Single spin, photon, and charge manipulation of NV center in diamond

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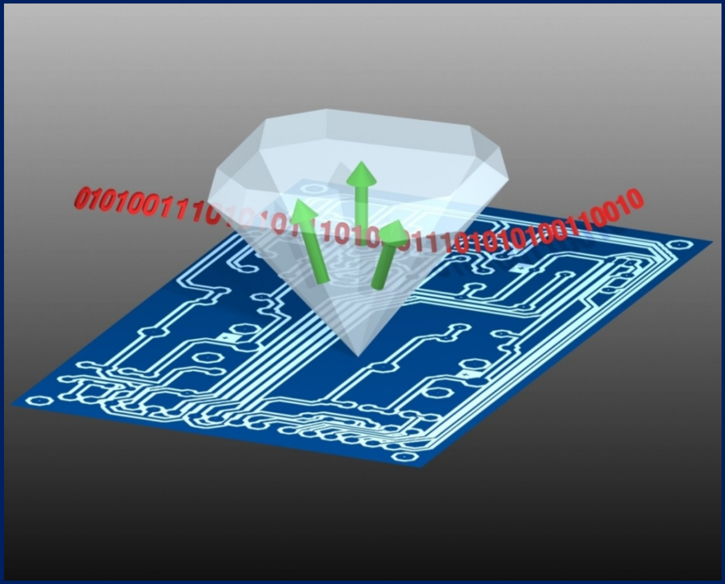

Collaborators and Acknowledgements

- Prof. Suzuki and group members (Osaka Univ.)
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- Prof. Hatano (Univ. of Tokyo Inst. Tech.), RENESAS
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- Prof. Kosaka (Yokohama Univ.)
- Dr. Semba, (NICT)
- Prof. Nemoto (NII)
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- Prof. F. Jelezko (Ulm Univ.)
- Dr. A. Gali (Wigner Research center.)

Osaka Univ

Content

1. Introduction

   NV center in diamond

2. Electric field effect on spin coherence of NV

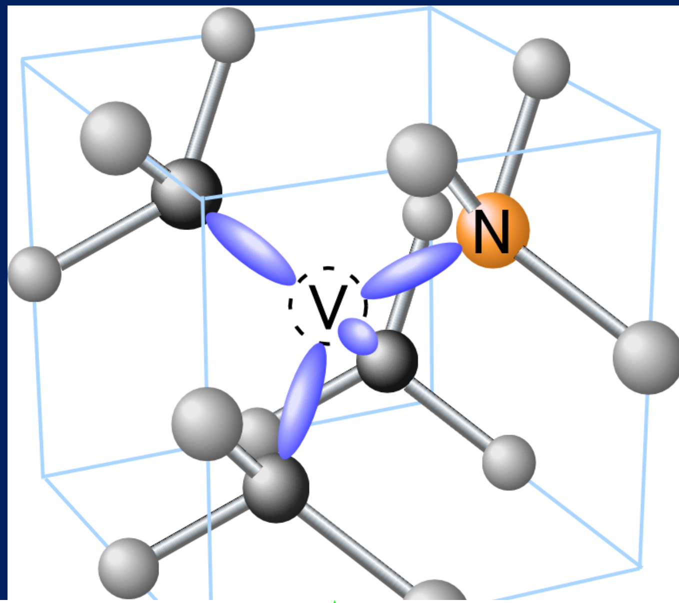
   S. Kobayashi, NM, et al., unpublished.

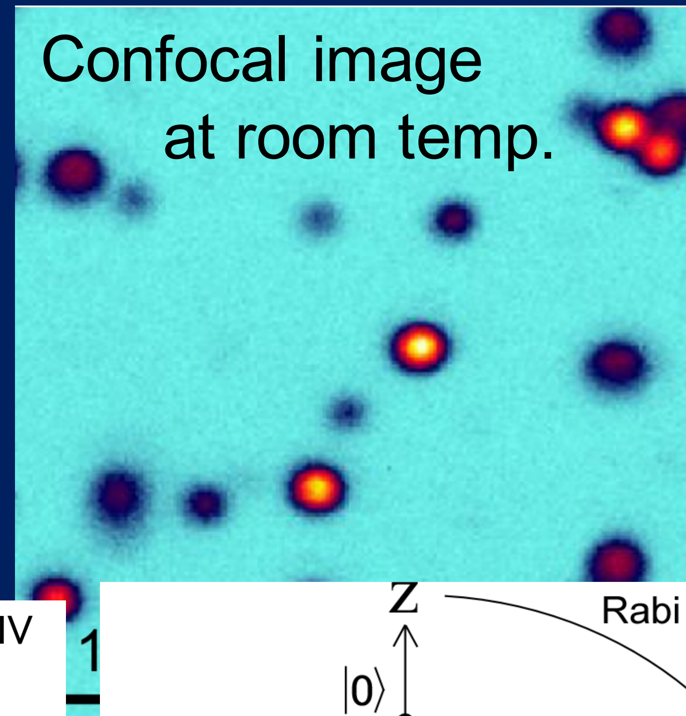
3. Selective alignment of N-V axis

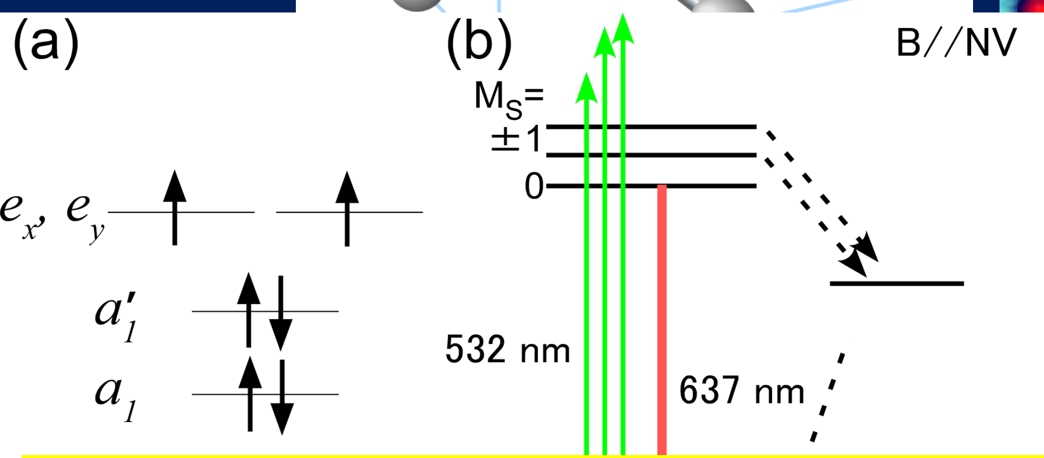
   Four-fold improvement of the magnetic field sensitivity

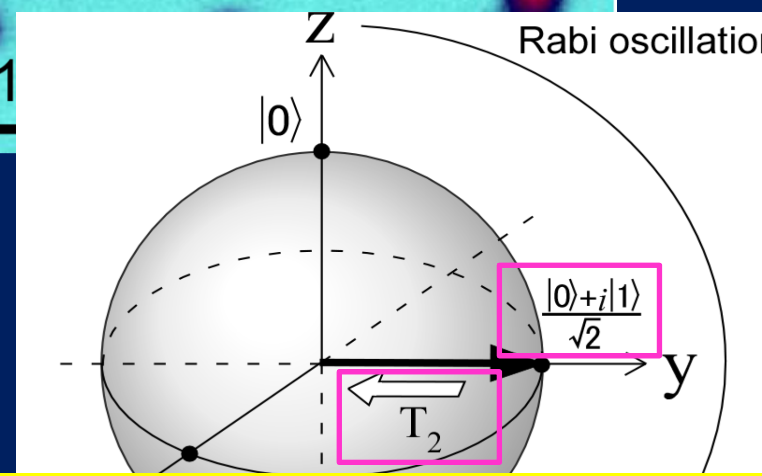
   T. Fukui, NM, et al., *Appl. Phys. Exp.* 7, 055201 (2014), selected in "Spotlights"
   T. Miyazaki, NM, et al., *Appl. Phys. Lett.* 105, 261601 (2014).

