

固体素子による量子技術: シリコン

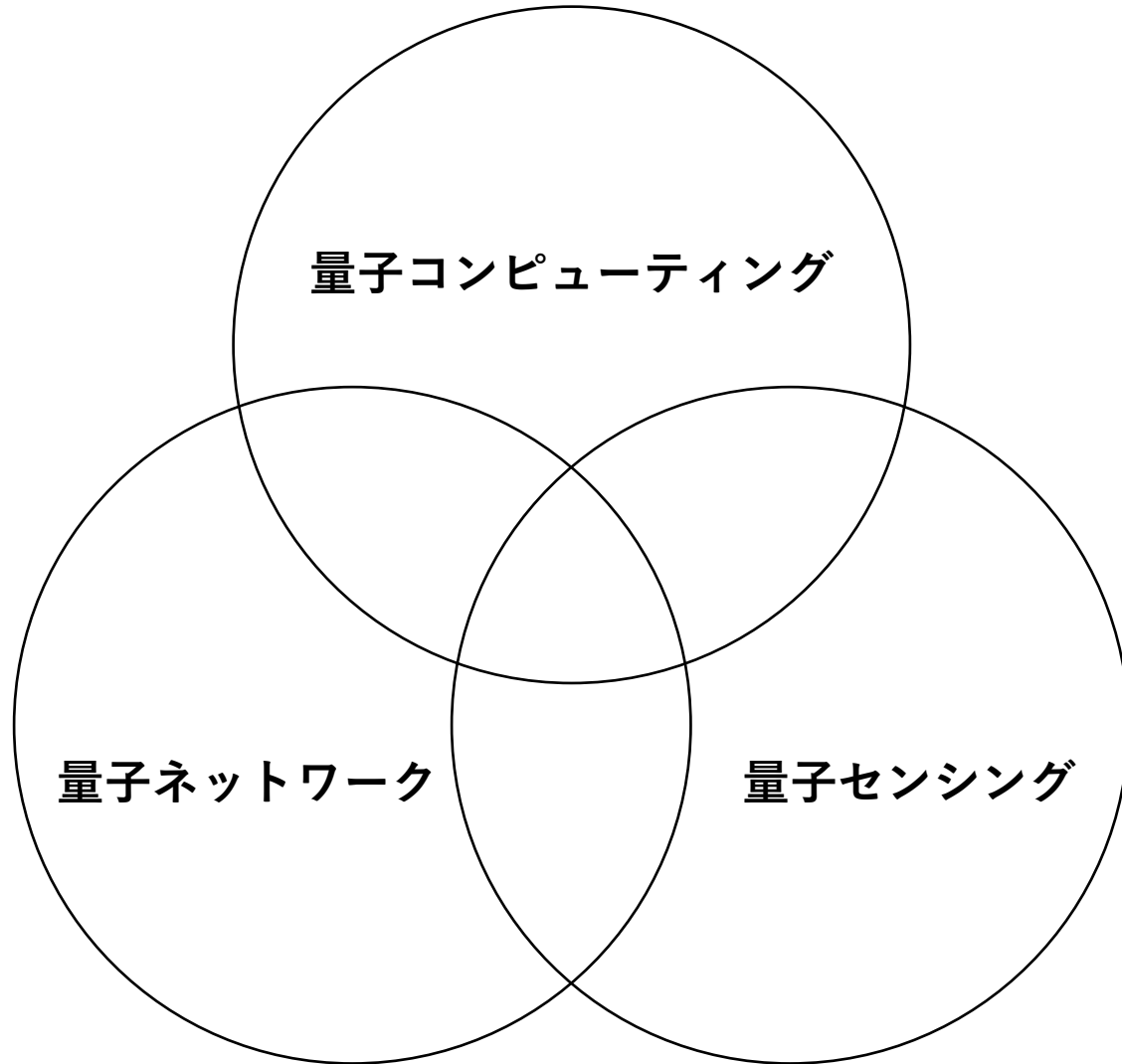
阿部 英介

理化学研究所 創発物性科学研究センター

応用物理情報特別講義A

2019年度春学期後半 金曜4限@14-202

量子技術

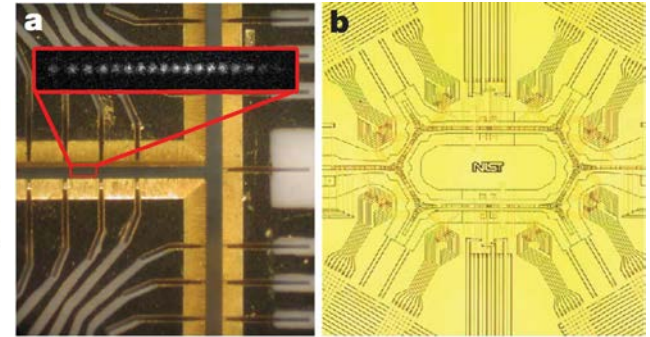
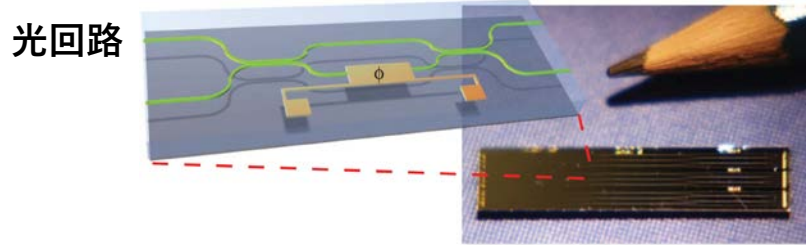


量子コンピューティング

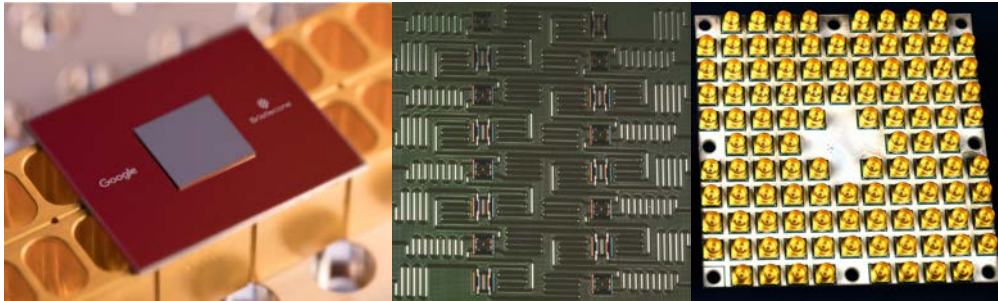
量子ネットワーク

量子センシング

量子技術のプラットフォーム



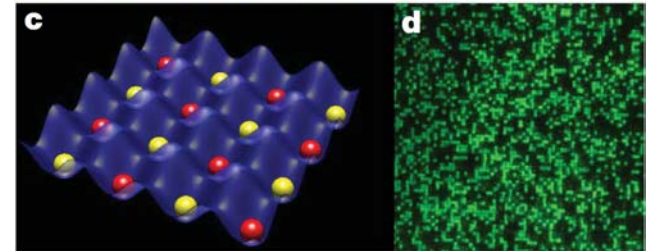
超伝導回路



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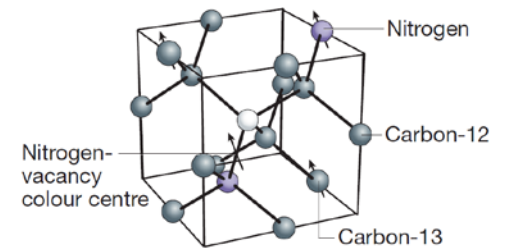
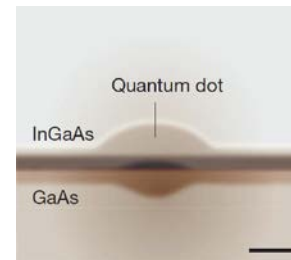
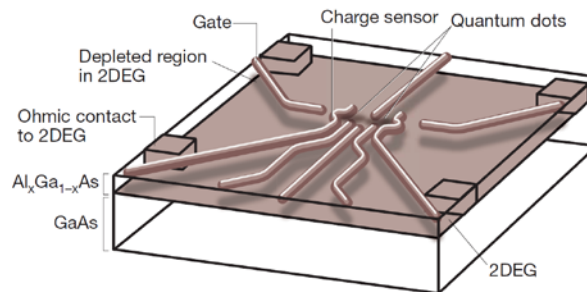
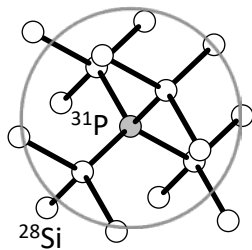
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捕捉イオン/冷却原子

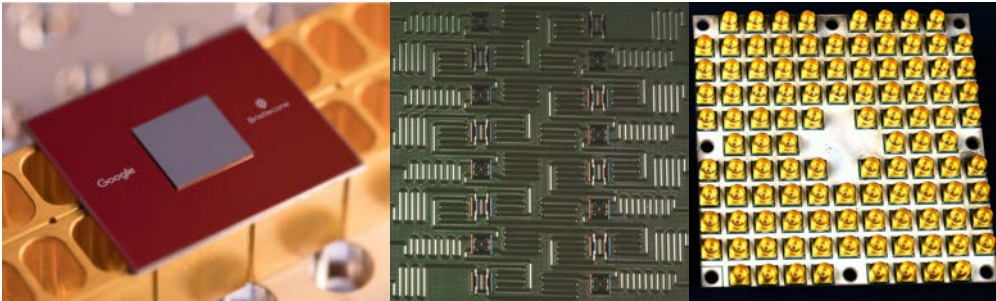
半導体スピン



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

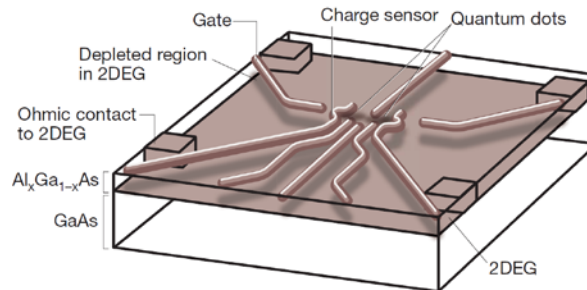
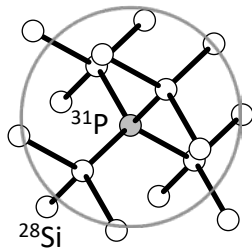


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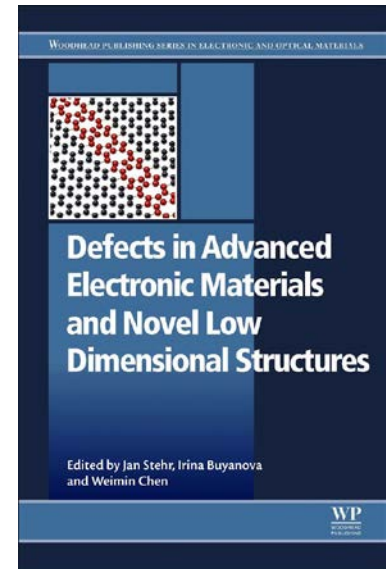
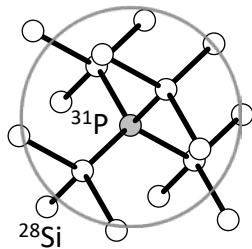
半導体スピン



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)

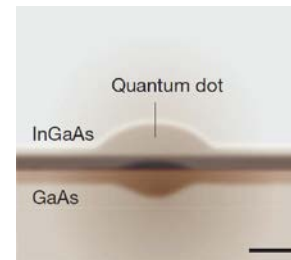
固体物理 **48 (11)**, 541 (2013) 山本 & 阿部

“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



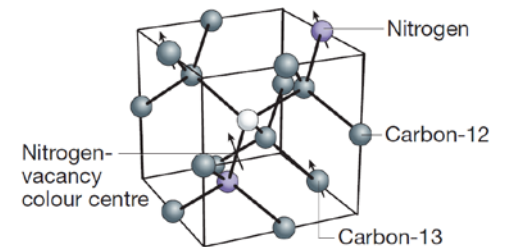
NEW DIAMOND **33 (2)**, 3 (2017) 阿部 & 伊藤

“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

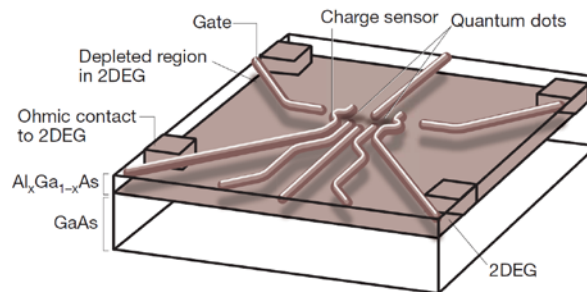
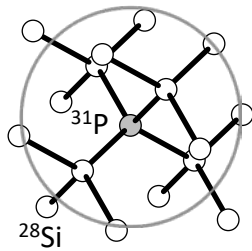
“Tutorial: Magnetic resonance with nitrogen-vacancy centers in diamond
—microwave engineering, materials science, and magnetometry”

半導体スピン



今回カバーする範囲

半導体スピン



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(**複製禁止定理**)
 - **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)

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.

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

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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

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

4. ユニバーサル量子ゲート

5. 射影測定

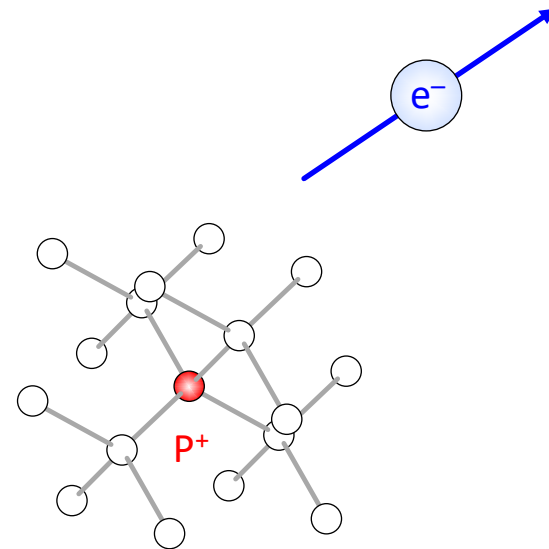
*1: Nature Mat. **11**, 143 (2012) Tyryshkin *et al.*

*2: Science **342**, 830 (2013) Saedi *et al.*

Fortschr. Phys. **48**, 771 (2000) DiVincenzo

シリコン中のリンドナー

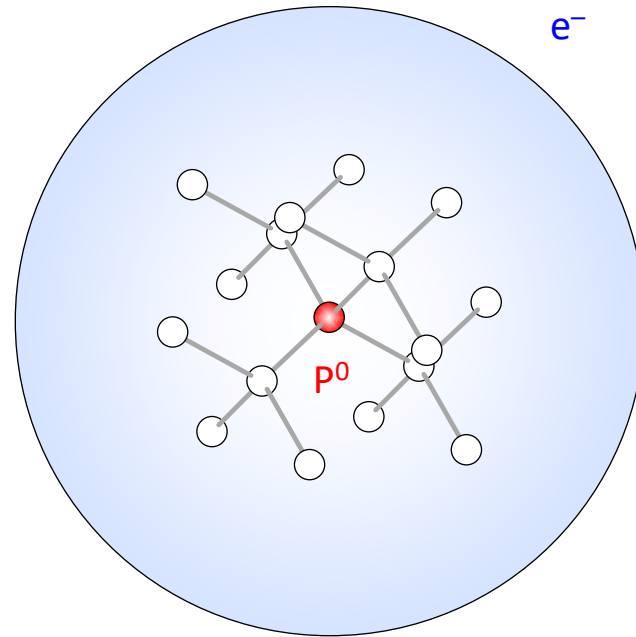
III (13)	IV (14)	V (15)
B	C	N
Al	Si	P
Ga	Ge	As



室温では100%イオン化
→ 自由電子として電気伝導に寄与

シリコン中のリンドナー

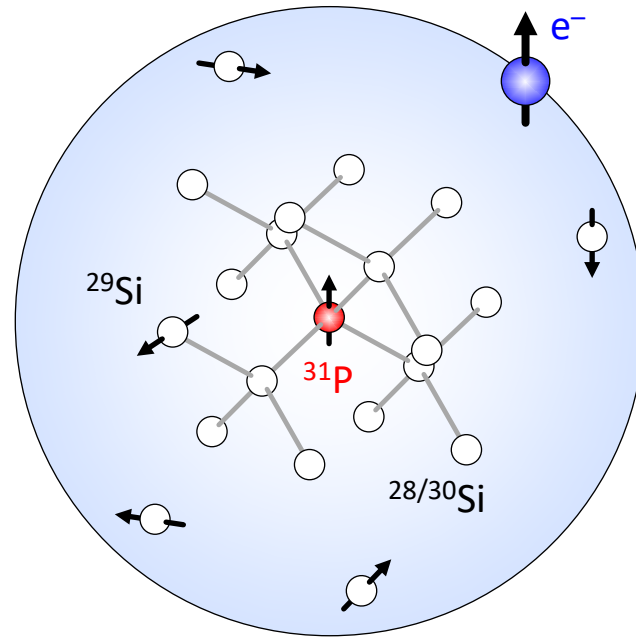
III (13)	IV (14)	V (15)
B	C	N
Al	Si	P
Ga	Ge	As



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



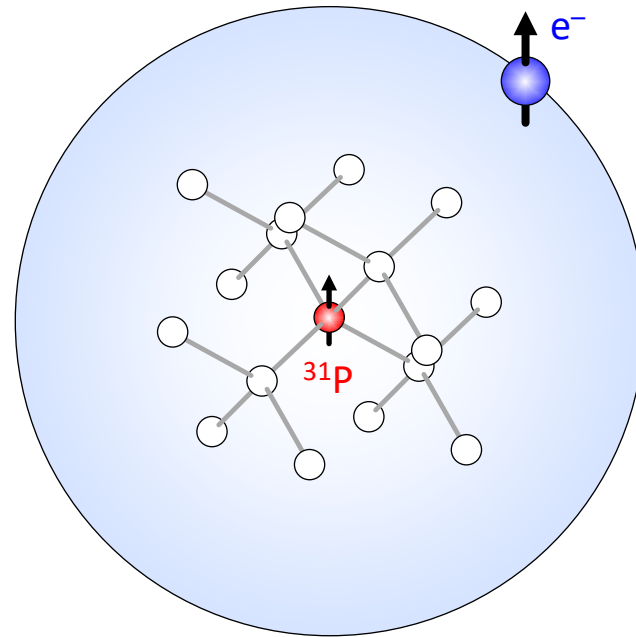
磁気環境

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

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

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

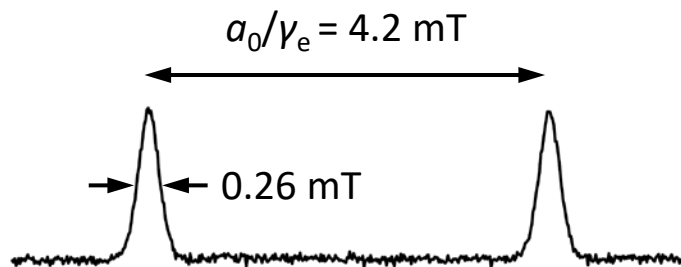
$$H_0 = \gamma_e B_0 S_z - \gamma_P B_0 I_z + a_0 S_z I_z$$

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

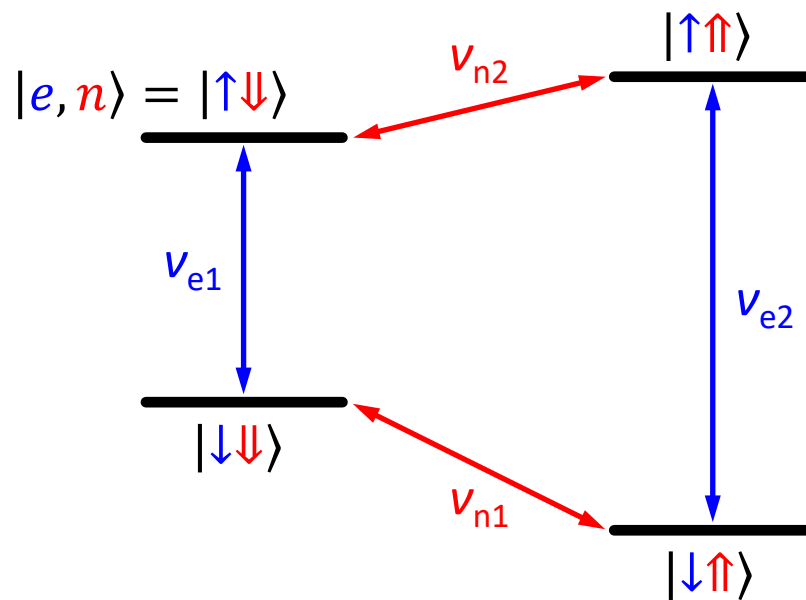
$$\gamma_e = 27.97 \text{ GHz/T}$$

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

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



アンサンブル電子スピン共鳴(natSi、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)

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

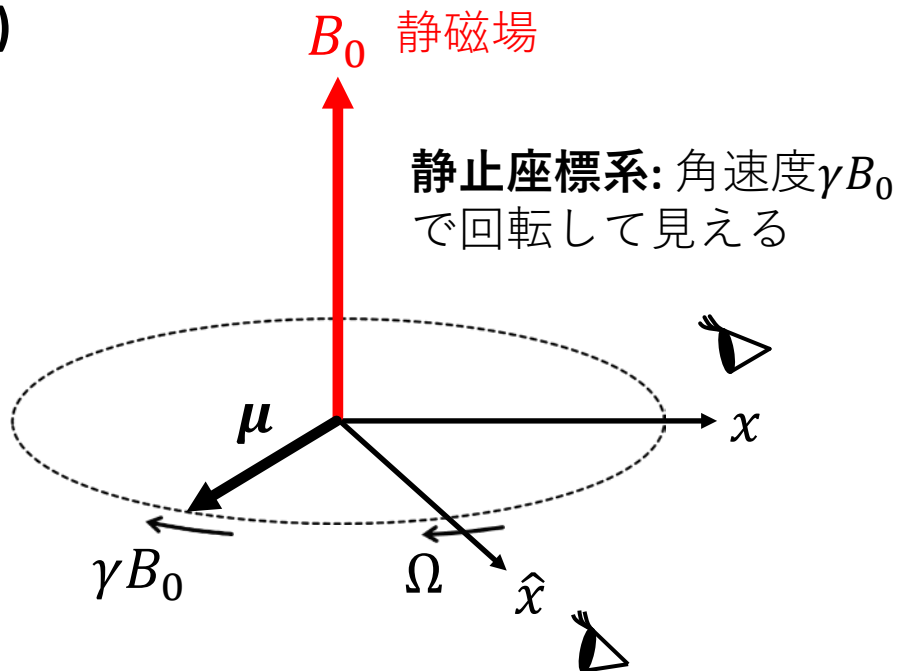
↑
磁気モーメント: $\boldsymbol{\mu} = \gamma \mathbf{J}$

↑
磁気回転比



Joseph Larmor
(1857–1942)

(from Wikipedia)



静磁場
 B_0

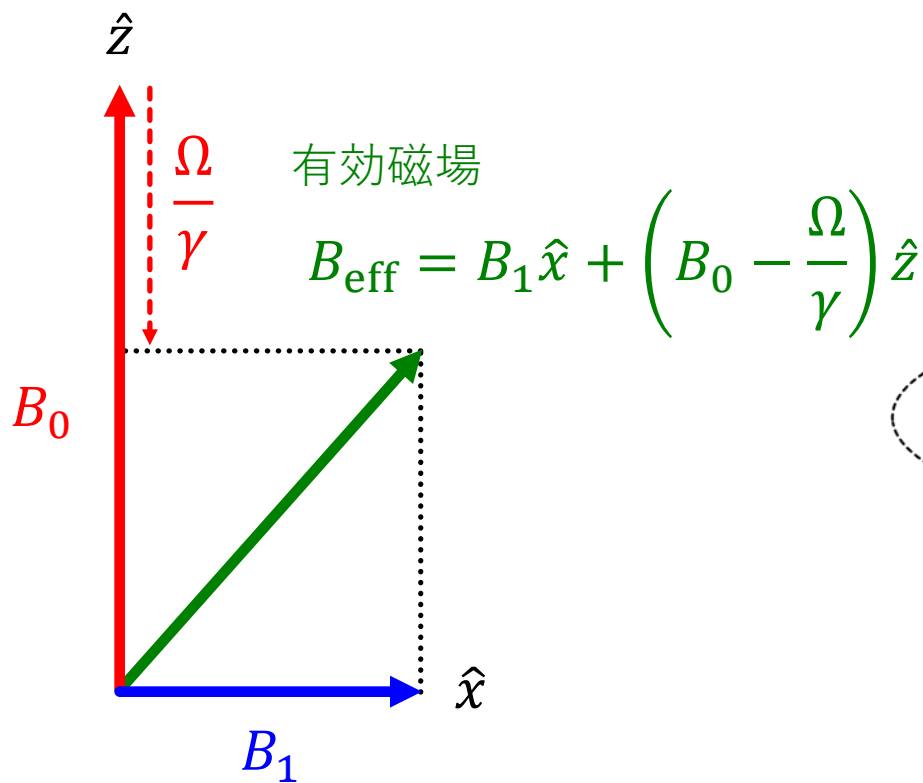
静止座標系: 角速度 γB_0
で回転して見える

角速度 Ω で回転する座標系:
遅くなって見える...なぜ??

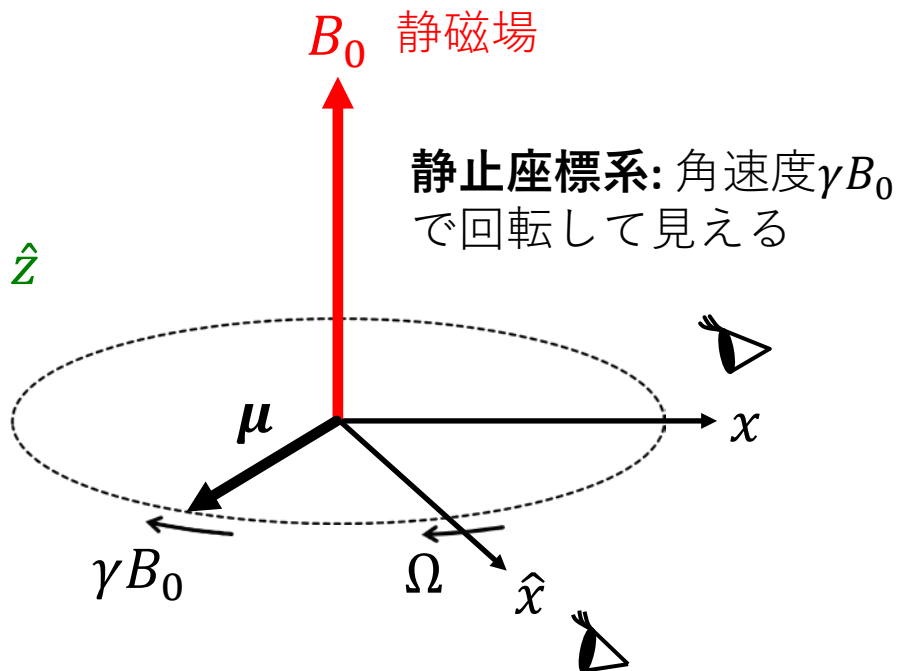


z方向の磁場が弱くなったから

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??



