2012年8月16日
FIRST夏期研修会 @ 宮古島

超伝導・ダイヤモンド複合系におけるメモリー動作

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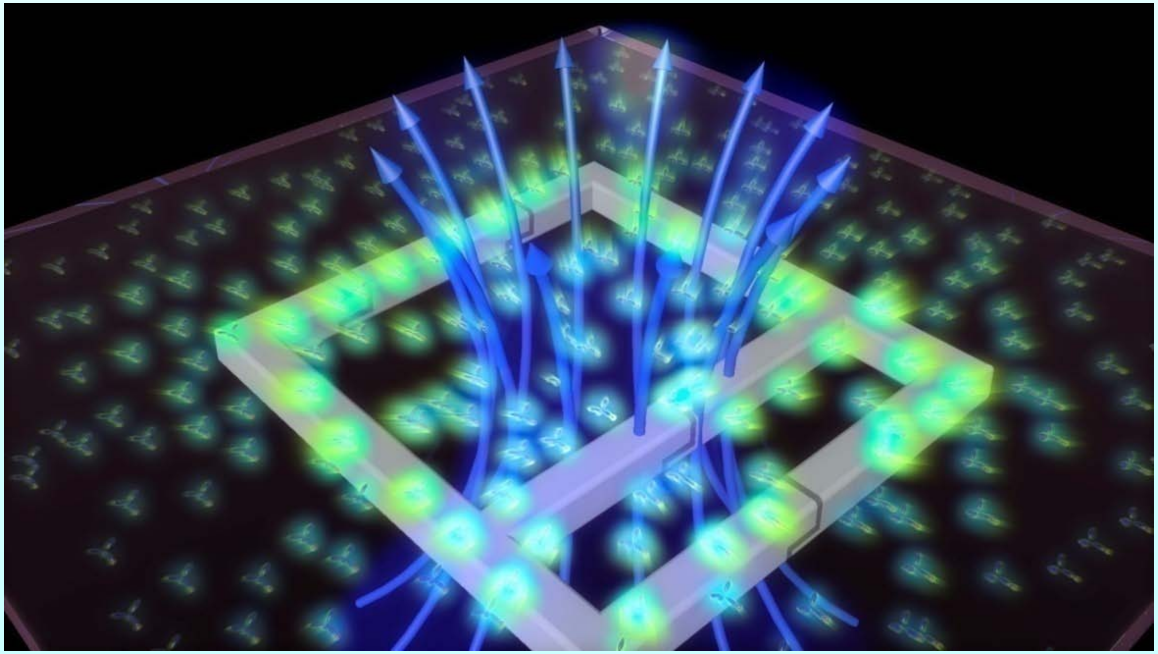
3 : National Institute of Informatics



Outline

1. Introduction
   Superconducting qubit
   Superconductor-diamond hybrid system

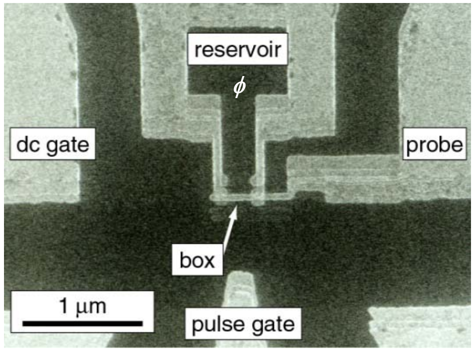
2. Experiment under zero in-plane magnetic field
   Strong coupling , coherent oscillations

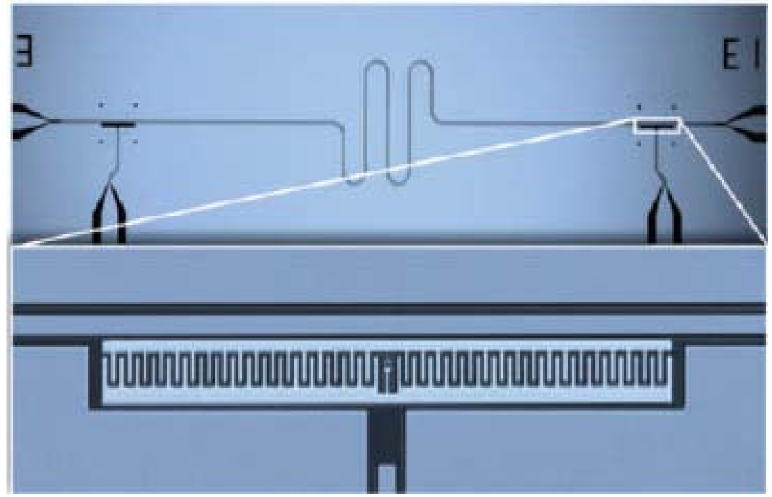
3. Experiment under zero in-plane magnetic field
   lower NV density
   coherence time is improved

4. Summary

Superconducting qubits

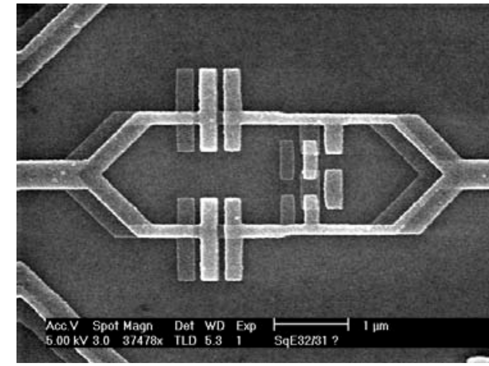
Charge (NEC)

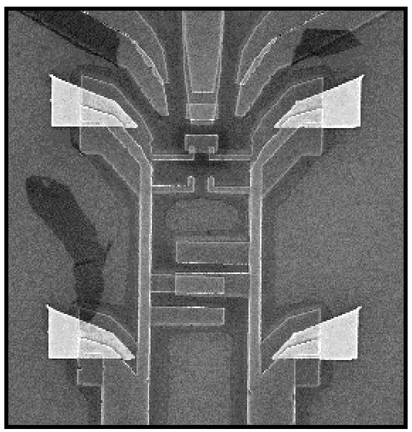




Transmon (Yale)

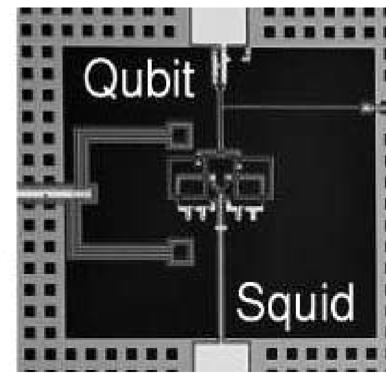
Flux (Delft)





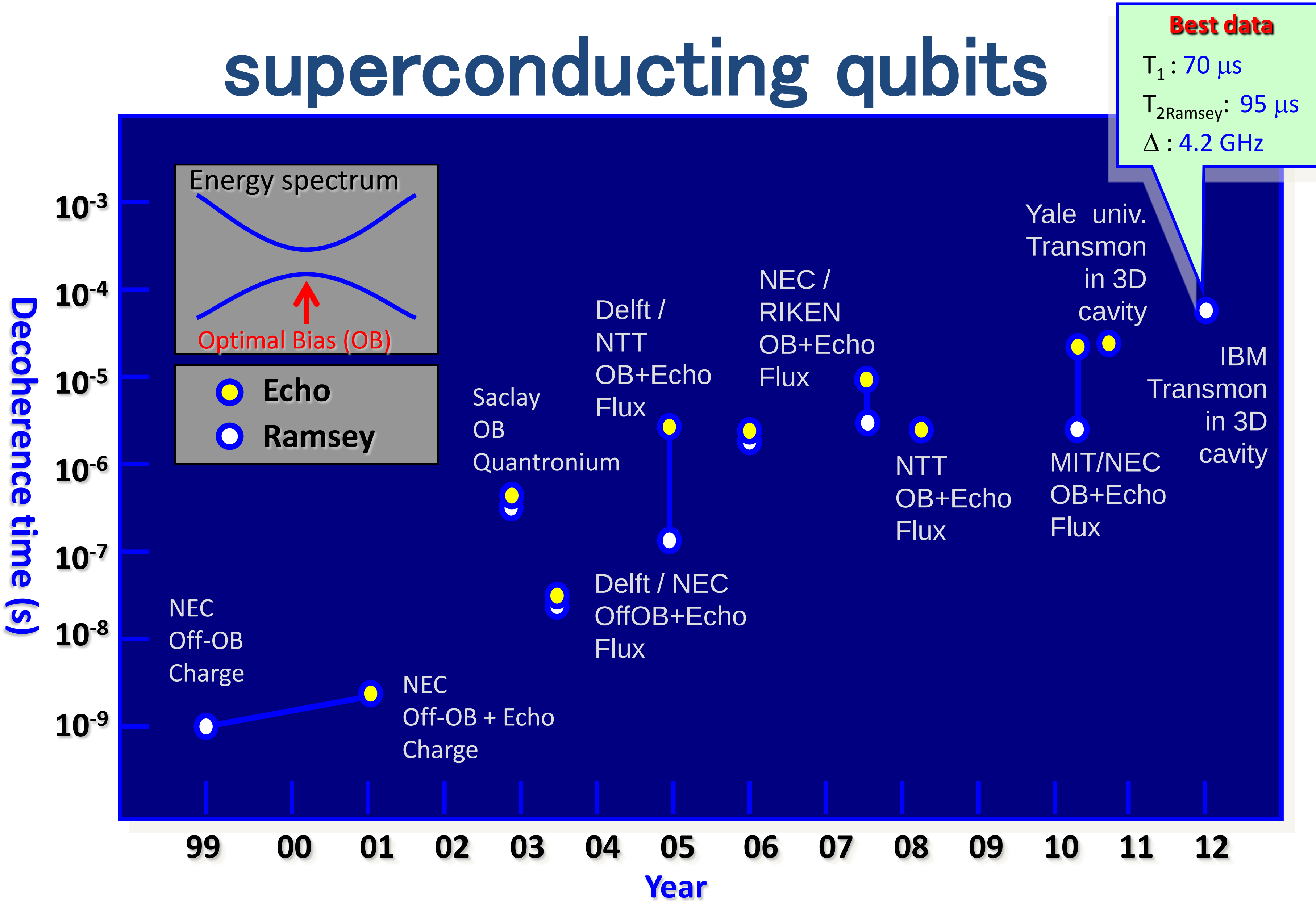
Quantronium
(Saclay)

Phase (UCSB)



	$E_J/E_C < 1$	$E_J/E_C \approx 1$	$1 < E_J/E_C$		$1 << E_J/E_C$
Type	charge	quantronium	transmon	flux	phase
Coherence time	0.5 μs	0.5 μs	25 μs (95 μs)	23 μs	0.15 μs

Coherence time of superconducting qubits

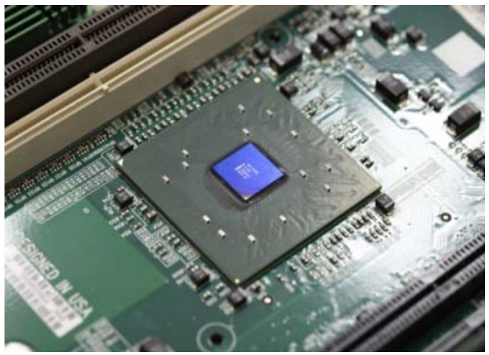


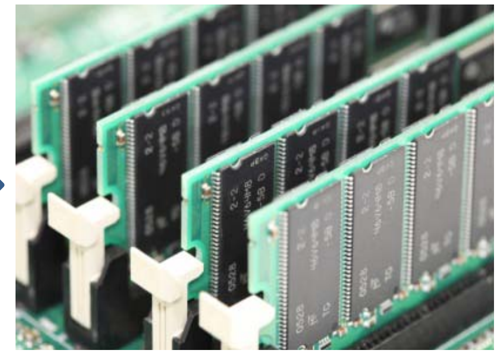
Based on J.S.Tsai's plot, NTT's data and the newest data are added.