NV center in diamond









Coherent Control and detection of Single spin at RT

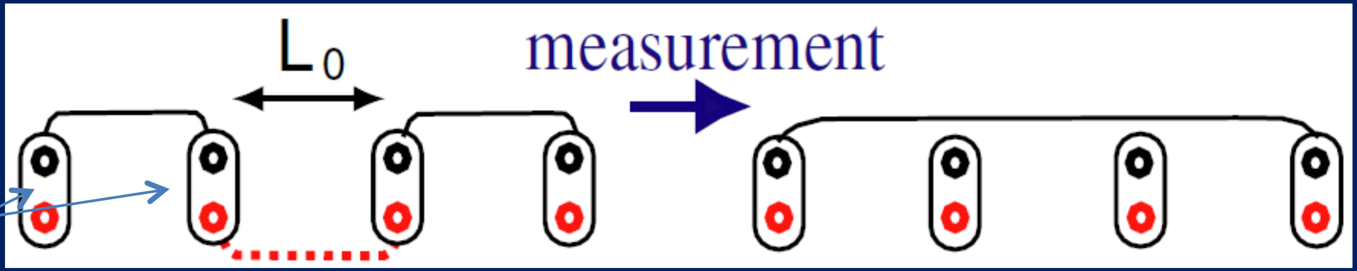
Unique character among solid state material

Quantum Cryptography

BB84: completely secure communication
by using single photon

Single photon source, Quantum repeater
("spin" for processing and memory, "Photon" for communication)

Quantum Repeater

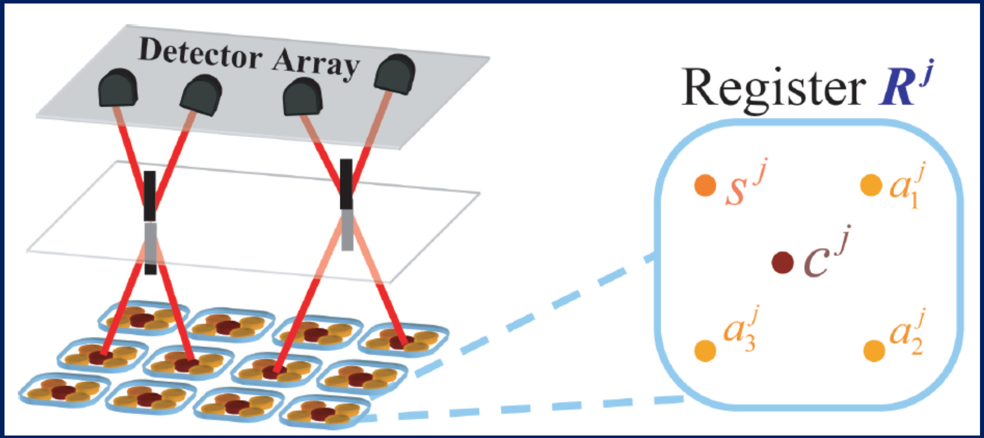


Black and Red ball represent spins (Qubits).

L. Childress, et al., PRL 2006.

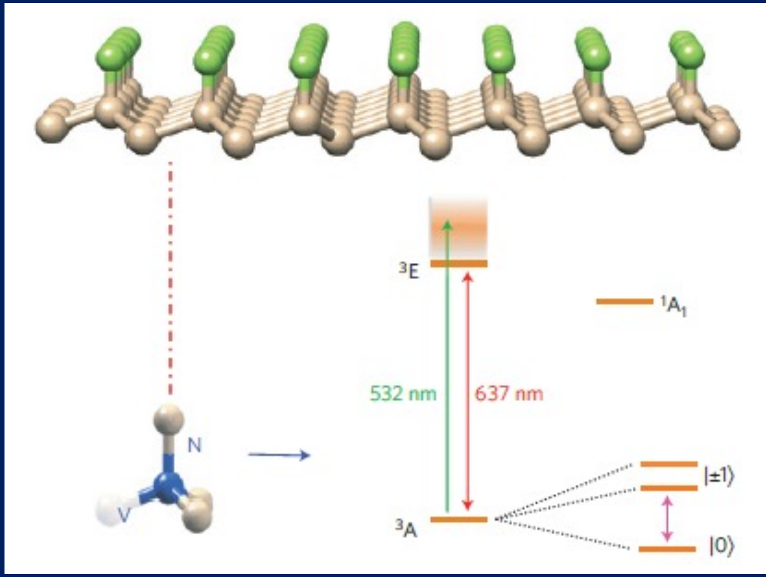
Quantum Computing

Distributed scalable quantum computer



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

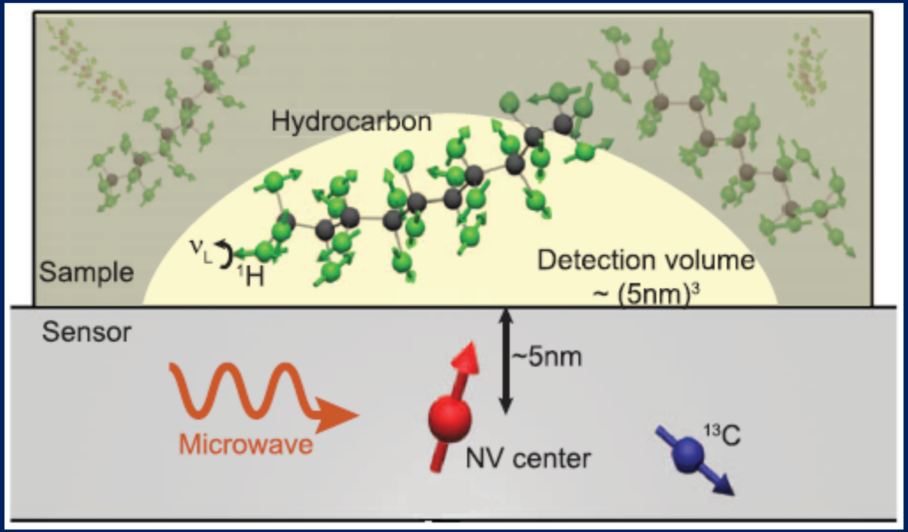
Quantum Simulation



Quantum simulation by NMR on the diamond surface: Initialization and readout is carried out by NV center
Cai et al., Nat. Commun. 2014

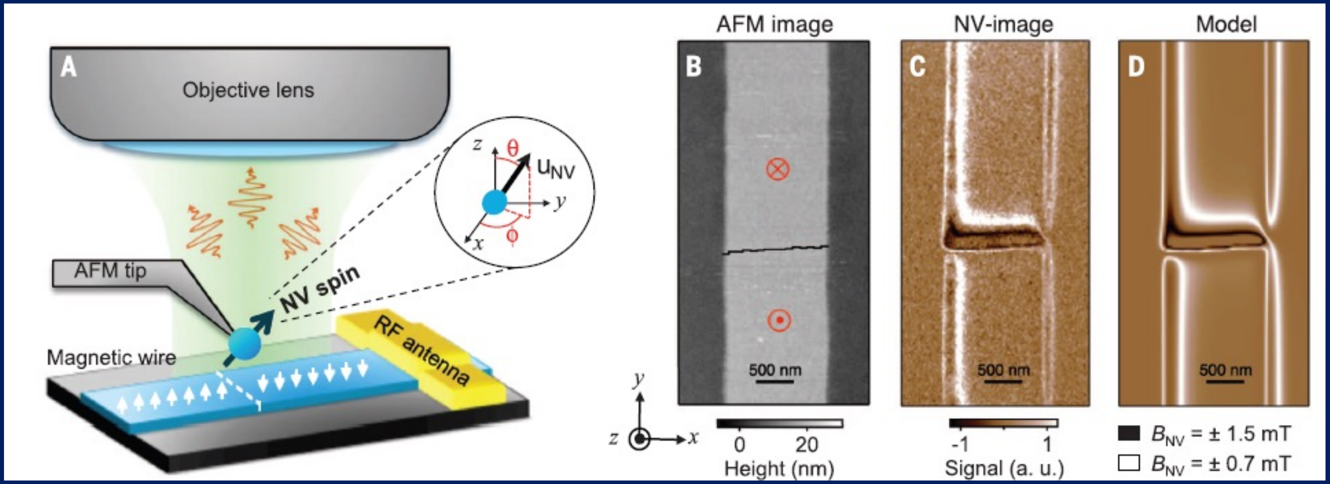
Sensor (Magnetic, Electric field, Temperature…)

High resolution and high sensitive sensor



NMR of molecules on diamond surface

Science 2013



Nanoscopy of domain walls

Science 2014

Scanning probe magnetometry (magnetic sensor)

Minimum detectable magnetic field

$$\delta B \simeq \frac{1}{g_s \mu_B} \frac{1}{R\sqrt{\eta}} \frac{1}{\sqrt{NtT_2^*}},$$

R: Measurement contrast
h: detection efficiency
N: number of spin centers
t: integration time

Single (RT)