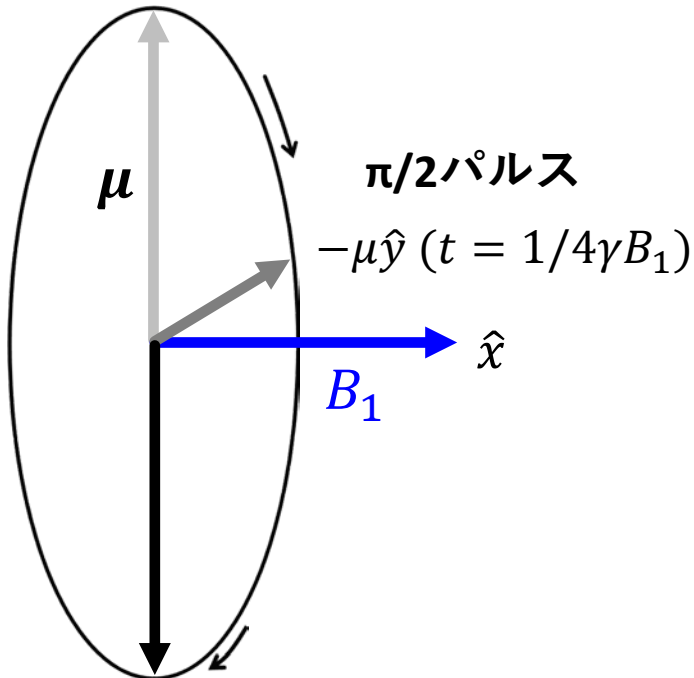
z 方向の磁場が弱くなったから

磁気共鳴

$\Omega = \gamma B_0$ で回転する座標系

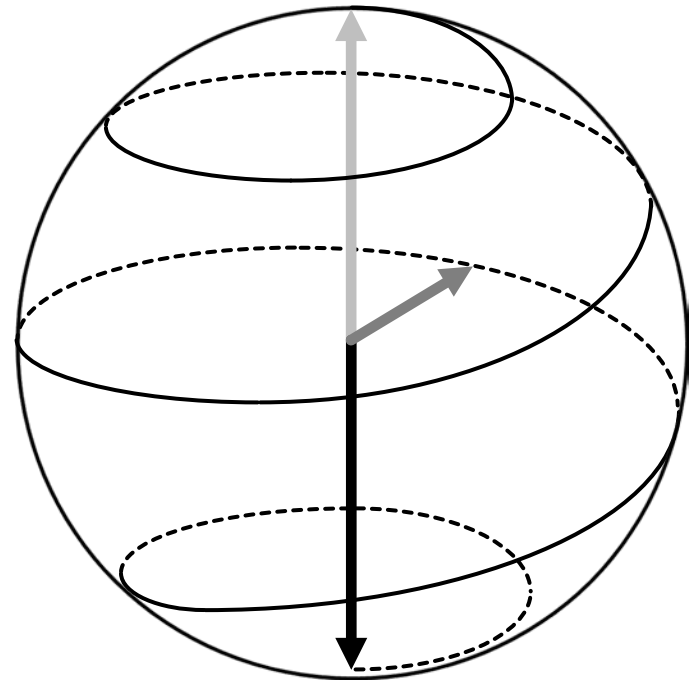
静止座標系

$\mu \hat{z} (t = 0)$



$-\mu \hat{z} (t = 1/2\gamma B_1)$

π パルス



- 交流磁場の位相を調整すれば $\pm \hat{x}, \pm \hat{y}$ 軸周りの回転が実現
- 静止座標系では z 軸周りの回転が加わる

指数演算子

シュレディンガー方程式の解

$$|\psi(t + \Delta t)\rangle = \exp\left(-i \frac{H\Delta t}{\hbar}\right) |\psi(t)\rangle$$

指数演算子

$$\begin{aligned} e^{iAx} &\equiv \sum_{n=0}^{\infty} \frac{(iAx)^n}{n!} \\ &= \sum_{k=0}^{\infty} \frac{(-1)^k}{(2k)!} (Ax)^{2k} + i \sum_{k=0}^{\infty} \frac{(-1)^k}{(2k+1)!} (Ax)^{2k+1} \\ &= \cos x \cdot I + i \sin x \cdot A \end{aligned}$$

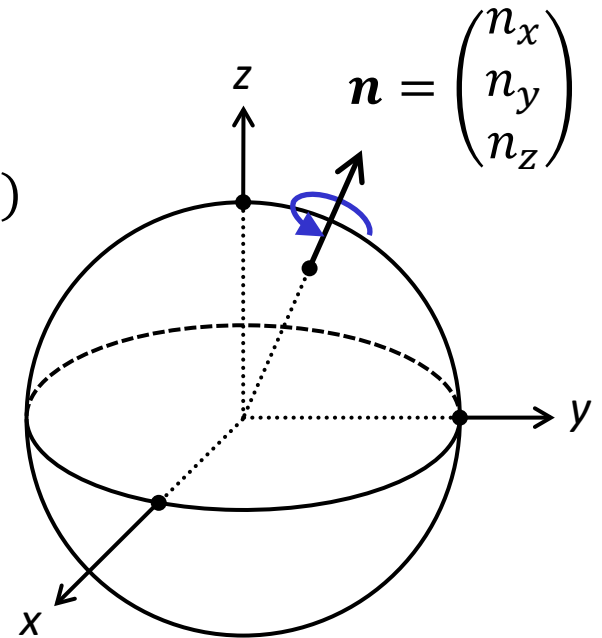
$$A^2 = I$$

回転ゲート

ブロッホ球の任意の軸周りの回転

$$R_n(\varphi) \equiv \exp\left(-i\frac{\varphi}{2}\mathbf{n}\cdot\boldsymbol{\sigma}\right)$$

$$= \cos\frac{\varphi}{2}\cdot I - i\sin\frac{\varphi}{2}(n_x X + n_y Y + n_z Z)$$



$$X^2 = Y^2 = Z^2 = I \quad \boldsymbol{\sigma} = \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}$$

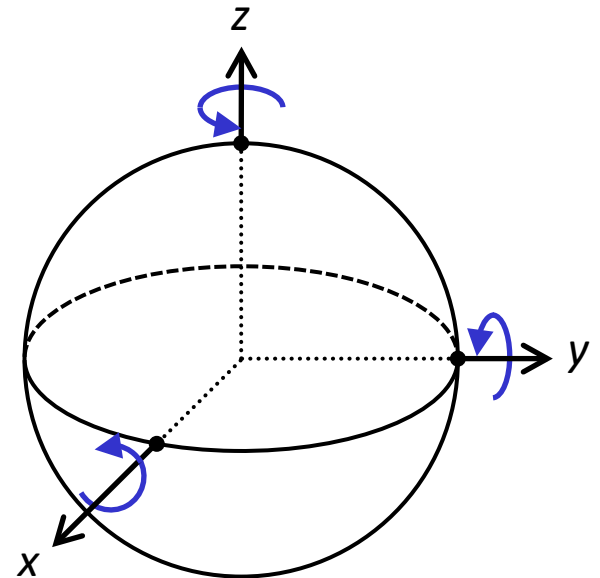
回転ゲート

x, y, z 軸周りの回転

$$R_x(\varphi) = e^{-i\varphi X/2} = \begin{pmatrix} \cos \frac{\varphi}{2} & -i \sin \frac{\varphi}{2} \\ -i \sin \frac{\varphi}{2} & \cos \frac{\varphi}{2} \end{pmatrix}$$

$$R_y(\varphi) = e^{-i\varphi Y/2} = \begin{pmatrix} \cos \frac{\varphi}{2} & -\sin \frac{\varphi}{2} \\ \sin \frac{\varphi}{2} & \cos \frac{\varphi}{2} \end{pmatrix}$$

$$R_z(\varphi) = e^{-i\varphi Z/2} = \begin{pmatrix} e^{-i\varphi/2} & 0 \\ 0 & e^{i\varphi/2} \end{pmatrix}$$



ブロッホ球と現実の座標系(実験室系、回転座標系)との対応は
物理系と実験の都合により異なる(設計の自由度が高い)

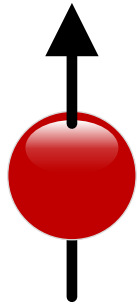
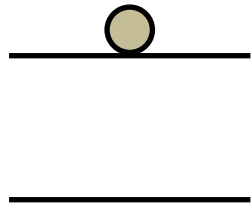
ZY分解

任意のユニタリ行列はz軸とy軸の回転の組み合わせで実現

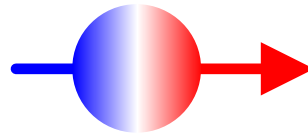
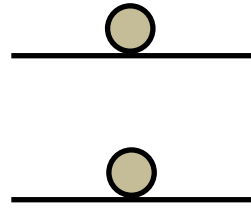
$$\begin{aligned} U &= \begin{pmatrix} e^{i(\alpha-\beta/2-\delta/2)} \cos \frac{\gamma}{2} & -e^{i(\alpha-\beta/2+\delta/2)} \sin \frac{\gamma}{2} \\ e^{i(\alpha+\beta/2-\delta/2)} \sin \frac{\gamma}{2} & e^{i(\alpha+\beta/2+\delta/2)} \cos \frac{\gamma}{2} \end{pmatrix} \\ &= e^{i\alpha} \begin{pmatrix} e^{-i\beta/2} & 0 \\ 0 & e^{i\beta/2} \end{pmatrix} \begin{pmatrix} \cos \frac{\gamma}{2} & -\sin \frac{\gamma}{2} \\ \sin \frac{\gamma}{2} & \cos \frac{\gamma}{2} \end{pmatrix} \begin{pmatrix} e^{-i\delta/2} & 0 \\ 0 & e^{i\delta/2} \end{pmatrix} \\ &= e^{i\alpha} R_z(\beta) R_y(\gamma) R_z(\delta) \end{aligned}$$

分解の仕方は一意ではない

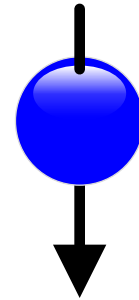
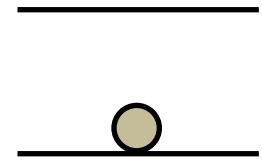
量子コヒーレンス



$$|0\rangle \equiv |\uparrow\rangle$$



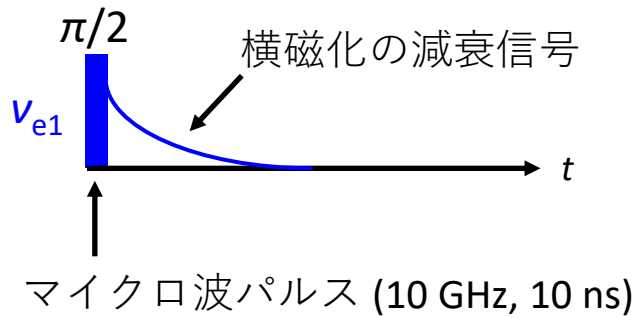
$$|\Psi\rangle = \alpha|0\rangle + \beta|1\rangle$$



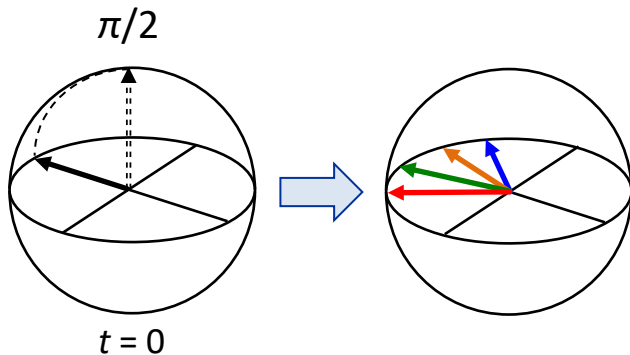
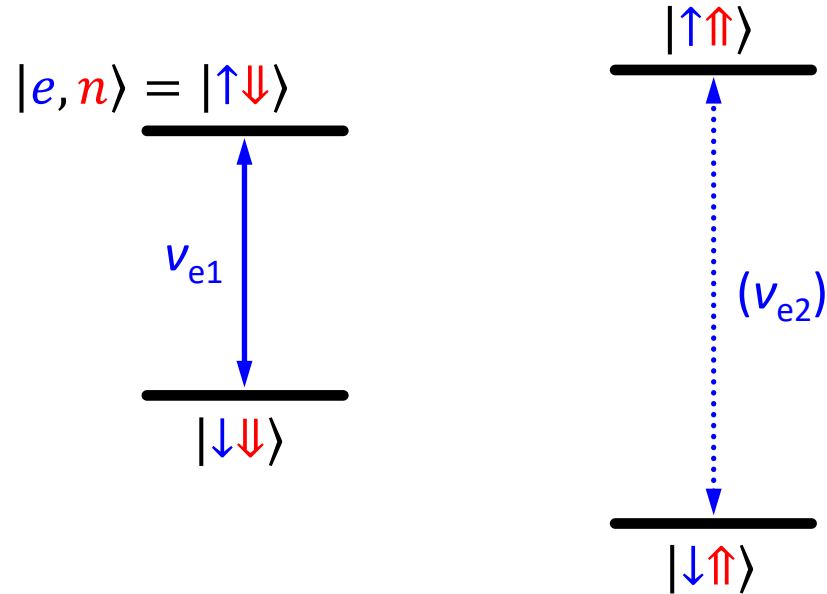
$$|1\rangle \equiv |\downarrow\rangle$$

T_2 : 重ね合わせ状態の持続時間

自由誘導減衰: T_2^*



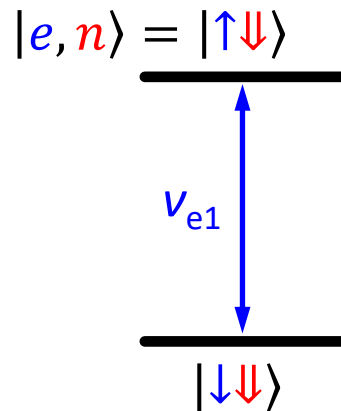
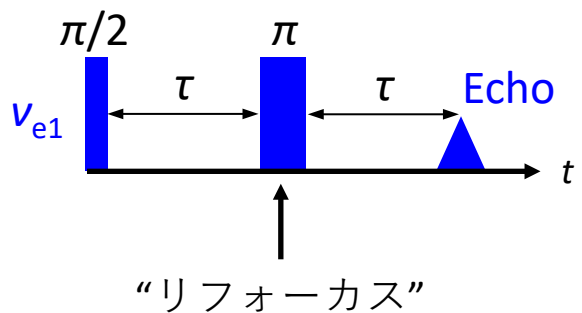
直感的には、スピンを横に向けて
信号の減衰を見ればよさそう



不均一性による見かけの減衰

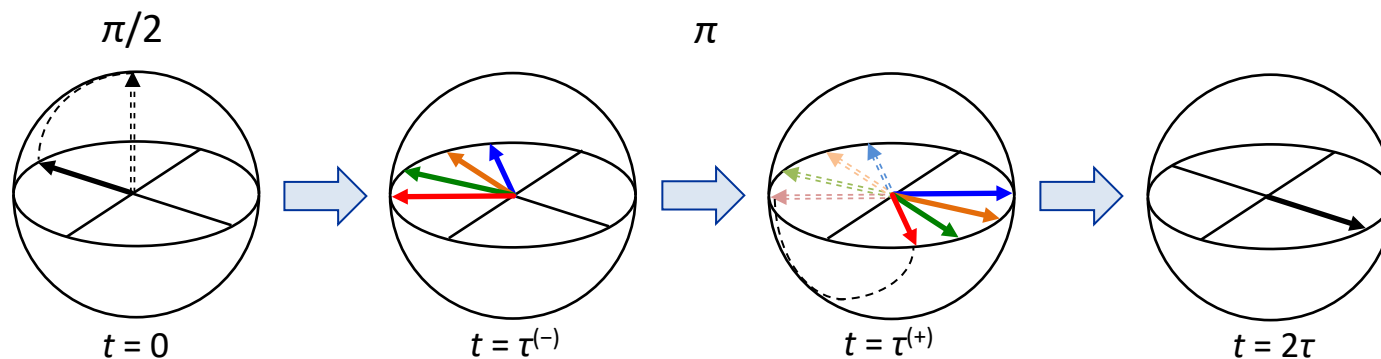
$$T_2^* \approx (\gamma_e 0.26 \text{ mT})^{-1} \approx 130 \text{ ns} \ll T_2 \approx 500 \mu\text{s}$$

スピンエコー: T_2



E. Hahn
(1921–2016)

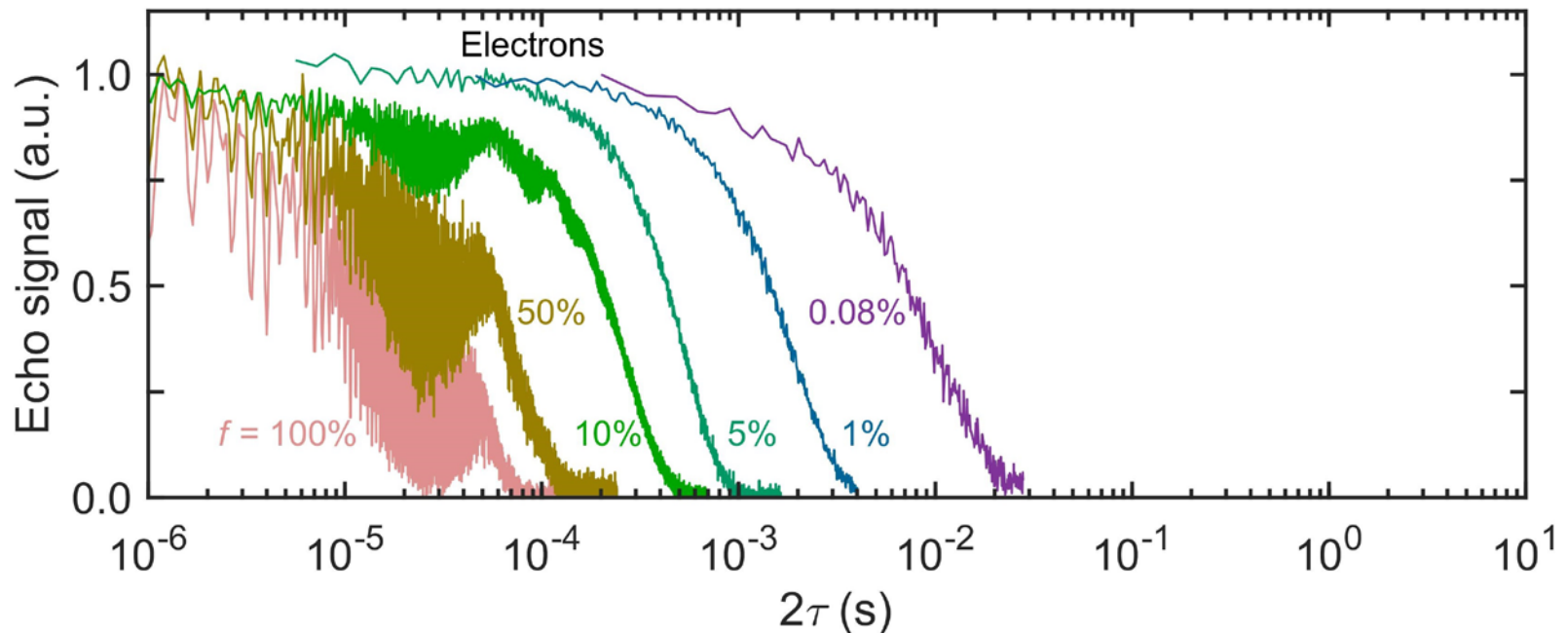
©G. Paul Bishop Jr.



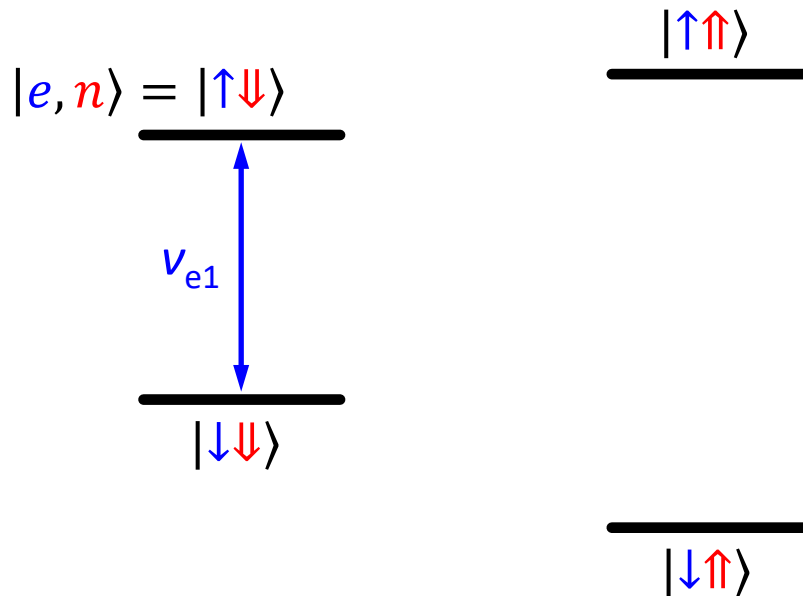
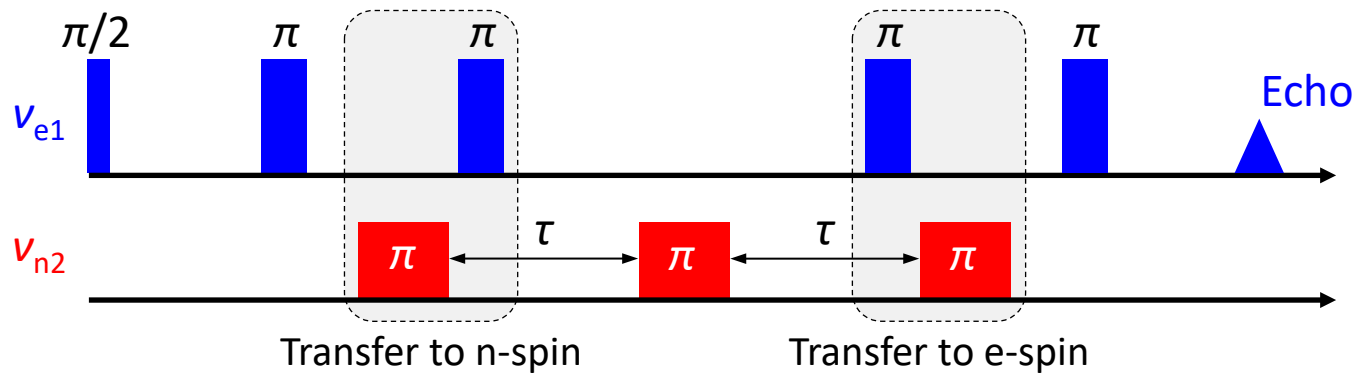
電子スピンコヒーレンス: T_{2e}

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

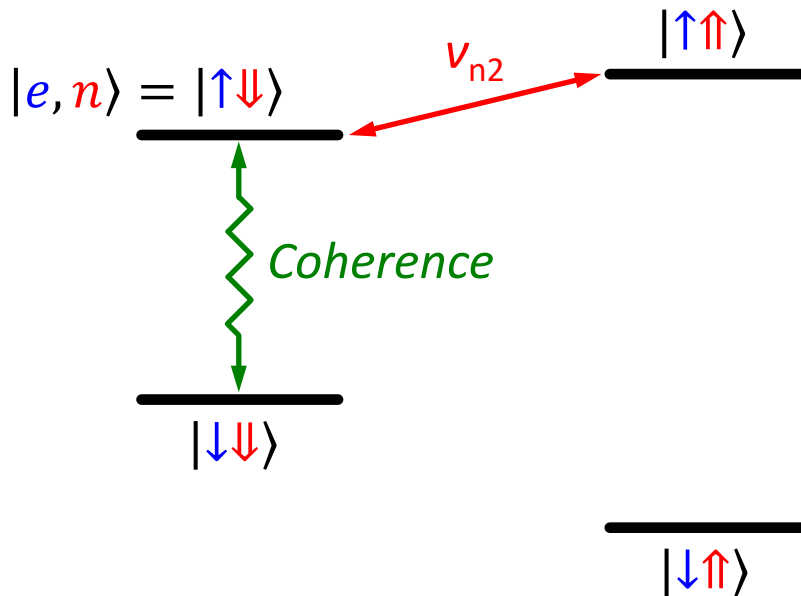
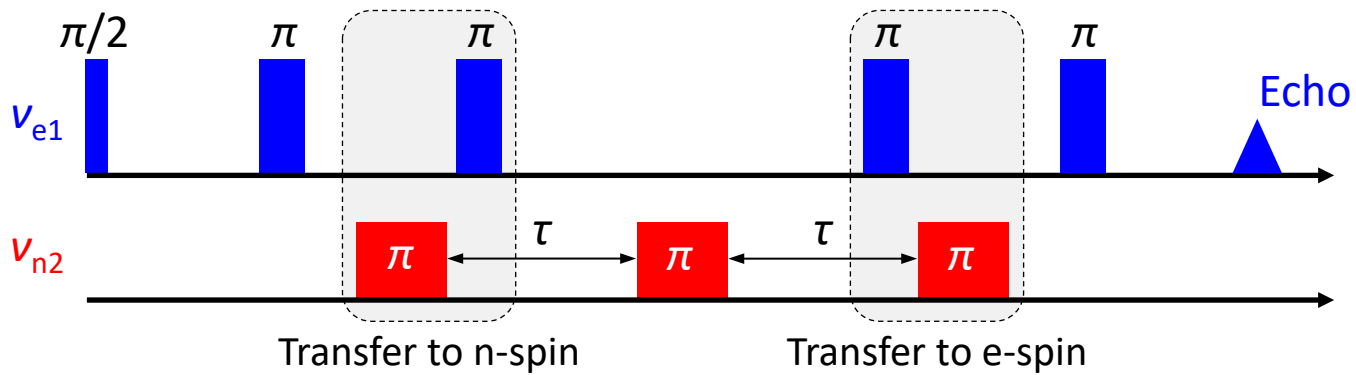


核スピンコヒーレンス: T_{2n0}



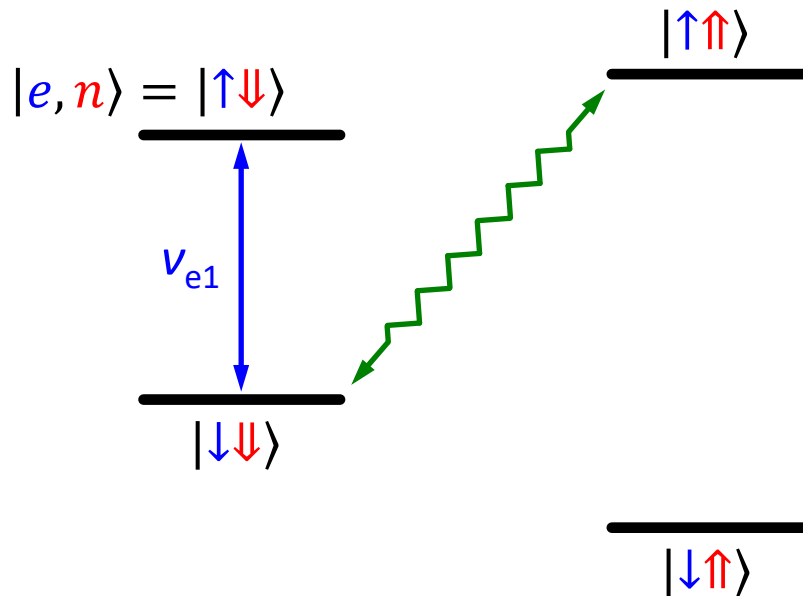
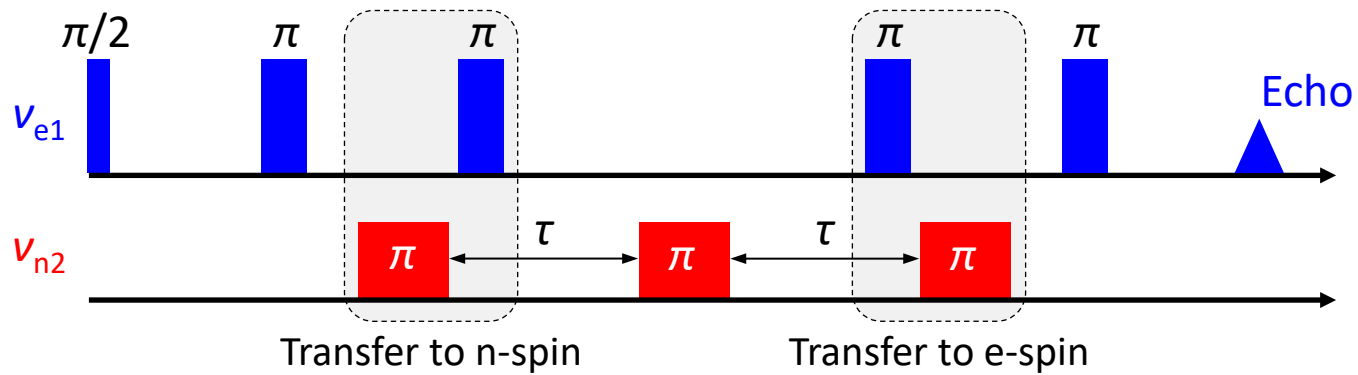
Electron Nuclear Double Resonance

核スピンコヒーレンス: T_{2n0}



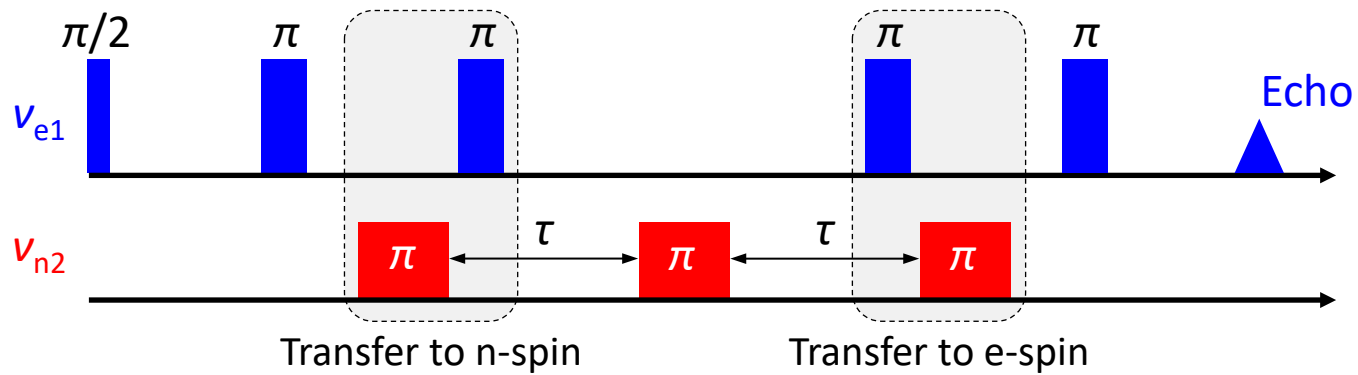
Electron Nuclear Double Resonance

核スピンコヒーレンス: T_{2n0}



Electron Nuclear Double Resonance

核スピンコヒーレンス: T_{2n0}



Electron Nuclear Double Resonance



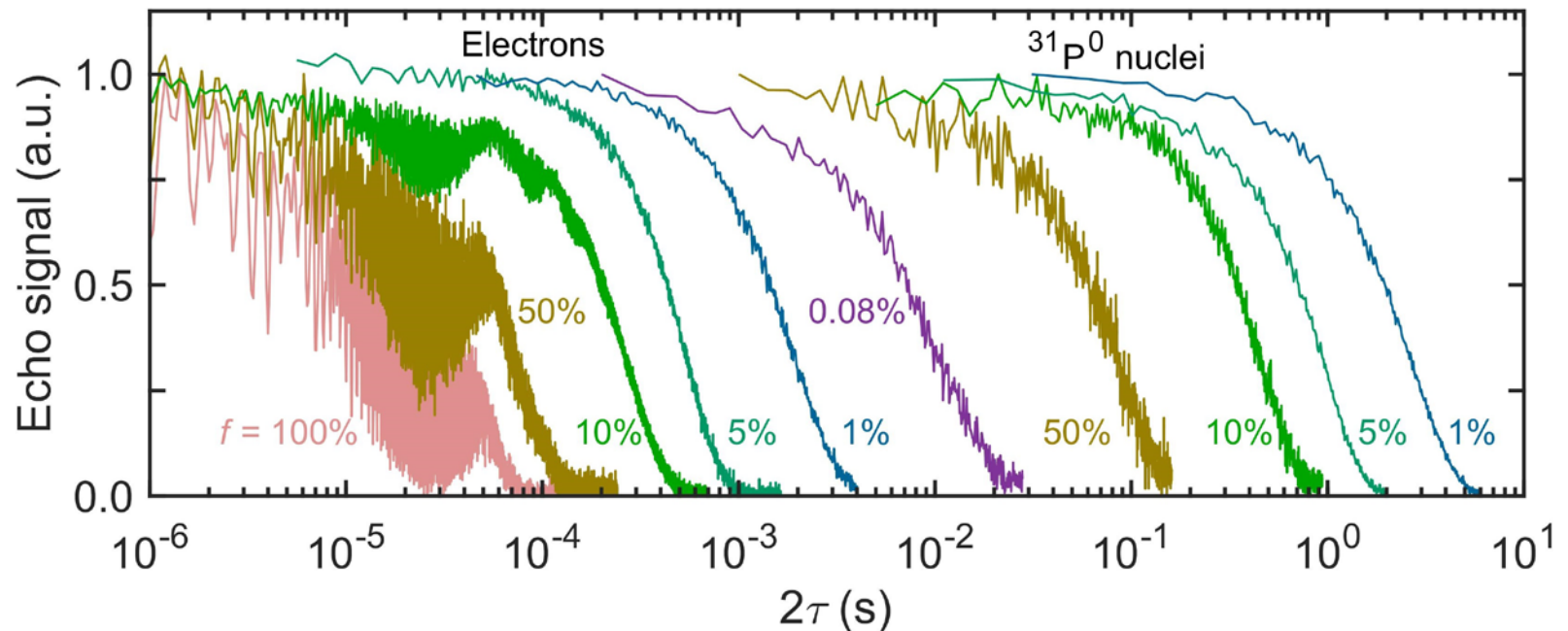
核スピンコヒーレンス: T_{2n0}

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

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



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.

