Scalable architecture for a room temperature solid-state quantum information processor

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Nature Communications 3, 800 (2012)

PHYS 596- Journal Club Presentation
Fall 2013

Group 9

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Photo: *Scientific American* **297**, 84-91 (2007)

Outline

- Introduction and Motivations (Derek)
- Physics of Nitrogen-Vacancy Center (Hassan)
- Realization of Scalable Quantum Processor (Ben)
- Citation Evaluation and Prospects (Evan)

A New Computer

- Single atom transistors are the limit and are predicted to be manufactured by 2020.
- 500 qubits = 2^{501} bits

(Waldner, Jean-Babtiste (2008). *Nanocomputers and swarm intelligence*. London: ISTE. Pp. 44-45.)

- 1 terabyte = 2^{43} bits
- Quantum Computers have applications in secure communications, high performance computing, simulation, and cryptography.
- Electron spins can transfer information of nuclear spins which can be used to create logic gates.

Nitrogen-Vacancy (NV) Color Centers in Diamond Utilization has Potential As Qubits

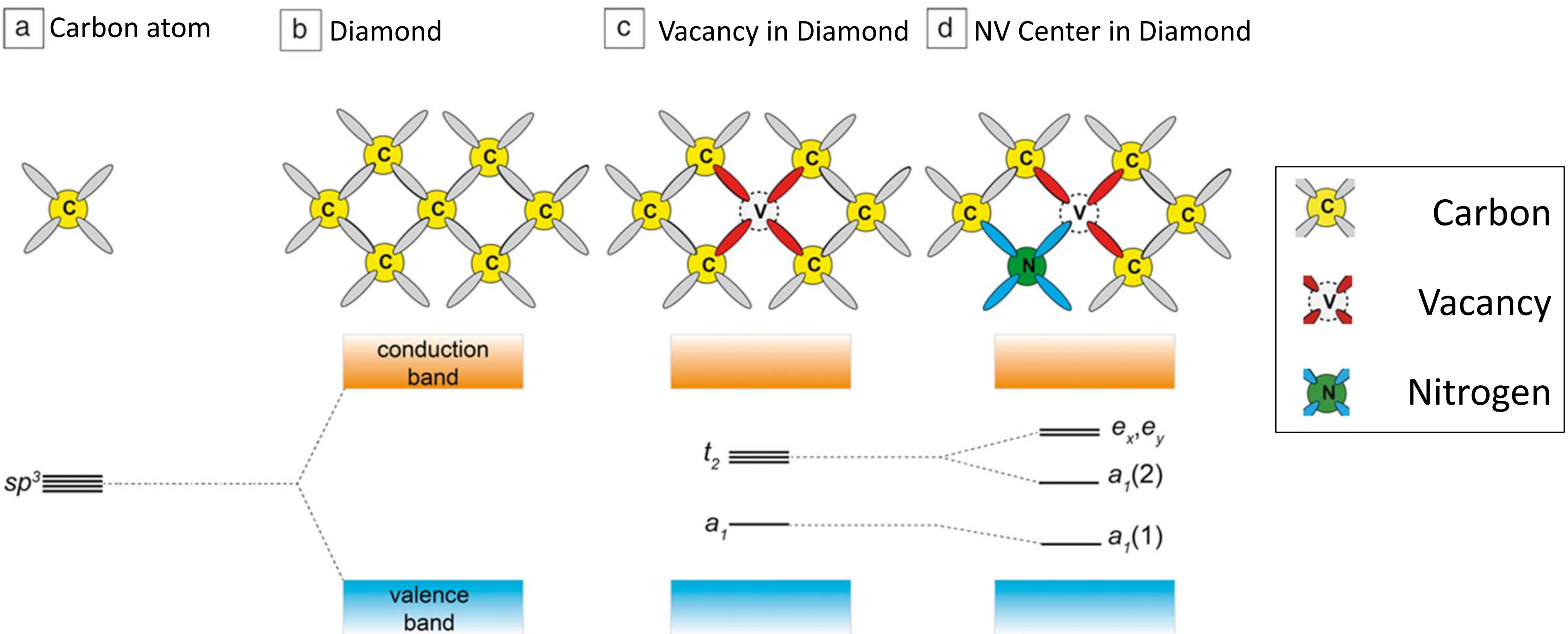
- Electronic Spins can be individually polarized, manipulated, and detected optically at room temperature.
- NV centers have localized nuclear spins with extremely long coherence times.
- Cheap to make NV.

