

半導体スピン用いた量子情報処理

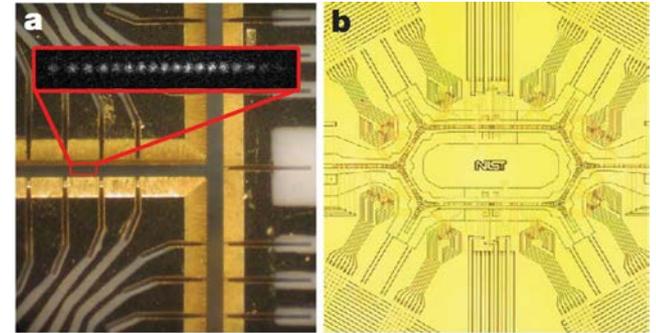
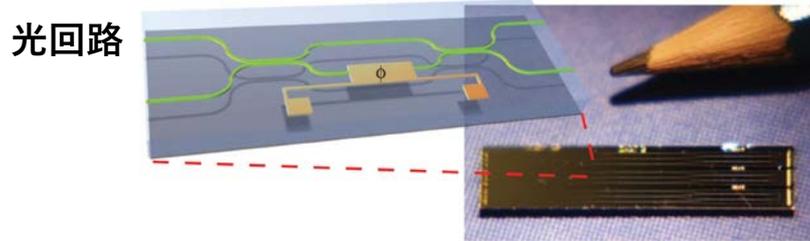
阿部 英介

慶應義塾大学スピントロニクス研究センター

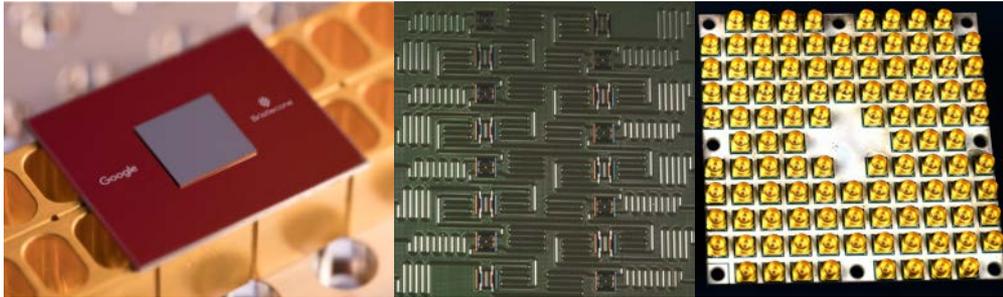
応用物理情報特別講義A

2018年度春学期後半 金曜4限@14-202

量子コンピュータ・ショーケース



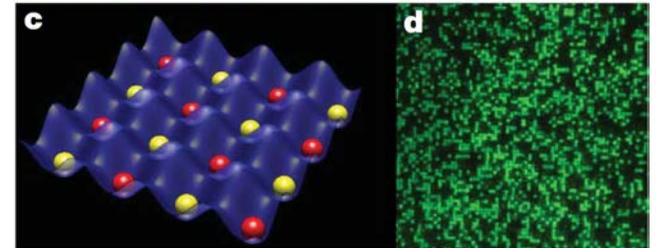
超伝導回路 (2018 ver.)



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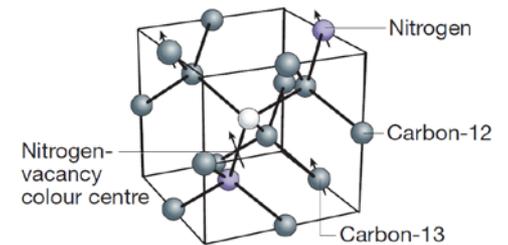
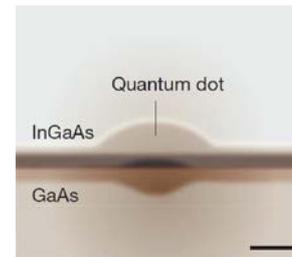
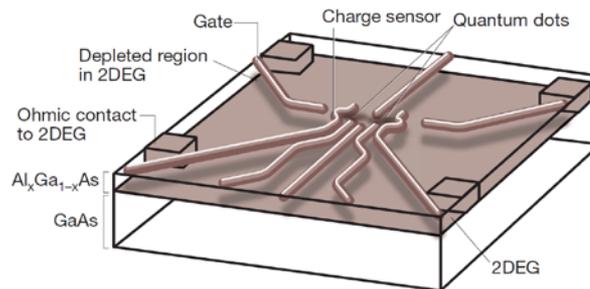
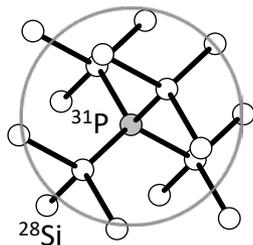
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捕捉イオン/冷却原子

半導体スピン

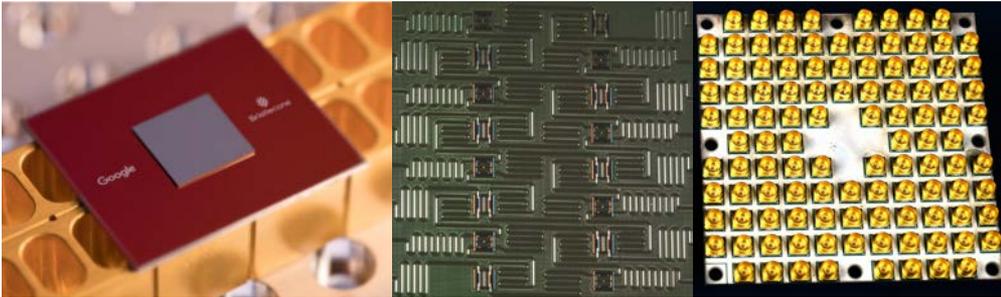


Nature **464**, 45 (2010) Ladd *et al.*

応用物理 **86 (6)**, 453 (2017) 阿部 & 伊藤

“固体量子情報デバイスの現状と将来展望 —万能デジタル量子コンピュータの実現に向けて”

超伝導回路 (2018 ver.)

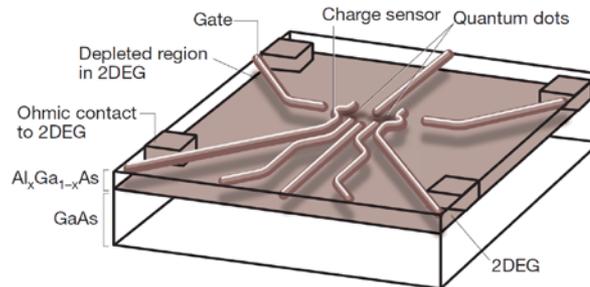
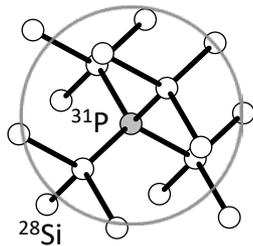


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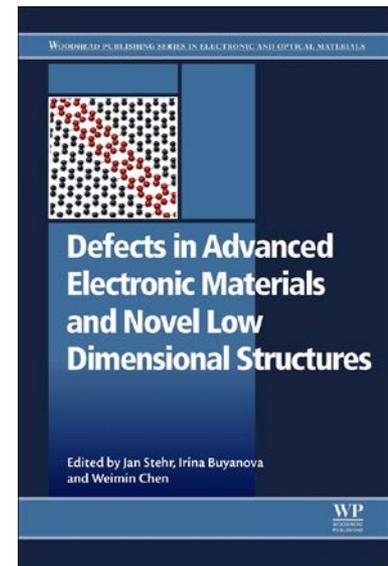
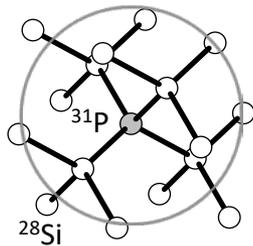
半導体スピン



Defects in Advanced Electronic Materials and Novel Low Dimensional Structures, P.241–263, Abe & Itoh

“Defects for quantum information processing in silicon”

半導体スピン



(June, 2018)

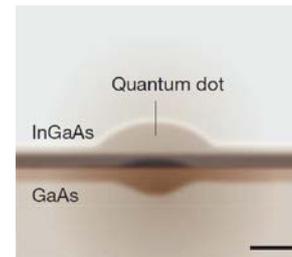
固体物理 **48 (11)**, 541 (2013) 山本 & 阿部

“光制御量子ドットスピンを用いた量子情報システムの
の現状と将来展望”

光技術コンタクト **51 (5)**, 10 (2013) 阿部

“量子中継と量子ドットスピン-光子間量子もつれ”

半導体スピン



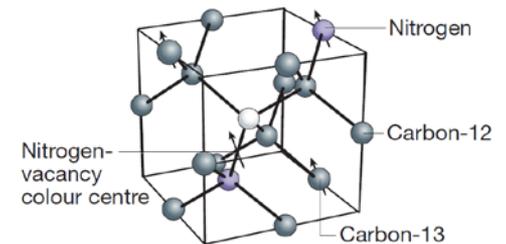
NEW DIAMOND **33 (2)**, 3 (2017) 阿部 & 伊藤

“スピントロニクス研究の原点からダイヤモンド
でのトレンド, 今後の展開まで”

J. Appl. Phys. **123**, 161191 (2018) Abe & Sasaki

“Tutorial: Magnetic resonance with nitrogen-vacancy centers in diamond
—microwave engineering, materials science, and magnetometry”

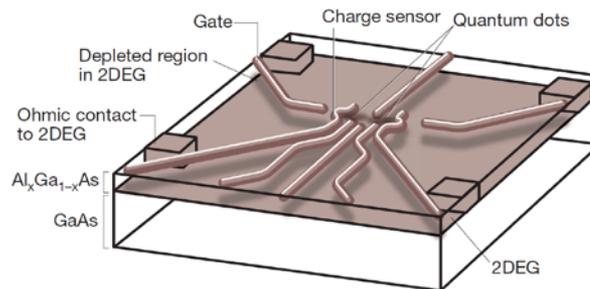
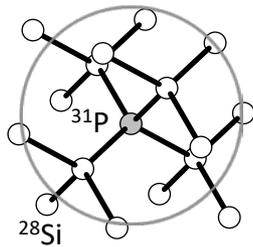
半導体スピン



本日カバーする範囲

(材料はシリコンに限定)

半導体スピン



講義内容

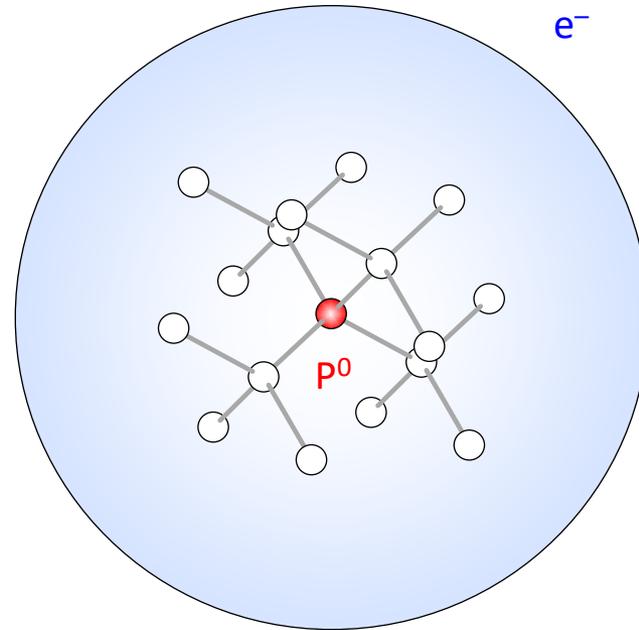
- **磁気共鳴と量子コヒーレンス**
 - アンサンブルリンドナー
- **シリコンスピン量子コンピュータ**
 - 単一リンドナー
 - MOS量子ドット
 - Si/SiGe量子ドット

講義内容

- **磁気共鳴と量子コヒーレンス**
 - アンサンブルリンドナー
- シリコンスピン量子コンピュータ
 - 単一リンドナー
 - MOS量子ドット
 - Si/SiGe量子ドット

シリコン中のリンドナー

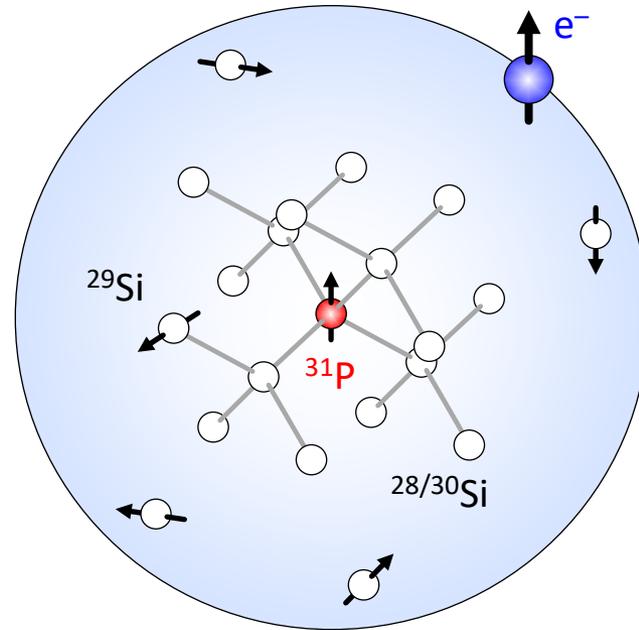
III (13)	IV (14)	V (15)
B	C	N
Al	Si	P
Ga	Ge	As



低温下(< 10 K): 電子はリンに束縛される
(水素原子様浅い不純物)

シリコン中のリンドナー

III (13)	IV (14)	V (15)
B	C	N
Al	Si	P
Ga	Ge	As



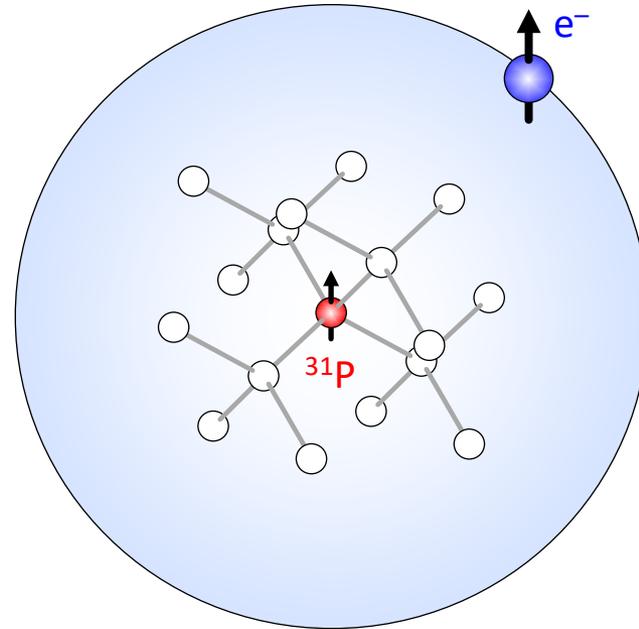
磁気環境

$^{28}\text{Si} : ^{29}\text{Si} (I = \frac{1}{2}) : ^{30}\text{Si} = 92.2\% : 4.7\% : 3.1\%$

$^{31}\text{P} (I = \frac{1}{2}) = 100\%$

シリコン中のリンドナー

III (13)	IV (14)	V (15)
B	C	N
Al	Si	P
Ga	Ge	As



磁気環境

同位体制御 $^{28}\text{Si} \rightarrow 99.995\%$

$^{31}\text{P} (I = 1/2) = 100\%$

シリコン中のリンドナー

スピンハミルトニアン

$$H_0 = \gamma_e B_0 S_z - \gamma_P B_0 I_z + a_0 S_z I_z$$

$$B_0 \sim 350 \text{ mT (X-band)}$$

$$\gamma_e = 27.97 \text{ GHz/T}$$

$$\gamma_P = 17.23 \text{ MHz/T}$$

$$a_0 = 117.53 \text{ MHz}$$

$$\gamma_e = g\mu_B$$

$$\hbar = 1$$

$$S_z = \frac{\sigma_z}{2} = \frac{1}{2} \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

$$I_z = \frac{\sigma_z}{2} = \frac{1}{2} \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

シリコン中のリンドナー

スピンハミルトニアン

$$H_0 = \gamma_e B_0 S_z - \gamma_P B_0 I_z + a_0 S_z I_z$$

$$= \frac{\gamma_e B_0}{2} (\sigma_z \otimes I) - \frac{\gamma_P B_0}{2} (I \otimes \sigma_z) + \frac{a_0}{4} (\sigma_z \otimes \sigma_z)$$

$$= \frac{\gamma_e B_0}{2} \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \otimes \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} - \frac{\gamma_P B_0}{2} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \otimes \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} + \frac{a_0}{4} \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \otimes \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

$$= \begin{pmatrix} \frac{\gamma_e B_0}{2} - \frac{\gamma_P B_0}{2} + \frac{a_0}{4} & 0 & 0 & 0 \\ 0 & \frac{\gamma_e B_0}{2} + \frac{\gamma_P B_0}{2} - \frac{a_0}{4} & 0 & 0 \\ 0 & 0 & -\frac{\gamma_e B_0}{2} - \frac{\gamma_P B_0}{2} - \frac{a_0}{4} & 0 \\ 0 & 0 & 0 & -\frac{\gamma_e B_0}{2} + \frac{\gamma_P B_0}{2} + \frac{a_0}{4} \end{pmatrix}$$

$|\uparrow\uparrow\rangle$ $|\uparrow\downarrow\rangle$ $|\downarrow\uparrow\rangle$ $|\downarrow\downarrow\rangle$

シリコン中のリンドナー

スピンハミルトニアン

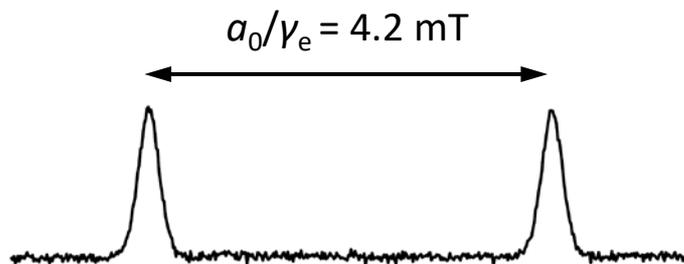
$$H_0 = \gamma_e B_0 S_z - \gamma_P B_0 I_z + a_0 S_z I_z$$

$$B_0 \sim 350 \text{ mT (X-band)}$$

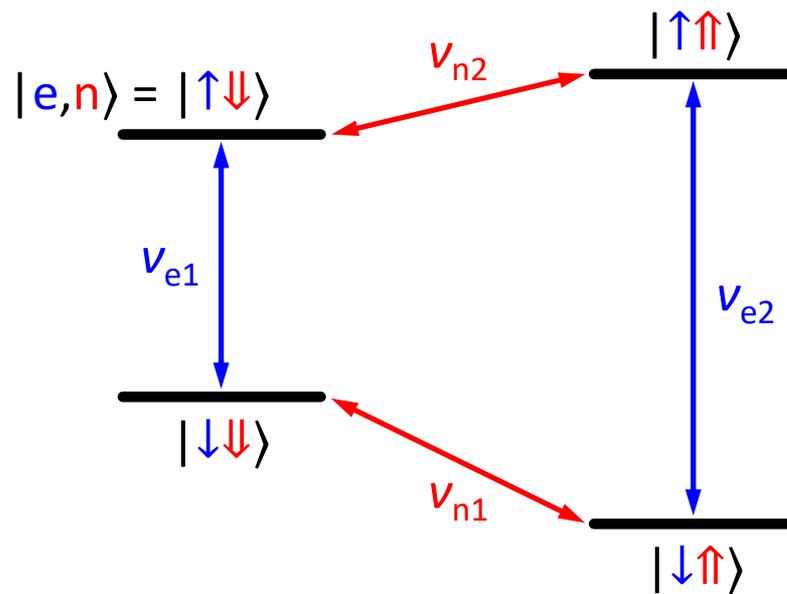
$$\gamma_e = 27.97 \text{ GHz/T}$$

$$\gamma_P = 17.23 \text{ MHz/T}$$

$$a_0 = 117.53 \text{ MHz}$$



アンサンブル電子スピン共鳴(磁場掃引)



$$\nu_{e1} = \gamma_e B_0 - a_0/2$$

$$\nu_{e2} = \gamma_e B_0 + a_0/2$$

$$\nu_{n1} = a_0/2 + \gamma_P B_0$$

$$\nu_{n2} = a_0/2 - \gamma_P B_0$$

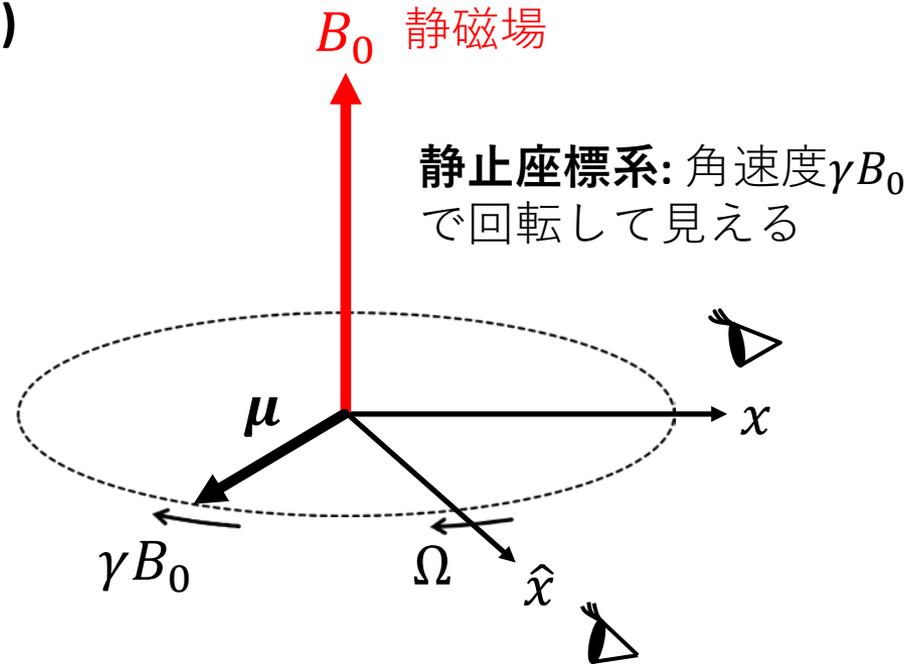
磁気共鳴

トルク方程式(ラーモア歳差運動)

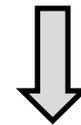
$$\frac{d\boldsymbol{\mu}}{dt} = \boldsymbol{\mu} \times \gamma \mathbf{B}_0$$

↑
磁気モーメント: $\boldsymbol{\mu} = \gamma \mathbf{J}$

↙
磁気回転比

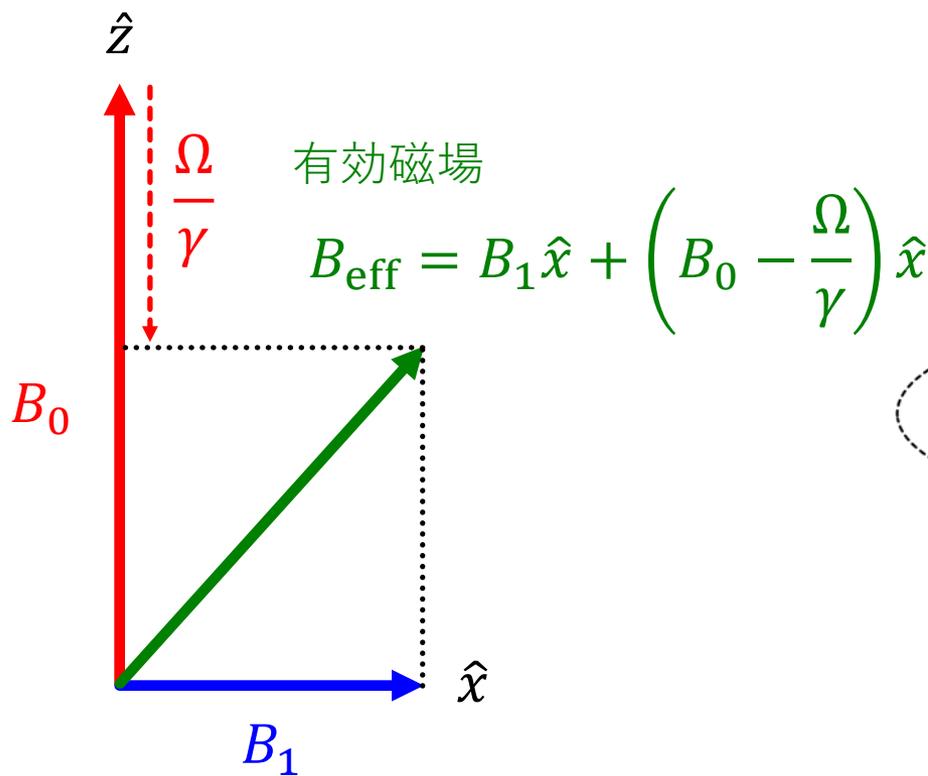


角速度 Ω で回転する座標系:
遅くなって見える. なぜ??

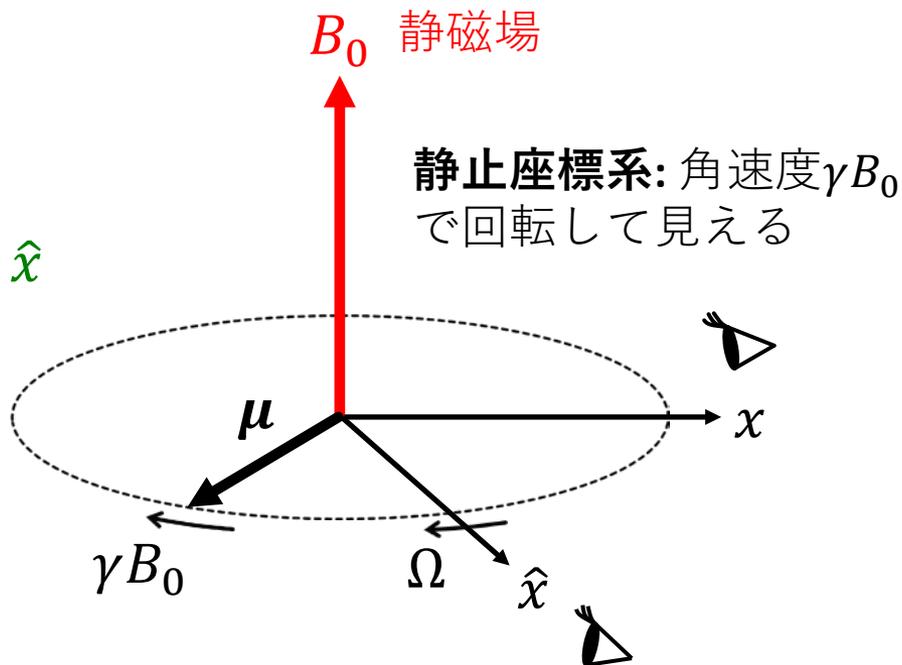


z 方向の磁場が弱くなったから

磁気共鳴



xy 平面を角速度 Ω で回転する交流磁場



角速度 Ω で回転する座標系:
遅くなって見える. なぜ??

