Center for
Quantum Networks
NSF Engineering Research Center

Solid-state quantum memories for quantum networks

Chaohan Cui

Research Faculty

University of Maryland — chaohan@umd.edu

Main instructor: Prof. Edo Waks, co-instructor: Michael Kwan

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Outline of this part

I. Introduction to Defects in Solid-State Systems
- Quantum dots: a good single-photon emitter
- Color center: an atomic-like defect with spin

II. Color Centers in Diamond for Quantum Memories
- NV centers
- Group-IV vacancy centers

III. Control of Color Centers in Diamond
- Strain tuning
- Zeeman splitting → External magnetic field tuning
- Hyperfine interaction → Nuclear spin coupled to electron spin

IV. State-of-the-art Demonstrations of Color Centers in Diamond in Quantum Networks
- NV center in bulk diamond
- SiV center strongly coupled to a photonic crystal cavity

Poll questions

Take-home message labelled in red.

I. Introduction to Defects in Solid-State Systems

Solid-state systems

Scalable (compatible to semiconductor industry)

Intro-level solid-state physics research target:

- Perfect crystal made of periodic atom lattices – translational symmetry
- Electron behaves as waves whose wavefunction is solved by Bloch's Theorem

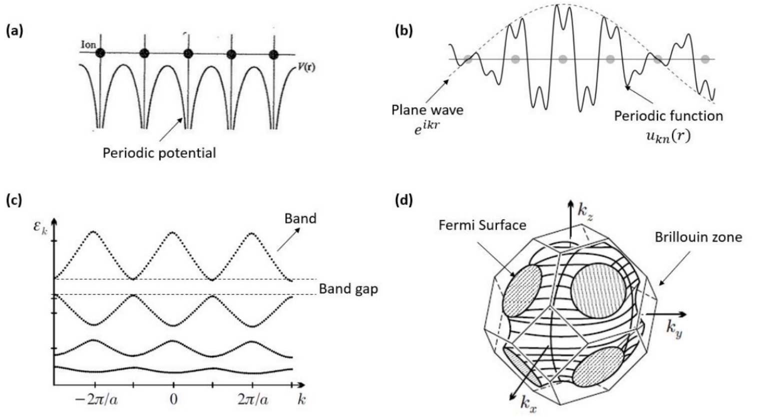
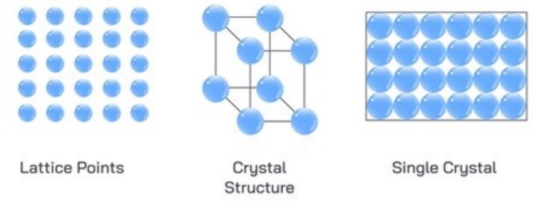
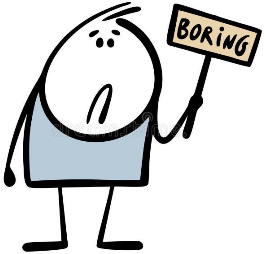


Figure. 1 Bloch Theorem: (a) Periodic lattice and the effective potential, (b) Bloch wave, (c) band structure, (d) Brillouin zone and Fermi Surface. From https://courses.physics.ucsd.edu/2018/Fall/physics211a/topic/bloch.pdf



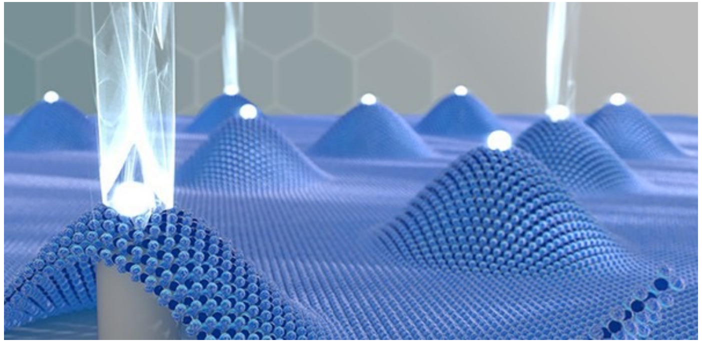


Defects in solid-state systems

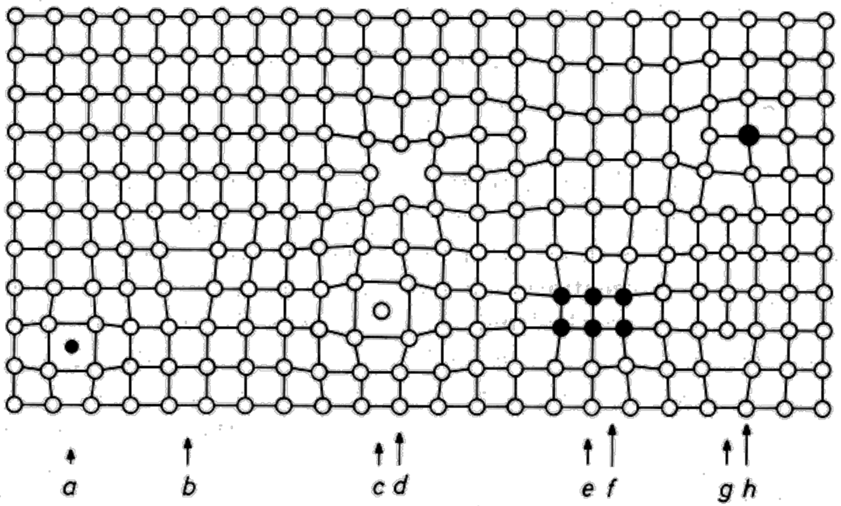
Defects – Break the translational symmetry → More interesting physics: two-level system = qubits

- Structural confinement (1~10 nm) – Quantum dots
- Missing/replacing/doping particles (~0.1 nm) – Color centers

Long coherence time
= quantum memory



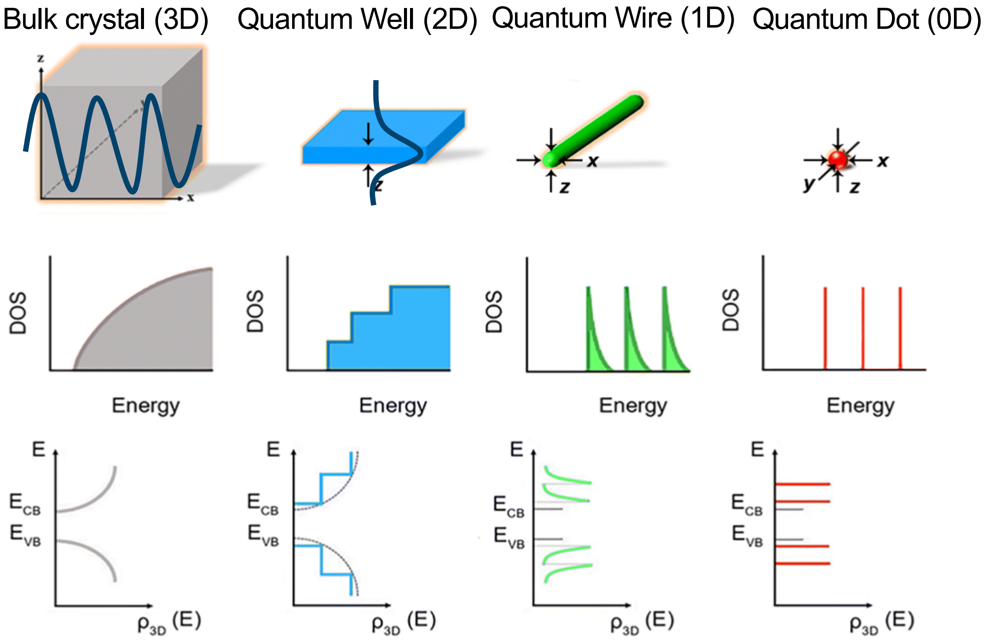
https://www.eng.cam.ac.uk/news/let-there-be-light-deterministic-arrays-quantum-emitters



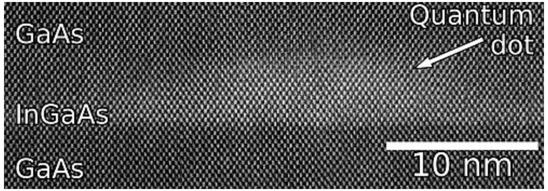
https://dtrinkle.matse.illinois.edu/MatSE584/index.html