B_{AC}=4.3 nT $Hz^{-1/2}$

Nature Mat. 2009

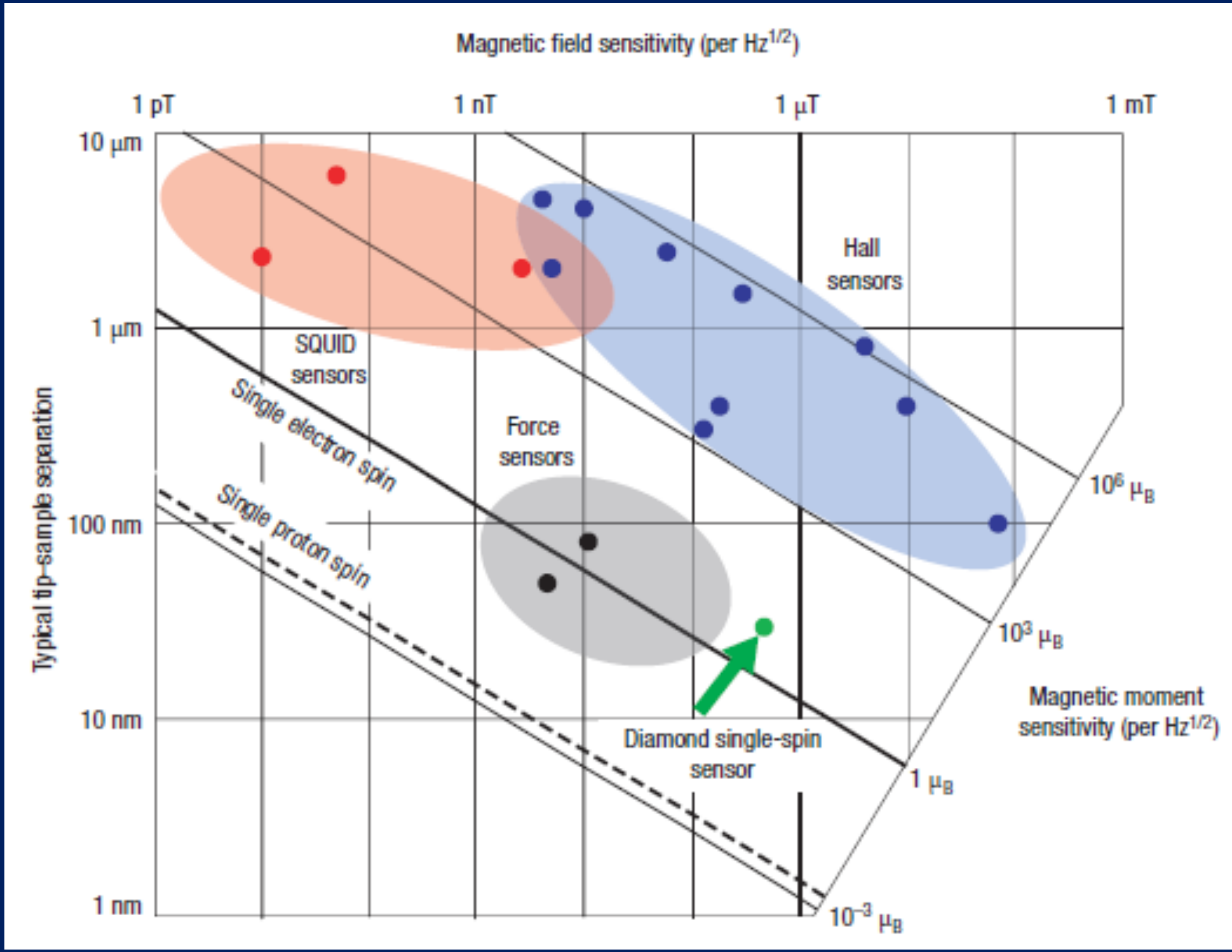
B_{DC}=0.3 mT $Hz^{-1/2}$

PRB 2009

Ensemble (RT)

B_{AC}=~ 100 pT $Hz^{-1/2}$

PRB 2012



C. Degan, Nature nanotechnology, 3, 643 (2008).

The previous and recent our researches

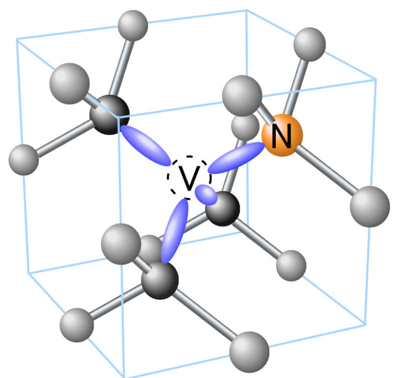
Spin

Quantum hybrid system with superconducting flux qubit
Nature 2011, Nature commun. 2014
Collaboration with NTT, NII

QIP by single spins
Science 2008,
Nature Materials 2009,
PRB 2009

Extension of T_2 by E field, unpublished

Electrical control of charge state
PRX 2014



Quantum
Opt-spintronics

Charge

Photon

Electrically driven single photon source
Nature Photonics 2012

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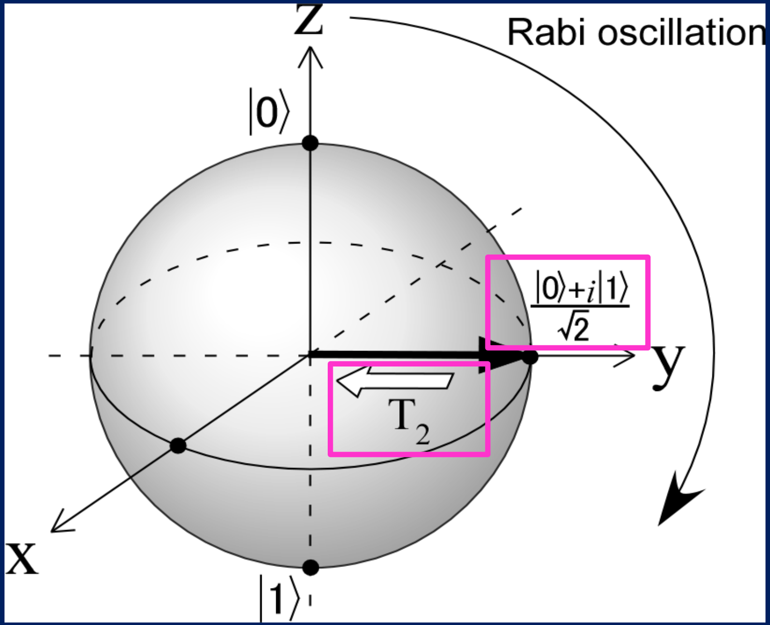
   T. Miyazaki, NM, et al., *Appl. Phys. Lett*. 105, 261601 (2014).

Coherence time (T_2) and Readout Contrast

- Quantum Memory time: Time to maintain superposition state
- Sensitivity (sensor)



Minimum detectable B (sensitivity) : 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)

Alignment of N-V axis, APEX 7, 055201 (2014) "Spotlights",

T_2 of electron spin of NV at RT

T_2 (electron spin in natural abundance of ^{13}C (I=1) diamond)

2003 50 ms T. A. Kennedy, et al., *APL,* 2003
2006 200 ms L. Childress, et al., *Science*, 2006
350 ms T. Gaebel, et al., *Nature physics,* 2006
2009 650 ms N. Mizuochi, et al., *PRB,* 2009
(77 K 2012 0.6 s B. Grotz, *Nat. Commun.* 2012)

T_2 (electron spin in ^{12}C (I=0) enriched diamond)

2009 1.8 ms G. Balasubramanian, et al., Nat. Mater. 2009.

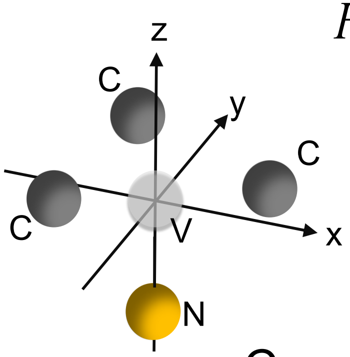
Contributions from Material Science

Extension by Dynamical decoupling
(Magnetic Resonance Technique)

Extension by other technique? Electrical?

Electric field effect on spin coherence of NV

■ Hamiltonian



C_{3V}

$$H_{gs} \quad hD_{gs} \; S_z^{\,2} \quad \frac{1}{3} S \; S \quad 1$$

$$_B g_e \mathbf{S} \; \mathbf{B}$$

$$d_{gs}^{\parallel} E_z \; S_z^{\,2} \quad \frac{1}{3} S \; S \quad 1$$

$$d_{gs} \quad E_x \; S_x S_y \quad S_y S_x \quad E_y \; S_x^{\,2} \quad S_y^{\,2}$$

Zero field split D_{gs} : 2870 MHz

Zeeman effect : 2.7 MHz/G

Electrical effect : $d_{gs}^{\parallel}$ /h = 0.35 Hz cm/V, $d_{gs}^{\perp}$ /h = 17 Hz cm/V

Electron spin interaction between unpaired spin are affected by E.