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.

Wolf Prize in Chemistry (2006)

1950年代に固体物理で業績を挙げたのち
生物物理(主に光合成)に転向

“...delighted to hear that EPR in Si is still alive and doing well and has branched out into new and exciting areas” (email to E.A. Dec. 2016)



G. Feher
(1924–2017)

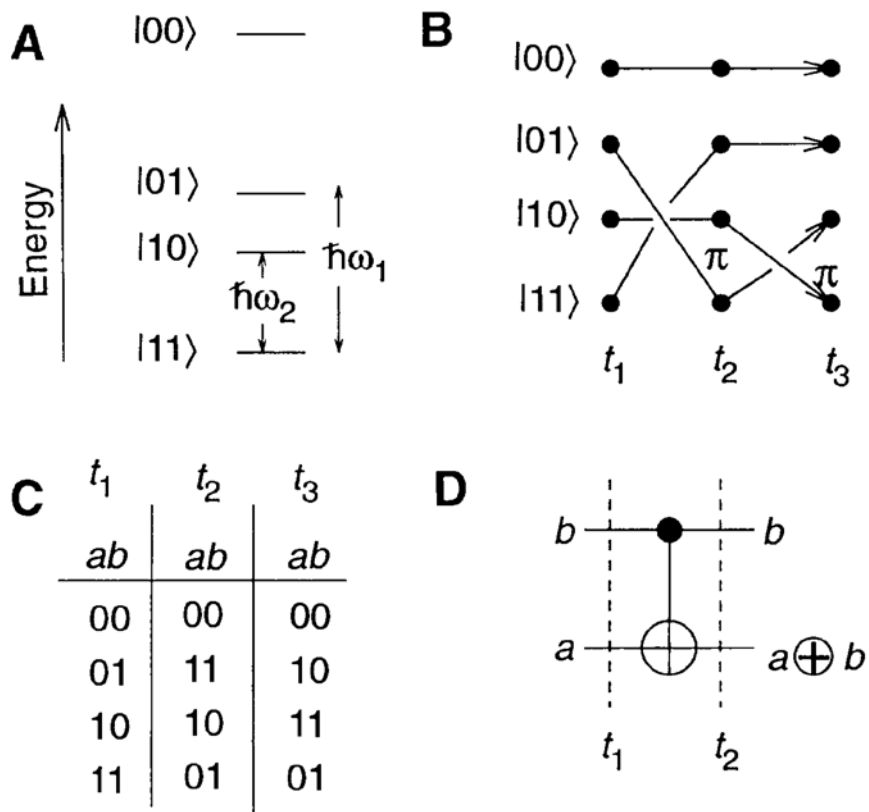
©R.A. Icaacson

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

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

Quantum Computation

David P. DiVincenzo

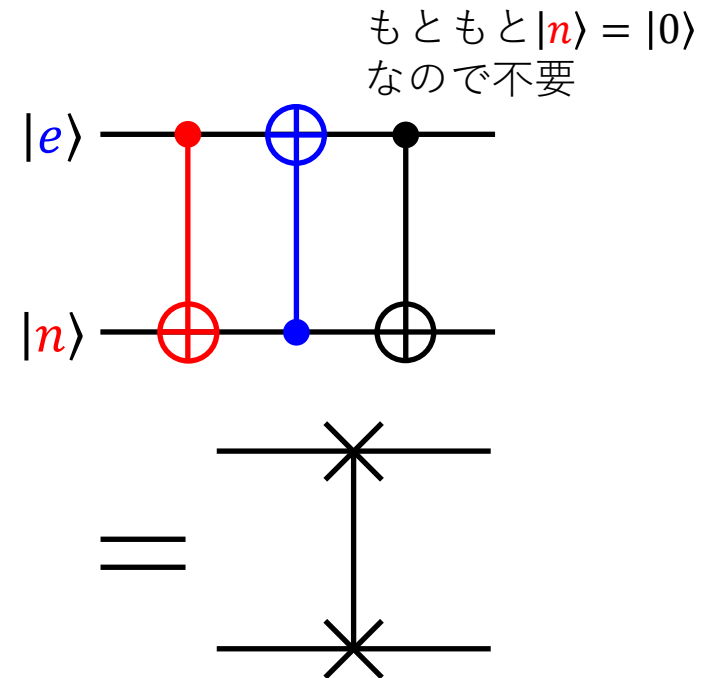
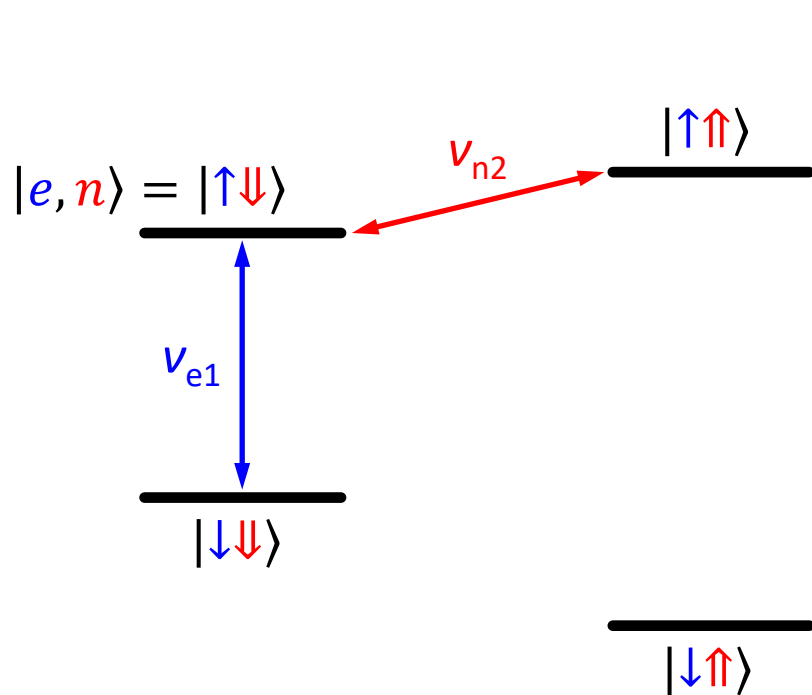
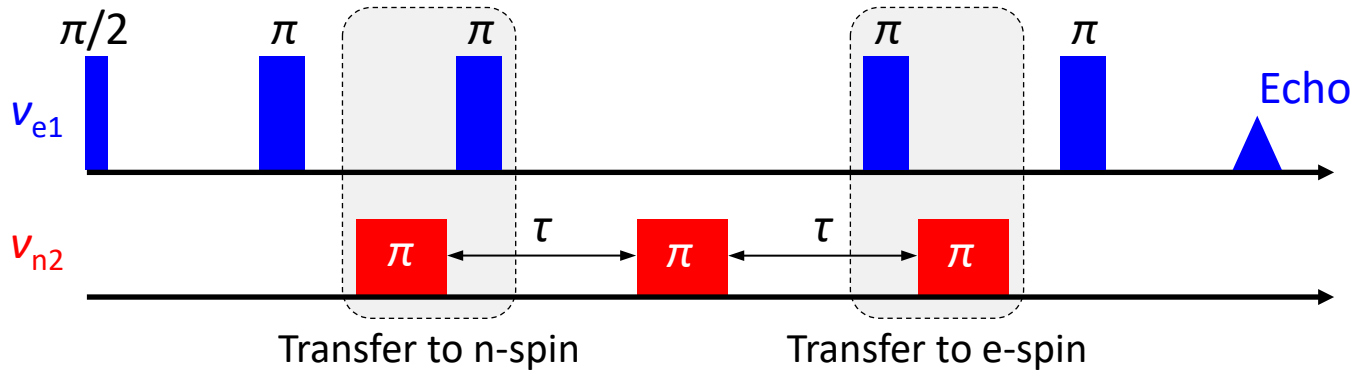


The XOR protocol is very closely related to procedures invented long ago in the field of resonance spectroscopies (13). In 1956, Feher introduced a procedure for polarization transfer in electron-nucleus double resonance (ENDOR), which contains the XOR protocol just discussed.

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.

ENDOR と SWAP

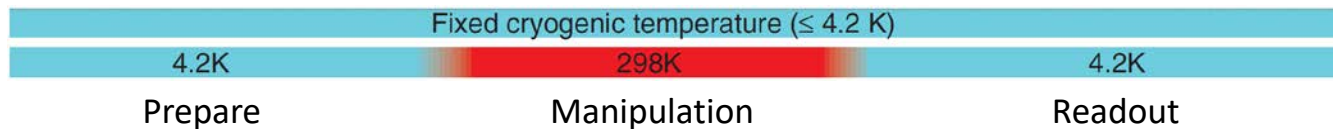
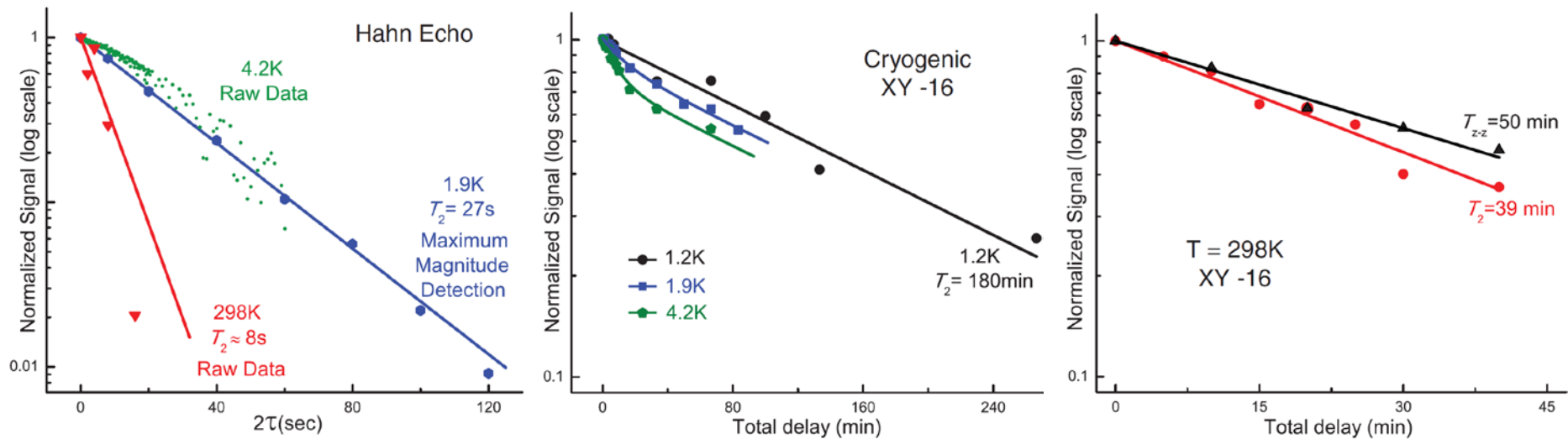


核スピンコヒーレンス: T_{2n+}

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

Auger-electron-detected NMR

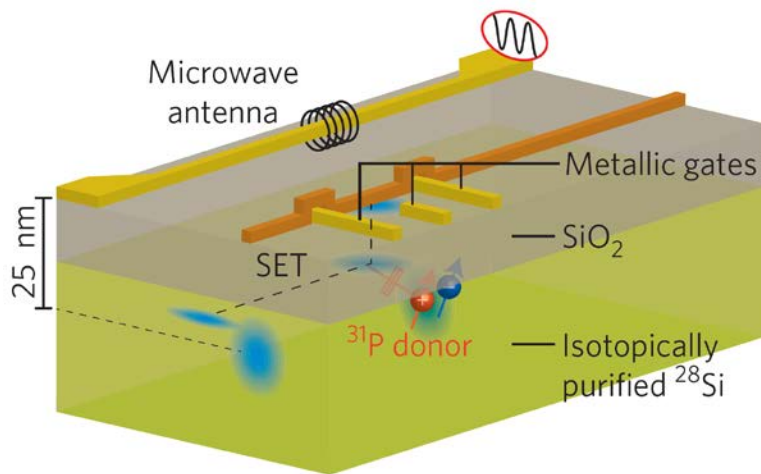
Kamyar Saeedi,¹ Stephanie Simmons,² Jeff Z. Salvail,¹ Phillip Dluhy,¹ Helge Riemann,³ Nikolai V. Abrosimov,³ Peter Becker,⁴ Hans-Joachim Pohl,⁵ John J. L. Morton,⁶ Mike L. W. Thewalt^{1*}



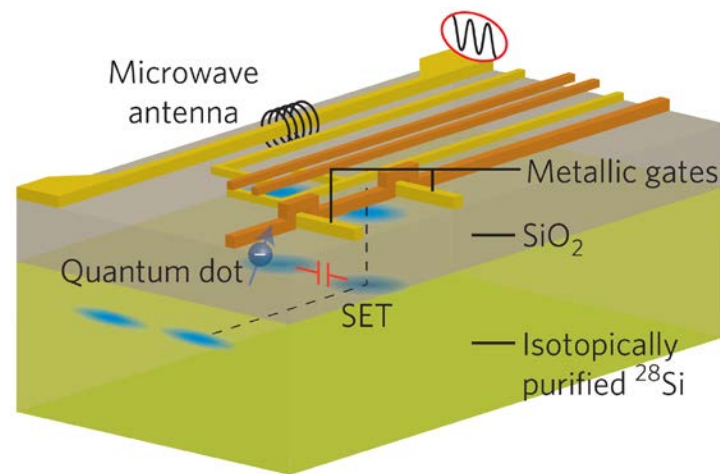
講義内容

- 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

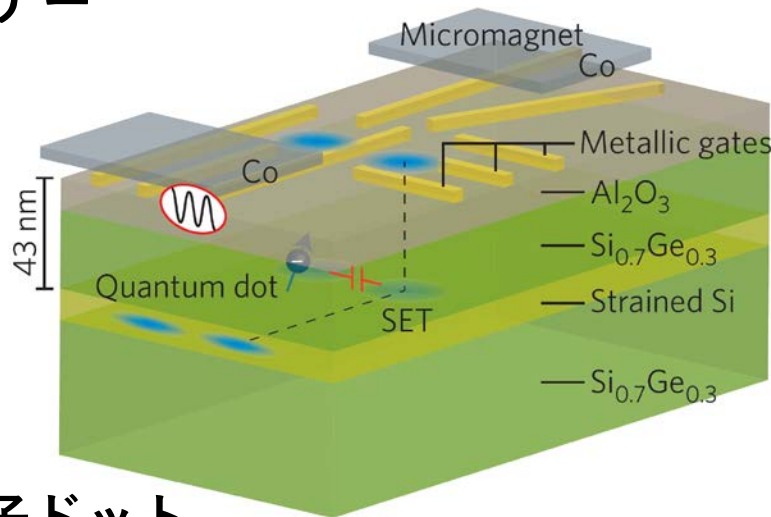
シリコンスピン量子ビット



単ーリンドナー



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

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

→ $T_{2e} = 10$ s, $T_{2n} = 180$ 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

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($T_2 \rightarrow \infty$)

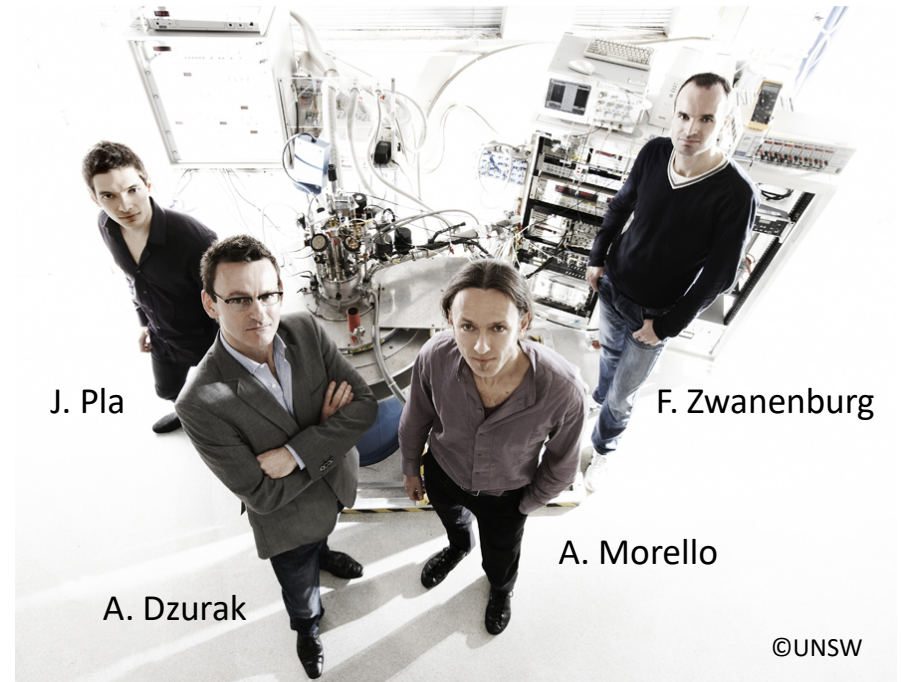
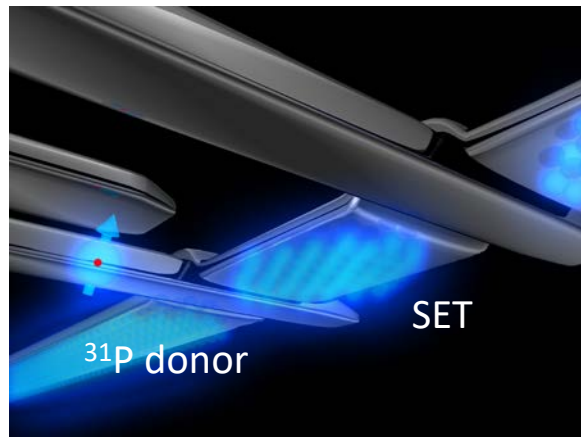
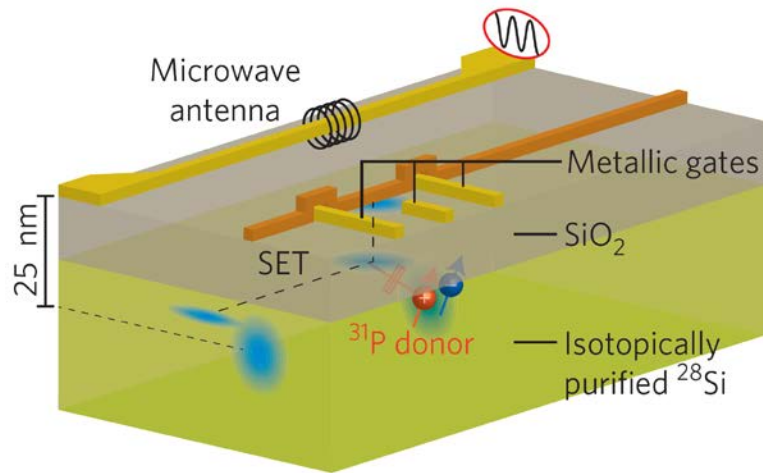
4. ユニバーサル量子ゲート
→ 1量子ビット制御 + CNOT

5. 射影測定
→ スピン・電荷変換

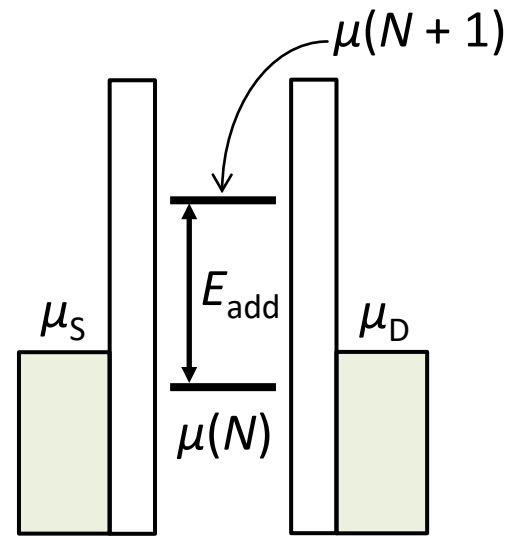
フェデリティ > 99%

Single-shot readout of an electron spin in silicon

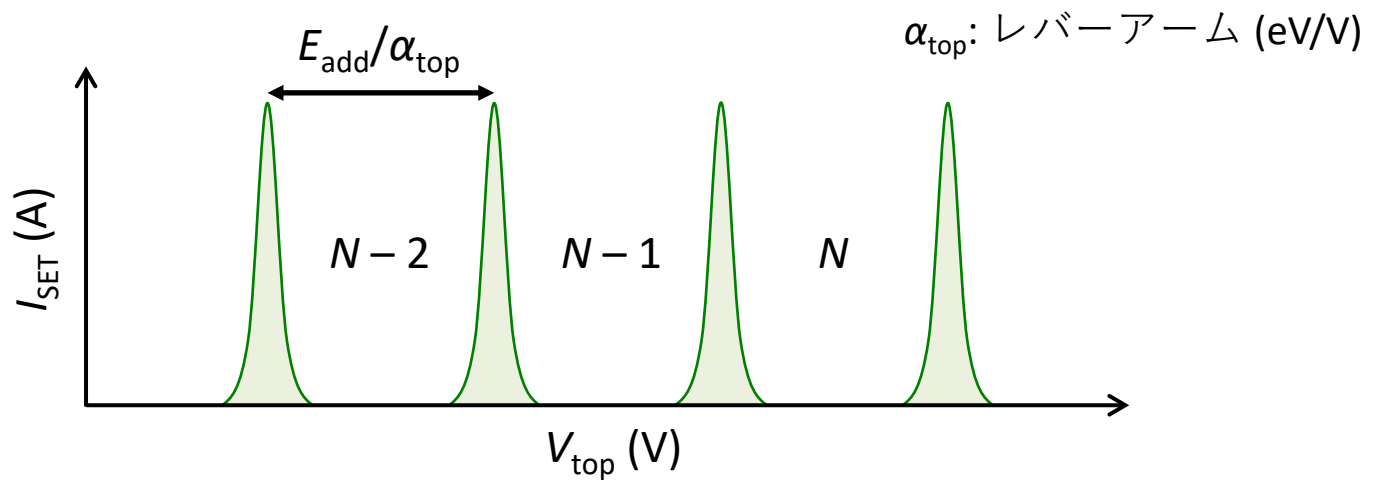
Andrea Morello¹, Jarryd J. Pla¹, Floris A. Zwanenburg¹, Kok W. Chan¹, Kuan Y. Tan¹, Hans Huebl^{1†}, Mikko Möttönen^{1,3,4}, Christopher D. Nugroho^{1†}, Changyi Yang², Jessica A. van Donkelaar², Andrew D. C. Alves², David N. Jamieson², Christopher C. Escott¹, Lloyd C. L. Hollenberg², Robert G. Clark^{1†}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



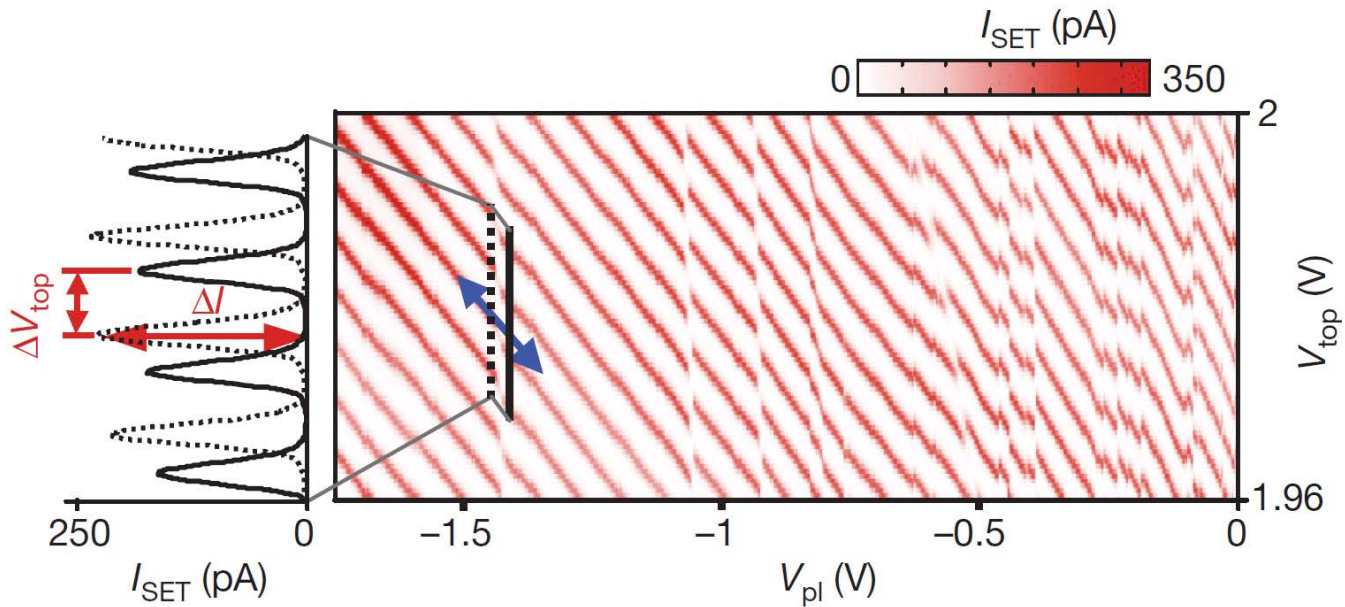
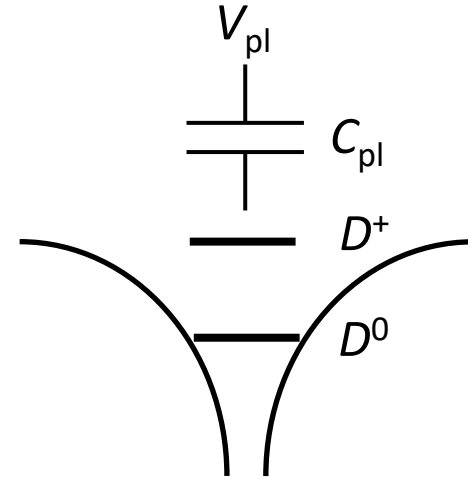
単電子トランジスタ