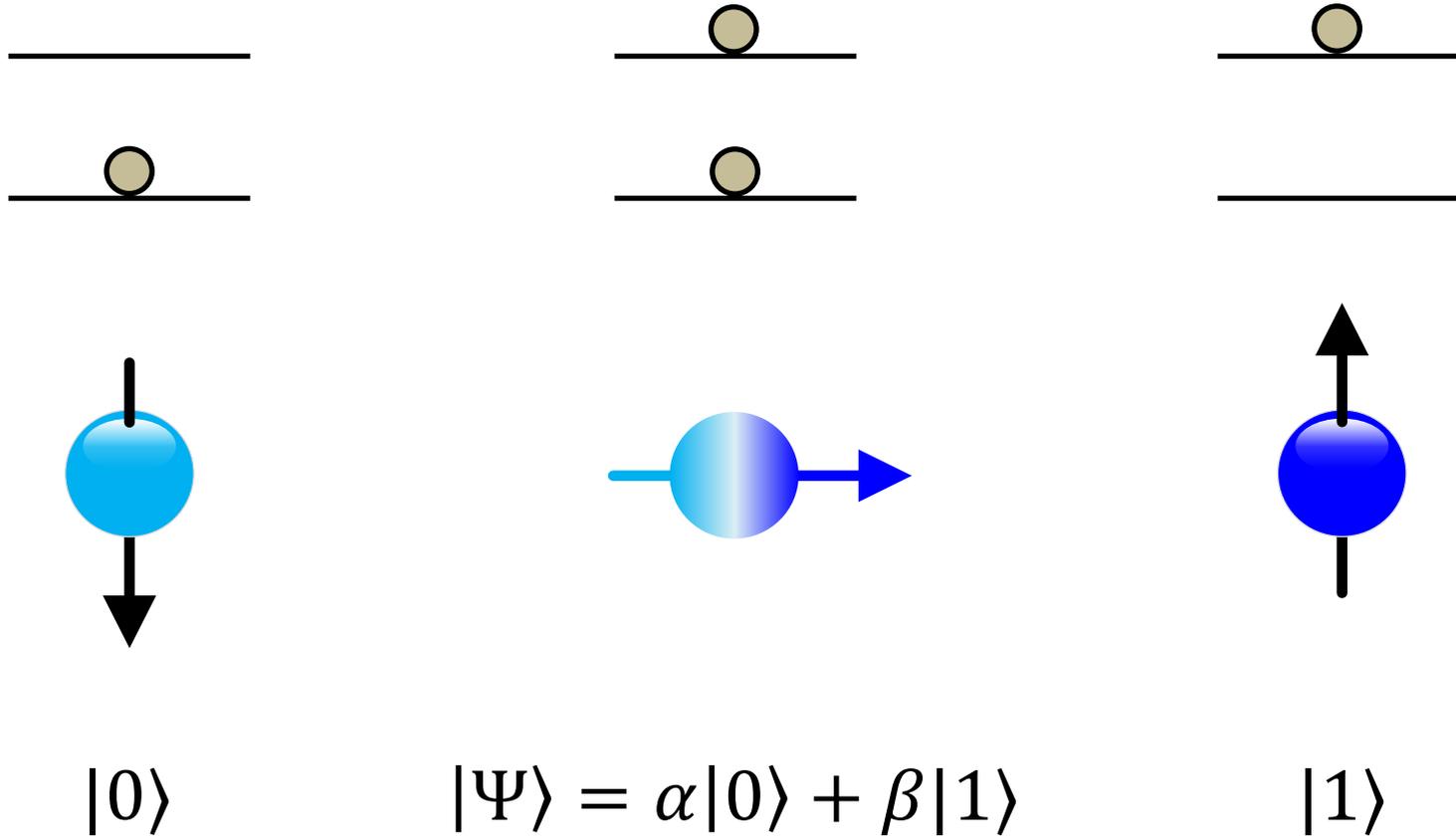


z 方向の磁場が弱くなったから

量子コンピューティングの難しさ

- 量子情報を**位相**に書き込み, **量子干渉**により解の状態を抜き出す
→ 計算中に**位相コヒーレンス**を保つことが必要
- 量子状態は**複製できない**(任意の状態 $|\phi\rangle$ に対して $U|\phi\rangle|0\rangle = |\phi\rangle|\phi\rangle$ となるユニタリ演算子 U は存在しない)
→ **量子誤り訂正符号 & 誤り耐性量子計算**
(フォールトトレラント, fault tolerant)

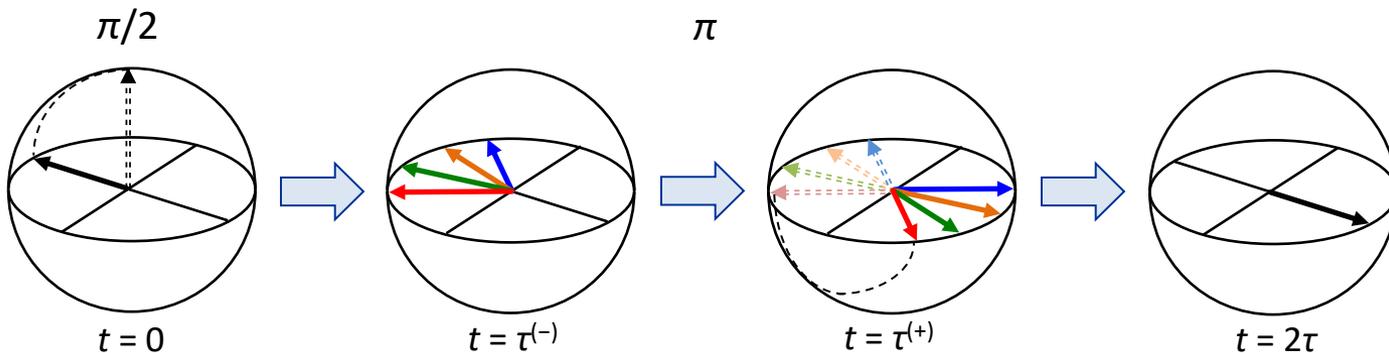
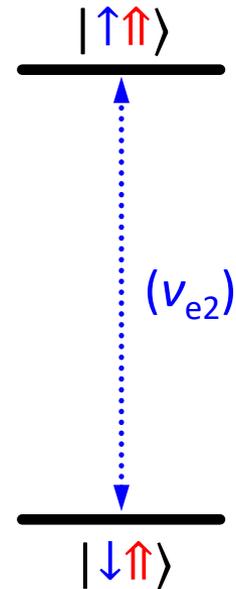
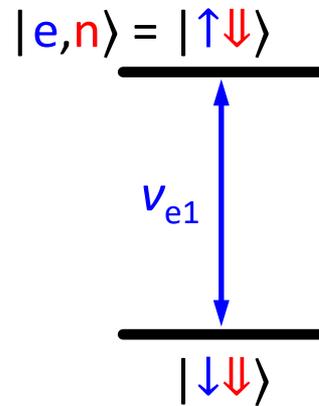
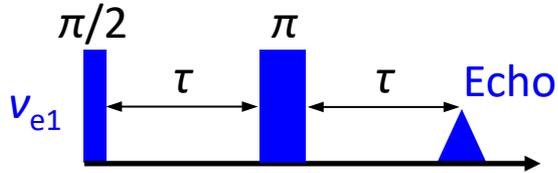
量子コヒーレンス



τ_2 : 重ね合わせ状態の持続時間

電子スピンのコヒーレンス: T_{2e}

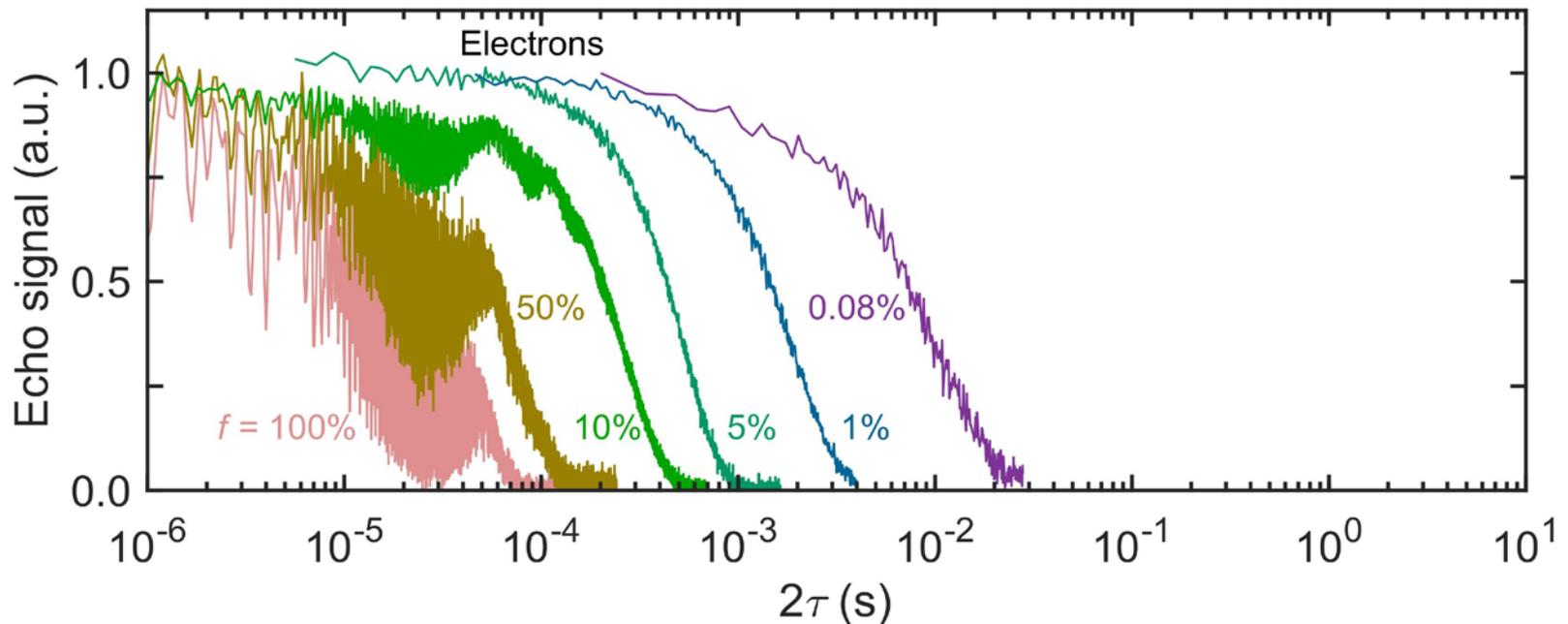
スピンエコー



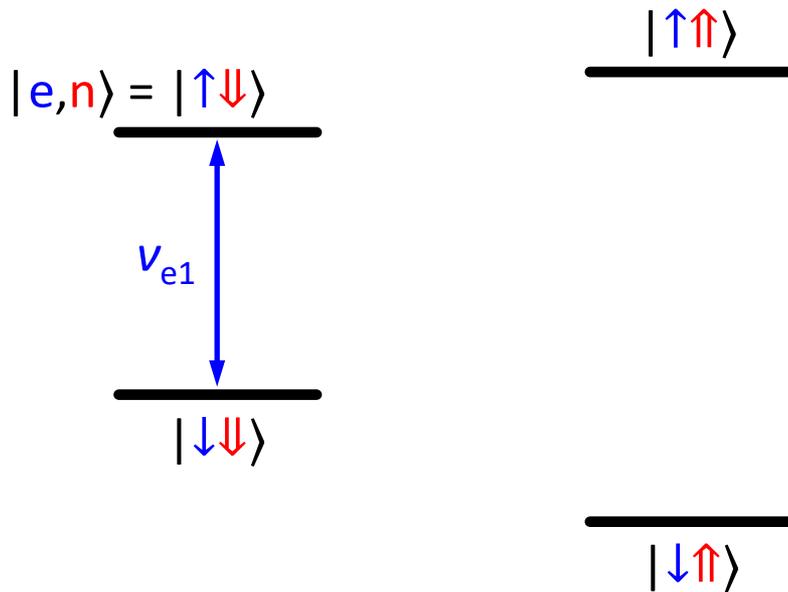
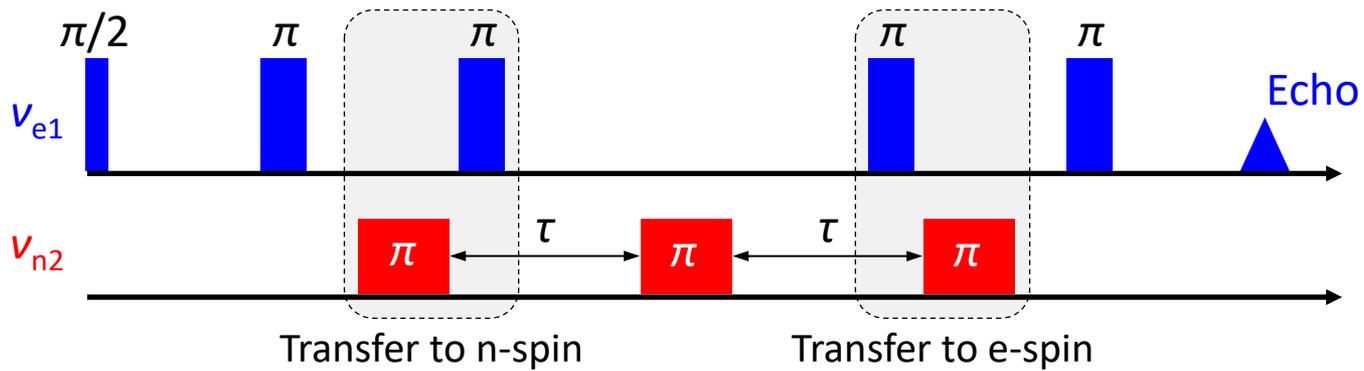
電子スピンコヒーレンス: T_{2e}

Electron spin coherence of phosphorus donors in silicon: Effect of environmental nuclei

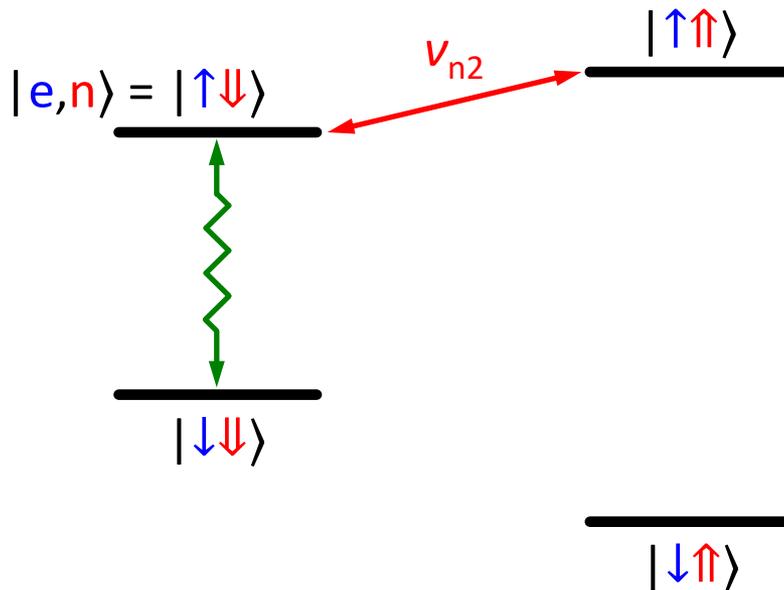
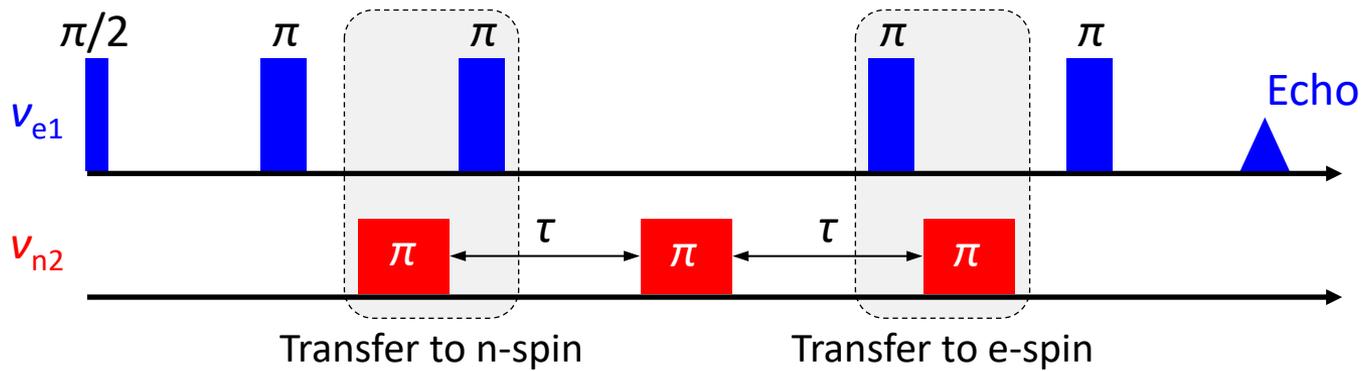
Eisuke Abe,^{1,2,*} Alexei M. Tyryshkin,³ Shinichi Tojo,² John J. L. Morton,^{1,4} Wayne M. Witzel,⁵ Akira Fujimoto,² Joel W. Ager,⁶ Eugene E. Haller,^{6,7} Junichi Isoya,⁸ Stephen A. Lyon,³ Mike L. W. Thewalt,⁹ and Kohei M. Itoh²



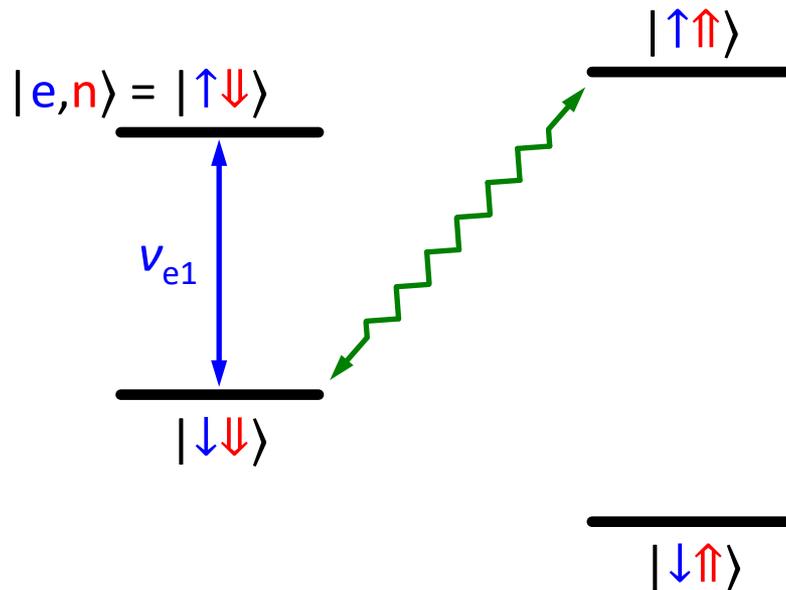
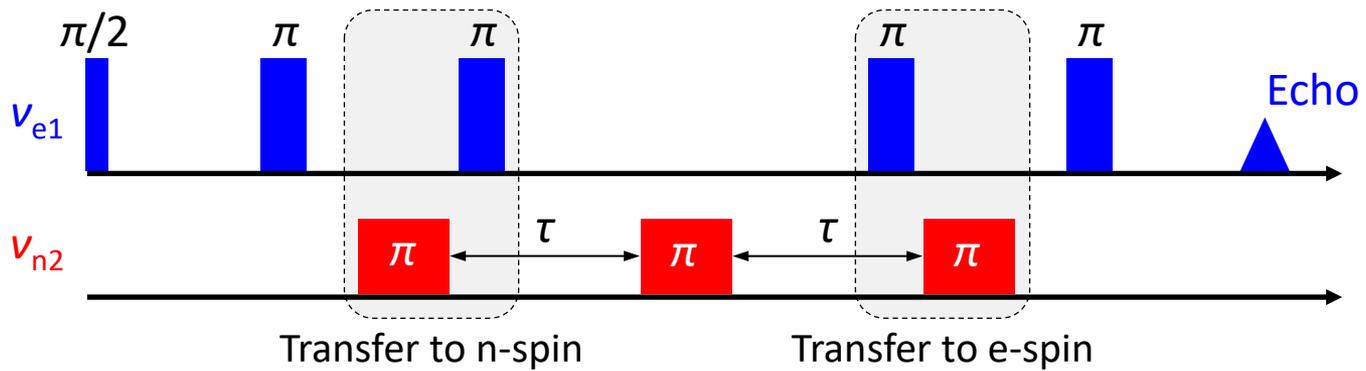
核スピンコヒーレンス: T_{2n0}



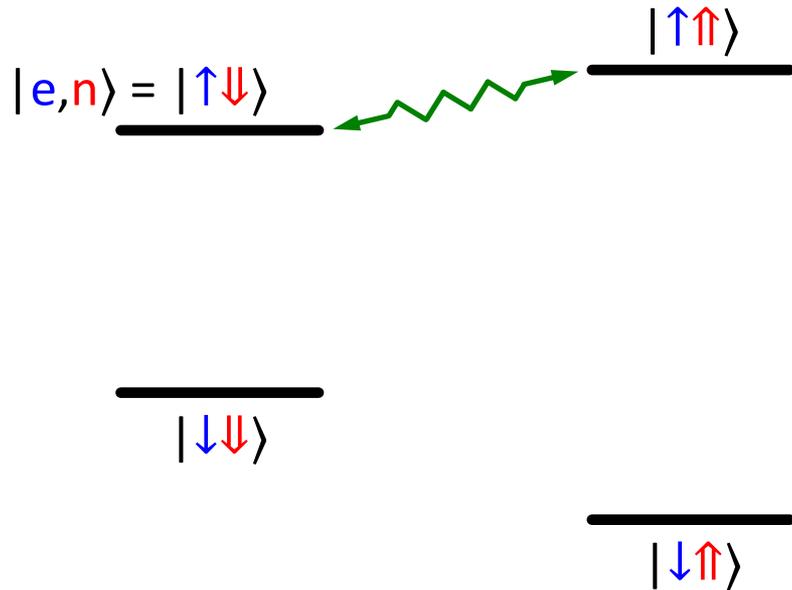
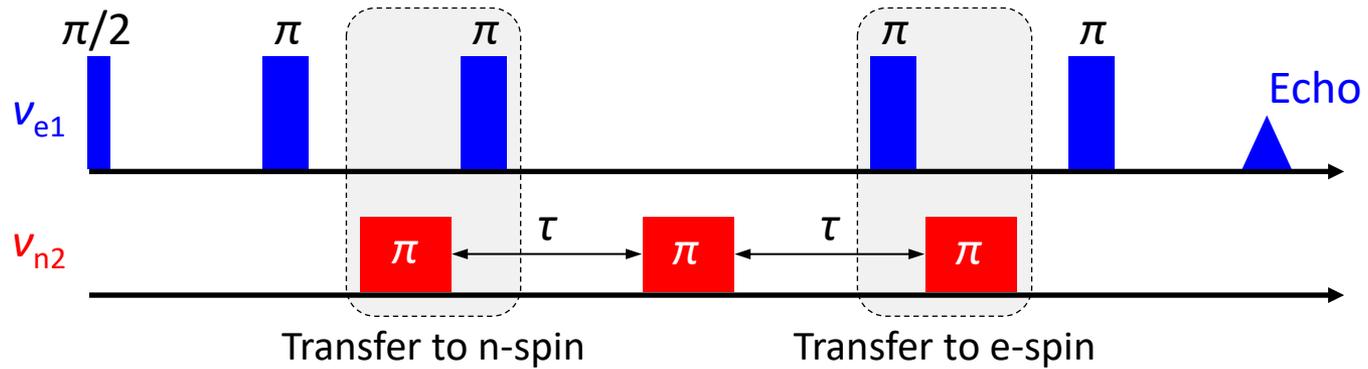
核スピンコヒーレンス: T_{2n0}



核スピンコヒーレンス: T_{2n0}



核スピンコヒーレンス: T_{2n0}



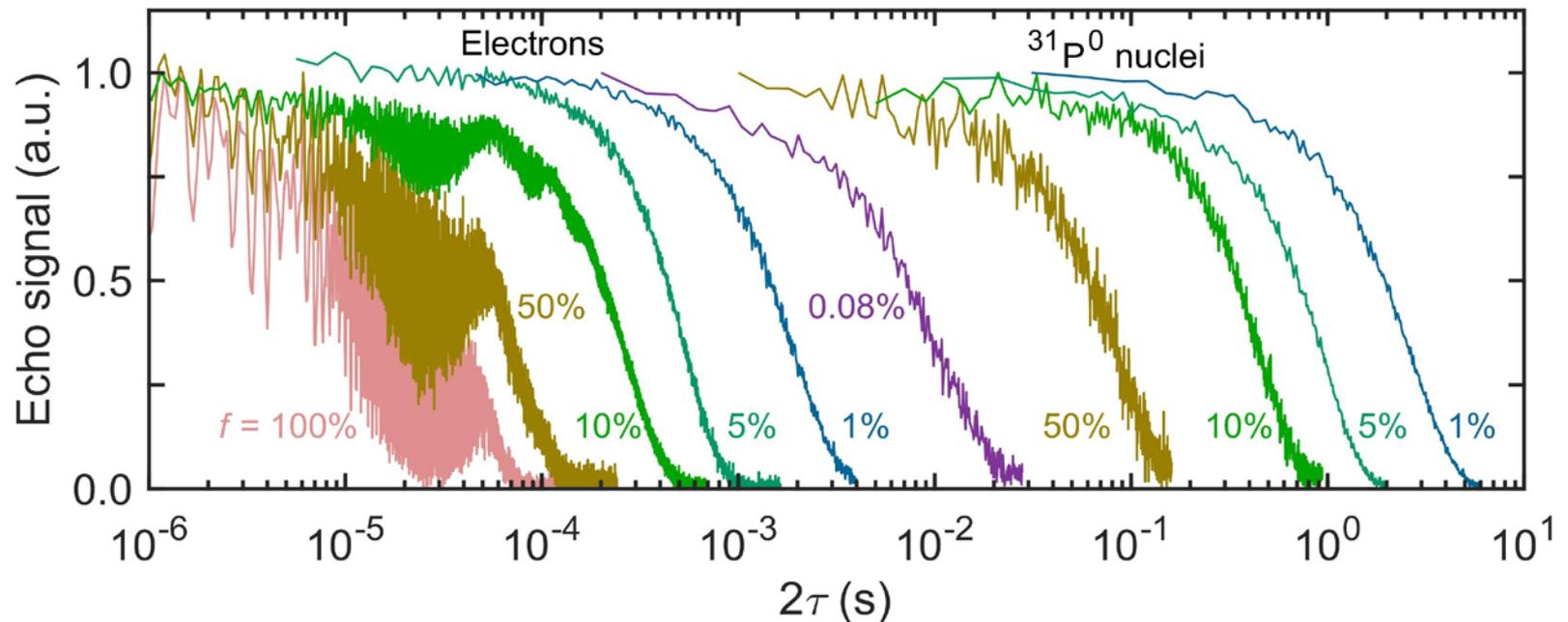
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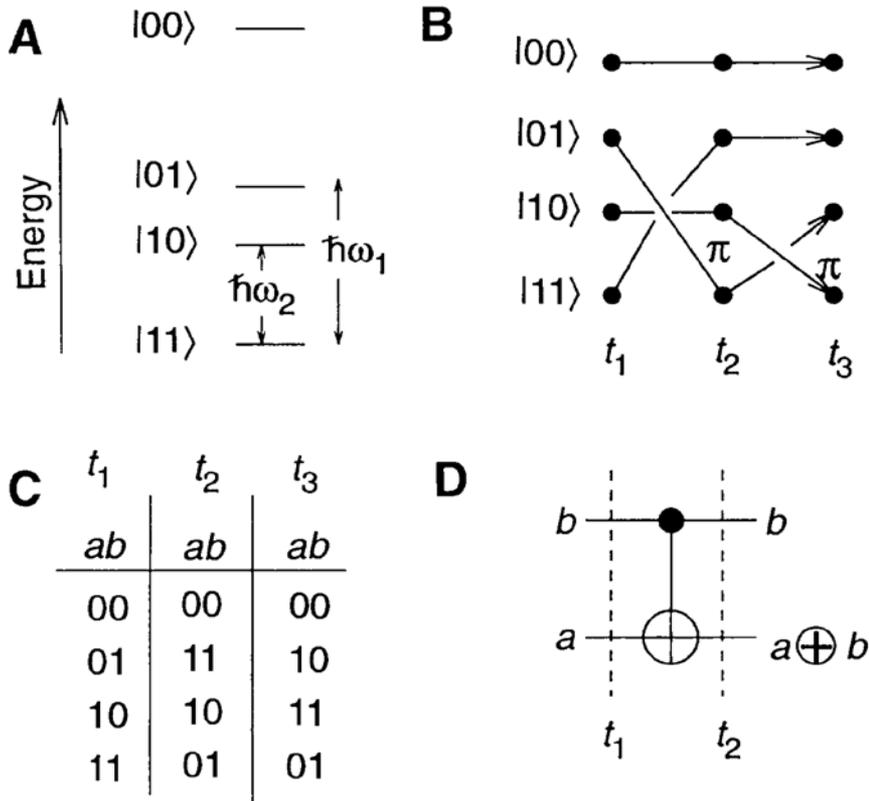
Nuclear spin decoherence of neutral ^{31}P donors in silicon: Effect of environmental ^{29}Si nuclei

Evan S. Petersen,¹ A. M. Tyryshkin,¹ J. J. L. Morton,² E. Abe,³ S. Tojo,³ K. M. Itoh,³ M. L. W. Thewalt,⁴ and S. A. Lyon¹



Quantum Computation

David P. DiVincenzo



The XOR protocol is very closely related to procedures invented long ago in the field of resonance spectroscopies (13). In 1956, Feher introduced a procedure for polarization transfer in electron-nucleus double resonance (ENDOR), which contains the XOR protocol just discussed.

for many purposes in physics, chemistry, and biology, it is highly desirable to move the spin state of an electron onto a nearby nucleus. The fact that this procedure also performs an interesting logical function, XOR, was not previously noted by ENDOR spectroscopists.