Quantum Dots: a good single-photon emitter

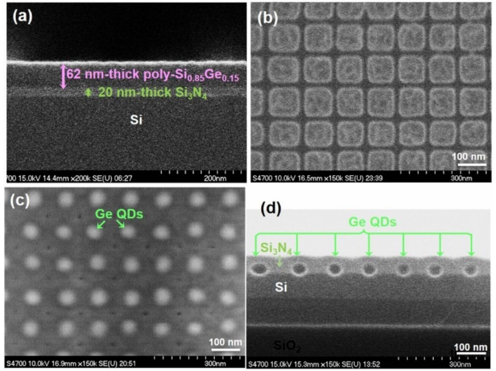
Structural confinement → Localized electron wavefunction, discretized energy levels



Bai B. et al.,Chem. Soc. Rev., 52, 318-360 (2023)

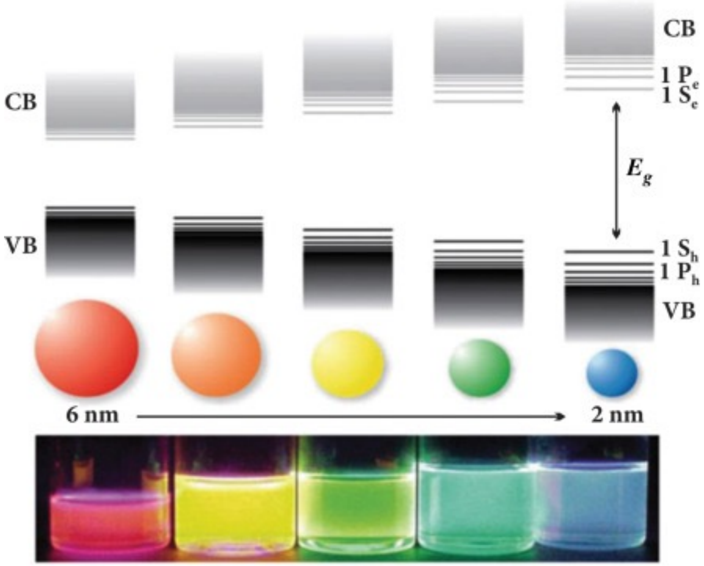


Wikipedia: SEM image of an InGaAs quantum dot



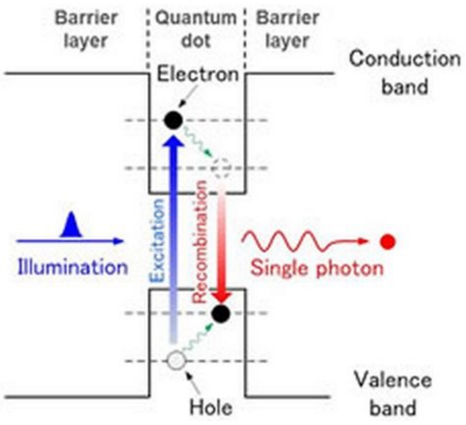
Hong, PY., Lin, CH., Wang, IH. *et al. Appl. Phys. A* **129**, 126 (2023).

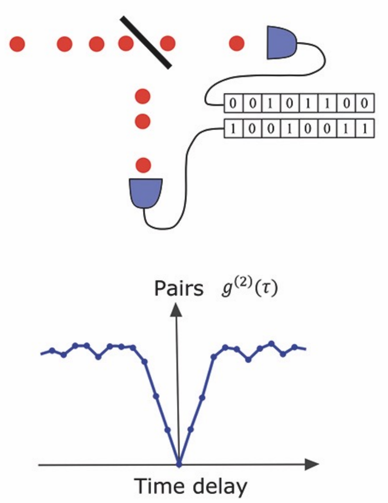
Emission wavelength (band gap) is determined by the size of quantum dot



https://www.sciencedirect.com/topics/engineering/quantum-confinement

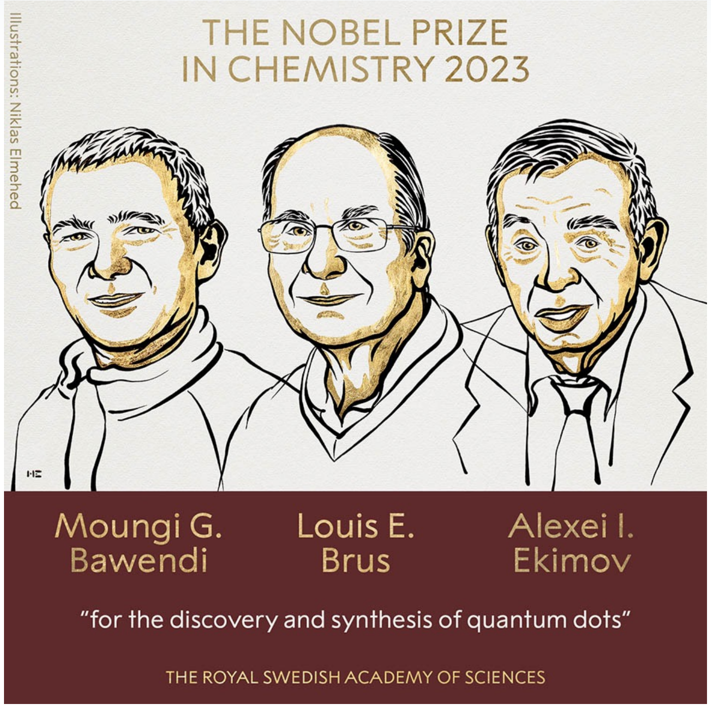
Good on-demand single-photon emitter:
One excitation gives one emitted photon



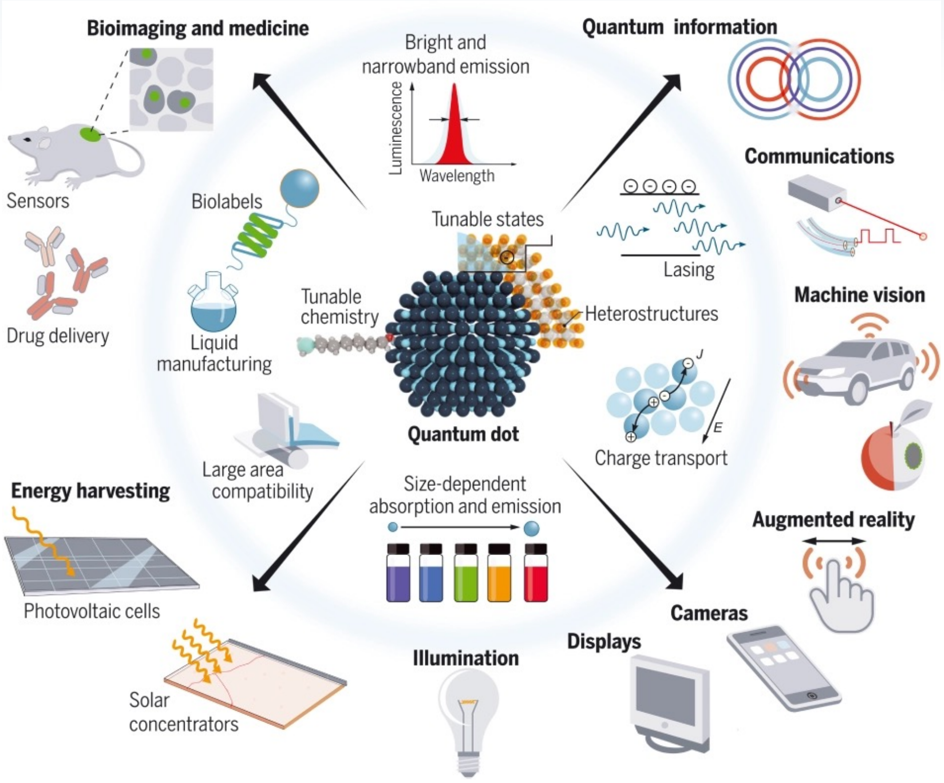


https://phys.org/news/2010-09-japanese-quantum-cryptographic-key-single-photon.html

https://analyticalscience.wiley.com/content/article-do/super-resolution-meets-quantum-optics