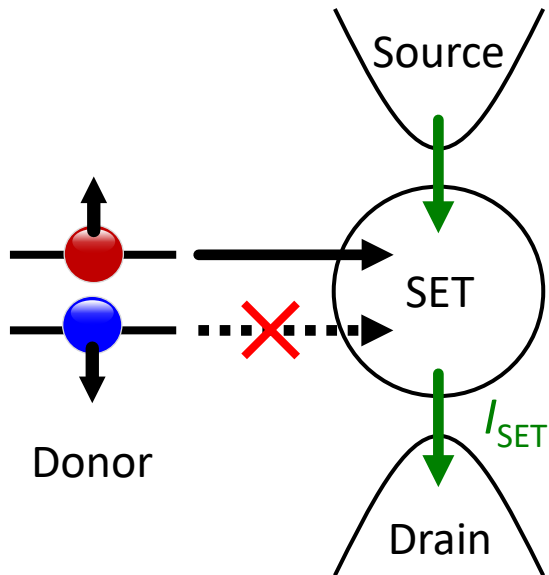
クーロン振動



ドナー-SETハイブリッド



スピン-電荷変換



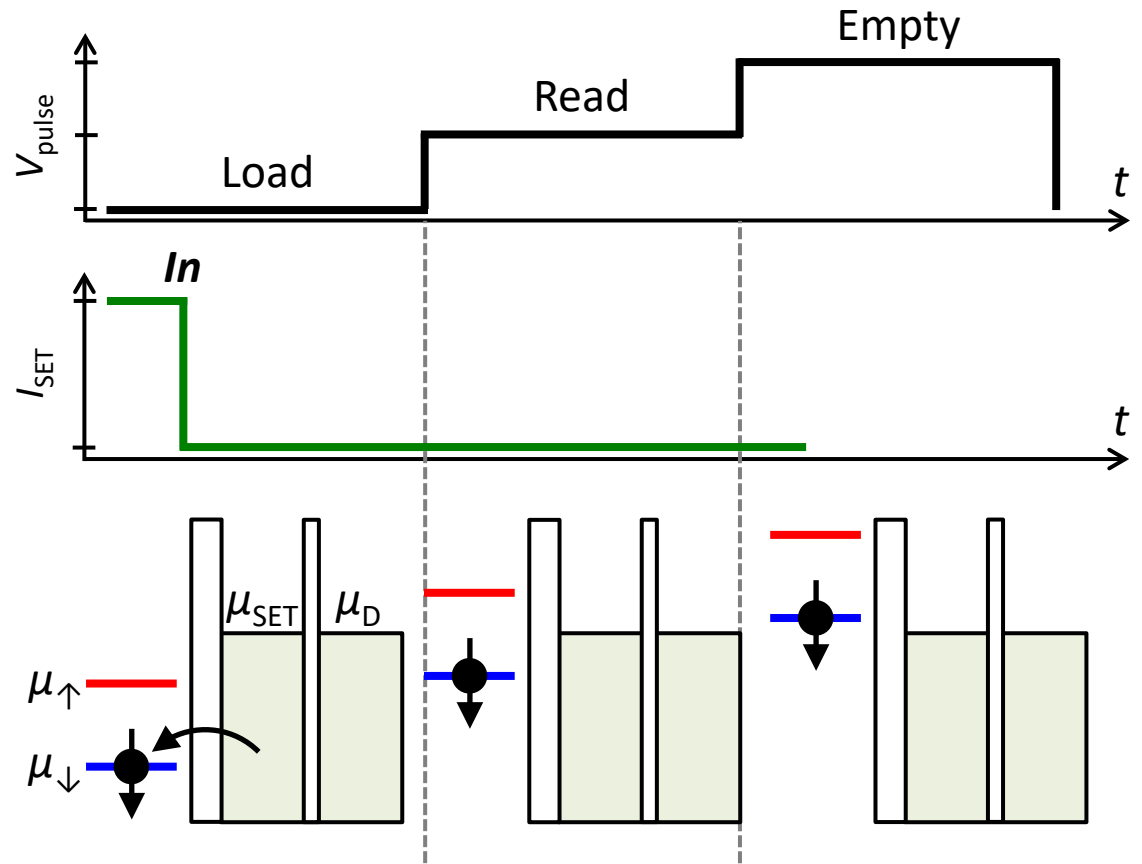
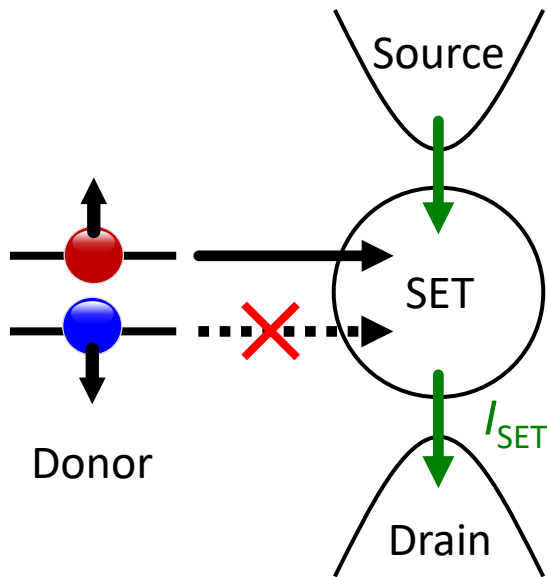
$$E(D^+) - E(D^0) = 45 \text{ meV}$$

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

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

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

スピン測定(↓)



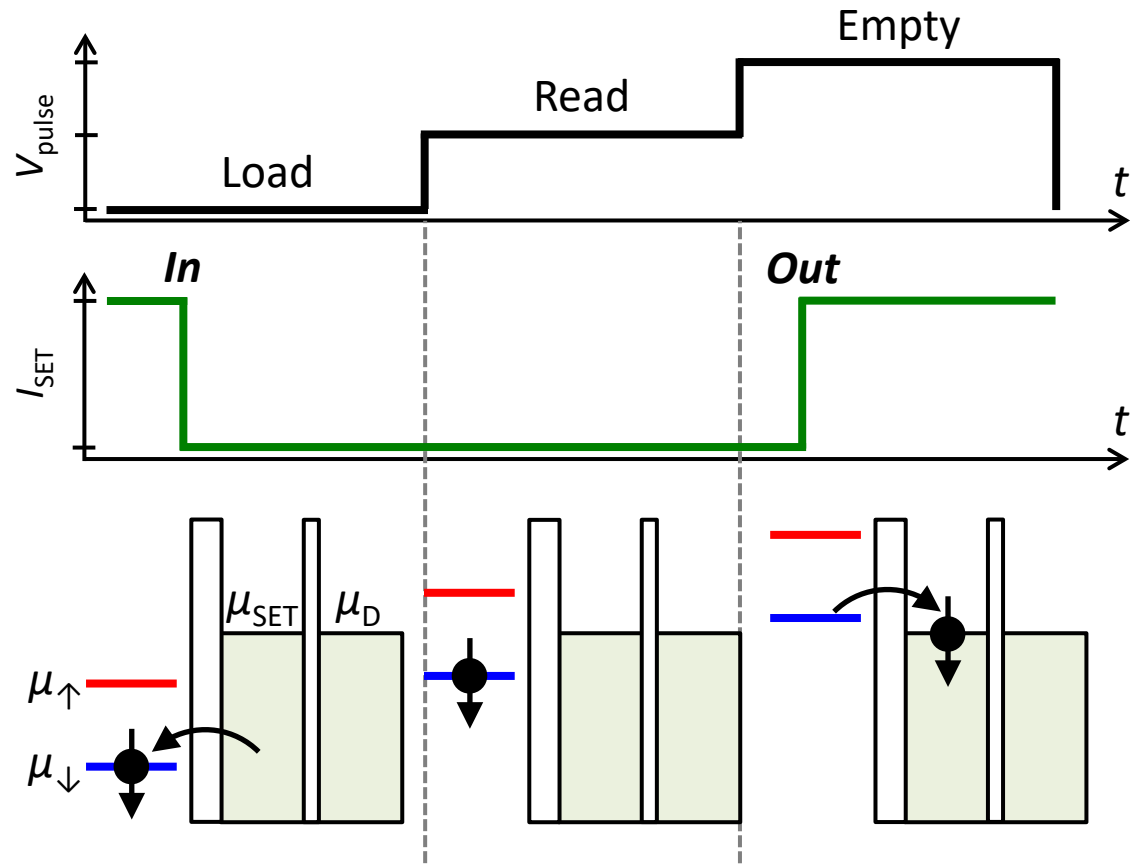
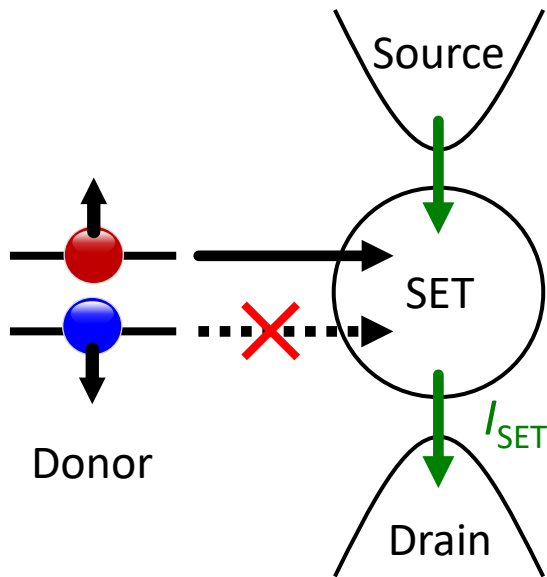
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スピン測定(↓)



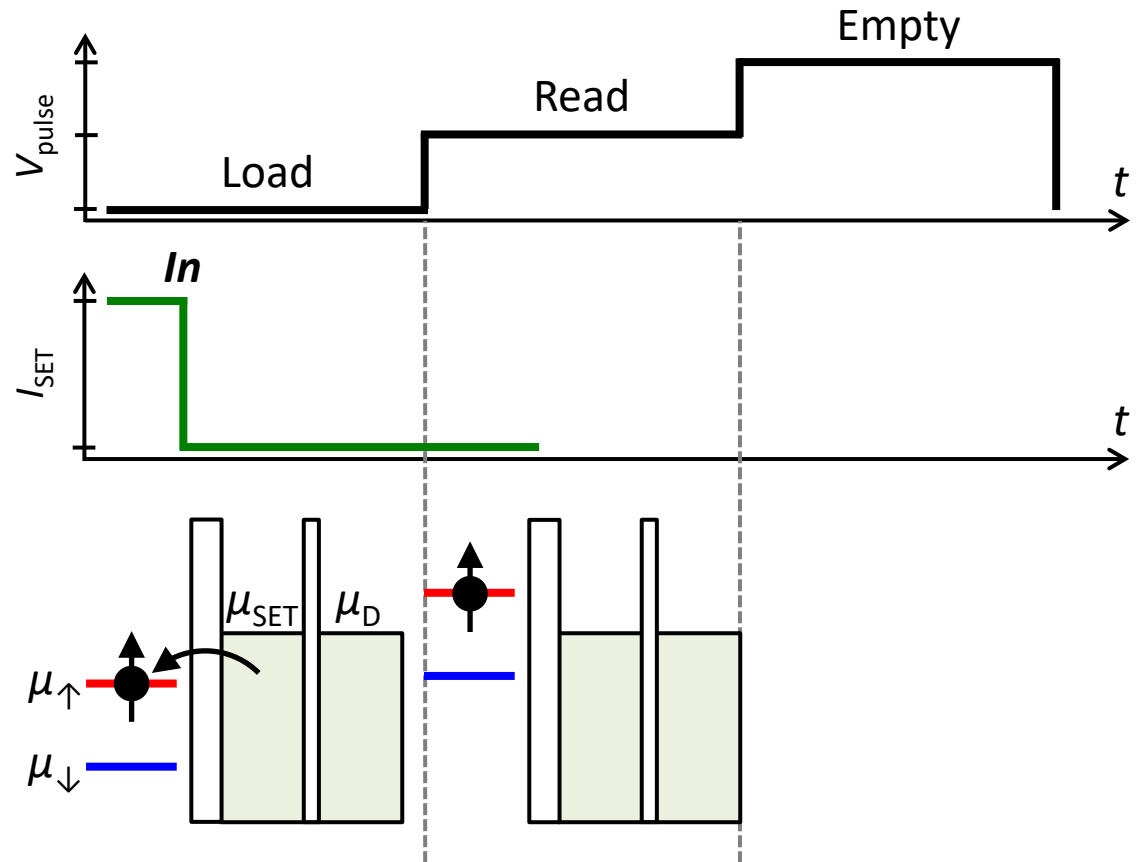
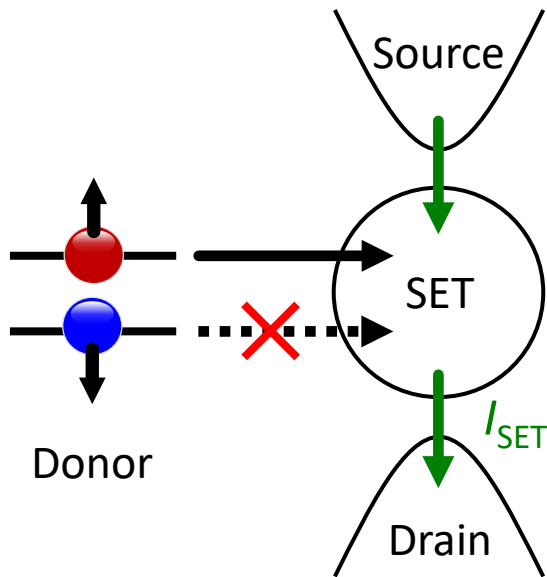
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スピン測定(↑)



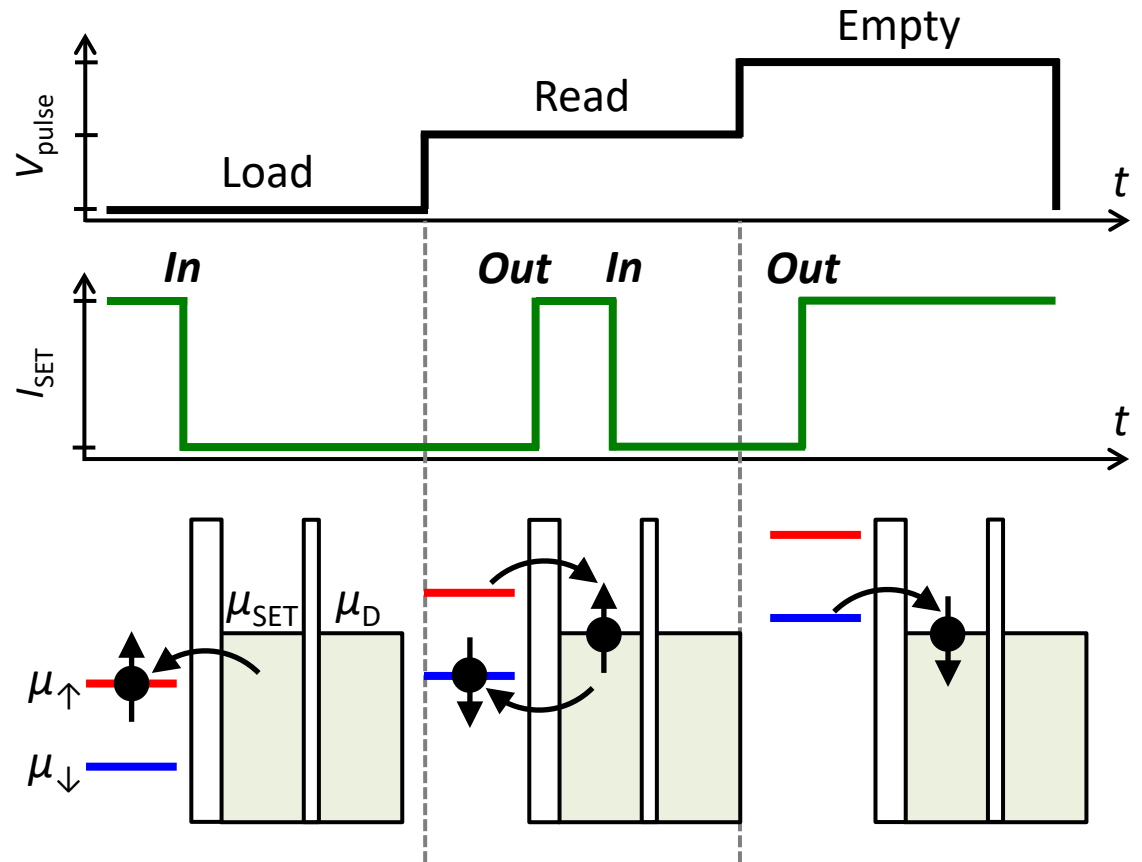
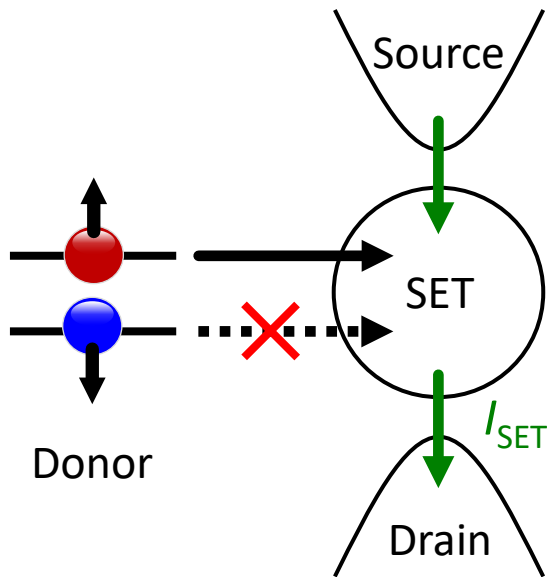
$$E(D^+) - E(D^0) = 45 \text{ meV}$$

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

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スピン測定(↑)



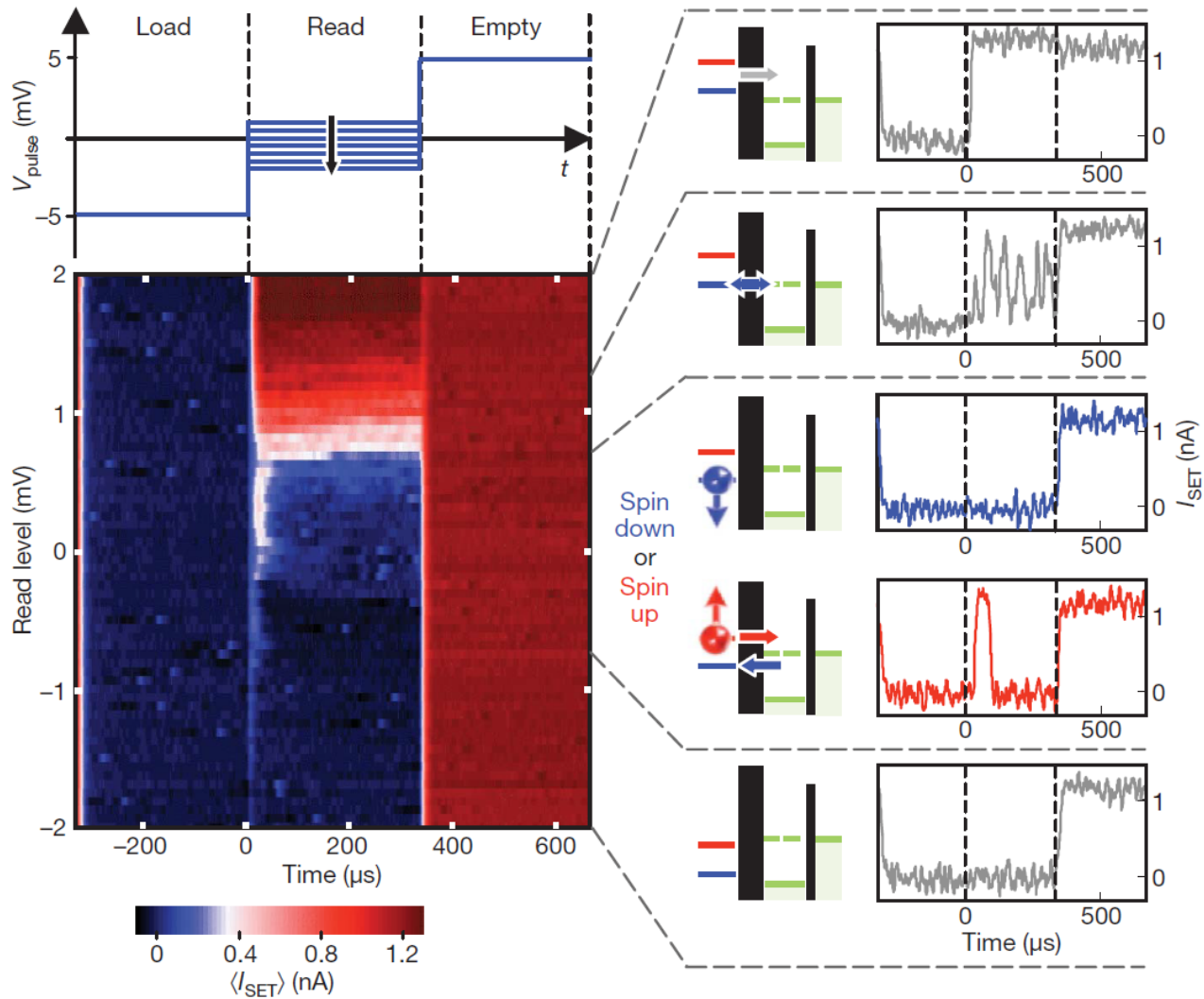
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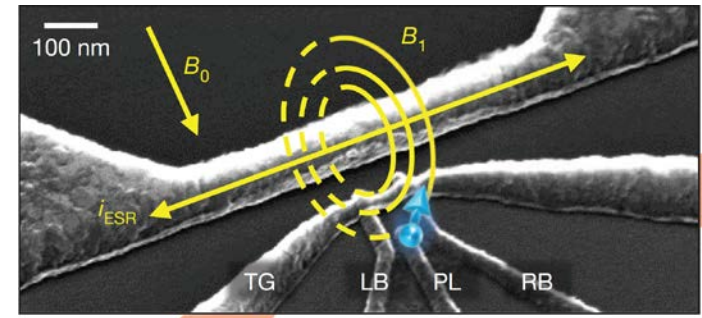
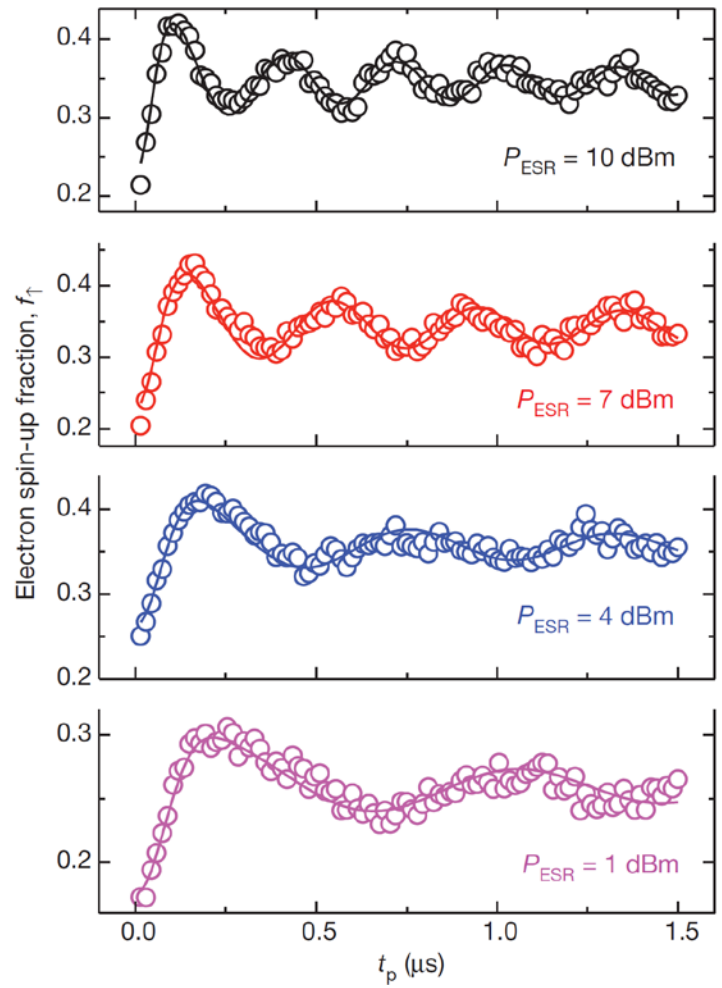
$$T_{\text{elec}} = 200 \text{ mK} = 17 \text{ } \mu\text{eV}$$

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

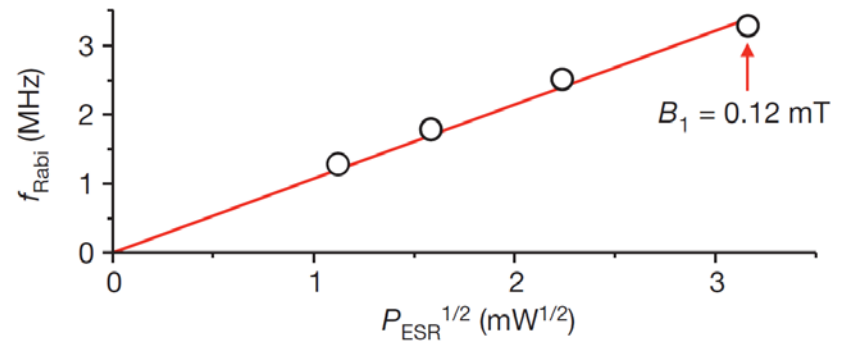
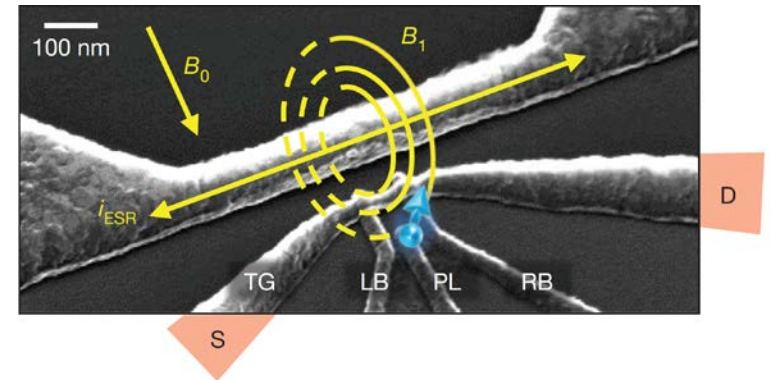
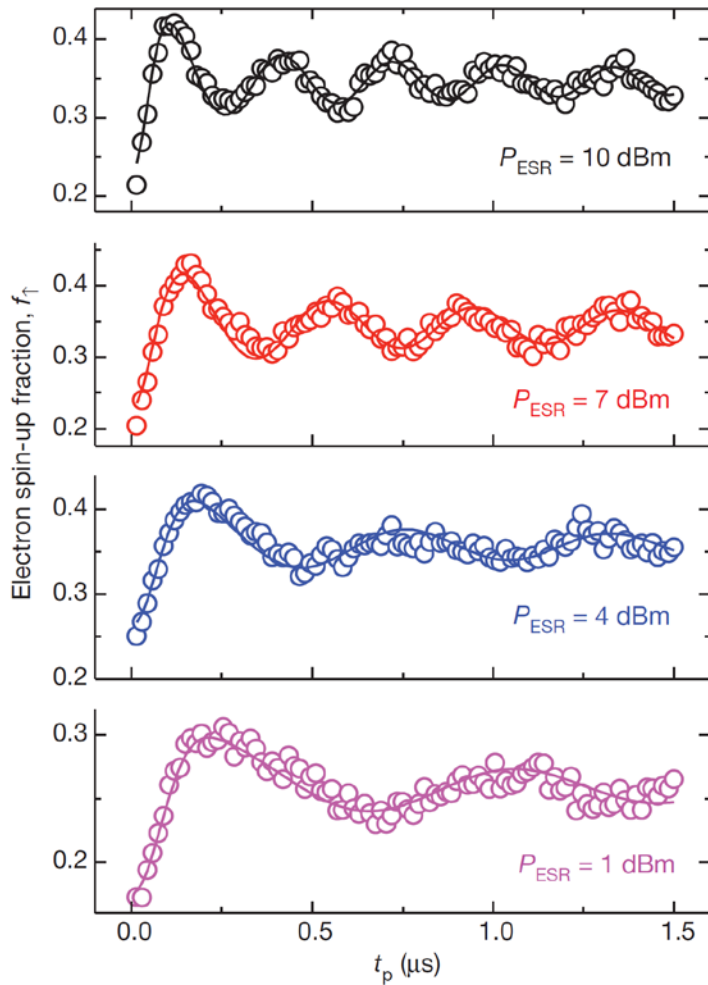