Table 1. *Status of NV diamond relative to DiVincenzo criteria.*

	Criteria	**Low temp**	**Room temp**
1	Well-defined qubits	✓	✓
2	Initialization to a pure state	✓	✓
3	Universal set of quantum gates	✓	✓
4	Qubit-specific measurement	✓	Progressing well
5	Long coherence times	✓	✓
6	Interconvert stationary and flying qubits	Progressing well	Maybe
7	Transmit flying qubits to distant locations	Progressing well	Progressing well

Hemmer et al., *Diamonds for Scalable Quantum Systems,* **SPIE Newsroom**, DOI 10.1117/2.1200711.0941

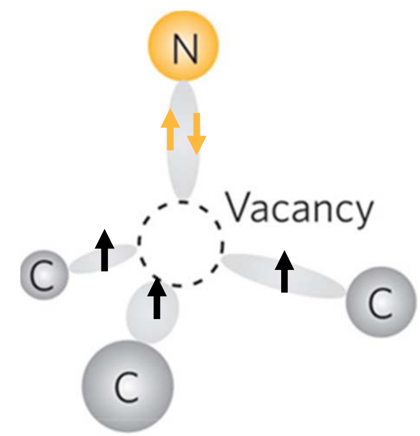
Nitrogen-Vacancy(NV) Formation in Diamond



MRS Bulletin **38**, 802-807 (2013)

Nitrogen-Vacancy(NV) electronic spin structure

- NV^0 has 3 (C) + 2 (N) = 5 electrons



Nature Physics **7**, 453-454 (2011)

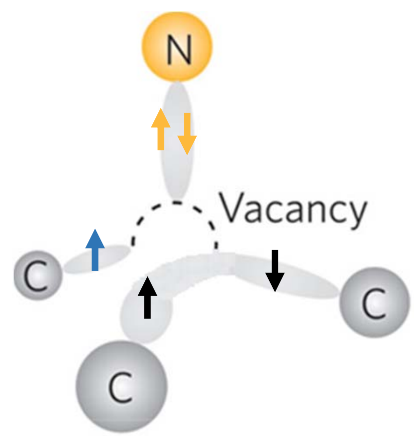
Nitrogen-Vacancy(NV) Structure

- NV^0 has 3 (C) + 2 (N) = 5 electrons

  2 electrons of C makes a quasi-covalent bond..

  2 electrons of N make a Lone pair.

  Only one electron left



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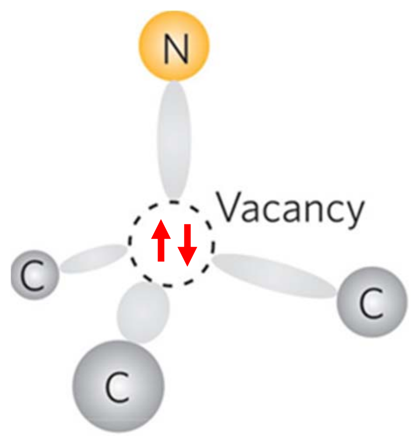


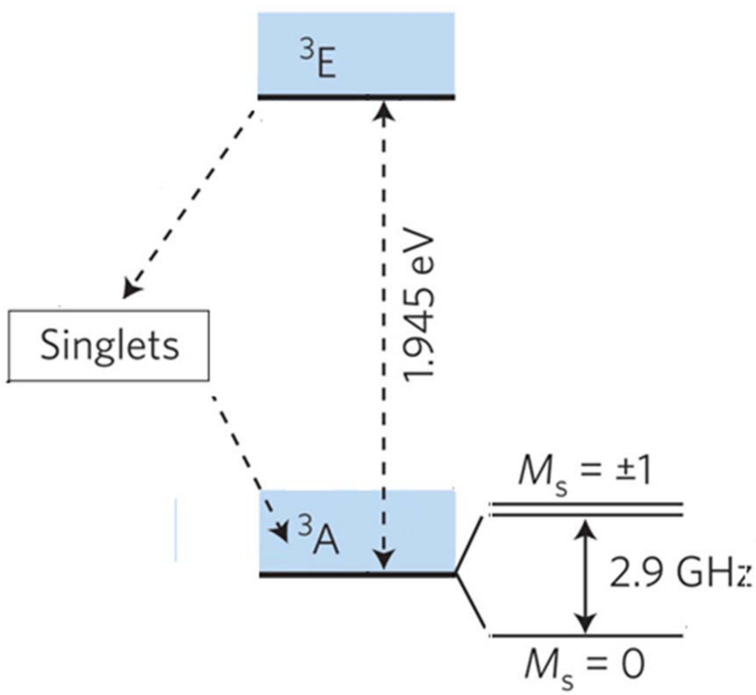
- NV^- has 1 + 5 = 6 electrons **(NV Center)**

  Pair up the last electron with an extra electron.