Components of Computers

Conventional computer

CPU:
processor
(semiconductor
device)

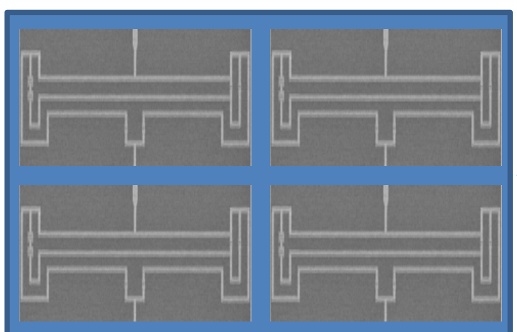




RAM: memory
(semiconductor
device)

Quantum computer using superconductor

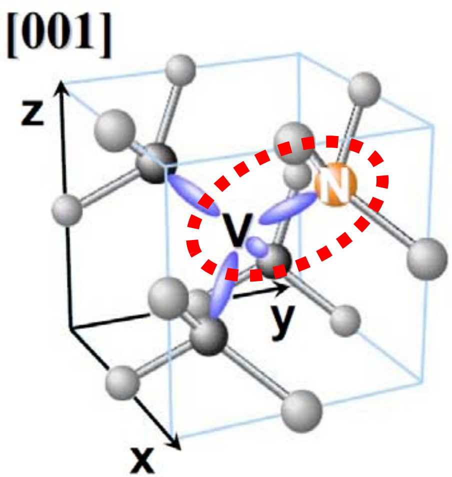
Quantum bit :
Processor +
memory
(superconducti
ng device)

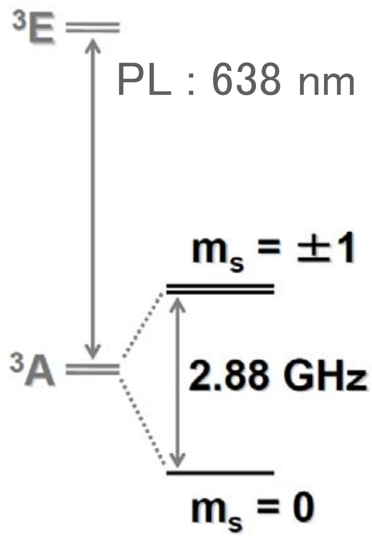


?

NV⁻ center

- coexistence of GHz and sub-PHz transitions

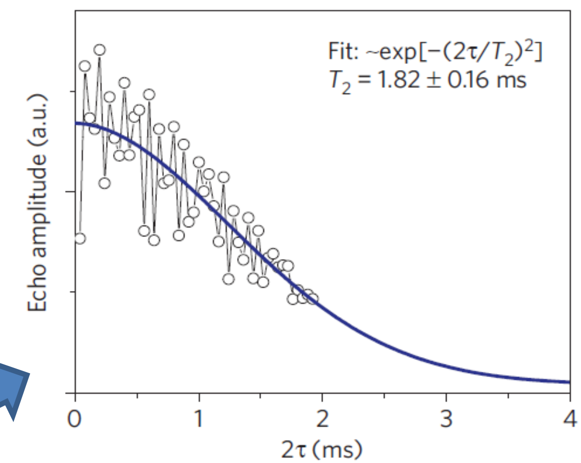




→ Telecomunication wavelength（QKD）

→ Microwave Compatible with superconducting qubit

~ ms coherence time at RT



G. Balasubramanian, et al., Nature material, **8**, 383 (2009)

① **Long T_2 at RT: 1.8 ms**
→ suitable for a memory

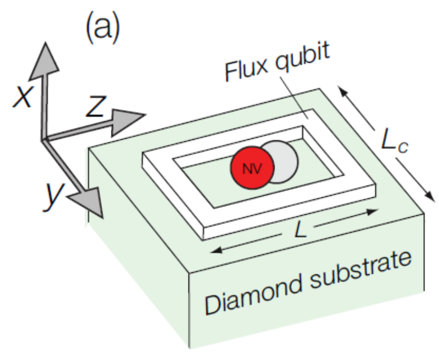
② **B=0 Ground state splitting : 2.88 GHz**
→ idealistic to couple to a superconducting qubit

③ coexistence of GHz (2.88 GHz) and sub-PHz transitions : **638 nm (0.47 PHz)**
→ microwave ⇔ optical freq region ： Quantum Frequency Converter / Transducer

Superconducting circuits and spin ensembles

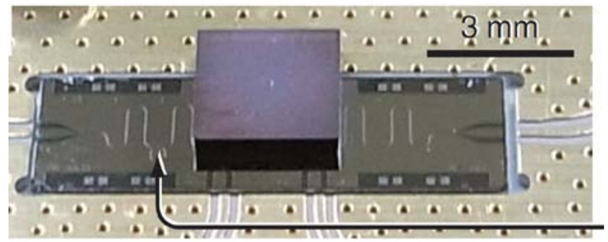
Flux-qubit ⇔ NV-diamond

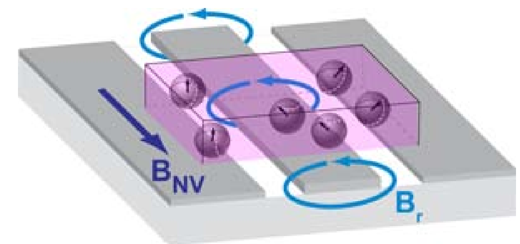
Proposal



D. Marcos, et al., PRL 105, 210501 (2010)

MW-resonator ⇔ NV-diamond





$g_{\text{ens}} = g_{\text{single}}\sqrt{N} >> \kappa,\gamma$ $\quad g_{\text{ens}} = 22\ \text{MHz}$

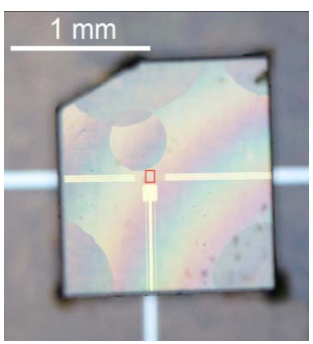
$N = 10^{12}$ $\quad g_{\text{sigle}} = 22\ \text{Hz}$

Y. Kubo, et al., PRL 105, 140502 (2010)

D. I. Schuster et al., PRL 105, 140501 (2010)

R. Amsuss et al., PRL 107, 060502 (2011)

Experiment (This work)



$g_{\text{ens}} = 70\ \text{MHz}$

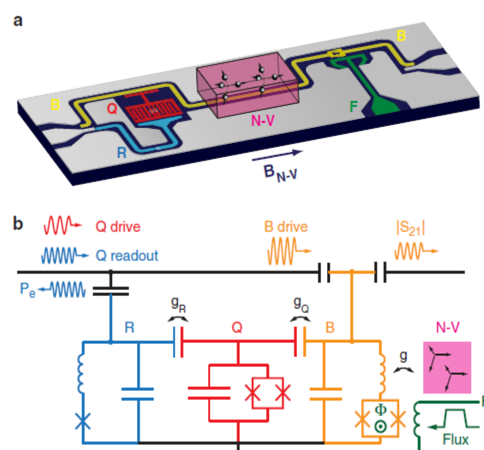
$g_{\text{single}} = 8.8\ \text{kHz}$

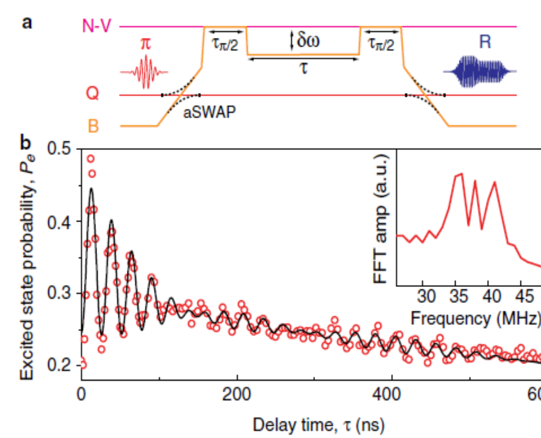
$N = 6\times10^{7}$

X. Zhu, S. S. et al., Nature 478, 221 (2011)

Transmon-qubit ⇔ MW-resonator ⇔ NV-diamond

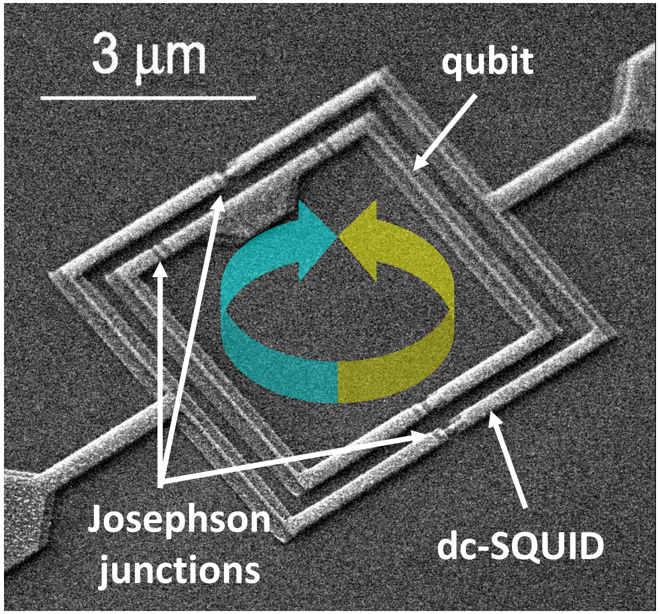
Y. Kubo, et al., PRL 107, 220501 (2011)

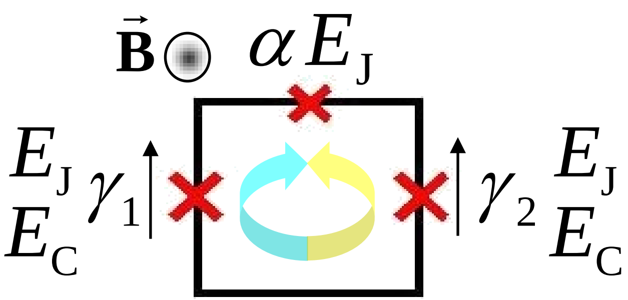


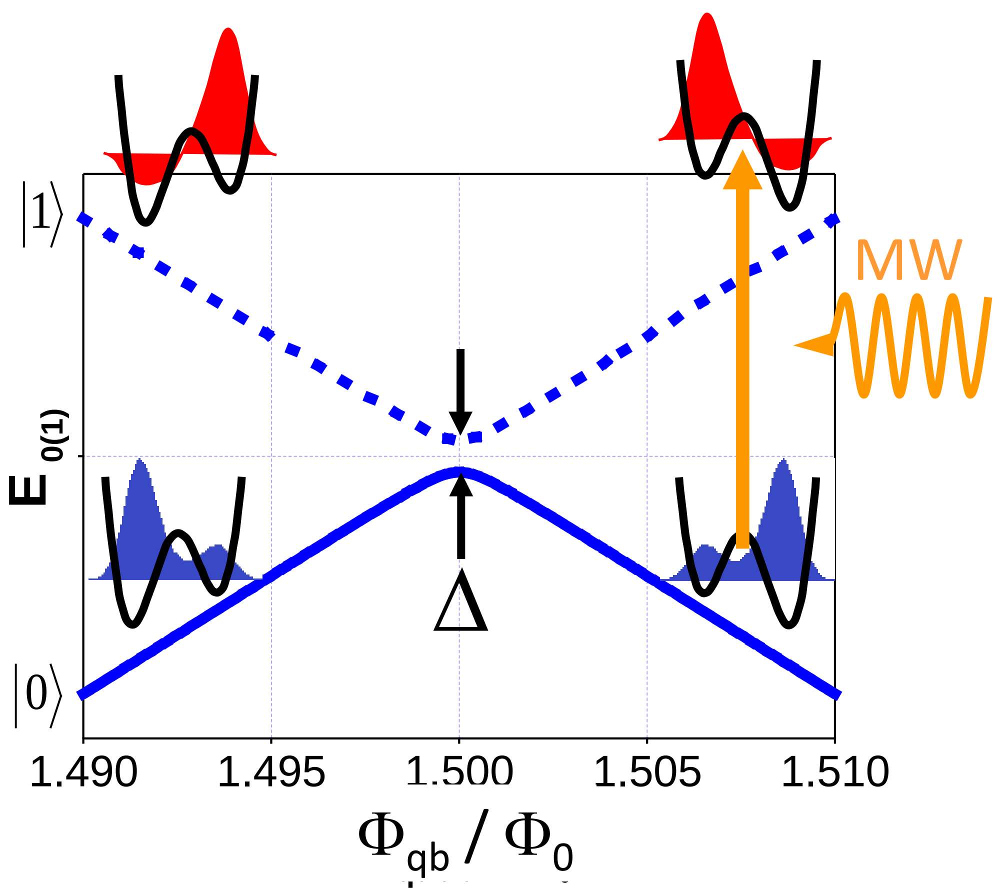


Superconducting flux qubits

Mooij et al. Science **285**, 1036 (1999)