Isidor Rabi
(1898–1988)
©Nobel Foundation

ラビ振動: natSiデバイス

A single-atom electron spin qubit in silicon

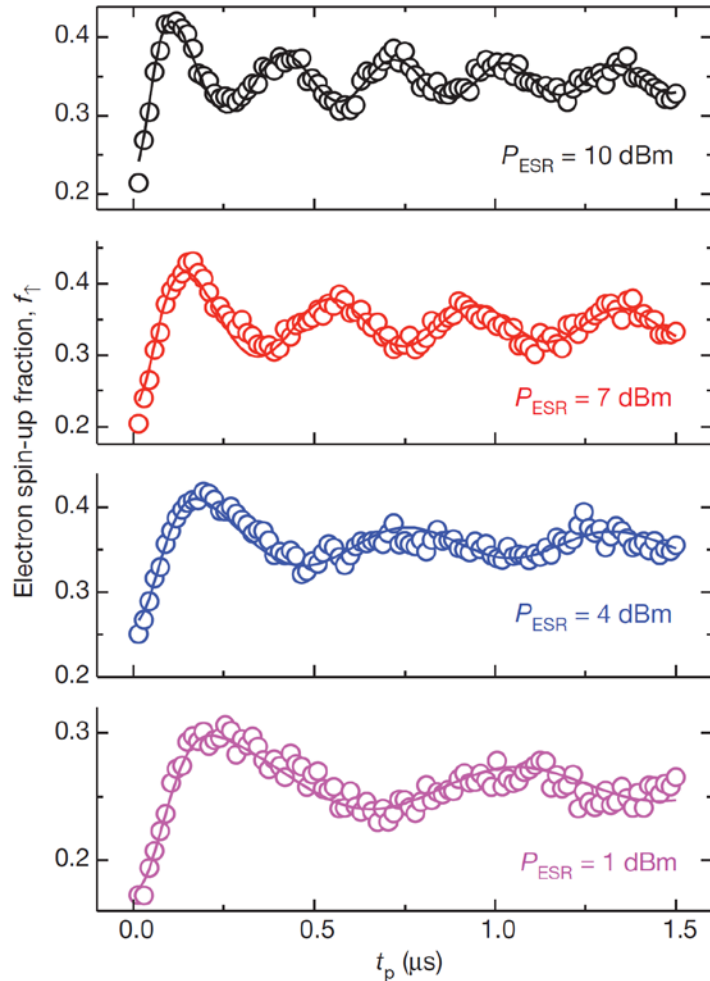
Jarryd J. Pla¹, Kuan Y. Tan^{1†}, Juan P. Dehollain¹, Wee H. Lim¹, John J. L. Morton^{2†}, David N. Jamieson³, Andrew S. Dzurak¹ & Andrea Morello¹



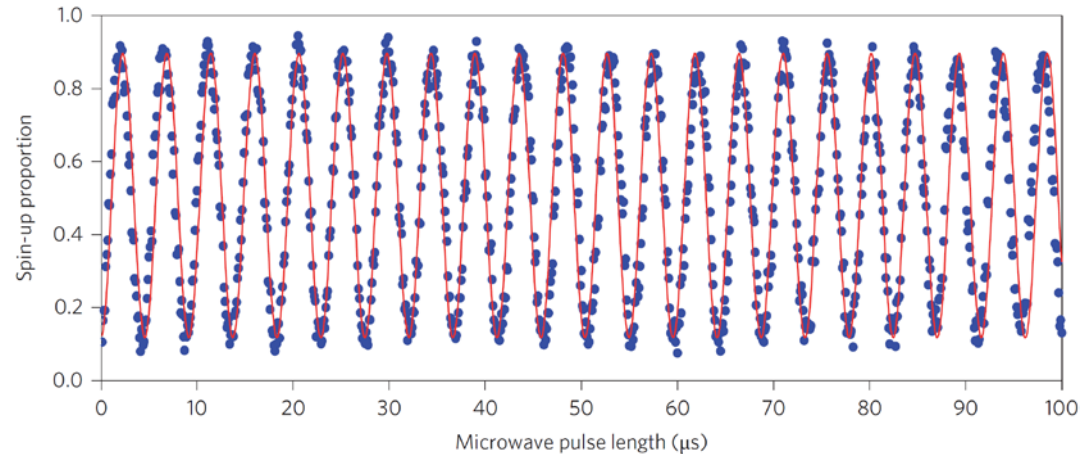
ラビ振動: natSiデバイス

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

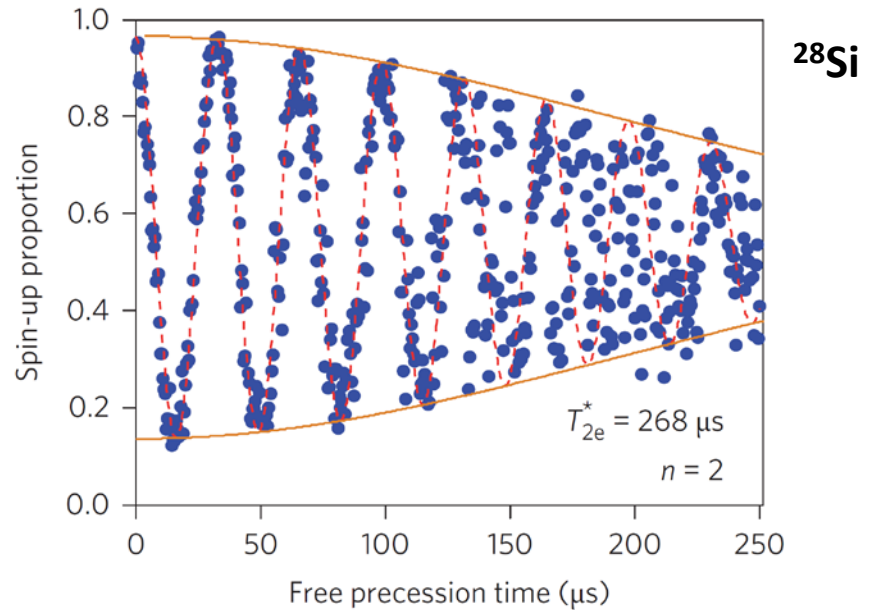
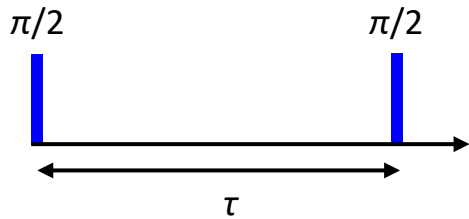


Nature Nano. **9**, 986 (2014) Muhonen *et al.*

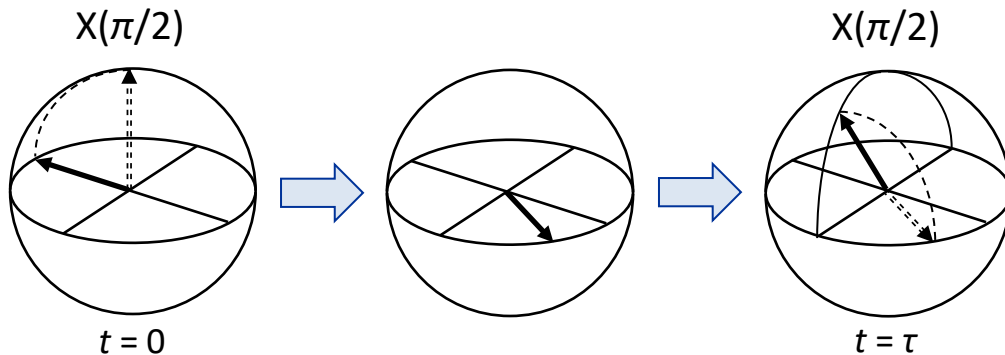
ラビ振動: natSiデバイス

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

ラムゼー干渉: T_{2e}^*



(共鳴から少し外れた回転系)

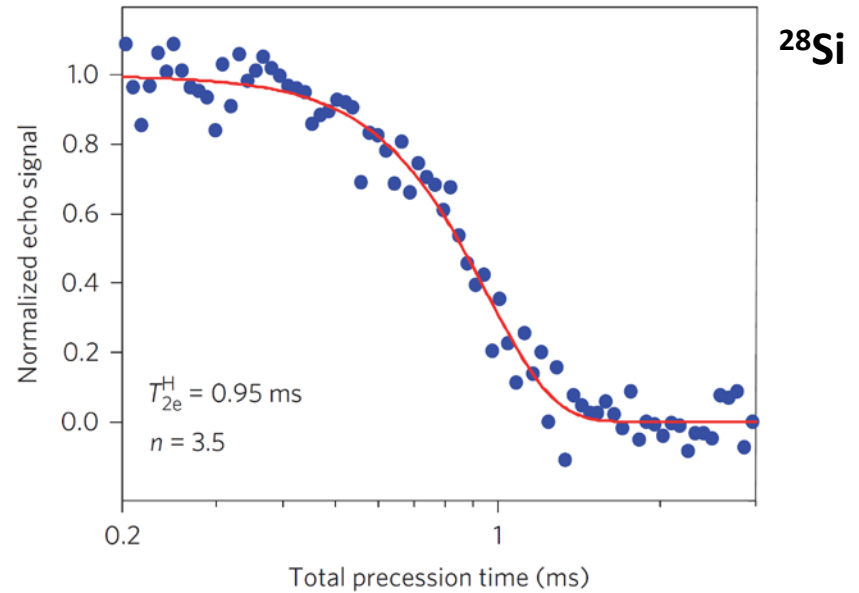
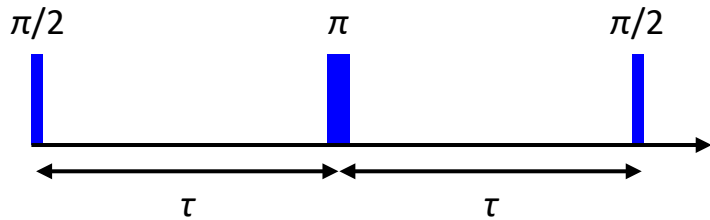


Norman Ramsey
(1915–2011)

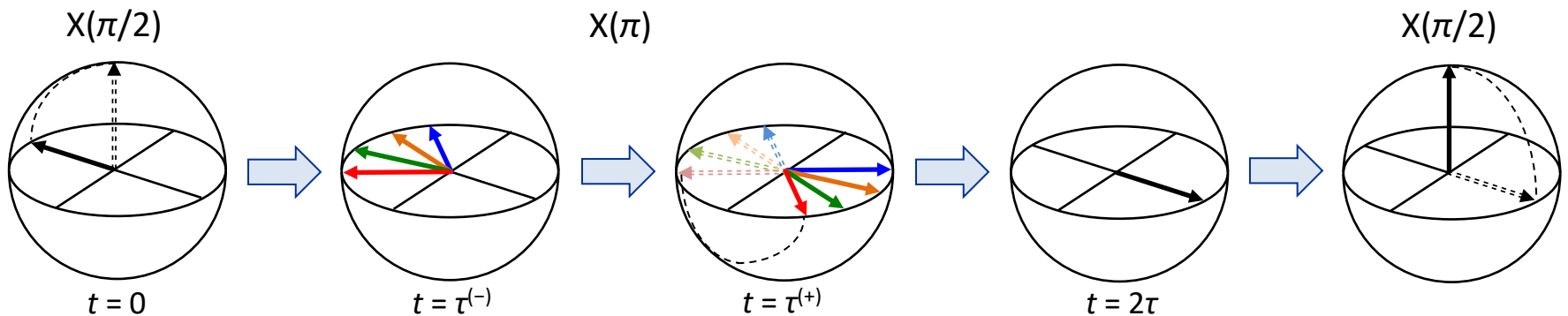
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スピンエコー: T_{2e}

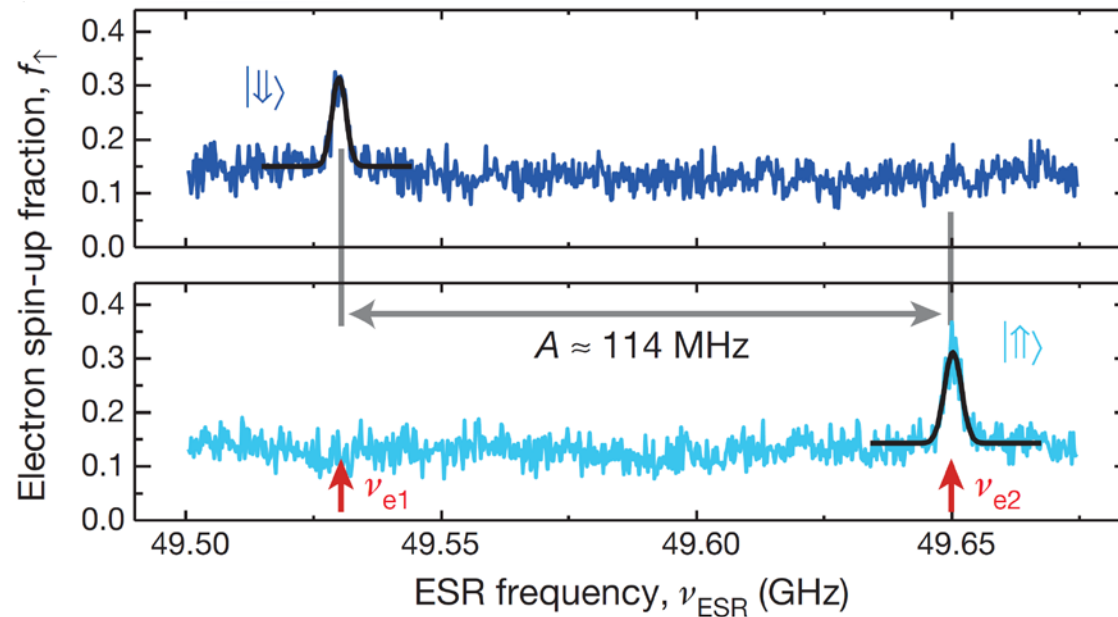


(共鳴周波数の回転系)



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

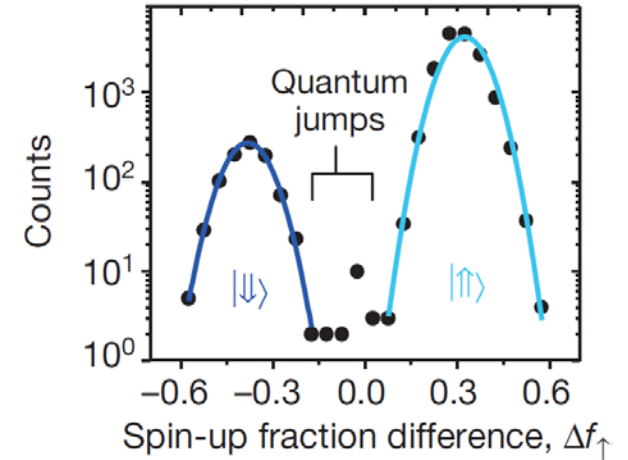
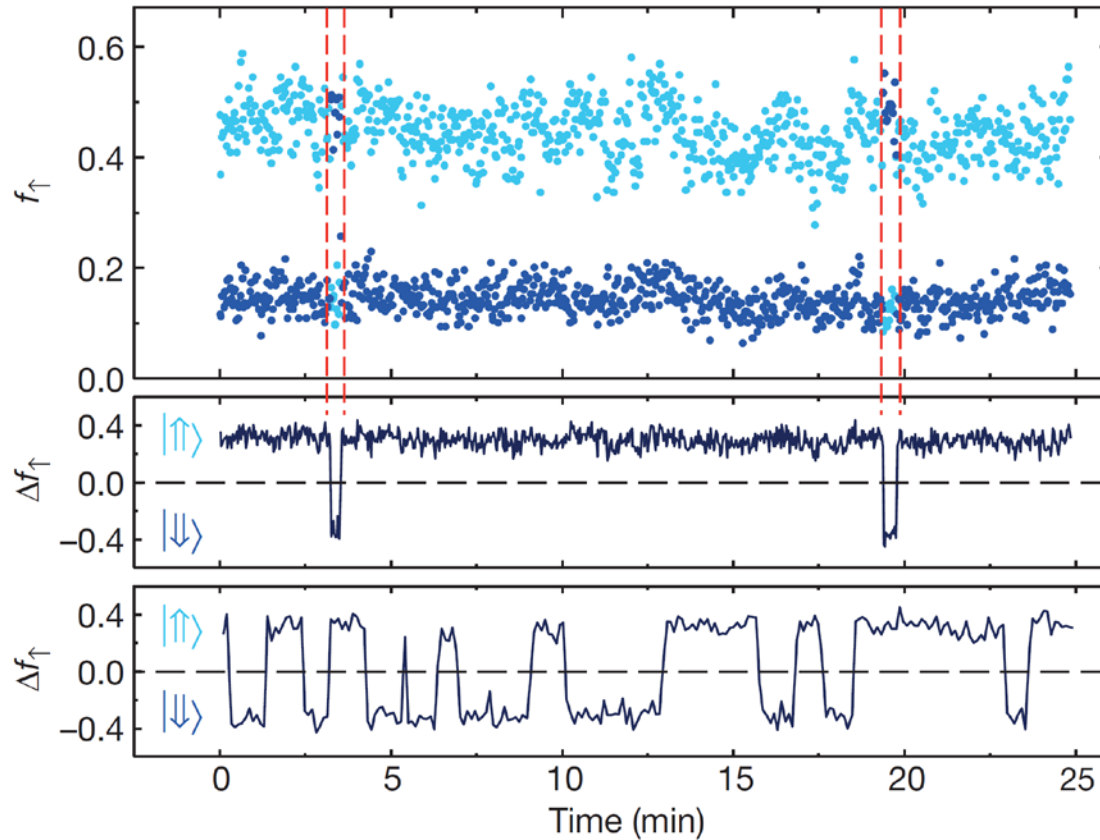
Jarryd J. Pla¹, Kuan Y. Tan^{1†}, Juan P. Dehollain¹, Wee H. Lim^{1†}, John J. L. Morton², Floris A. Zwanenburg^{1†}, David N. Jamieson³, Andrew S. Dzurak¹ & Andrea Morello¹



- 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

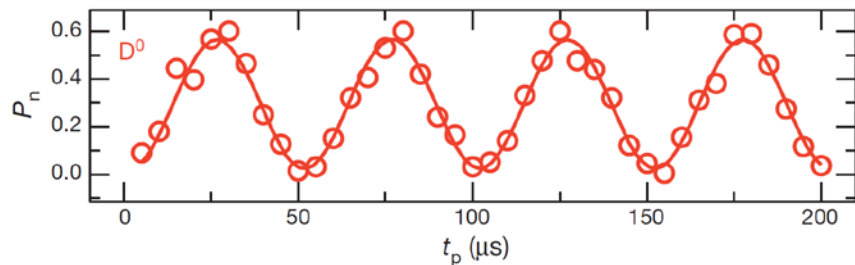
High-fidelity readout and control of a nuclear spin qubit in silicon

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

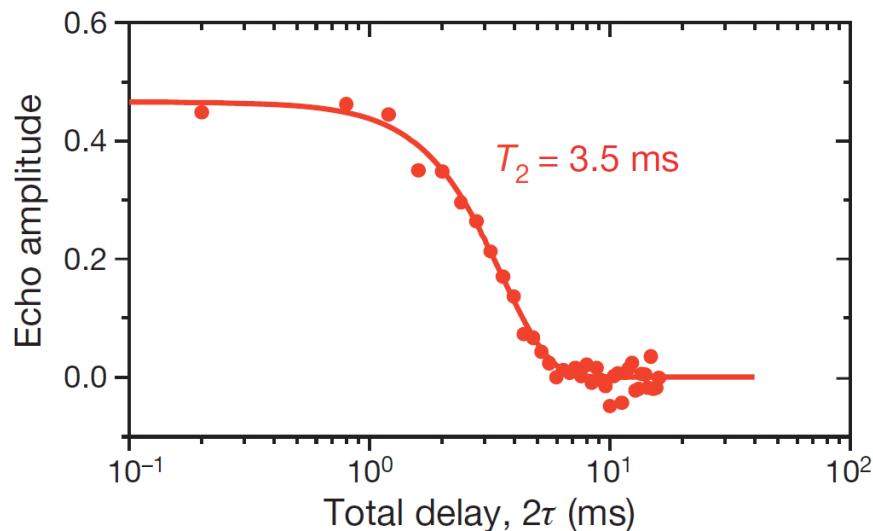
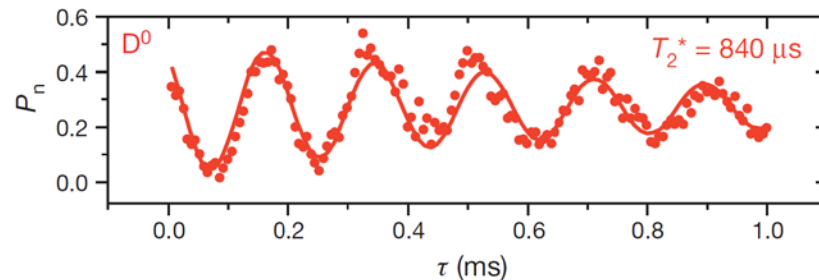


単一核スピンコヒーレント制御

ラビ振動(^{nat}Si)



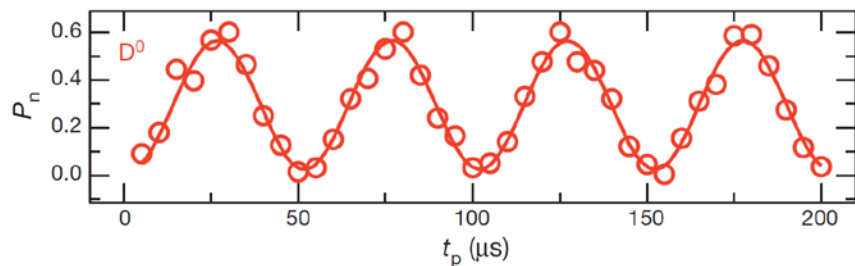
ラムゼー干渉(^{nat}Si)



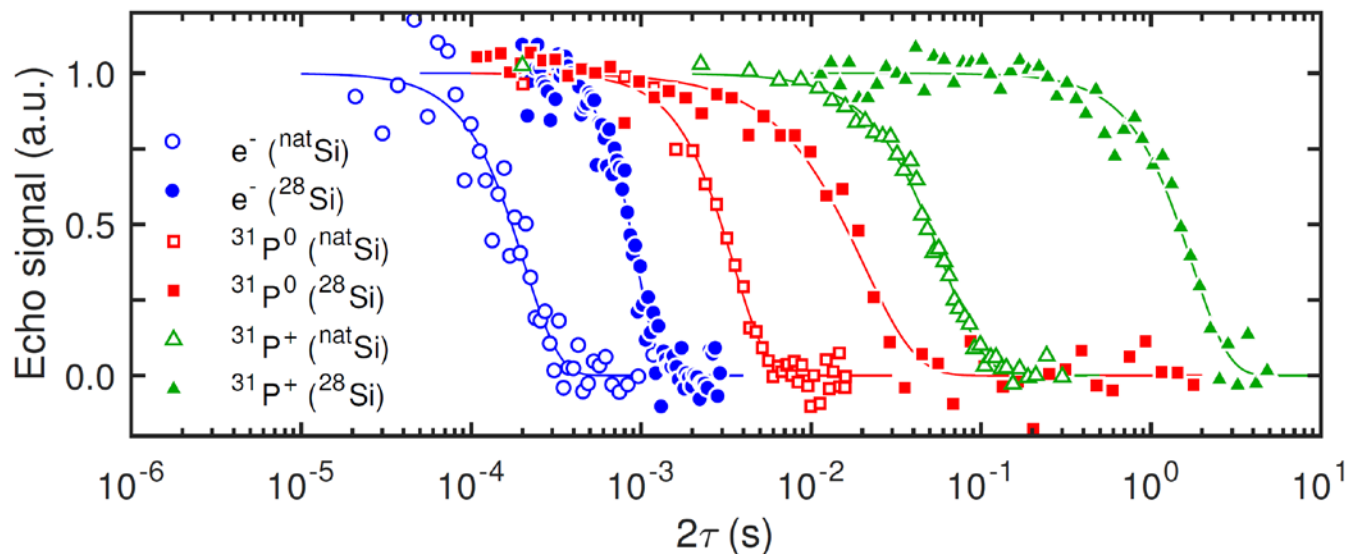
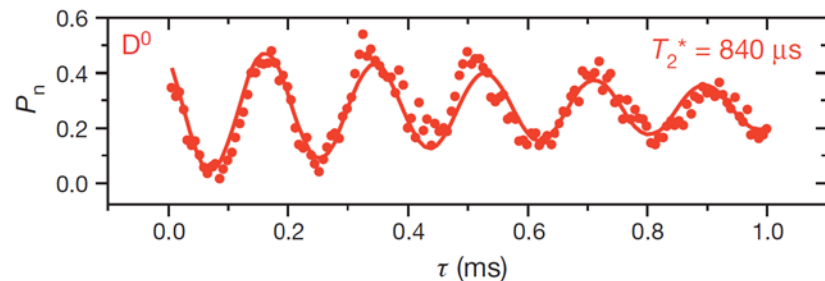
エコー(^{nat}Si)

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)

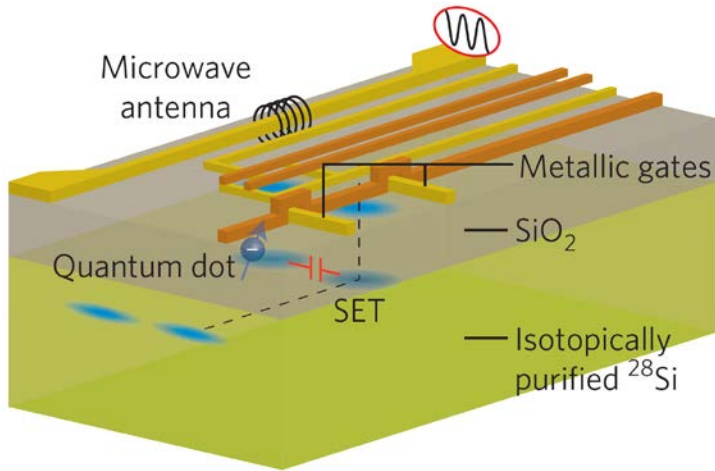


Nature **489**, 541 (2012) Pla *et al.*

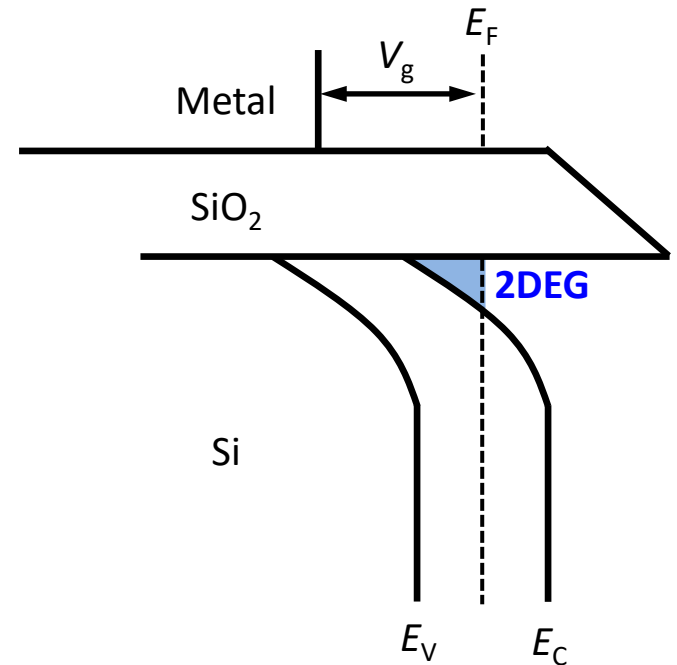
Nature **496**, 334 (2013) Pla *et al.*

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

界面MOS構造



反転層の形成

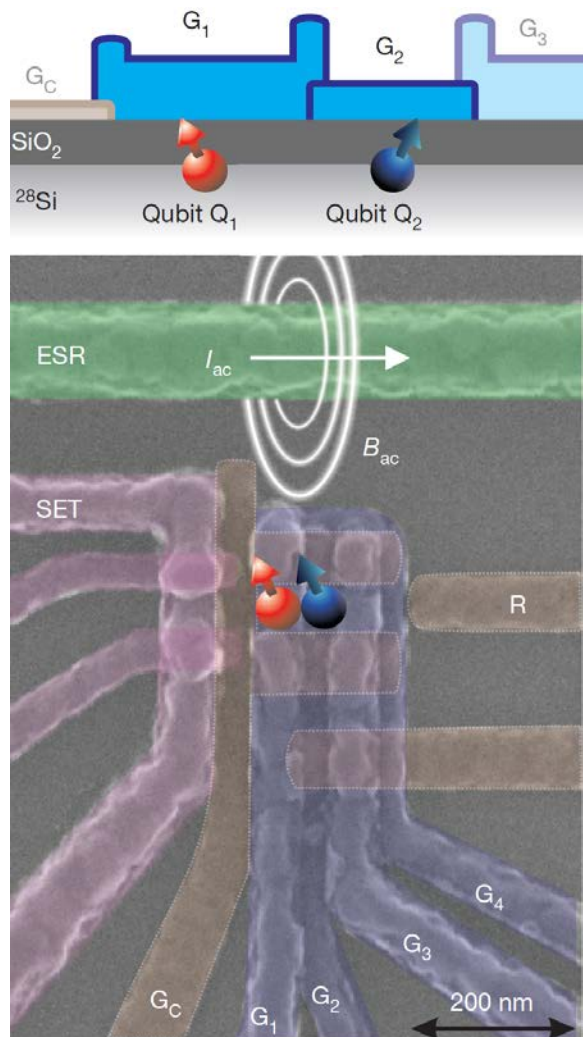


(L to R) J. Muhonen, A. Morello, M. Veldhorst, A. Dzurak

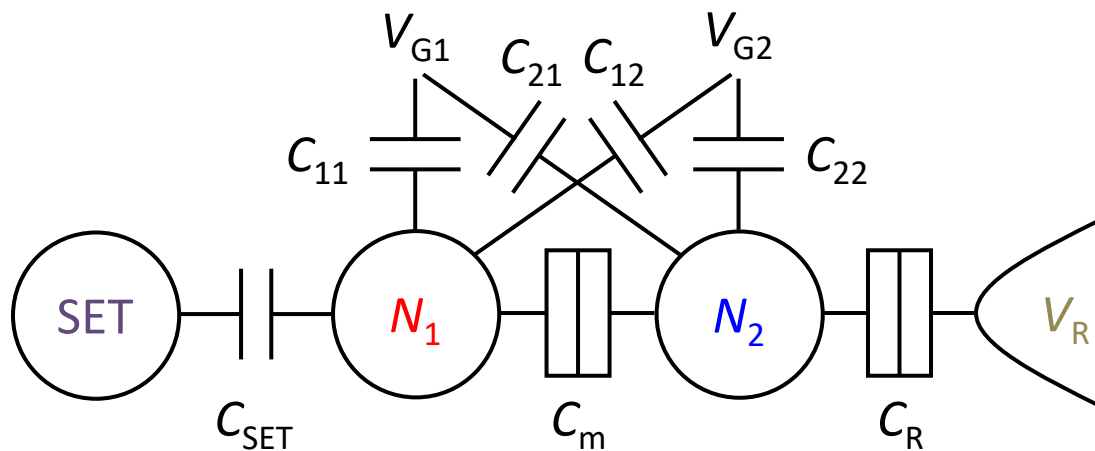
$$^{28}\text{Si} : ^{29}\text{Si} (I = \frac{1}{2}) : ^{30}\text{Si} = 92.2\% : 4.7\% : 3.1\%$$