  Spin triplet (S=1) Spin singlet (S=0)

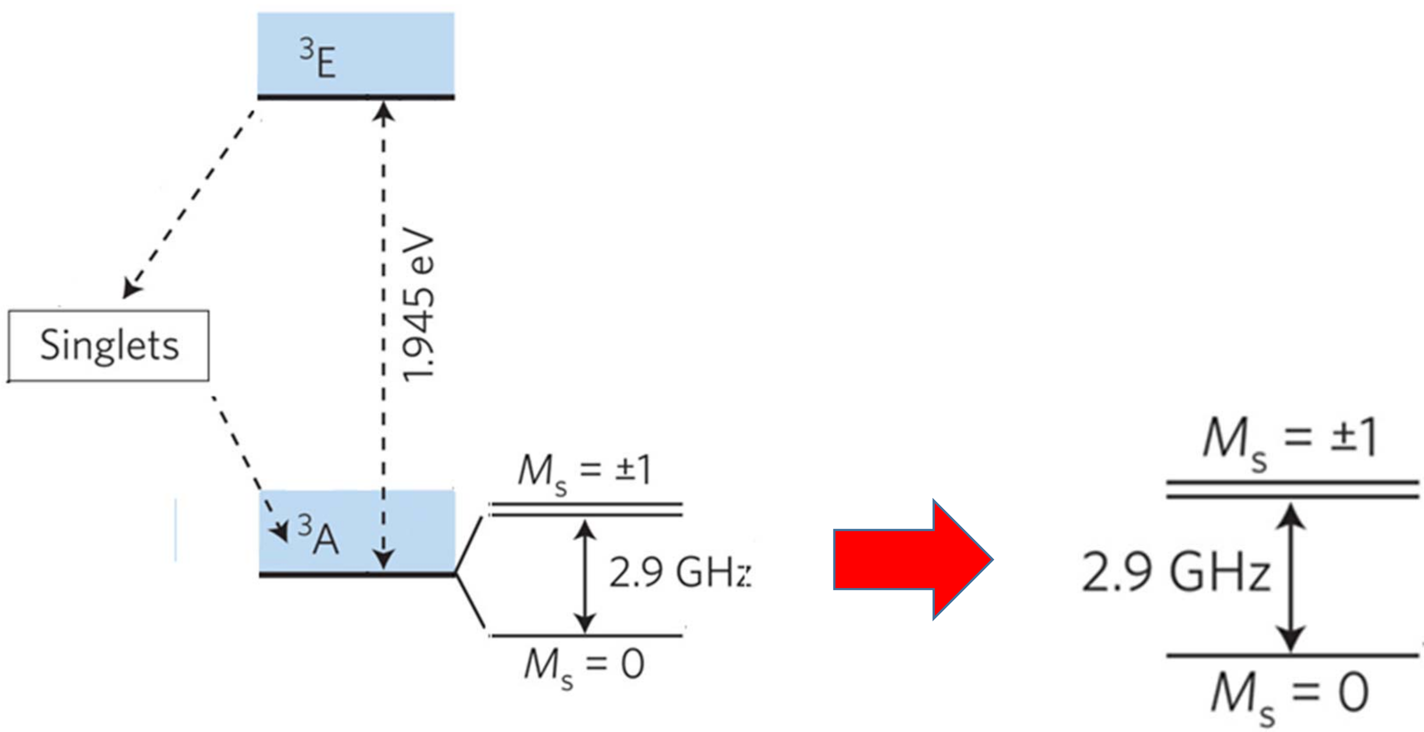
Nature Physics **7**, 453-454 (2011)

Electronic energy levels of NV Center



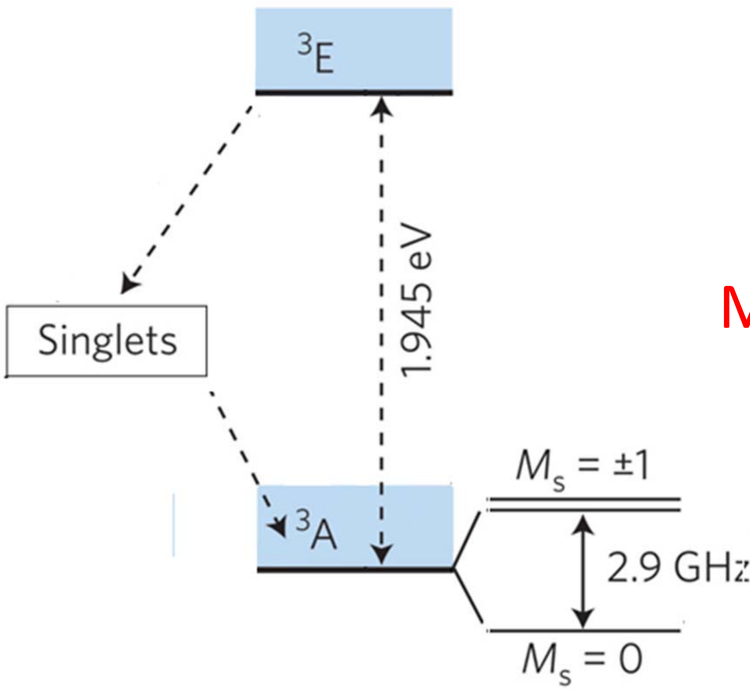
Nature Physics **7**, 453-454 (2011)

