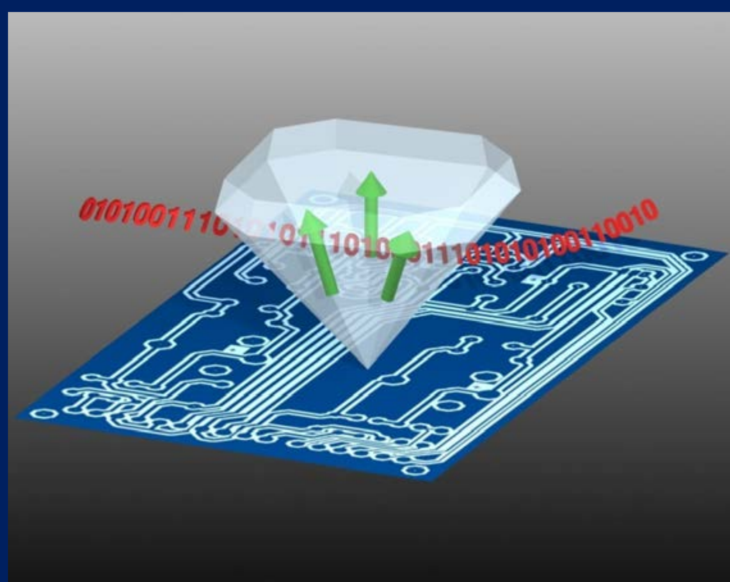
First夏季研修会

ダイヤモンド中のNV中心を用いた量子情報処理

Norikazu Mizuochi

Engineering Science, Osaka University

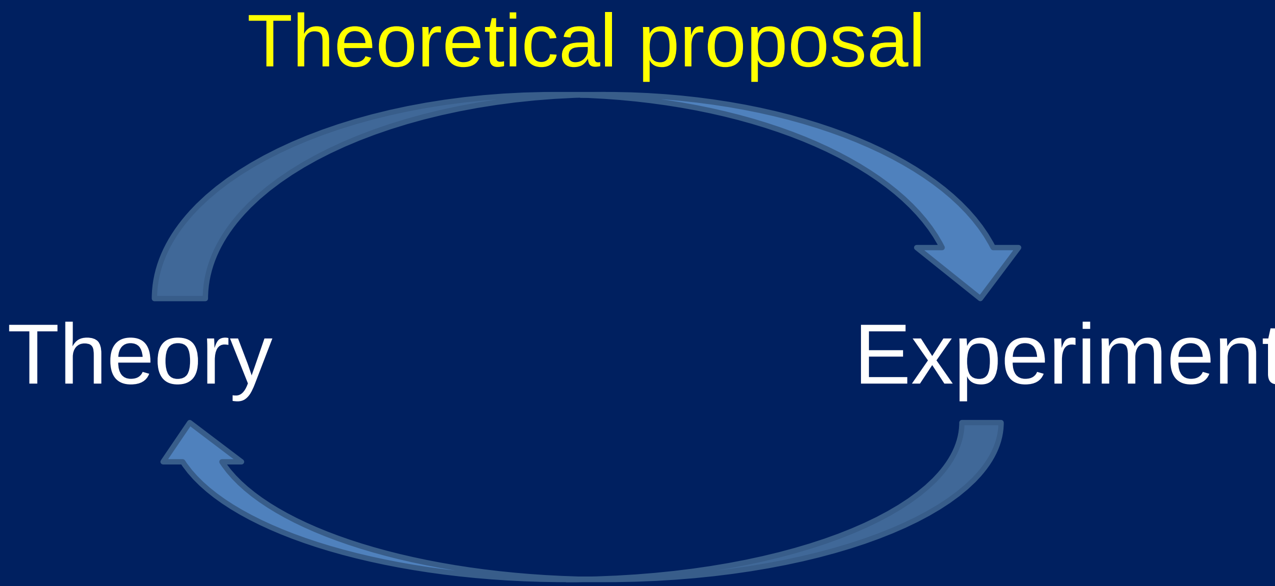


Collaborators and Acknowledgements

- Prof. Suzuki and group members (Osaka Univ.)
- Dr. Yamasaki and group members (AIST)
- Prof. Semba and group members (NTT)
- Prof. Kosaka (Tohoku Univ.)
- Prof. J. Wrachtrup and group members (Stuttgart Univ.)
- Prof. F. Jelezko (Ulm Univ.)
- Dr. A. Gali (Budapest Univ.)

Osaka Univ

Quantum information science and technology



Demonstration : Importance to show whether we can realize or not.

Proposal for practical architecture, system

Contents

Introduction of NV center in diamond

Historical view

Electronic states of NV center

Previous and Recent topics in NV center

何がなされてきたか？ NV中心で何ができるか？

Recent our results

Multi-qubit by Nuclear spins

Poster session (By Shimo-oka)

Electrical control

Electrically driven single photon source at room temperature based on NV center. *Nature Photonics*, 6, 299, 2012

Recent results

Diamond

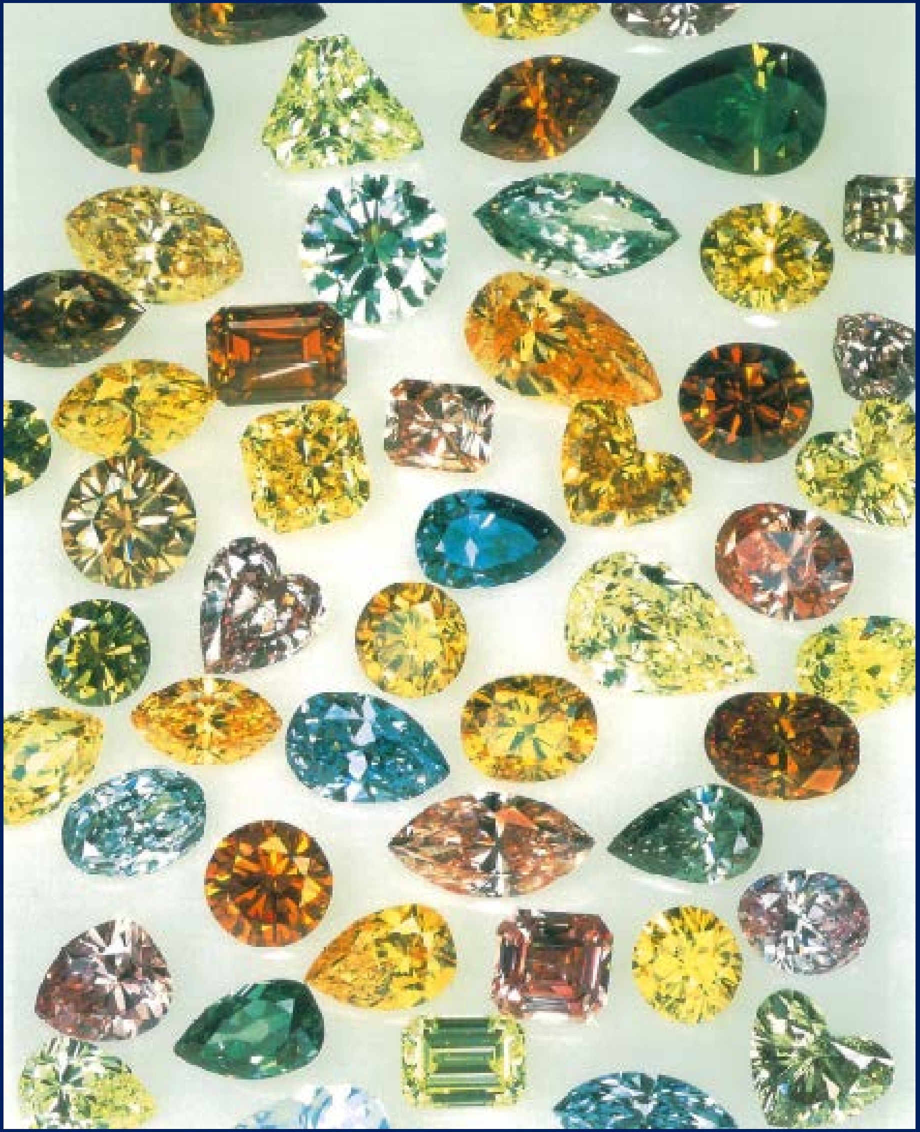
近年、きれいで大きなダイヤモンドが人工的に
合成されるように！

既にいくつかの企業から販売！

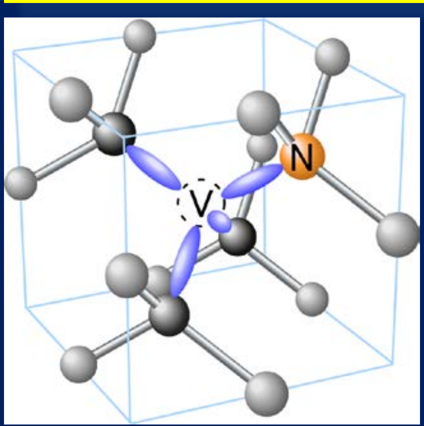
デビアスの子会社からもCVDで
合成されたダイヤモンドを販売

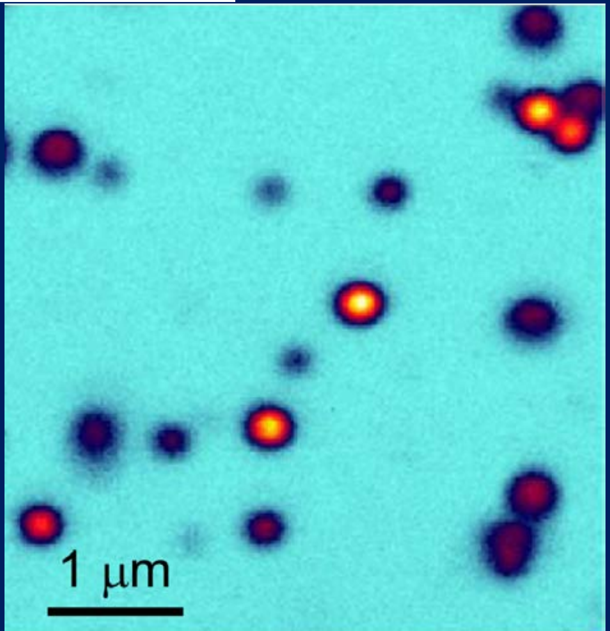
既に1cm角が売られ、近い将来、
1インチ角の試料も販売されると
いう.

Diamond



Impurities can incorporate : Various colors

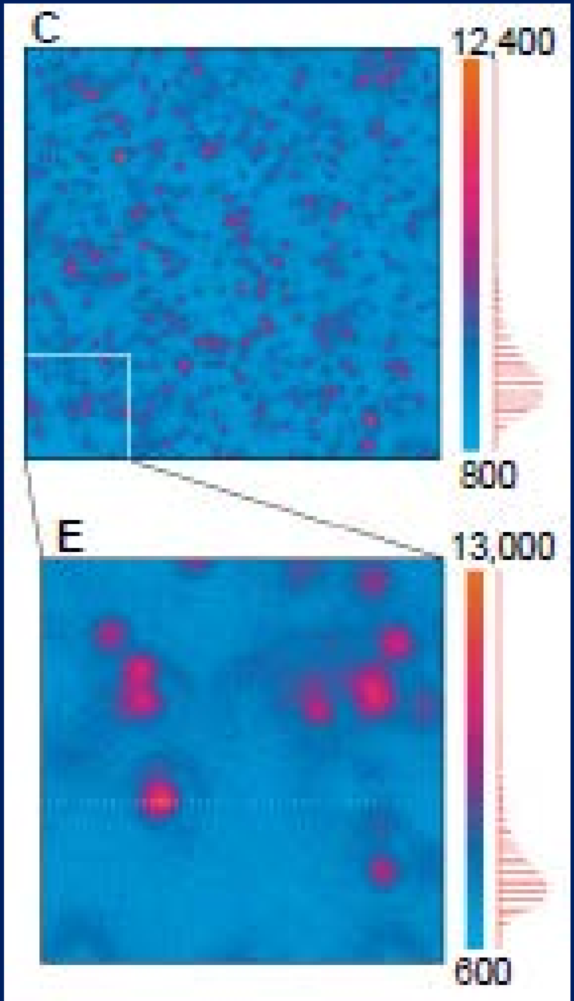


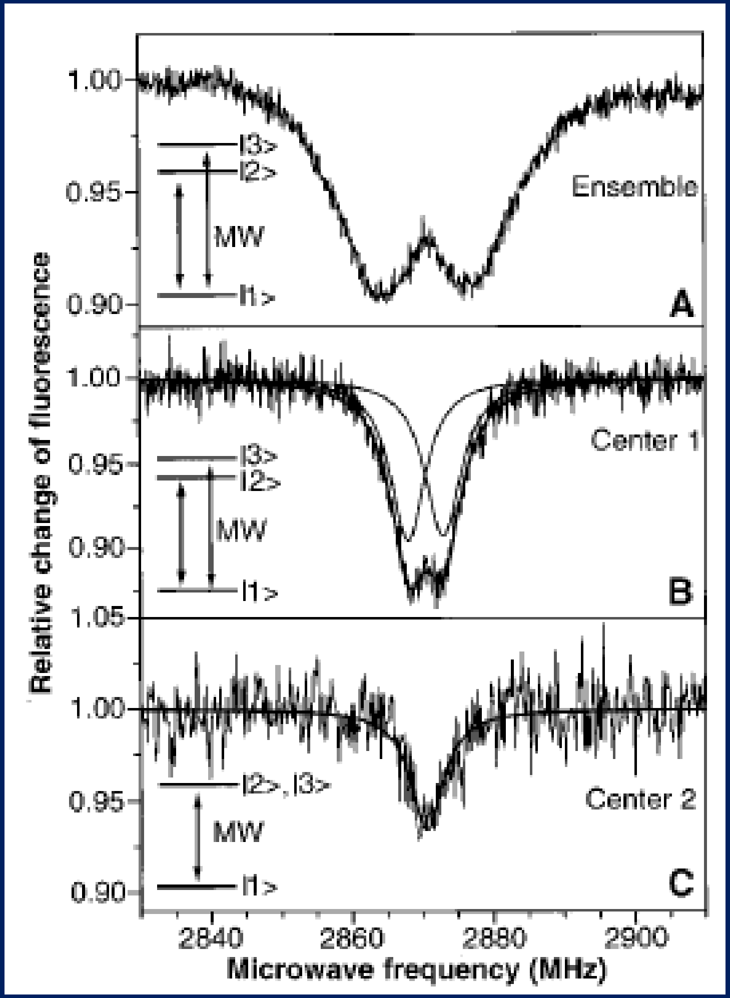


Historical view (1/3)

"Scanning confocal optical microscopy and magnetic resonance on single defect centers: Single NV center"

A. Gruber, A. Dräbenstedt, C. Tietz, L. Fleury, J. Wrachtrup,* C. Borczyskowski, *Science*, 276, 2012, 1997





Prof. Dr. J. Wrachtrup

Historical view (2/3)

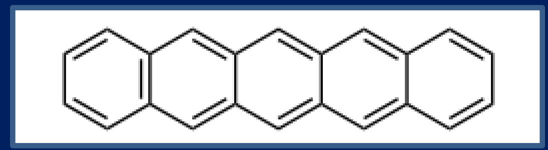
VOLUME 65, NUMBER 21 PHYSICAL REVIEW LETTERS 19 NOVEMBER 1990

Single Pentacene Molecules Detected by Fluorescence Excitation in a *p*-Terphenyl Crystal

M. Orrit and J. Bernard

Centre de Physique Moléculaire Optique et Herztienne, Centre National de la Recherche Scientific et Université de Bordeaux I, 351, Cours de la Libération, F-33405 Talence CEDEX, France

(Received 9 July 1990)



Prof. M. Orrit

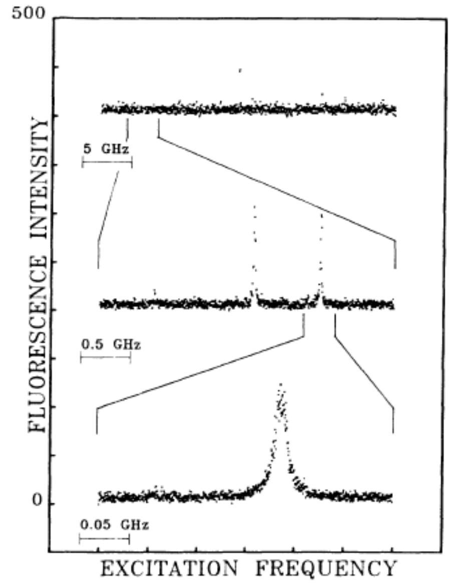


FIG. 2. Shape of a single molecule's excitation peak at different frequency scales. The bottom spectrum is approximately Lorentzian with FWHM about 12 MHz. The vertical scale is in counts/channel.