F. Dolde *et al*., Nature Phys. 7, 459–463 (2011)

■ Change of Resonant frequency $D_{gs} \quad _B g_e B \;, \; d_{gs} E$

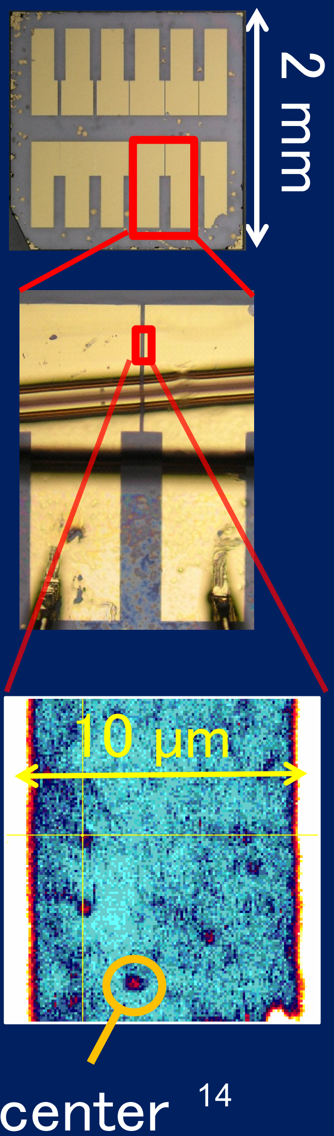
$$\sqrt{\;_B^2 g_e^2 B_z^2 \quad d_{gs} \;{}^2 E \;{}^2} \Big/ \hbar$$

Magnetic noise may be suppressed in case $_B^2 g_e^2 B_z^2 \quad d_{gs} \;{}^2 E \;{}^2$

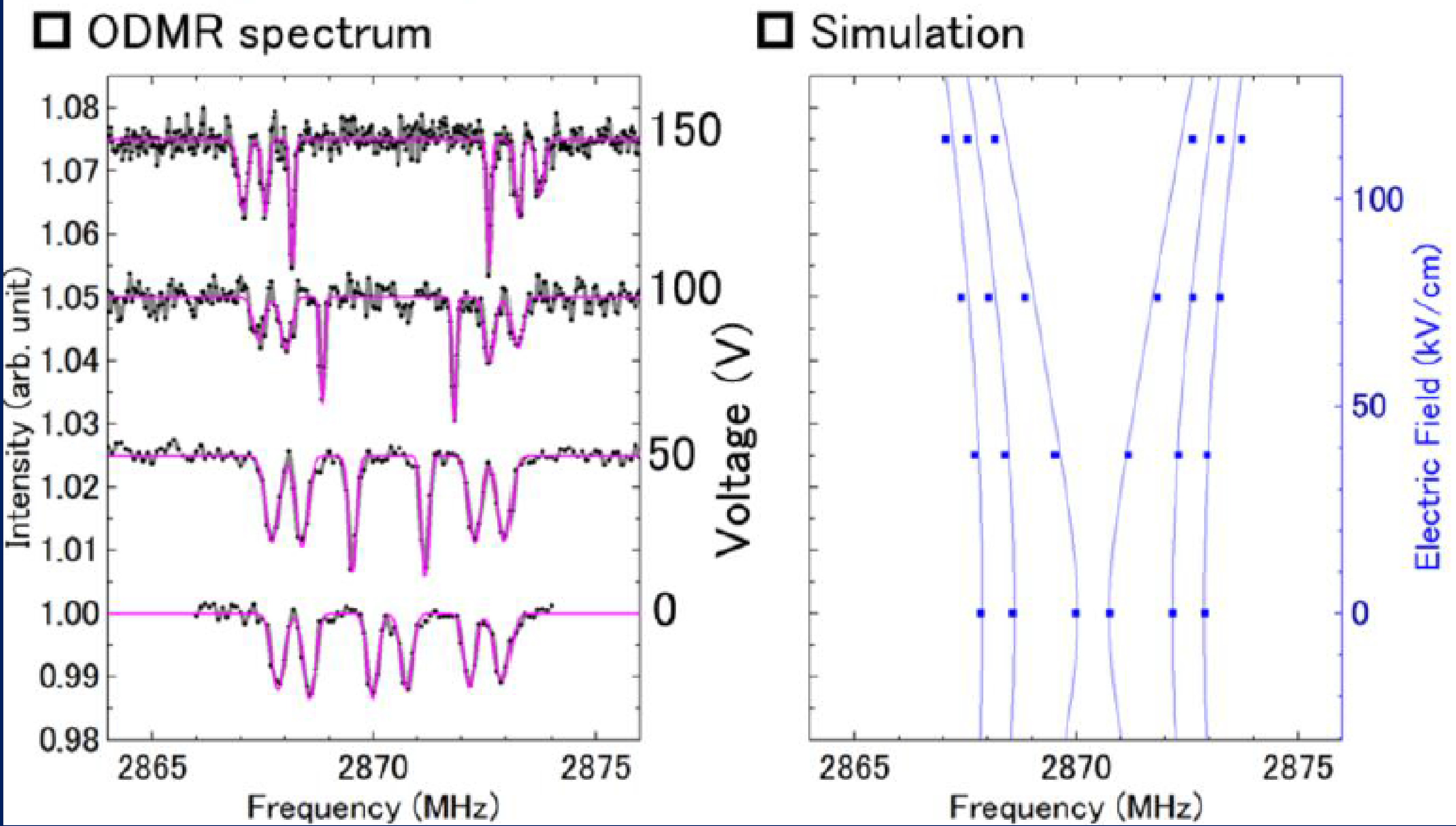
Extension of T_2 by applying Electric field.

Sample and measurement

- NV center in diamond
  - Ion implantation (30 keV, 600 ℃, 6×10^{10} $1/cm^2$, Au mask was used for small hole)
  - Anneal (1000 ℃, 120 min)
- Electrode
  - EB lithography
  - Diamond(001) / Ti (10 nm) / Au (100 nm)
- Home built confocal microscope