Only focus on the lowest energy levels

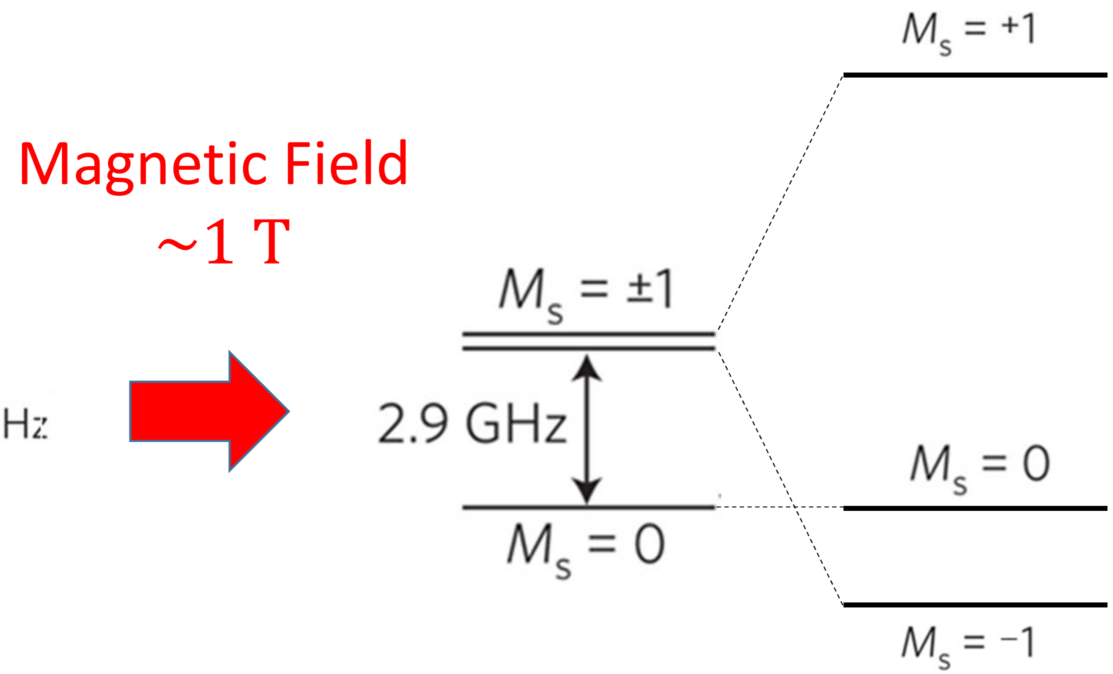


Nature Physics **7**, 453-454 (2011)