Applications of quantum dots

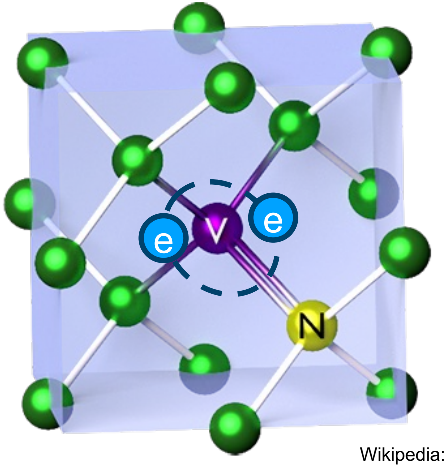


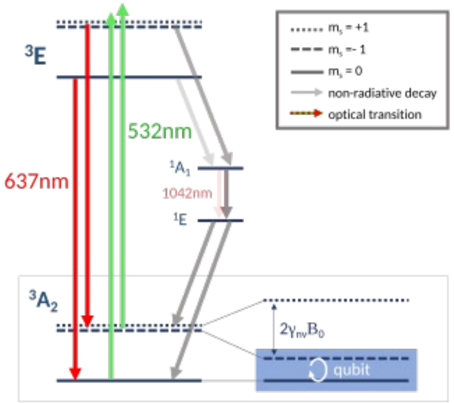
https://orbitskyline.com/blog/semiconductor-evolution-with-quantum-dots/

Color center: an atomic-like defect with spin

Missing/replacing/doping particles → like a trapped atom (electron orbit) in the crystal lattice

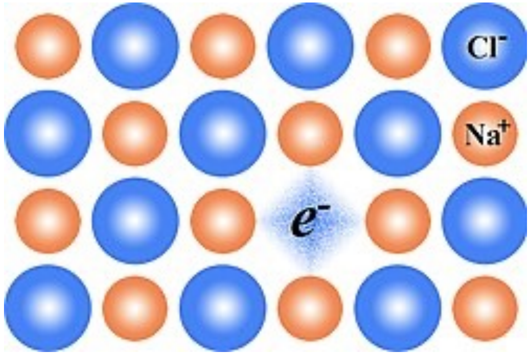
NV$^-$ center in Diamond



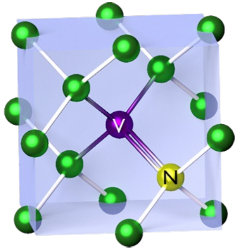


Wikipedia: Nitrogen-vacancy center

F ('Farbzentrum') center in NaCl



Color center vs. Quantum dot



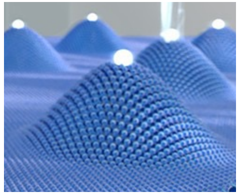
Color center in diamond

- Smaller size (~0.1 nm): by vacancy of host atoms or other doped atoms
- Atom-like electron orbit & energy level within the host bandgap

→ **Good quantum memory**

→

- Better spin (qubit) property – longer coherence time (also depending on host material: Diamond is great as C^{12} has zero nuclear spin)
- Emission wavelength tuning range is limited



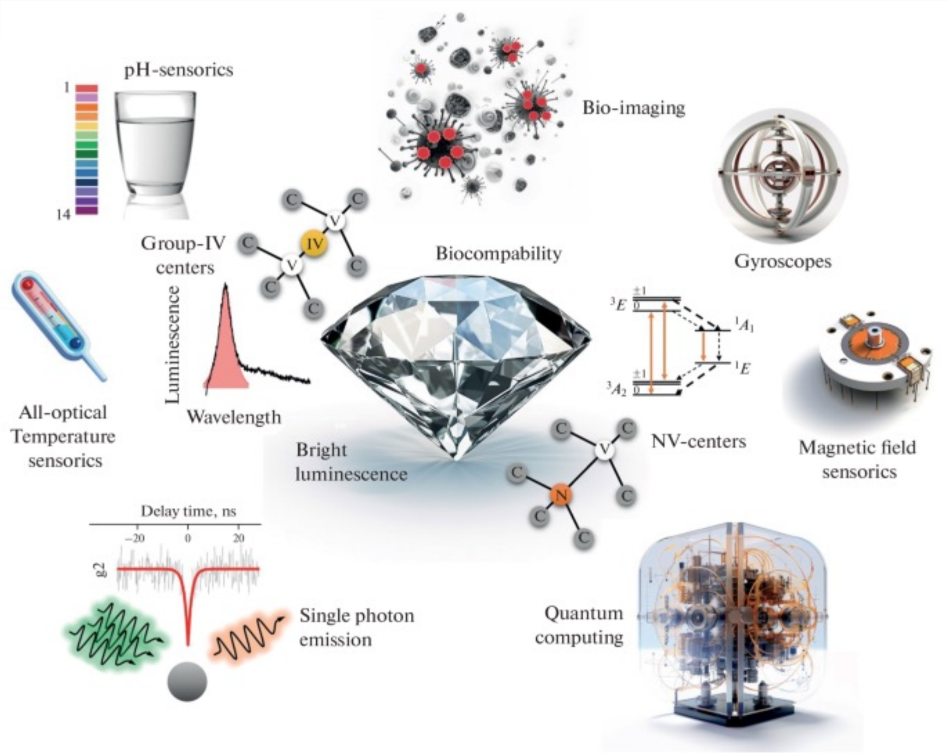
- Larger size (1~10 nm) : many atoms forms a structure
- Creating discrete energy levels within the bandgap

→

- Emission wavelength can be engineered
- Higher emission rate (Brighter)

Quantum dot → **Good single-photon source**

Applications of color centers in diamond



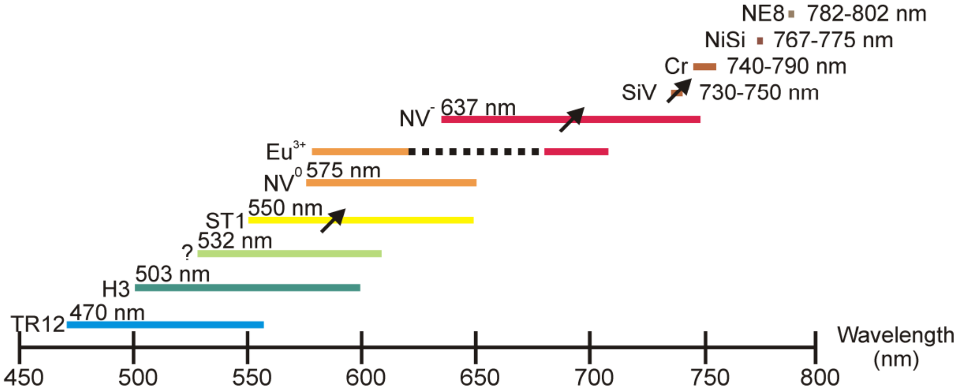
Neliubov, A.Y. *Bull. Russ. Acad. Sci. Phys.* **87** (Suppl 3), S421–S428 (2023).

II. Color Centers in Diamond for Quantum Memories

Types of color center in diamond

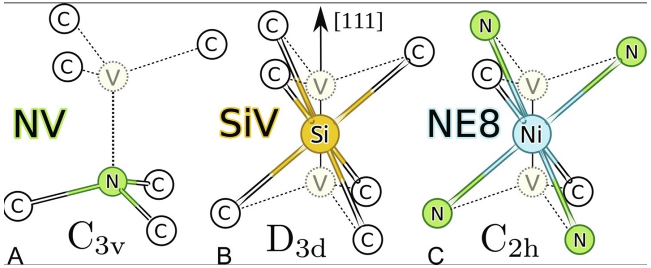
Is Diamond transparent? No, high-density color centers make them colorful

https://www.zaquant.uni-stuttgart.de/projects/microdiamonds/

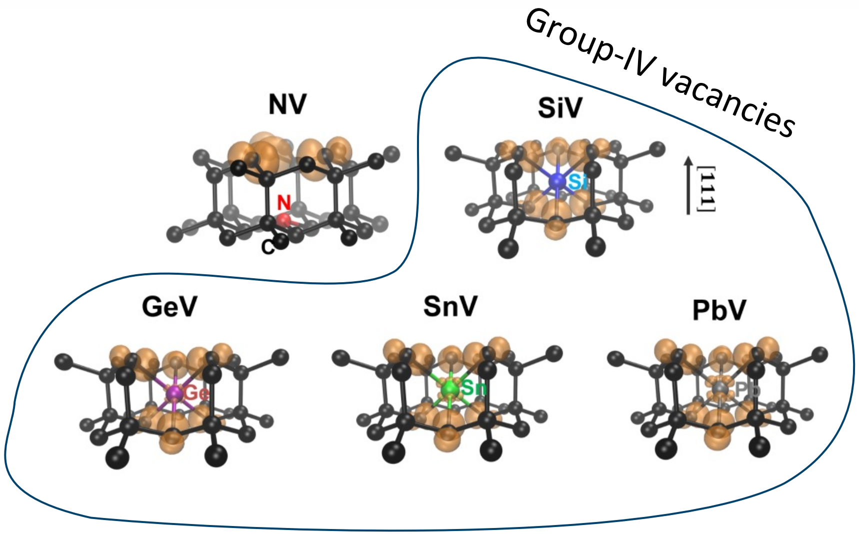


Aharonovich, I. & Neu, E. Diamond Nanophotonics. Adv. Opt. Mater. 2, 911–928 (2014)

Diamond color centers is categorized by symmetry (geometry / arrangement), and doped atom



Thiering, G., & Gali, A. In *Semiconductors and semimetals* (Vol. 103, pp. 1-36). Elsevier. (2020).



