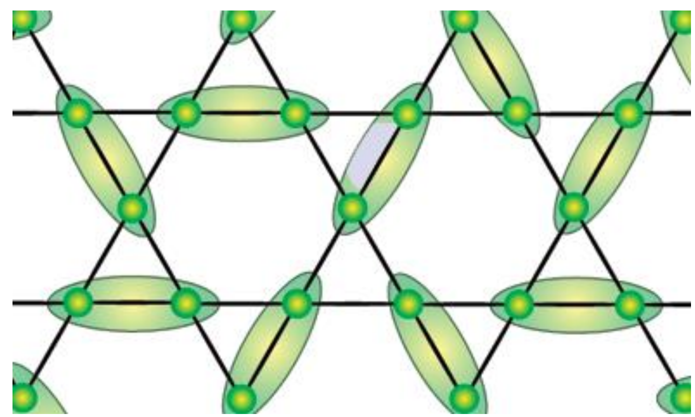
A. Young et al., *Nature* **505**, 528 (2014)

Magnetic skyrmions



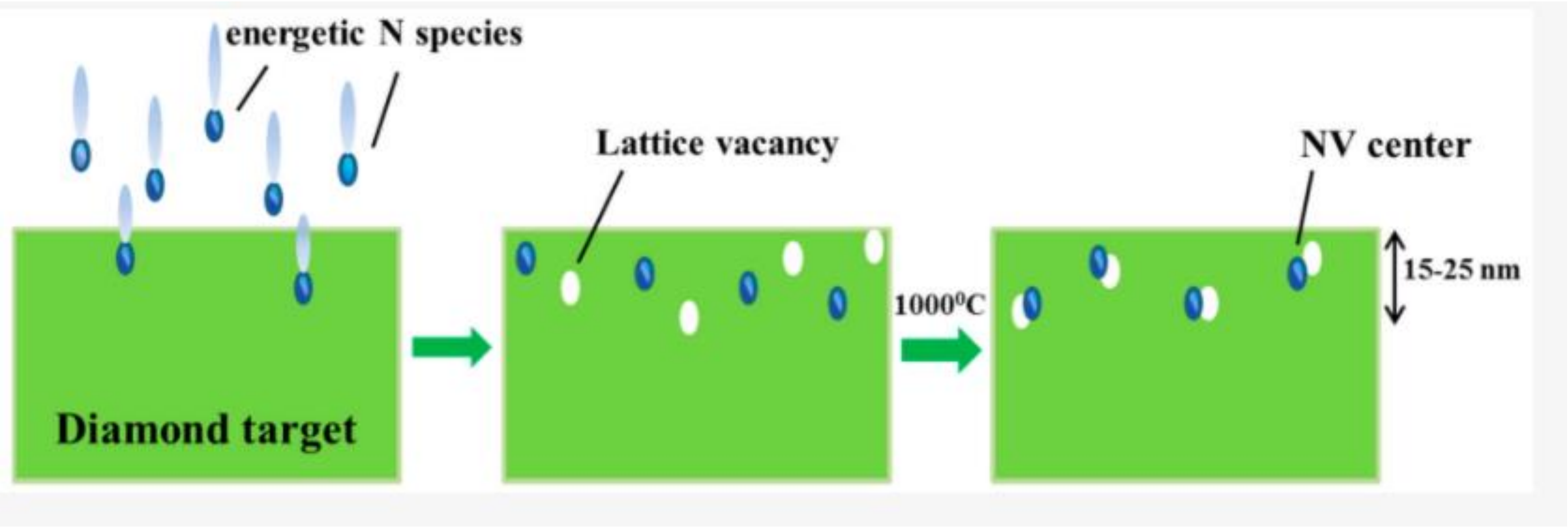
N. Nagaosa et al., *Nature Nanotech.* **8**, 899 (2013)