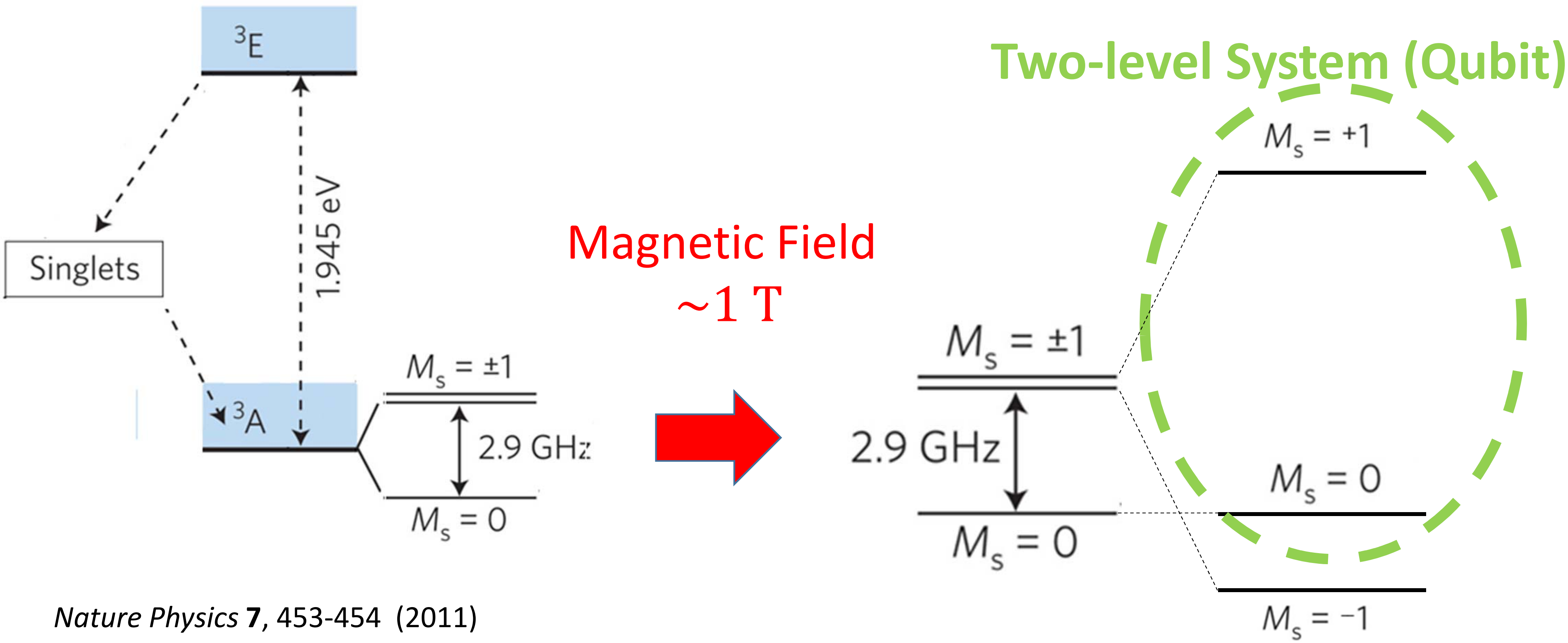
Magnetic field split the levels further



Nature Physics **7**, 453-454 (2011)



Pick two energy levels as an effective Qubit

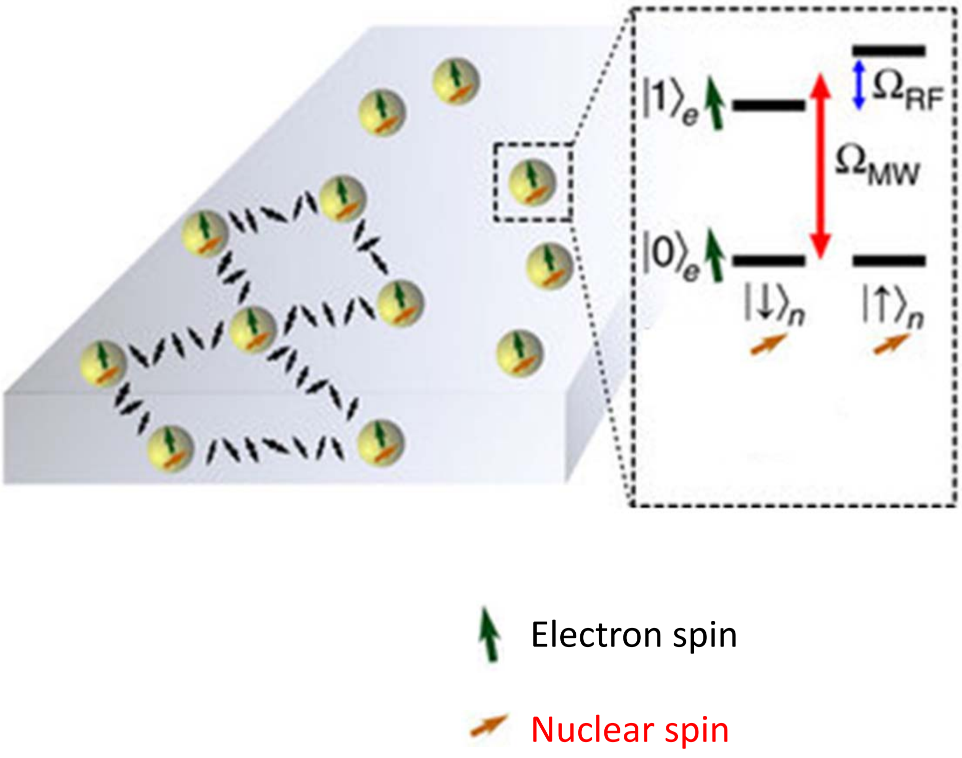


Nature Physics **7**, 453-454 (2011)

NV-Center As a Controllable Quantum Memory

- Nuclear spin: Memory bit storing information

- Electronic spin: Transfer bit
  copy/paste
  bit processing



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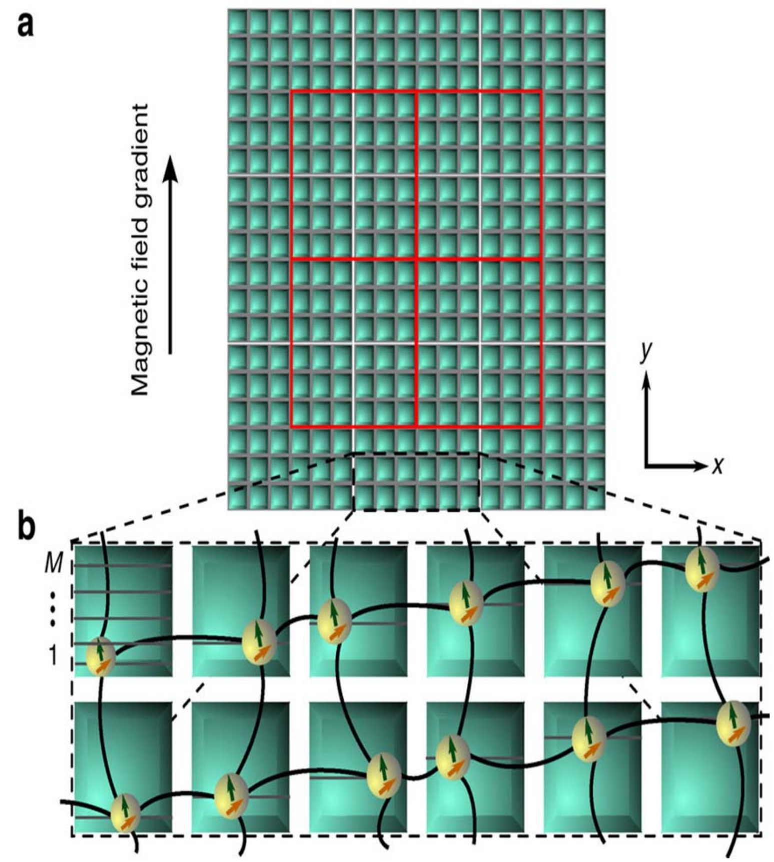
NV-Center Qubits Allow a Scalable Architecture