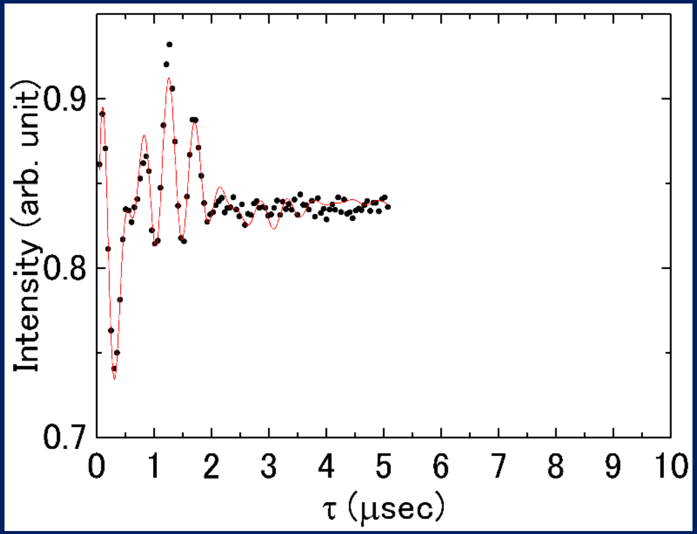


ODMR spectra and simulation



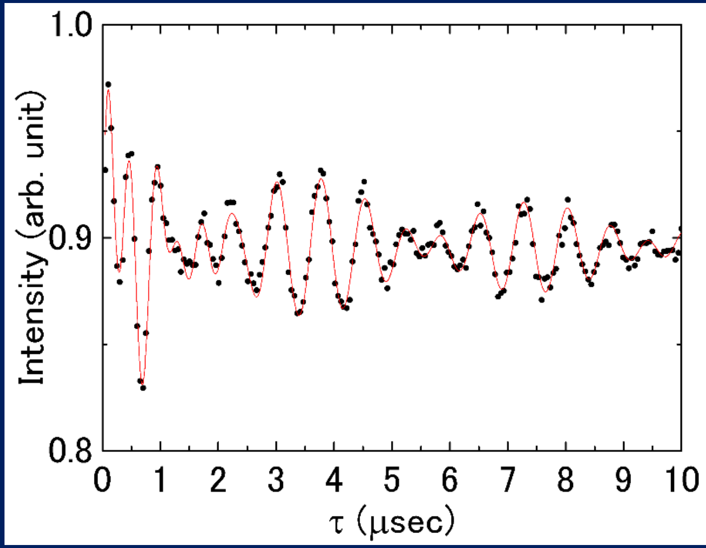
Free induction decy（T_2^*）

0 kV/cm



$T_2^* = 1.2$ μsec

80 kV/cm

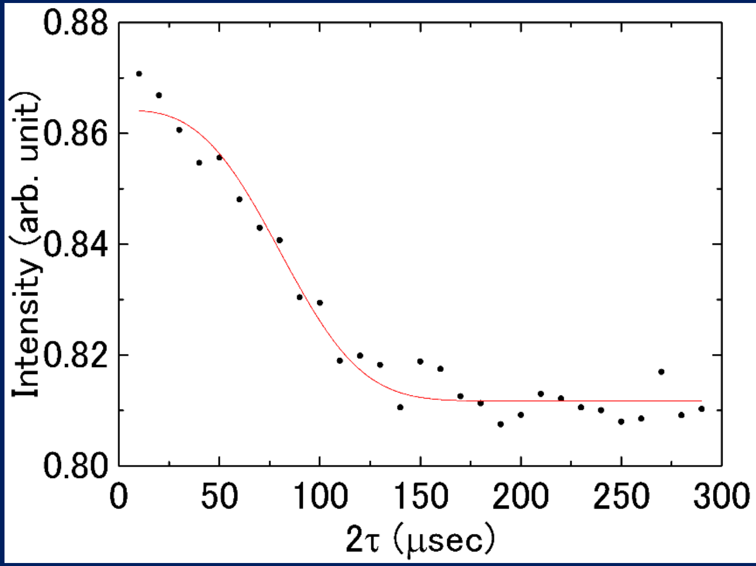


$T_2^* = 11$ μsec

Extension of T_2^* increased by E field !

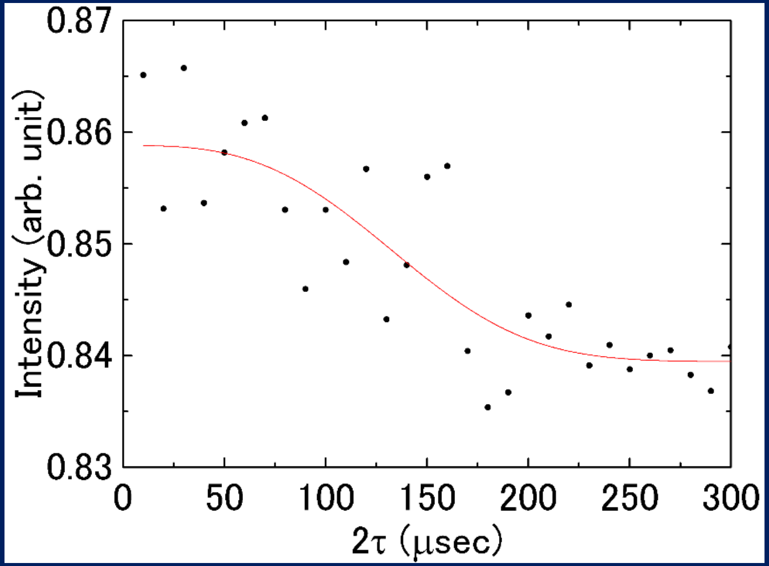
Hahn Echo meas. (T_2)

0 kV/cm



T_2 = 92±3 μsec

80 kV/cm



T_2 = 152±19 μsec

Extension of T_2 by E field !

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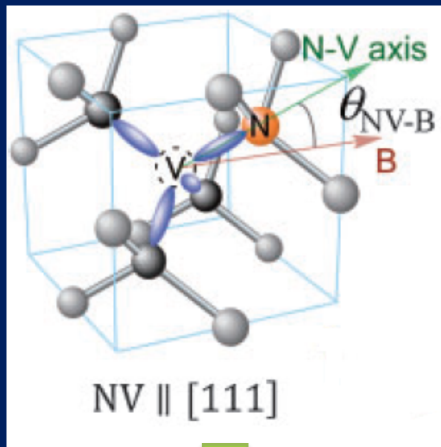
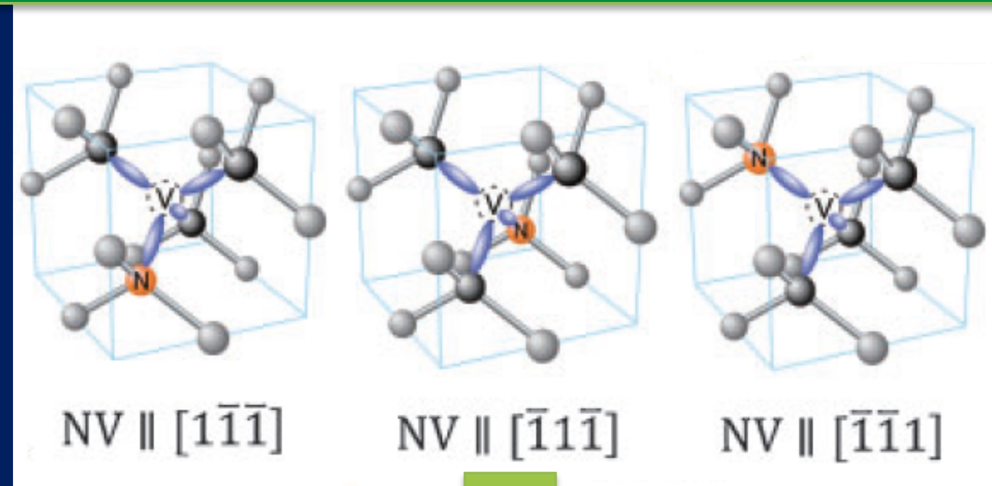
Magnetic field sensor sensitivity



the readout signal



the background signal

Magnetic field sensitivity : η

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

C : readout contrast

n_{NV}: The number of NV

: Measurement time

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

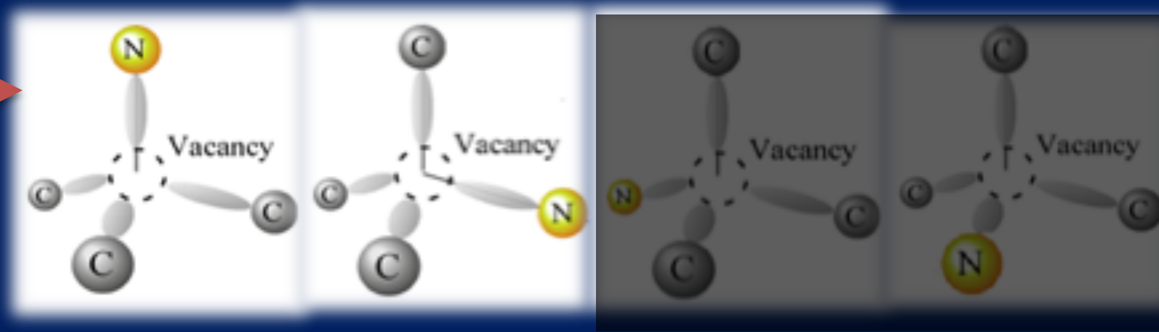
η Four-fold enhancement due to four possible orientation

It is important to control NV orientation for magnetic sensor

Previous research

CVD layer

(110) and (100)
diamond substrate



NV centers aligned along two of the four orientation.

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

A. M. Edmonds, et. al., Phys. Rev. B **86,** 035201(2012)

using (100)-CVD diamond, the readout contrast and magnetic field sensitivity can be enhanced by a factor of two.

$$\frac{1}{C\sqrt{n_{NV}}}$$

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

However, perfect alignment has not yet been realized….