Fig. 2. The action of the two-qubit XOR gate.

Method of Polarizing Nuclei in Paramagnetic Substances

G. FEHER

Bell Telephone Laboratories, Murray Hill, New Jersey

(Received May 31, 1956)

OVERHAUSER¹ has shown that a saturation of the electron spin resonance leads to a large enhancement of the nuclear polarization. A necessary condition for this enhancement is that the nuclei relax via the electrons whose resonance is being saturated.

The scheme proposed in this paper, applicable to substances which show a resolved hyperfine structure, places no requirements on the detailed relaxation mechanism of either the electron or the nucleus. It requires, however, that one sweep through a certain fraction of the external magnetic field in a time short compared to either relaxation time.



G. Feher (©R.A. Icaacson)

Electron Nuclear DOuble Resonance

Phys. Rev. **103**, 500 (1956) Feher

Polarization of Phosphorus Nuclei in Silicon

G. FEHER AND E. A. GERE

Bell Telephone Laboratories, Murray Hill, New Jersey

(Received May 31, 1956)

IN the preceding Letter a scheme for polarizing nuclei was described. This Letter deals with the experimental verification of the scheme.

Electron Nuclear DOuble Resonance

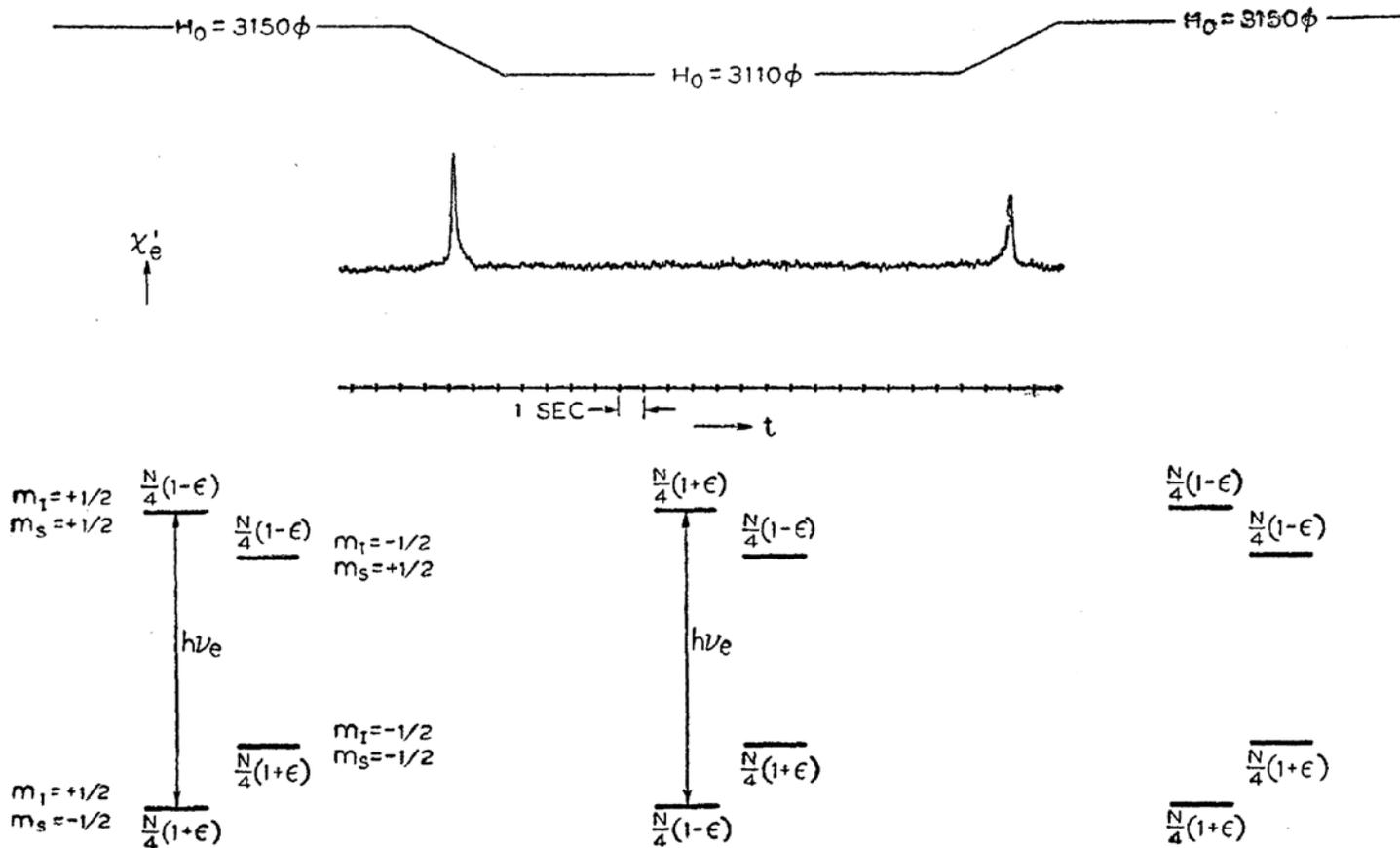
Polarization of Phosphorus Nuclei in Silicon

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(Received May 31, 1956)

Electron Nuclear DOuble REsonance



(π -pulse on e -spin)

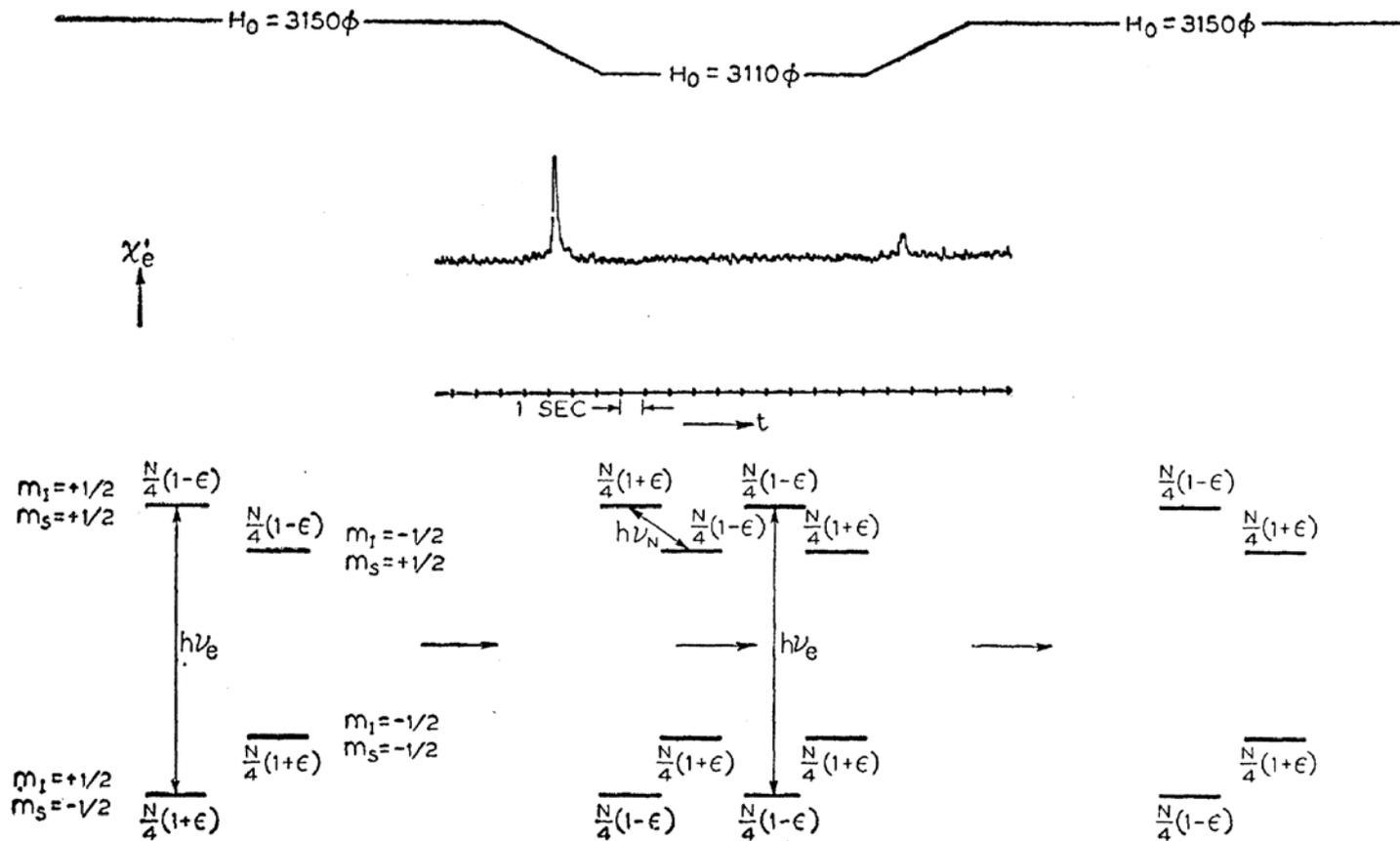
Polarization of Phosphorus Nuclei in Silicon

G. FEHER AND E. A. GERE

Bell Telephone Laboratories, Murray Hill, New Jersey

(Received May 31, 1956)

Electron Nuclear DOuble Resonance



(π -pulse on e -spin)

(π -pulse on n -spin)

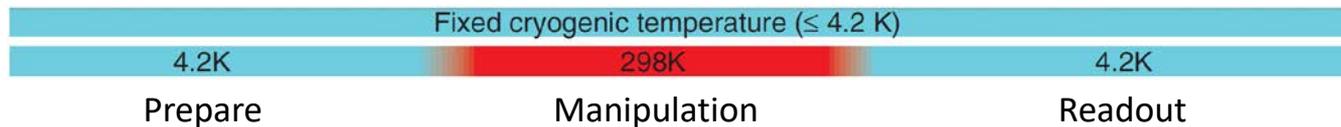
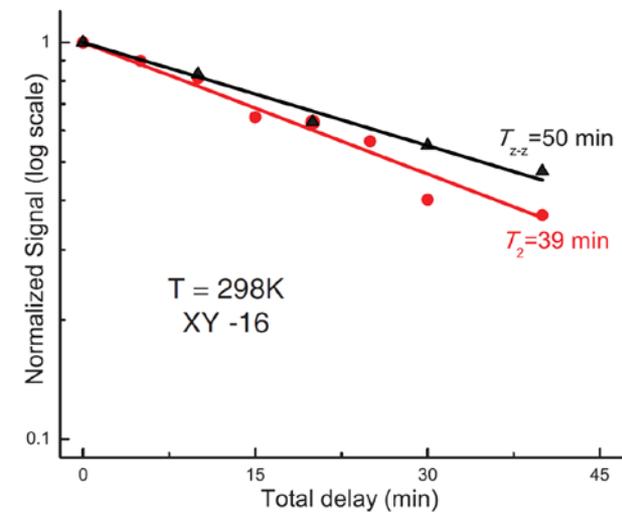
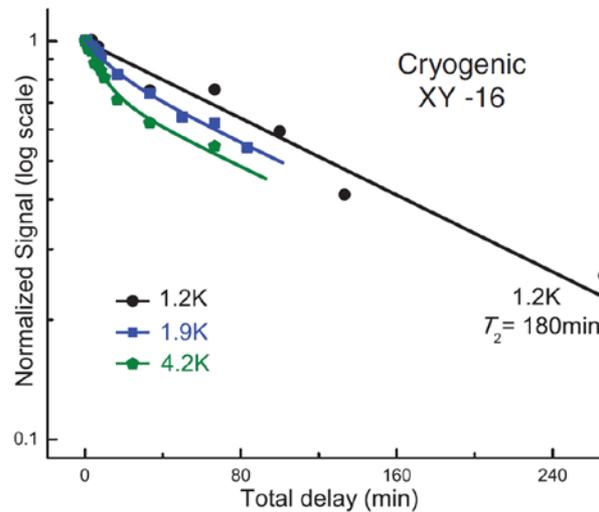
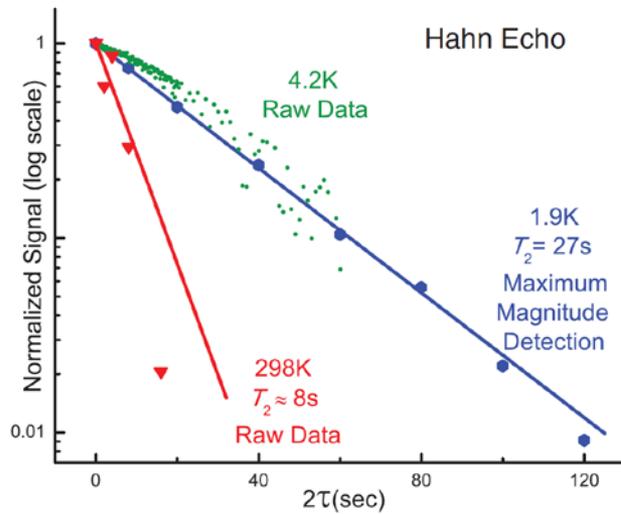
Phys. Rev. **103**, 501 (1956) Feher & Gere

核スピンコヒーレンス: T_{2n+}

Room-Temperature Quantum Bit Storage Exceeding 39 Minutes Using Ionized Donors in Silicon-28

Auger-electron-detected NMR

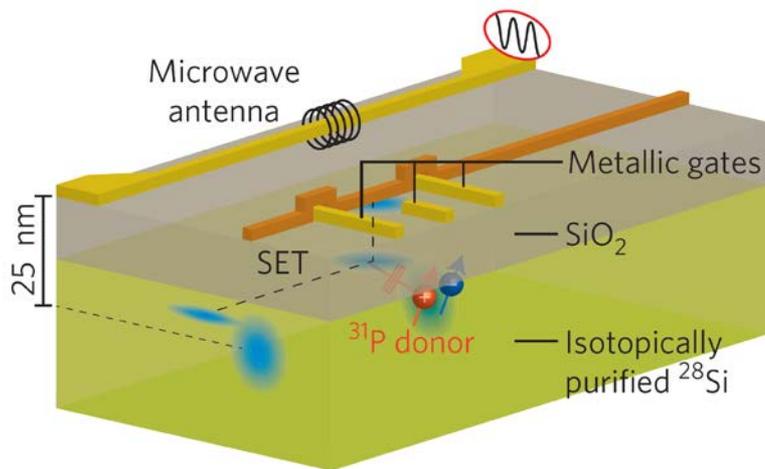
Kamyar Saeedi,¹ Stephanie Simmons,² Jeff Z. Salvail,¹ Phillip Dluhy,¹ Helge Riemann,³ Nikolai V. Abrosimov,³ Peter Becker,⁴ Hans-Joachim Pohl,⁵ John J. L. Morton,⁶ Mike L. W. Thewalt^{1*}



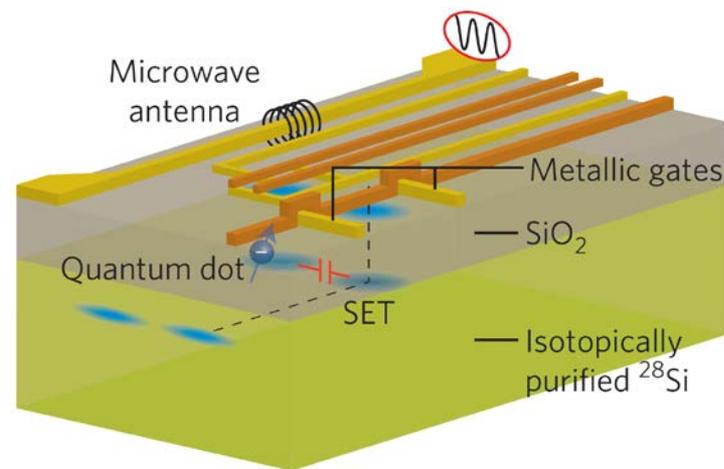
講義内容

- 磁気共鳴と量子コヒーレンス
 - アンサンブルリンドナー
- **シリコンスピン量子コンピュータ**
 - 単一リンドナー
 - MOS量子ドット
 - Si/SiGe量子ドット

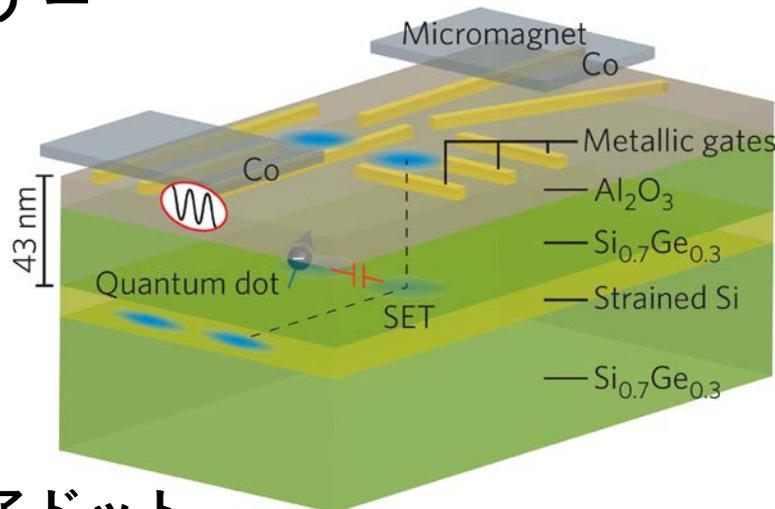
シリコンスピク量子ビット



単一リンドナー



MOS量子ドット



Si/SiGe量子ドット

ディビンチェンゾの要請

1. スケーラブルな量子ビット列
2. 初期化
3. 長いコヒーレンス時間
4. ユニバーサル量子ゲート
5. 射影測定



D. DiVincenzo
(©RWTH Aachen U.)

ディビンチェンゾの要請

1. スケーラブルな量子ビット列

→ スピン系における最大の課題

2. 初期化

→ スピン緩和(T_1), スピン依存トンネル etc

3. 長いコヒーレンス時間

*1: Nature Mat. **11**, 143 (2012) Tyryshkin *et al.*

→ $T_{2e} = 10$ s (*1), $T_{2n} = 180$ min

4. ユニバーサル量子ゲート

→ 1量子ビット制御 + CNOT

5. 射影測定

→ スピン・電荷変換



D. DiVincenzo
(©RWTH Aachen U.)

ディビンチェンゾの要請

1. スケーラブルな量子ビット列
→ スピン系における最大の課題

2. 初期化
→ スピン緩和(T_1), スピン依存トンネル etc

3. 長いコヒーレンス時間
→ 表面符号による誤り耐性($T_2 \rightarrow \infty$)

4. ユニバーサル量子ゲート
→ 1量子ビット制御 + CNOT

5. 射影測定
→ スピン・電荷変換

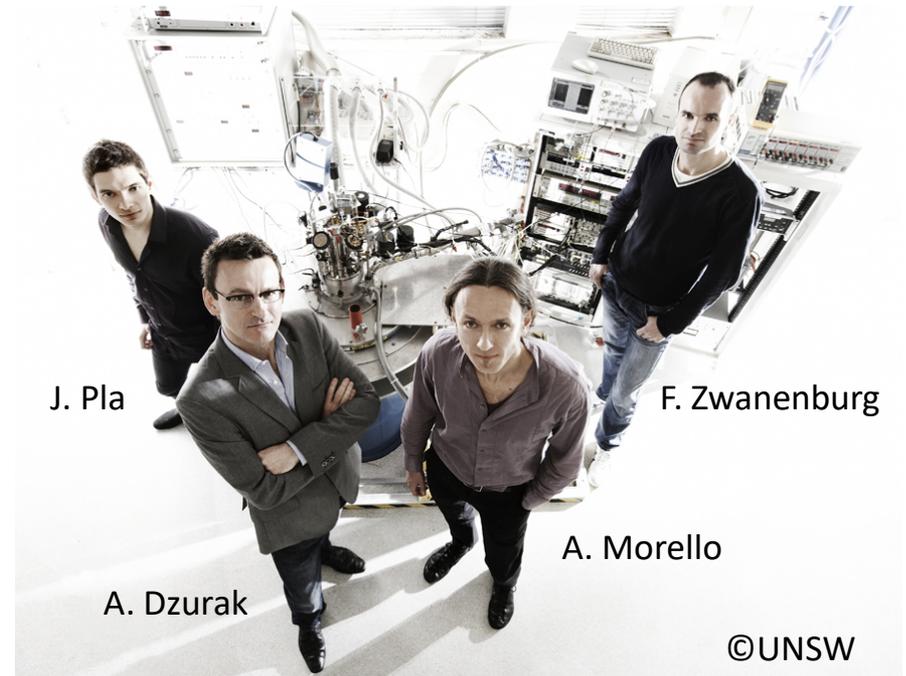
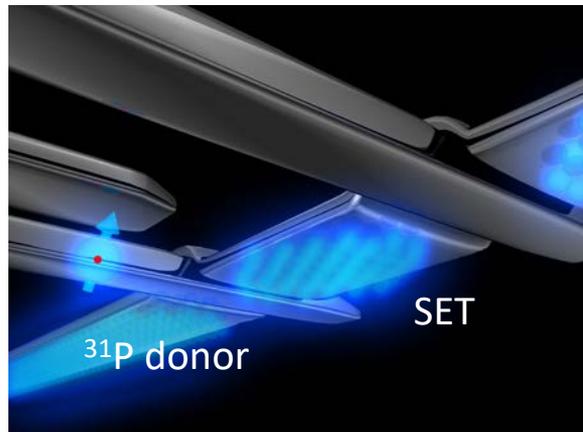
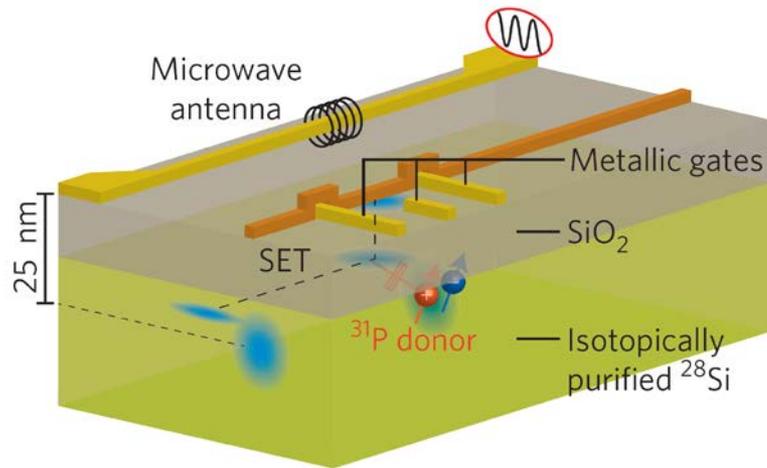
フェデリティ > 99%



D. DiVincenzo
(©RWTH Aachen U.)

Single-shot readout of an electron spin in silicon

Andrea Morello¹, Jarryd J. Pla¹, Floris A. Zwanenburg¹, Kok W. Chan¹, Kuan Y. Tan¹, Hans Huebl^{1†}, Mikko Möttönen^{1,3,4}, Christopher D. Nugroho^{1†}, Changyi Yang², Jessica A. van Donkelaar², Andrew D. C. Alves², David N. Jamieson², Christopher C. Escott¹, Lloyd C. L. Hollenberg², Robert G. Clark^{1†} & Andrew S. Dzurak¹



J. Pla

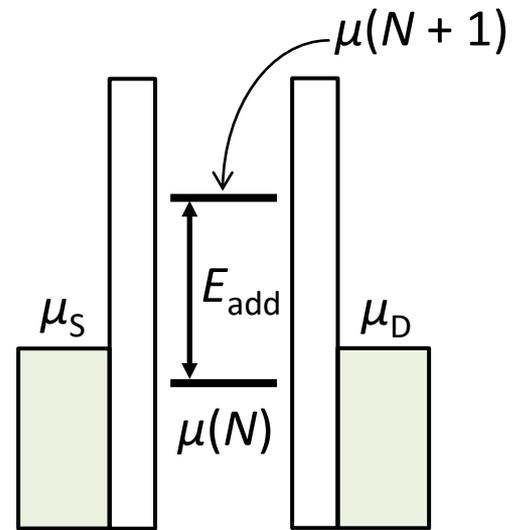
F. Zwanenburg

A. Morello

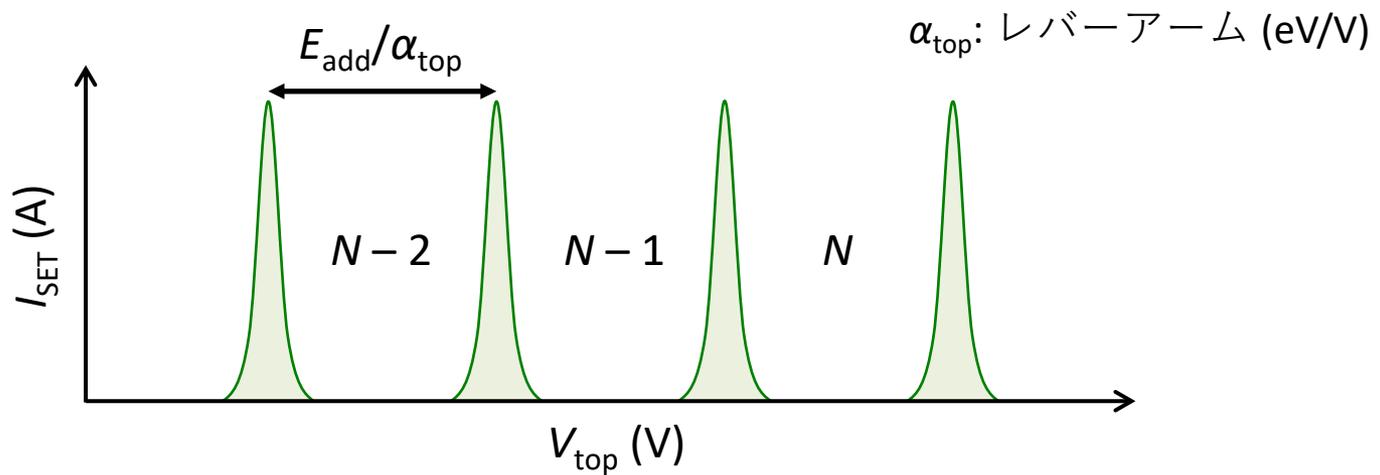
A. Dzurak

©UNSW

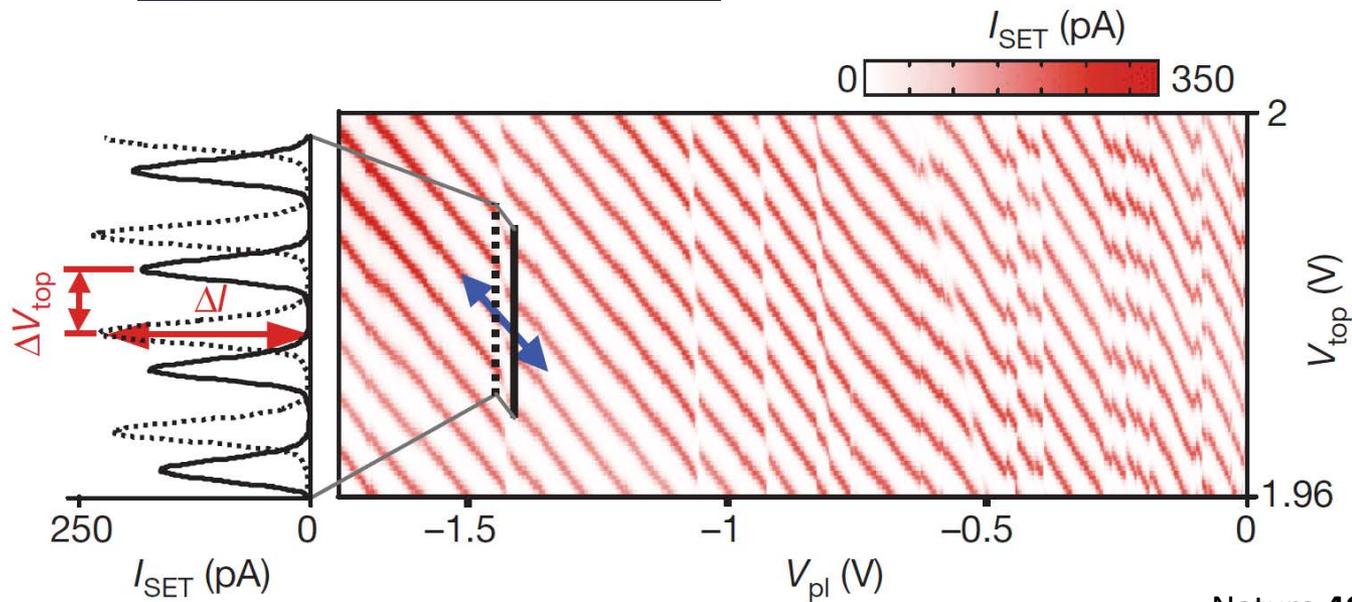
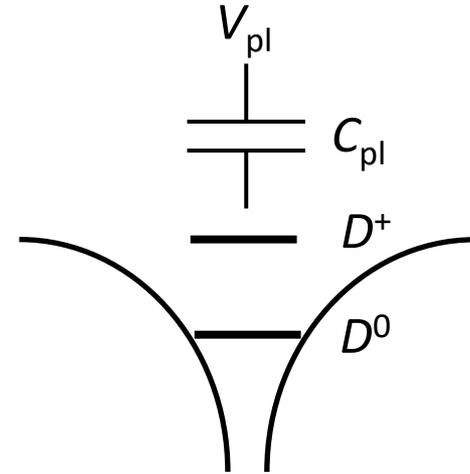
単電子トランジスタ