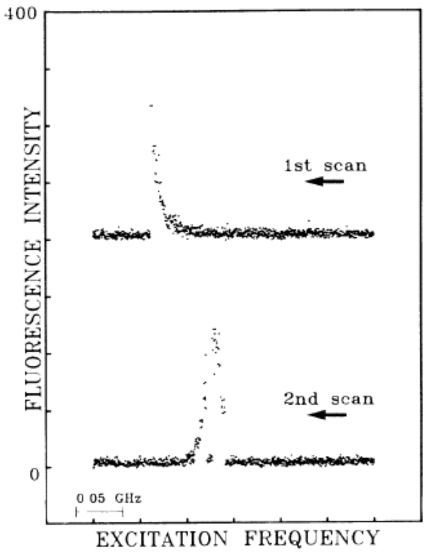


FIG. 4. Two successive scans of the excitation spectrum of a single molecule suggesting a photophysical hole-burning process. The sudden intensity falls and surges might arise from the flip-flops of a two-level system in the neighborhood of the molecule. The time per channel was 0.08 s and a scan lasted about 1 min. The vertical scale is in counts/channel.

Historical view (3/3)

Optical detection of magnetic resonance in a single molecule

J. Wrachtrup*, C. von Borczyskowski*, J. Bernard†, M. Orrit† & R. Brown†

* Fachbereich Physik, Freie Universität Berlin, Arnimallee 14, 1000 Berlin 33, Germany
† Centre de Physique Moléculaire Optique et Hertzienne, u.a. 283 du C.N.R.S., Université Bordeaux I, 33405 Talence cedex, France

NATURE · VOL 363 · 20 MAY 1993

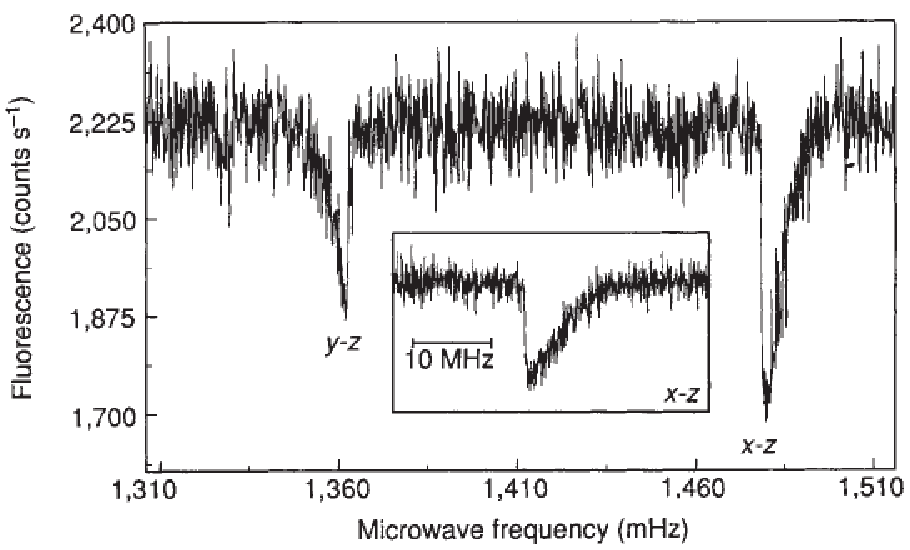


FIG. 1 Decrease of the fluorescence intensity of a single pentacene molecule when the microwave field is resonant with the *y–z* or the *x–z* transition. The inset shows the *x–z* transition on an enlarged frequency scale, on reducing the microwave power by a factor of ~30.

Electronic states of NV center (1/5)

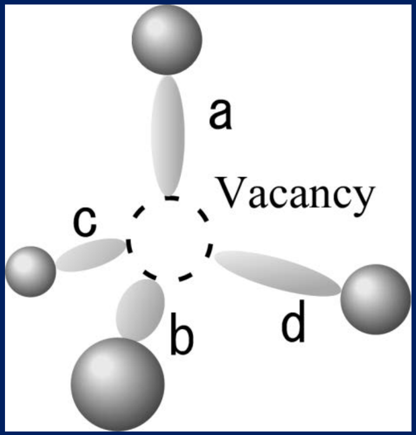
Why it has S=1 ? About optical property.

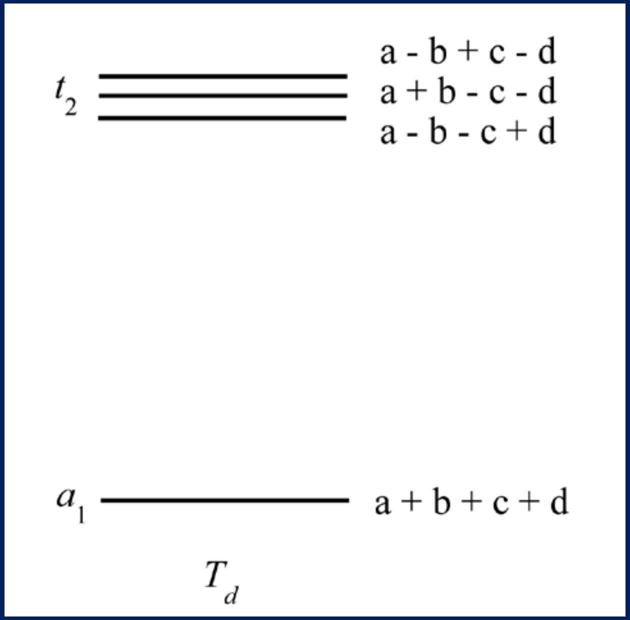
ダングリングボンド軌道（原子軌道）の線形結合
:LCAO分子軌道による理解

各エネルギーレベルの性質を定性的に理解

C. A. Coulson and M. J. Kearsley, Proc. R. Soc. Lond. A 1957 241, 433.
G. D. Watkins, “Deep defects in semiconductors”

四面体対称（T_d）の場合

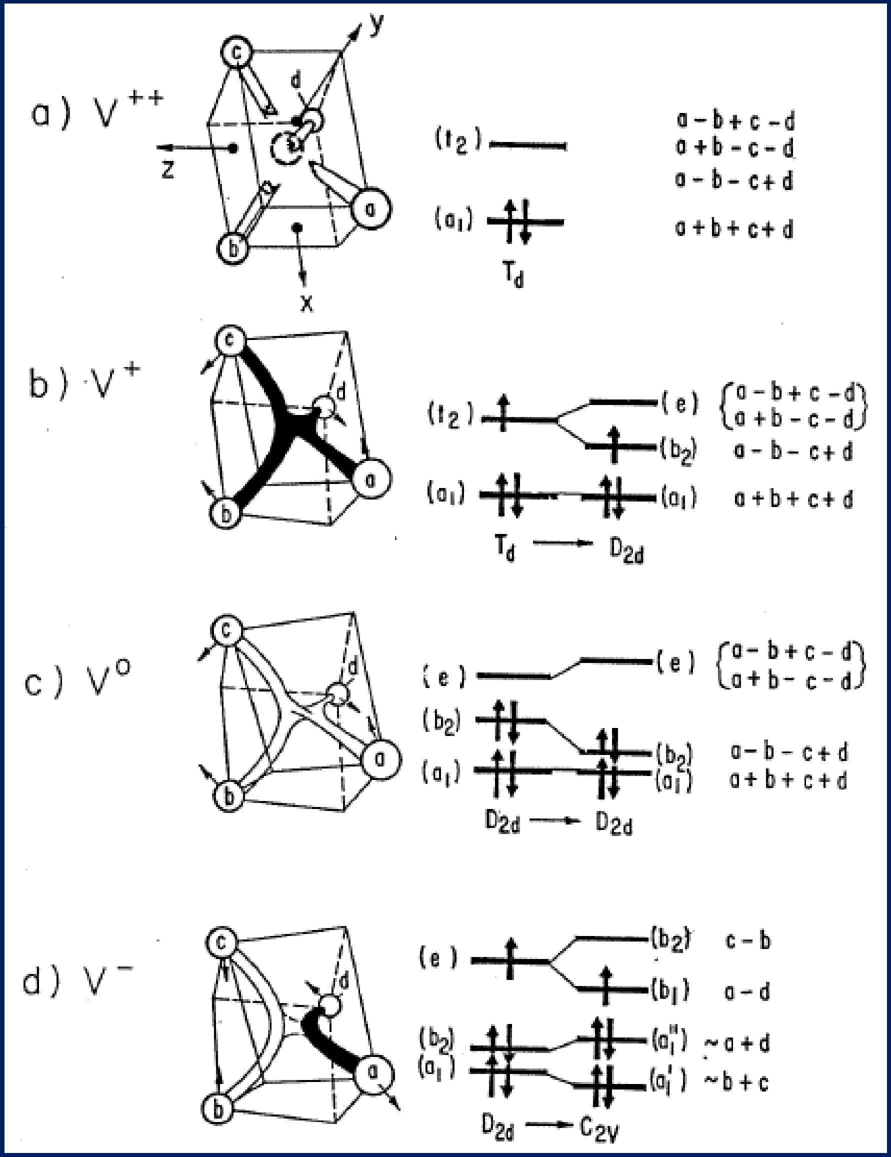




Electronic states of NV center (2/5)

Example in Si

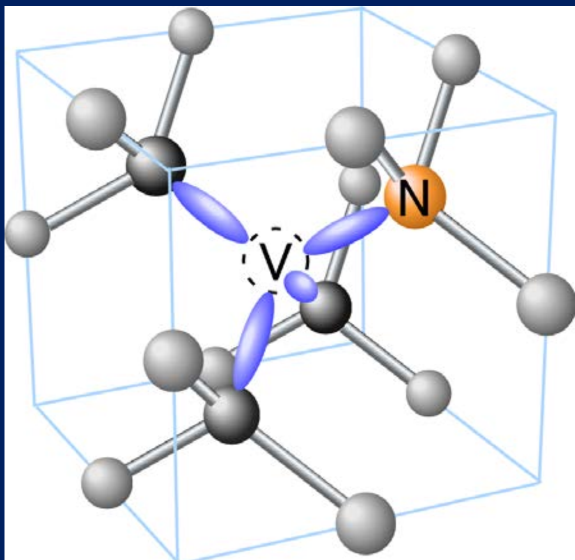
In Si, the structure distorts, but does not in diamond.



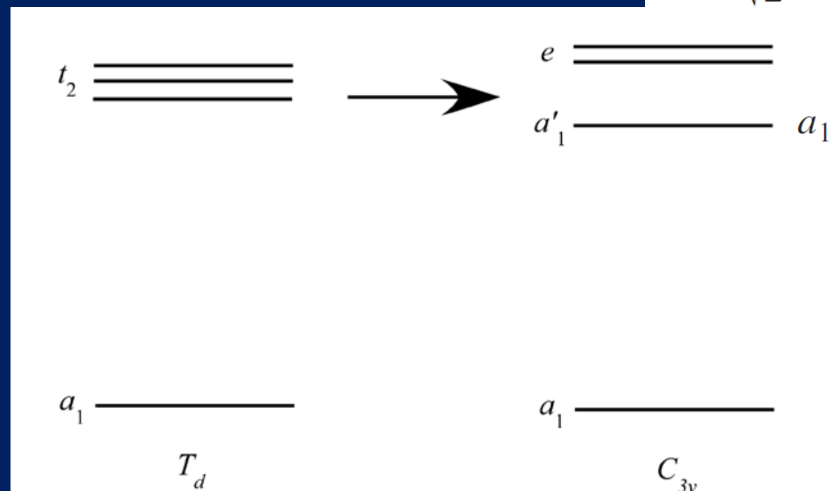
G. D. Watkins, “Deep defects in semiconductors”

Electronic states of NV center (3/5)

S. Felton, et al., PRB 77, 081201, 2008.



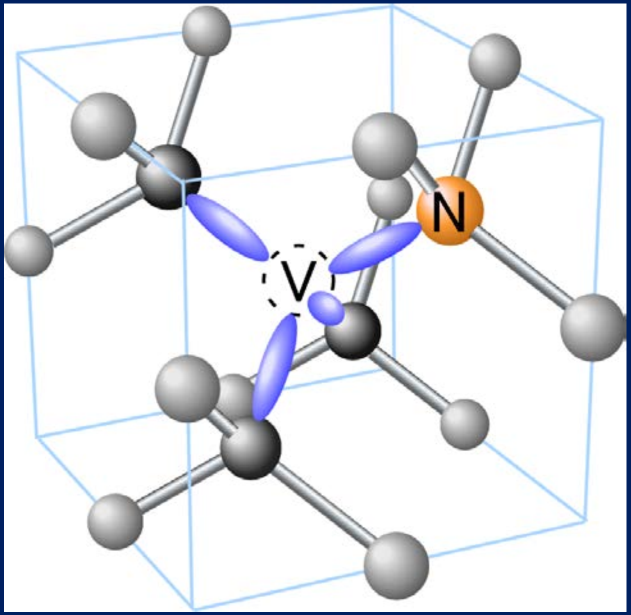
$$e = \frac{1}{\sqrt{2}}(\varphi_a - \varphi_b), \quad \frac{1}{\sqrt{6}}(2\varphi_c - \varphi_b - \varphi_a)$$

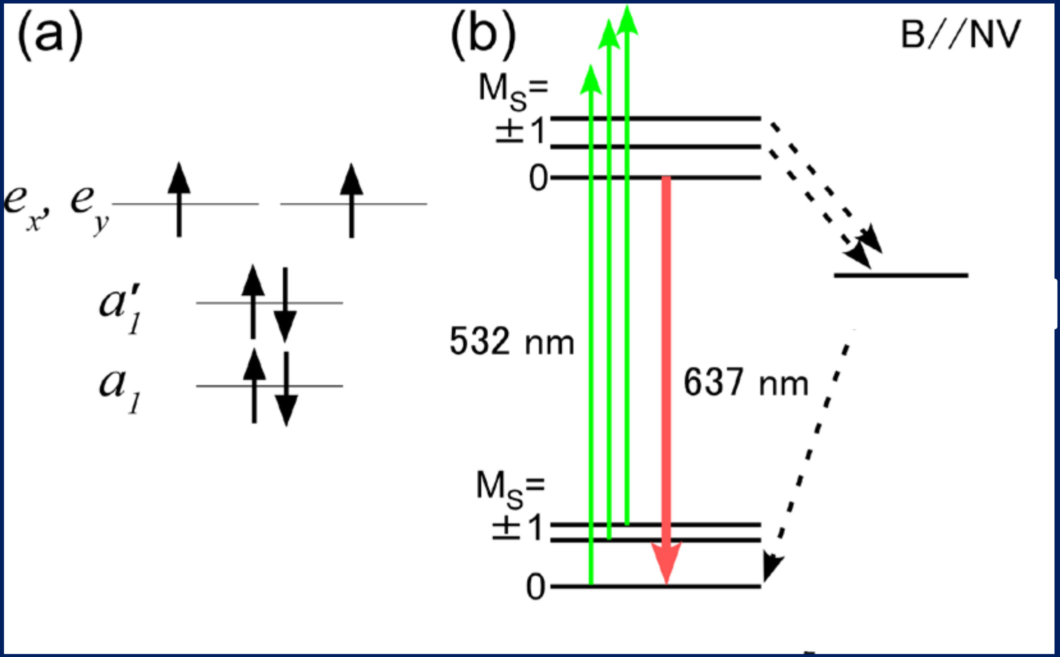


$$a_{1C} = \frac{1}{\sqrt{3}}(\varphi_a + \varphi_b + \varphi_c)$$

$$a_{1N} = \varphi_N$$

Electronic states of NV center (4/5)