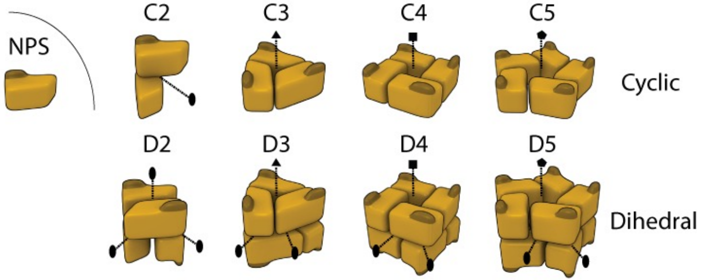


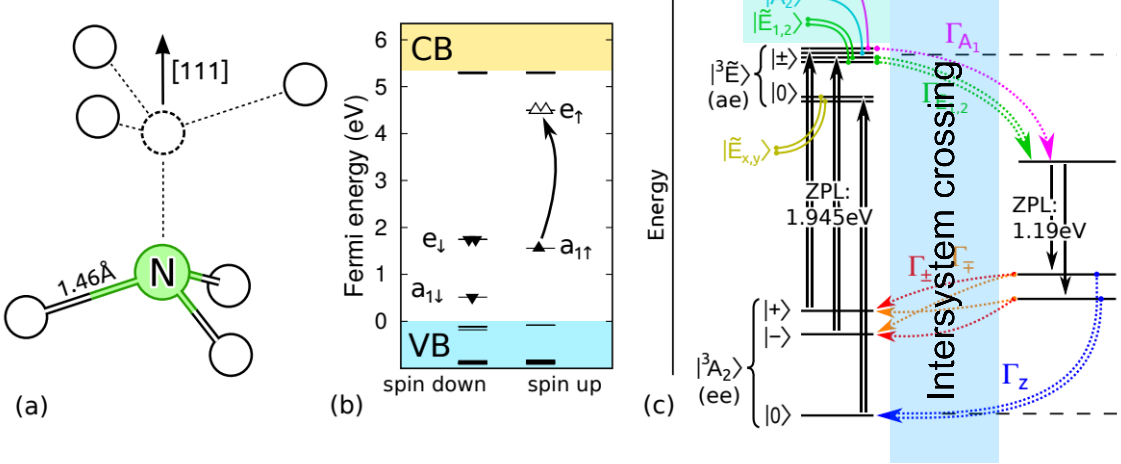
Figure 1: Structures and spin polarization densities of spin-defects in diamond, including the negatively-charged nitrogen-vacancy (NV) center, and the neutral group-IV vacancy complexes XV (with X=Si, Ge, Sn, and Pb).

Ma, H., Sheng, N., Govoni, M., & Galli, G. *Physical Chemistry Chemical Physics*, *22*(44), 25522-25527 (2020).

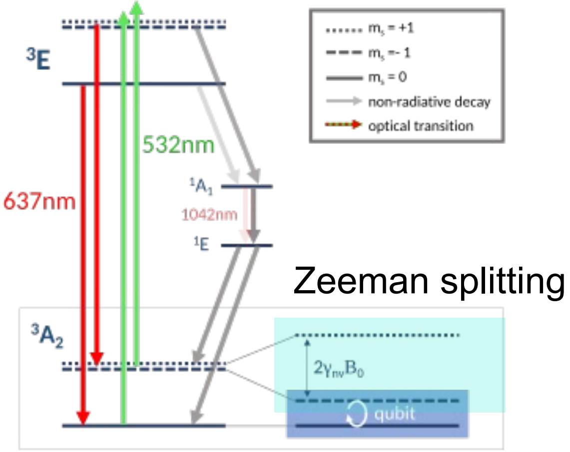
Nitrogen Vacancy (NV) center in diamond

Phonon coupled states

Two unpaired electrons in NV^-



Thiering, G., & Gali, A. *arXiv:1803.02561*. (2018).



Wikipedia: Nitrogen-vacancy center

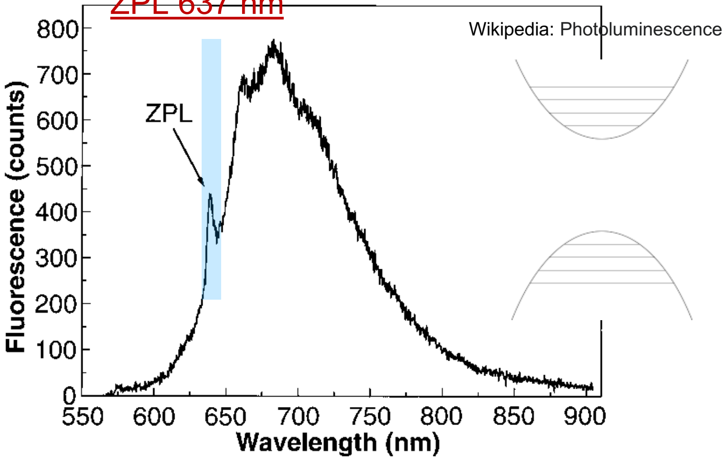
Still not as good as an atom in the vacuum: Under non-zero temperature, the electron wavefunction couples to phonon (AC vibrations) of host crystal lattice – dynamic Jahn-Teller effect

Zero-phonon line (ZPL) and phonon sideband

From zero-phonon-coupled excited state decaying to zero-phonon-coupled ground state

NV Photoluminescence (PL) spectrum

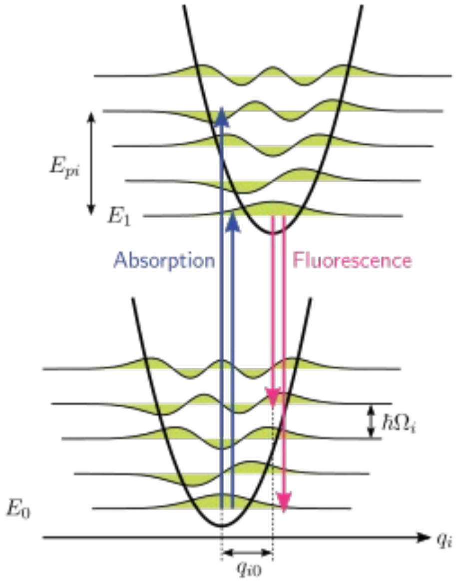
ZPL 637 nm



Gruber, A., et al, *Science*, *276*(5321), 2012-2014. (1997)

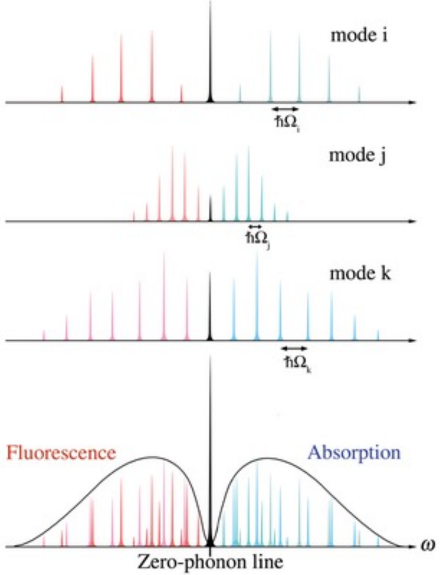
Debye-Waller Factor is ~3%: only 3% light is emitted as ZPL wavelength