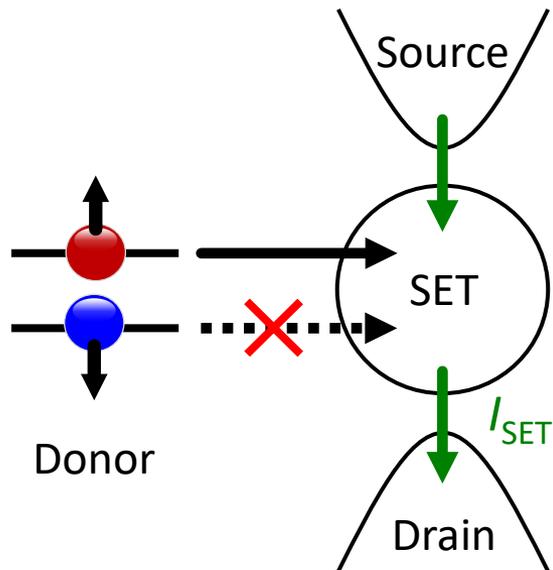
クーロン振動



ドナー・SETハイブリッド



スピン・電荷変換



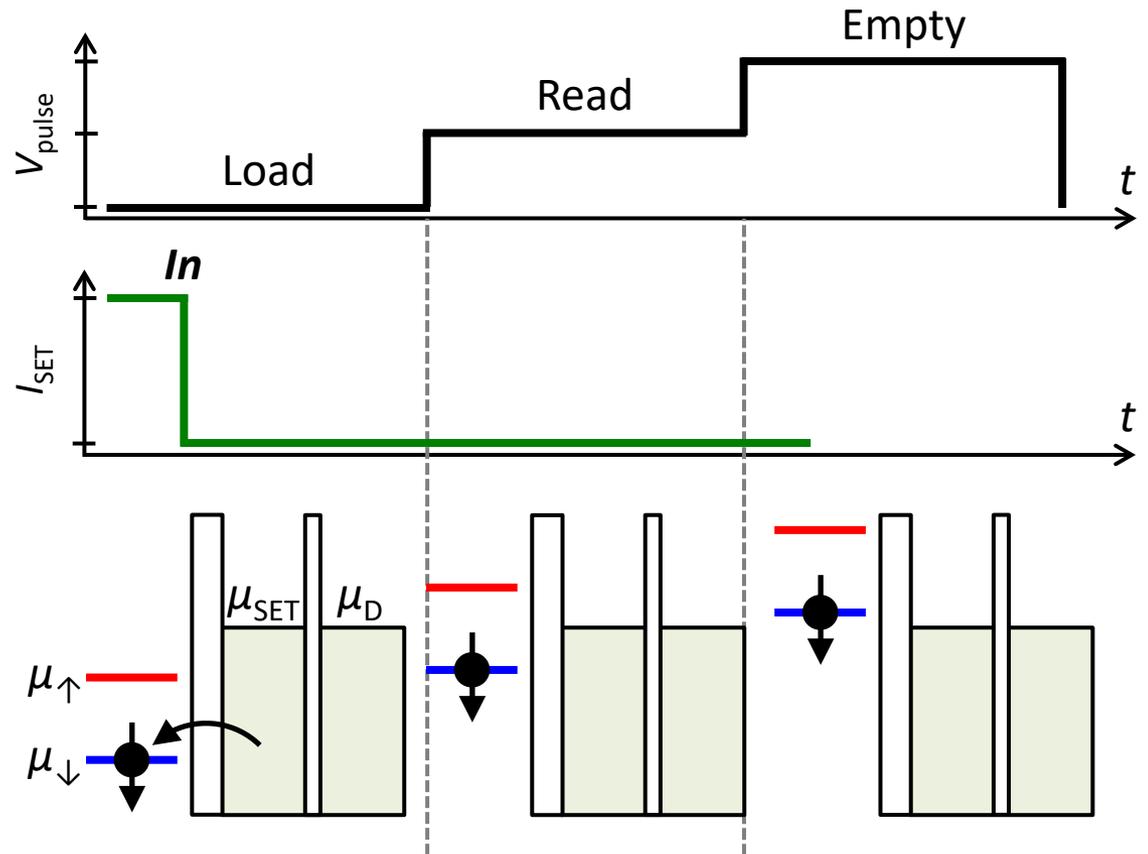
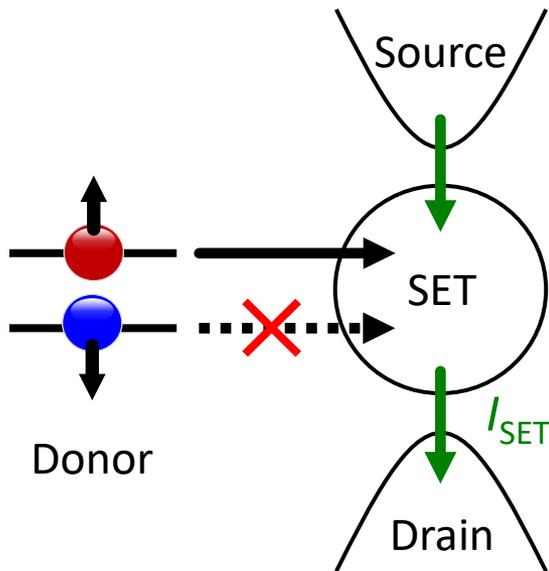
$$E(D^+) - E(D^0) = 45 \text{ meV}$$

$$E_C = 1.5 \text{ meV}$$

$$E_z = 28 \text{ GHz} = 116 \text{ } \mu\text{eV} @ B_0 = 1 \text{ T}$$

$$T_{\text{elec}} = 200 \text{ mK} = 17 \text{ } \mu\text{eV}$$

スピン測定(↓)



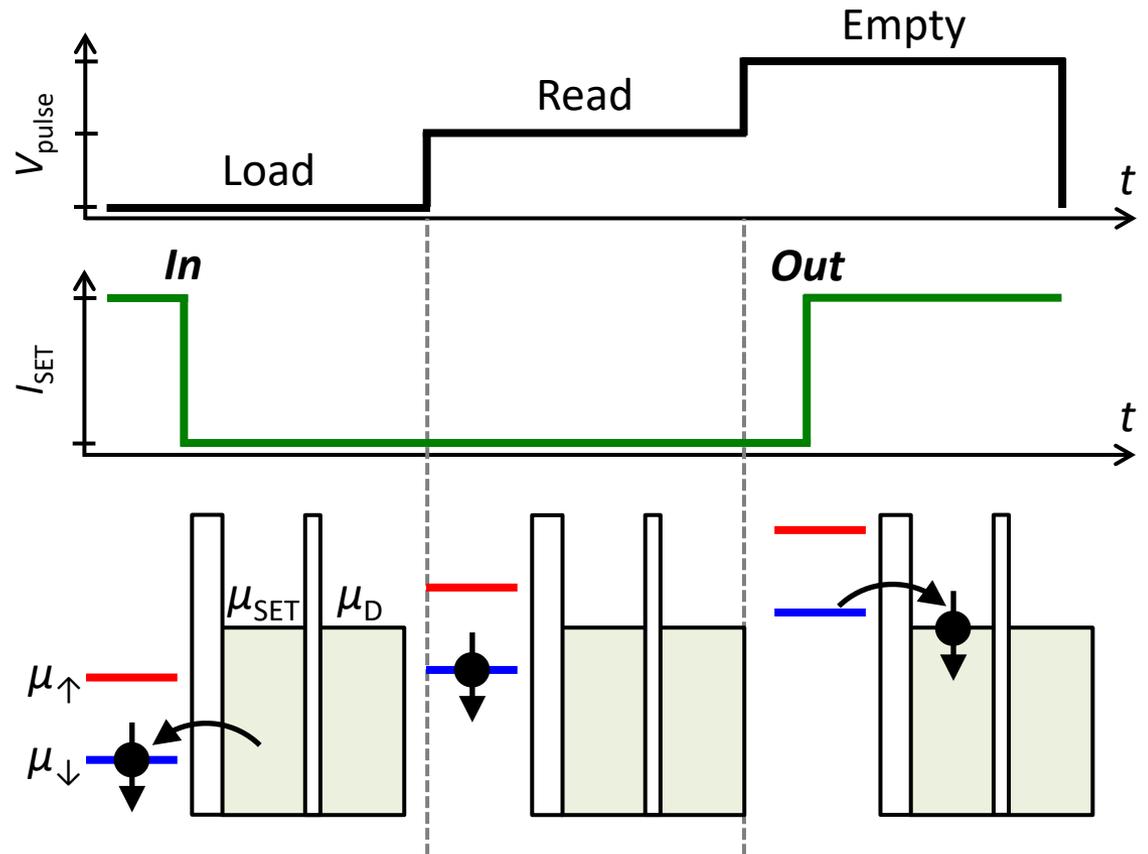
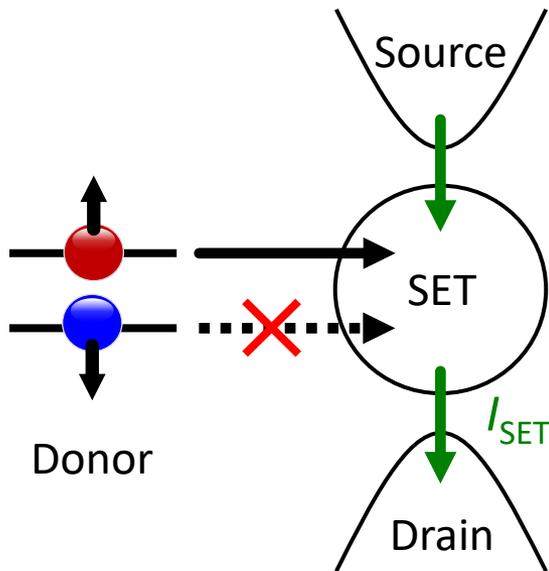
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スピン測定(↓)



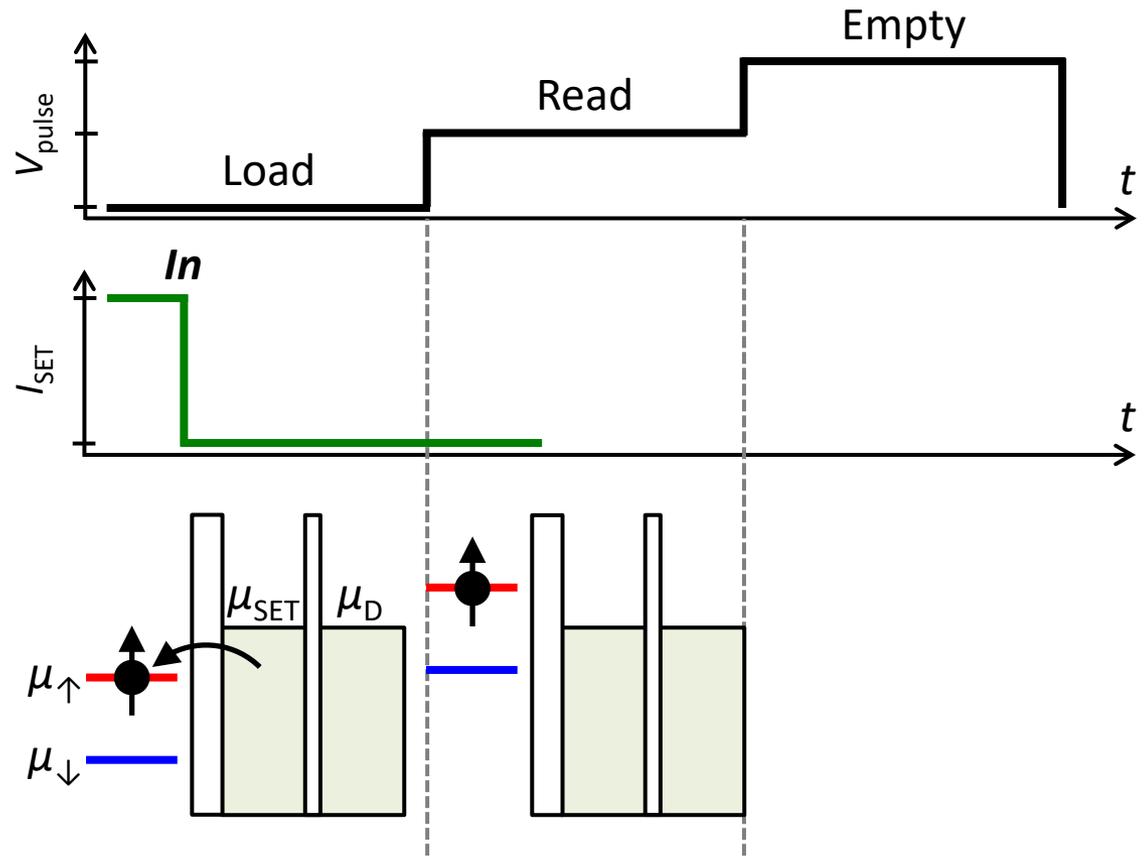
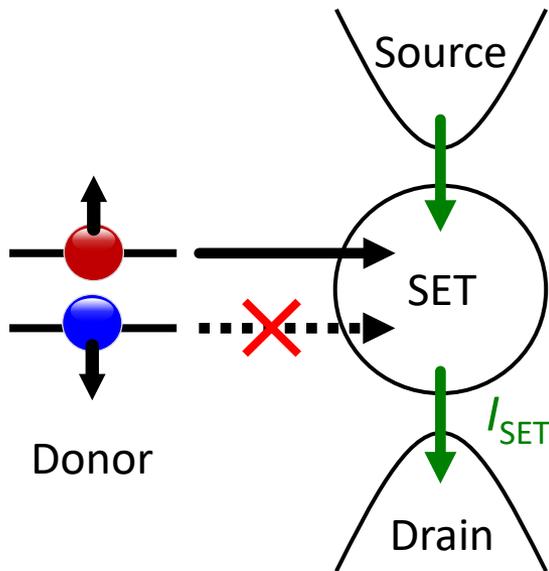
$$E(D^+) - E(D^0) = 45 \text{ meV}$$

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$$E_z = 28 \text{ GHz} = 116 \text{ } \mu\text{eV} @ B_0 = 1 \text{ T}$$

$$T_{\text{elec}} = 200 \text{ mK} = 17 \text{ } \mu\text{eV}$$

スピン測定(↑)



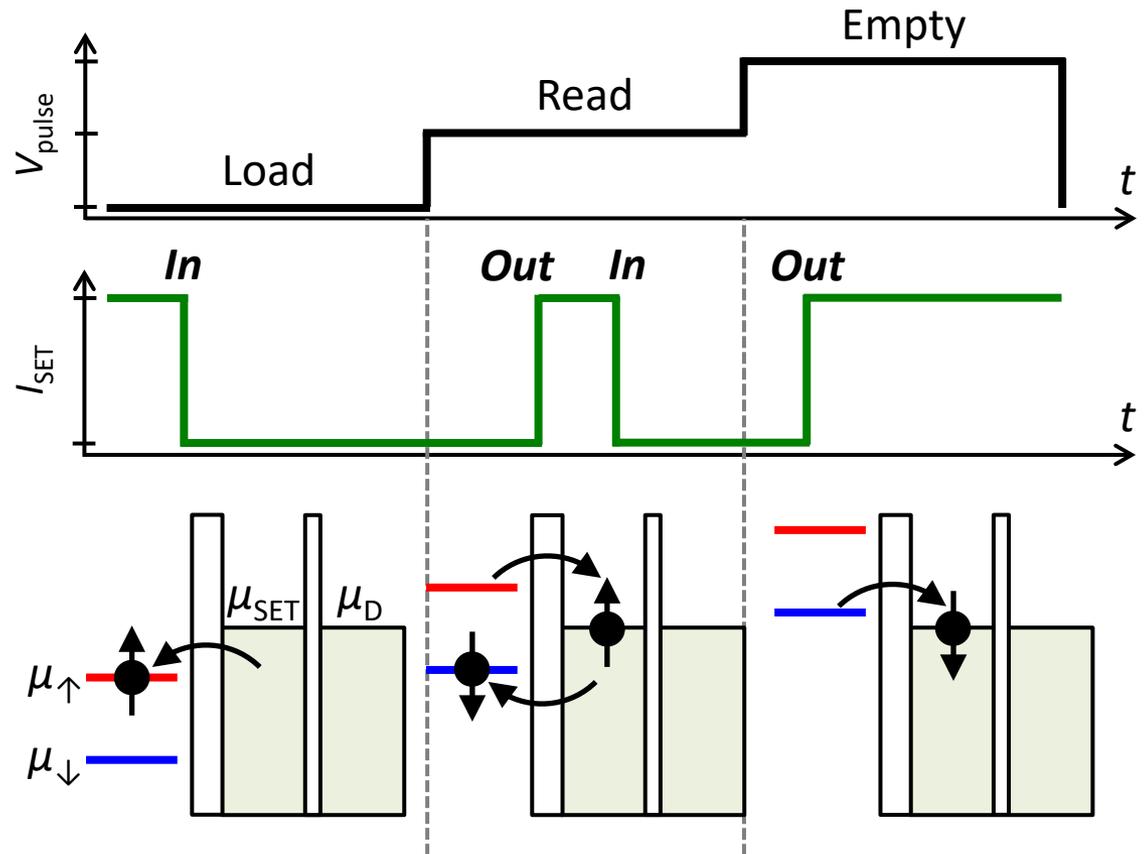
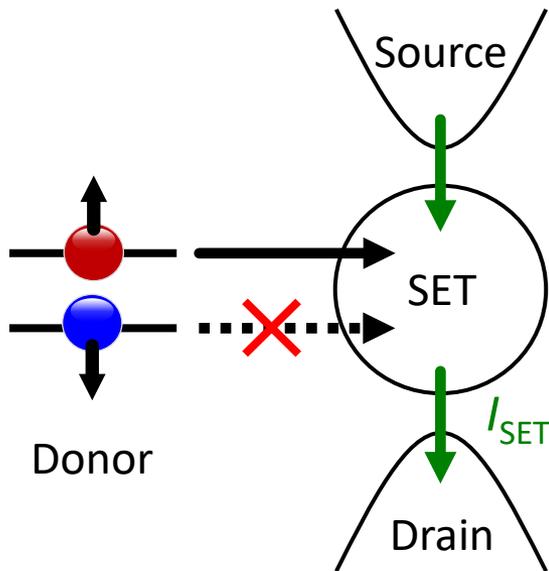
$$E(D^+) - E(D^0) = 45 \text{ meV}$$

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スピン測定(↑)



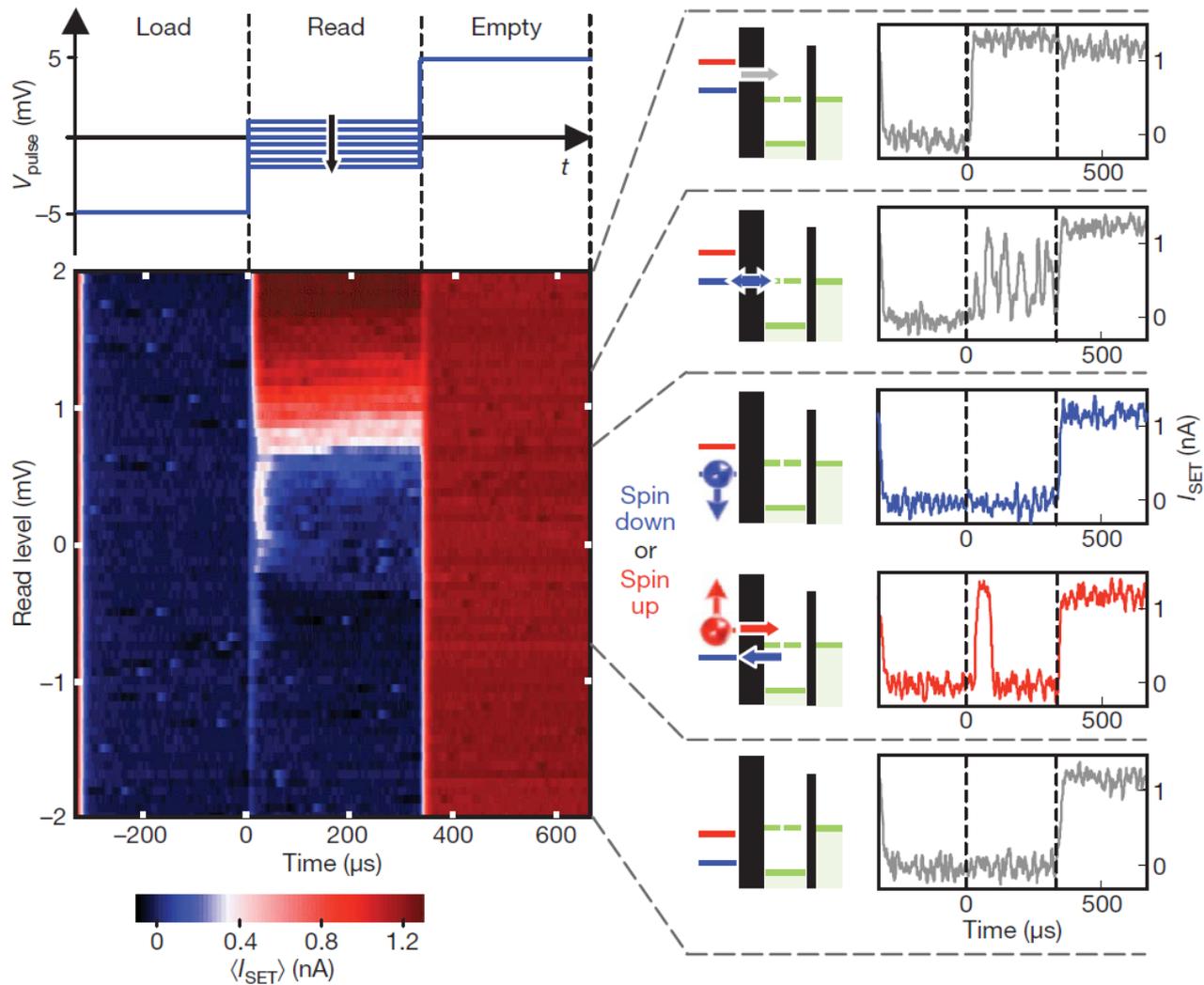
$$E(D^+) - E(D^0) = 45 \text{ meV}$$

$$E_C = 1.5 \text{ meV}$$

$$E_z = 28 \text{ GHz} = 116 \text{ } \mu\text{eV} @ B_0 = 1 \text{ T}$$

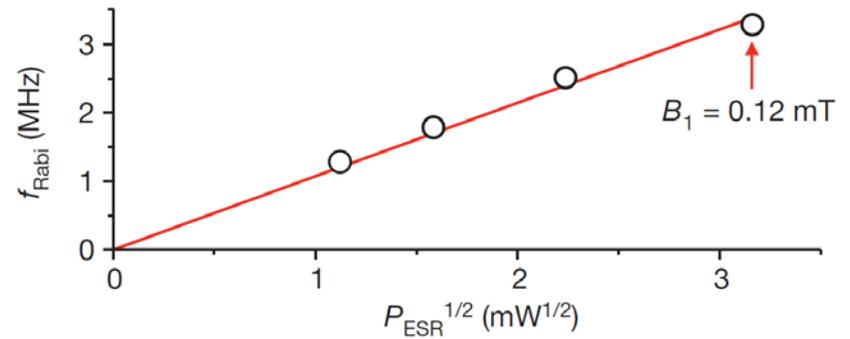
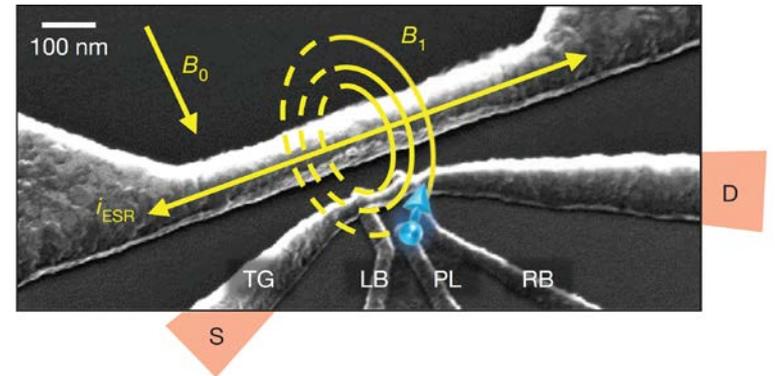
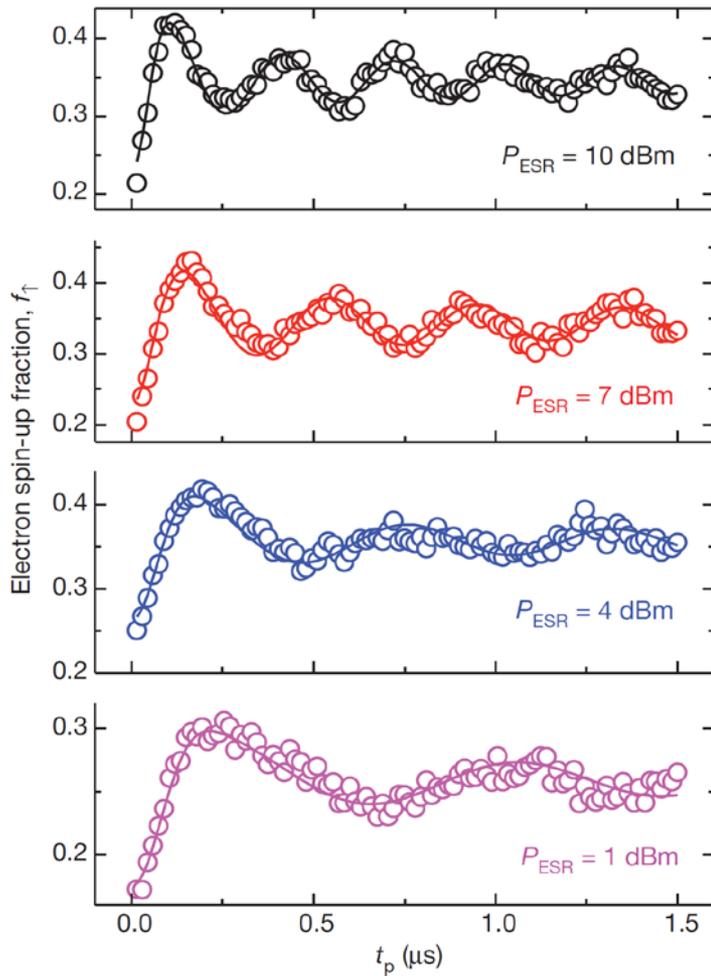
$$T_{\text{elec}} = 200 \text{ mK} = 17 \text{ } \mu\text{eV}$$