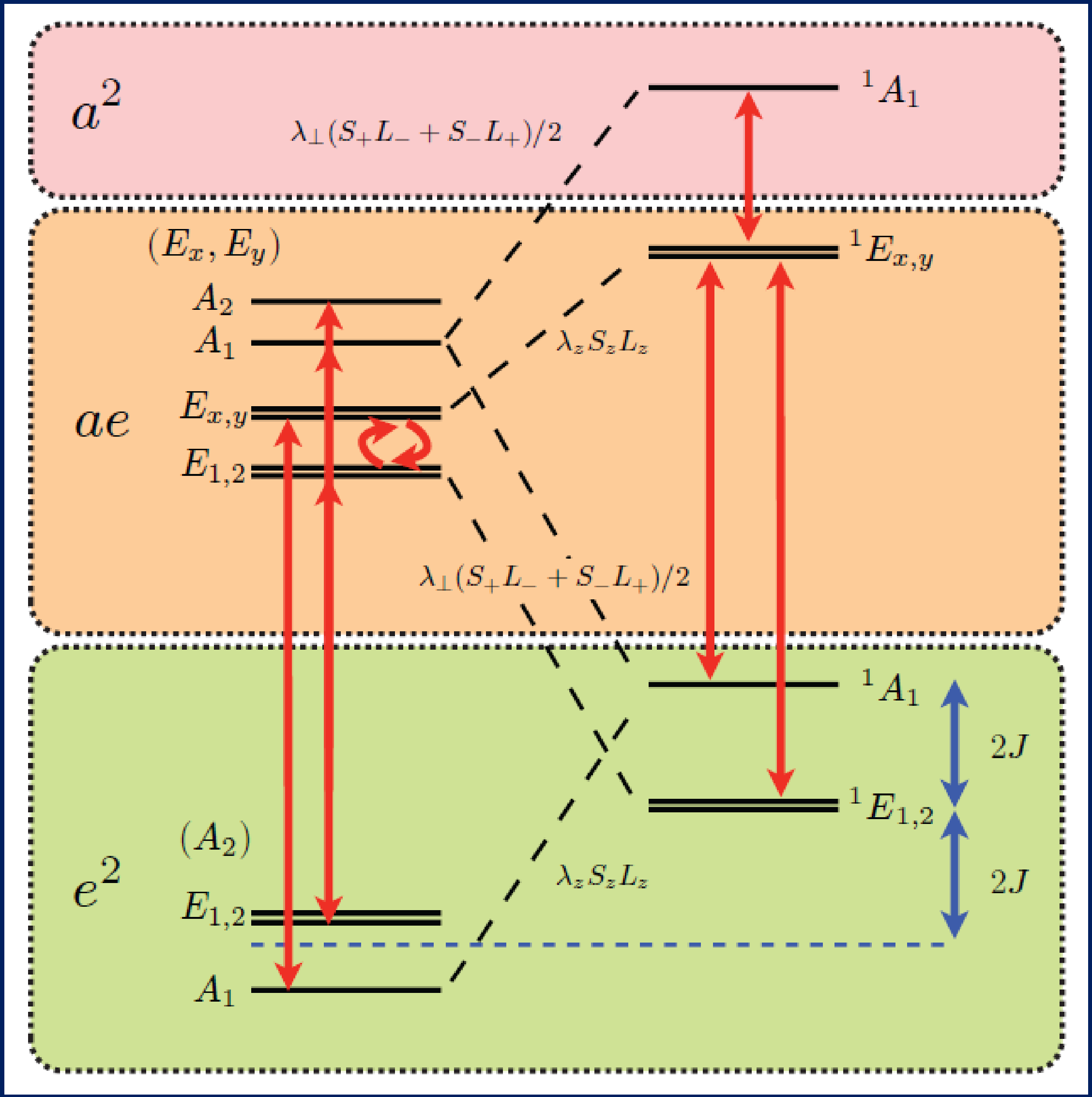


Electronic states of defect in deep level within band-gap

- Spin (S=1) with long spin coherence time
- Strong and stable emission (Fluorescence)

Control and detection of single spin at RT

Electronic states of NV center (5/5)



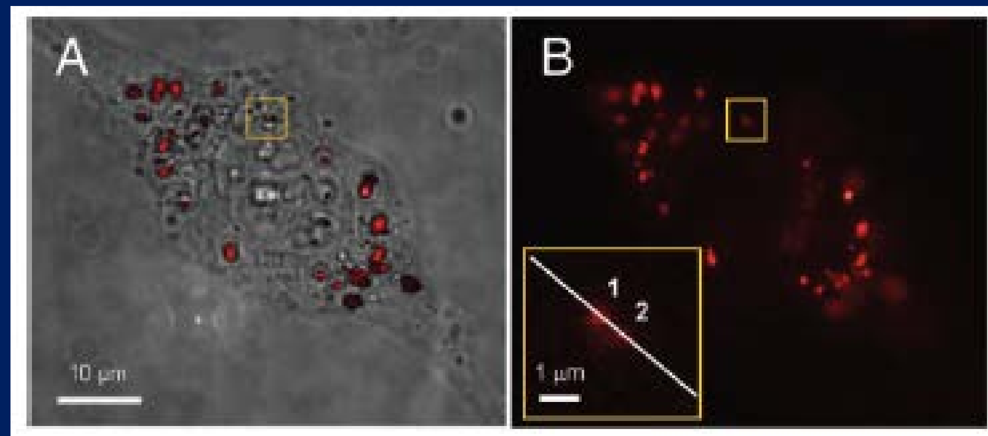
・スピンースピン相互作用、スピン軌道相互作用を考慮した詳細な電子状態

・群論（対称性）による定性的な理解だけでなく、ab initio法による定量的な議論

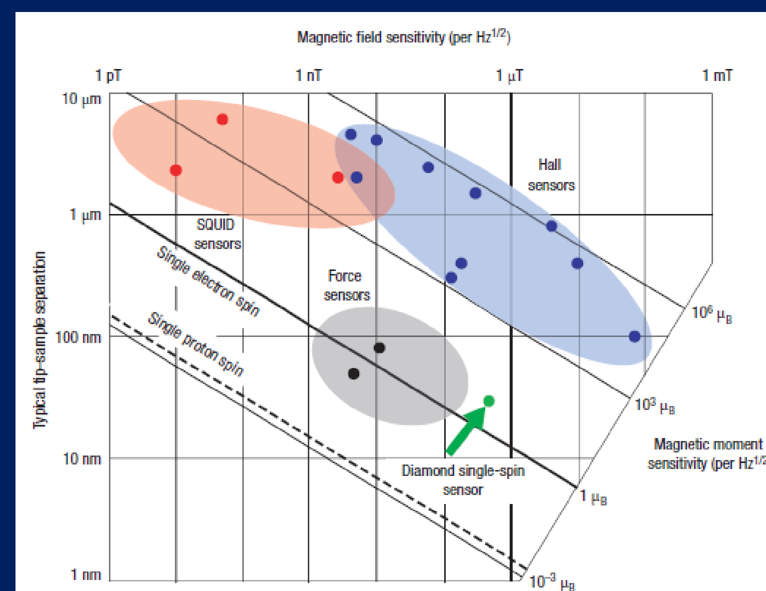
J. Maze et al., NJP, 13 (2011) 025025.

Topic (other than quantum information science)

Single fluorescent nanodiamonds as cellular biomarkers (PNAS 2007)



Scanning probe magnetometry (magnetic sensor) (Nature, 455, 648, 2008)



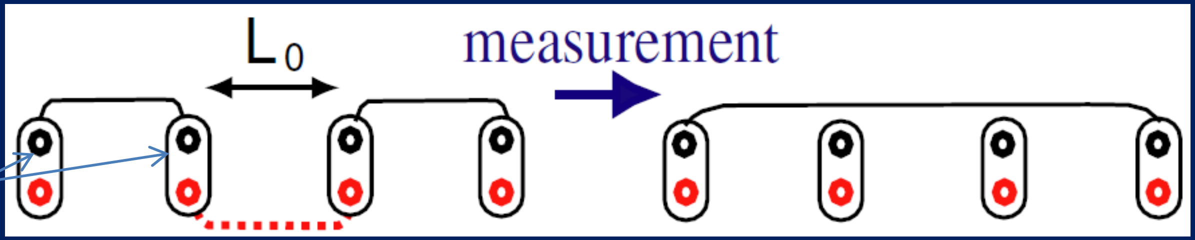
Nature nanotechnology, 3, 643, 2008. (NEWS & VIEWS)

Characteristics of NV center (quantum information science)

- Ground triplet state (Electron spin quantum number S=1)
- In solid material, coherent control of single spin at RT is only possible in NV center. (Science 1997)
- Long coherence time（T_{2e} > 1 ms at RT, Nature Material 2009, T_{2n} > 1 s at RT, Science 2012）.
- Optical initialization of electron spin and nuclear spin
- Entanglement between photon and spin （Nature 2010）
- QND meas. of nuclear spin at RT. (Science 2010)
- Single shot meas. of electron spin. (Nature 2011)
- Multi-qubits by nuclear spins (N. Mizuochi et al., PRB 2009 …)
- Bell state among single nulear spins T_2 = 5ms at RT. (P. Neumann, N. Mizuochi et al., Science 2008)

Quantum network ("spin" for processing and memory, "Photon" for communication)

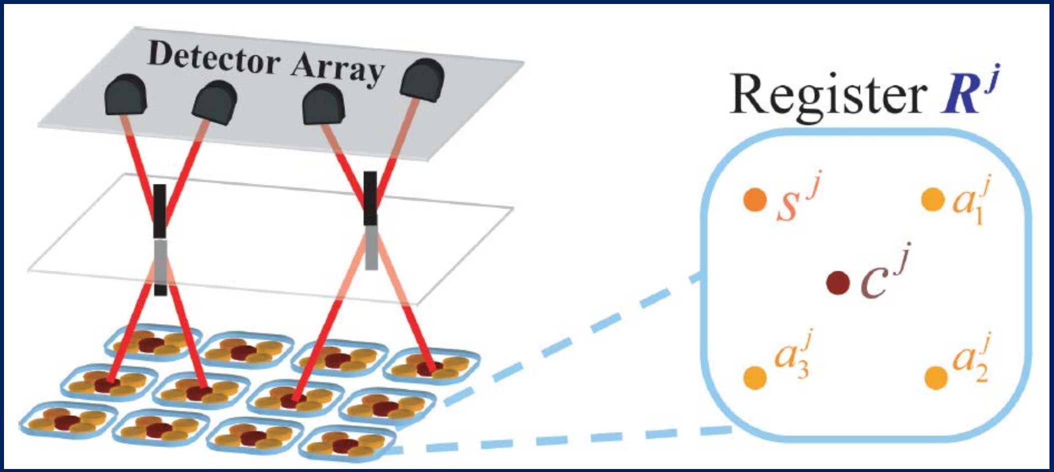
Quantum Cryptography (single photon source, quantum repeater)



Quantum Repeater

Black and Red ball represent spins (Qubits).

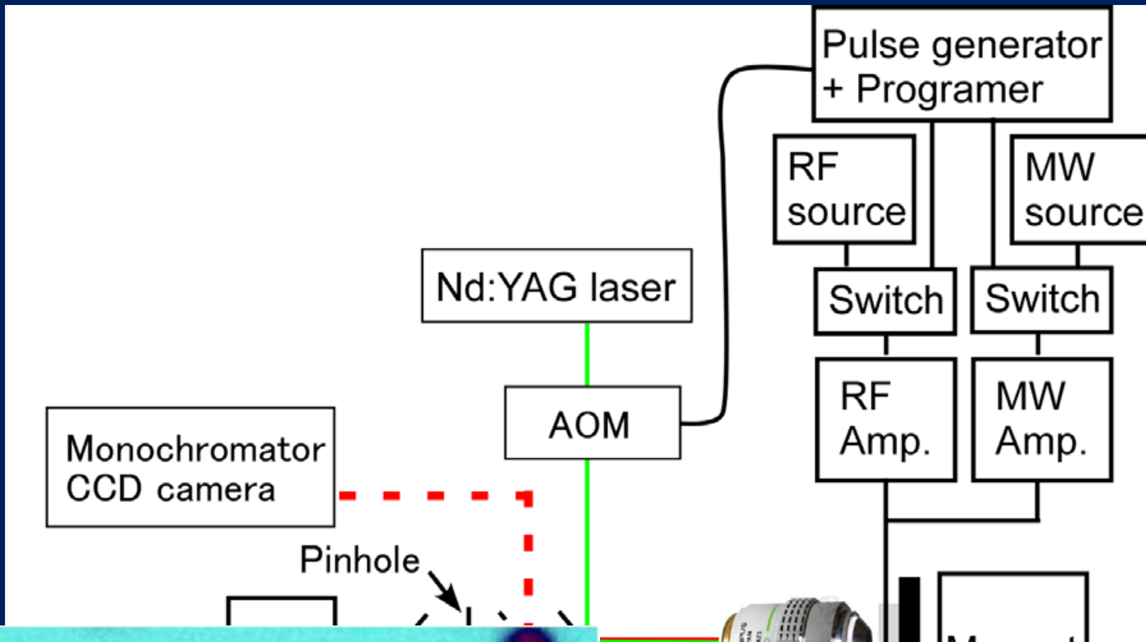
Distributed scalable quantum computer

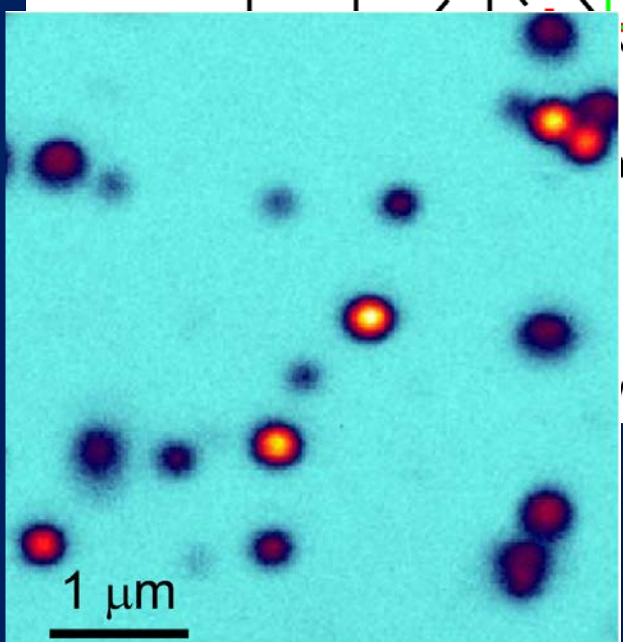


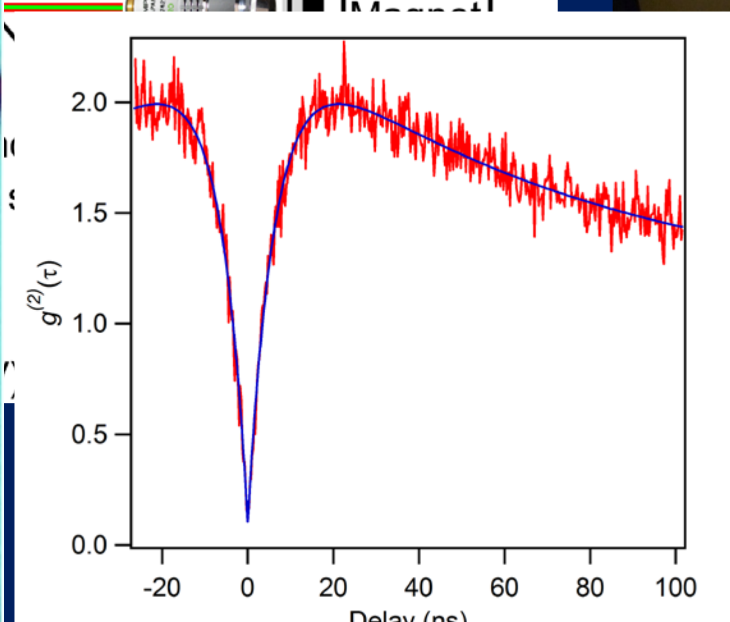
It consists of 5 qubits quantum registers. Jiang et al., PRA 2007

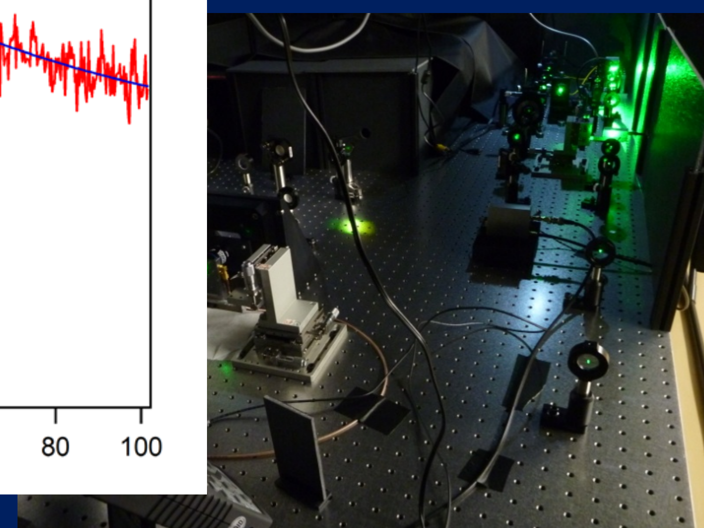
Several-qubit solid system with optical accessibility

Measurement system (in Osaka Univ.)