Three levels of hierarchy:

- Single plaquettes (~100´s nm)
- Super-plaquettes (~10 μm)
- Array of super-plaquettes

B$_z$ gradient in the **y** direction.

Unique access to the levels of each plaquette.



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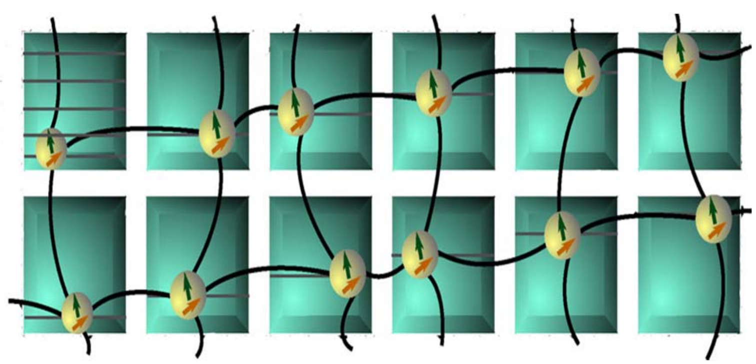
Dark spin chain data bus



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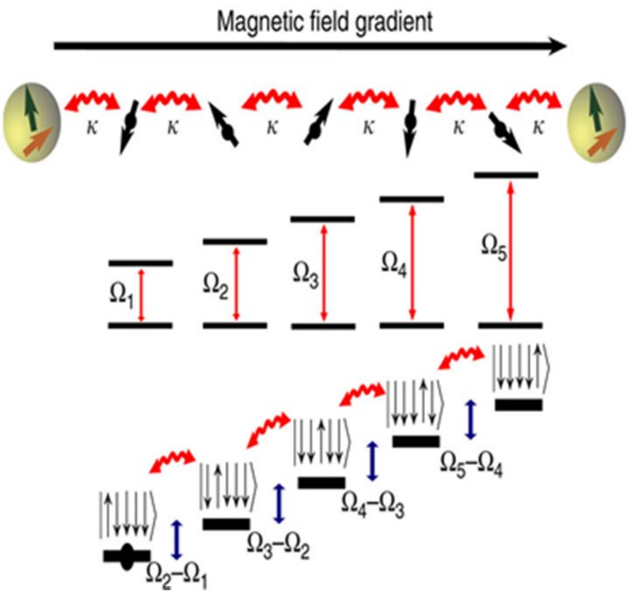
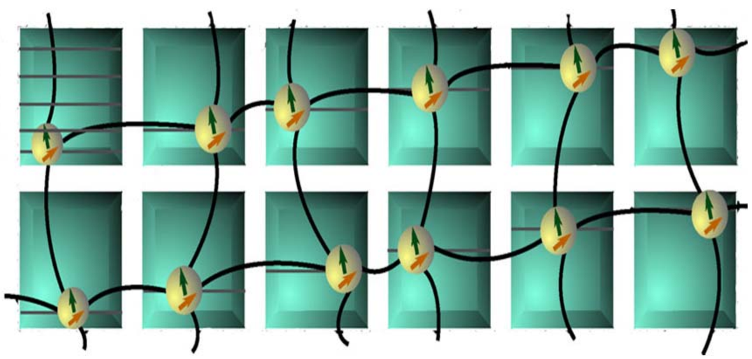
Dark spin chain data bus

- Swap in the **y** direction

Adiabatically tuning Rabi frequencies (individual)





Nature Comm. **3**, 800 (2012)