Quantum spin liquid



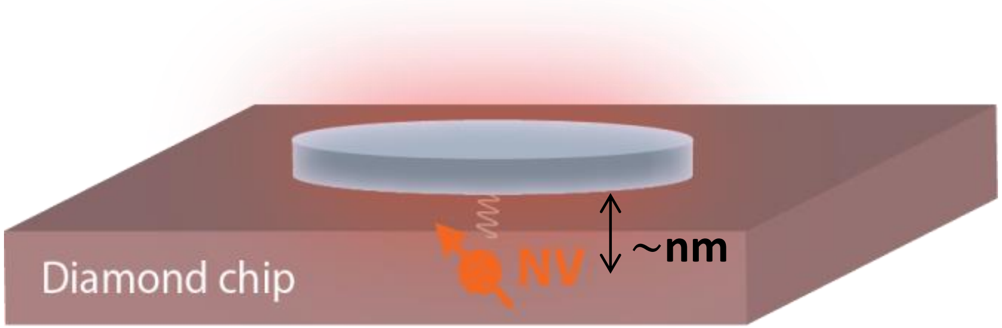
L. Clark et al., *Phys. Rev. Lett.* **110**, 207208 (2013)

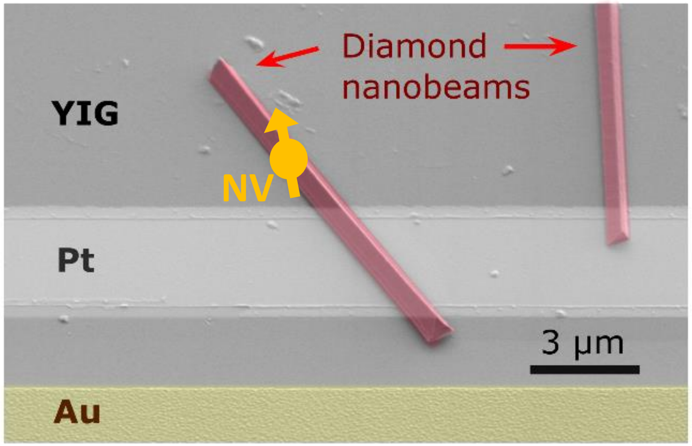
Creation of NV centers



A. Haque at al., *J. Manuf. Mater. Process.* **1**, 6, 2017.

Three methods to bring NV close to the sample to ensure nanometer detection sensitivity





C. H. R. Du et al., *Science* **357**, 195 (2017)

P. Maletinsky et al., *Nat. Nanotechnol.* **7**, 320 (2012)

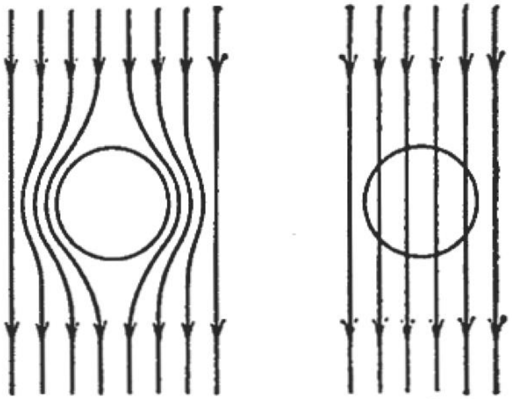
Levitation of a superconductor above a magnet

1933: Meissner-Ochsenfeld effect

- The *Meissner-Ochsenfeld effect* (1933)

Magnetic field does not penetrate the sample.

Ideal conductor! Ideal diamagnetic!

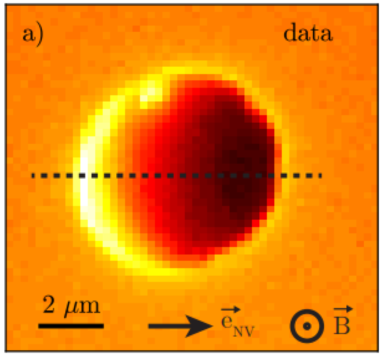


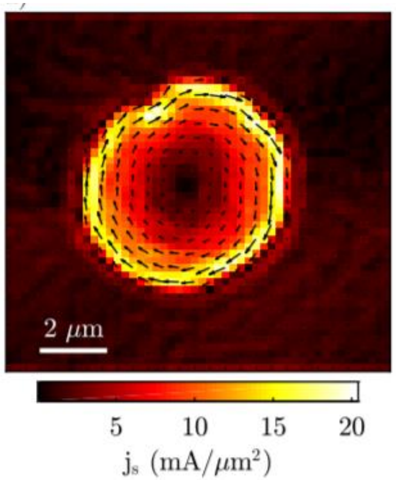
MAGLEV: flying train

- No wheels
- No drivers
- 400 miles/h
- New York to Los Angeles in just under seven hours