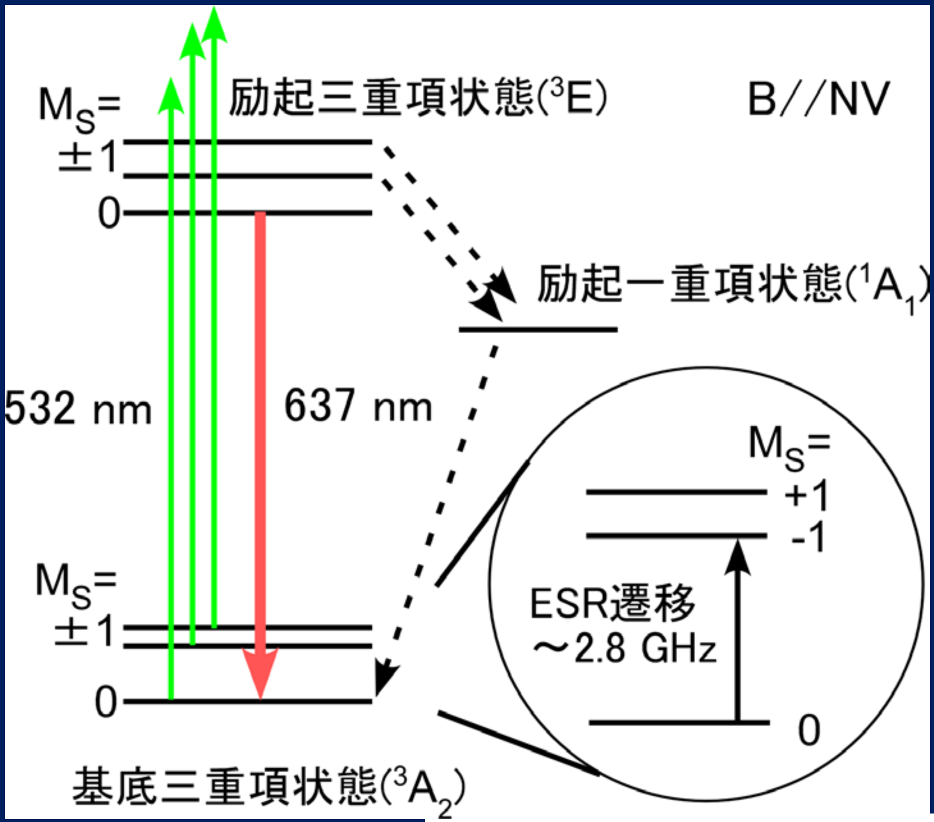


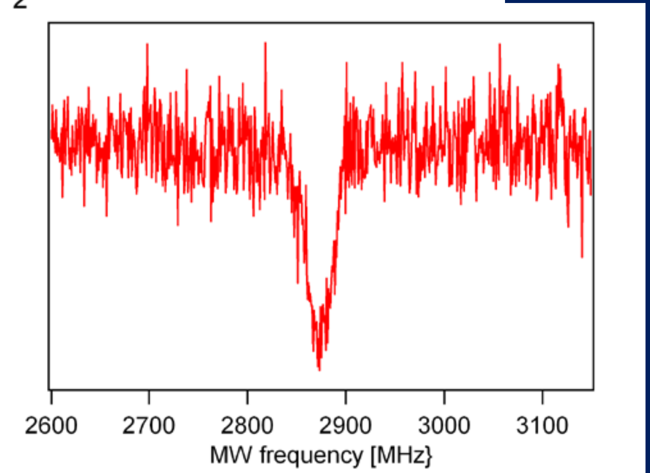






Optically detected magnetic resonance (ODMR)





Laser excitation (532 nm) plays very important roles as initialization and read out the spin states.

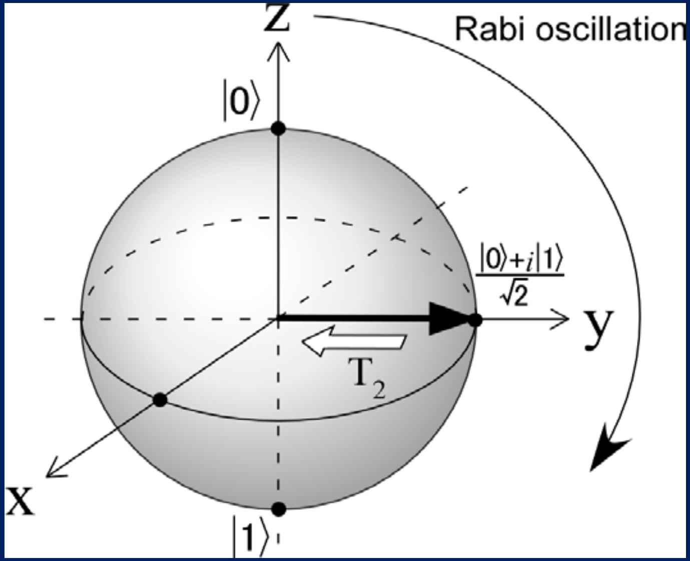
Pure state can be prepared.

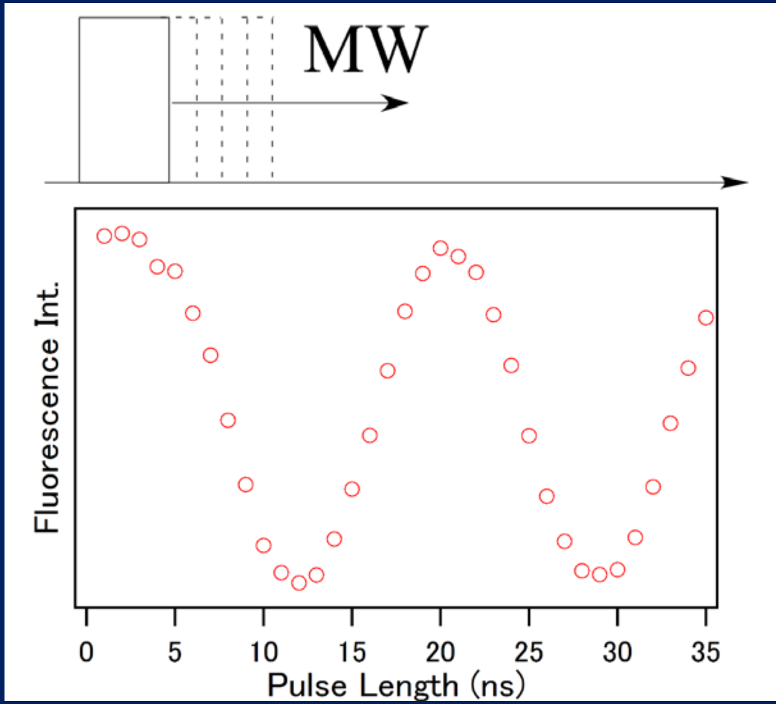
We detect Single NV and repeat detection cycles.

Control of spin

By spin resonance

$$\mathbf{H} = g\beta\,\mathbf{S}\cdot\mathbf{B}_1$$





π/2 pulse : coherence generation
π pulse : inversion

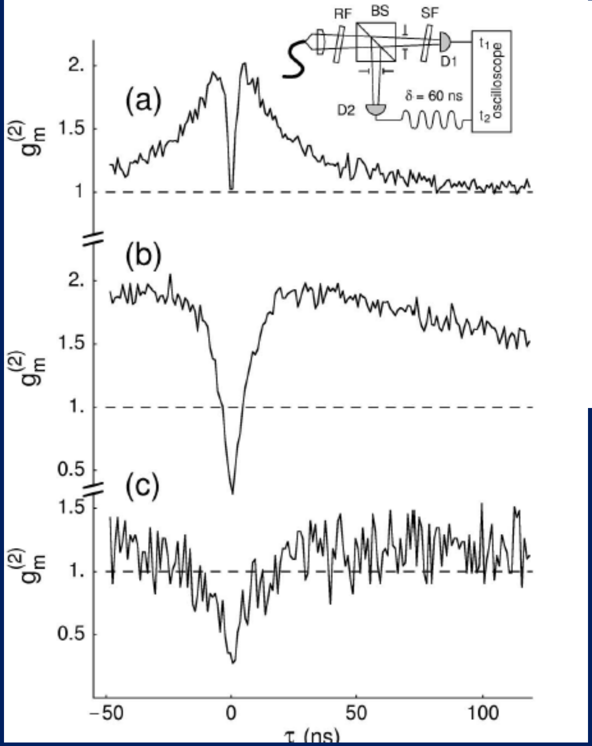
Previous and Recent topics in NV center (1)

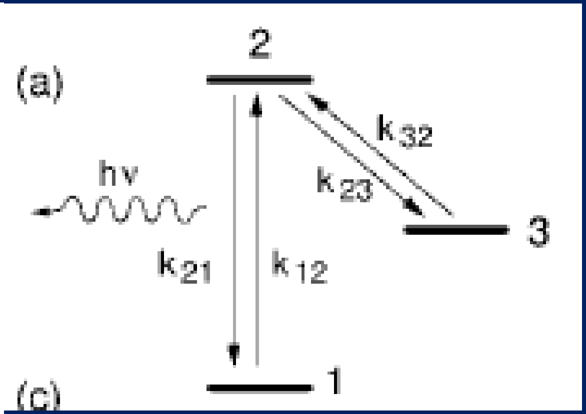
Demonstration of single photon source at RT

Stable Solid-State Source of Single Photons

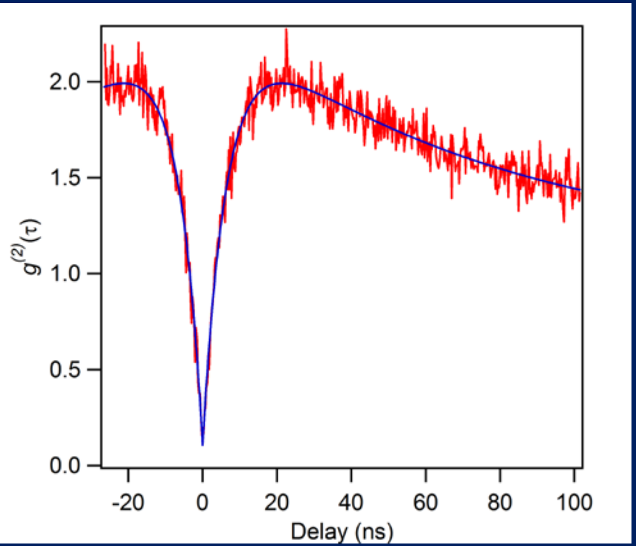
Christian Kurtsiefer,[1] Sonja Mayer,[1] Patrick Zarda,[2] and Harald Weinfurter[1,2]
[1]*Sektion Physik, Ludwig-Maximilians-Universität, D-80799 München, Germany*
[2]*Max-Planck-Insitut für Quantenoptik, D-85748 Garching, Germany*

PHYSICAL REVIEW LETTERS 10 JULY 2000





Our measurement

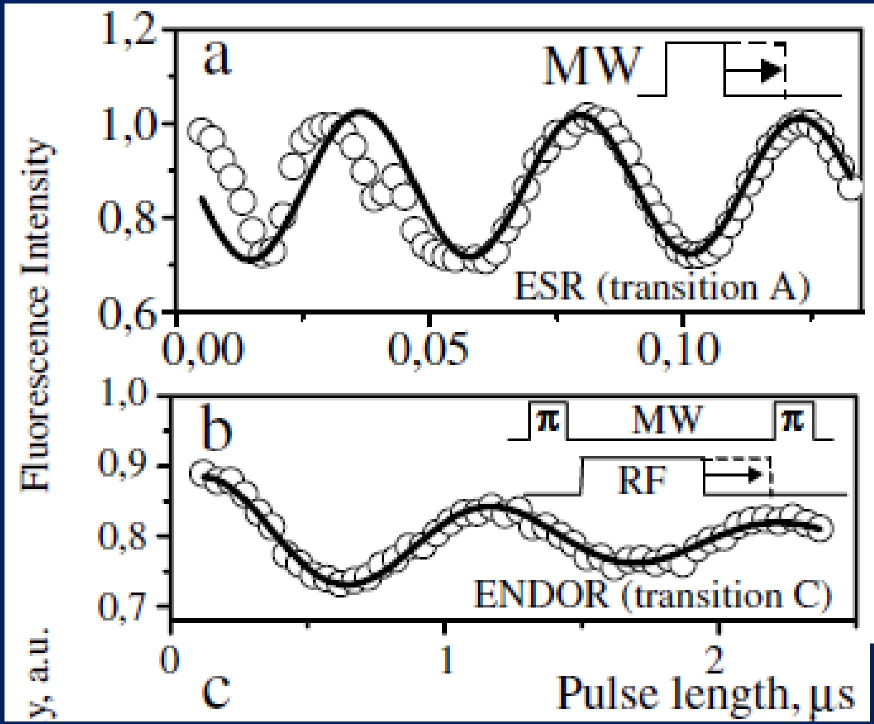


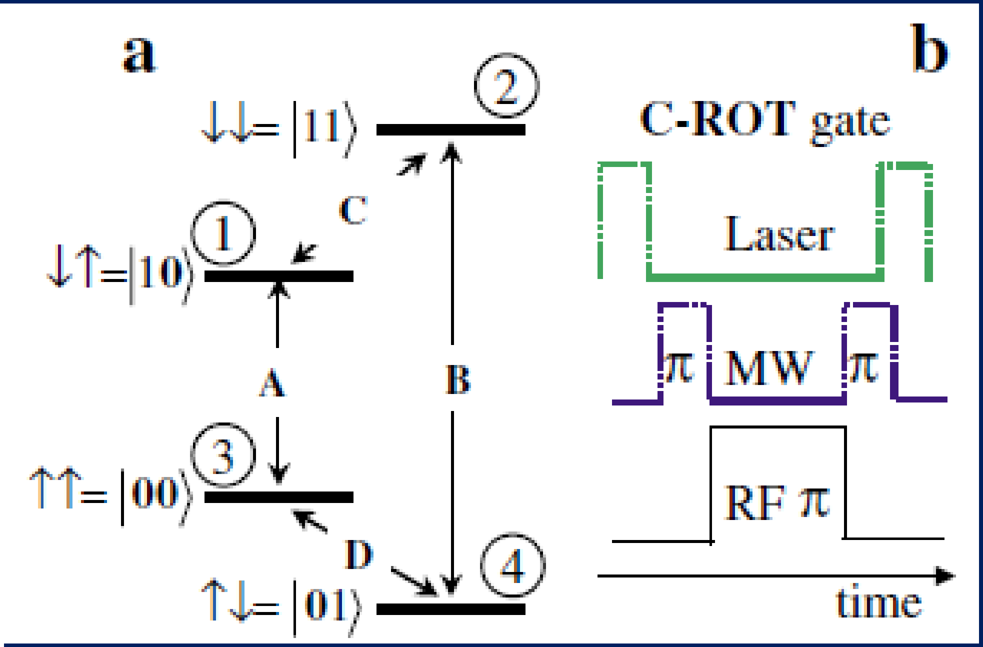
645 nm ~ 800 nm

Previous and Recent topics in NV center (2)

CNOT gate of two qubit
(NV-^{13}C, electron spin and ^{13}C nuclear spin)

F. Jelezko et al., *Phys. Rev. Lett,* 93, 130501, 2004





(CROT is equivalent to CNOT gate except for a $\pi/2$ rotation of the nuclear spin around z-axis.)