電子スピン単発読み出し



A single-atom electron spin qubit in silicon

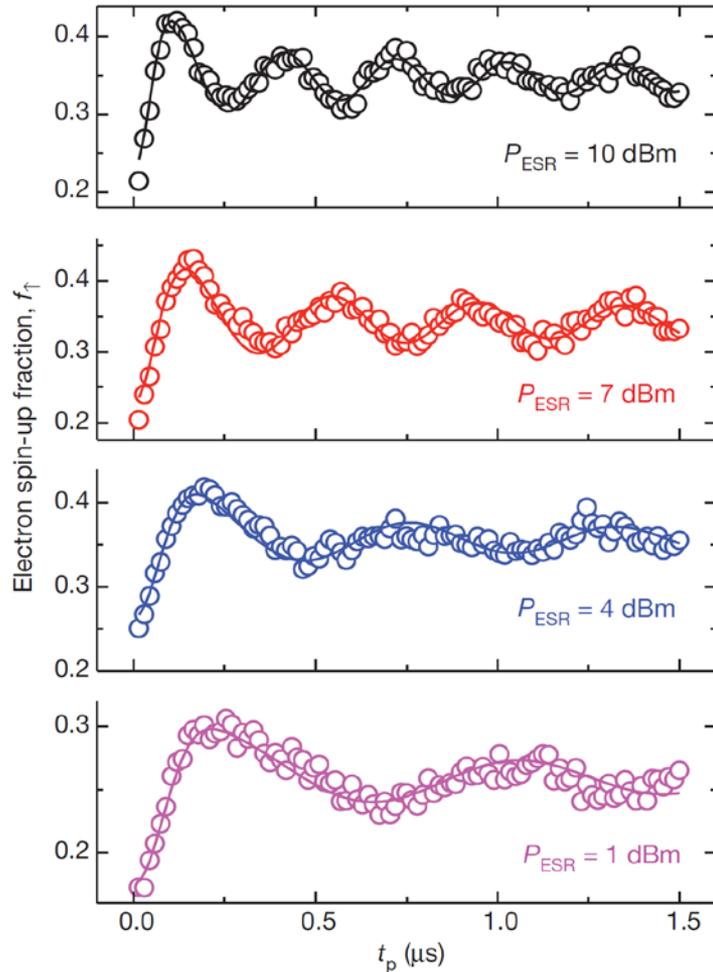
Jarryd J. Pla¹, Kuan Y. Tan^{1†}, Juan P. Dehollain¹, Wee H. Lim¹, John J. L. Morton^{2†}, David N. Jamieson³, Andrew S. Dzurak¹ & Andrea Morello¹



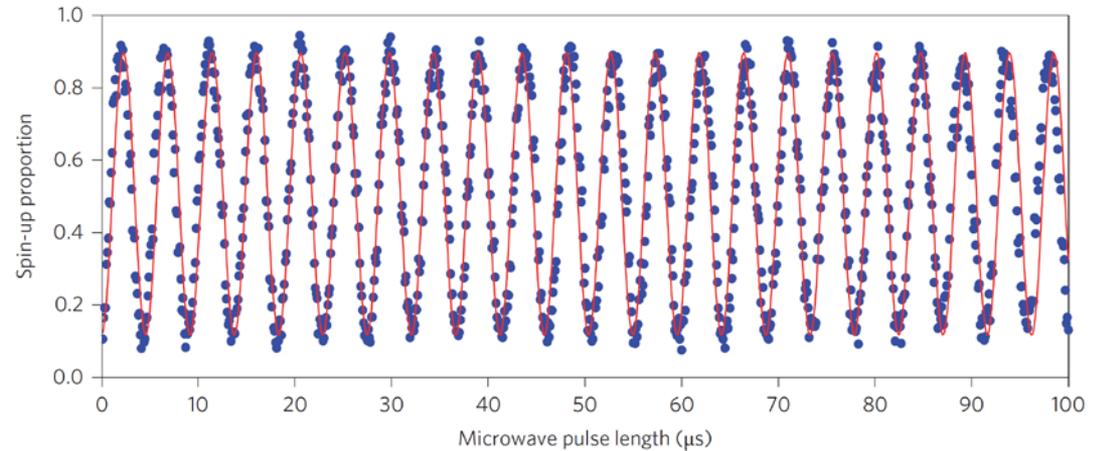
ラビ振動: natSiデバイス

A single-atom electron spin qubit in silicon

Jarryd J. Pla¹, Kuan Y. Tan^{1†}, Juan P. Dehollain¹, Wee H. Lim¹, John J. L. Morton^{2†}, David N. Jamieson³, Andrew S. Dzurak¹ & Andrea Morello¹



同位体²⁸Si(99.92%)デバイス

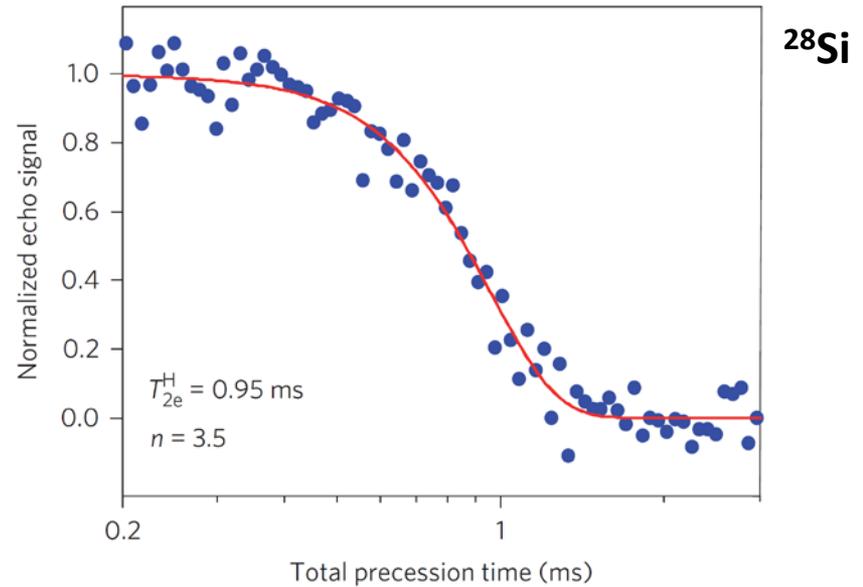
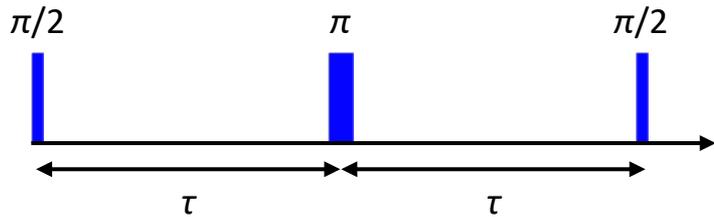


Nature Nano. **9**, 986 (2014) Muhonen *et al.*

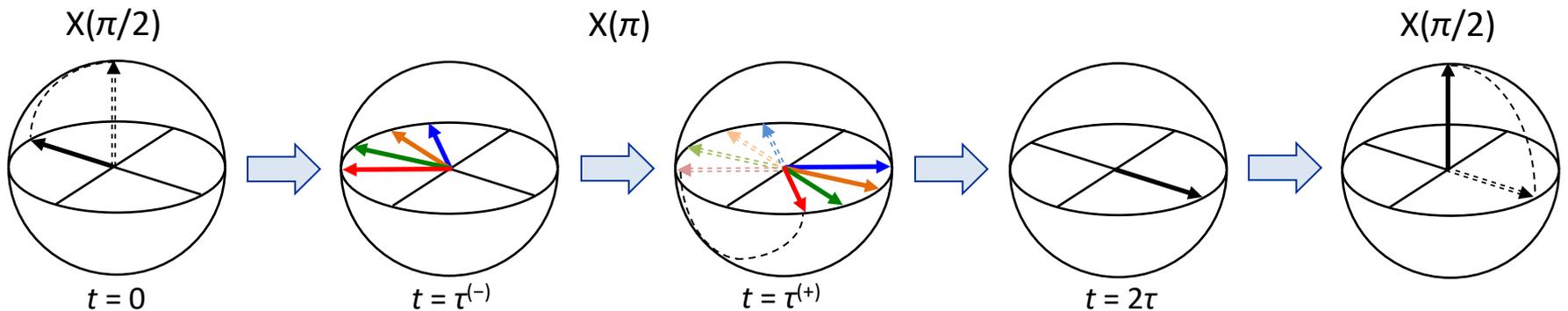
ラビ振動: natSiデバイス

Nature **489**, 541 (2012) Pla *et al.*

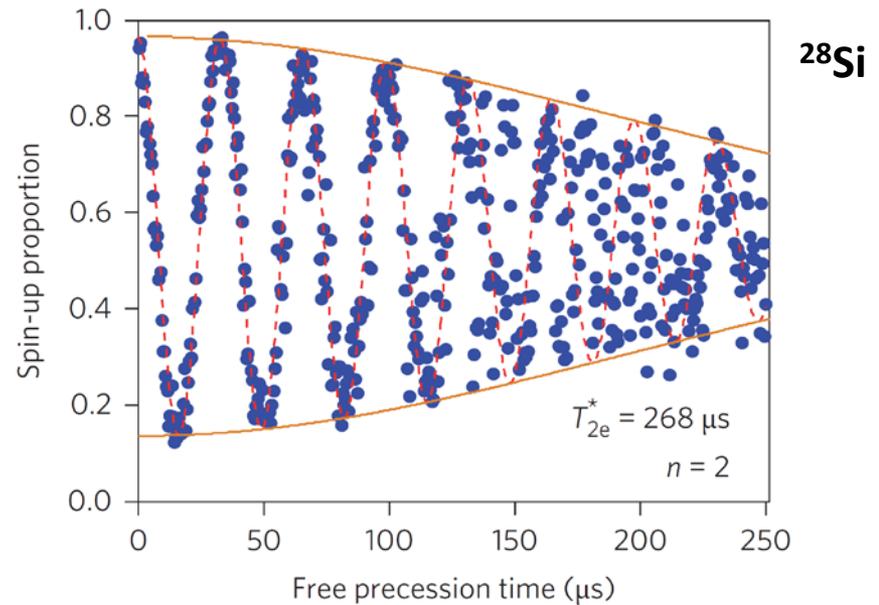
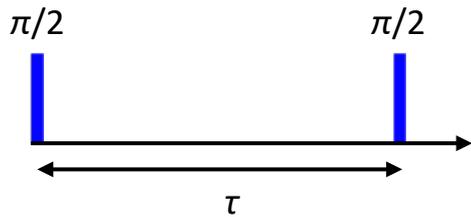
スピンエコー: T_{2e}



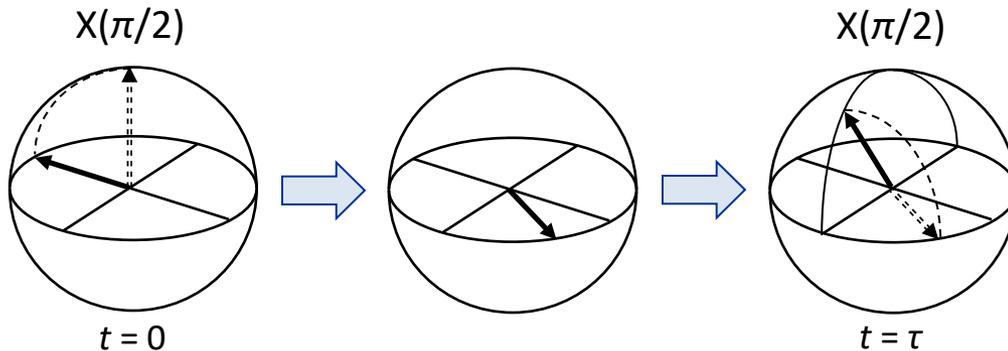
(共鳴周波数の回転系)



ラムゼー干渉: T_{2e}^*

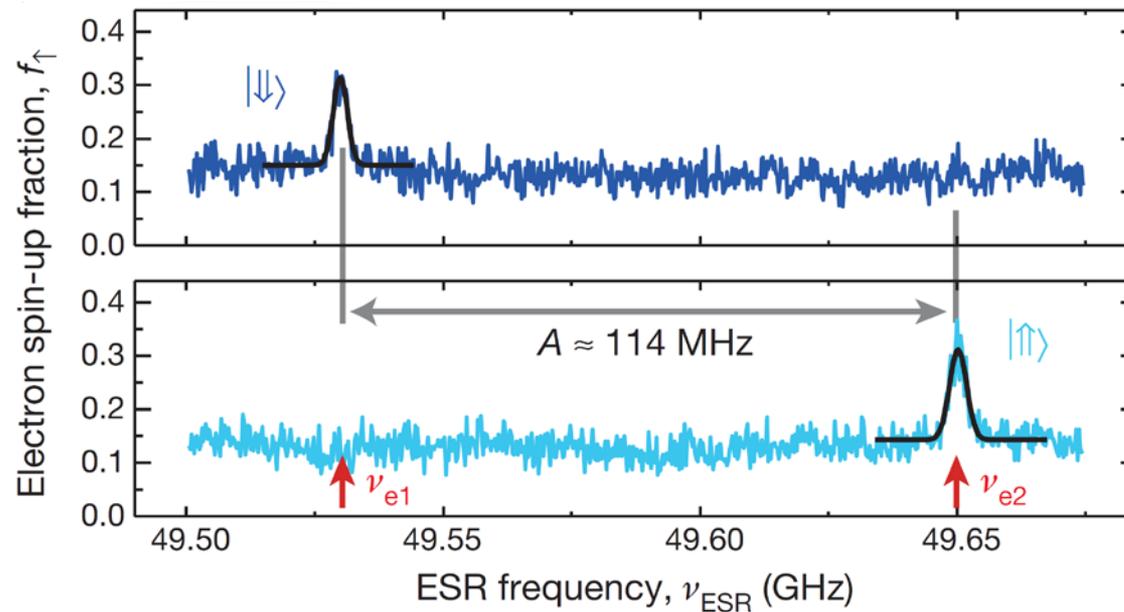


(共鳴から少し外れた回転系)



High-fidelity readout and control of a nuclear spin qubit in silicon

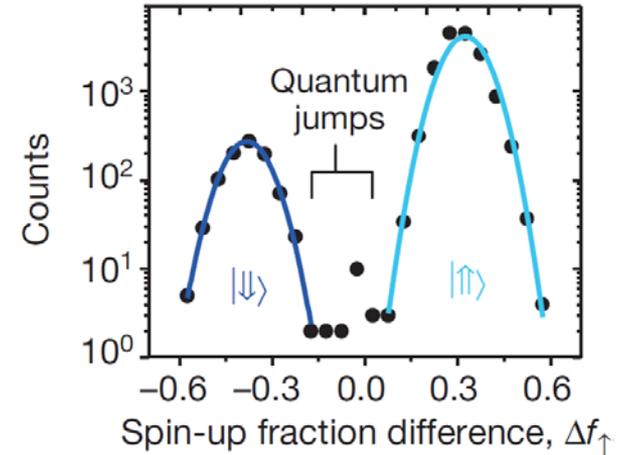
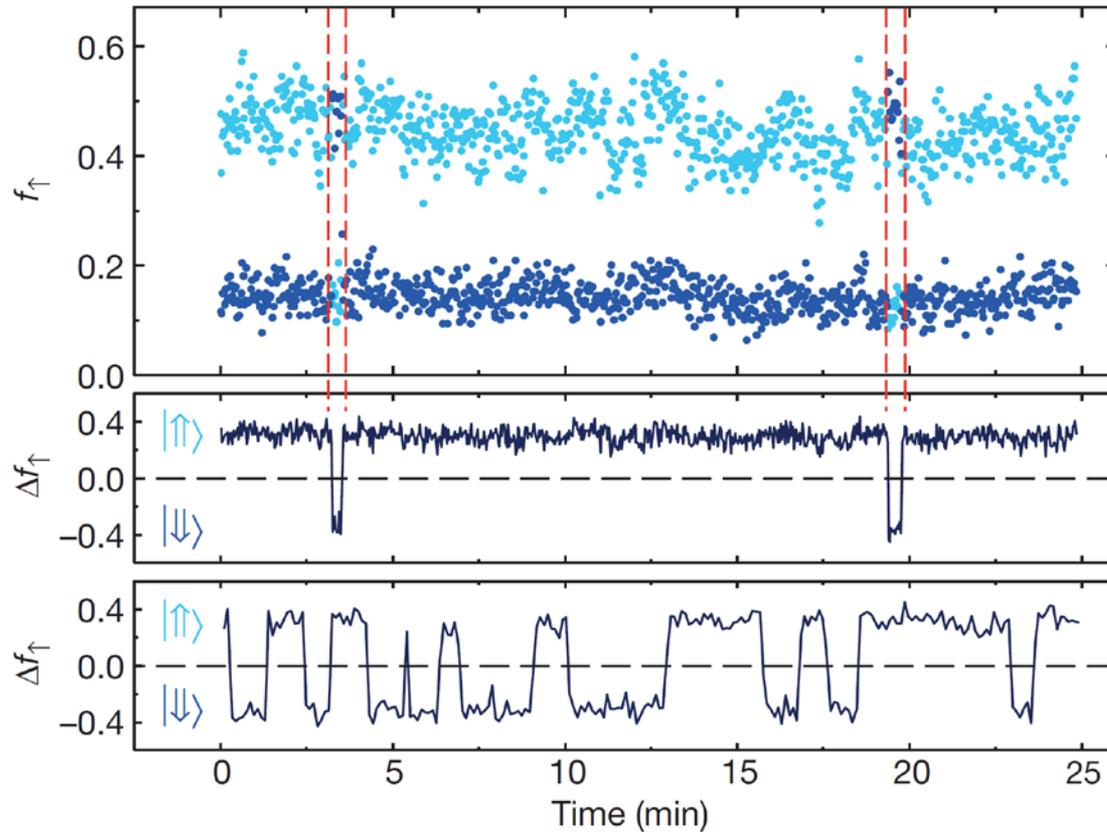
Jarryd J. Pla¹, Kuan Y. Tan^{1†}, Juan P. Dehollain¹, Wee H. Lim^{1†}, John J. L. Morton², Floris A. Zwanenburg^{1†}, David N. Jamieson³, Andrew S. Dzurak¹ & Andrea Morello¹



- 電子スピン遷移周波数 $\nu_{e1,2} = \gamma_e B_0 \mp a_0/2$ は核スピン状態に依存する
 - 電子スピン遷移によって核スピン状態は変わらない
- 量子非破壊(QND)測定

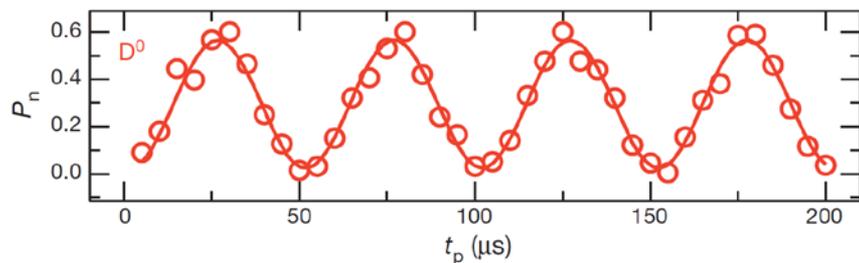
High-fidelity readout and control of a nuclear spin qubit in silicon

Jarryd J. Pla¹, Kuan Y. Tan^{1†}, Juan P. Dehollain¹, Wee H. Lim^{1†}, John J. L. Morton², Floris A. Zwanenburg^{1†}, David N. Jamieson³, Andrew S. Dzurak¹ & Andrea Morello¹

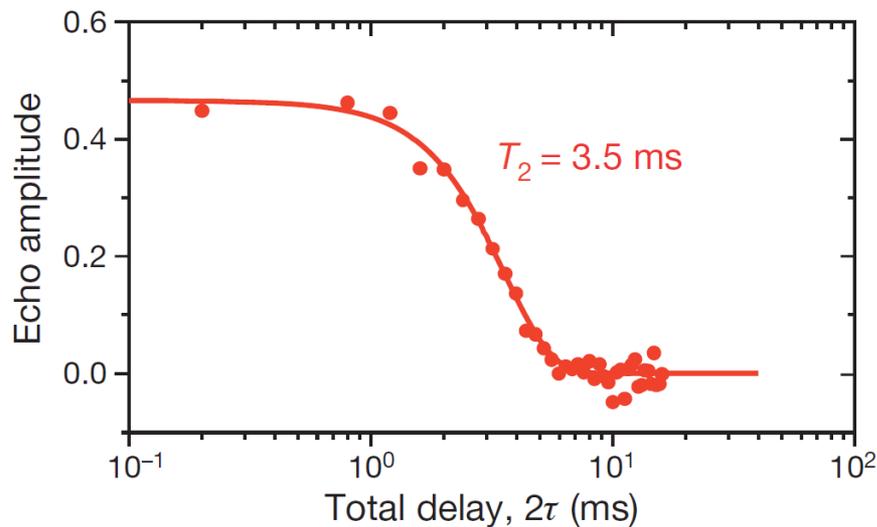
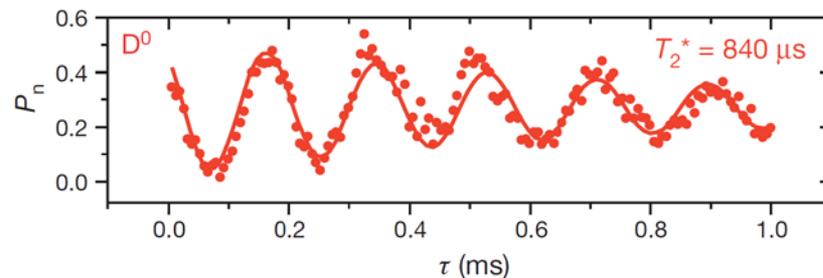


単一核スピンコヒーレント制御

ラビ振動(^{nat}Si)



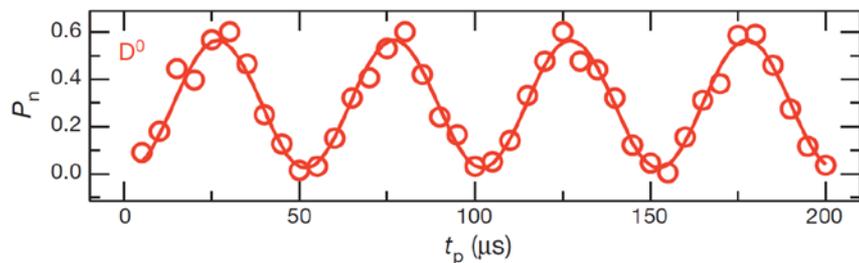
ラムゼー干渉(^{nat}Si)



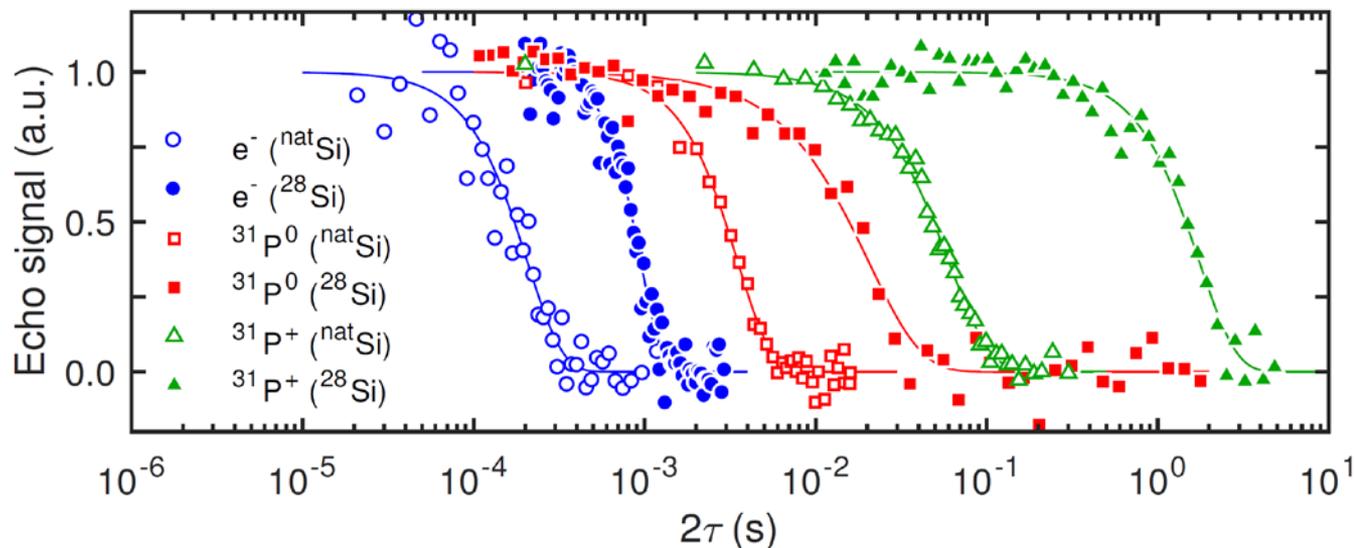
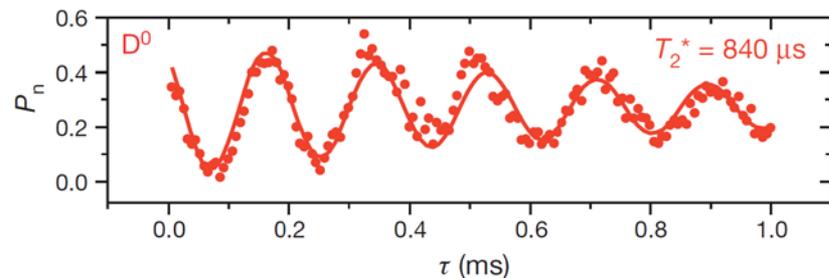
エコー(^{nat}Si)

単一核スピンコヒーレント制御

ラビ振動(^{nat}Si)



ラムゼー干渉(^{nat}Si)



Nature **489**, 541 (2012) Pla *et al.*

Nature **496**, 334 (2013) Pla *et al.*

Nature Nano. **9**, 986 (2014) Muhonen *et al.*

An addressable quantum dot qubit with fault-tolerant control-fidelity

M. Veldhorst^{1*}, J. C. C. Hwang¹, C. H. Yang¹, A. W. Leenstra², B. de Ronde², J. P. Dehollain¹, J. T. Muhonen¹, F. E. Hudson¹, K. M. Itoh³, A. Morello¹ and A. S. Dzurak^{1*}