$$\rightarrow ^{28}\text{Si} = 99.2\%$$

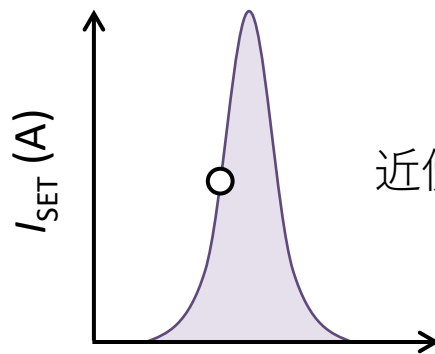
MOS型2重量子ドット



クロストーク

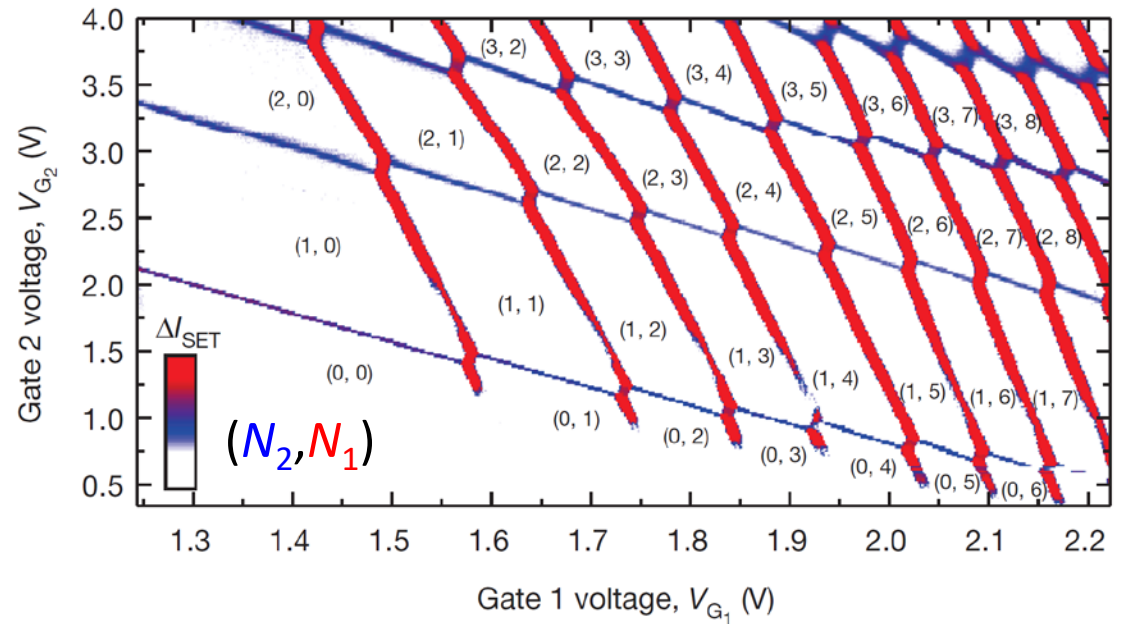
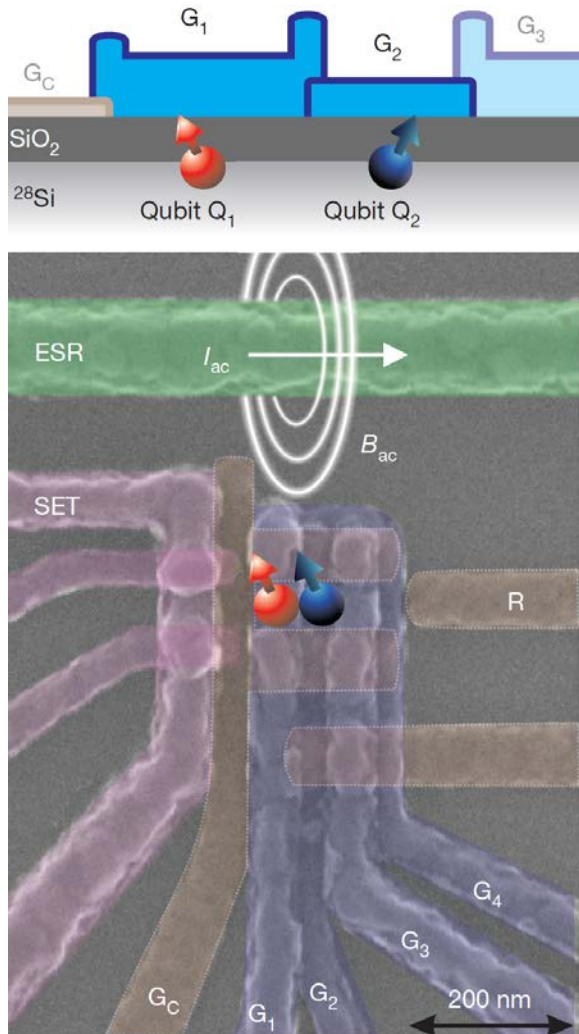


SET電荷センサ



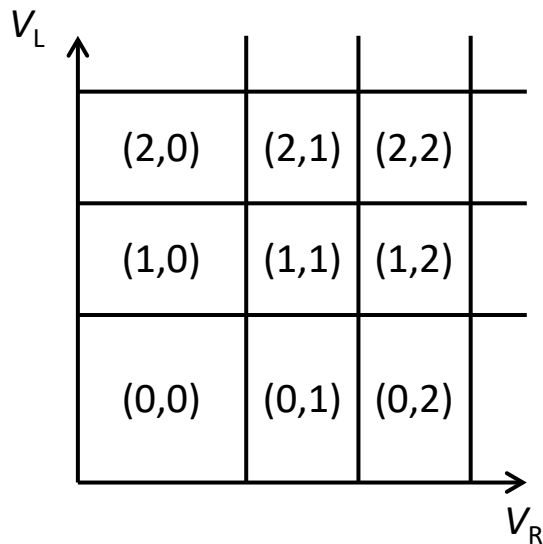
近傍のQDsの電子数変化に
鋭敏に応答

MOS型2重量子ドット



スタビリティダイアグラム

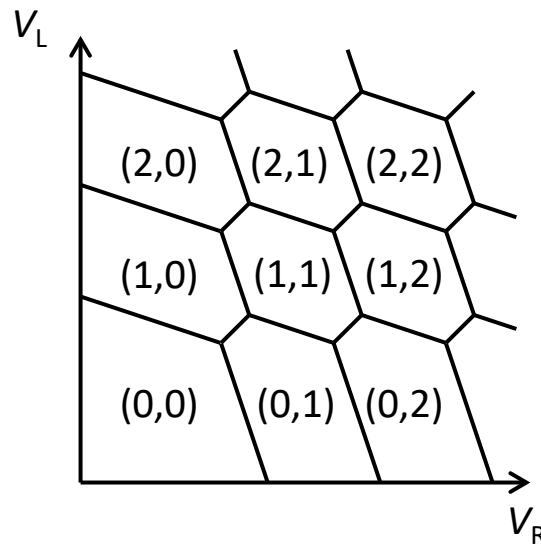
$$C_M \rightarrow 0$$



弱結合

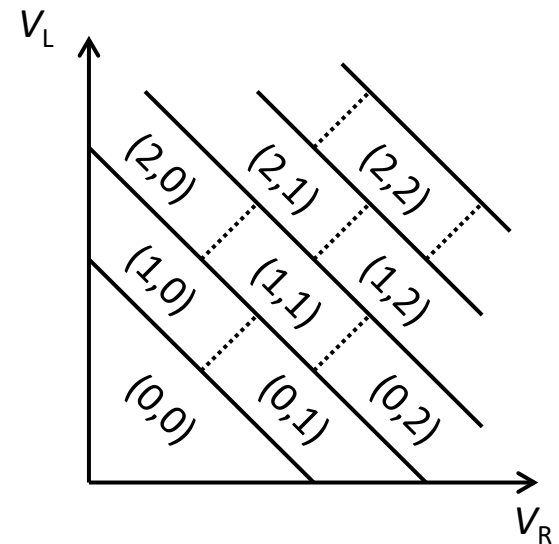
独立のドットとして
振る舞う

$$C_M \gg C_{S,D,LL,RR,LR,RL}$$



ハニカム構造

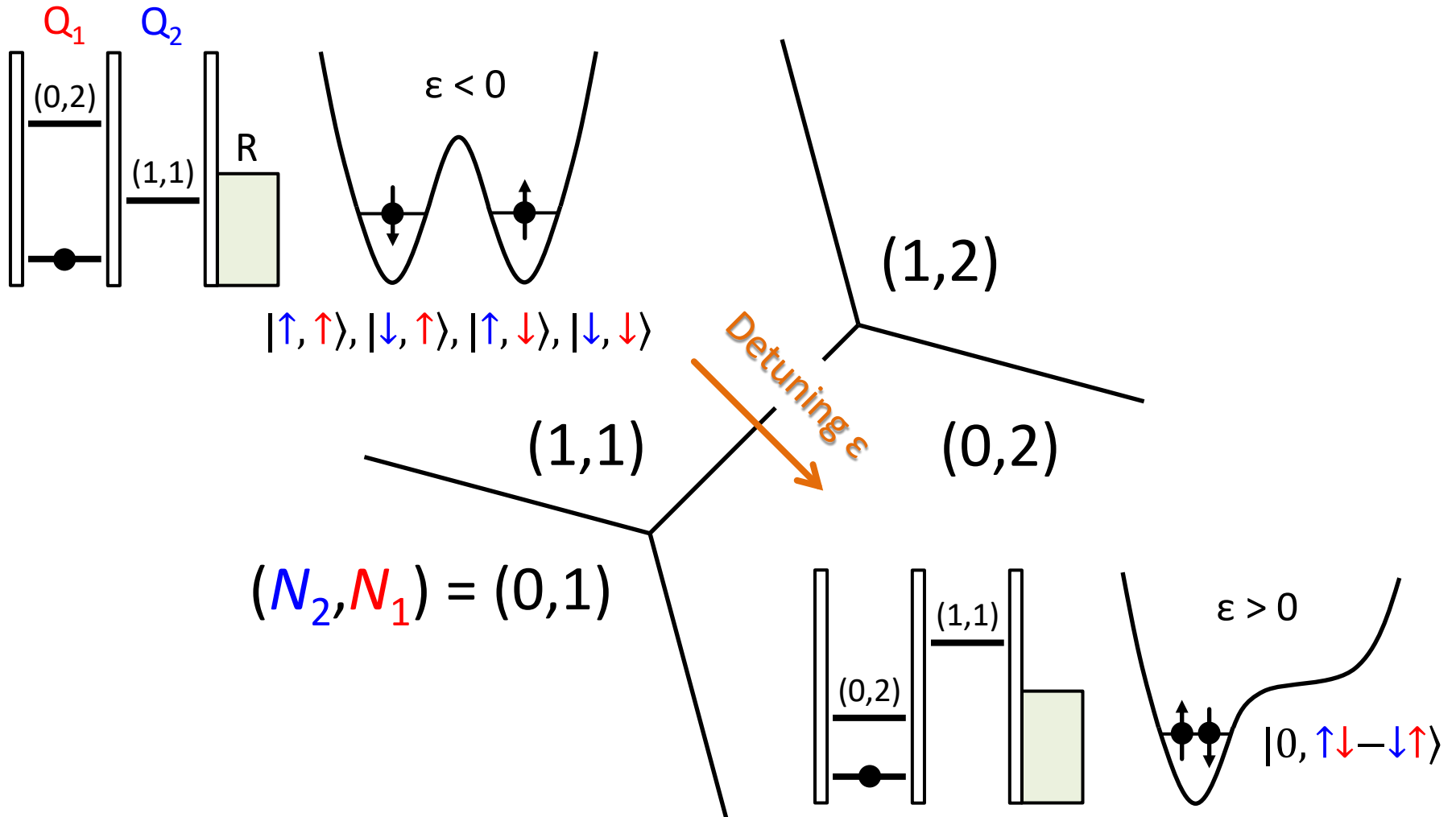
相互に影響しあう



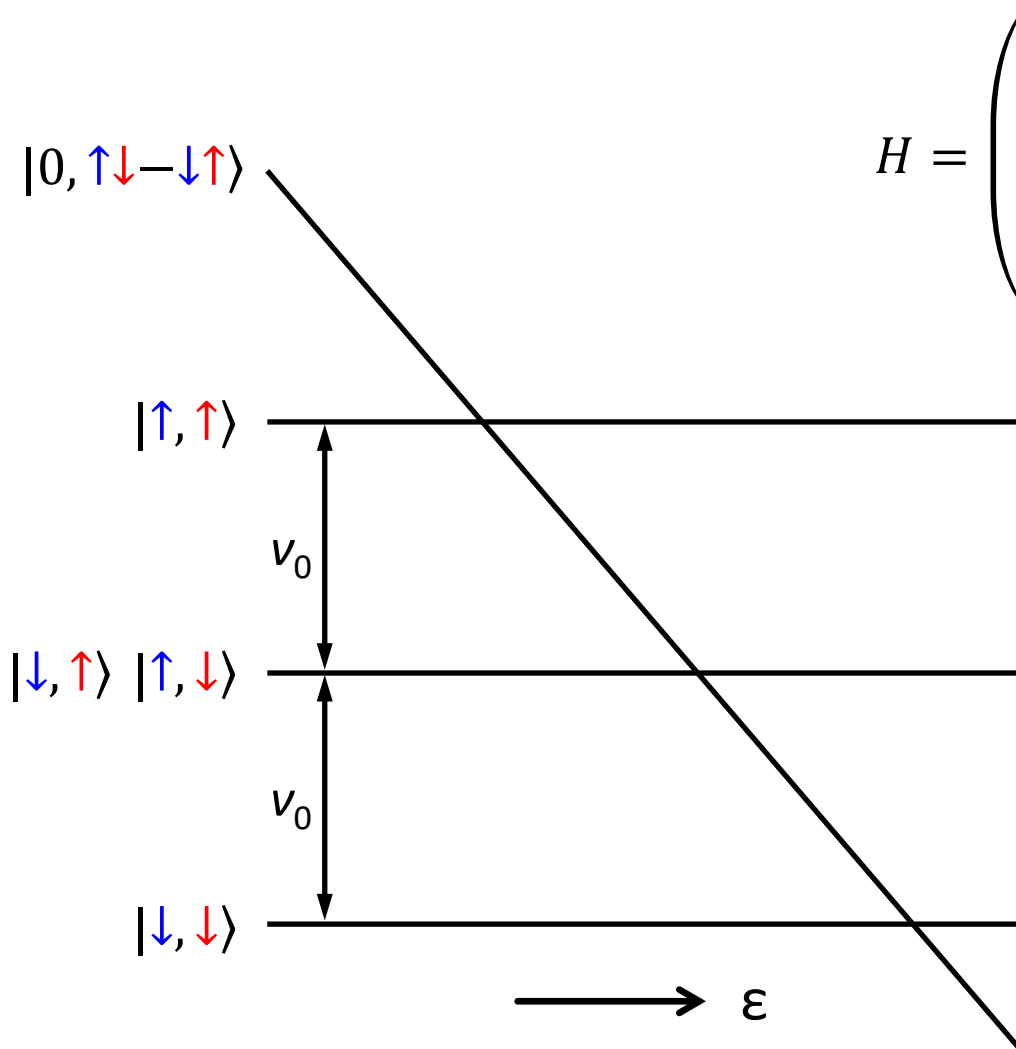
強結合

1つのドットとして
振る舞う

2電子状態



2電子状態



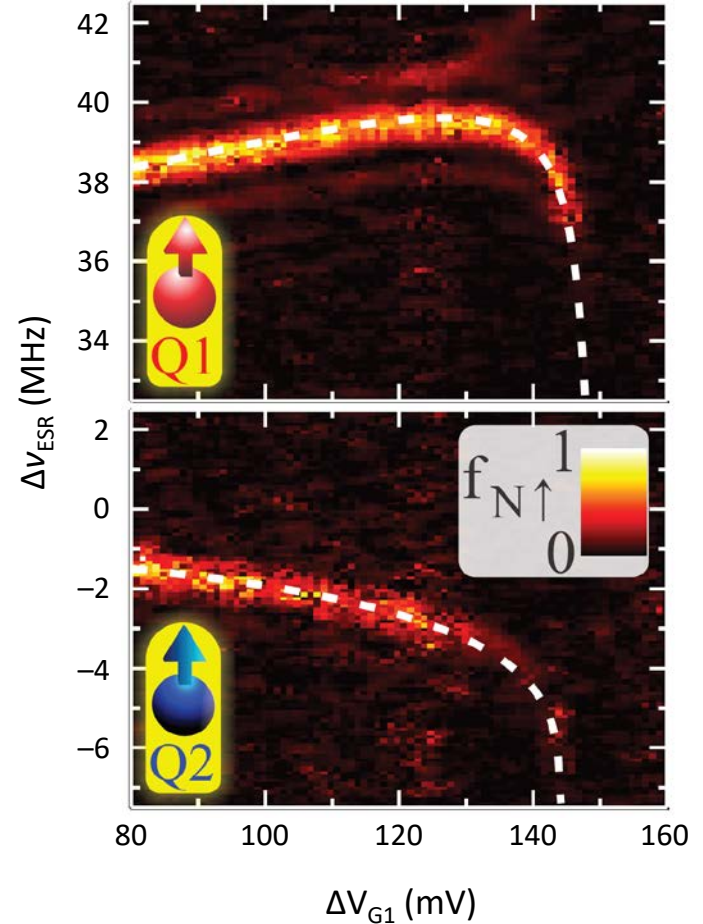
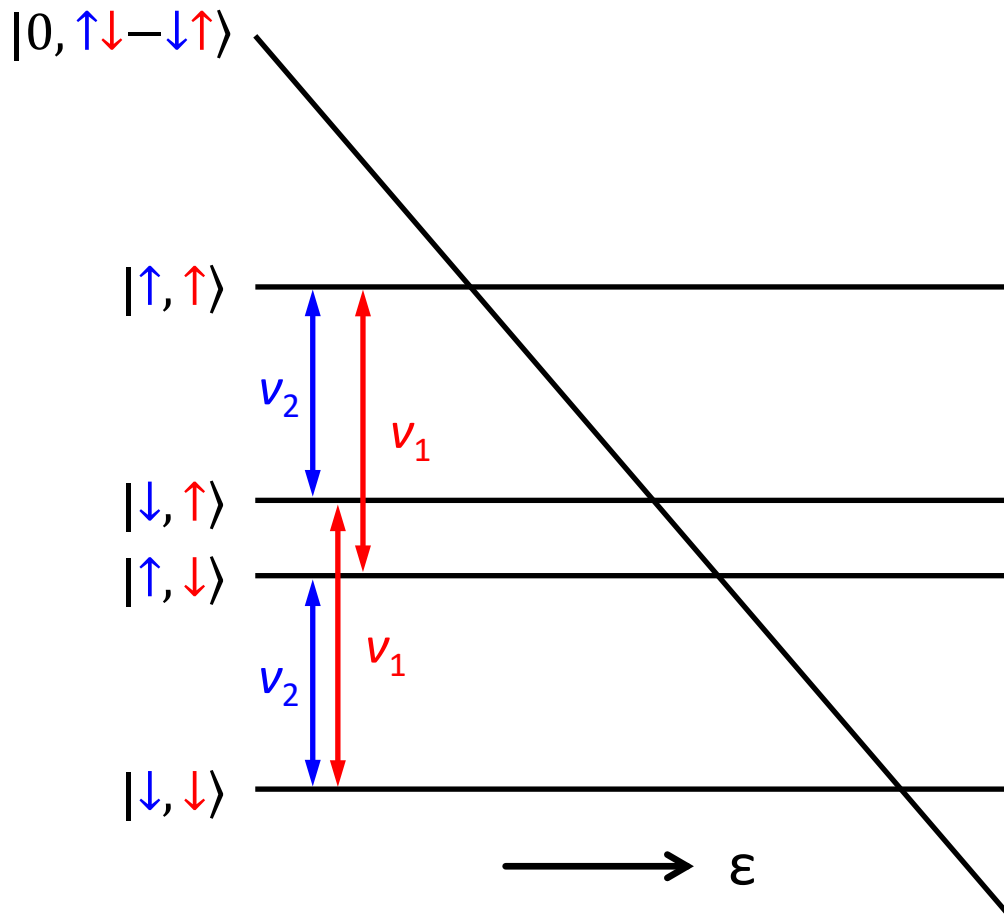
$$H = \begin{pmatrix} U - \varepsilon & 0 & 0 & 0 & 0 \\ 0 & E_z & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -E_z \end{pmatrix}$$

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

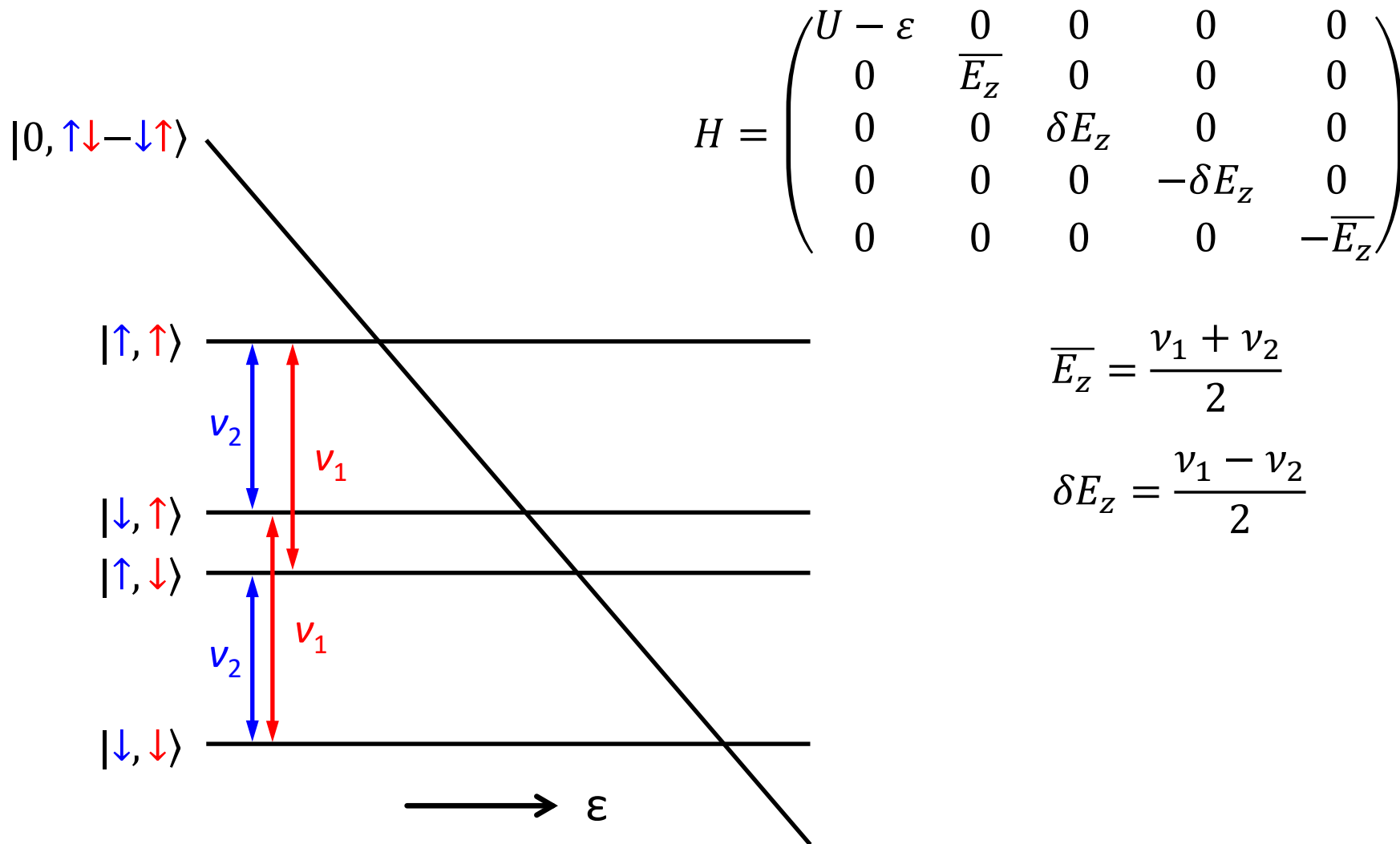
$$\nu_0 = 39.14 \text{ GHz @ } B_0 = 1.4 \text{ T}$$

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

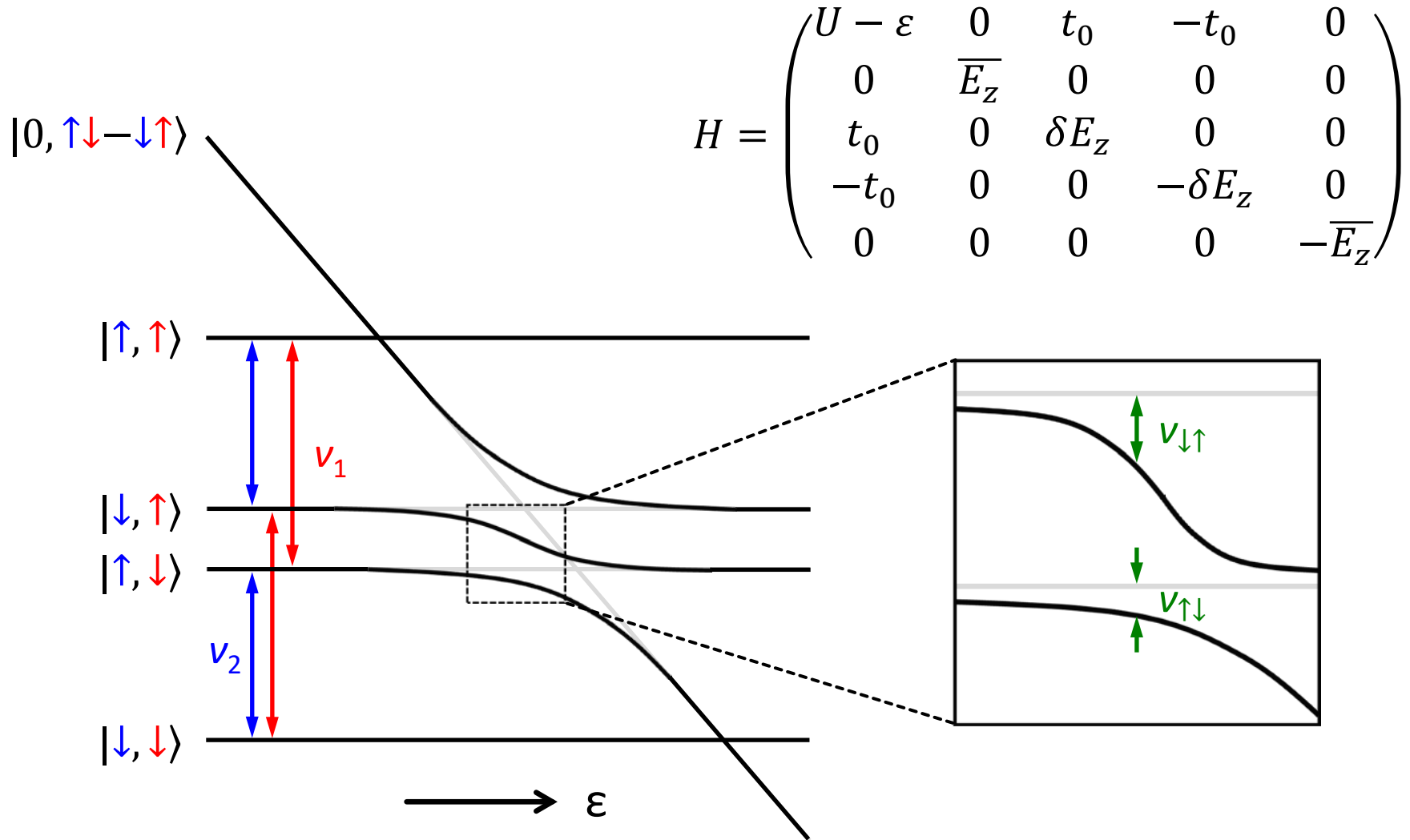


$$H = \begin{pmatrix} U - \epsilon & 0 & 0 & 0 & 0 \\ 0 & \overline{E}_z & 0 & 0 & 0 \\ 0 & 0 & \delta E_z & 0 & 0 \\ 0 & 0 & 0 & -\delta E_z & 0 \\ 0 & 0 & 0 & 0 & -\overline{E}_z \end{pmatrix}$$