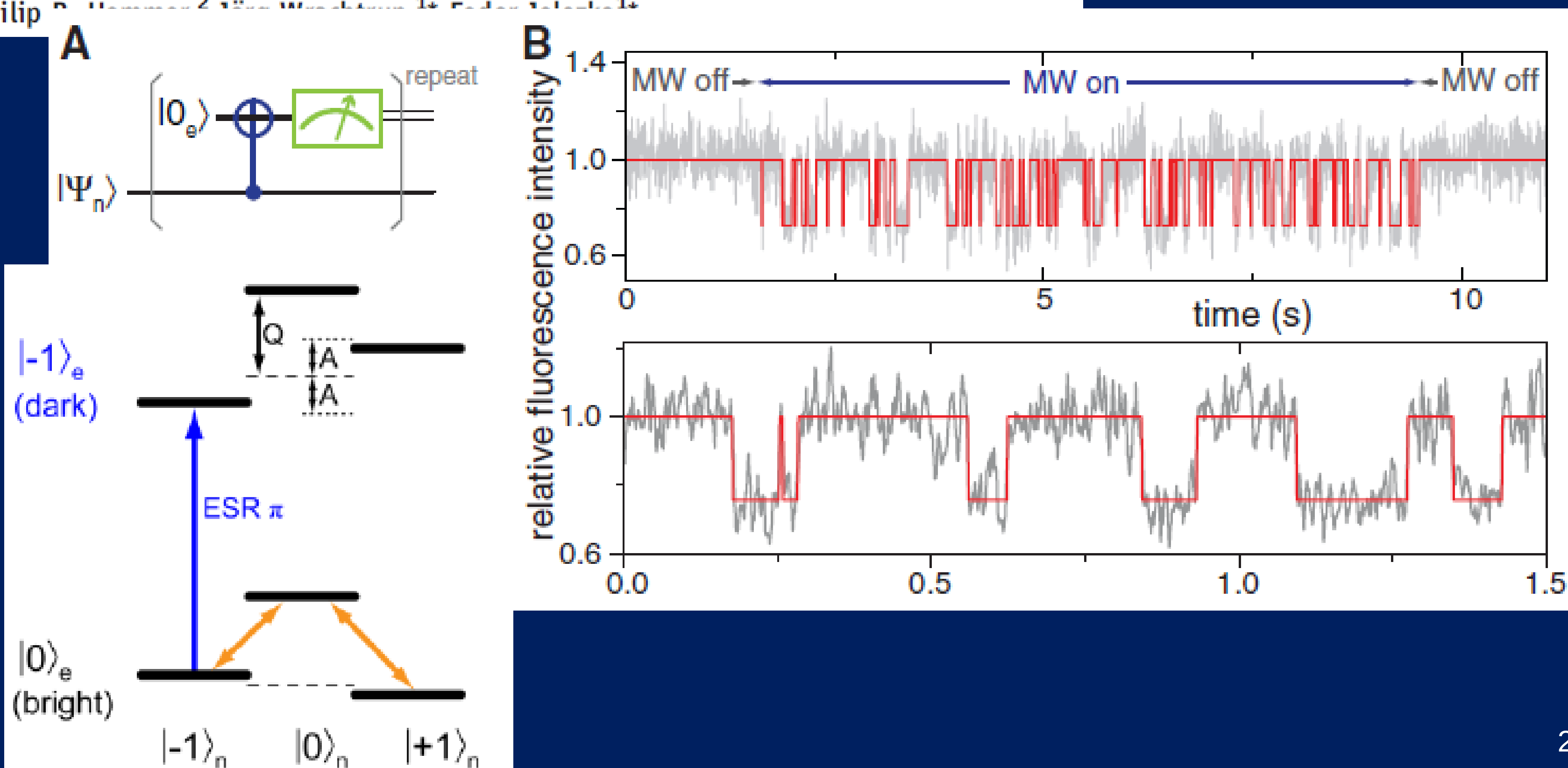
Previous and Recent topics in NV center (3)

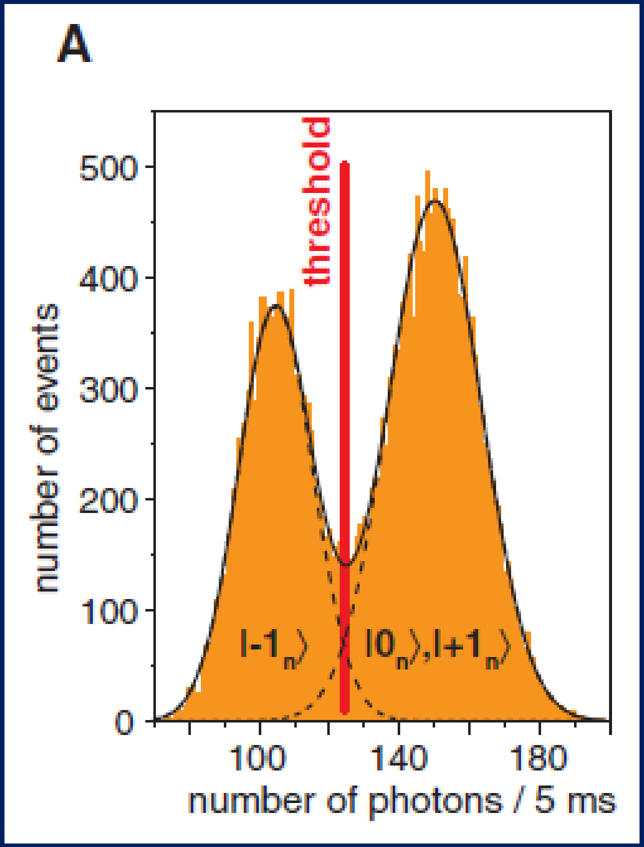
Quantum non-demolition measurement, Projective measurement of a single nuclear spin at RT

Single-Shot Readout of a Single Nuclear Spin

Philipp Neumann,[1] Johannes Beck,[1] Matthias Steiner,[1] Florian Rempp,[1] Helmut Fedder,[1]
Philip

Science 2010





The jumps occurs nuclear-electron flip-flop process.

hyperfine Hamiltonian $H_A = (\hat{S}_+\hat{I}_- + \hat{S}_-\hat{I}_+)A_\perp/2 + \hat{S}_z\hat{I}_zA_\parallel$

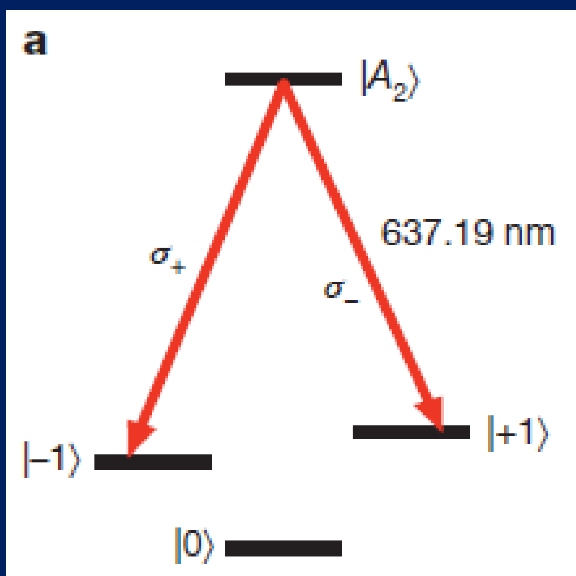
Previous and Recent topics in NV center (4)

Entanglement between spin and photon (Low temp.)

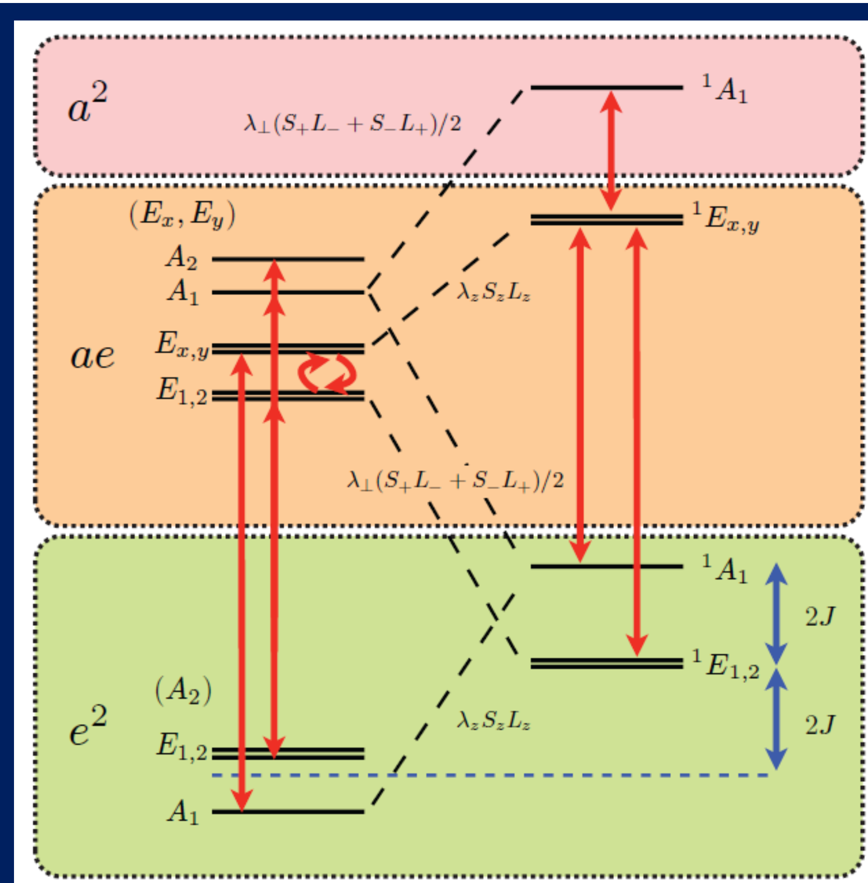
Quantum entanglement between an optical photon and a solid-state spin qubit

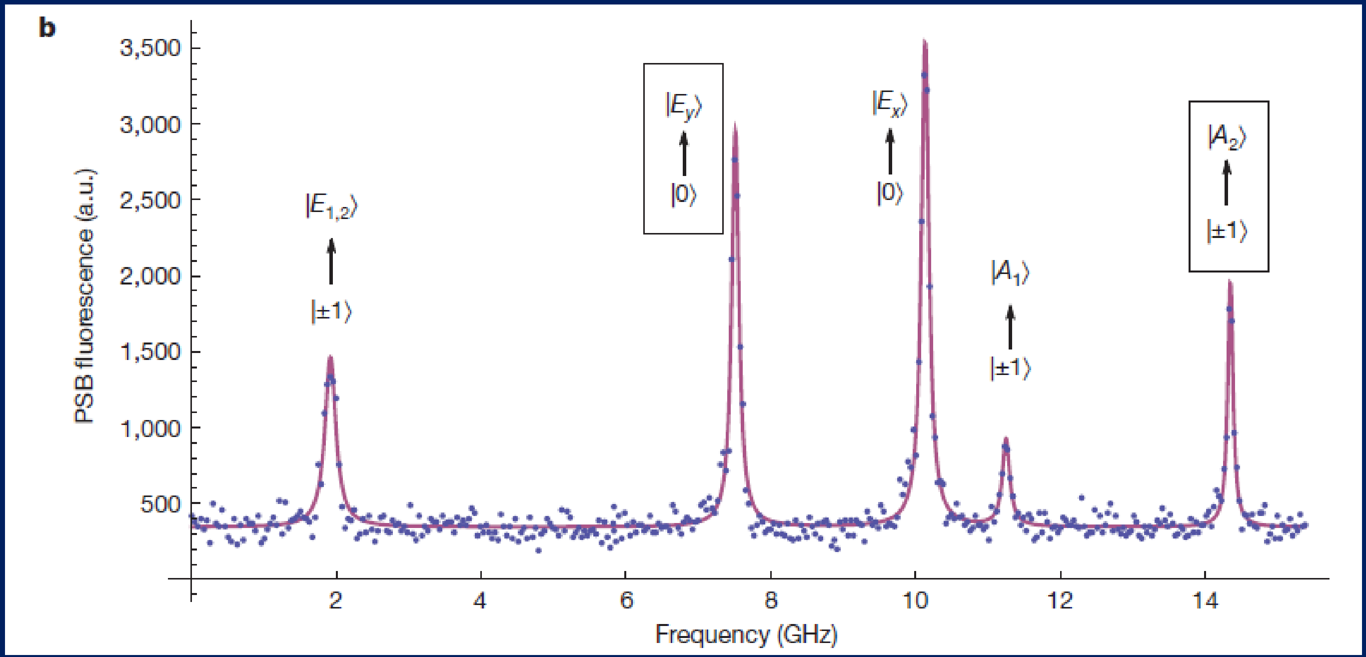
E. Togan[1]*, Y. Chu[1]*, A. S. Trifonov[1], L. Jiang[1,2,3], J. Maze[1], L. Childress[1,4], M. V. G. Dutt[1,5], A. S. Sørensen[6], P. R. Hemmer[7], A. S. Zibrov[1] & M. D. Lukin[1]

Nature 2010



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





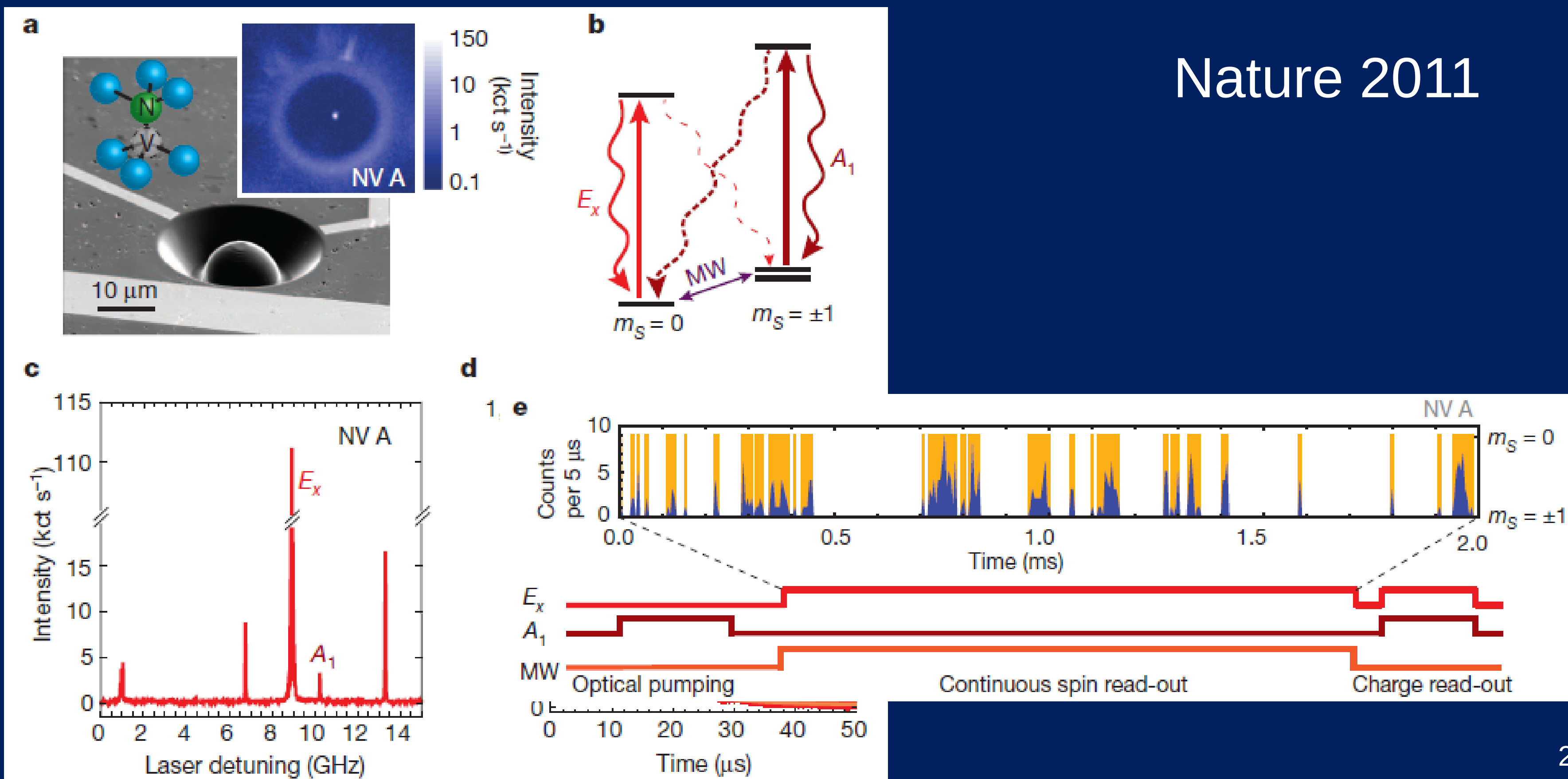
b
PSB fluorescence (a.u.)
3,500
3,000
2,500
2,000
1,500
1,000
500
2
4
6
8
10
12
14
Frequency (GHz)
|E1,2⟩
|±1⟩
|Ey⟩
|0⟩
|Ex⟩
|0⟩
|A1⟩
|±1⟩
|A2⟩
|±1⟩

Previous and Recent topics in NV center (5)
QND measurement, Projective measurement of a single electron spin (Low temp.)