Measure Static Field of Superconductor

Meissner effect

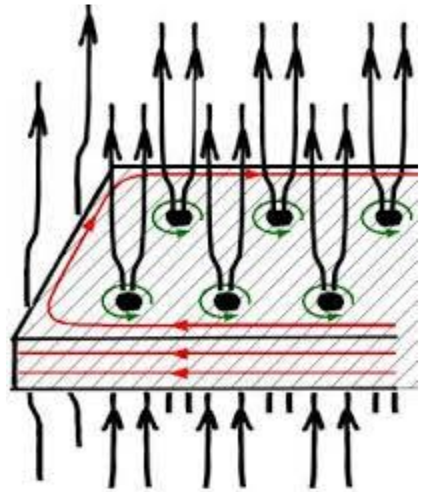


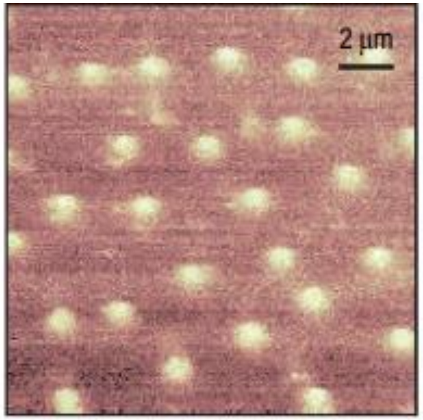


(2018)

N.M. Nusran, *New J. Phys.* **20**, 043010 (2018)