LETTER

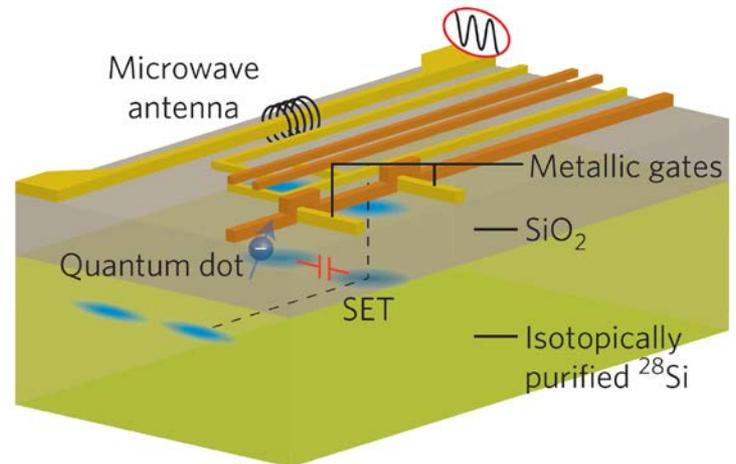
doi:10.1038/nature15263

A two-qubit logic gate in silicon

M. Veldhorst¹, C. H. Yang¹, J. C. C. Hwang¹, W. Huang¹, J. P. Dehollain¹, J. T. Muhonen¹, S. Simmons¹, A. Laucht¹, F. E. Hudson¹, K. M. Itoh², A. Morello¹ & A. S. Dzurak¹



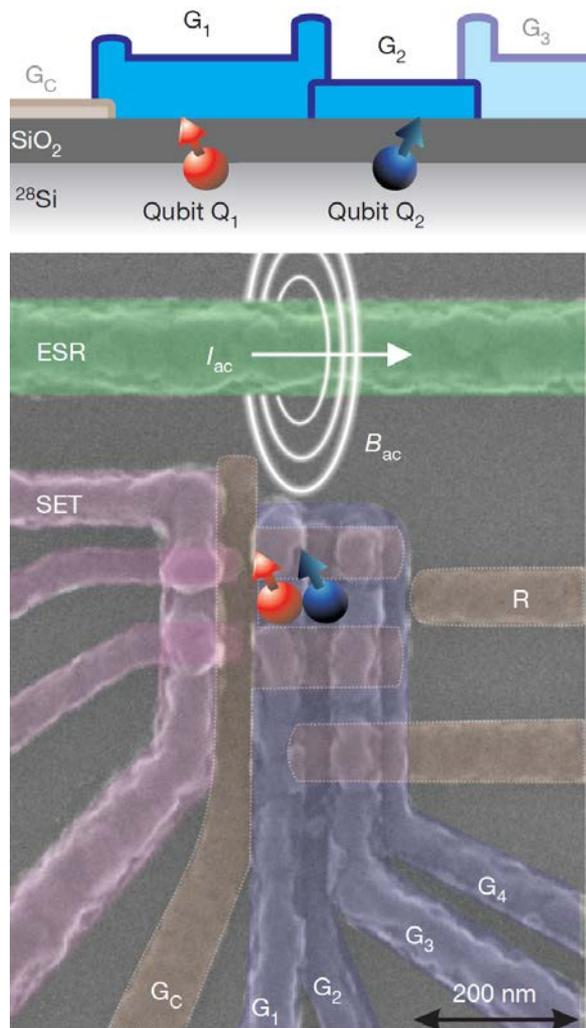
(L to R) J. Muhonen, A. Morello, M. Veldhorst, A. Dzurak



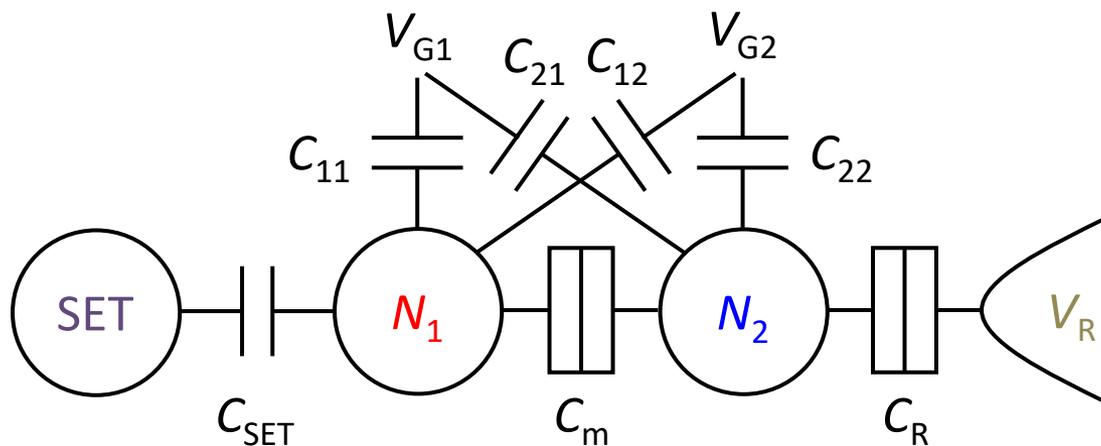
Nature Nano. **9**, 981 (2014) Veldhorst *et al.*

Nature **526**, 410 (2015) Veldhorst *et al.*

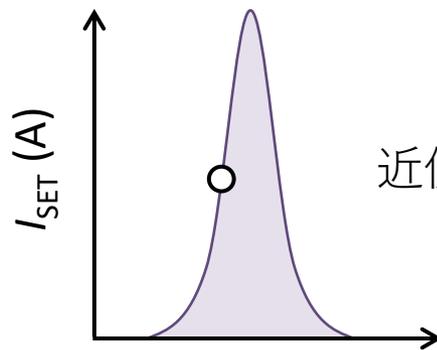
MOS型2重量子ドット



クロストーク

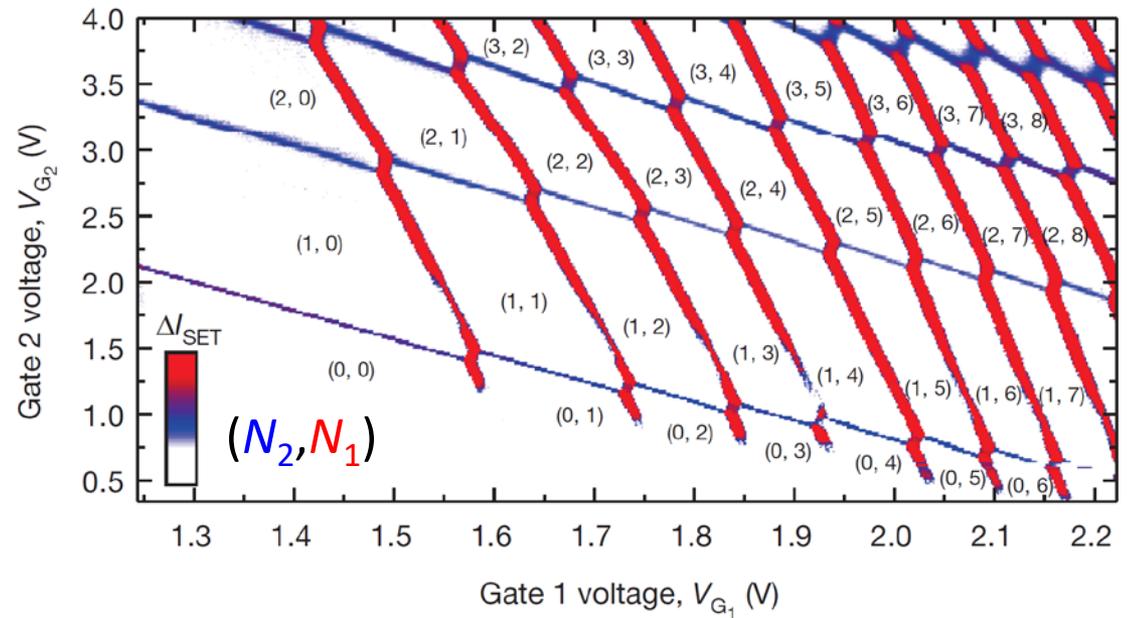
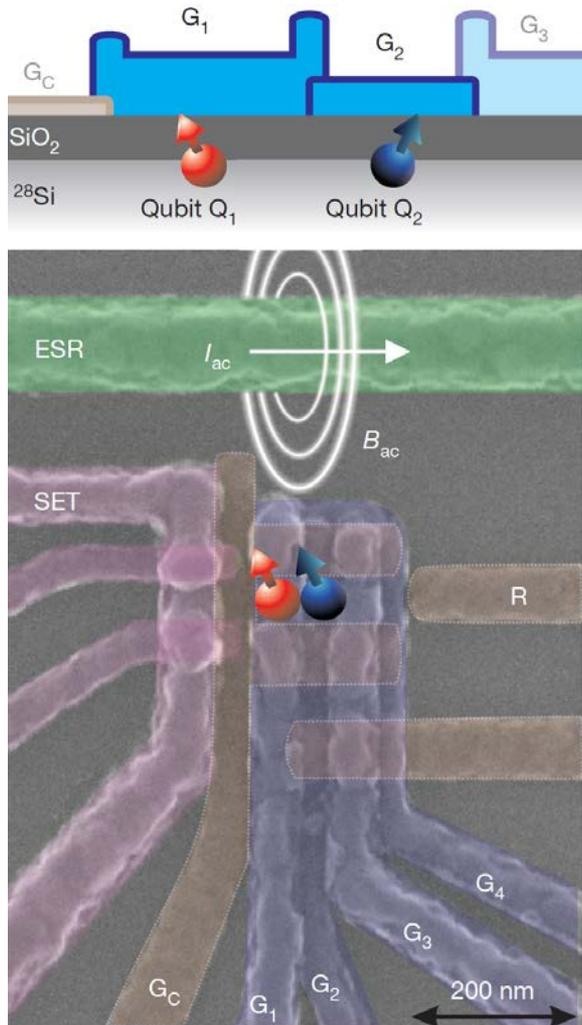


SET電荷センサ

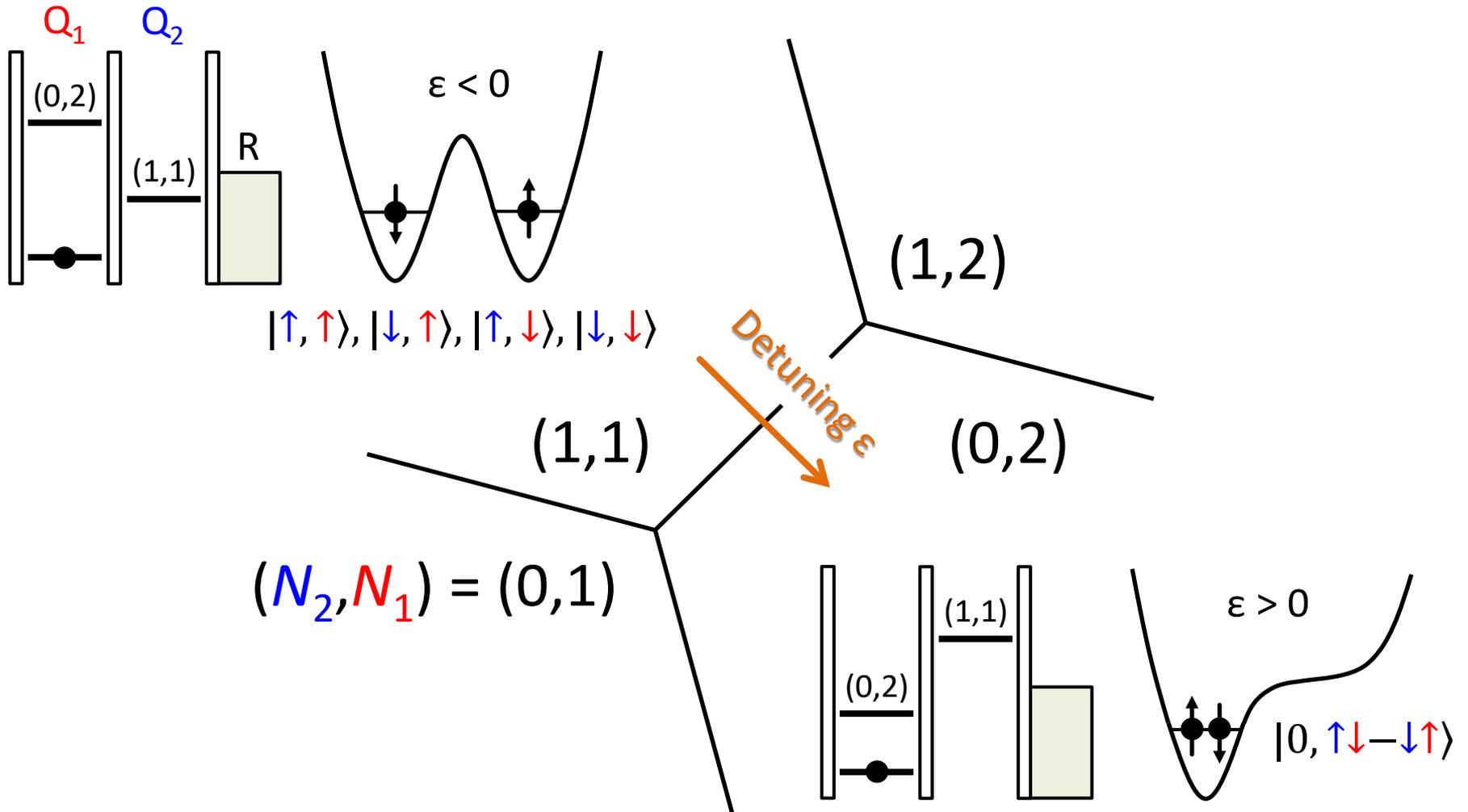


近傍のQDsの電子数変化に
鋭敏に応答

MOS型2重量子ドット

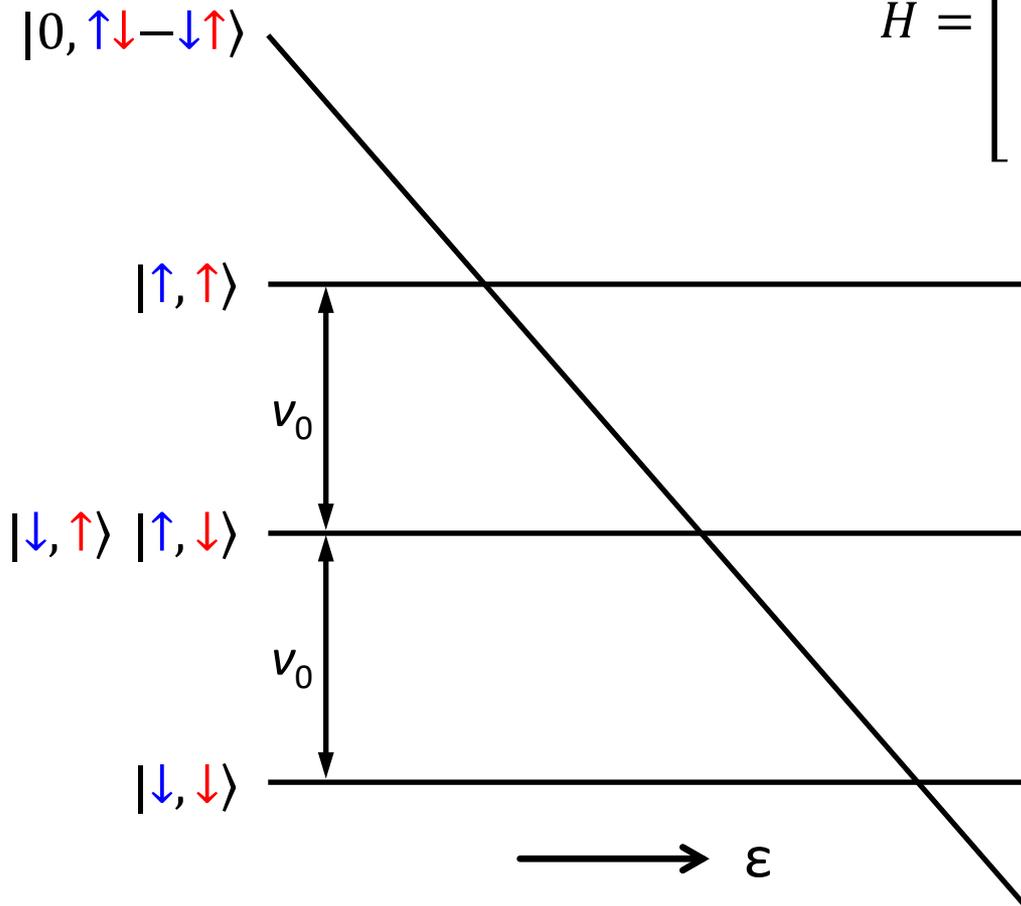


2電子状態



2電子状態

$$H = \begin{bmatrix} U - \varepsilon & 0 & 0 & 0 & 0 \\ 0 & E_z & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -E_z \end{bmatrix}$$

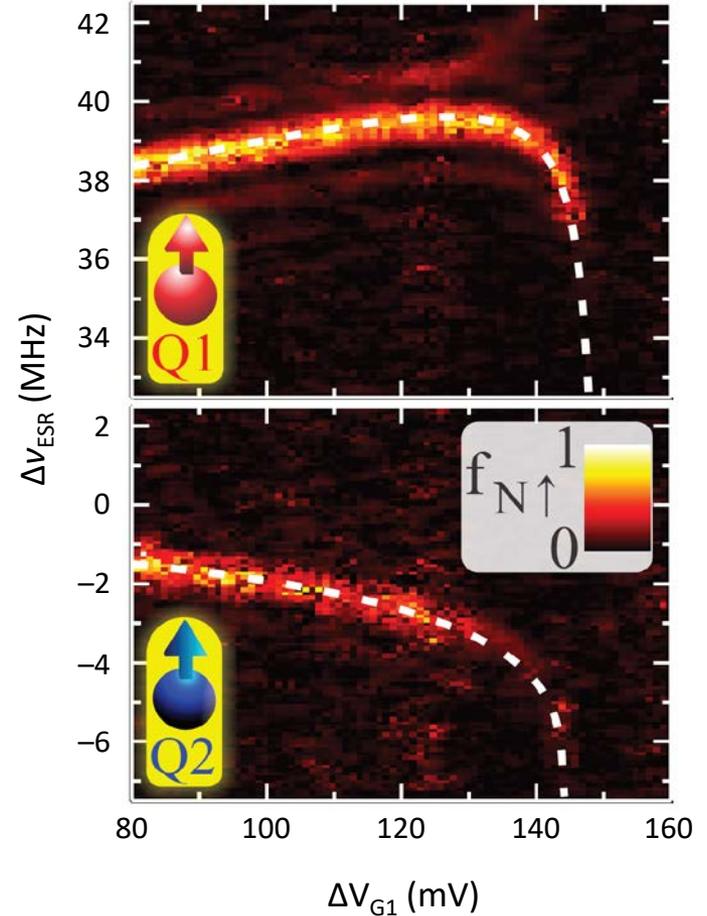
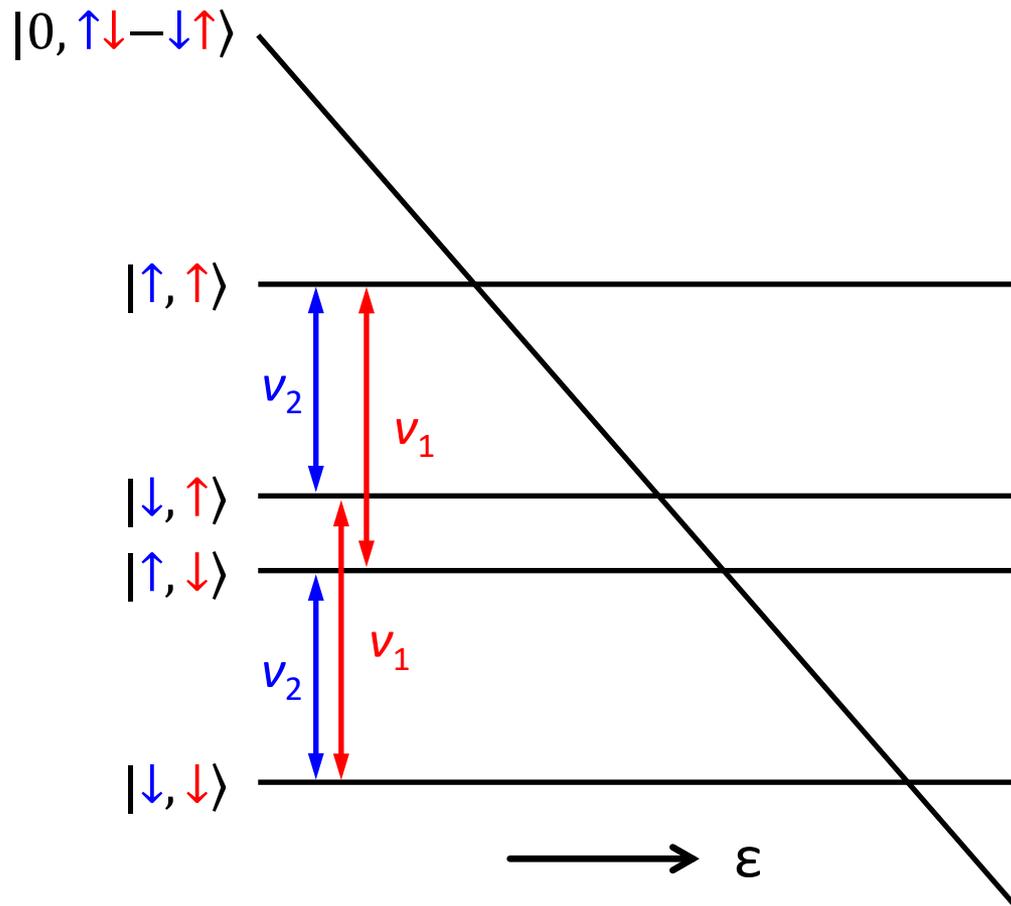


$$E_z = \gamma_e B_0 = h\nu_0$$

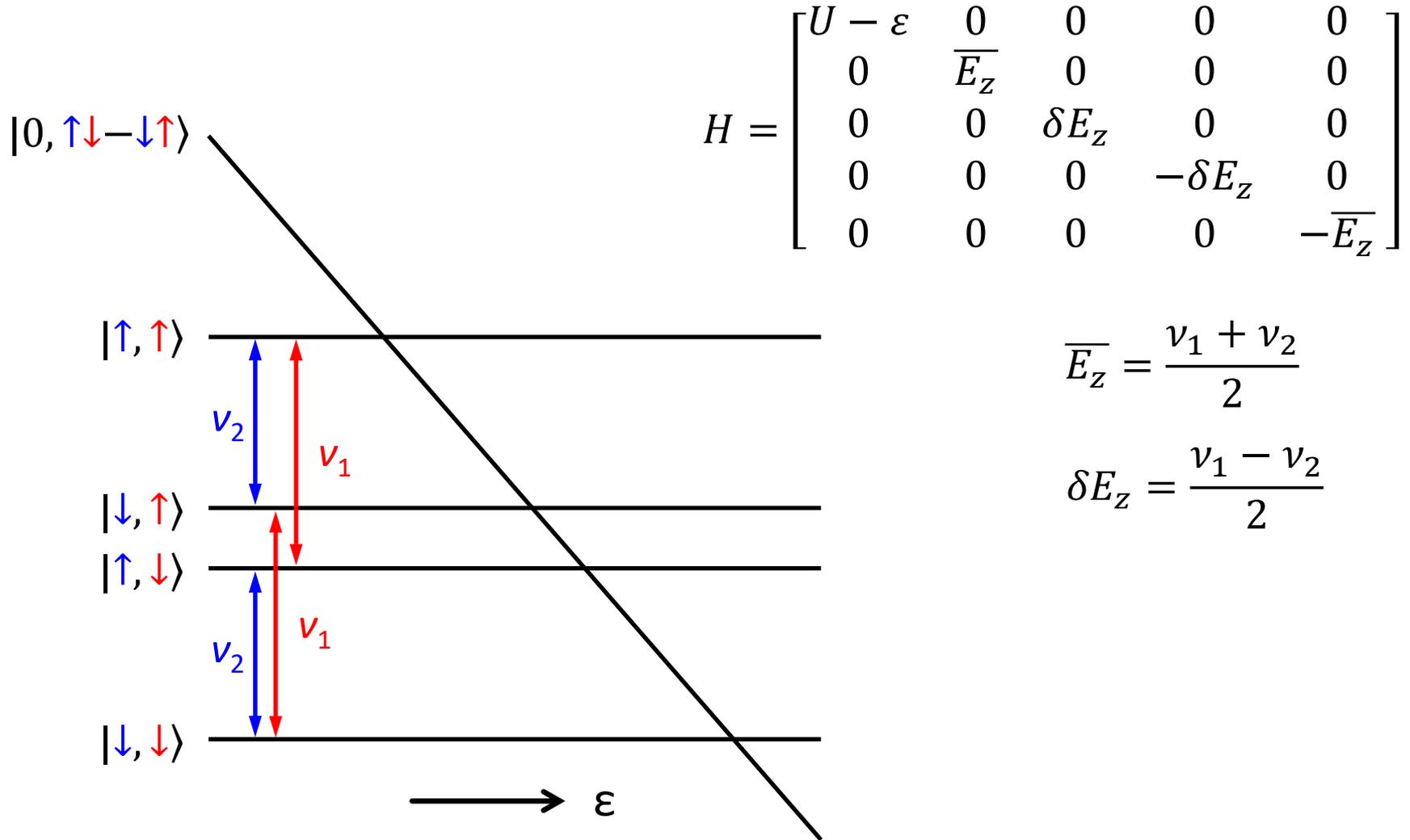
$$\nu_0 = 39.14 \text{ GHz @ } B_0 = 1.4 \text{ T}$$