Why broad? Phonon sideband



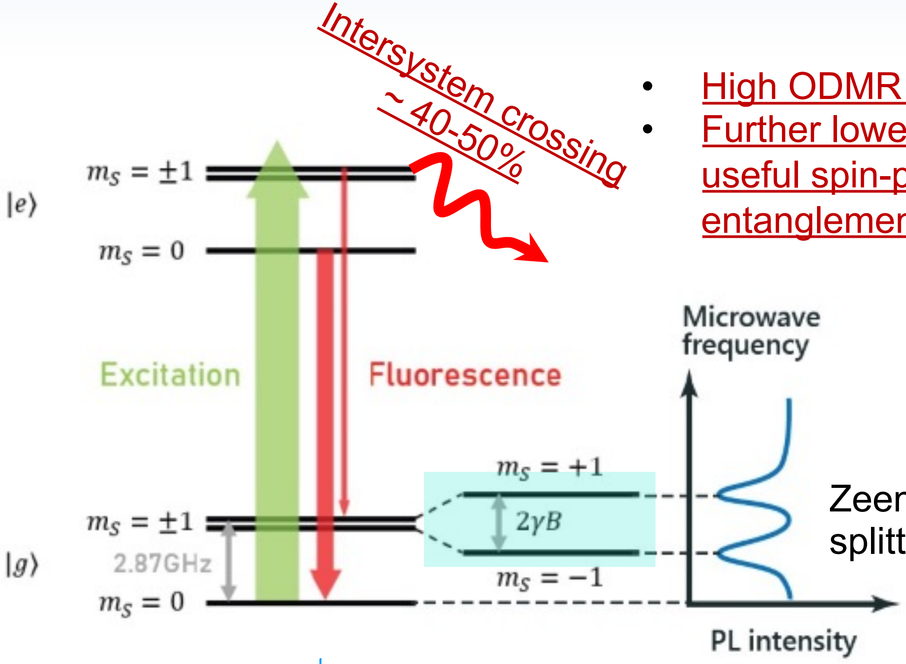
Wikipedia: Franck–Condon principle

Why continuous? Various phonon processes



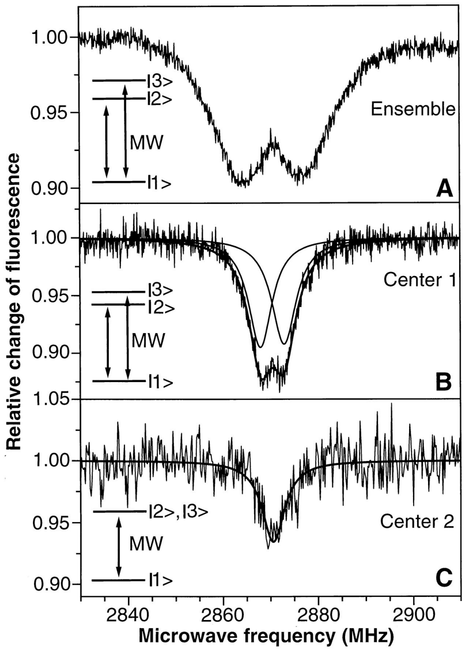
Wikipedia: Zero-phonon line and phonon sideband

Optically Detected Magnetic Resonance (ODMR)



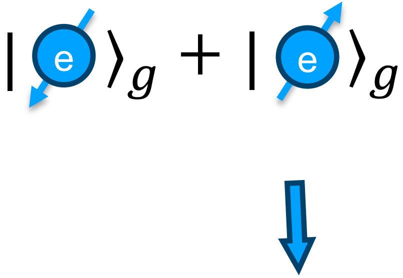
- High ODMR contrast
- Further lower the useful spin-photon entanglement rate

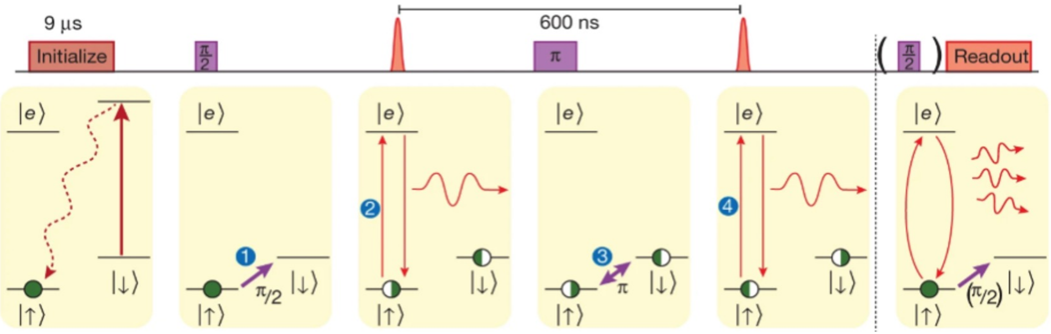
Gruber, A., et al, *Science*, *276*(5321), 2012-2014. (1997)



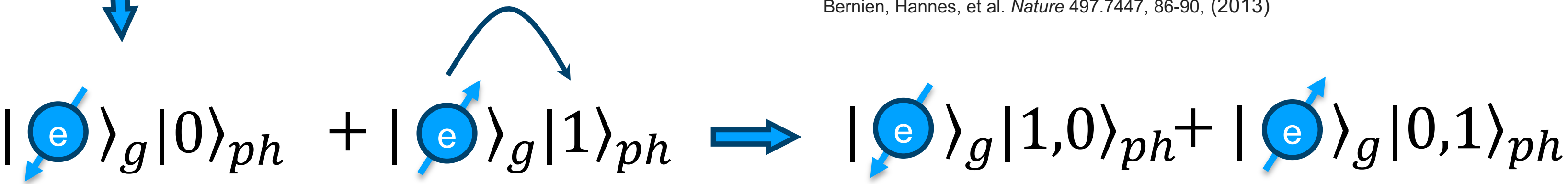
Application: sensing external magnetic field

Generating spin-photon entanglement by NV





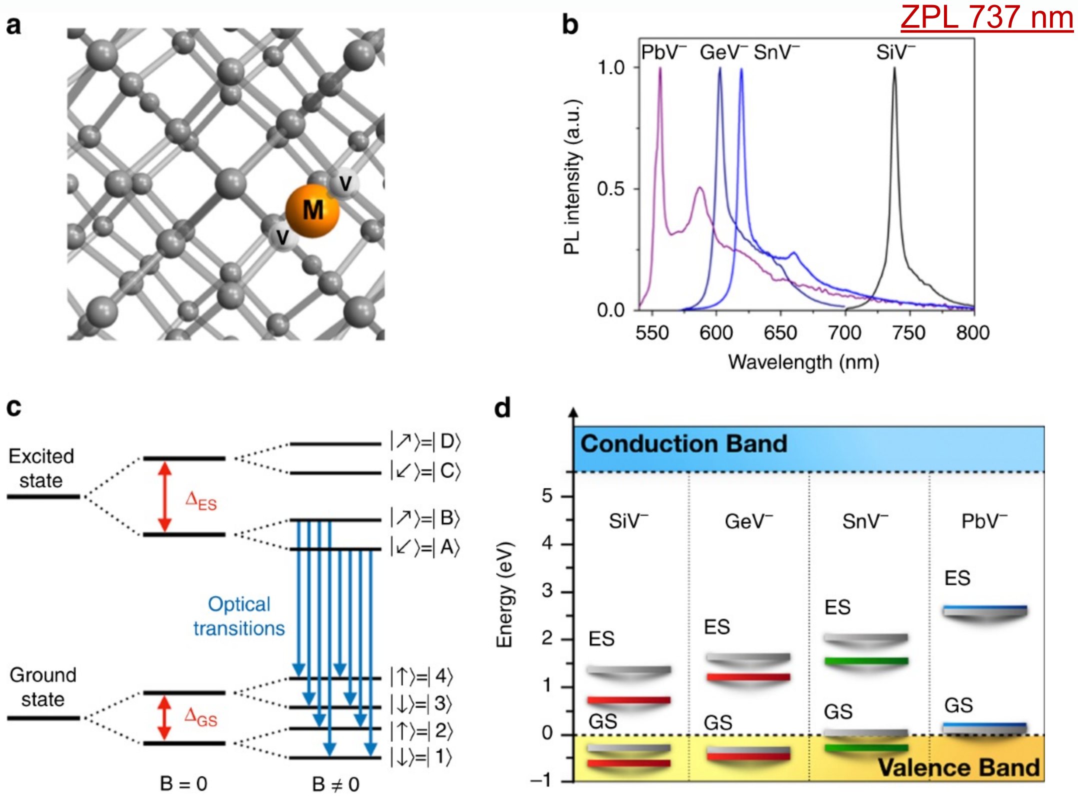
Bernien, Hannes, et al. *Nature* 497.7447, 86-90, (2013)



NV electron spin has a good coherence time T2 ~ 2 ms @ room temperature

Balasubramanian, G., Neumann, P., Twitchen, D. *et al. Nature Mater* **8**, 383–387 (2009).