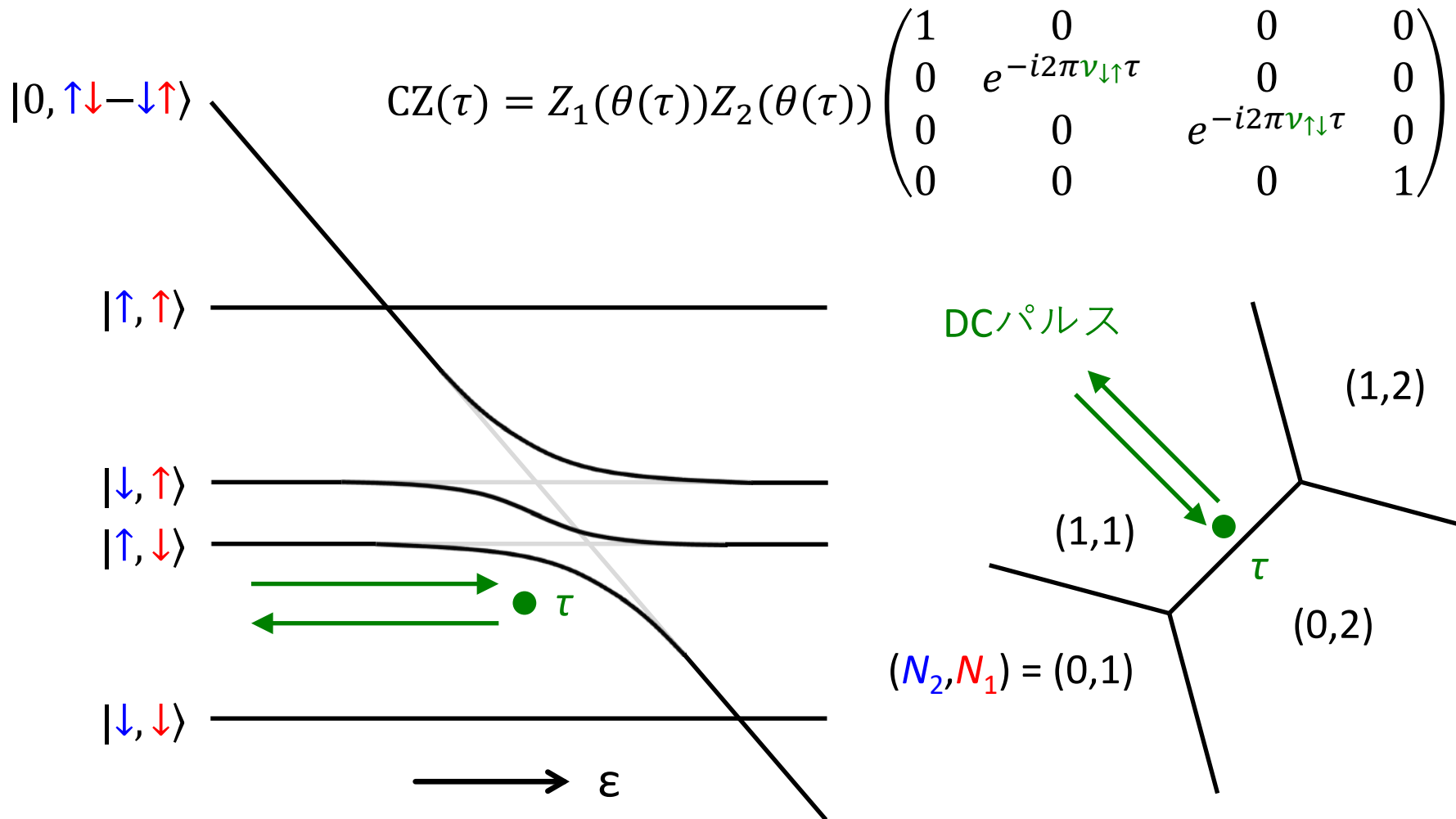
$$\overline{E}_z = \frac{v_1 + v_2}{2}$$

$$\delta E_z = \frac{v_1 - v_2}{2}$$

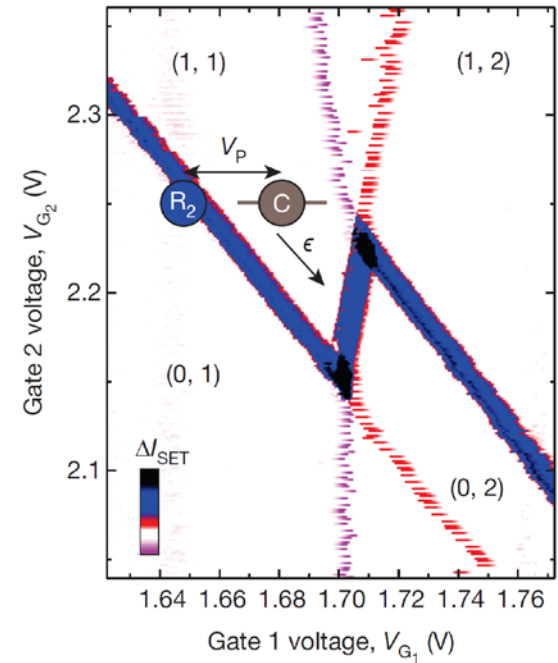
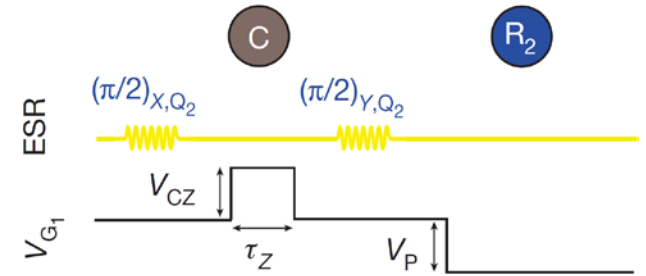
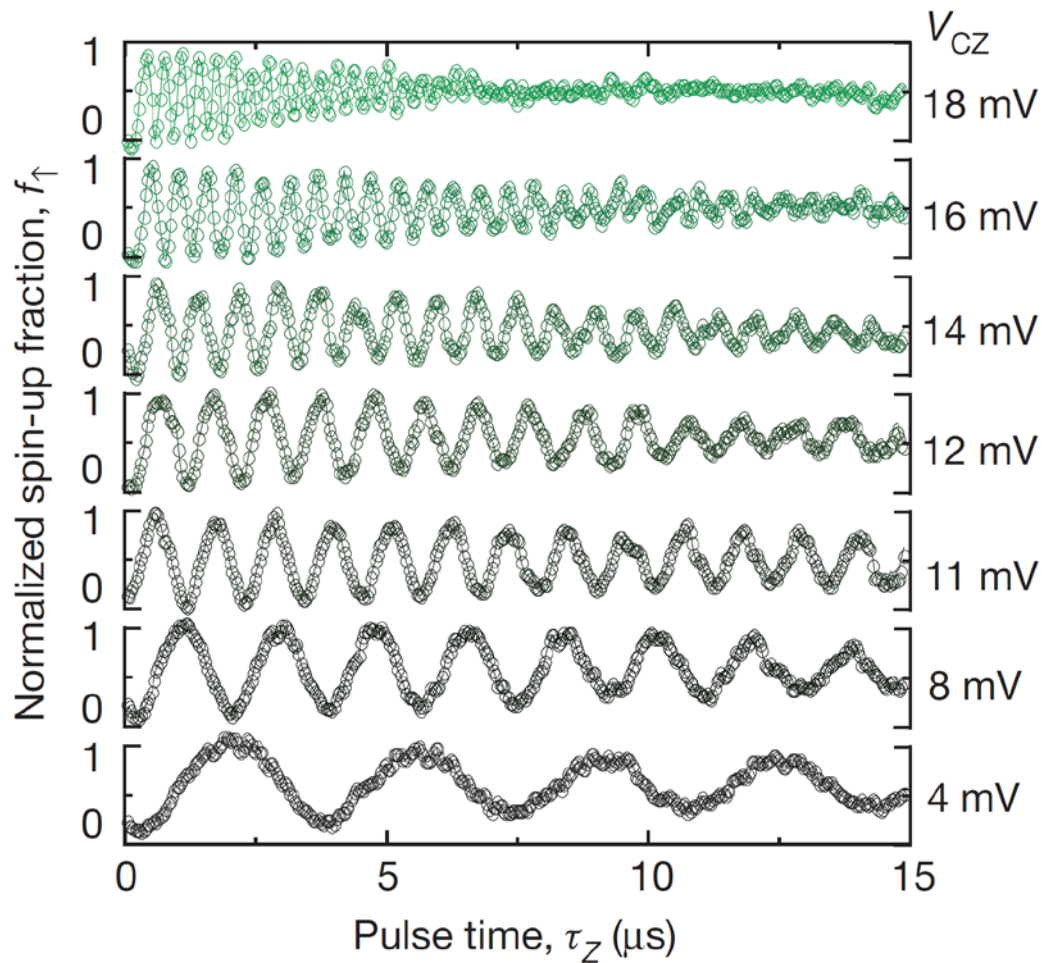
2電子状態



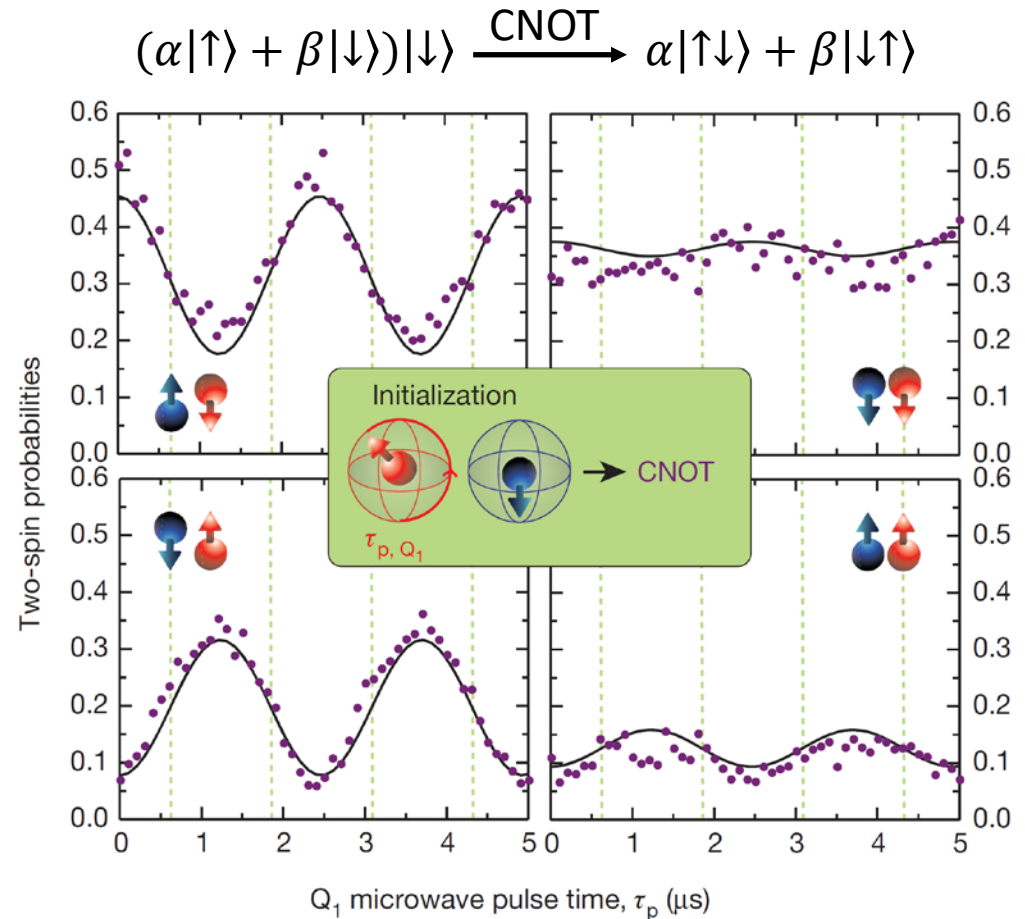
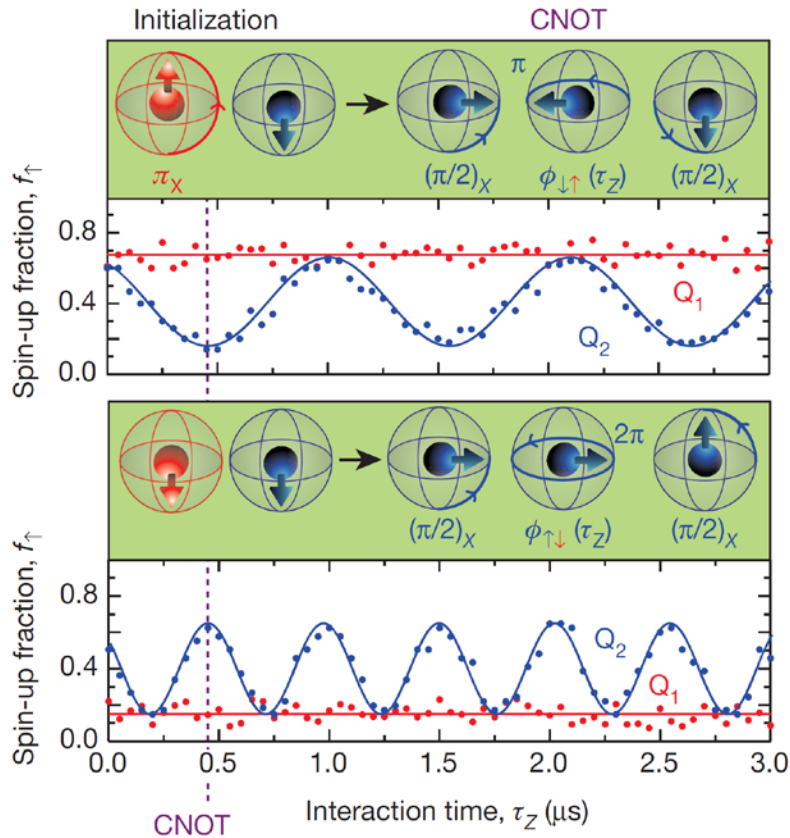
CZゲート



CZゲート

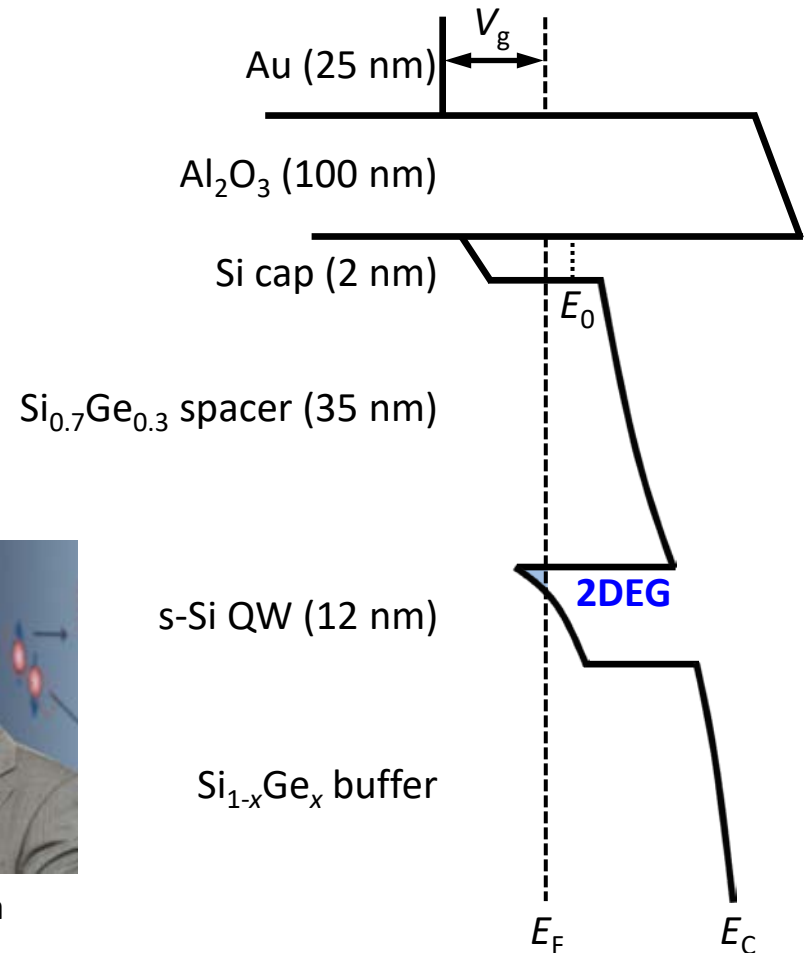
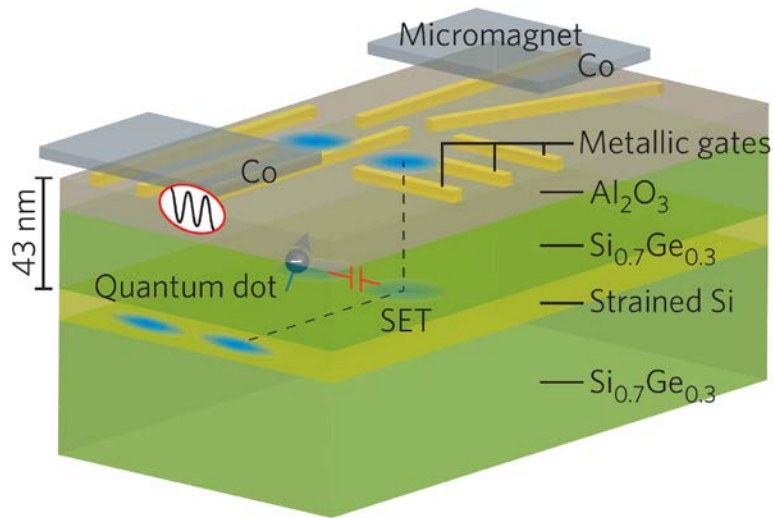


CNOTゲート



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

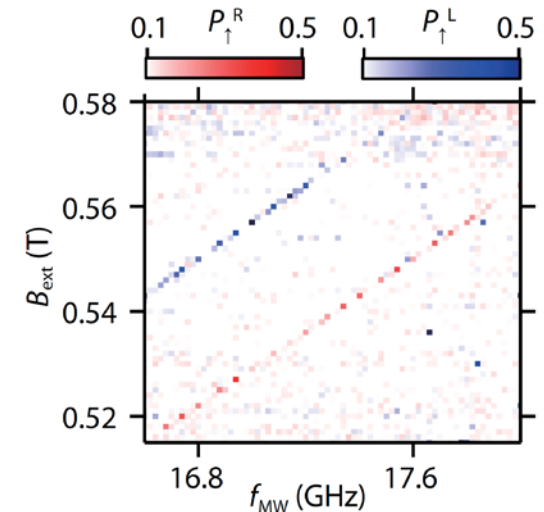
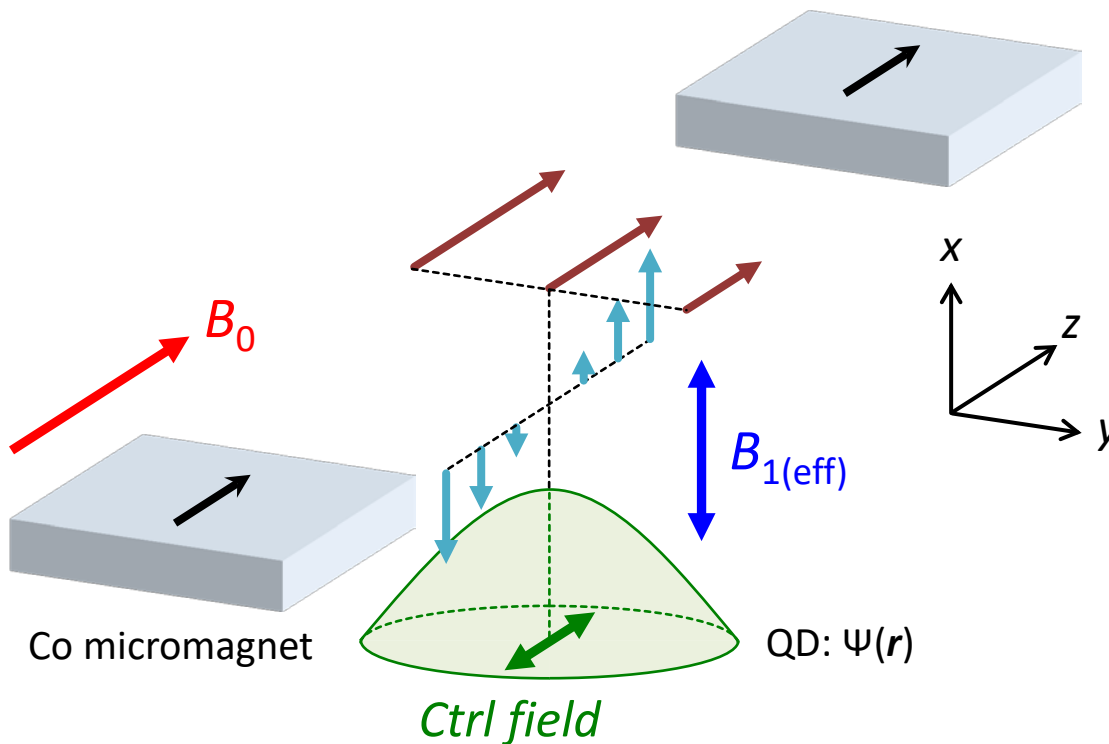


S. Tarucha

©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



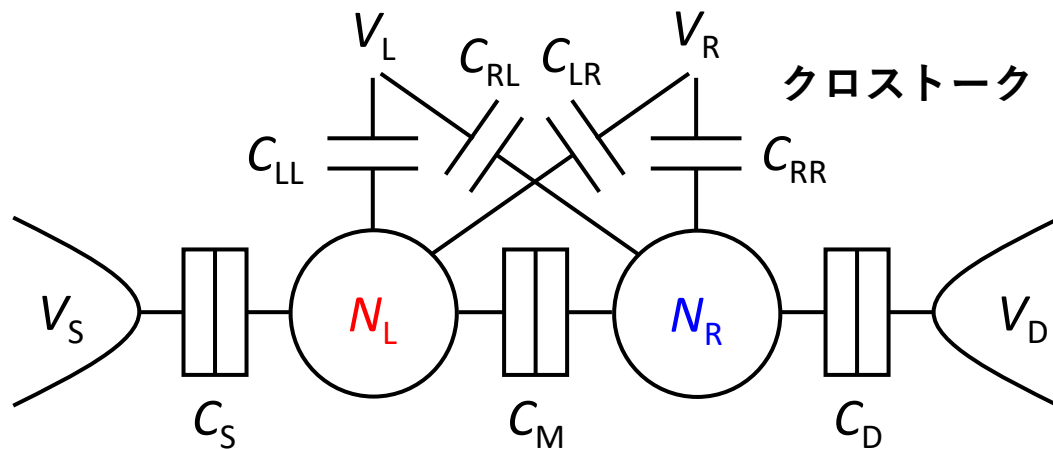
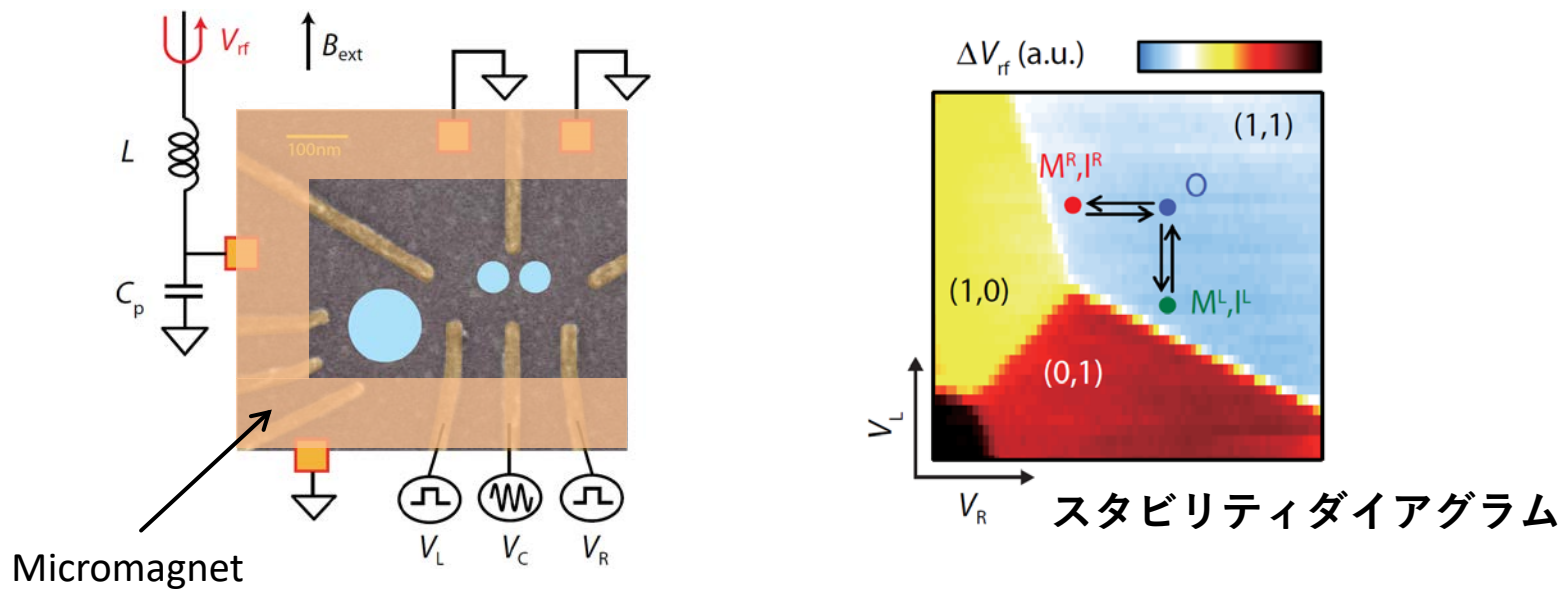
Sci. Adv. **2**, e1600694 (2016) Takeda *et al.*

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

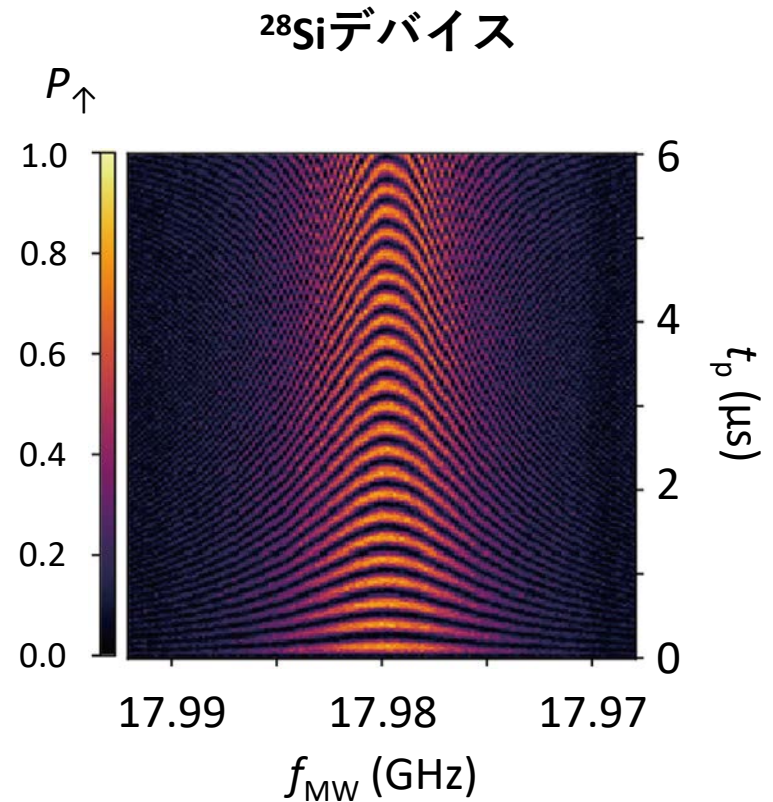
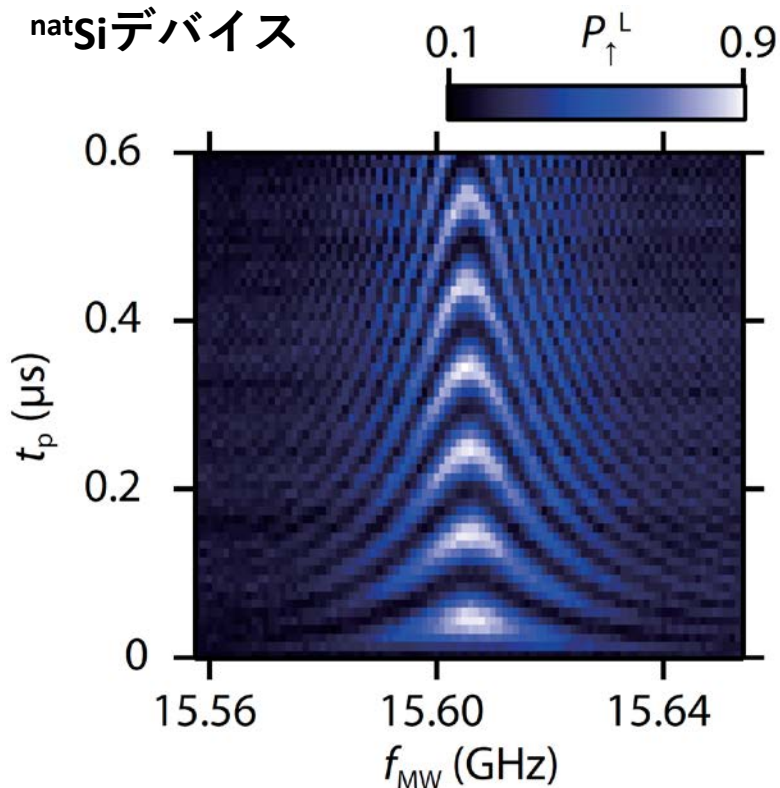
(GaAs QD) Nature Phys. **4**, 776 (2008) Pioro-Ladrière *et al.*