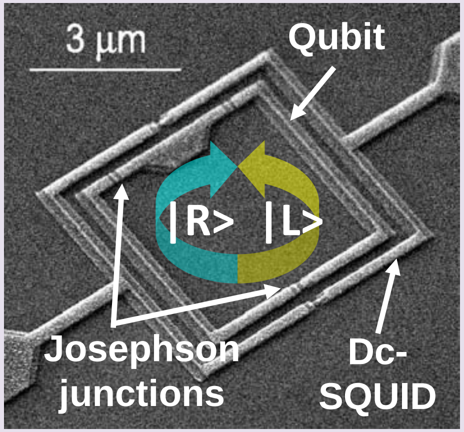


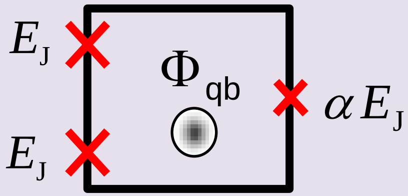
$$H_{qb} = \frac{\varepsilon(\Phi_{qb})}{2}\sigma_Z + \frac{\Delta}{2}\sigma_X + A_{MW}\sigma_Z \cos(\omega_{MW} t)$$

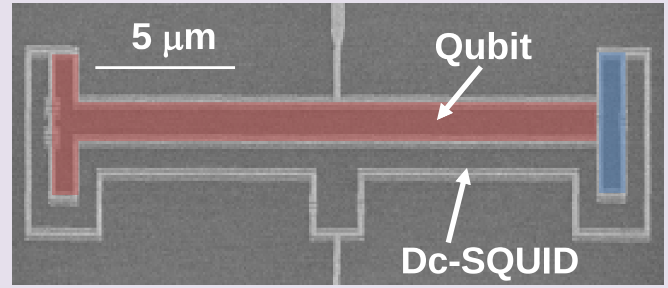
$$\varepsilon = I_P(\Phi_{qb} - 1.5\Phi_0)$$

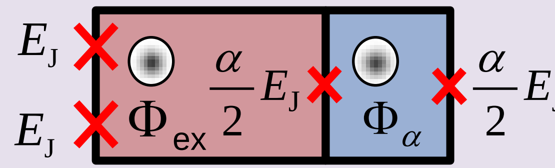
$$\hbar = 1$$

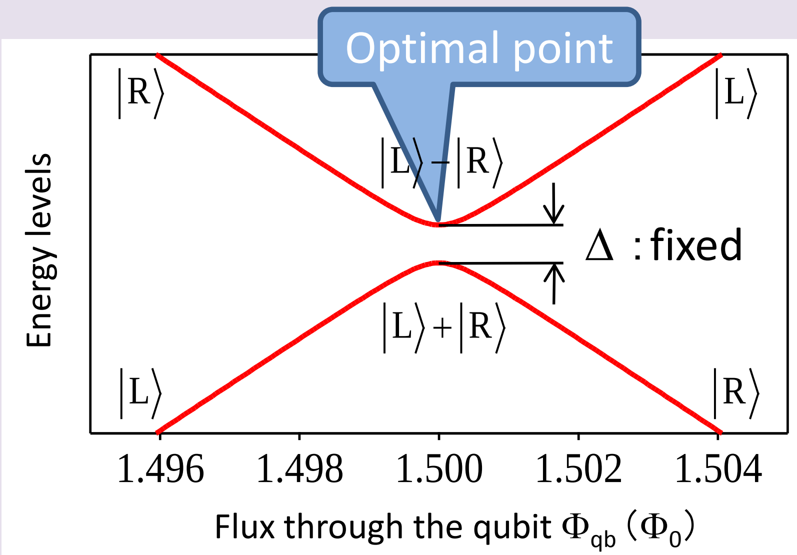
Gap tunable flux qubits

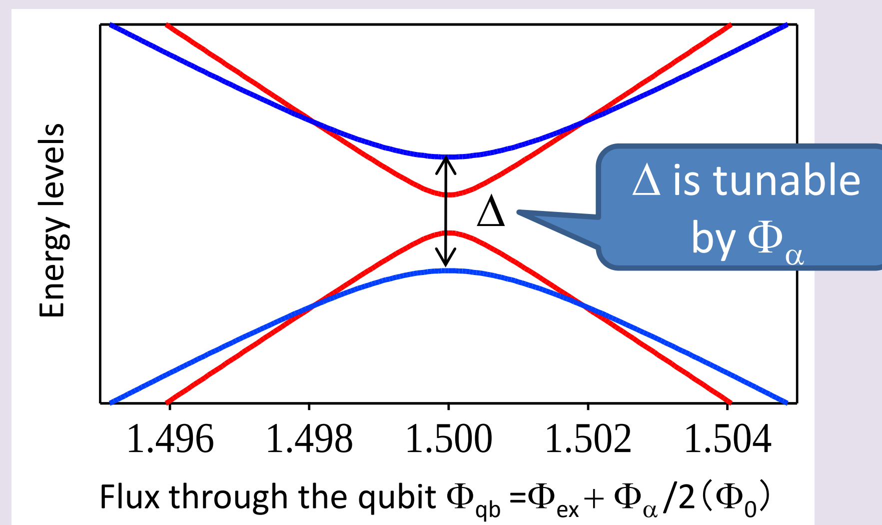










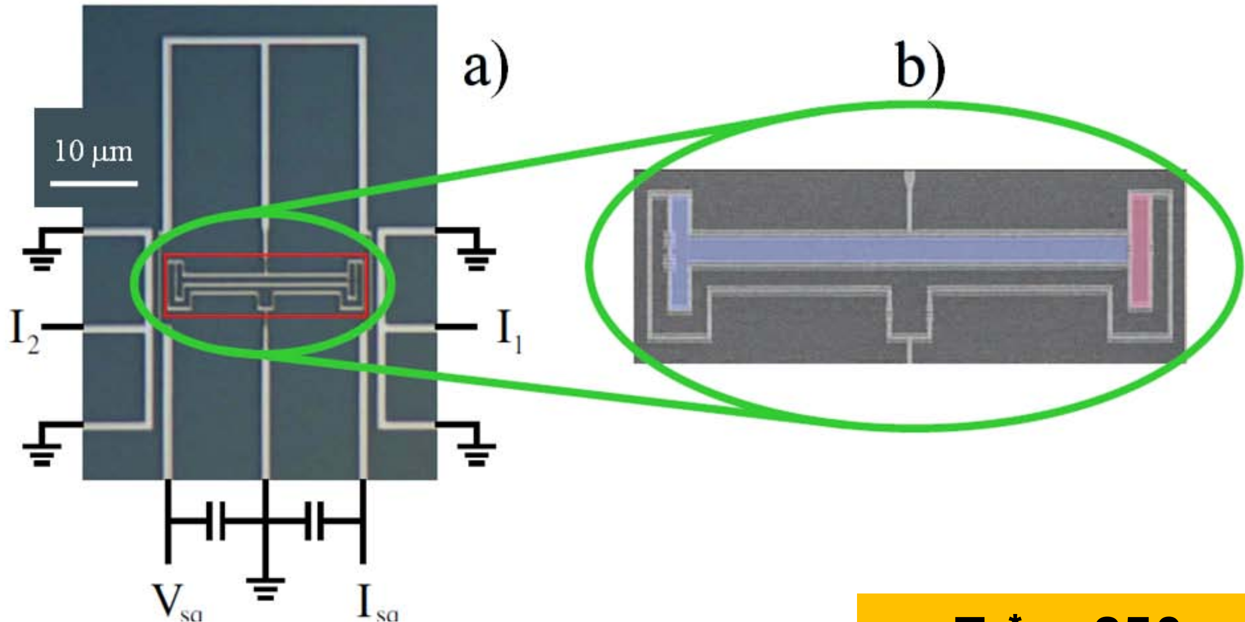


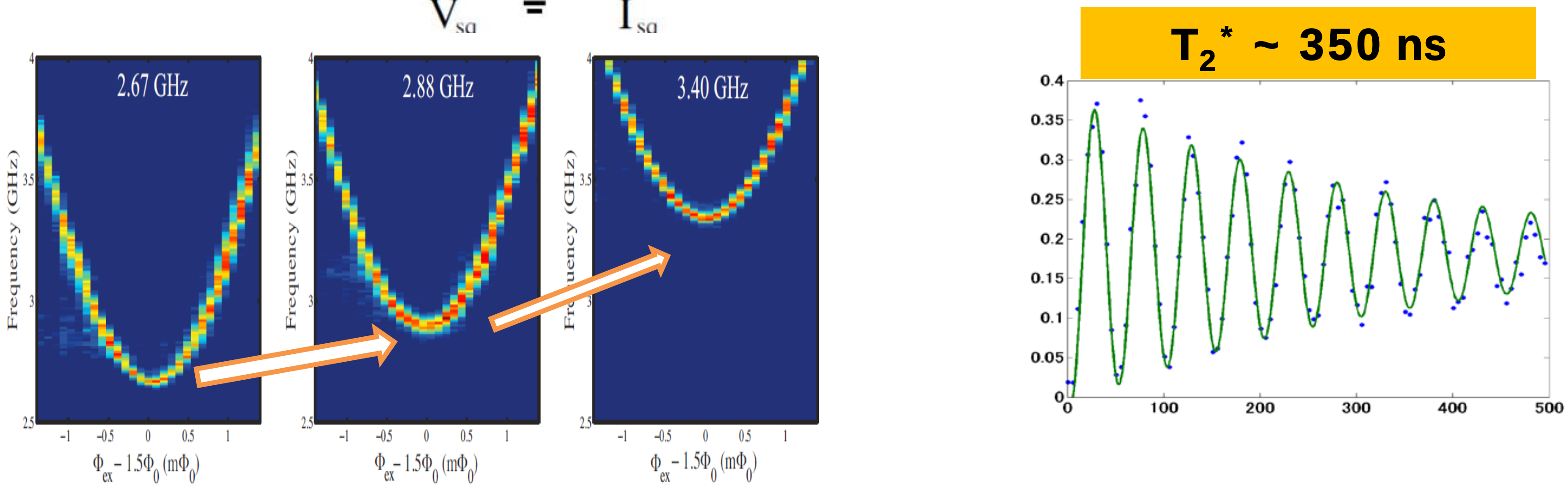
$$H_{qb} = \frac{\varepsilon(\Phi_{qb})}{2}\sigma_Z + \frac{\Delta}{2}\sigma_X$$

$$H_{qb} = \frac{\varepsilon(\Phi_{qb})}{2}\sigma_Z + \frac{\Delta(\Phi_\alpha)}{2}\sigma_X$$