Group-IV vacancy center in diamond: SiV, SnV, GeV, PbV

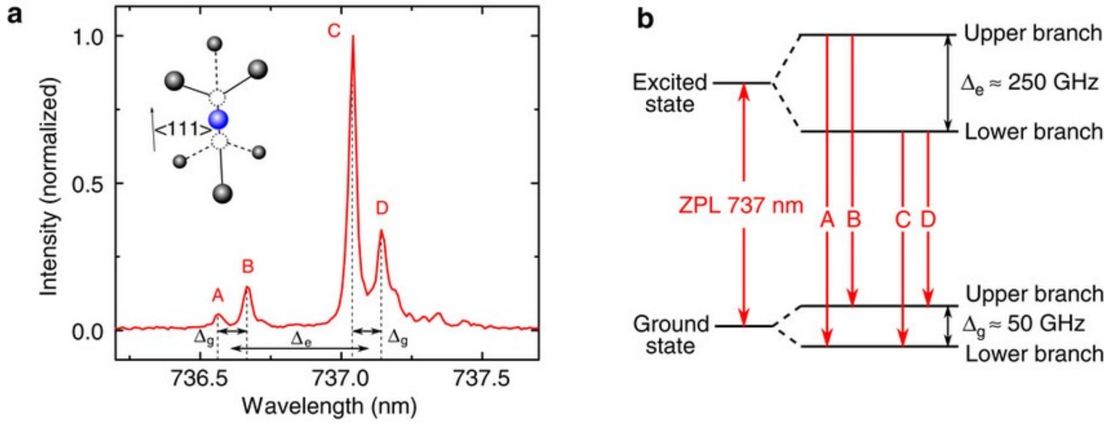


Comparing to NV:

- One unpaired electron S=1/2.
- Spin-orbital coupling – ground & excited state zero-field splitting = four energy levels without external B field, sensitive to strain/phonon.
- Inversion symmetry – less sensitivity to charge noises = can be integrated close to surface or nanostructures
- No intersystem crossing – higher generation rate of spin-photon entanglement
- Debye-Waller Factor is ~70% – less phonon sideband

Bradac, C., Gao, W., Forneris, J. *et al.* *Nat Commun* **10**, 5625 (2019).

At 4K, PL resolves four optical transitions



Müller, T., Hepp, C., Pingault, B., Neu, E., Gsell, S., Schreck, M., ... & Atatüre, M. *Nature communications*, *5*(1), 3328 (2014).

SiV can only keep long spin coherence time at sub-1K due to ground-state splitting ~50GHz.

T2*~10 μs @ 500mK

If working at 4K, thermal photon (black body radiation) and phonon (lattice vibration) will cause random flips between two ground-states branches.

III. Control of Color Centers in Diamond

Control knobs

Why do we need to control the color center?

We need to save quantum states into nuclear spin with much longer coherence time. We may also need to compensate the spectral diffusion

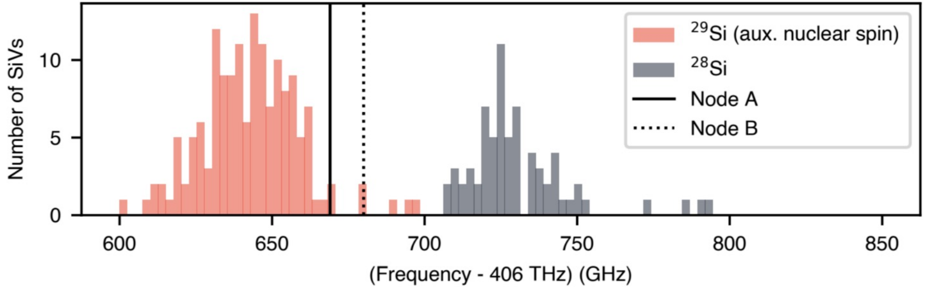
Other than RF/MW pulse control (Rabi oscillation), what other control knobs do we have?

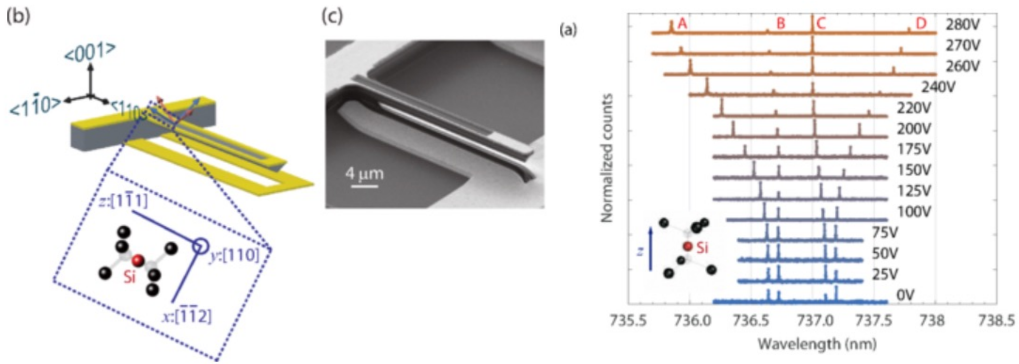
1. Strain – deform the crystal lattice → adds to the zero-field splitting
2. External B-field – Zeeman effect → split different spin states
3. Nuclear spin – Hyperfine interaction between electron spin and nuclear spin → energy splitting

$$H = \underbrace{DS_z^2}_{\text{Zero-Field Splitting}} + \underbrace{g\mu_B \mathbf{B}\cdot\mathbf{S}}_{\text{Zeeman Effect}} + \underbrace{\mathbf{S}\cdot\mathbf{A}\cdot\mathbf{I}}_{\text{Hyperfine Interaction}} + \underbrace{E(S_x^2 - S_y^2)}_{\text{Strain}}$$

Strain tuning

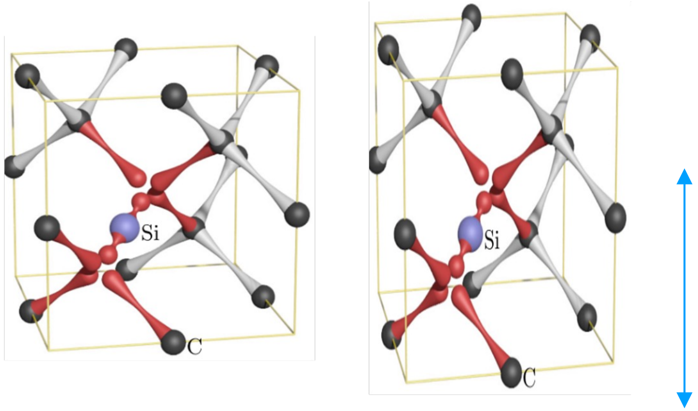
Inhomogeneous broadening by unknown local strain





Meesala, S., et al. *Physical Review B*, *97*(20), 205444 (2018).

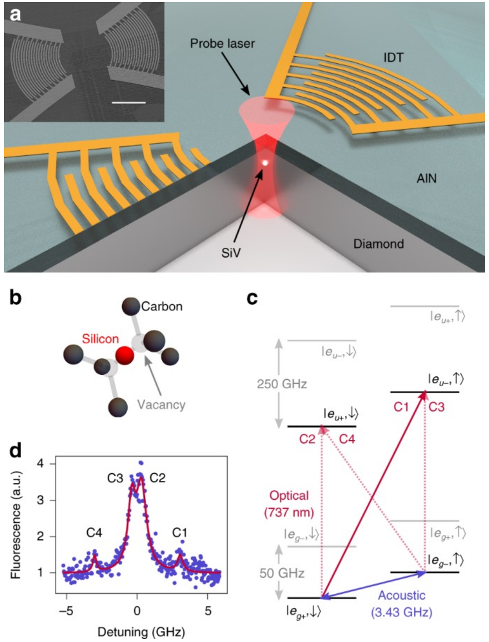
<u>Strain tuning can significantly increase the ground-state zero field splitting to ~THz, keeping the system coherent when working at a higher temperature.</u>