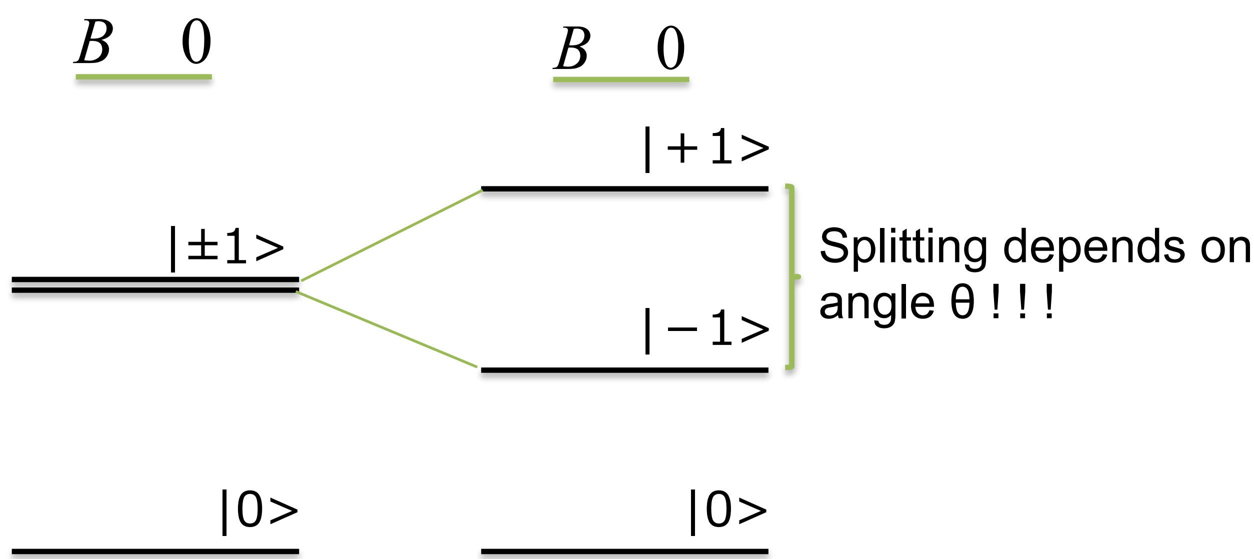
We will show the perfect alignment of NV centers in (111)-CVD diamond

Angular dependence of resonance

Spin Hamiltonian of NV center under magnetic field (B)

$$\mathscr{H}_S = DS_z^2 + E(S_x^2 - S_y^2) + g_s \mu_B \vec{B} \cdot \vec{S}$$

D, E : zero field splitting parameter
gs : electron g-value
μB : Bohr magneton



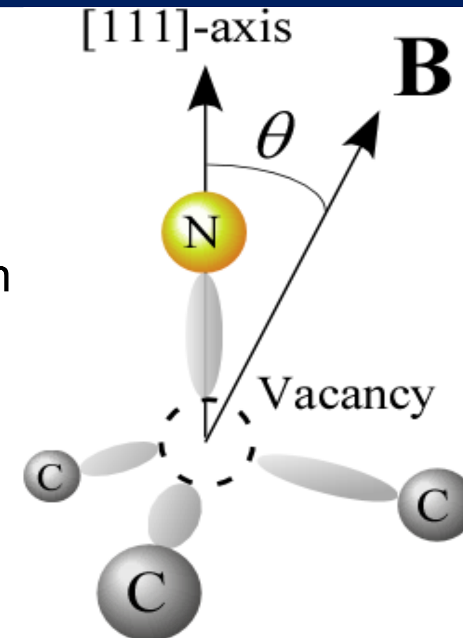
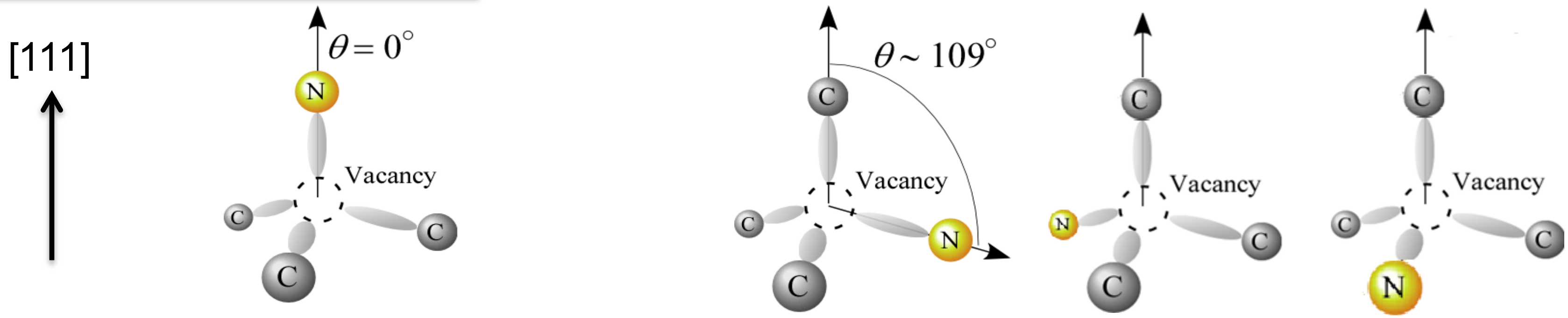


Fig. electronic spin structure of ground state of NV center

Splitting width depends on angular θ between the direction of NV axis and magnetic field

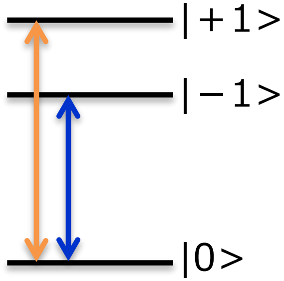
Investigation of the NV orientation by ESR

In the case of B//[111]