High-fidelity projective read-out of a solid-state spin quantum register

Lucio Robledo[1]*, Lilian Childress[2]*, Hannes Bernien[1]*, Bas Hensen[1], Paul F. A. Alkemade[1] & Ronald Hanson[1]

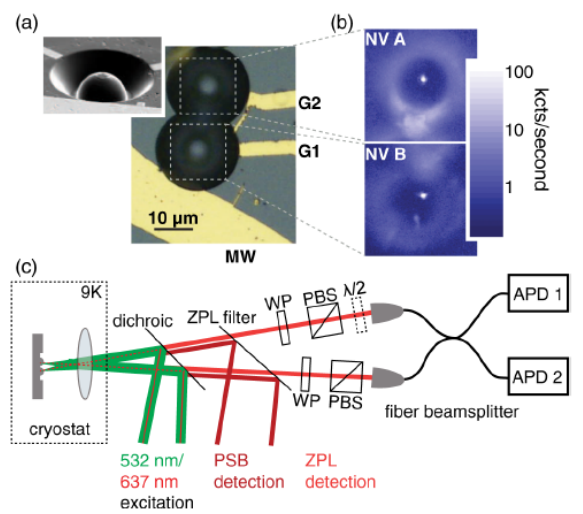
Nature 2011



Previous and Recent topics in NV center (6)
Two-photon quantum interference (Low temp.)

Two-Photon Quantum Interference from Separate Nitrogen Vacancy Centers in Diamond

Hannes Bernien,[1,*] Lilian Childress,[2] Lucio Robledo,[1] Matthew Markham,[3] Daniel Twitchen,[3] and Ronald Hanson[1]
[1]*Kavli Institute of Nanoscience Delft, Delft University of Technology, PO Box 5046, 2600 GA Delft, The Netherlands*
[2]*Department of Physics and Astronomy, Bates College, 44 Campus Avenue, Lewiston, Maine 04240, USA*
[3]*Element Six, Ltd., Kings Ride Park, Ascot, Berkshire SL5 8BP, United Kingdom*
(Received 14 October 2011; published 26 January 2012)



Quantum Interference of Single Photons from Remote Nitrogen-Vacancy Centers in Diamond

A. Sipahigil,[1] M. L. Goldman,[1] E. Togan,[1] Y. Chu,[1] M. Markham,[2] D. J. Twitchen,[2] A. S. Zibrov,[1]
A. Kubanek,[1,*] and M. D. Lukin[1]
[1]*Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA*
[2]*Element Six Ltd, Kings Ride Park, Ascot SL5 8BP, United Kingdom*
(Received 17 December 2011; published 3 April 2012)

Previous our researches

Nuclear spin

Prototype systems for engineering quantum states
Small interction with environment

○ Long coherence time at RT.
× It is not easy to access.

In our research ↓

Optical detection and manipulation of single nuclear spins through Single NV center in diamond

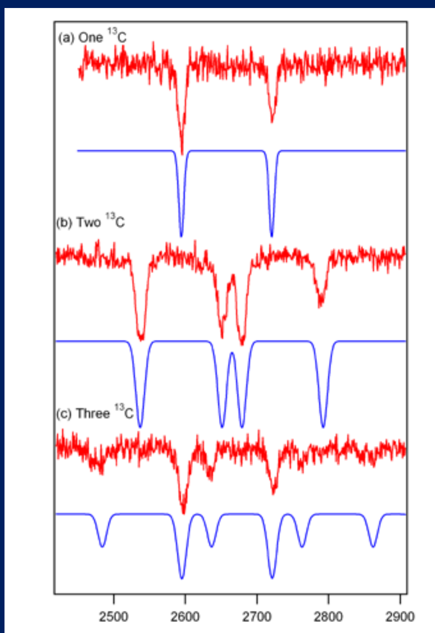
^{13}C (I=1/2) conc. Natural abundance = 1.1 %

Multi-qubits system by ^{13}C enriched high quality diamond

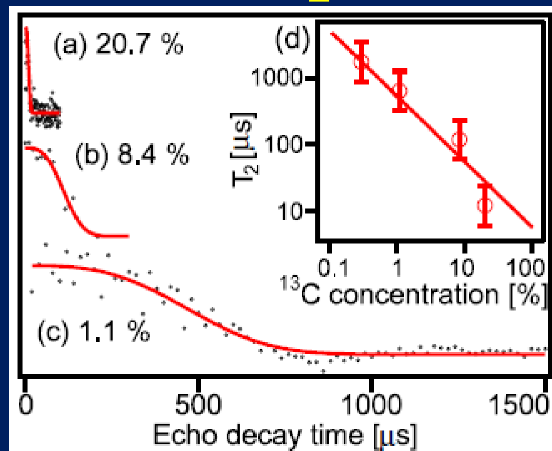
Effects on coherence time by nuclear spin

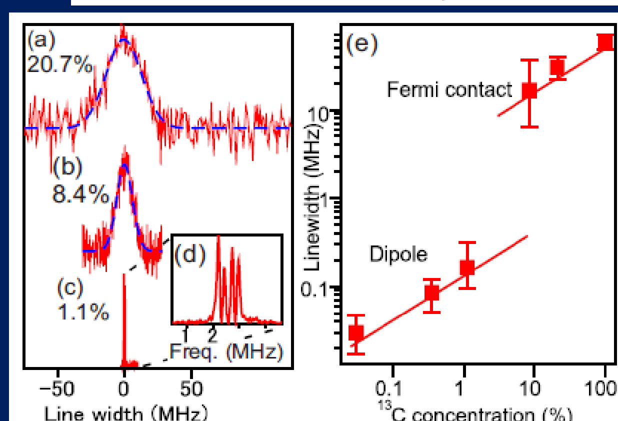
Previous our researches

Multi-qubit systems by ^{13}C nuclear spin



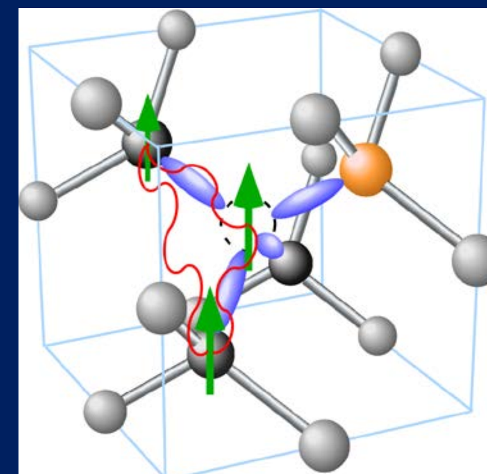
Elucidation and control of T_2 and $T2^*$





N. Mizuochi, et al., *PRB* 2009 (Editors' suggestion)
G. Balasubramanian, et al., *Nature materials, 2009.*

Multipartite entanglement among single spins in Diamond



Entanglement of 3 qubit : Largest number in solid state!

P. Neumann*, N. Mizuochi*, et al., *Science*, (2008)

T_2 of electron spin of NV in natural abundance diamond at RT

	T_2 (electron spin)	
2003	50 μs	T. A. Kennedy, et al., *APL,* 2003
2006	200 μs	L. Childress, et al., *Science*, 2006
	350 μs	T. Gaebel, et al., *Nature physics,* 2006
2009	700 μs	N. Mizuochi, et al., *PRB,* 2009

T_2 of electron spin is increasing development of diamond growth technique. It was dominated by electron spin of impurities and/or defects.

In ^{12}C enriched diamond, T_2 = 1.8 ms

G. Balasubramanian, et al., *Nature materials, 2009.*
N. Mizuochi, et al., *PRB* 2009 (Editors' suggestion)

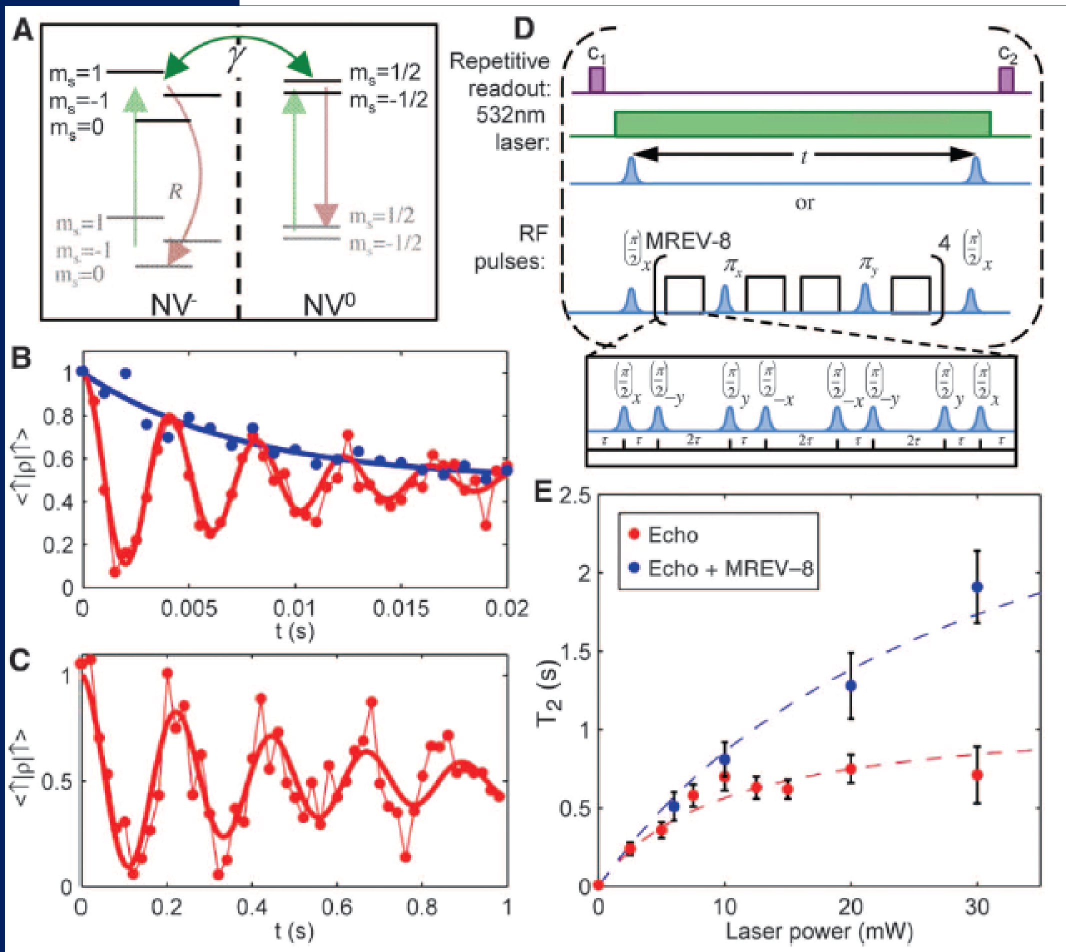
Previous and Recent topics in NV center (7)

Long coherence time (>1 s) of single nuclear spin at RT

Room-Temperature Quantum Bit Memory Exceeding One Second

P. C. Maurer,[1]* G. Kucsko,[1]* C. Latta,[1] L. Jiang,[2] N. Y. Yao,[1] S. D. Bennett,[1] F. Pastawski,[3] D. Hunger,[3] N. Chisholm,[4] M. Markham,[5] D. J. Twitchen,[5] J. I. Cirac,[3] M. D. Lukin[1]†

Nature 2012



Ionization and deionization

NV$^-$ ⇔ NV^0

When γ >> Hyperfine int.

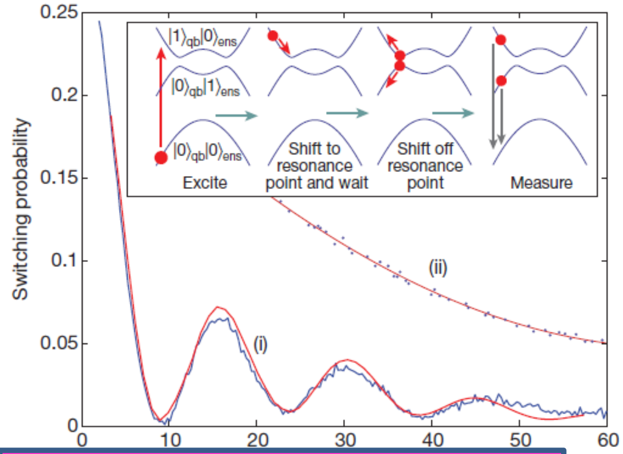
Interaction between electron and nuclear spins is strongly supressed.

"Electrically driven single photon source at room temperature in diamond"

Nature Photonics, 2012
Collaboration with AIST and Stuttgart Univ.

Coherent coupling of a superconducting flux qubit to an electron spin ensemble in diamond

Xiaobo Zhu[1], Shiro Saito[1], Alexander Kemp[1], Kosuke Kakuyanagi[1], Shin-ichi Karimoto[1], Hayato Nakano[1], William J. Munro[1], Yasuhiro Tokura[1], Mark S. Everitt[2], Kae Nemoto[2], Makoto Kasu[1], Norikazu Mizuochi[3,4] & Kouichi Semba[1]



Nature 2011
(Collaboration with NTT and NII)

Spin

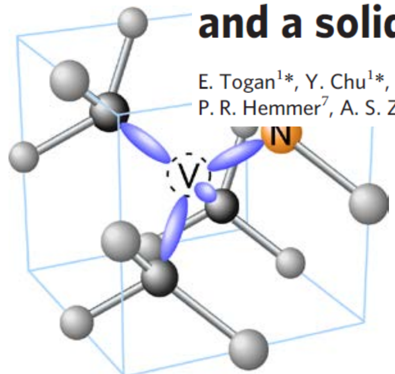
Nature Materials 2009,
PRB 2009

Quantum entanglement between an optical photon and a solid-state spin qubit

E. Togan[1*], Y. Chu[1*], A. S. Trifonov[1], L. Jiang[1,2,3], J. Maze[1], L. Childress[1,4], M. V. G. Dutt[1,5], A. S. Sørensen[6], P. R. Hemmer[7], A. S. Zibrov[1] & M. D. Lukin[1]

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

Nature 2011, Harvard



Quantum

Electrically driven single-photon source at room temperature in diamond

Nature Photonics 6, 299-303, 2012

N. Mizuochi[1,2*], T. Makino[3,4], H. Kato[3,4], D. Takeuchi[3,4], M. Ogura[3,4], H. Okushi[3,4], M. Nothaft[5], P. Neumann[5], A. Gali[6,7], F. Jelezko[8], J. Wrachtrup[5] and S. Yamasaki[3,4]

Quantum interface among single spin, photon, and charges

In NV center, field of electrical control is frontier.

Toward electrical control of qubit

Electrical control is interested in the points…

- Electrically driven single photon source @RT
- Electrical control of spin and photon: Can optical excitation, detection, and manipulation be replaced by electrical ones in NV?
- Parallel, independent Local operation within optical diffraction limit. (impossible only in optical operation)
- Integration into on-chip quantum devices.