F. G. Paauw, et al., PRL(2009), X. Zhu, SS et al., APL(2010)

Gap tunable flux qubits

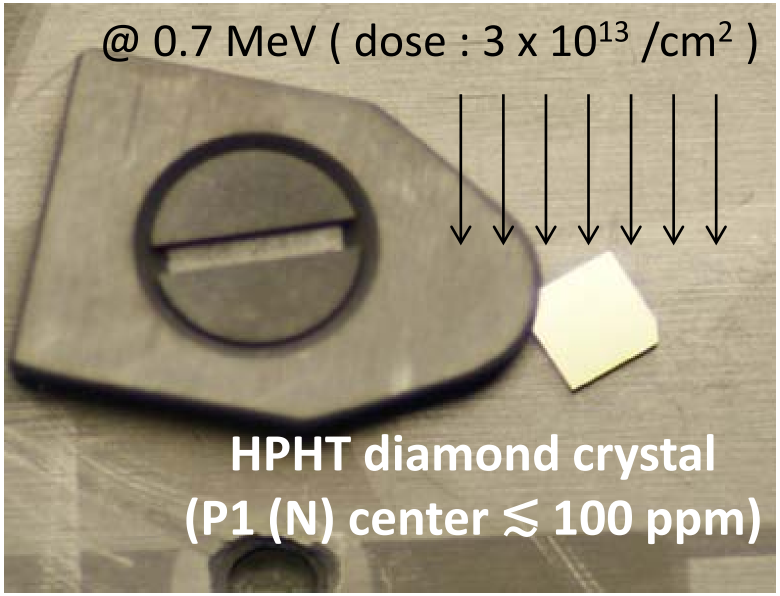




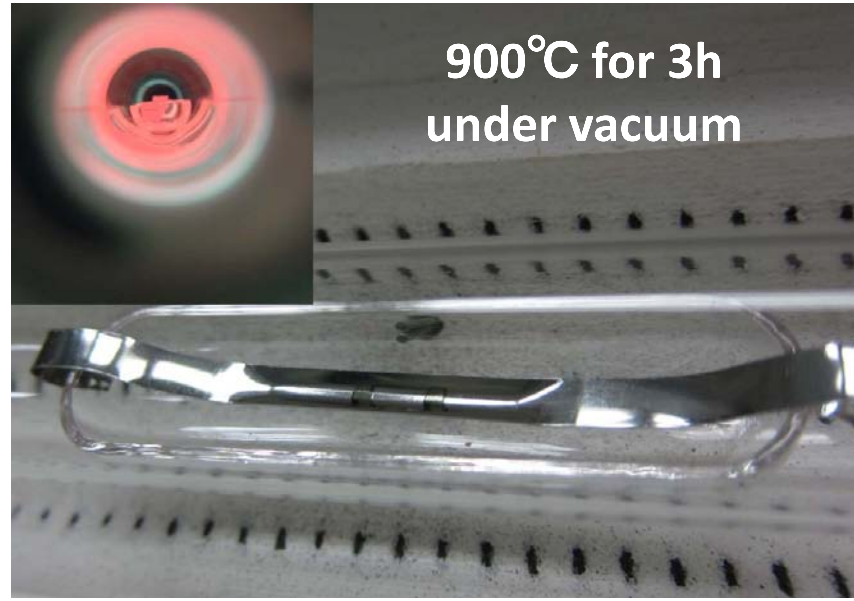
X. Zhu, SS, et al., Appl. Phys. Lett. 97, 102503 (2010)

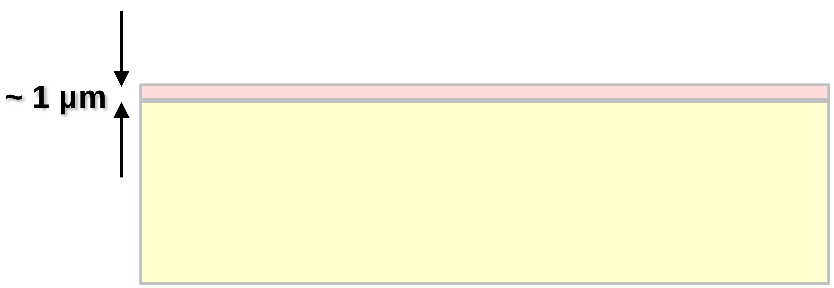
Preparation of diamond samples

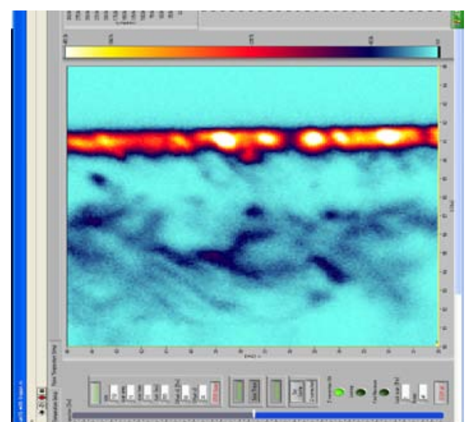
$^{12}C^{++}$ ion implantation

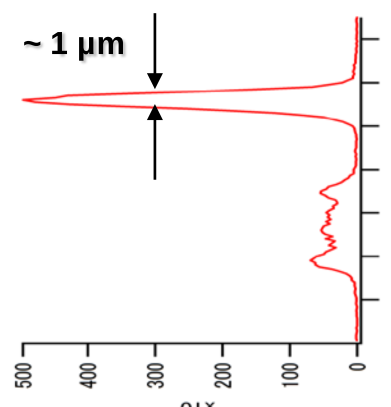


Annealing







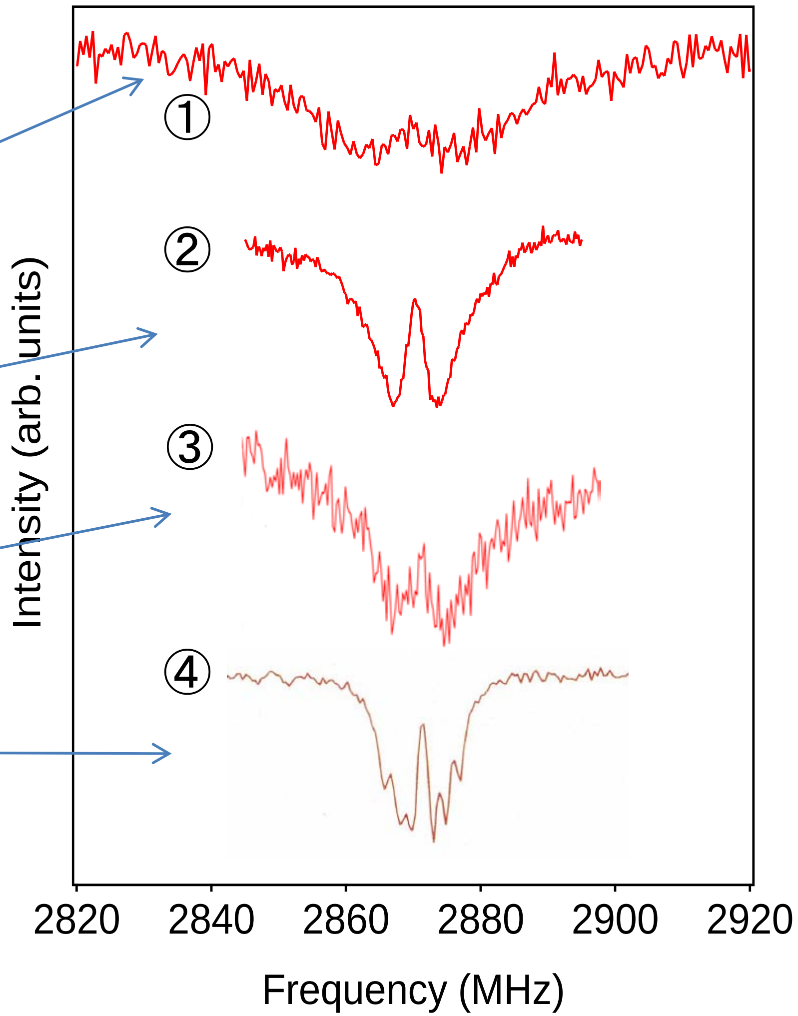


Photoluminescence measured by Prof. Mizuochi and Mr. Simooka

Evaluation of diamond samples

Type	N conc. (ppm)	NV^- density (cm^{-3})
① HTHP Ib	1-100	1.1×10^{18}
② HTHP Ib	1-100	4.7×10^{17}
③ HTHP Ib	1-100	6.8×10^{16}
④ CVD IIa	1-10	3.0×10^{16}

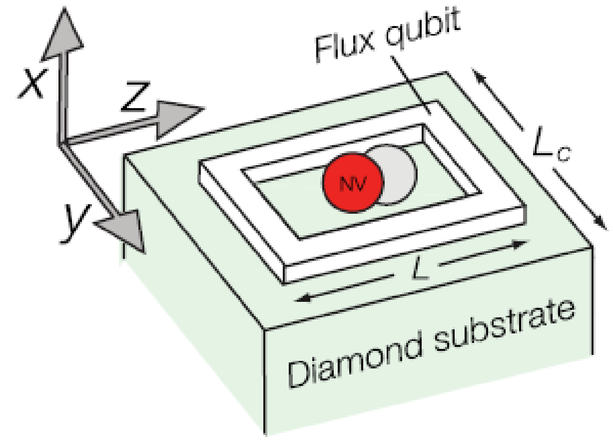
ODMR measurements



Total Hamiltonian

Marcos, D. *et al.* *Phys. Rev. Lett.* **105,** 210501 (2010)

Total Hamiltonian $\hat{H} = \hat{H}_{\text{qubit}} + \hat{H}_{\text{NV}} + \hat{H}_{\text{I}}$



Qubit Hamiltonian $H_{\text{qubit}} = \frac{\epsilon}{2}\hat{\sigma}_z + \frac{\Delta}{2}\hat{\sigma}_x$

NV Hamiltonian $H_{\text{NV}} = \sum_{j=1}^{N} \omega_{\text{NV}}^{(j)} (|-1\rangle_j \langle -1| - |0\rangle_j \langle 0|)$

Interaction Hamiltonian

$$H_I = \sum_{i=1}^{N} (|L\rangle\langle L| \, g\mu_{\text{B}} \overrightarrow{B}_i \cdot \overrightarrow{S}^{(i)} - |R\rangle\langle R| \, g\mu_{\text{B}} \overrightarrow{B}_i \cdot \overrightarrow{S}^{(i)})$$

$$= \hat{\sigma}_z \sum_{i=1}^{N} g\mu_B \overrightarrow{B}_i \cdot \overrightarrow{S}^{(i)}$$

Interaction Hamiltonian

After using rotating wave approximation, we obtain the following JC type model when an inhomogeneous broadening is negligible

$$H = \frac{\sqrt{\Delta + \epsilon^2}}{2}\hat{\sigma}'_z + (D - g\mu_B B_z)\hat{b}^\dagger\hat{b} + \frac{1}{\sqrt{2}}\sqrt{\sum_{j=1}^{N}|g\mu_B B_\perp^{(j)}|^2}\sin\theta(\hat{\sigma}'_+\hat{b} + \hat{\sigma}'_-\hat{b}^\dagger)$$

Collective coupling strength

$$\hat{b}^\dagger = \frac{1}{\sqrt{\sum_{i=1}^{N}|g\mu_B B_\perp^{(i)}|^2}}\sum_{i=1}^{N} g\mu_B B_\perp^{(i)}\overline{S}_+^{(i)}$$

$$\sin\theta = \frac{\Delta}{\sqrt{\Delta^2+\epsilon^2}}$$

$$[b, b^\dagger] = 1$$

This behaves like a harmonic oscillator !