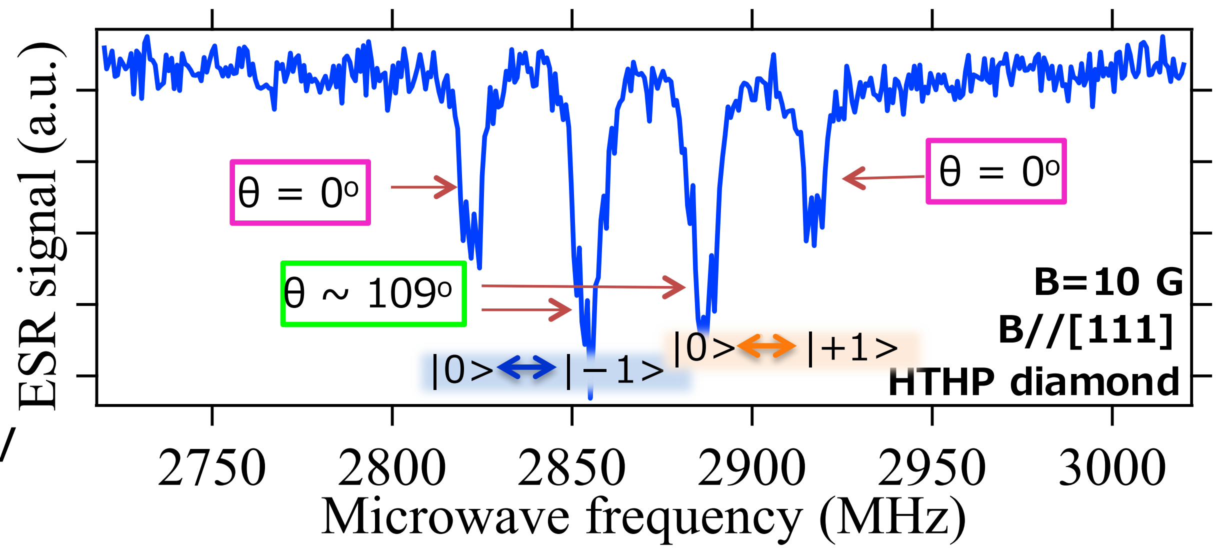


When NV orientation is along [111] direction, $\theta = 0°$

When NV orientation is along except for [111] direction, $\theta \sim 109°$



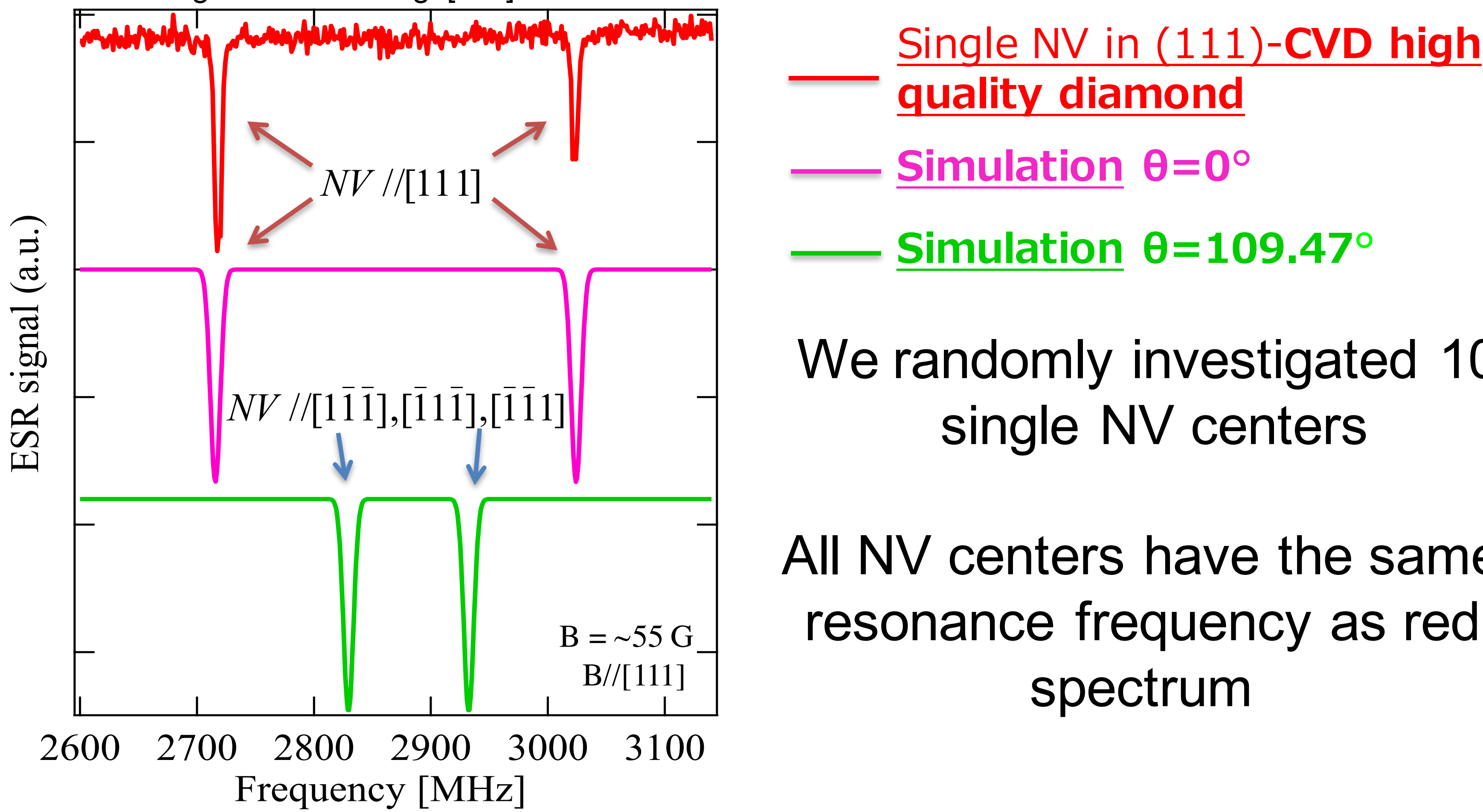
Electronic spin structure of NV center under B



Assignment of the NV orientation by magnetic resonance

Measurement result ~single ~

ESR spectra of single NV center under magnetic field along [111]-axis



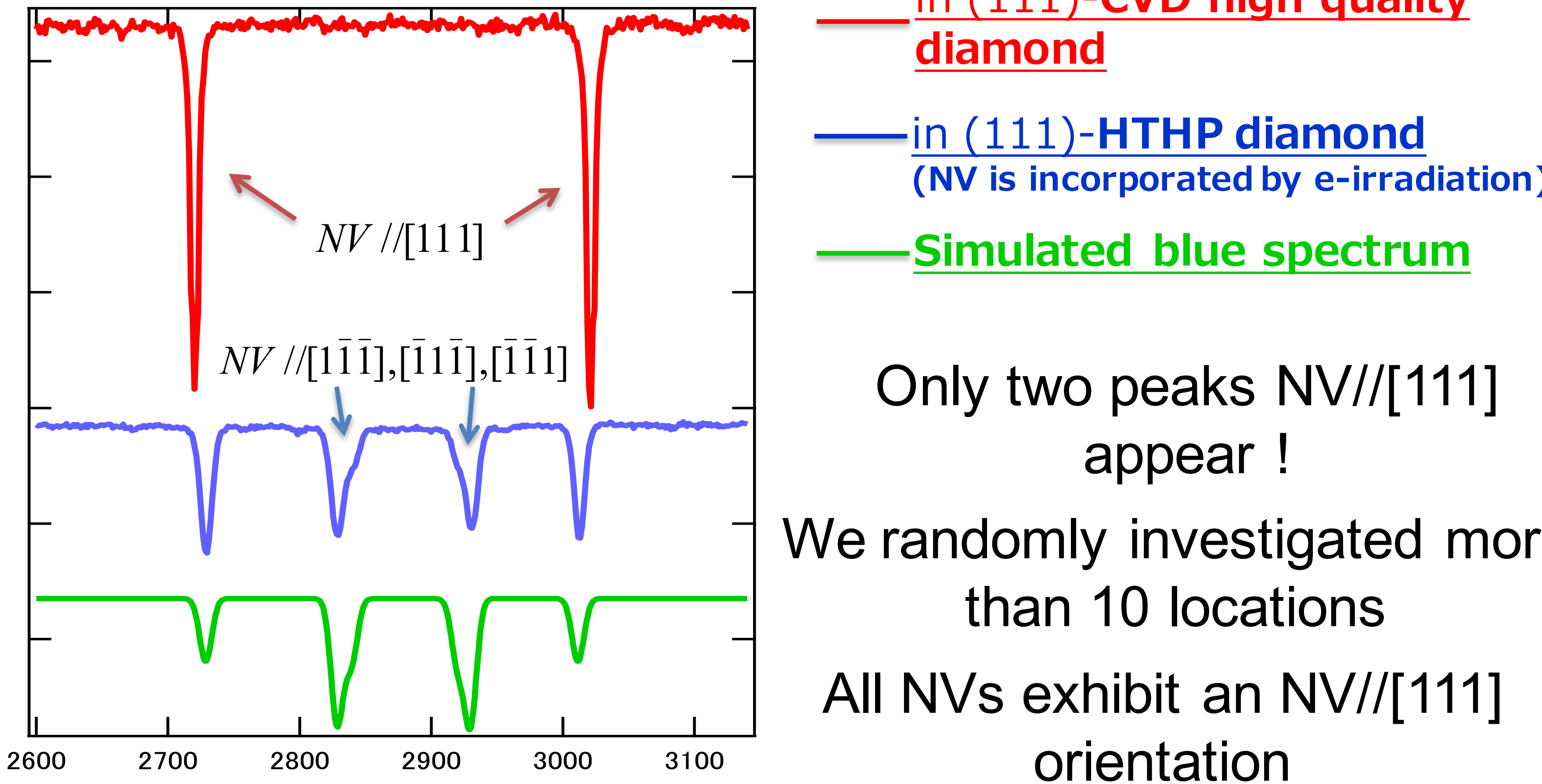
We randomly investigated 100 single NV centers

All NV centers have the same resonance frequency as red spectrum

The orientation of more than 99% of the single NV centers in (111)-CVD diamond were aligned along the [111] axis

Measurement result ~ensemble ~

Fig. ODMR spectra of ensemble NV centers under magnetic field along [111]-axis



Only two peaks NV//[111] appear !

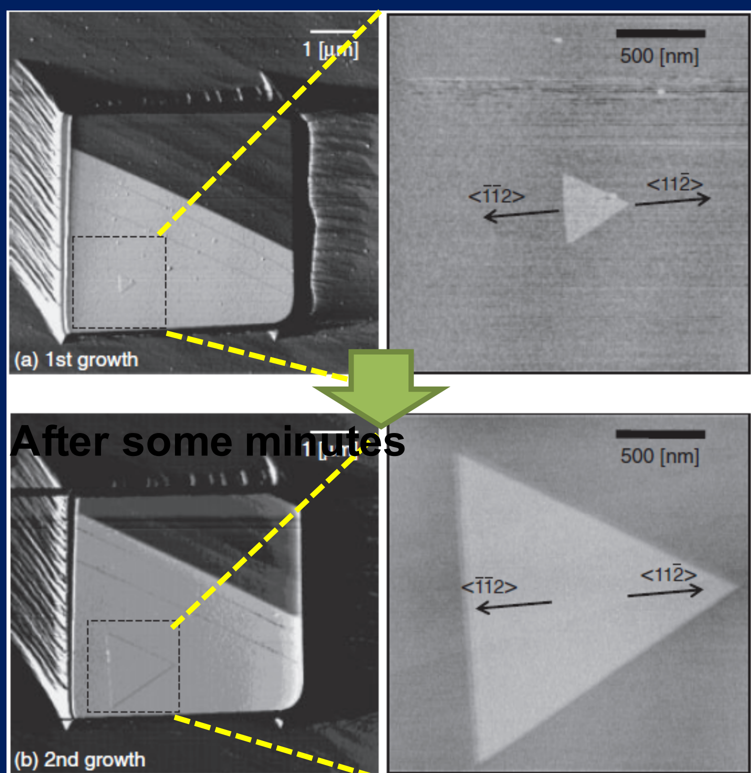
We randomly investigated more than 10 locations