2電子状態

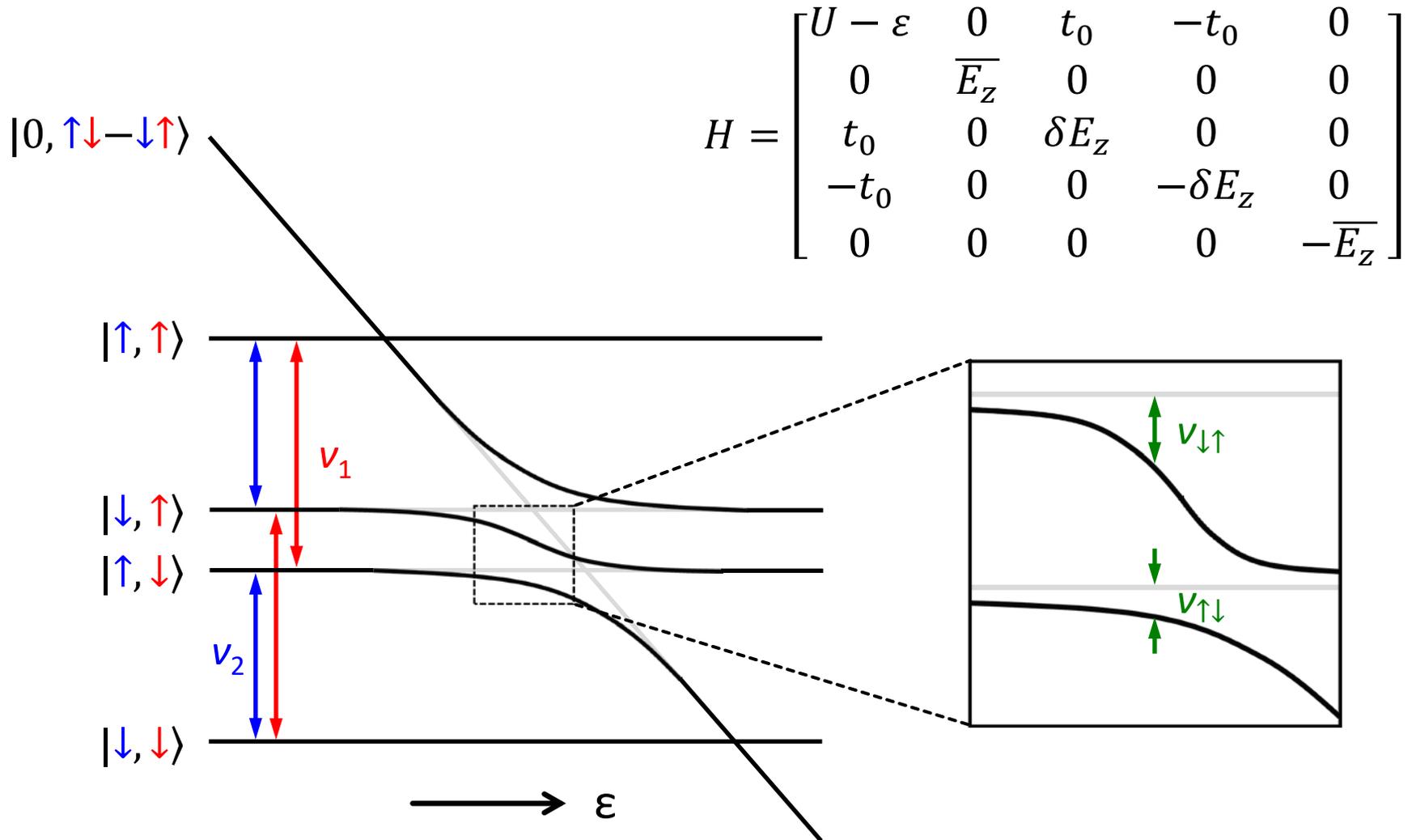
電場によるESR周波数制御: シュタルク効果



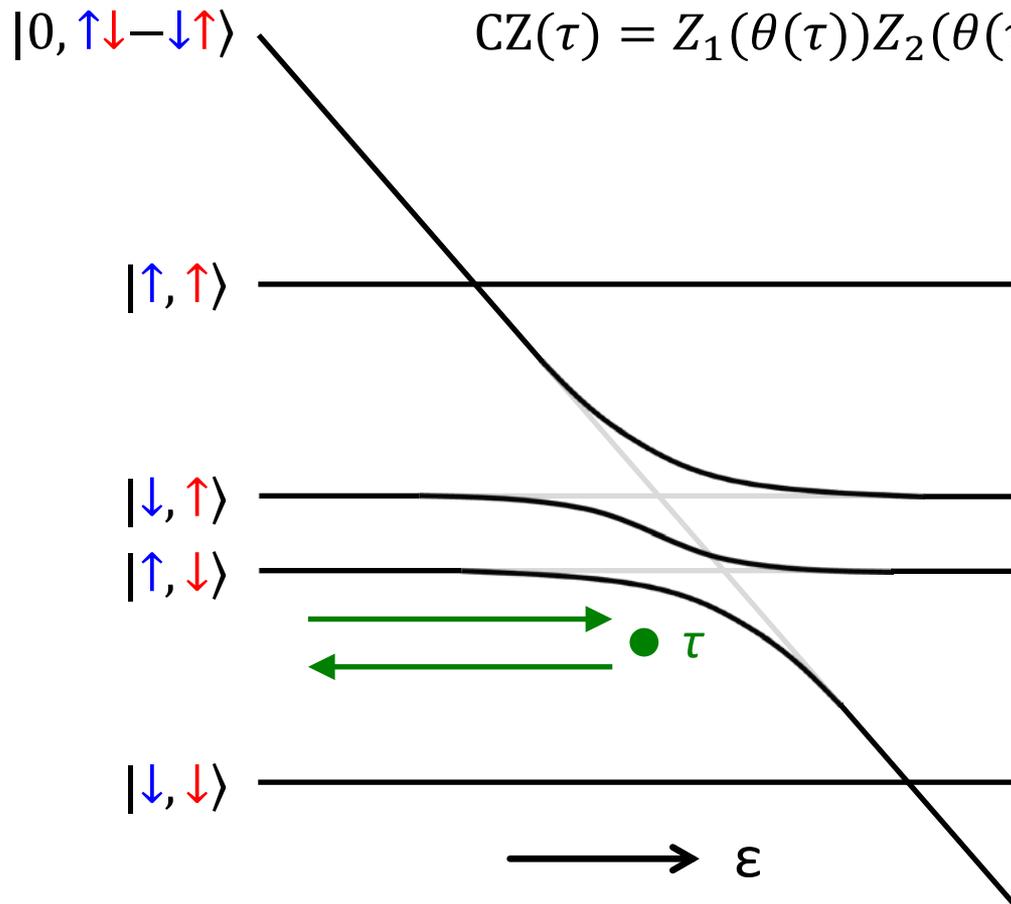
2電子状態



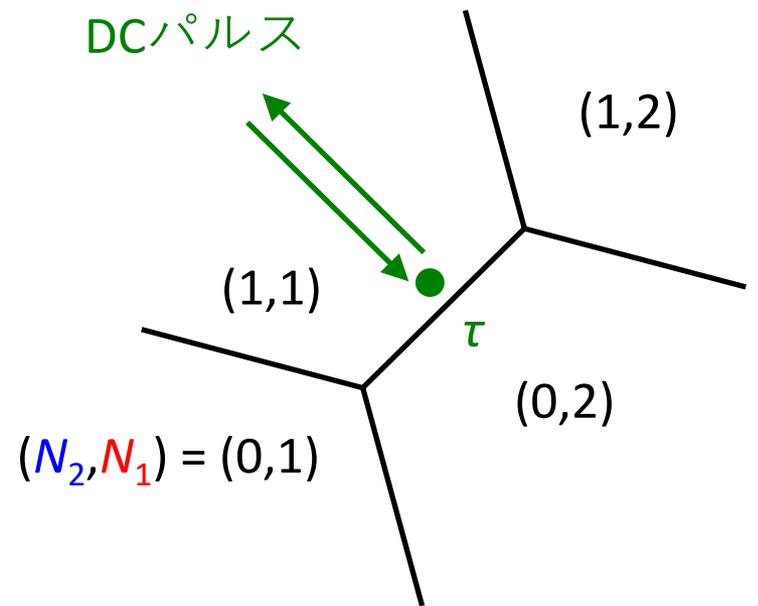
2電子状態



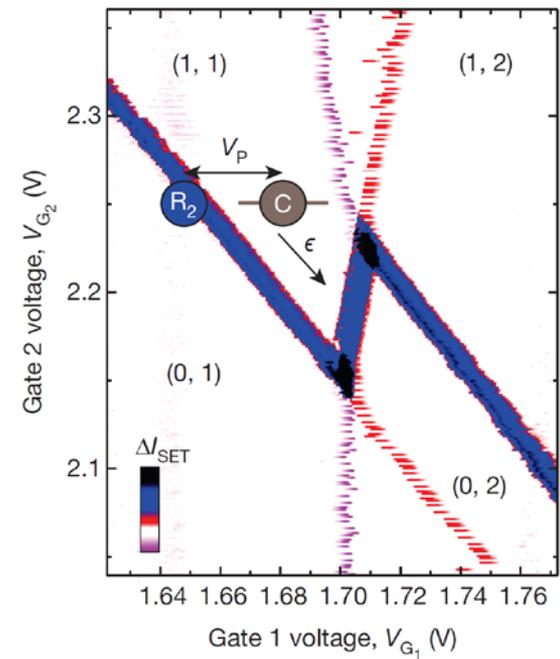
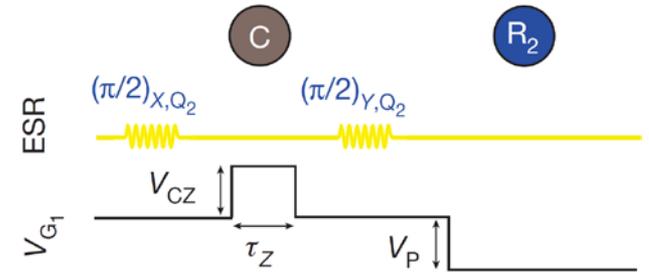
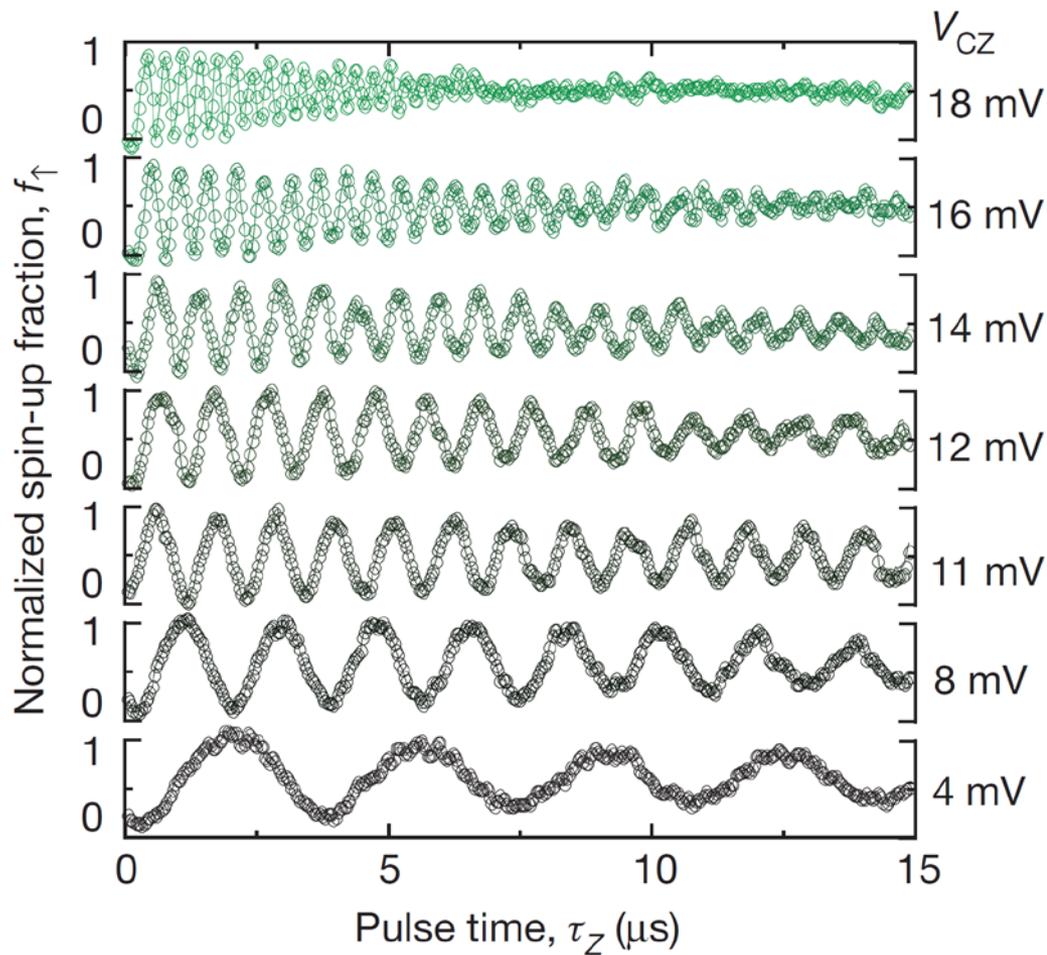
CZゲート



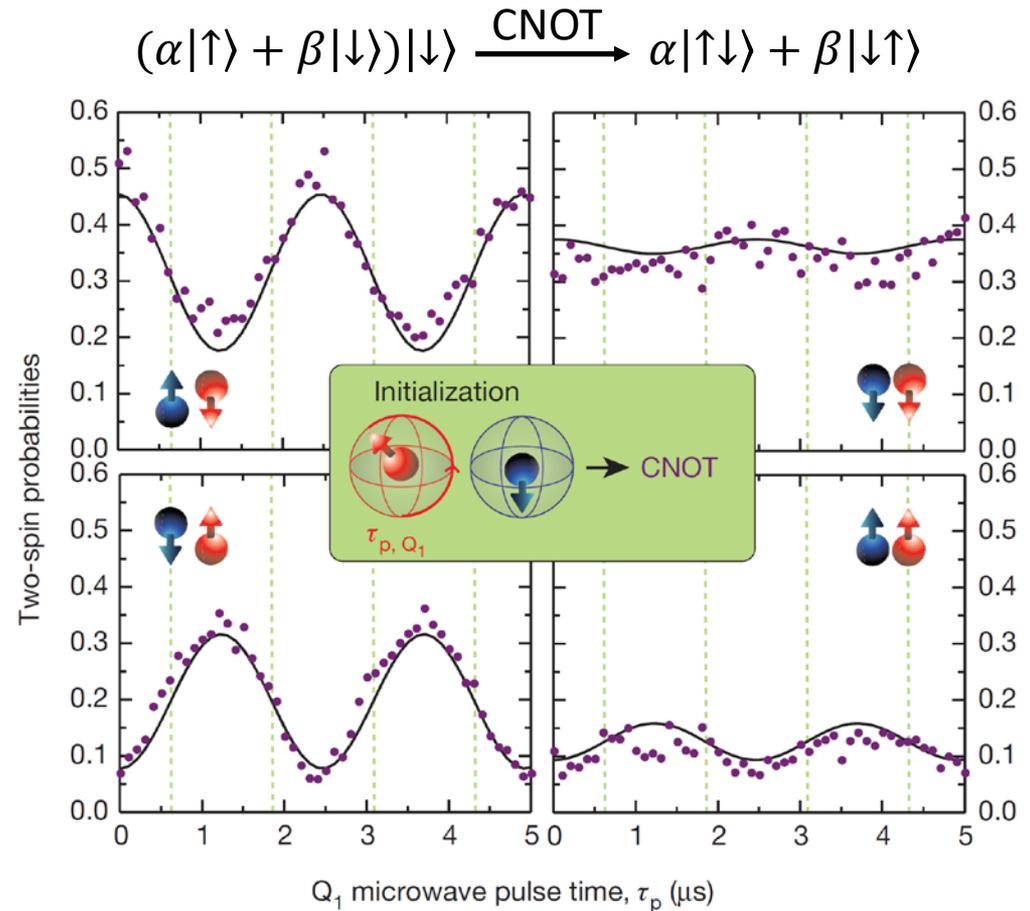
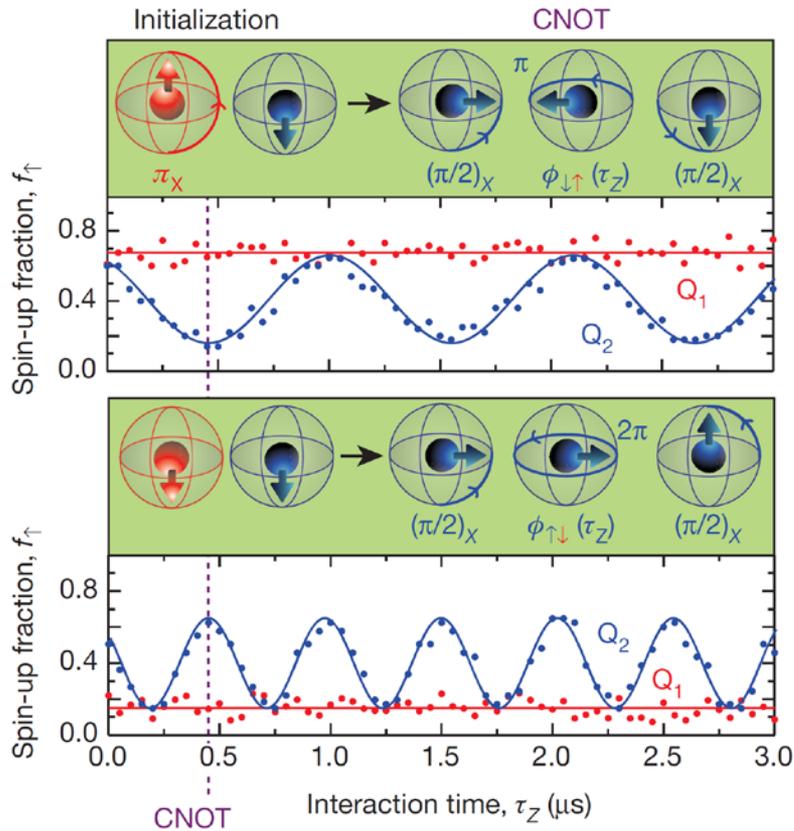
$$CZ(\tau) = Z_1(\theta(\tau))Z_2(\theta(\tau)) \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & e^{-i2\pi\nu_{\downarrow\uparrow}\tau} & 0 & 0 \\ 0 & 0 & e^{-i2\pi\nu_{\uparrow\downarrow}\tau} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$



CZゲート

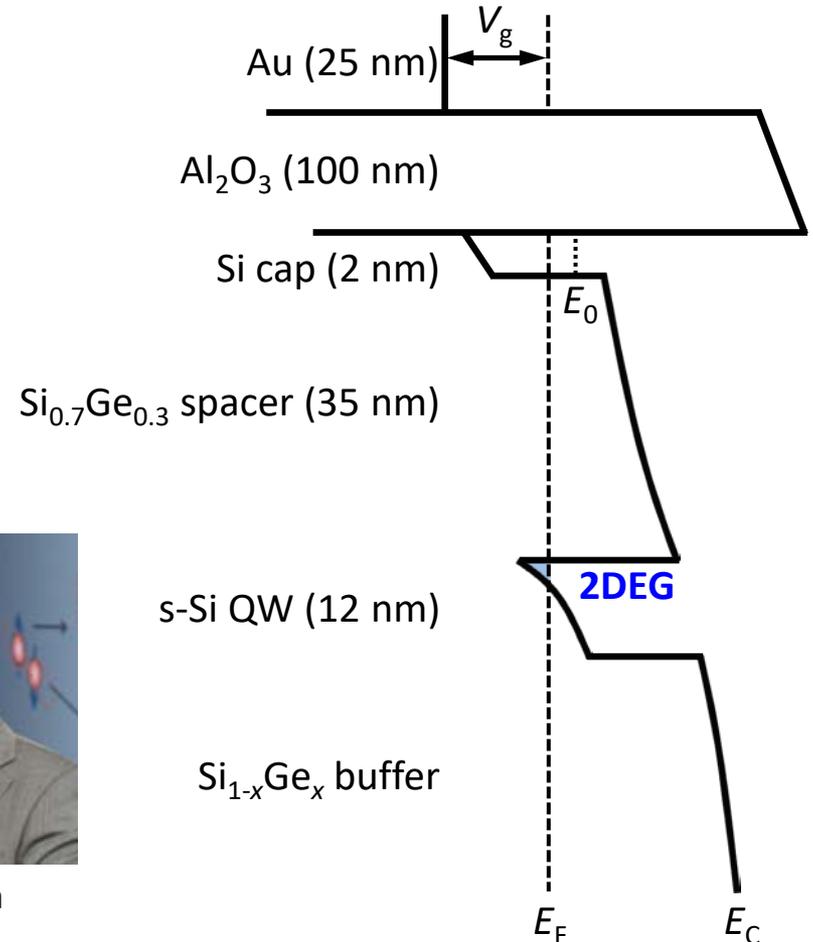
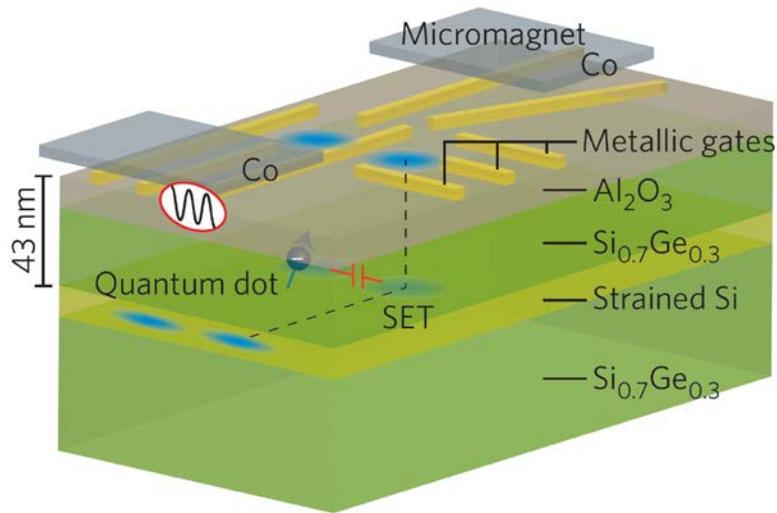


CNOTゲート



Si/SiGeへテロ構造

ノンドープ構造による蓄積型QD



L. Vandersypen
(©QuTech, TU Delft)



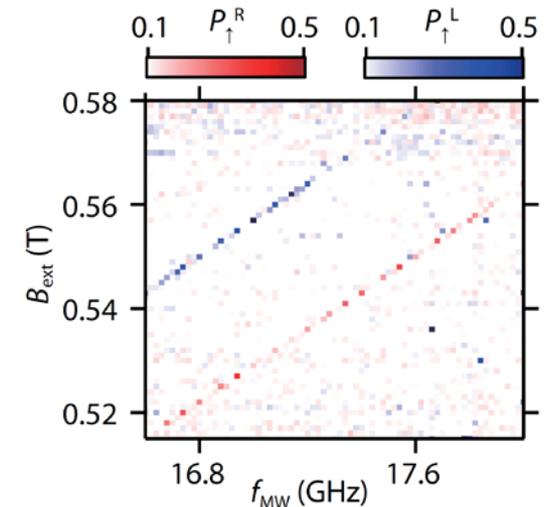
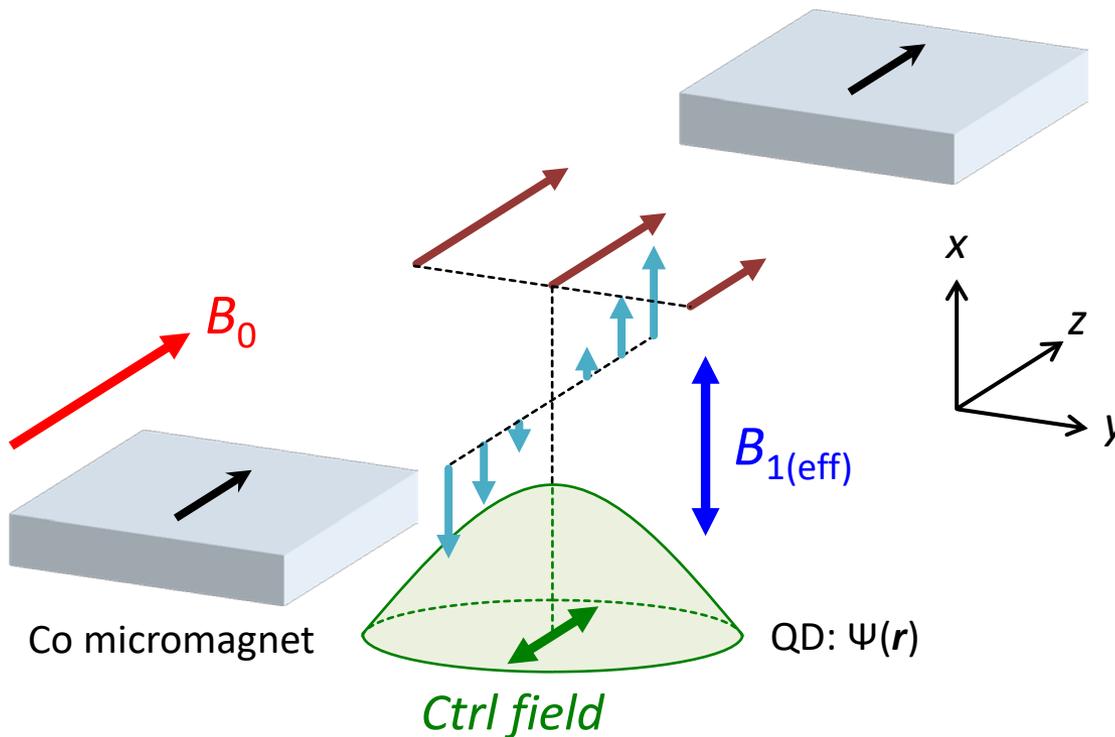
J. Petta
(©Princeton)



S. Tarucha
(©RIKEN)

電気双極子スピン共鳴

- **y方向の磁場勾配**によって共鳴周波数を制御
- **±z方向に電子波動関数を“揺する”**ことで**x方向に実効的な交流磁場**を生成



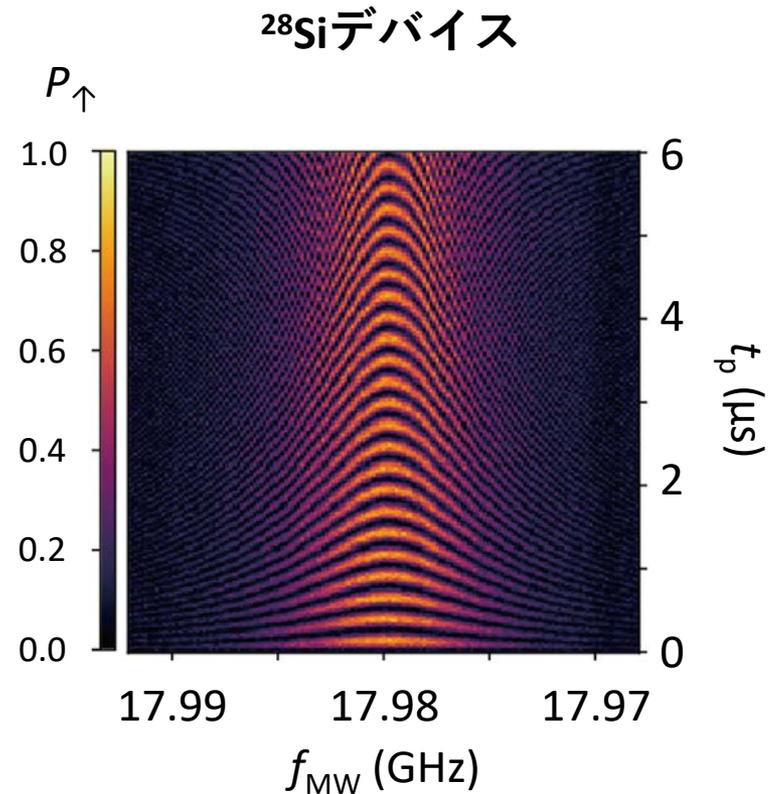
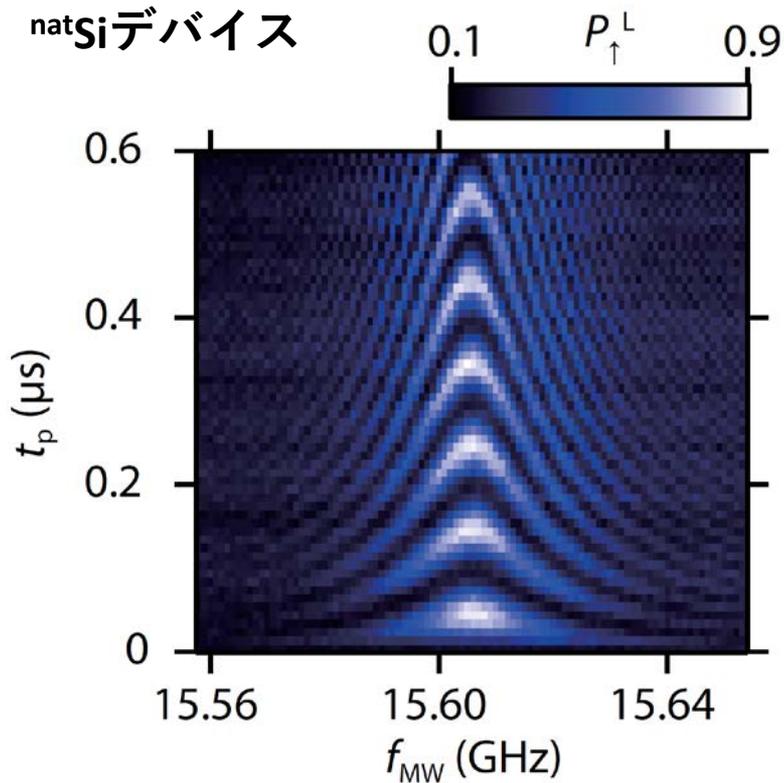
Sci. Adv. **2**, e1600694 (2016) Takeda *et al.*