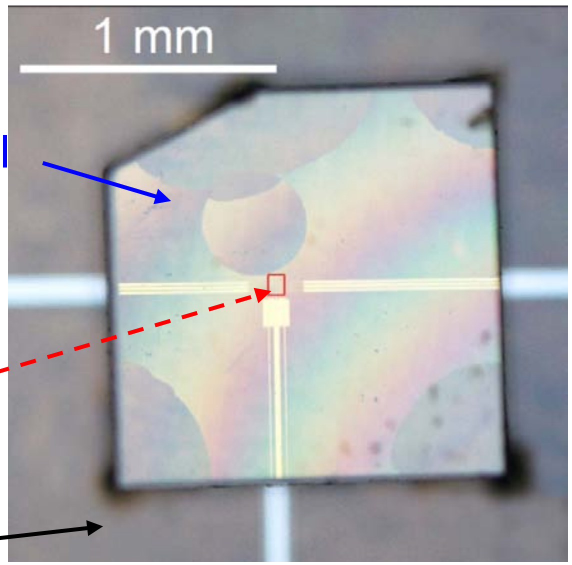
$$\overline{S}_+ = \frac{1}{\sqrt{2}}(|1\rangle + |-1\rangle)\langle 0|$$

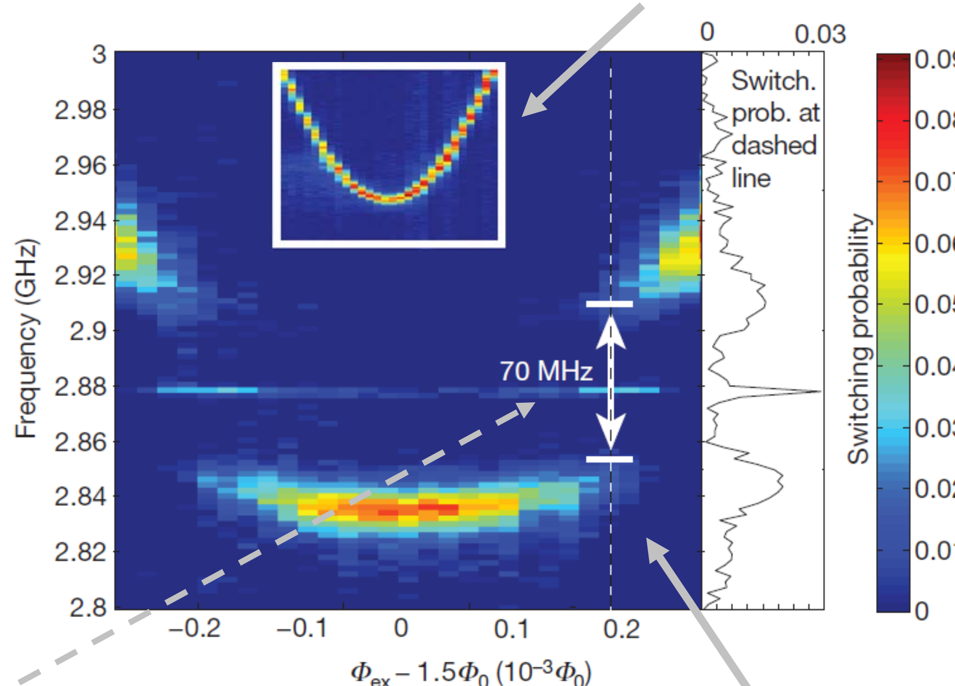
Marcos, D. *et al.* *Phys. Rev. Lett.* **105**, 210501 (2010)

HPHT Diamond (NV: 1.1 x $10^{18}cm^{-3}$)

NV center concentration: 1.1 x 10^{18} cm^{-3} , N2 concentration : 1–100 ppm

- Diamond mounted flux qubit





70 MHz splitting shows strong coupling between NV centers and a flux qubit

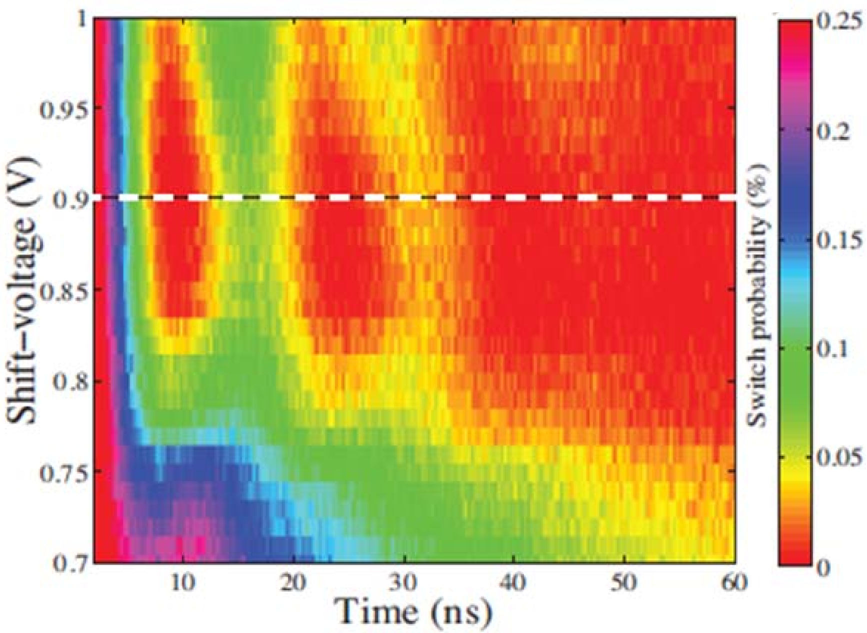
X. Zhu, SS, et al., Nature 478, 221 (2011)

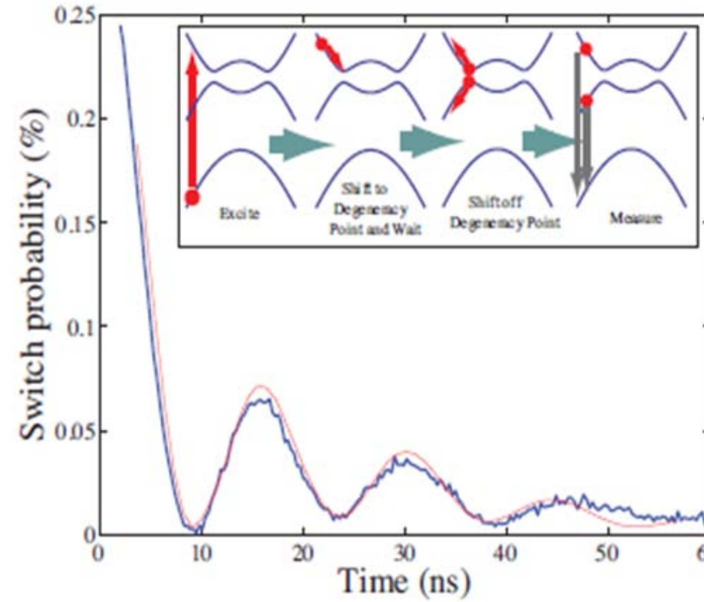
HPHT Diamond (NV: 1.1 x $10^{18}cm^{-3}$)

Coherent oscillations between qubit and NV spin ensemble

$$|1\rangle_{qb}|0\rangle_{ens} \rightleftharpoons |0\rangle_{qb}|1\rangle_{ens}$$

$$|0\rangle_{ens} = |00\cdots0\rangle$$
$$|1\rangle_{ens} = (1/\sqrt{N})\sum_i S_{+,i}|00\cdots0\rangle$$





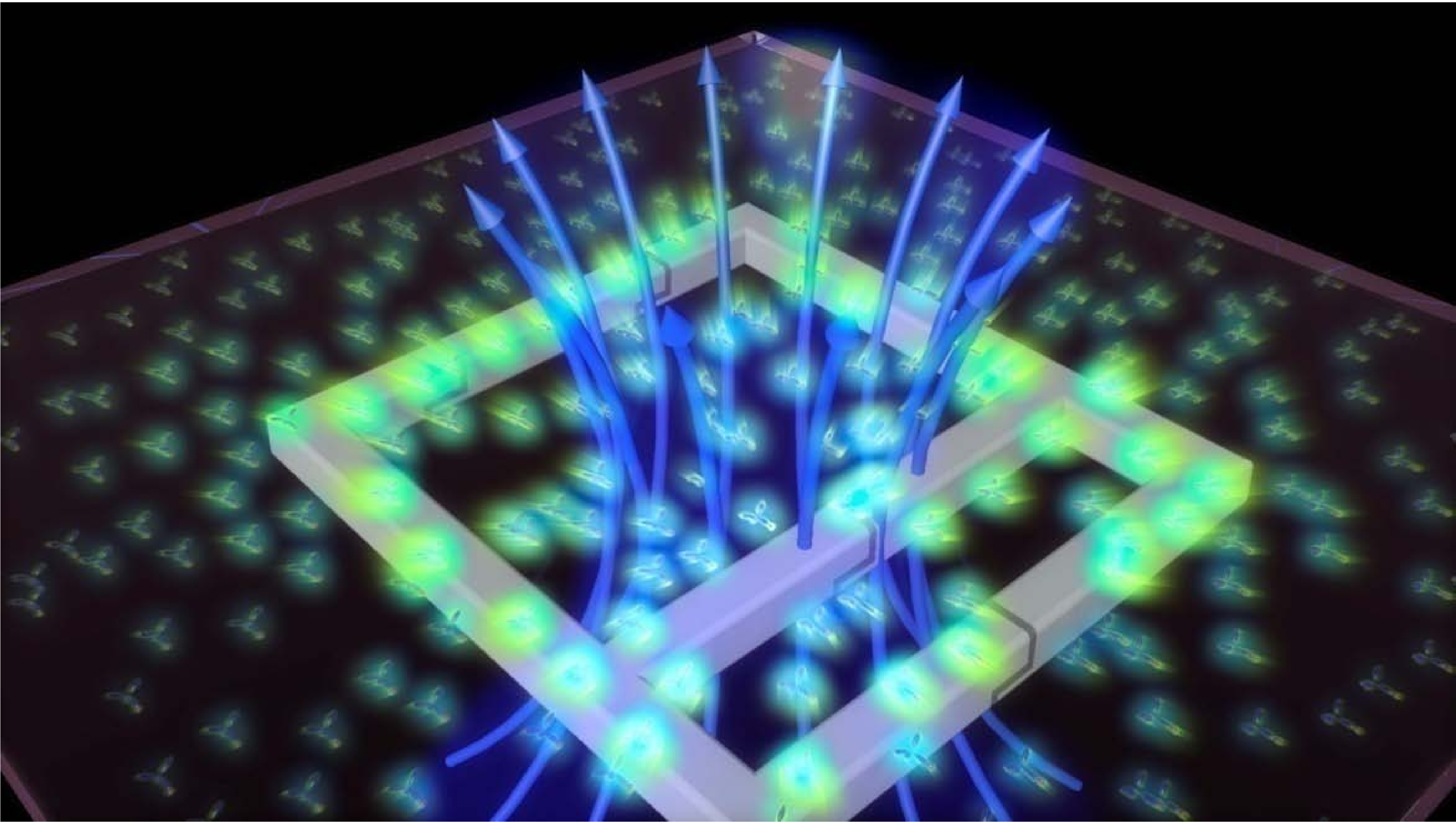
Single energy quantum is exchanged between a macroscopic superconducting flux qubit and macroscopic number of NV$^-$ spins

X. Zhu, SS, et al., Nature 478, 221 (2011)

Without a diamond chip
T1_qb = 300 ns @ 2.88GHz
T2* _qb= 280 ns

With a diamond chip
T1_qb = 150 ns @ 3.12 GHz
T2*_qb = 140 ns

T1_NV >> 10us
T2*_NV = ?