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

2重量子ドット



電気双極子スピン共鳴



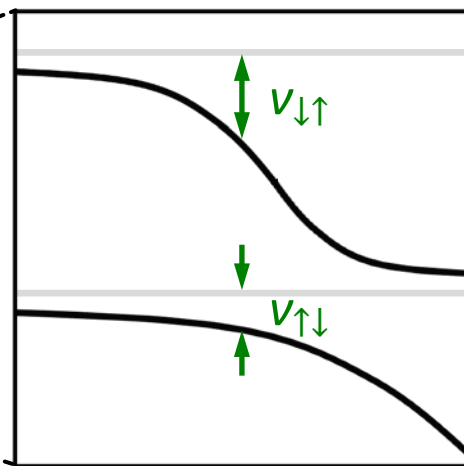
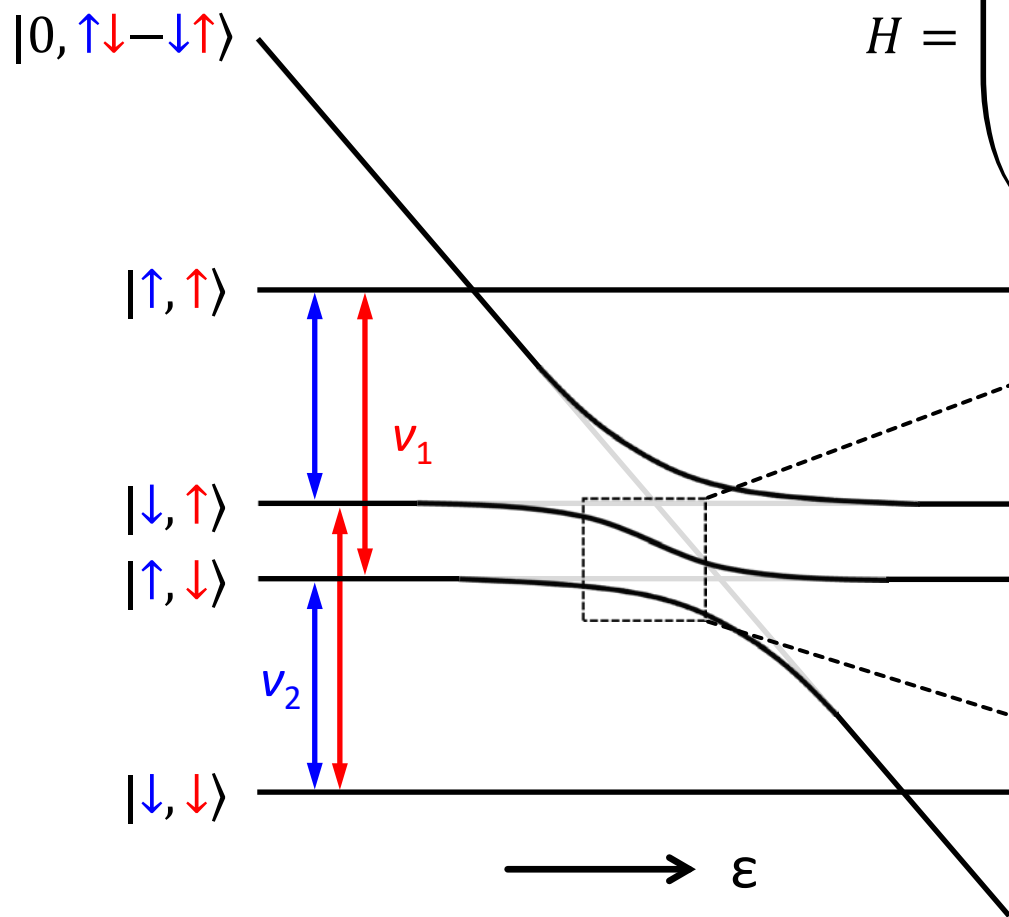
- ラビ周波数 $f_R \approx 30$ MHz
- フィデリティ $F^{RB} = 99.6\% \rightarrow > 99.9\%$
- $T_2^* = 2 \mu\text{s} \rightarrow 20 \mu\text{s}$, $T_2^{\text{CPMG}} = 3.1$ ms

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

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

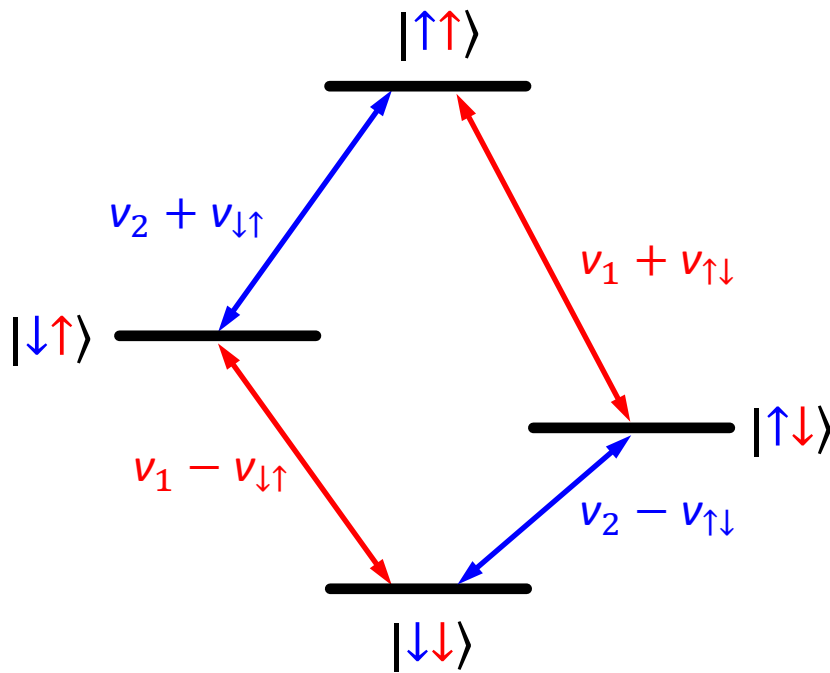
2量子ビットゲート

$$H = \begin{pmatrix} U - \varepsilon & 0 & t_0 & -t_0 & 0 \\ 0 & \overline{E}_Z & 0 & 0 & 0 \\ t_0 & 0 & \delta E_Z & 0 & 0 \\ -t_0 & 0 & 0 & -\delta E_Z & 0 \\ 0 & 0 & 0 & 0 & -\overline{E}_Z \end{pmatrix}$$



CROTゲート

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



CROT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

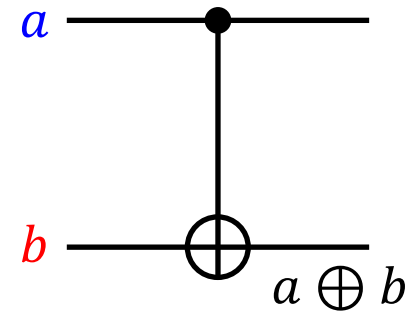
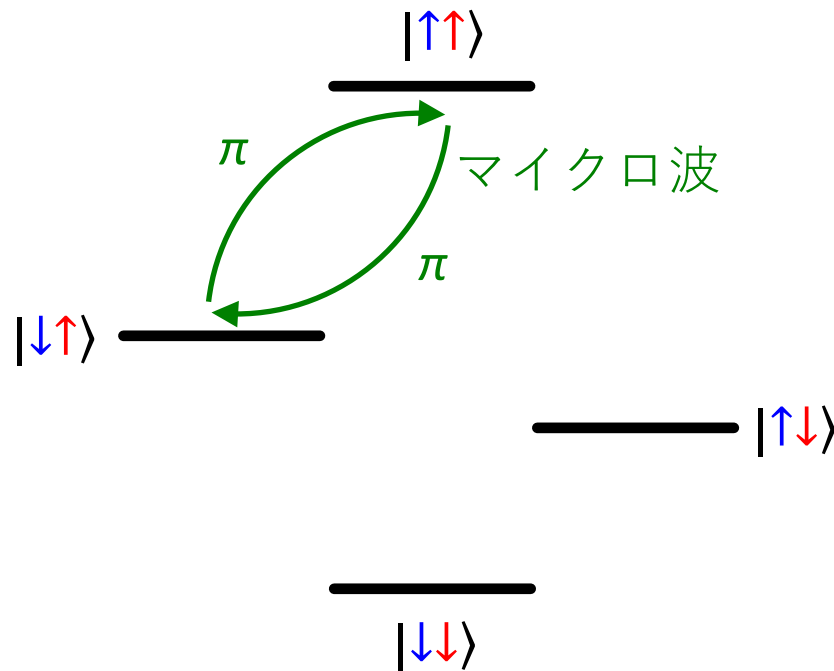
e.g. CNOTゲート

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

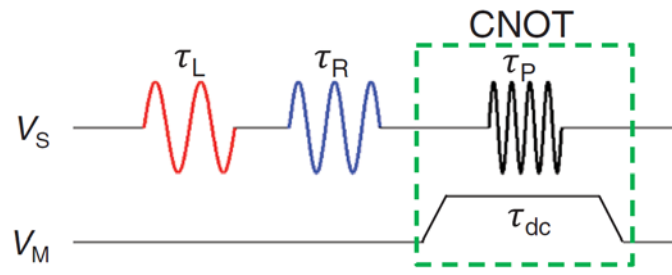
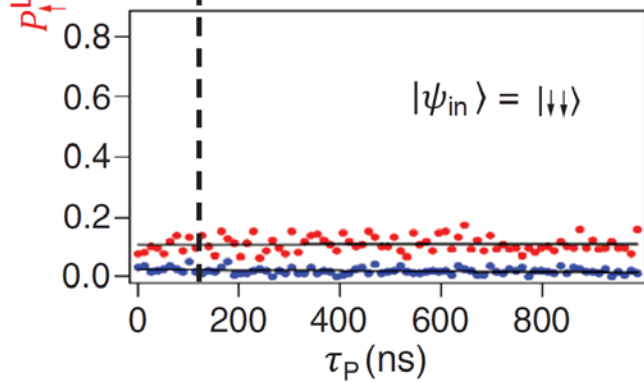
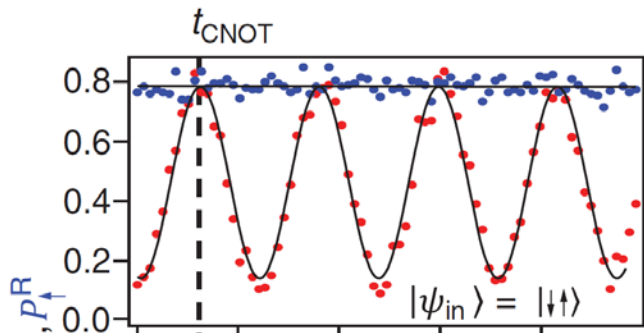
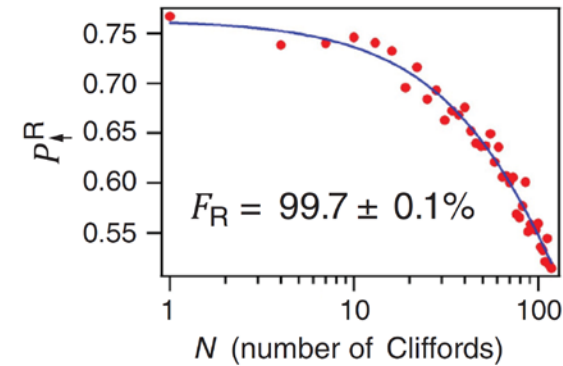
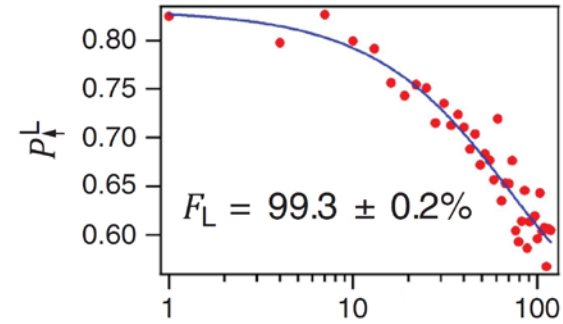
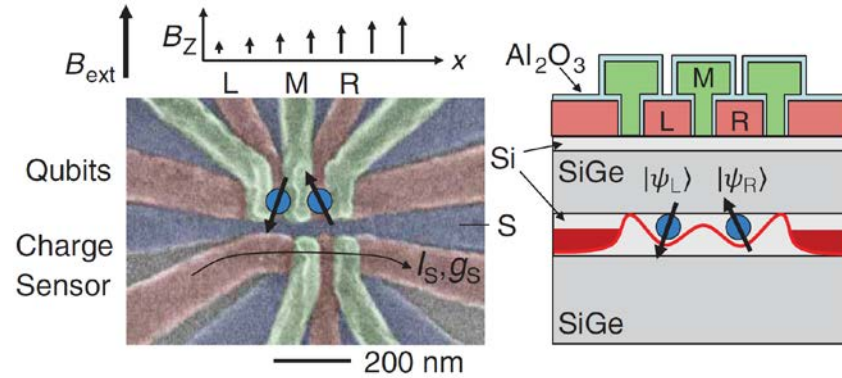
$$|\uparrow\downarrow\rangle = |10\rangle \longrightarrow |11\rangle$$

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

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

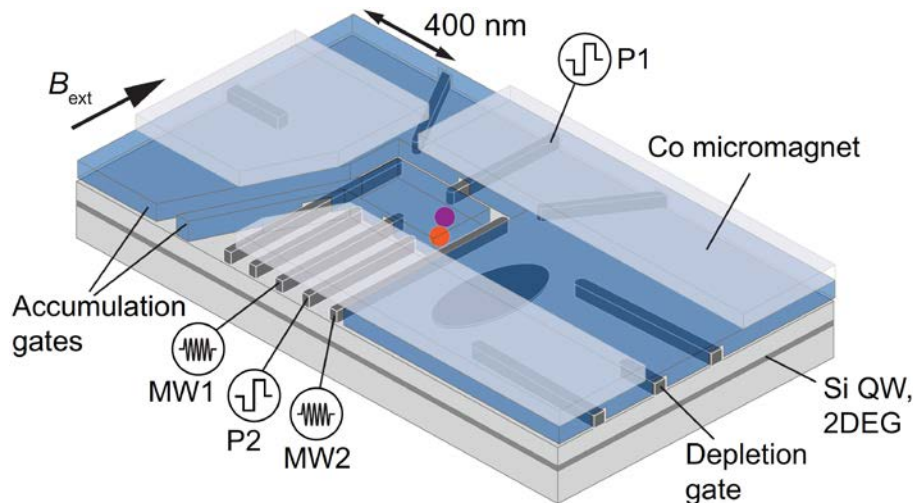
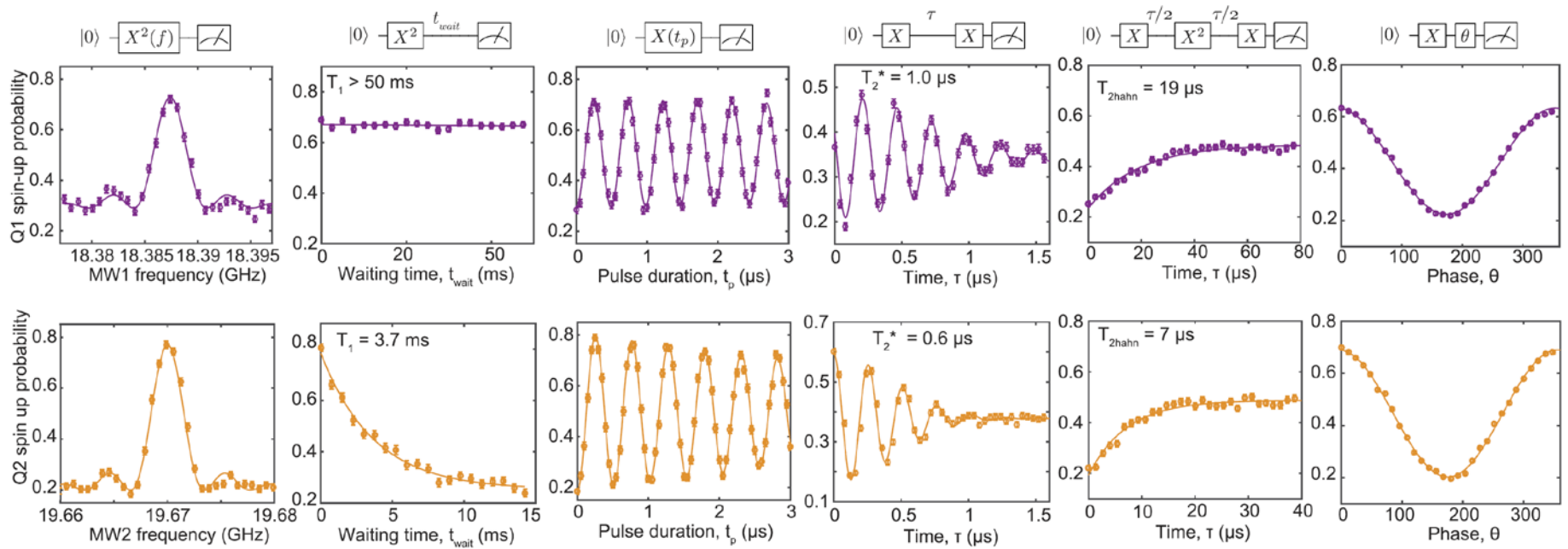


CNOTゲート

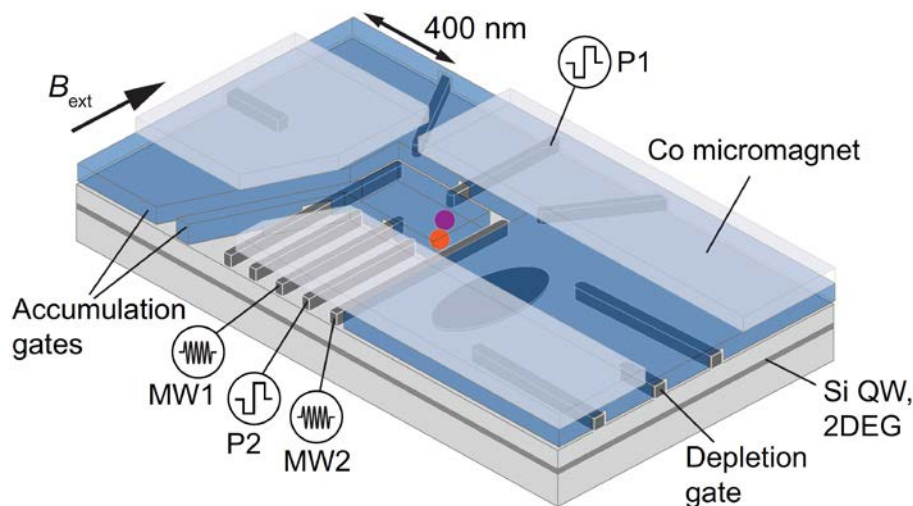
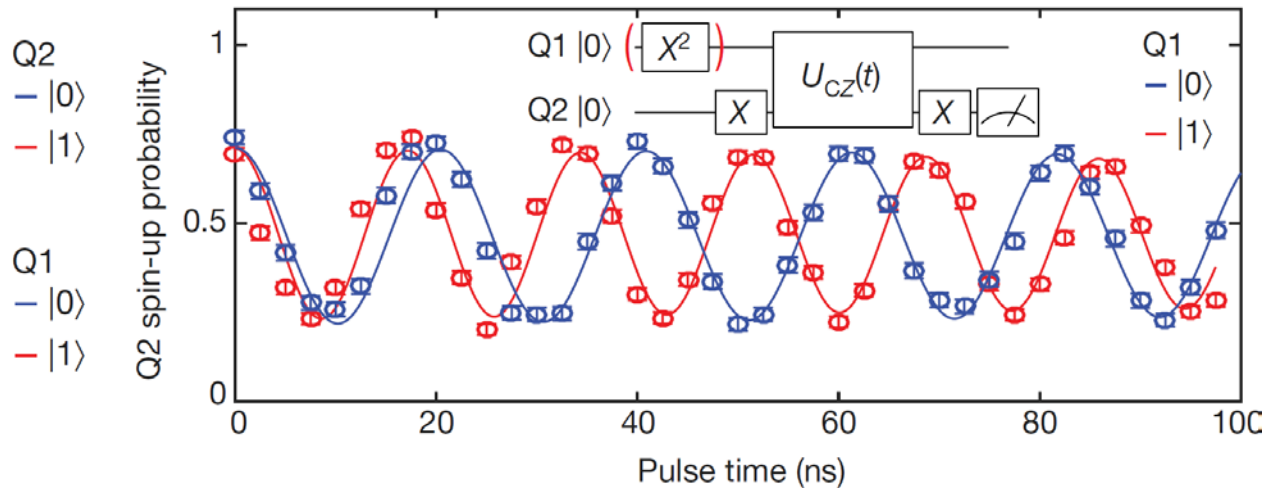
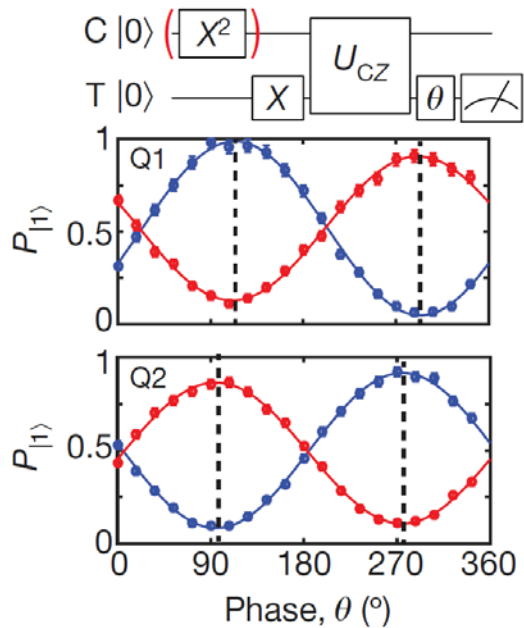


$F^{Bell} = 78\%$

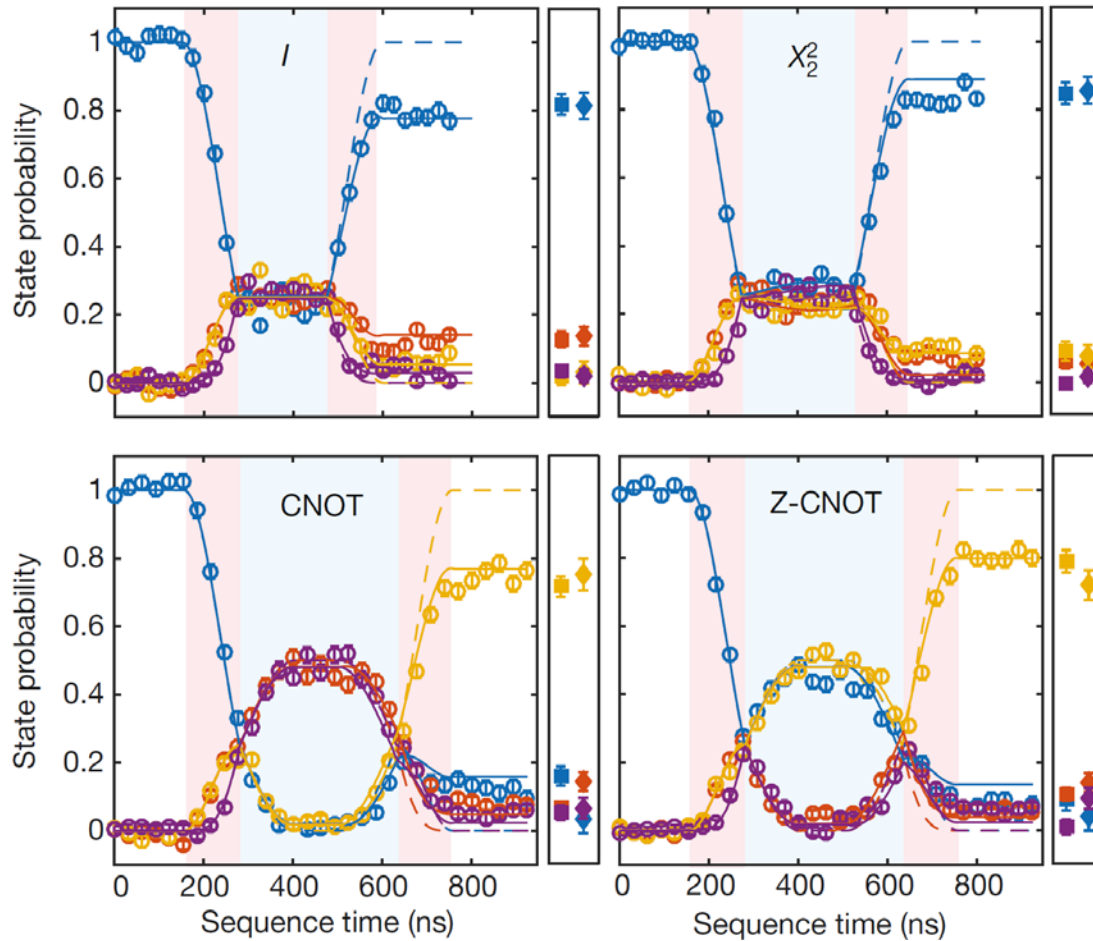
2量子ビットプロセッサ



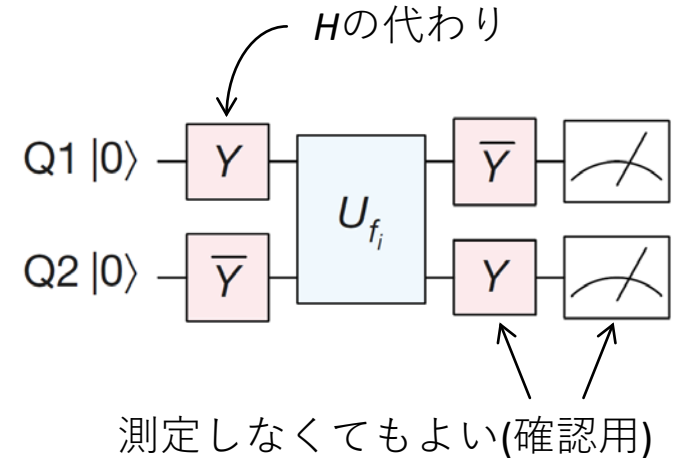
2量子ビットプロセッサ



ドイチェージョザアルゴリズムの実行



○ Experiment - - - Ideal ——— With noise
 ● $|00\rangle$ ● $|01\rangle$ ● $|10\rangle$ ● $|11\rangle$



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	$T_{2e}^{\text{CPMG}} = 559 \text{ ms}$ $T_{2n+}^{\text{CPMG}} = 35.6 \text{ s}$ $F_{2n+} = 99.99\% (*1)$	cf. $F_{ZZ, \sqrt{S}} = 90\% (*4)$ cf. $F^{\text{Bell}(e-n)} = 97\% (*5)$	“フリップフロップ” 量子ビット(*8)
MOS量子ドット	$T_2^{\text{CPMG}} = 28 \text{ ms}$ $F^{\text{RB}} = 99.6\% (*2)$	$F^{\text{Bell}} = 89\%$ $F^{\text{RB}} = 98\% (*6)$	CMOS/DRAM技術 との融合(*9,10)
Si/SiGe量子ドット	$T_2^{\text{CPMG}} = 3.1 \text{ ms}$ $F^{\text{RB}} > 99.9\% (*3)$	$F^{\text{Bell}} = 89\% (*7)$	スピン-MW光子結合 による回路QED(*11,12)

*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 **571**, 371 (2019) He *et al.* (donor QDs)
 *5: Nature Nano. **11**, 242 (2016) Dehollain *et al.*
 *6: Nature **569**, 532 (2019) Huang *et al.*

*7: Nature **555**, 633 (2018) Watson *et al.*
 *8: Nature Commun. **8**, 450 (2017) Tosi *et al.*
 *9: Nature Commun. **8**, 1766 (2017) Veldhorst *et al.*
 *10: Sci. Adv. **4**, eaar3960 (2018) Li *et al.*
 *11: Nature **555**, 599 (2018) Mi *et al.*
 *12: Science **359**, 1123 (2018) Samkharadze *et al.*