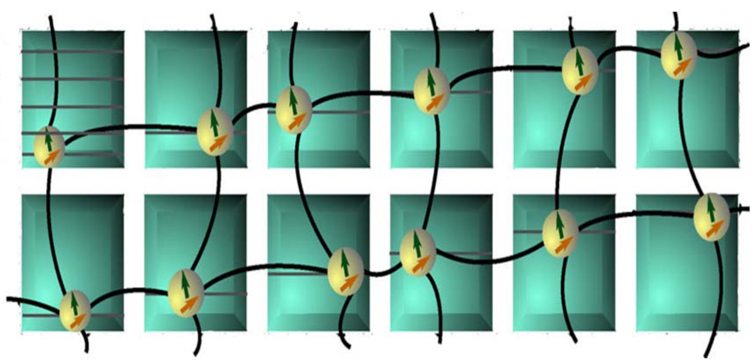
Dark spin chain data bus

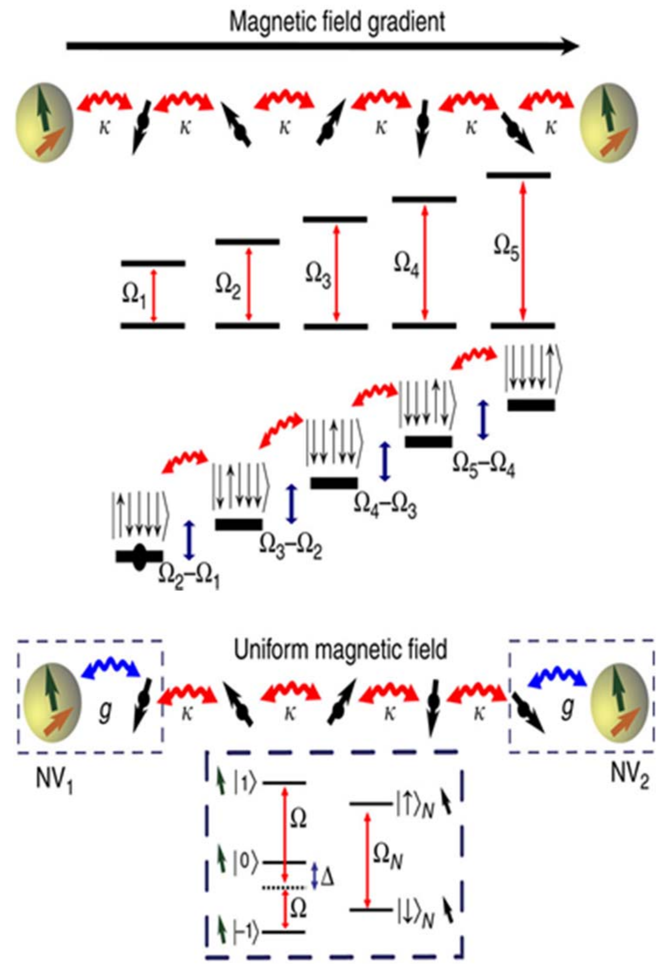
- Swap in the **y** direction

  Adiabatically tuning Rabi frequencies (individual)

- Swap in the **x** direction

  Turning off and on the $\mathbf{B}_z$ field (global)





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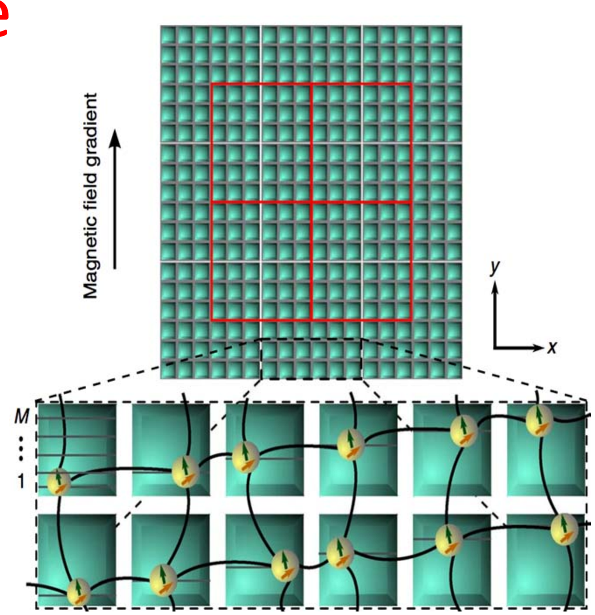
Article summary

Proposed a scalable solid state architecture which assembles different pieces of QC into a chip with finite size:

- NV center register

- DSCB mediator

- Individual control + Scalable



Scalable architecture of NV-centers in Diamond.

Author’s comments

- Looks promising
- Compatibility with quantum error correction & fault-tolerant QC
- Solid experimental support

Open questions:

Still require much efforts in various aspects, e.g. engineering, material science.

New directions:

Properties of NV centers related to electric strain
Plenty of room for optimization

Citation report

Published on 24 Apr 2012 on *Nature Communications*

Citations so far: 19(Scopus); 25(Google scholar).

Previous relevant work: plenty!

e.g.

- *Quantum Computing Using Defects,* by Weber et. al. 2010;

- *Quantum communication through an unmodulated spin chain*, by Bose, S. in 2003. Physical Review Letters, 91(20), 207901/1-207901/4.

Citing paper summary

Published on 24 Apr 2012 on *Nature Communications*

Citations so far: 19(Scopus); 25(Google scholar).