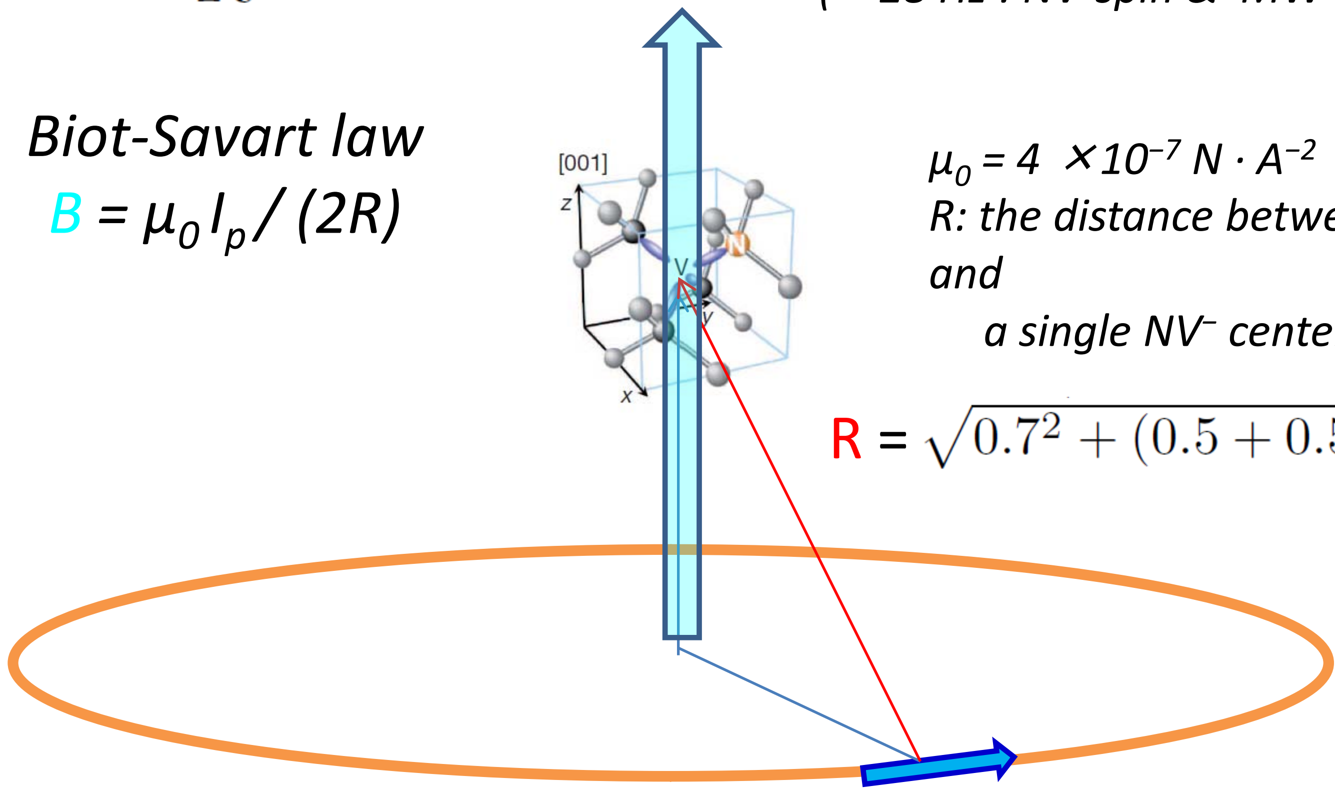


Coupling strength of a flux qubit to a single spin

$$g_i \sim \frac{g_e \mu_0 \mu_B I_p}{R} \sim 8.8\ \mathrm{kHz}$$

×300 larger than
(~28 Hz : NV-spin & MW-TL resonator)

Biot-Savart law
$B = \mu_0 I_p / (2R)$



$\mu_0 = 4\ \times 10^{-7}$ N · A^{-2}
R: the distance between a flux-qubit and
a single NV^- center.

R = $\sqrt{0.7^2 + (0.5+0.5)^2} \sim 1.2\ \mu\mathrm{m}$

I_p = 300 nA

$g_{ens} = 70$ MHz, $g_{ens} = g_{single}\sqrt{N}$ → $N = 6 \times 10^7$

Problems

The qubit coherence is good, $\Delta \sim 3$ GHz

$T_1 \sim 150$ ns

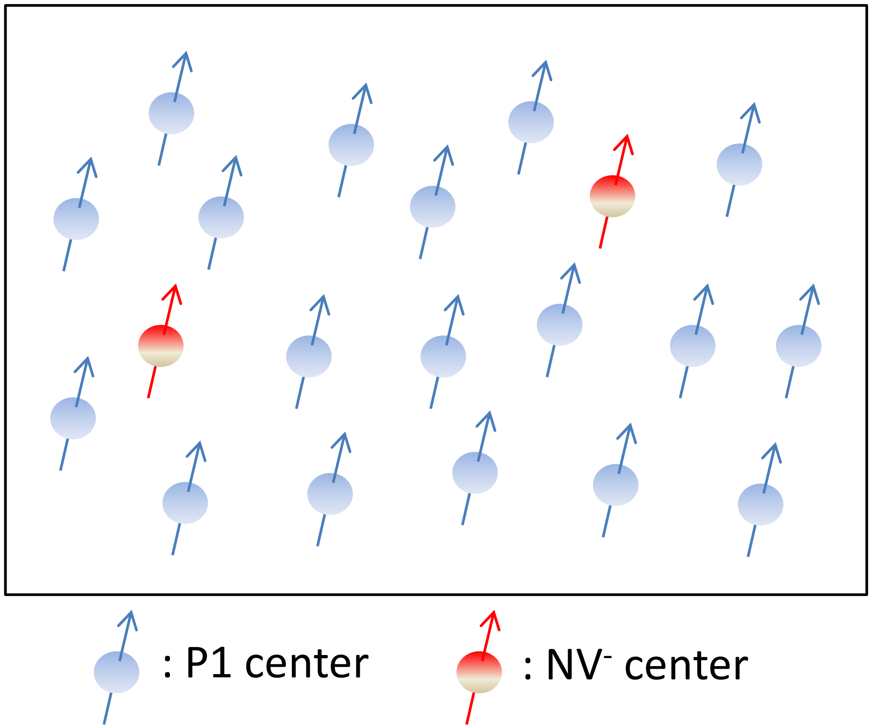
$T_2^* \sim 140$ ns

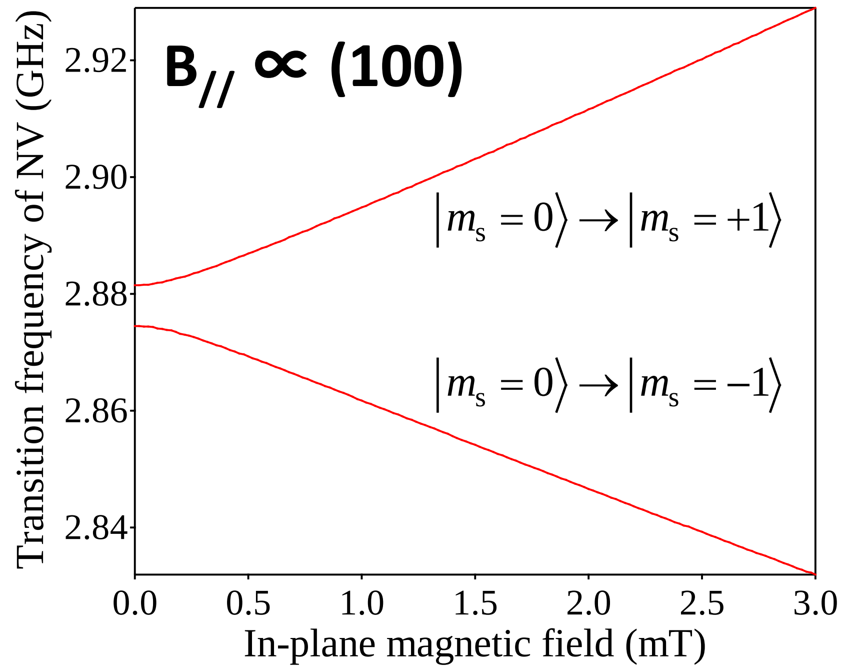
But the decay time of vacuum Rabi is short,

$T_{decay} \sim 20$ ns

T_2 of NV^- itself seems to be very short !

Possible reasons





Dense P1 center (spin ½)

$\lesssim$100 ppm

NV^- density is also high

~ 1.1 x 10^{18} cm^{-3}

➡ Reduce a spin density

Degeneracy of $|m_s = \pm 1>$

Splitting due to strain

⬇

Apply in-plane magnetic field

Diamond samples

Type	N conc. (ppm)	NV^- density (cm^{-3})
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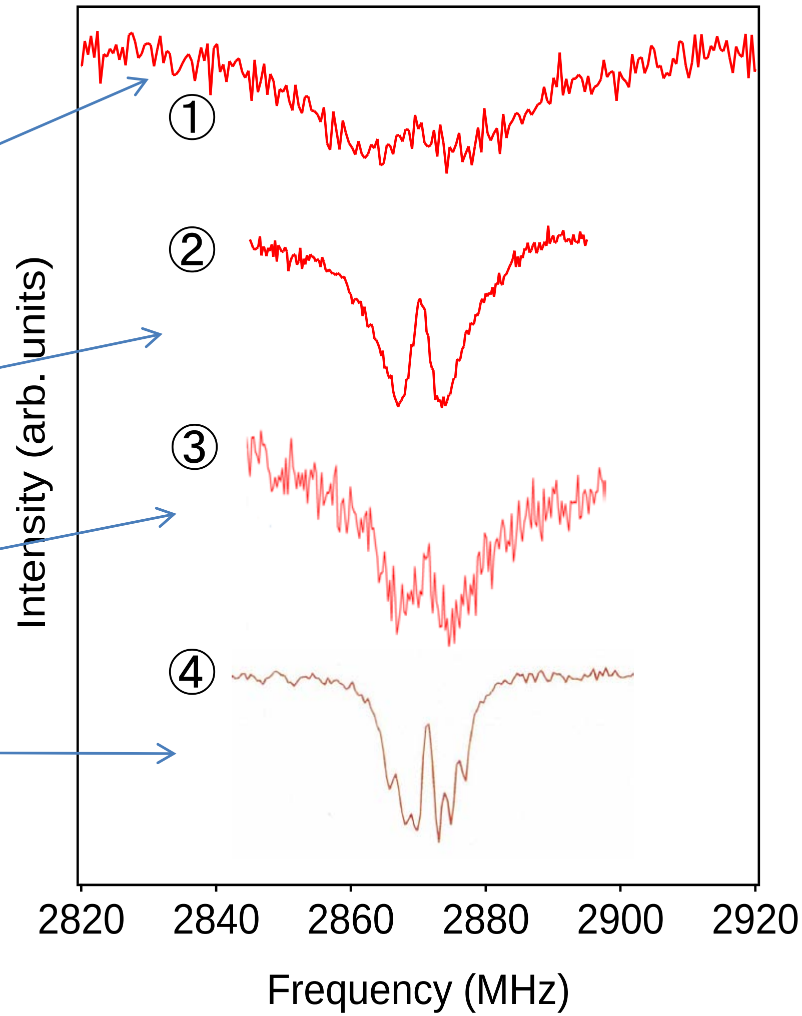
ODMR measurements

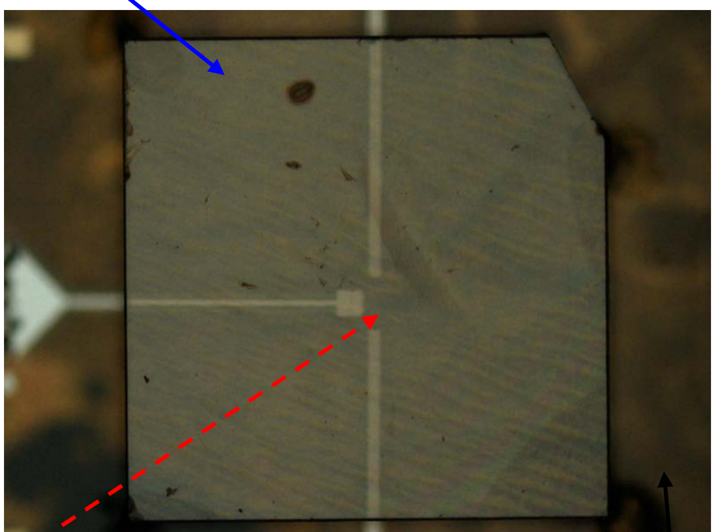


CVD Diamond (NV: $3 \times 10^{16} cm^{-3}$)

