

シリコンスピン 量子コンピュータ開発の現状

阿部英介

慶應義塾大学スピントロニクス研究センター

2018年5月22日@NIMS

第7回つくば量子情報サロン

「量子コンピュータデバイス研究の最前線」

Keio University



Quantum computers

T. D. Ladd^{1,†}, F. Jelezko², R. Laflamme^{3,4,5}, Y. Nakamura^{6,7}, C. Monroe^{8,9} & J. L. O'Brien¹⁰

Over the past several decades, quantum information science has emerged to seek answers to the question: can we gain some advantage by storing, transmitting and processing information encoded in systems that exhibit unique quantum properties? Today it is understood that the answer is yes, and many research groups around the world are working towards the highly ambitious technological goal of building a quantum computer, which would dramatically improve computational power for particular tasks. A number of physical systems, spanning much of modern physics, are being developed for quantum computation. However, it remains unclear which technology, if any, will ultimately prove successful. Here we describe the latest developments for each of the leading approaches and explain the major challenges for the future.

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

VOLUME 89, NUMBER 1

PHYSICAL REVIEW LETTERS

1 JULY 2002

All-Silicon Quantum Computer

T. D. Ladd,* J. R. Goldman, F. Yamaguchi, and Y. Yamamoto[†]

Quantum Entanglement Project, ICORP, JST, Edward L. Ginzton Laboratory, Stanford University, Stanford, California 94305-4085

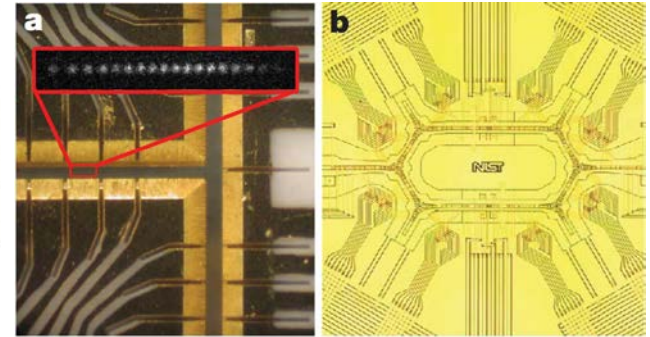
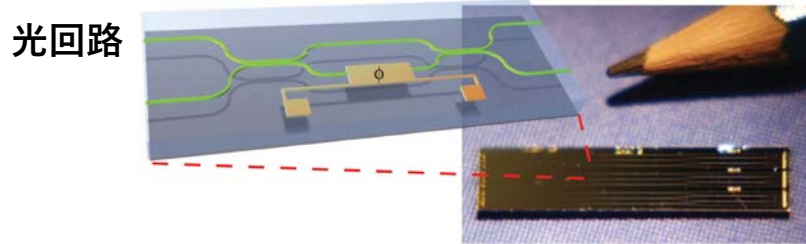
E. Abe and K. M. Itoh[‡]

Department of Applied Physics and Physico-Informatics, Keio University, Yokohama 223-8522, Japan

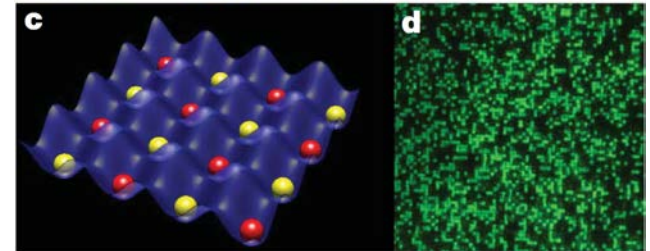
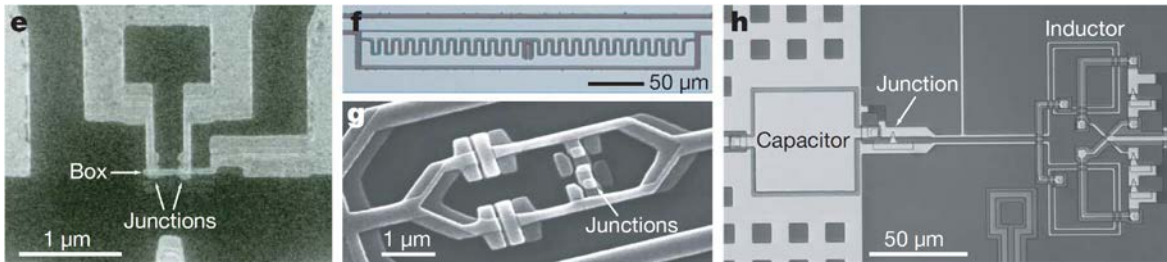
(Received 10 September 2001; published 12 June 2002)

Phys. Rev. Lett. **89**, 017901 (2002) Ladd *et al.*

量子コンピュータ・ショーケース

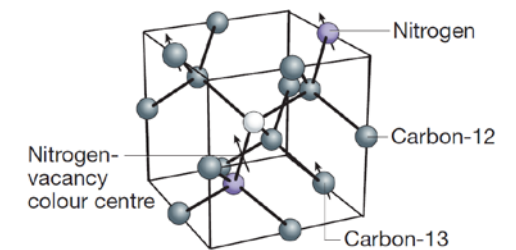
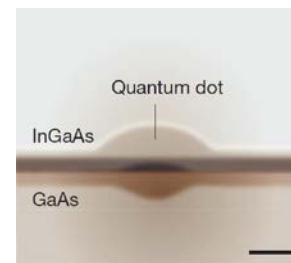
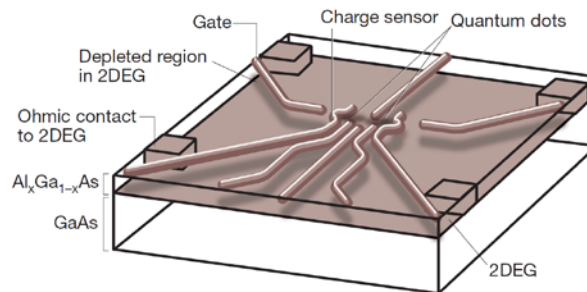