All NVs exhibit an NV//[111] orientation

We show the orientation of ~99% of the NV centers in (111)-CVD diamond can be aligned along the [111] axis

(111)-CVD diamond growth ~Kink flow~

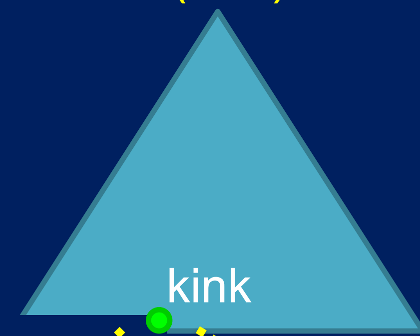
How to grow (111)-diamond by CVD

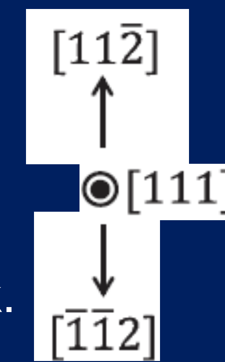


AFM image of diamond surface

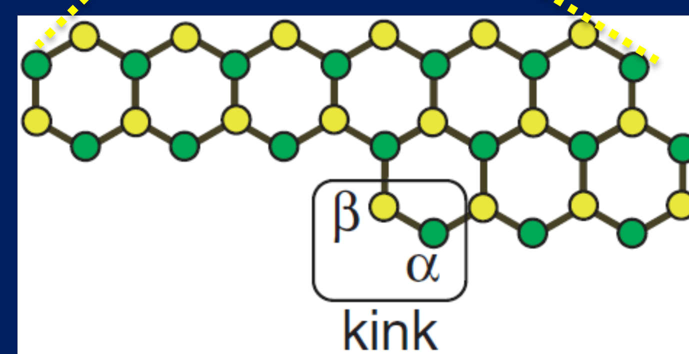
N. Tokuda, et al., Jpn. J. Appl. Phys. (2014)

kink flow of (111)-diamond island





Diamond growth occur at kink.



(111)- diamond bi-layer structure

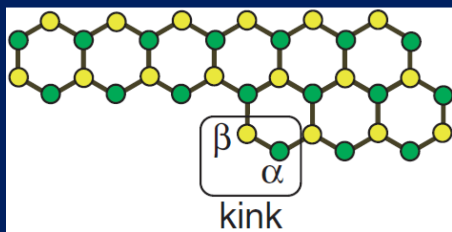
α site is the top C atom in bi-layer
β site is the second C atom in bi-layer

(111)-diamond grows by C atom incorporation to α and β site in kink

Theoretical study

We calculated which N is easy to be incorporated at α or β site

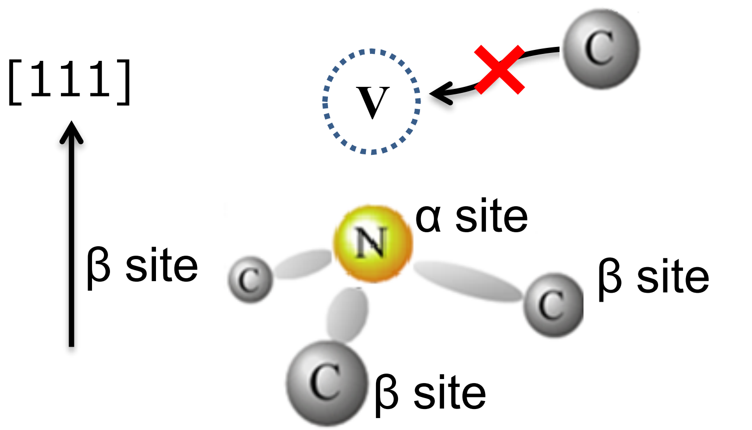
(With first-principles calculation)



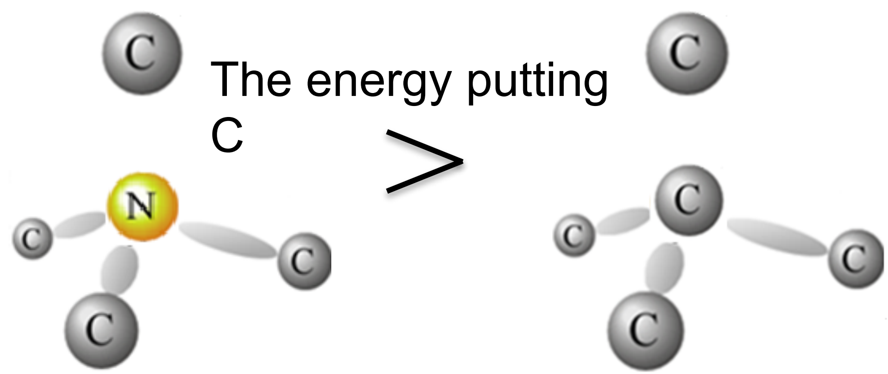
The N at the α kink site is energetically favorable.

(0.51 eV)

When an N atom is incorporated at α site



N atom doesn't have lone pairs.
So, C is difficult to put on N atom



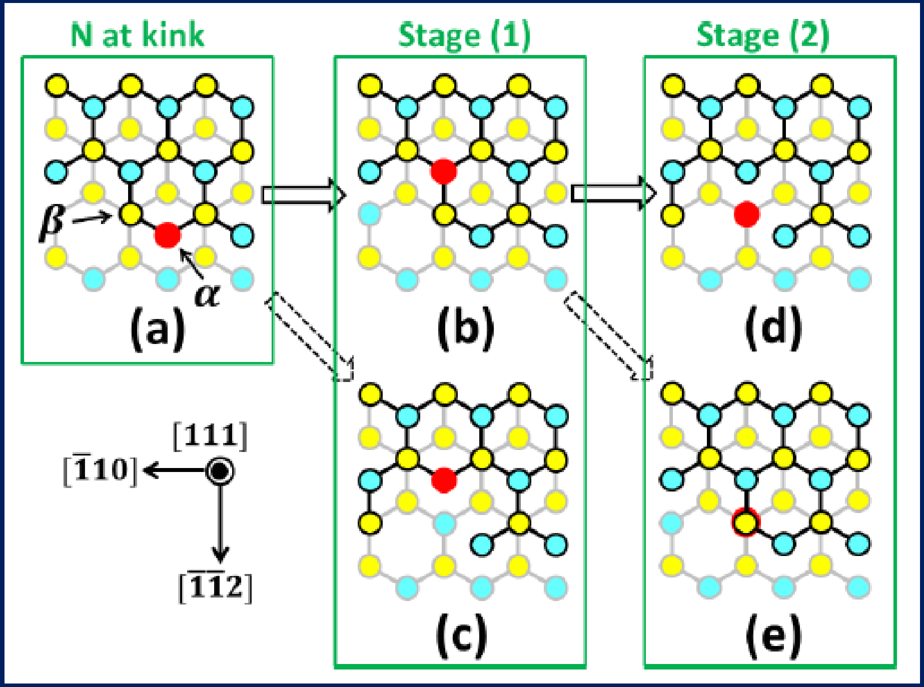
The energy putting C on N atom is larger (3 eV) than ones on C itself

Atomistic mechanism of perfect alignment of nitrogen-vacancy centers in diamond

Takehide Miyazaki[1,6], Yoshiyuki Miyamoto[1,6], Toshiharu Makino[2,6], Hiromitsu Kato[2,6], Satoshi Yamasaki[2,6], Takahiro Fukui[3], Yuki Doi[3], Norio Tokuda[4], Mutsuko Hatano[5,6], and Norikazu Mizuochi[3,6]

first-principles calculation

T. Miyazaki, NM, et al., *Appl. Phys. Lett*. 105, 261601 (2014).



If N atom is incorporated in this mechanism, perfect alignment by CVD can be realized!

Summary

- Extension of coherence time by electric field.

  S. Kobayashi, NM, et al., unpublished

- The orientation of more than 99% of the NV centers could be aligned along the [111] axis. The mechanism was discussed.

  T. Fukui, NM, et al., *Appl. Phys. Exp*. 7, 055201 (2014), selected in "Spotlights"
  T. Miyazaki, NM, et al., *Appl. Phys. Lett*. 105, 261601 (2014).

Important in application for quantum information, sensing, …