Similar work on scalable quantum simulators

- *A large-scale quantum simulator on a diamond surface at room temperature* by Cai et. al. published in Nature, 2013;
- *Controllable Quantum Spin Glasses with Magnetic Impurities Embedded in Quantum Solids* by Lemeshko et. al. in Phys Rev B, 2013.

Other work on details of the implementation

- *High-resolution Correction Spectroscopy of C-13 Spins near a NV-center in* Diamond by Laraoui et. al. 2013 in *Nature Communications;*
- *Practicality of Spin Chain Wiring in Diamond Quantum Technologies* by Ping et. al. in 2013, Phys. Rev. Lett.

Progress made and to be made after this work…

A number of research groups/collaborations are actively working on NV-center related applications, both theory and experiments

Quantum Engineering Group (MIT)

- NV center related quantum register manipulation
- Quantum simulators
- Diamond magnetometer

Walsworth Group (Harvard University)

- magnetometry using NV centers to enhance magnetic resolution (e.g. Optical Magnetic Imaging of Living Cells)

Quantum Photonics Laboratory (MIT)

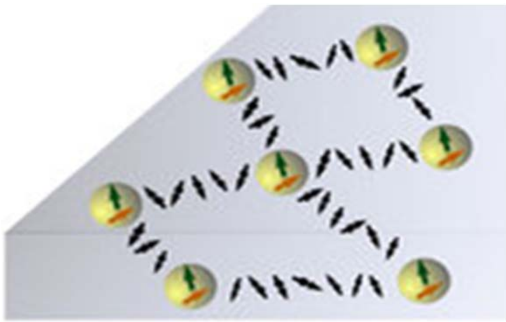
- Fabrication of high purity diamond nanocrystals

Critiques and Comments

- Ideas in the paper are presented in a clear and coherent manner.

- More details on experimental realization and how to integrate different elements.

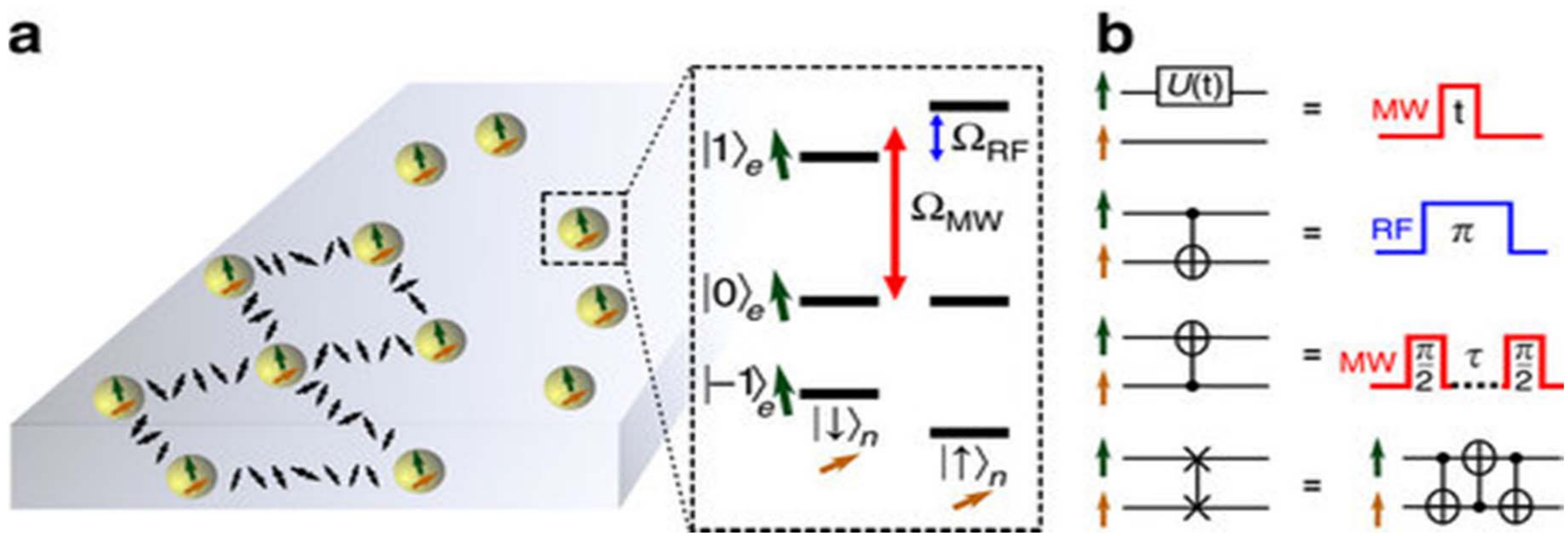
- Simulations are done in T=50 K not room temperature as advertised!



Thank You!

Single bit processing

$$H_{e,n} = \Delta_0 S_z^2 + \mu_e B S_z + \mu_n B I_z + A S_z I_z$$



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