Single photon source by QD

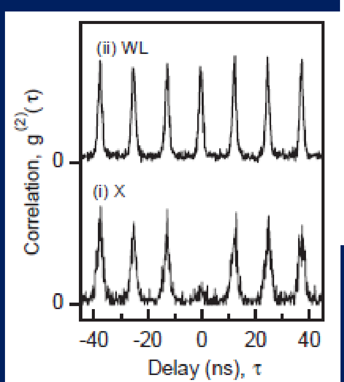
See, C. Santori, D. Fattal, Y. Yamamoto, "Single-photon Devices and Applications (Wiley, 2010)

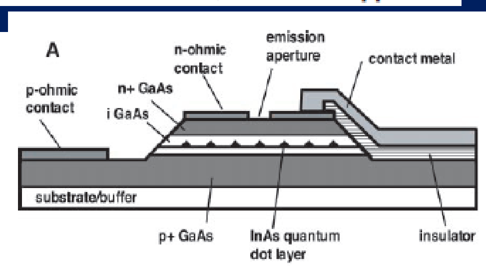
Electrically Driven Single photon Source by quantum dot at 5K

4 JANUARY 2002 VOL 295 SCIENCE

Electrically Driven Single-Photon Source

Zhiliang Yuan,[1] Beata E. Kardynal,[1] R. Mark Stevenson,[1] Andrew J. Shields,[1*] Charlene J. Lobo,[2] Ken Cooper,[2] Neil S. Beattie,[1,2] David A. Ritchie,[2] Michael Pepper[1,2]





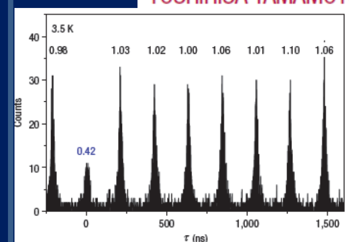
At 5 K

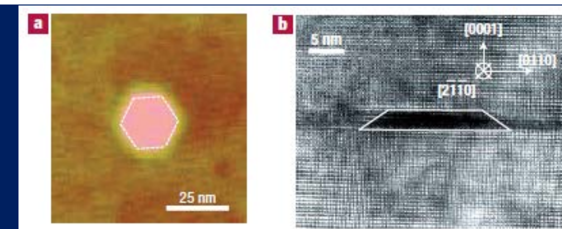
In quantum dot at 200K, PL (not EL)

Nature Materials, 5, 887 2006

A gallium nitride single-photon source operating at 200 K

SATOSHI KAKO[1*], CHARLES SANTORI[1,2†], KATSUYUKI HOSHINO[1‡], STEPHAN GÖTZINGER[2§], YOSHIHISA YAMAMOTO[2] AND YASUHIKO ARAKAWA[1*]





In quantum dot (CdSe) at RT, PL (not EL)

Quantum correlation among photons from a single quantum dot at room temperature

P. Michler*, A. Imamoğlu*, M. D. Mason†, P. J. Carson†, G. F. Strouse† & S. K. Buratto†

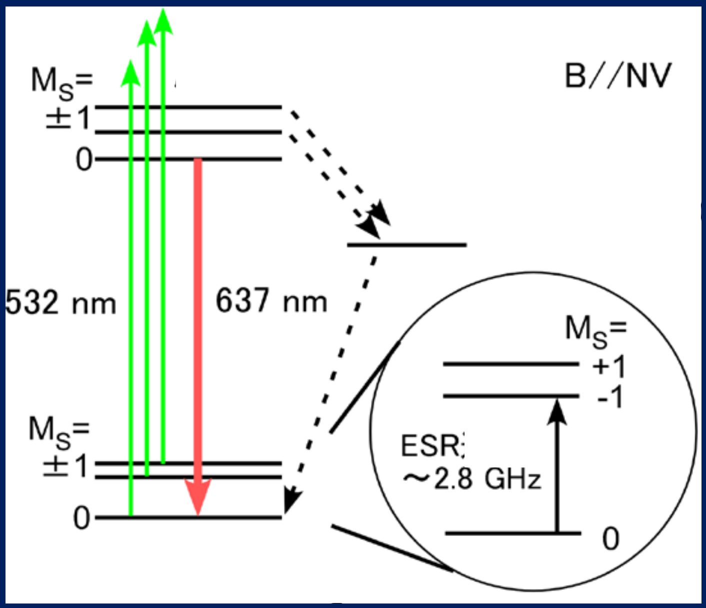
Nature 2000

Requirement of cryogenic temperatures due to the necessity to confine carriers within dot

The electrically driven single photon source at RT: Challenging

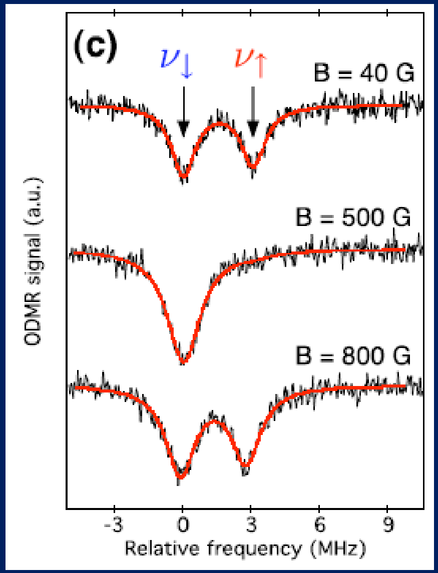
Polarization of spin (= control of spin state) by optical pumping

Electron spin



By spin selective deactivation due to SOC.

Nuclear spin



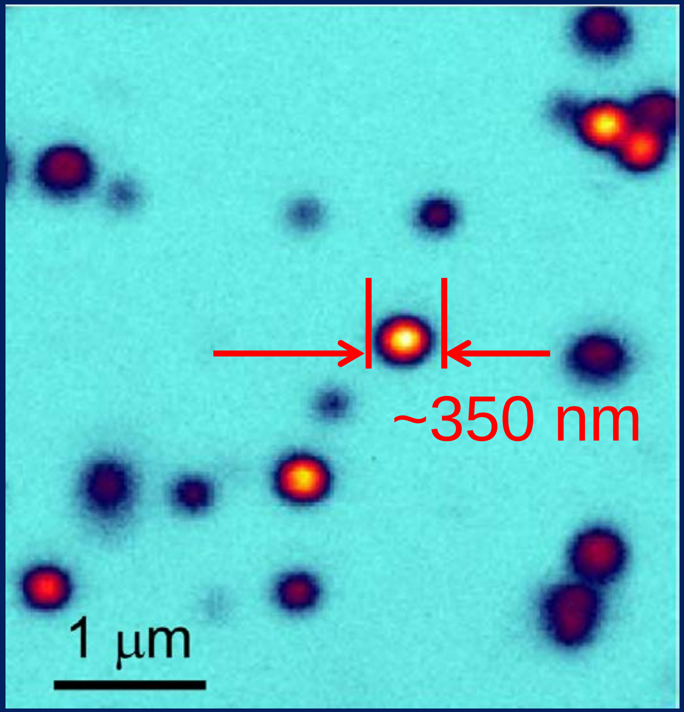
By mixing of the excited states

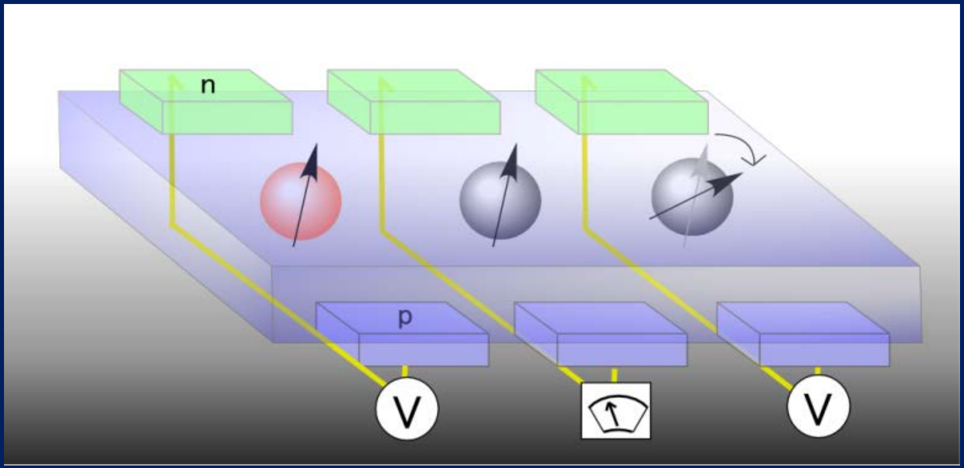
V. Jacques et al., *PRL*, 102, 057403 (2009)

Nuclear spin polarization > 98%

These control can be realized by electrical excitation in principle.

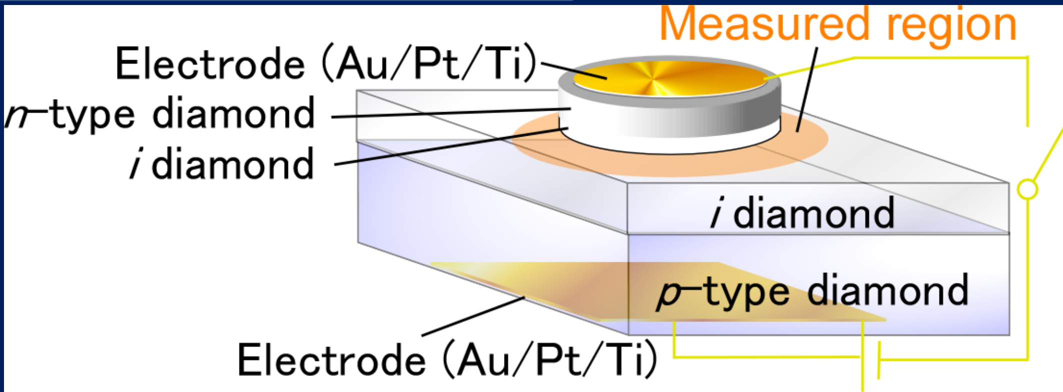
Toward parallel and independent local operation within optical resolution





Importance for quantum information processing in principle and for integration into elaborated device

Device structure



Overview of procedure

Dopings of P and B cause color centers, so we introduced ultra-pure i-layer ($<10^4/cm^2$, $<10^7/cm^3$)

Mesa structure was fabricated to detect NV center in i-layer

N was doped by ion-implantation because of extremely small number of native NV center in i-layer

Electrode (Au/Pt/Ti) was deposited.

Synthesis condition

PIN
p-type Sub, [B]~$10^{19}cm^{-3}$
I : 10mm
n : [P]~$10^{18}cm^{-3}$ (~500nm)

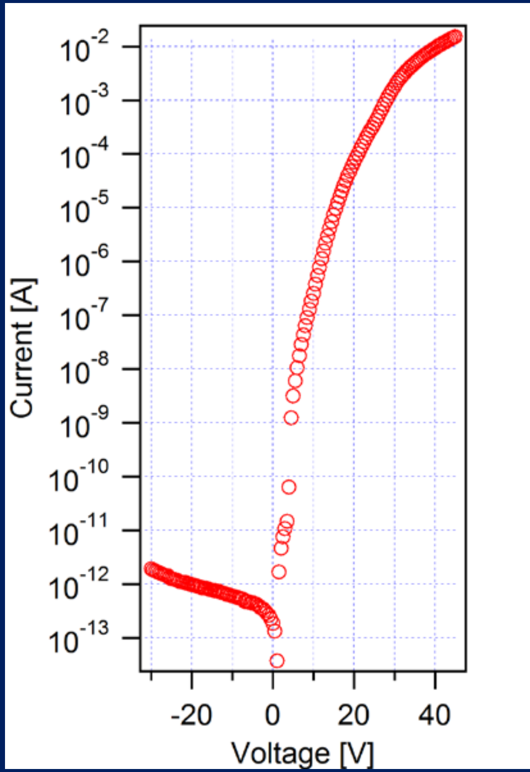
(001) substrate

Electrode:
Top: f200mm dots, Ti(30nm)/Pt(30nm)/Au(100nm)
Bottom:
1.5mmx1.5mm Square, Ti(30nm)/Pt(30nm)/Au(100nm)

Hydrogenation, hot filament.
Plasma treatment (Oxygen) to clean the surface

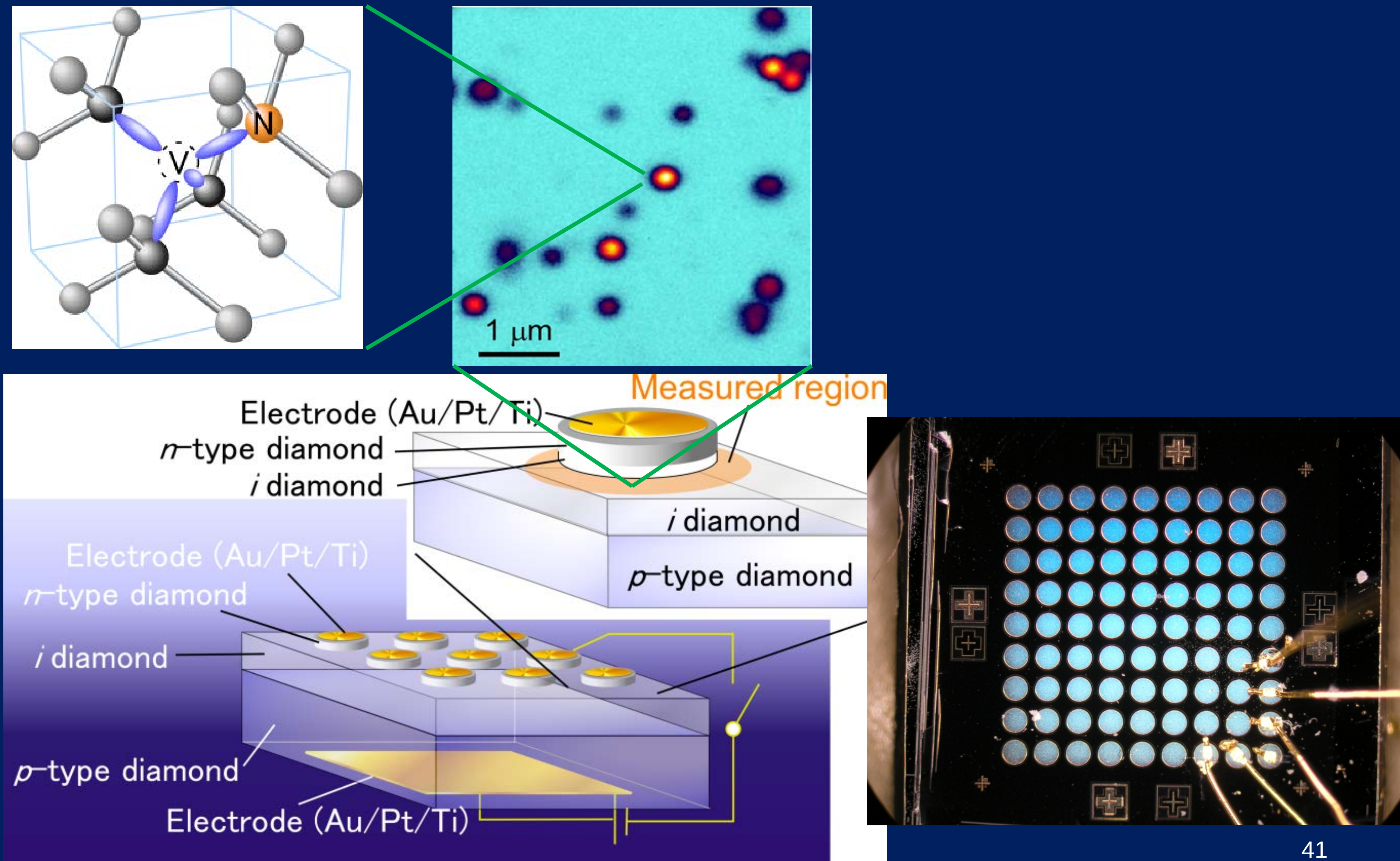
Post Annealing: 420^{o}C, Ar, 30min

Nitrogen was ion-implanted after depositing N film.
(180 keV, 1×10^9 atom/cm^2)



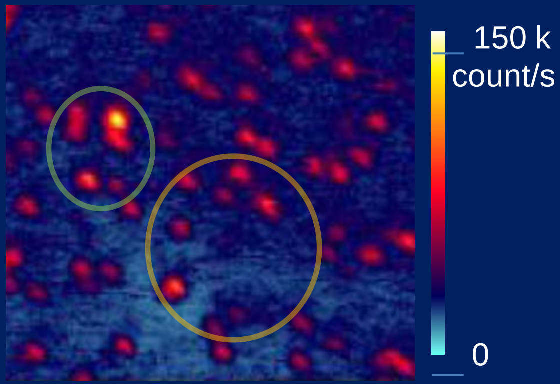
IV characteristic
(rectification ratio of about 10^9 at 30V)

Device structure

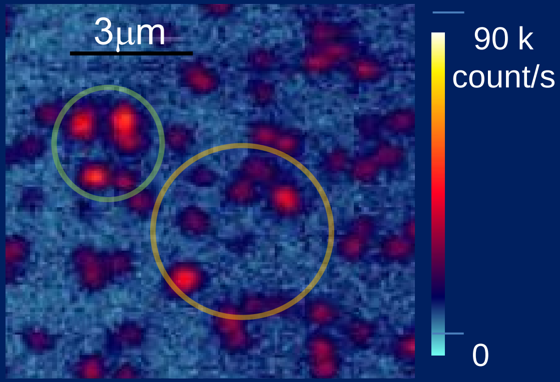


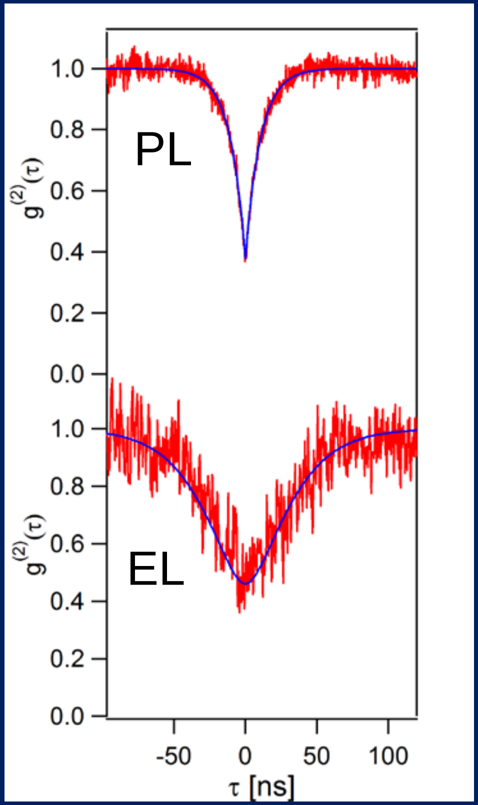
Results

PL image



EL image





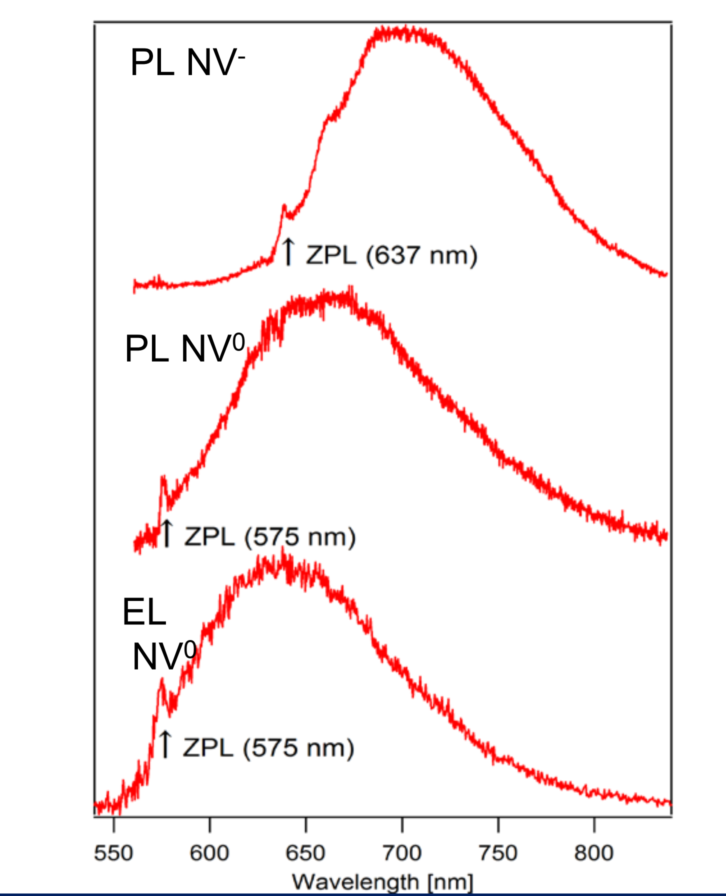
$g^{(2)}(0) < 0.5$

EL from the same region as PL!