Local potential (static EM) changes

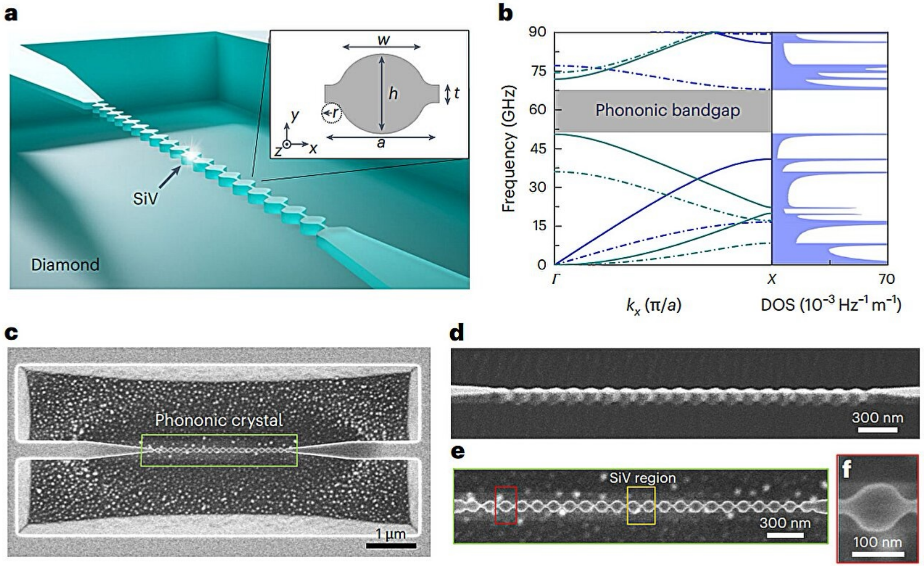
Acoustic control

Acoustic wave (phonon) is used to pump the transition instead of using microwave (photon)



Maity, S., Shao, L., Bogdanović, S. *et al.* *Nat Commun* **11**, 193 (2020)

Phonon crystal creates phonon bandgap to reduce phonon coupling to ground-state splitting

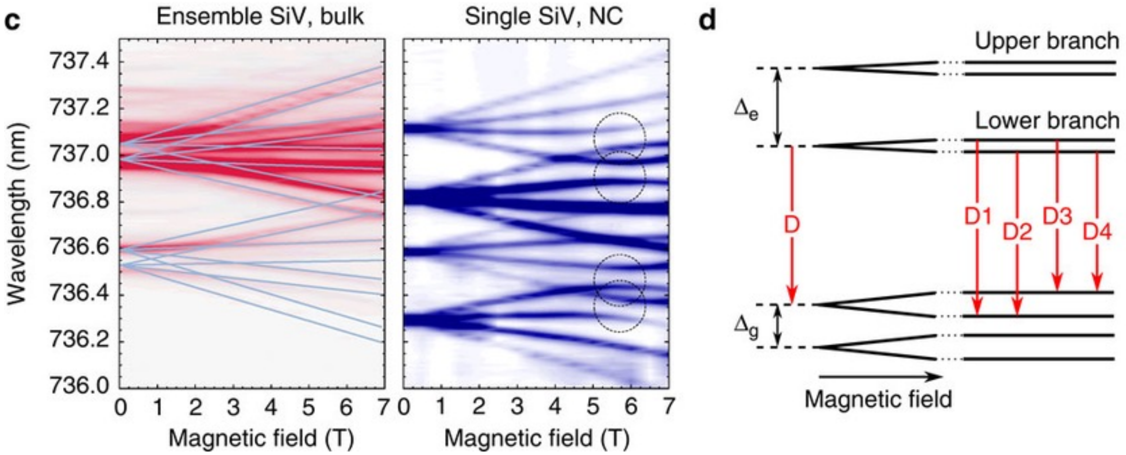


Kuruma, K., Pingault, B., Chia, C. et al. *Nat. Phys*. 21, 77–82 (2025).

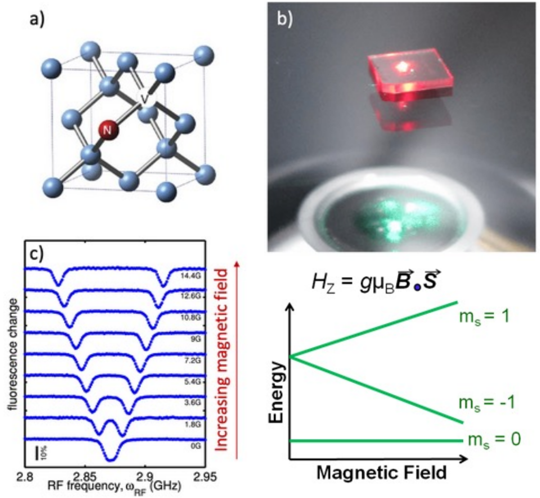
Zeeman splitting: External magnetic field tuning

The key to implement spin-control with RF and MW

SiV



NV

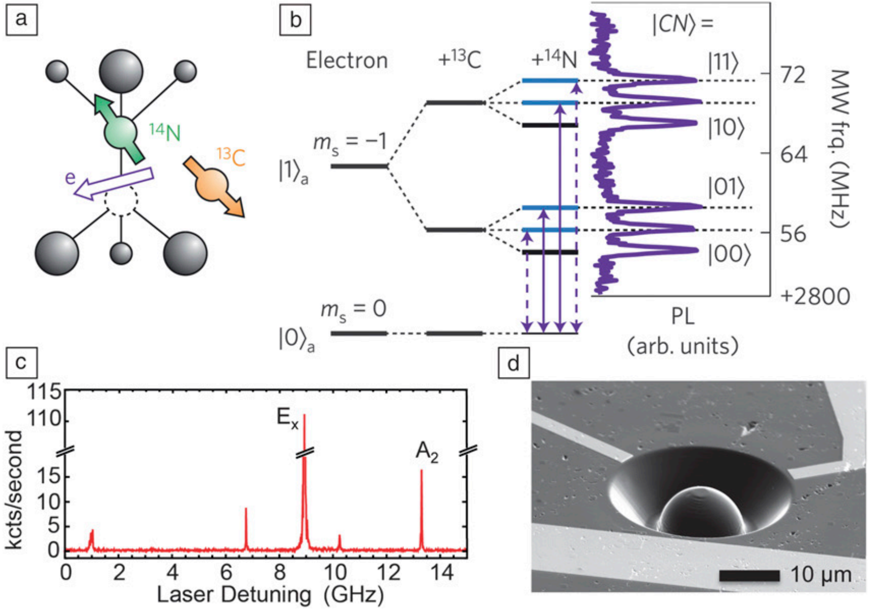


Müller, T., Hepp, C., Pingault, B., Neu, E., Gsell, S., Schreck, M., ... & Atatüre, M. *Nature communications*, *5*(1), 3328 (2014).

Hyperfine interaction — Nuclear spin

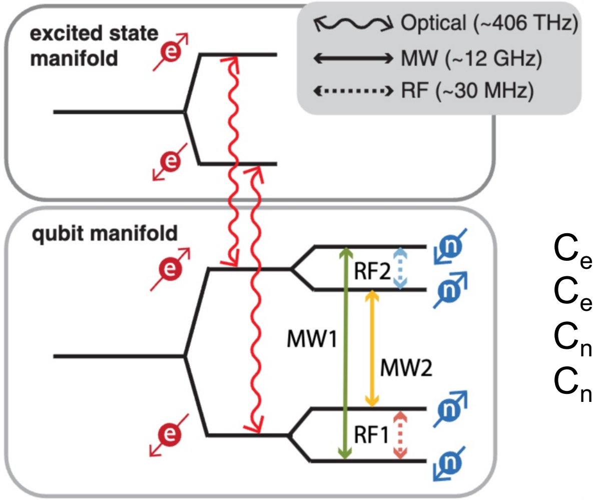
Now we can control two spin qubits by RF and MW

NV-C^{13} Hyperfine



Lilian Childress and Ronald Hanson, MRS Bulletin , Volume 38 , Issue 2: Nitrogen-vacancy centers: Physics and applications, 2013, pp. 134 - 138

SiV-Si^{29} Hyperfine



Stas, P-J., et al. Science 378.6619, 557-560 (2022).

C_eNOT_n= RF1,
C_eNOT_n= RF2,
C_nNOT_e= MW1,
C_nNOT_e= MW2

Do we need nuclear spin for color center in diamond quantum memory?

<u>Yes.</u> Nuclear spins have small magnetic moments, effectively decoupling them from environmental noise.