(Theory) Phys. Rev. Lett. **96**, 047202 (2006) Tokura *et al.*

(GaAs QD) Nature Phys. **4**, 776 (2008) Pioro-Ladrière *et al.*

(Magnet design) Appl. Phys. Express **8**, 084401 (2015) Yoneda *et al.*

電気双極子スピン共鳴

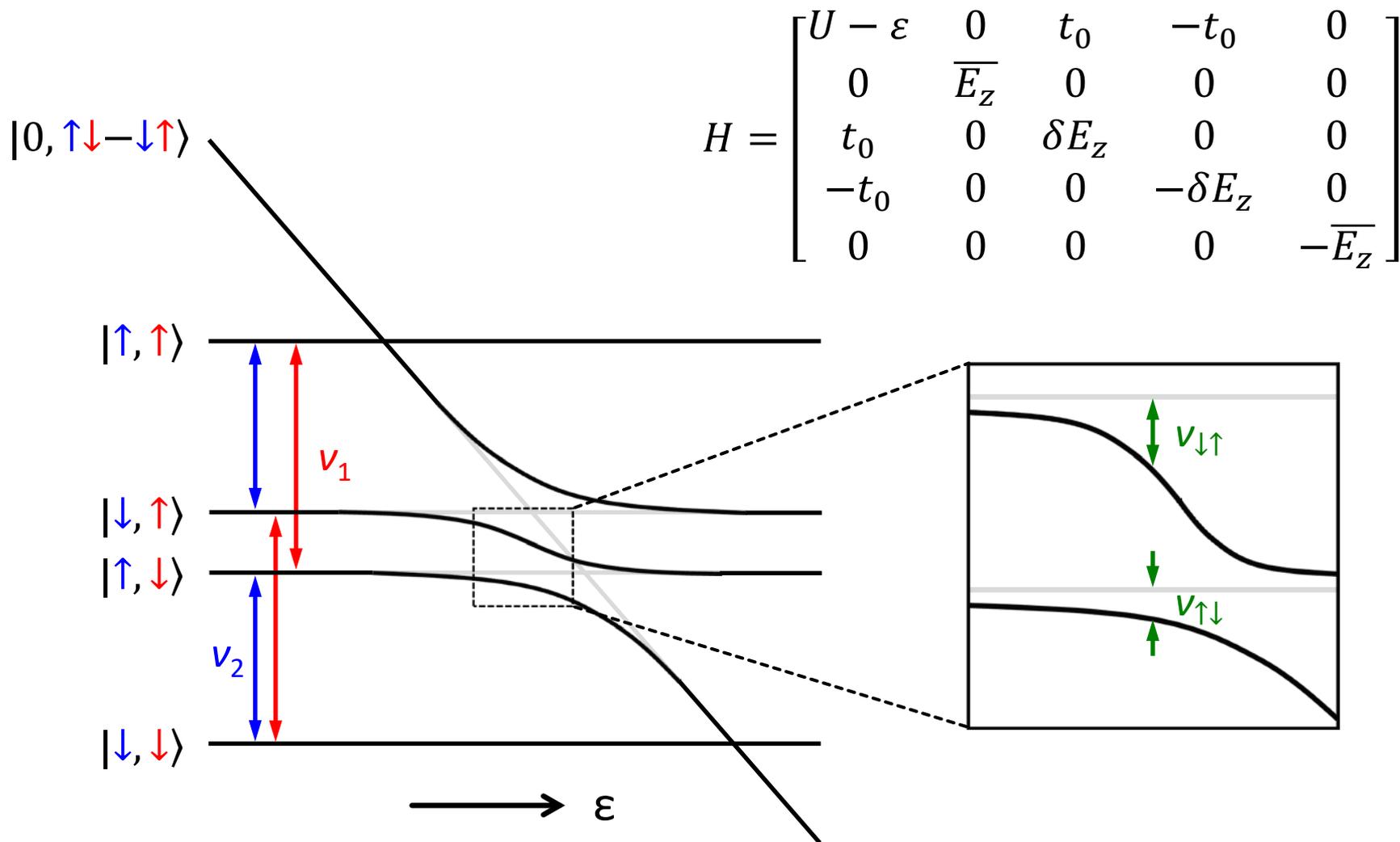


- ラビ周波数 $f_R \approx 30$ MHz
- フィデリティ $F^{\text{RB}} = 99.6\% \rightarrow > 99.9\%$
- $T_2^* = 2 \mu\text{s} \rightarrow 20 \mu\text{s}$, $T_2^{\text{CPMG}} = 3.1$ ms

Sci. Adv. **2**, e1600694 (2016) Takeda *et al.*

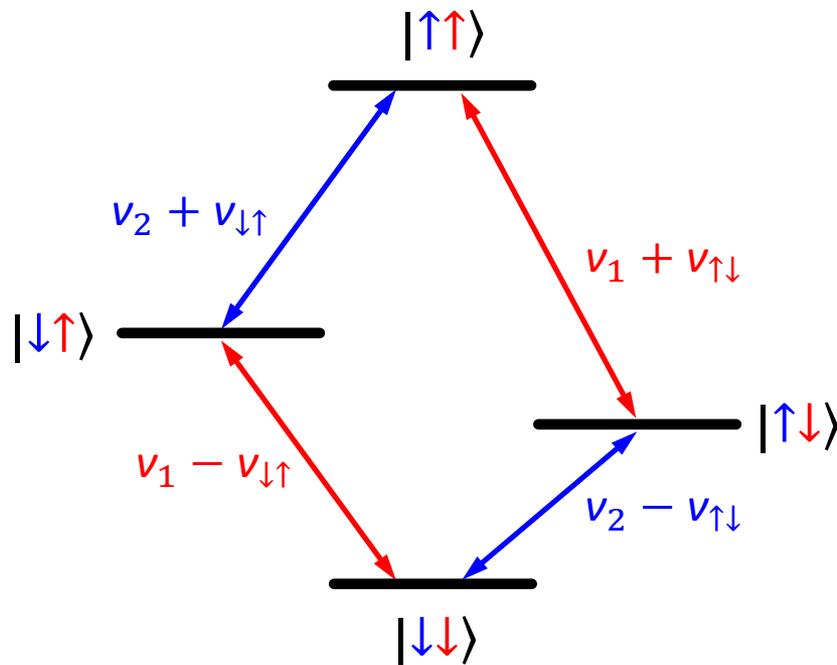
Nature Nano. **13**, 102 (2018) Yoneda *et al.*

2量子ビットゲート



CROT(制御回転)ゲート

- $\varepsilon \rightarrow 0$ では全ての遷移が異なる周波数を持つ



CROT(制御回転)ゲート

- $\epsilon \rightarrow 0$ では全ての遷移が異なる周波数を持つ
- 選択励起の π パルスにより2量子ビットゲートが実現可能

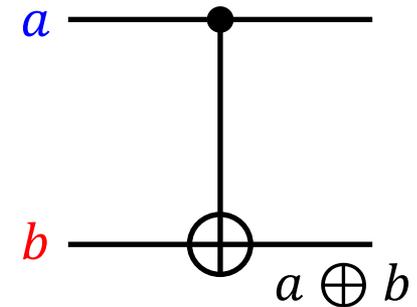
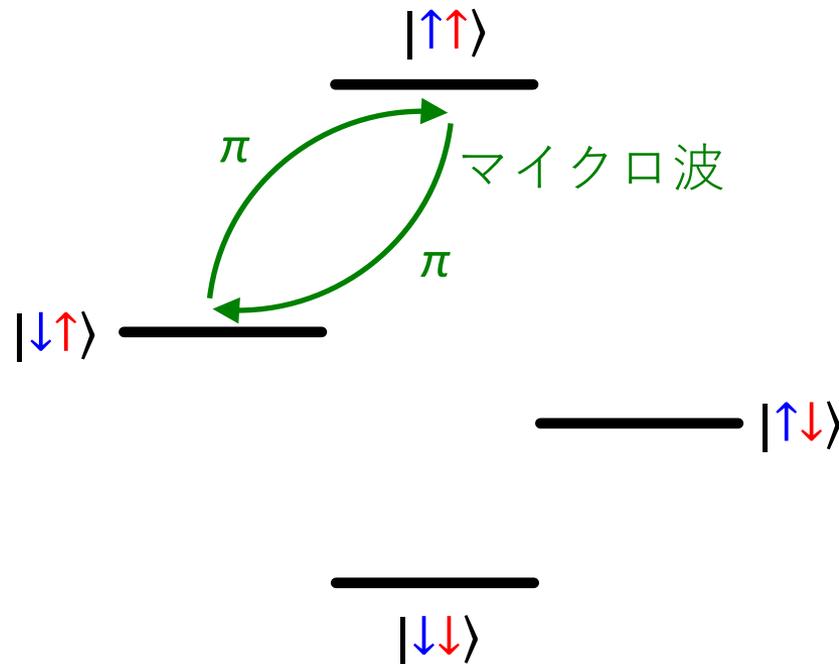
e.g. CNOTゲート

$$|\uparrow\uparrow\rangle = |11\rangle \longrightarrow |10\rangle$$

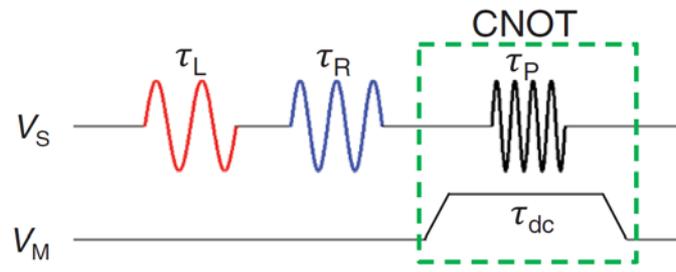
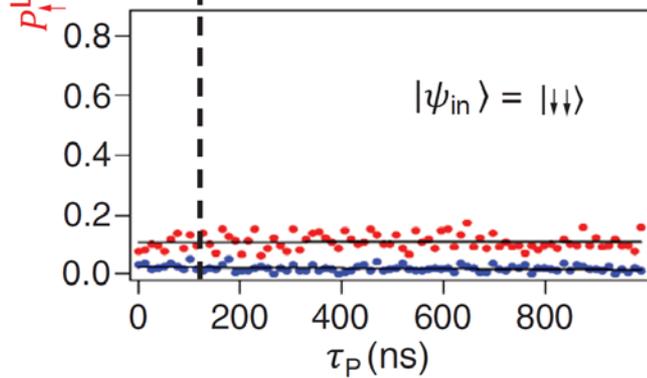
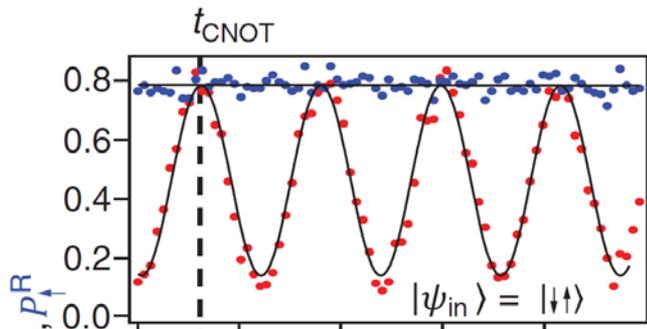
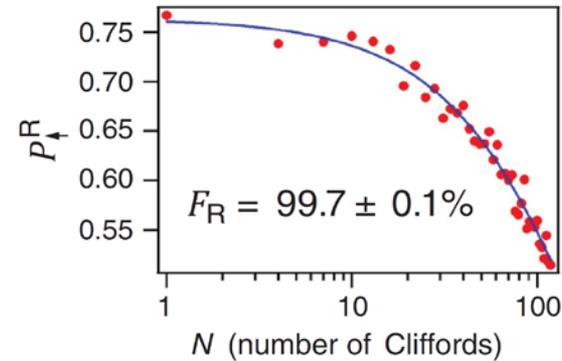
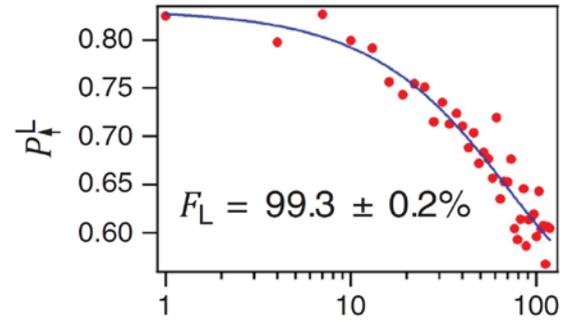
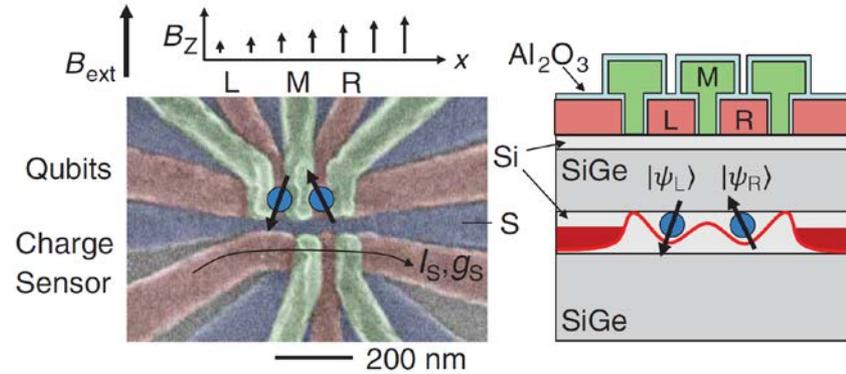
$$|\uparrow\downarrow\rangle = |10\rangle \longrightarrow |11\rangle$$

$$|\downarrow\uparrow\rangle = |01\rangle \longrightarrow |10\rangle$$

$$|\downarrow\downarrow\rangle = |00\rangle \longrightarrow |00\rangle$$

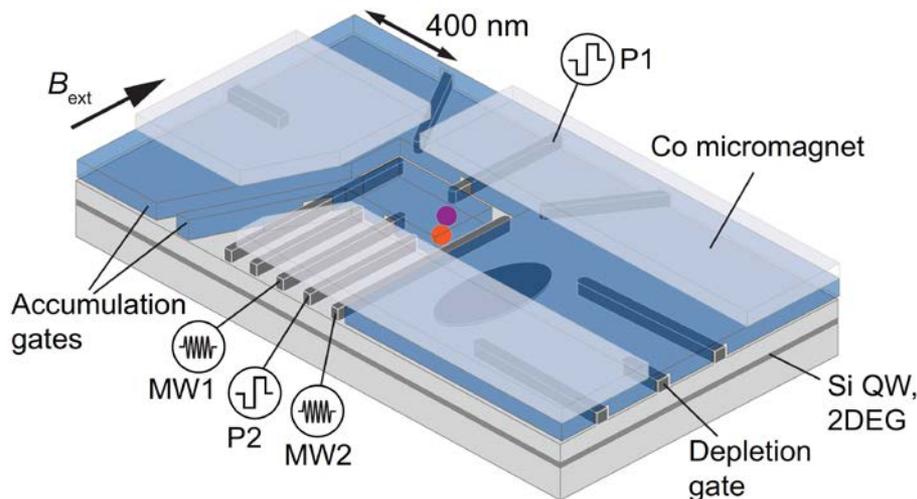
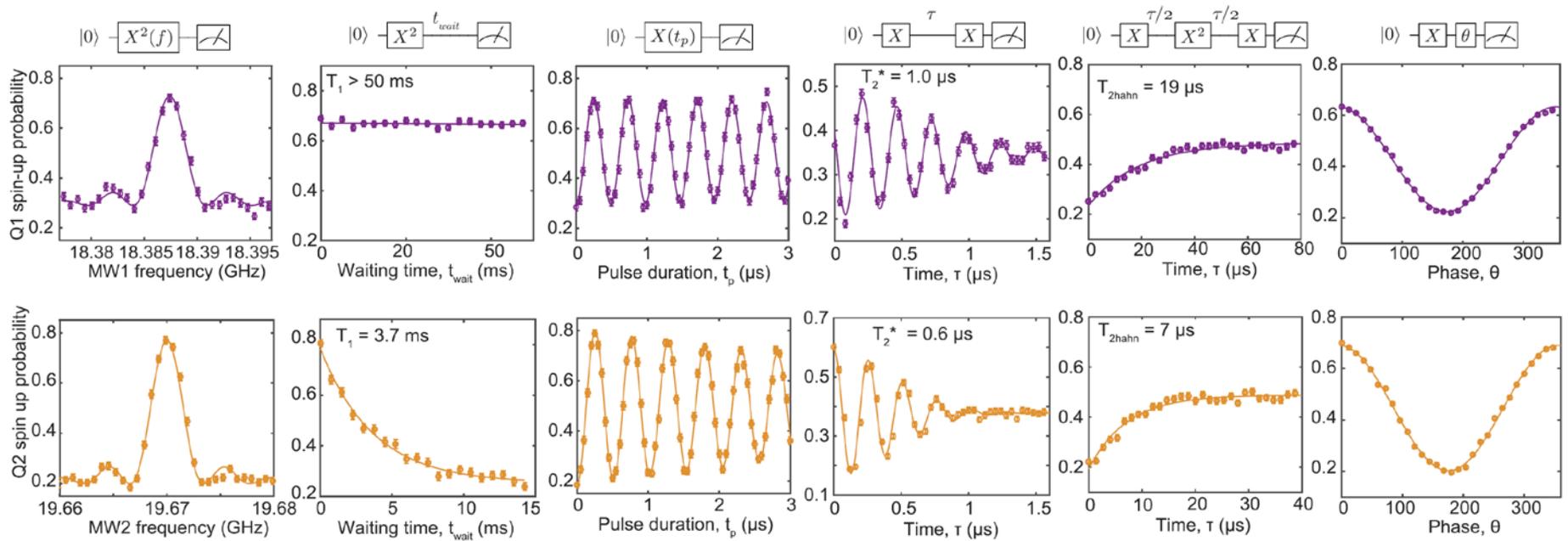


CNOTゲート

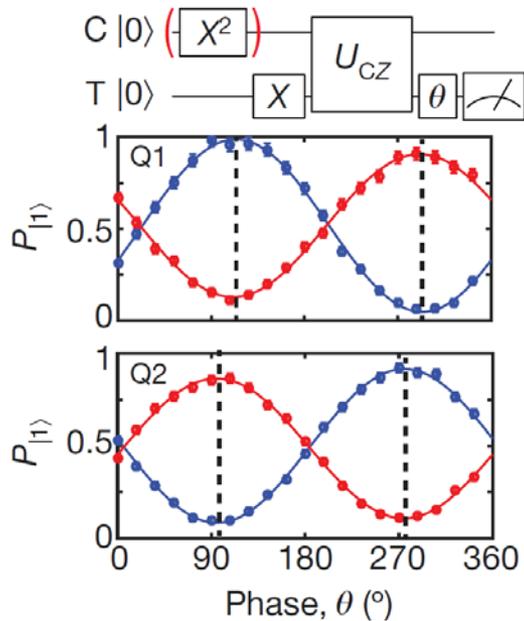


$F^{Bell} = 78\%$

2量子ビットプロセッサ

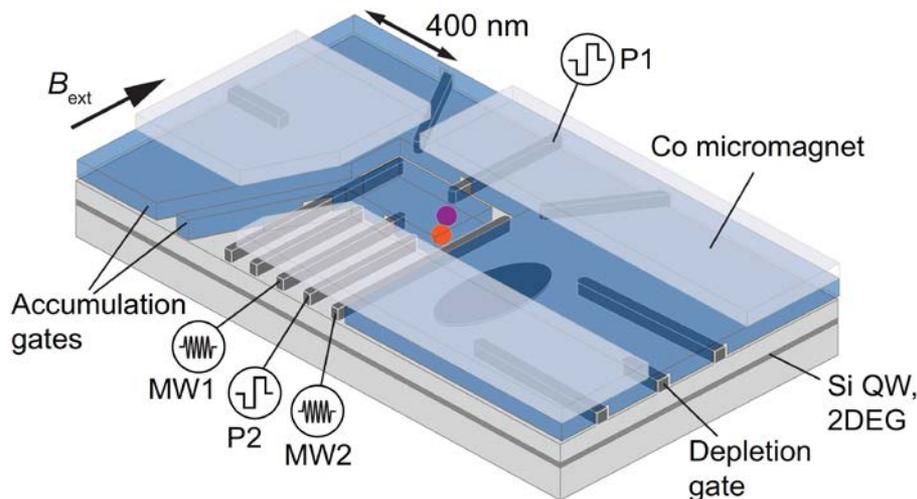
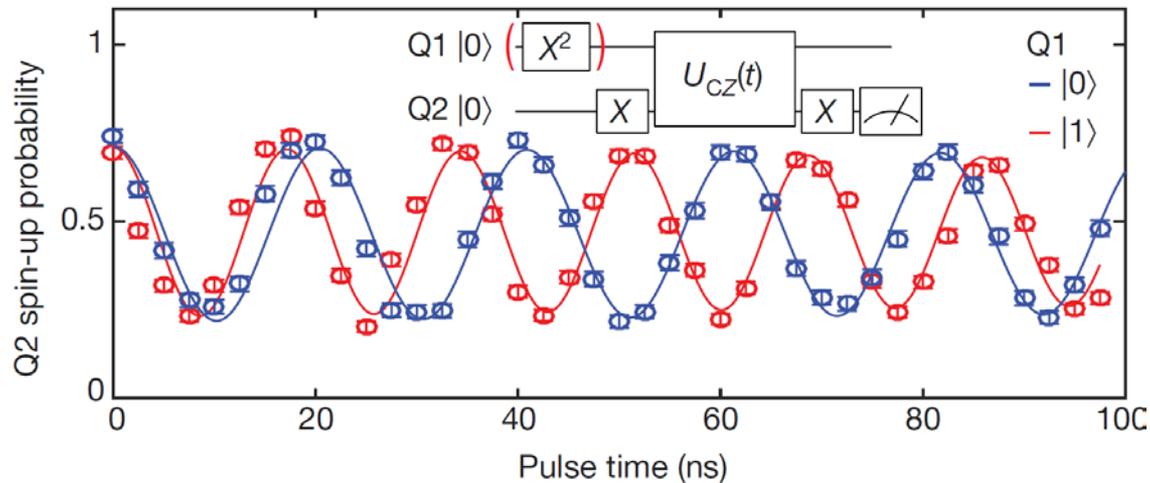


2量子ビットプロセッサ

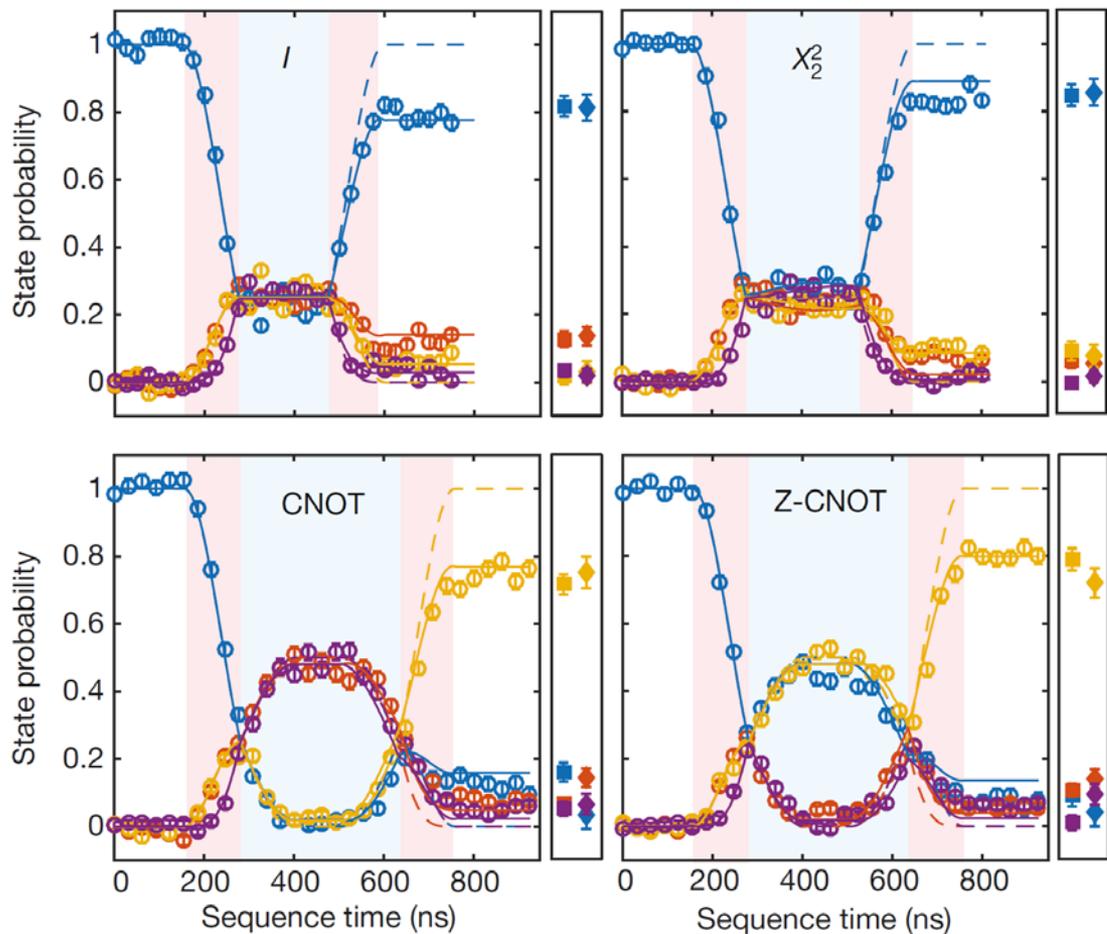


Q2
— $|0\rangle$
— $|1\rangle$

Q1
— $|0\rangle$
— $|1\rangle$

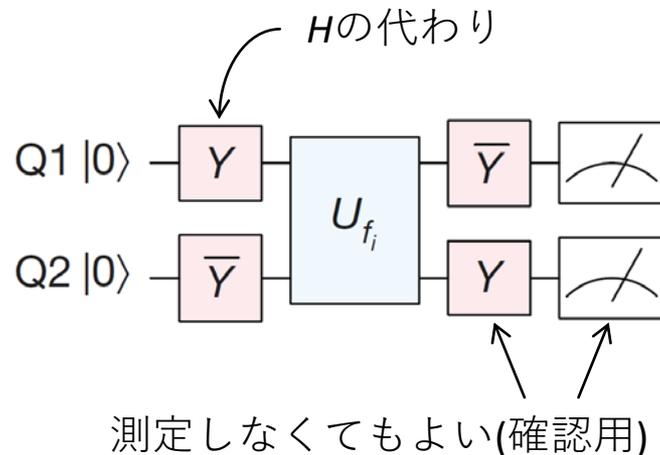


ドイチュ・ジョザアルゴリズムの実行



○ Experiment - - - Ideal ——— With noise

● |00> ● |01> ● |10> ● |11>



シリコンスピンの実験の現状

方式	1量子ビット	2量子ビット	多量子ビット化
単一リンドナー	$T_{2e}^{\text{CPMG}} = 559 \text{ ms}$ $T_{2n+}^{\text{CPMG}} = 35.6 \text{ s}$ $F_{2n+} = 99.99\% (*1)$	N/A cf. $F^{\text{Bell}(e-n)} = 97\% (*4)$	“フリップフロップ” 量子ビット(*7)
MOS量子ドット	$T_2^{\text{CPMG}} = 28 \text{ ms}$ $F^{\text{RB}} = 99.6\% (*2)$	CNOT (*5)	CMOS/DRAM技術 との融合(*8,9)
Si/SiGe量子ドット	$T_2^{\text{CPMG}} = 3.1 \text{ ms}$ $F^{\text{RB}} > 99.9\% (*3)$	$F^{\text{Bell}} = 89\% (*6)$	スピン-MW光子結合 による回路QED(*10,11)

*1: Nature Nano. **9**, 986 (2014) Muhonen *et al.*

*2: Nature Nano. **9**, 981 (2014) Veldhorst *et al.*

*3: Nature Nano. **13**, 102 (2018) Yoneda *et al.*

*4: Nature Nano. **11**, 242 (2016) Dehollain *et al.*

*5: Nature **526**, 410 (2015) Veldhorst *et al.*

*6: Nature **555**, 633 (2018) Watson *et al.*

*7: Nature Commun. **8**, 450 (2017) Tosi *et al.*

*8: Nature Commun. **8**, 1766 (2017) Veldhorst *et al.*

*9: arXiv:1711.03807 Li *et al.*

*10: Nature **555**, 599 (2018) Mi *et al.*

*11: Science **359**, 1123 (2018) Samkharadze *et al.*

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