NV center concentration: 3×10^{16} cm^{-3} , N2 concentration : 1–10 ppm

- Diamond mounted flux qubit

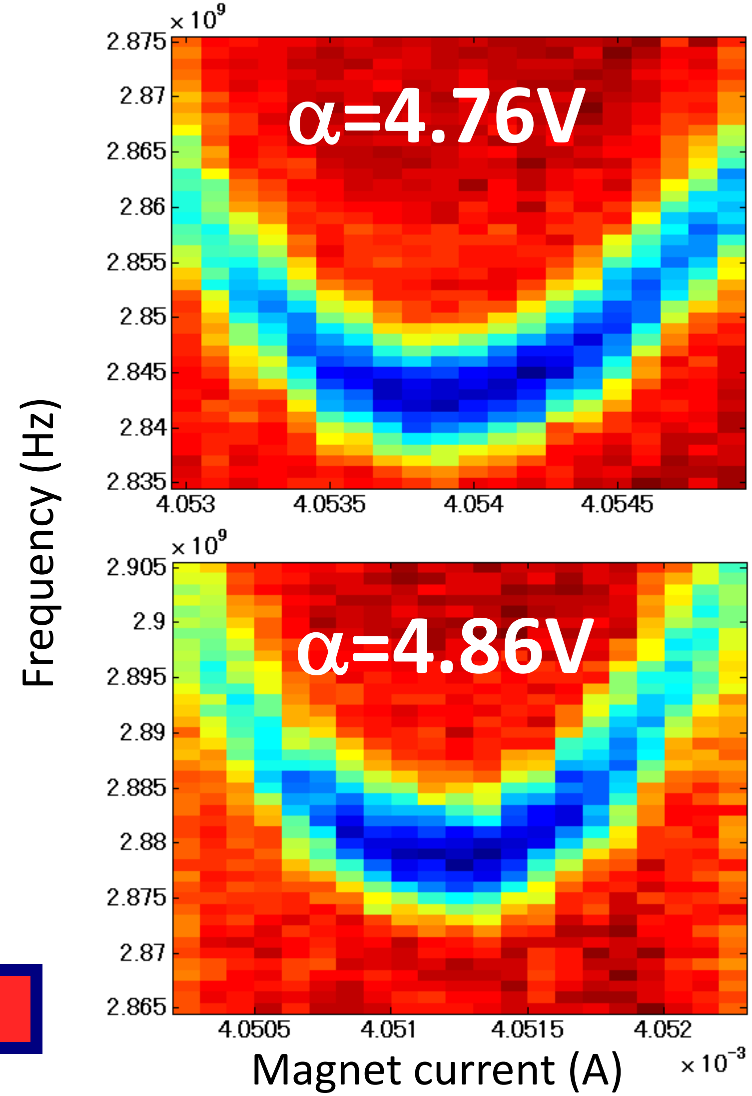
Diamond crystal



Gap tunable flux qubit (type I)

Sapphire substrate

No signal from NV centers



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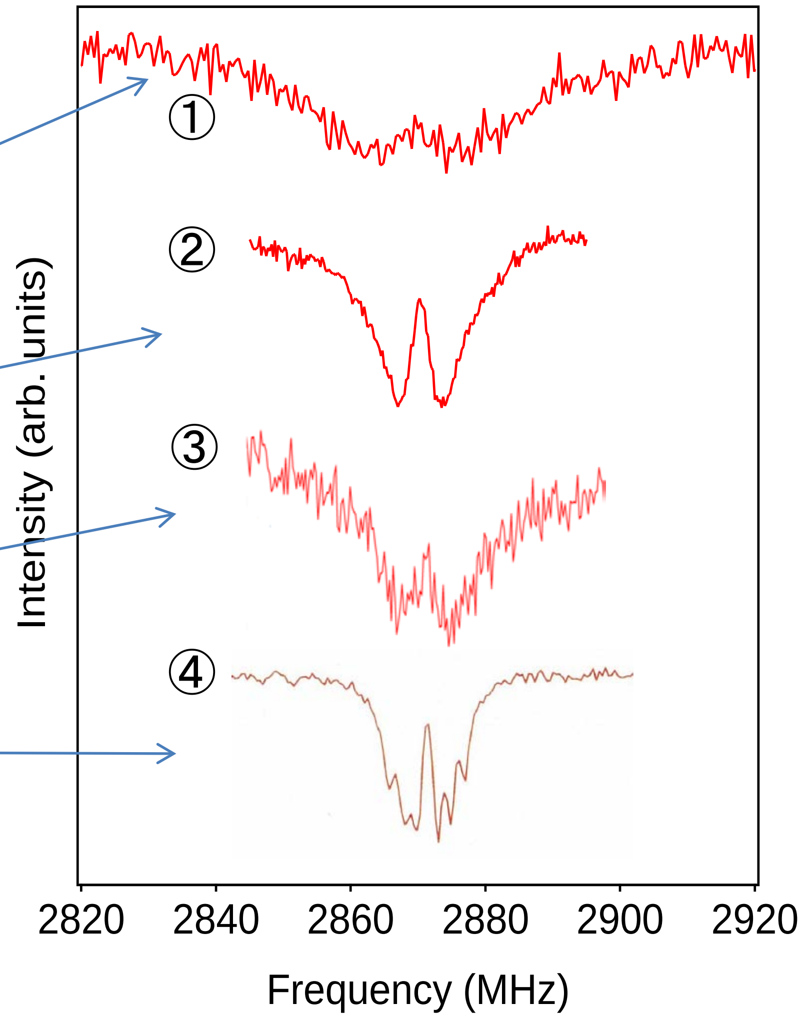
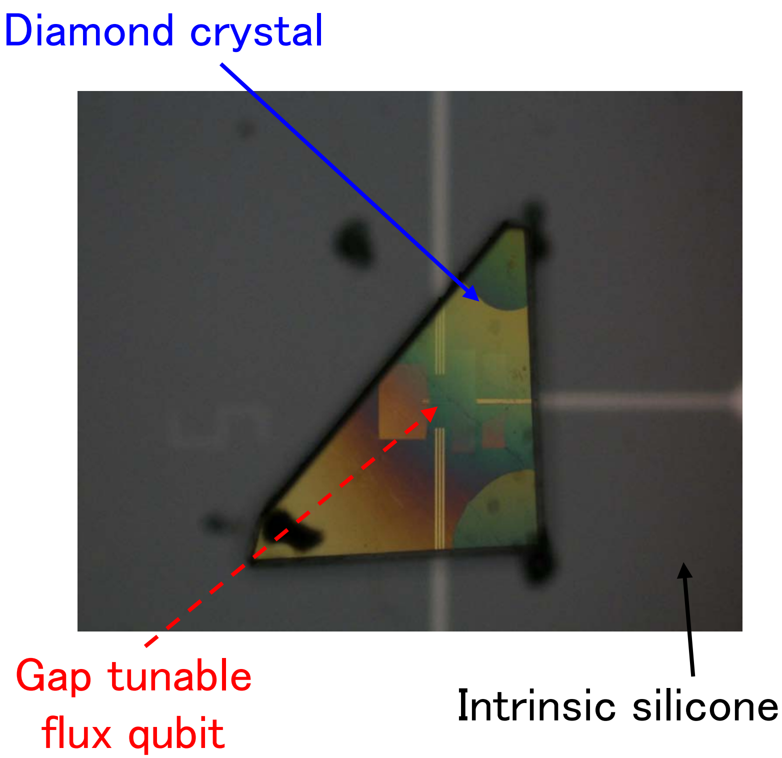
ODMR measurements

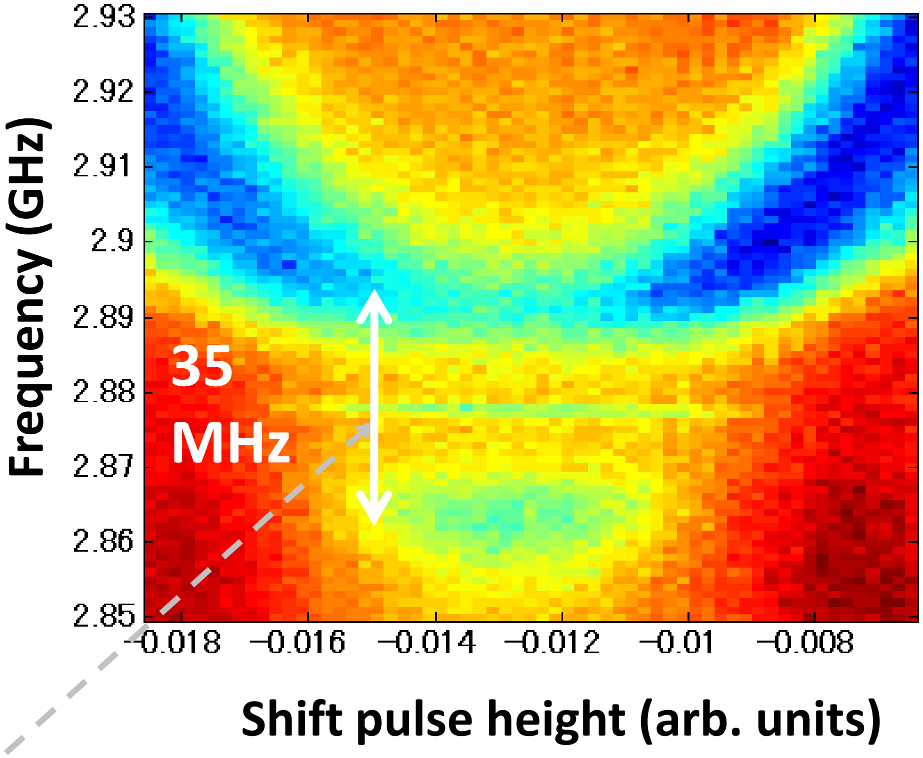


HPHT Diamond (NV: $4.7 \times 10^{17} cm^{-3}$)