For NV quantum memory:

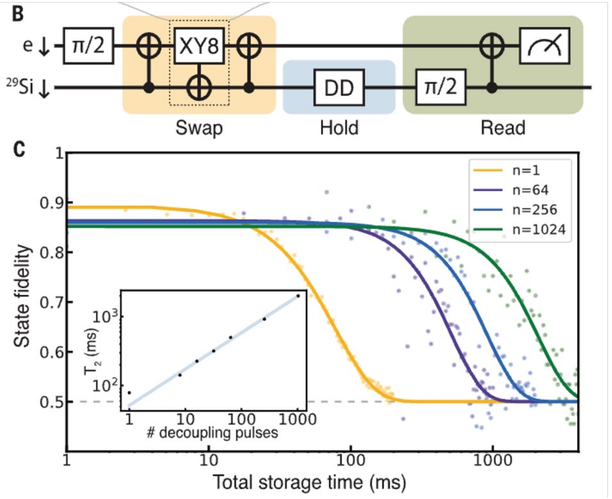
- Electron coherence time is limited by the magnetic noise of other C^{13} spin bath.
- The nuclear spin is immune to this dipolar noise, extending storage from ms to seconds and potentially minutes.
- Can free electron spin for sensing tasks.

For Group-IV quantum memory:

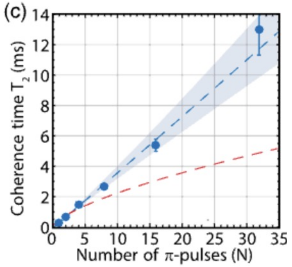
- Electron coherence can be destroyed by thermal phonons (orbital mixing) at 4K.
- The nucleus has no orbital angular momentum to couple to phonons, enabling quantum memory keep coherence at a slightly higher temperature.

Dynamical decoupling

SiV state save to Si[29] nuclear spin



SiV state save to electron spin



Extension of the coherence time T2 of the SiV nuclear spin to 2s (State of the art) much longer than the electron spin (DD applied) with T2~13 ms

Sukachev, Denis D., et al. *Physical review letters* 119(22), 223602 (2017).
Stas, P-J., et al. *Science* 378.6619, 557-560, (2022).

IV. State-of-the-art Demonstrations of Color Centers in Diamond in Quantum Networks

NV center in bulk diamond with solid immersion lens

Seminal works from Hanson Group (QuTech, Delft)

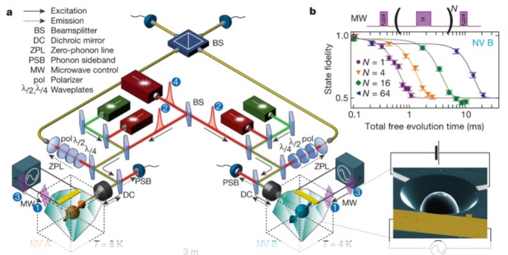
Remote entanglement between 2 NVs
Bernien, Hannes, et al. "Heralded entanglement between solid-state qubits separated by three metres." *Nature* **497,** 86-90 (2013)

Loophole-free Bell Inequality Violation
Hensen, B. et al. "Loophole-free Bell inequality violation using electron spins separated by 1.3 kilometres." *Nature* **526**, 682–686 (2015).

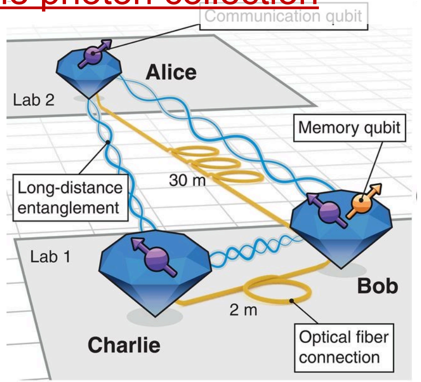
Entanglement Distillation
Kalb, N. et al. "Entanglement distillation between solid-state quantum network nodes." *Science* **356**, 928–932 (2017).

Multi-Node Quantum Network
Pompili, M. et al. "Realization of a multinode quantum network of remote solid-state qubits." *Science* **372**, 259–264 (2021).

Qubit Teleportation
Hermans, S.L.N. et al. "Qubit teleportation between non-neighbouring nodes in a quantum network." *Nature* **605**, 663–668 (2022).



Solid immersion lens: enhance the photon collection



Entanglement rate: 10 Hz (1 link)
~0.025 Hz (2 links with swap)

Center for
Quantum Networks
NSF Engineering Research Center

SiV center strongly coupled to a photonic crystal cavity

Seminal works from the Lukin & Loncar Group (Harvard University)

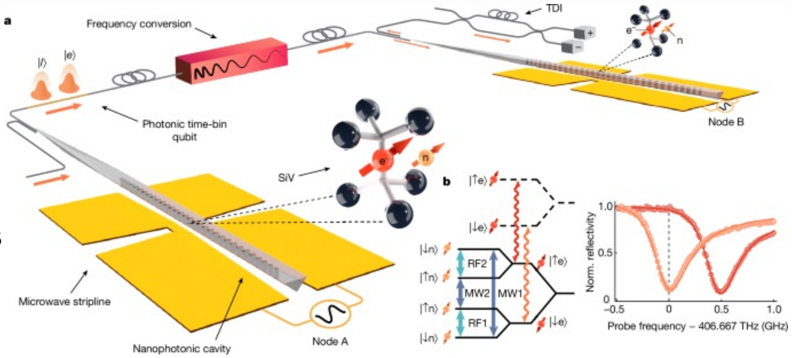
Foundations of Integrated SiV Nanophotonics
Sipahigil, A. et al. "An integrated diamond nanophotonics platform for quantum-optical networks." *Science* **354**, 847–850 (2016).

Photon-Mediated Interactions
Evans, R. et al. "Photon-mediated interactions between quantum emitters in a diamond nanocavity." *Science* **362**, 662–665 (2018).

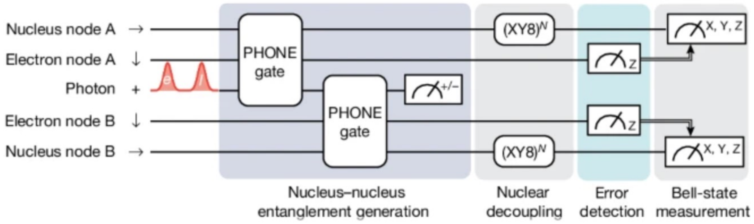
Memory-Enhanced Quantum Communication
Bhaskar, M. et al. "Experimental demonstration of memory-enhanced quantum communication." *Nature* **580**, 60–64 (2020).

Multi-Node Quantum Network
Stas, P. J. et al. “Robust multi-qubit quantum network node with integrated error detection.” *Science* **378**, 557-560 (2022).

Telecom Quantum Network over Boston
Knaut, C.M., Suleymanzade, A., Wei, YC. et al. Entanglement of nanophotonic quantum memory nodes in a telecom network. *Nature* **629**, 573–578 (2024).



Reflect-cavity acts as a control-transmission gate between the photon and spin states



Entanglement rate: 0.25 Hz over 35 km

Poll questions

Poll question 6
Which of the following is NOT an advantage of using color centers as quantum memories?
A. Very long coherence times
B. Efficient spin–photon interfaces
C. Good scalability
D. Operation at room temperature

Poll question 7
What is the approximate zero-phonon-line (ZPL) emission wavelength of the SiV center in diamond?
A. 637 nm
B. 737 nm
C. 1550 nm
D. 493 nm

Poll questions

Poll question 8

What is the approximate zero-phonon-line (ZPL) emission wavelength of the NV center in diamond?

A. 637 nm

B. 737 nm

C. 1550 nm

D. 493 nm

Poll question 9

Which statement best describes the hyperfine interaction in a diamond color-center system?

A. The interaction between the electron spin and the nuclear spin

B. The interaction between an external magnetic field and the electron spin

C. The interaction between an external magnetic field and the nuclear spin

D. The interaction between the electron’s orbital motion and its spin

Poll questions

Poll question 10
Which type of energy-level splitting is most sensitive to lattice strain (considering relative percentage change)?
A. Hyperfine splitting
B. Zeeman splitting
C. Spin–orbit–induced splitting
D. The energy gap between the ground and excited electronic states (ZPL energy)

Poll question 11
Which of the following statements is NOT true?
A. The SiV center is formed when a silicon atom occupies a split-vacancy site between two missing carbon atoms
B. The NV center is formed by replacing two neighboring carbon atoms with one nitrogen atom in the middle
C. The SiV center has inversion symmetry, while the NV center does not, making SiV less sensitive to charge noise
D. Both SiV and NV centers typically require cryogenic temperatures to achieve long spin coherence times

Questions?

Contact me at chaohan@umd.edu