Vortices

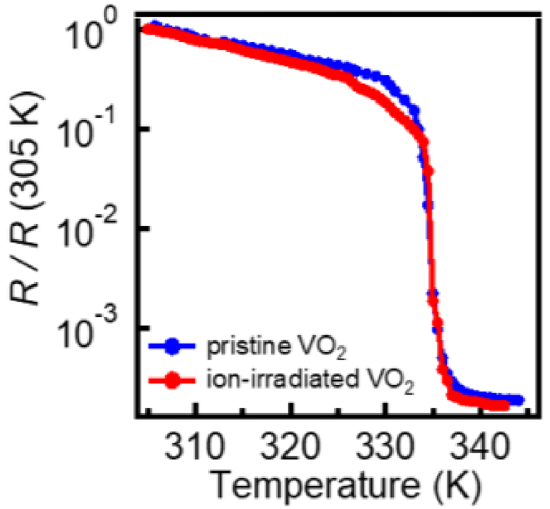


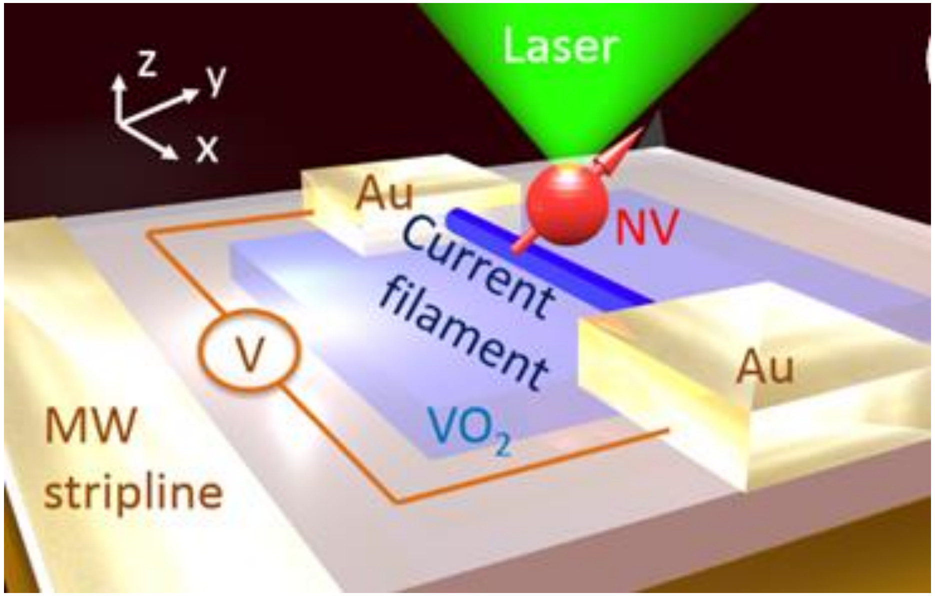


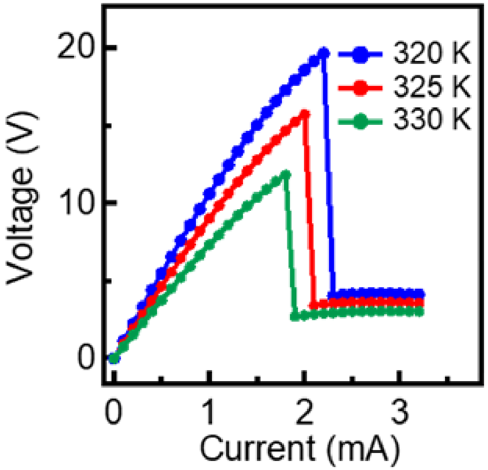
L. Thiel et al., *Nature Nanotechnology* **11**, 677 (2016)

M. Pelliccione et al., *Nature Nanotechnology* **11**, 700 (2016)

Quantum sensing of devices with insulator to metal transition for Neuromorphic computing

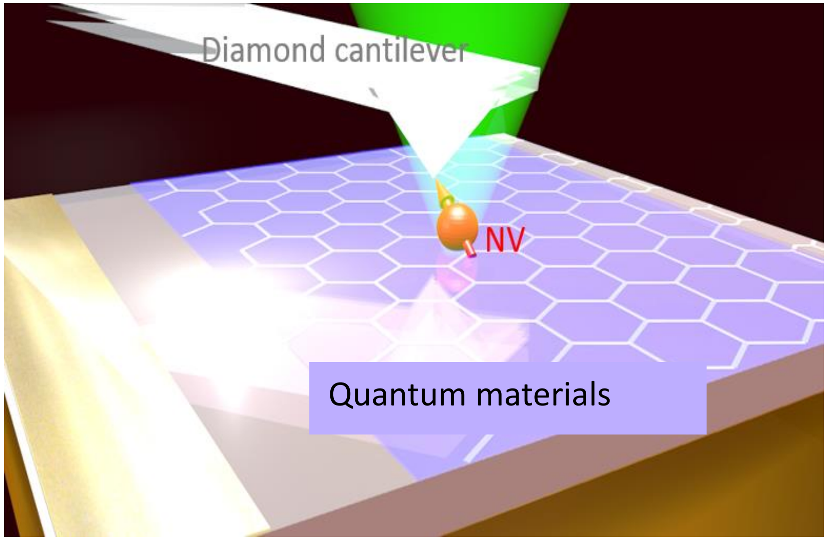




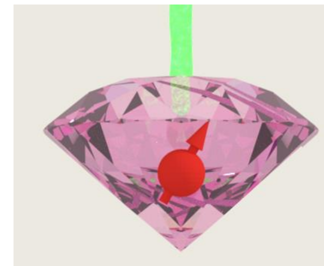


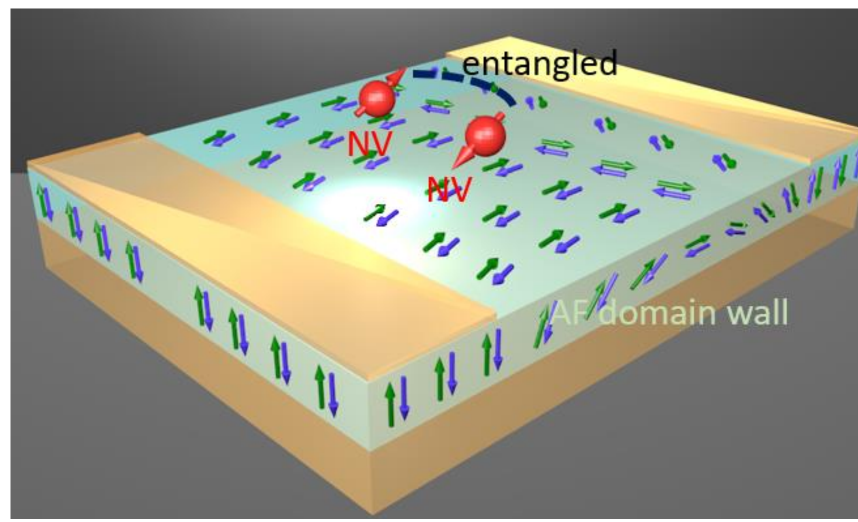
Mechanism: electrochemical or thermal?
What is the temperature and magnetic field environment ?

N. J. McLaughlin *et al.*, arXiv:2009.02886.



Our lab works on quantum sensing and quantum information processing





c1du@ucsd.edu