NV center concentration: 4.7×10^{17} cm^{-3} , N2 concentration : 1–100 ppm

- Diamond mounted flux qubit





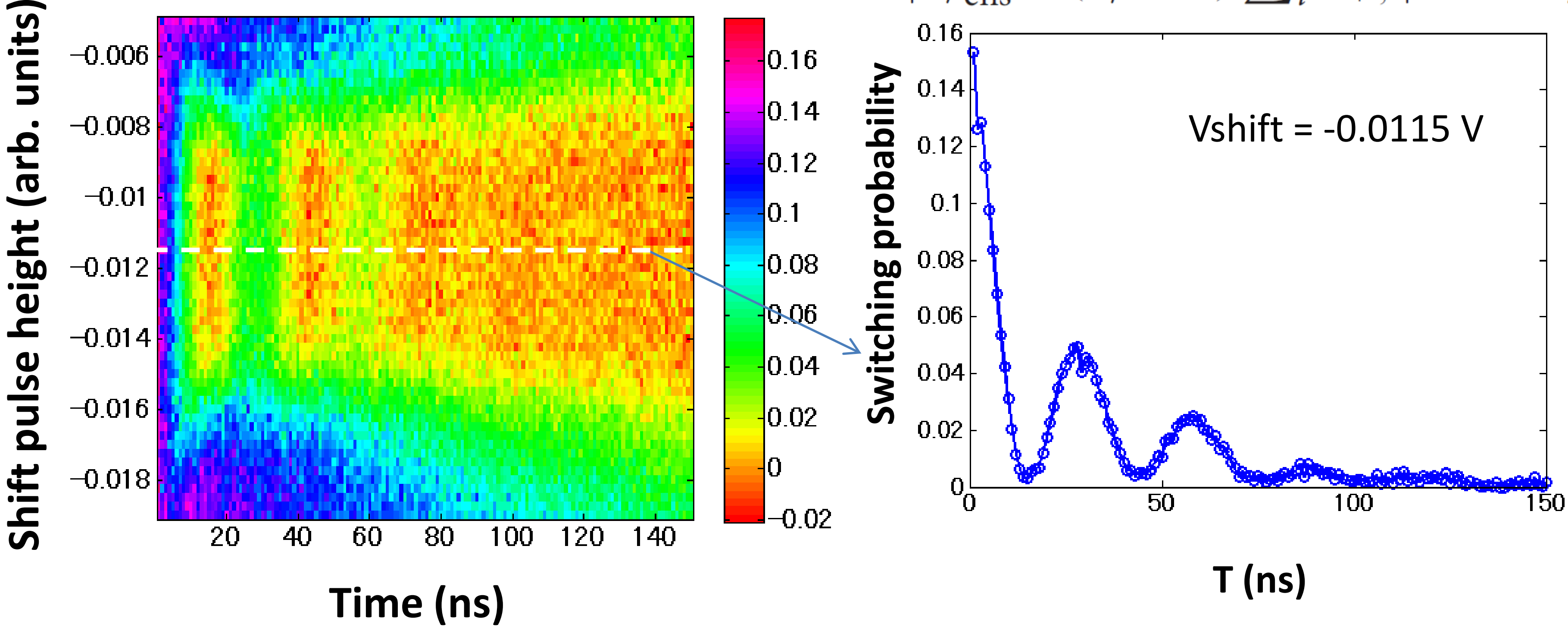
35 MHz splitting shows strong coupling between NV centers and a flux qubit

HPHT Diamond (NV: 4.7 x 10^{17}cm^{-3})

Coherent oscillations between qubit and NV spin ensemble

$$|1\rangle_{qb}|0\rangle_{ens} \rightleftharpoons |0\rangle_{qb}|1\rangle_{ens}$$

$$|0\rangle_{ens} \doteq |00\cdots0\rangle$$
$$|1\rangle_{ens} = (1/\sqrt{N})\sum_i S_{+,i}|00\cdots0\rangle$$



Without a diamond chip
T1_qb = 900 ns @ 2.88GHz
T2* _qb= 280 ns

With a diamond chip
T1_qb = 270 ns @ 2.78 GHz
T2*_qb = 100 ns

T1_NV >> 10us
T2*_NV = ?

HPHT Diamond (NV: $4.7 \times 10^{17} cm^{-3}$)

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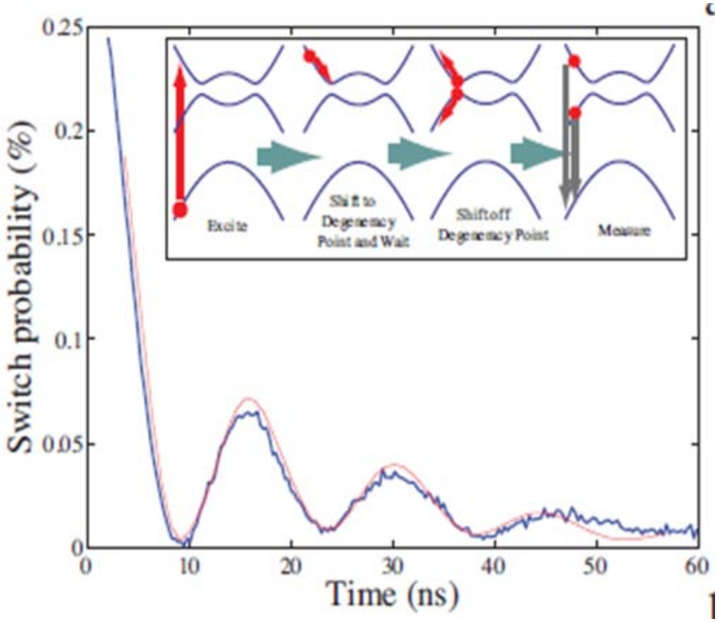

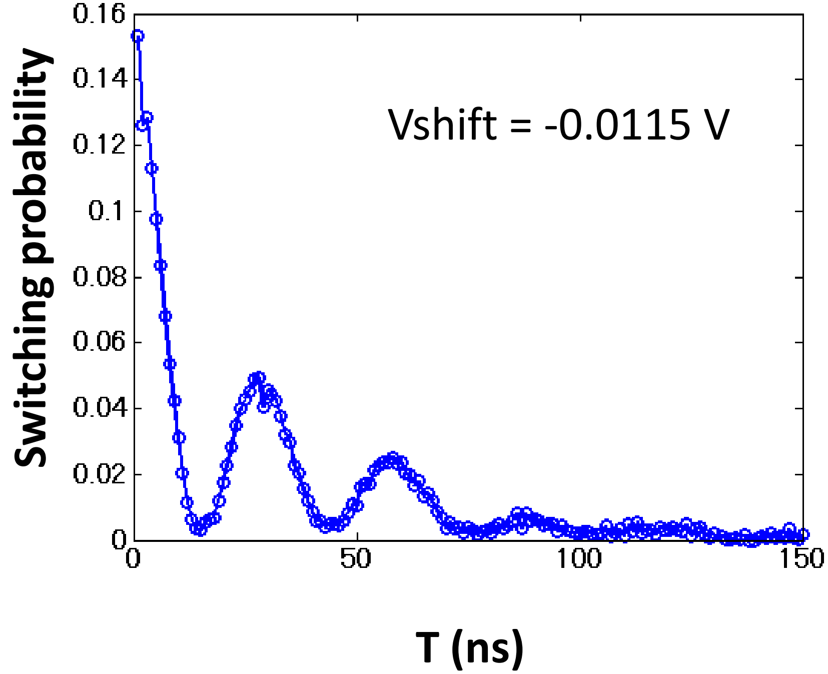

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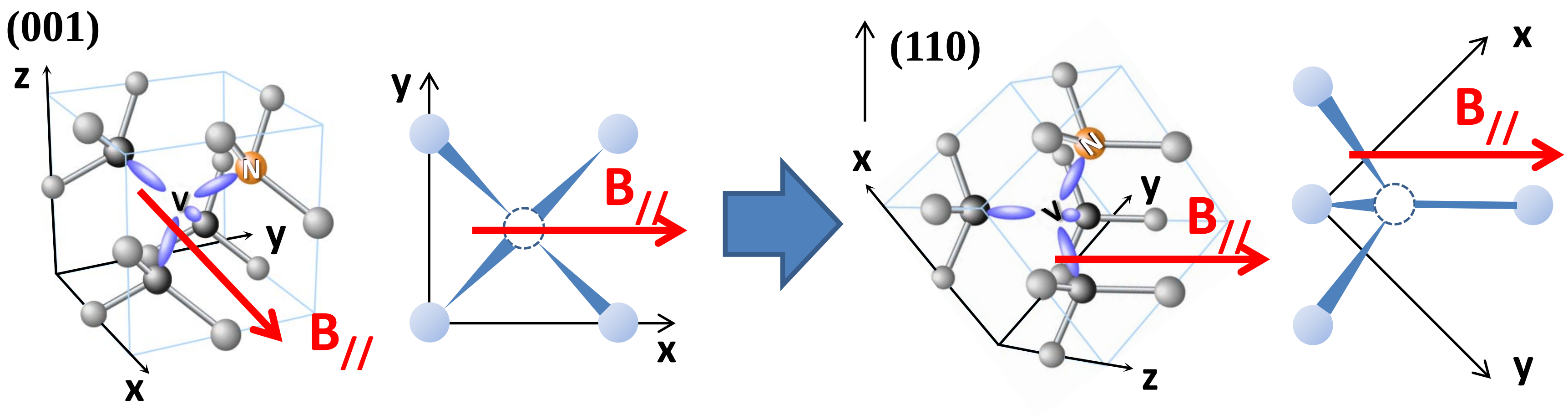
T1_NV >> 10us
T2*_NV = ?

To improve coherence time of the NV ensemble

Change the direction of the in-plane magnetic field

(001) substrate, $B_{//} \propto$ (100) (110) substrate, $B_{//} \propto$ (111)



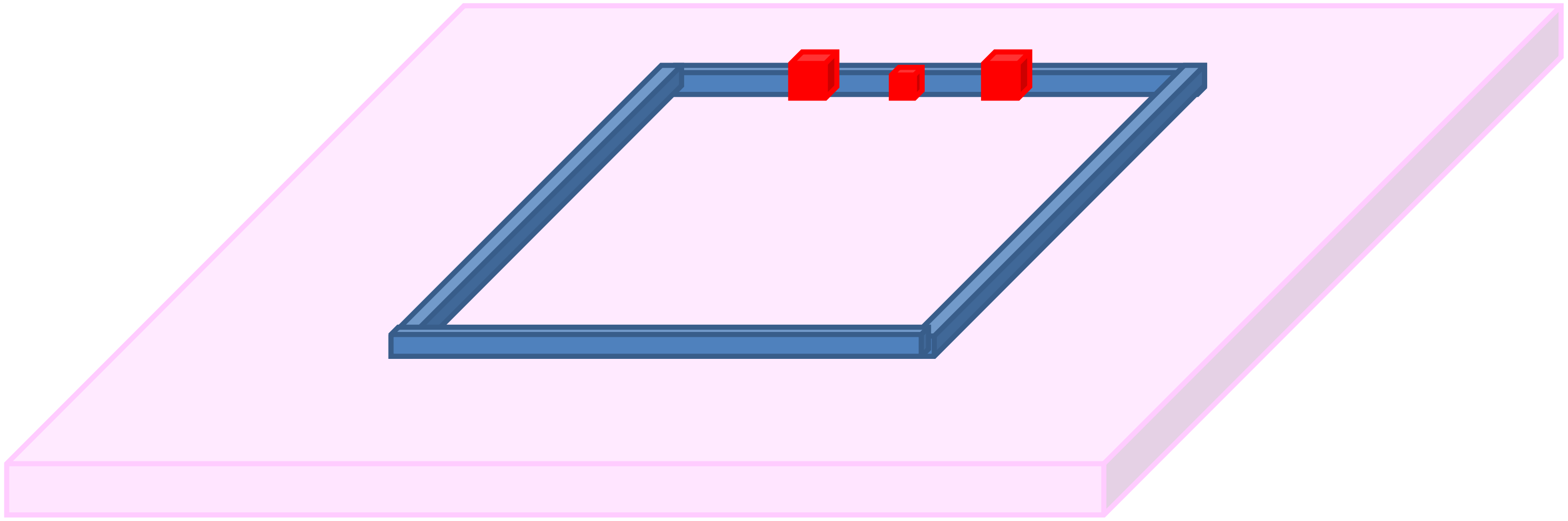
Improve the quality of diamond

Reduce P1 center (N impurity) from 100 ppm to 25 ppm
Increase the qubit persistent current from 300 nA to 600 nA

Same coupling strength of 30 MHz can be expected

To increase the coupling strength

Fabricate a flux qubit directly on a diamond substrate



A qubit persistent current x 10

The distance between the qubit and the NV ensemble x 1/10

⇩

We can reduce the number of NVs by 1/10000

$N=1x10^7$ -> $N=1x10^3$

Summary

- Flux qubit – spin ensemble hybrid system

- High NV density, zero in-plane magnetic field
  - Strong coupling and coherent oscillation
  - Decay time of the oscillation is about 20 ns

- Middle NV density, zero in-plane magnetic field
  - Strong coupling and coherent oscillation
  - Decay time of the oscillation is about 40 ns