The first observation of EL of single quantum system and photon statistics at room temperature !

See also researches submitted after our submission. (1) diamond LED (APL , 99, 251106,2011), (2) Organic LED (Nature Comm. 2012, doi 10.1038)

Spectra and charge state



Oxidized surface

PL: NV^- (ZPL: 637 nm)

Hydrogenated surface

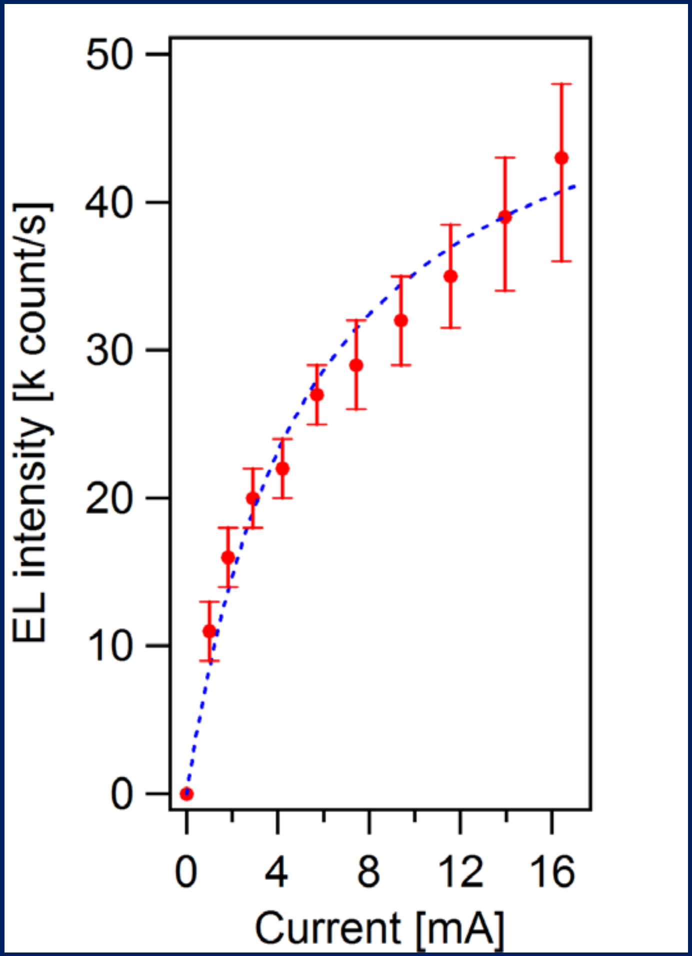
PL: NV^0 (ZPL: 575 nm)

EL: NV^0 (ZPL : 575 nm)

EL was observed from NV^0.

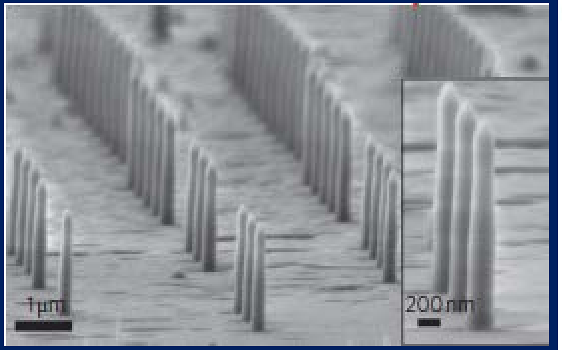
A significant number of holes due to the higher concentration of B (~10^{19}/cm^3) compared to that of P (~10^{18}/cm^3).

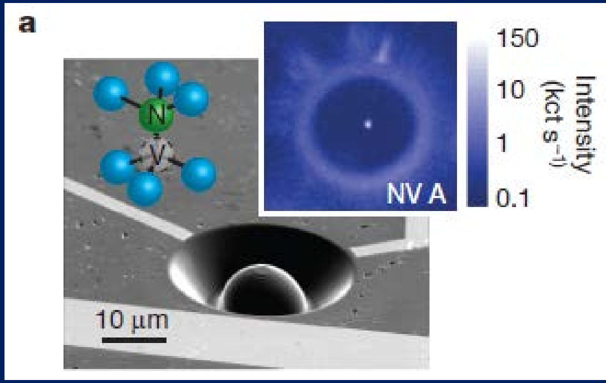
EL intensity



5×10^4 count/s at RT

Limit by high temperature due to high current



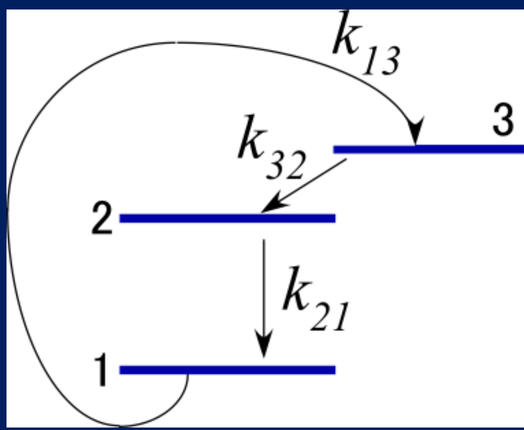


Nanowire, SIL: 10 times

By revising structures, the emission intensity will approach strongest levels (around 10^7 count/s, T << RT, Nature Photo. 2007).

Mechanism of excitation

Simulation of autocorrelation function



$$\begin{pmatrix}\dot{\rho}_1\\ \dot{\rho}_2\\ \dot{\rho}_3\end{pmatrix} = \begin{pmatrix}-k_{13} & k_{21} & 0\\ 0 & -k_{21} & k_{32}\\ k_{13} & 0 & -k_{32}\end{pmatrix}\begin{pmatrix}\rho_1\\ \rho_2\\ \rho_3\end{pmatrix}$$

$$g^{(2)}(\tau) = \rho_2(\tau)/\rho_2(\infty) = 1 + c_2 e^{\lambda\tau} + c_3 e^{\gamma\tau}$$

$$\lambda = (-b - \sqrt{b^2 - 4c})/2,\ \gamma = (-b + \sqrt{b^2 - 4c})/2$$

$$b = k_{13} + k_{21} + k_{32},$$

$$c = k_{13}k_{21} + k_{21}k_{32} + k_{13}k_{32}$$

$$c_2 = (k_{13} + \lambda)(k_{32} + \lambda)(k_{32} + \gamma + k_{13})/c_1(\gamma - \lambda)\lambda\, k_{13}$$

$$c_3 = (k_{13} + \gamma)(k_{32} + \gamma)(k_{32} + \lambda + k_{13})/c_1(\gamma - \lambda)\gamma\, k_{13}$$

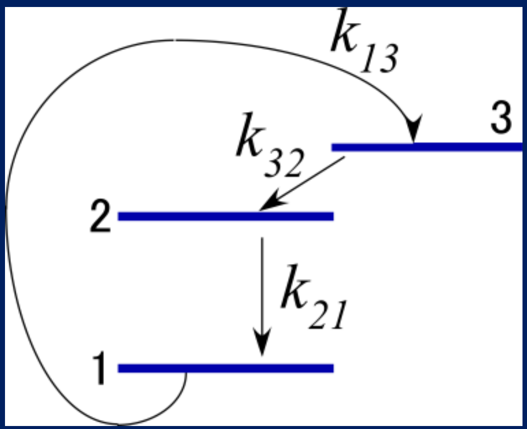
$$c_1 = -c_2 - c_3 + 1$$

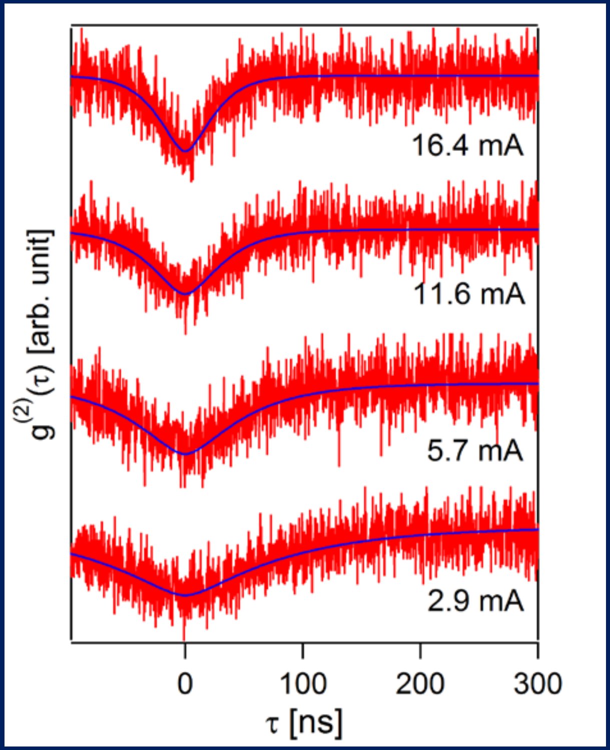
The 3rd state : additional rate determining step in consecutive reactions

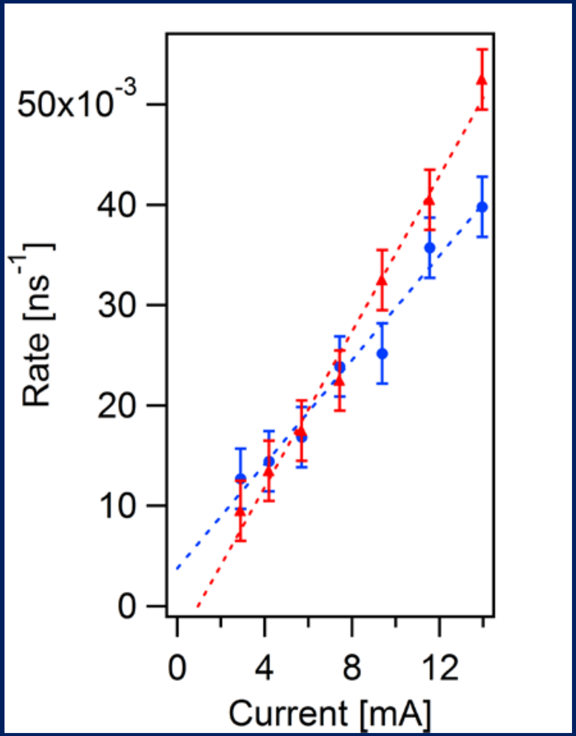
P. W. Watkins, *Physical Chemistry*, Oxford University press (1989).

Mechanism of excitation

Simulation of autocorrelation function







$1/k_{32}$ = 266 ns

$(k_{13})^{-1}$ at 4 mA is measured to be about 80 ns

Mechanism of excitation

Recombination rate by the Shockley-Read-Hall statistics

$$U = \sigma_n \sigma_p v_{th} N_t (pn - n_i^2) / \{ \sigma_n (n + n_i) + (p + n_i) \},$$

$$U/N_t \approx \sigma_n v_{th} \Delta n \ .$$

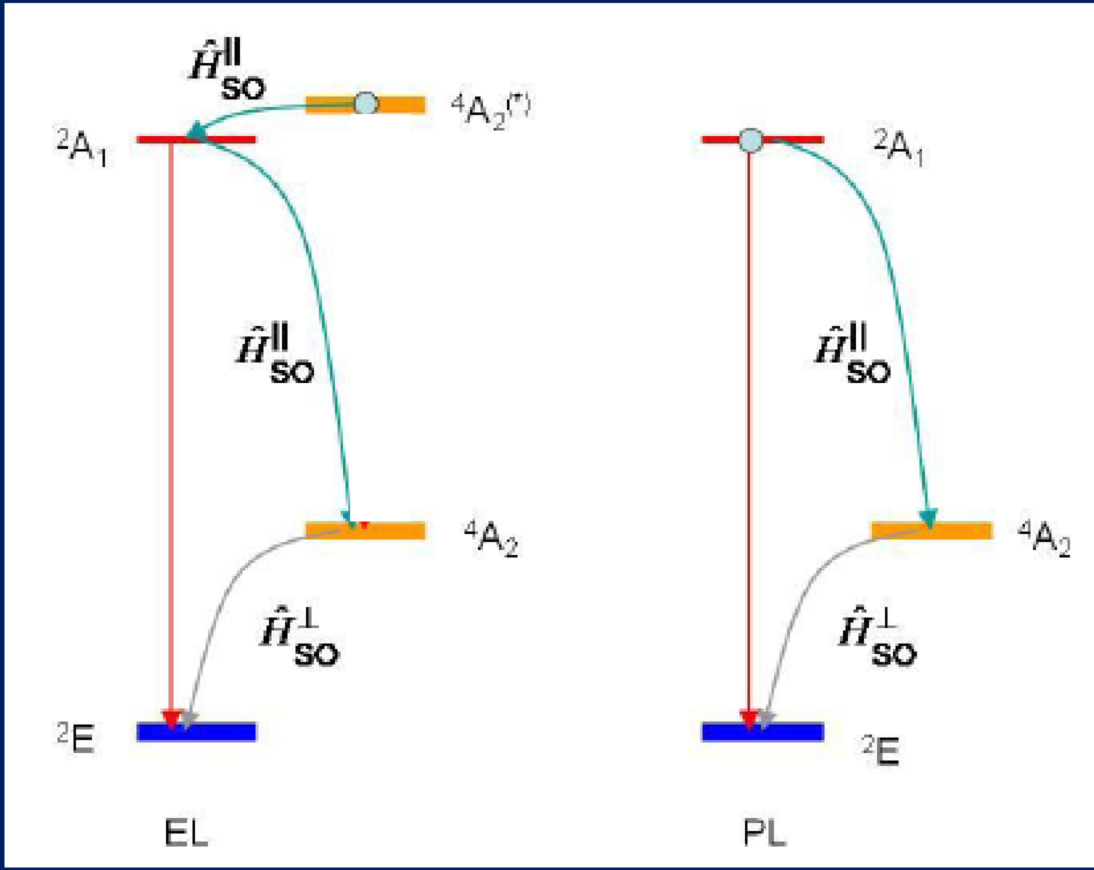
k_{13}^{-1} = 20 ns (4 mA)

EL is generated by electron-hole recombination at the defect

NV act as interface between carrier and photon

A tentative explanation for the different kinetics of EL and PL

Group theory considerations and *ab initio* calculations for excitation energies



an *S=3/2* excited state of a loosely bound hole and a strongly bound electron on NV^0

The excited quartet state $^4A_2^{(*)}$ is 0.05 eV higher.

Summary

- Recent topics were presented.
- The first observation of EL of single quantum system and photon statistics at room temperature.
- It provides new function and degree of freedom with promising applications not only as single photon source but also as spintronics for quantum communication and processing.

Open Position (Post-Doctorial fellow) in our group

Thank you very much for your attention!