超伝導回路



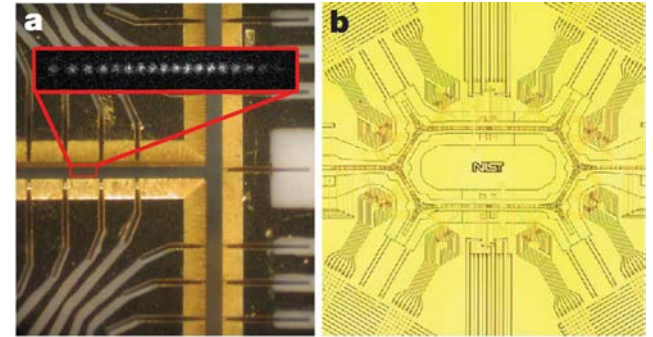
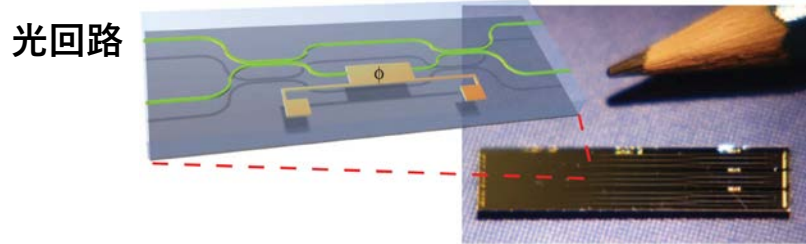
捕捉イオン/冷却原子

半導体スピン

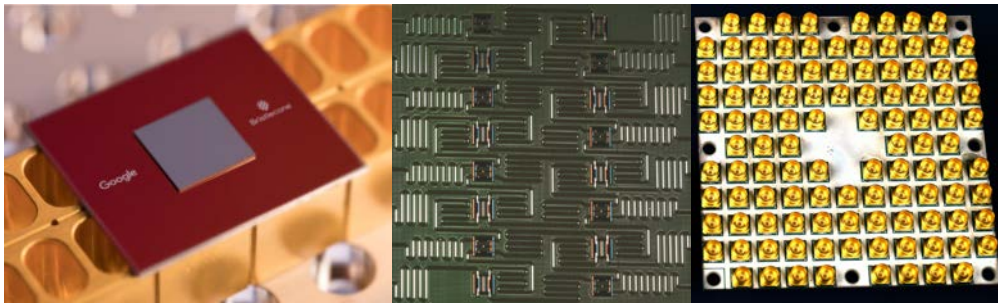


Nature **464**, 45 (2010) Ladd *et al.*

量子コンピュータ・ショーケース



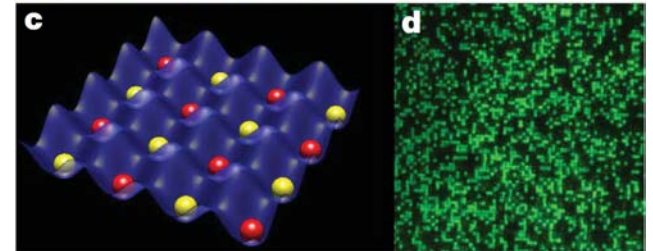
超伝導回路 (2018 ver.)



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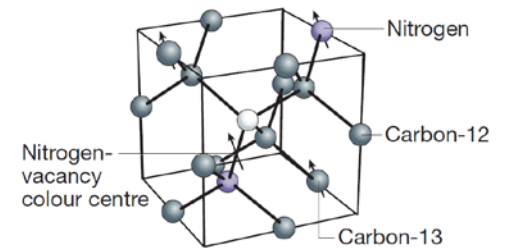
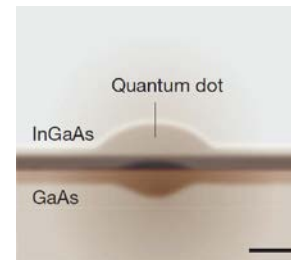
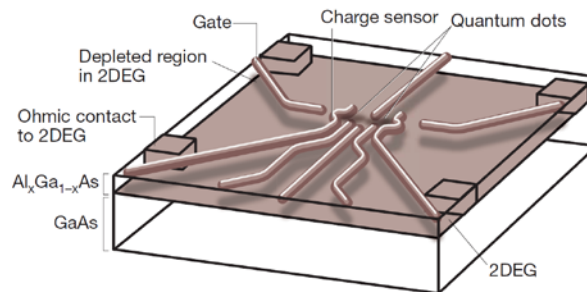
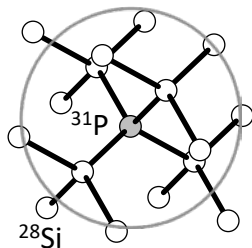
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捕捉イオン/冷却原子

半導体スピン

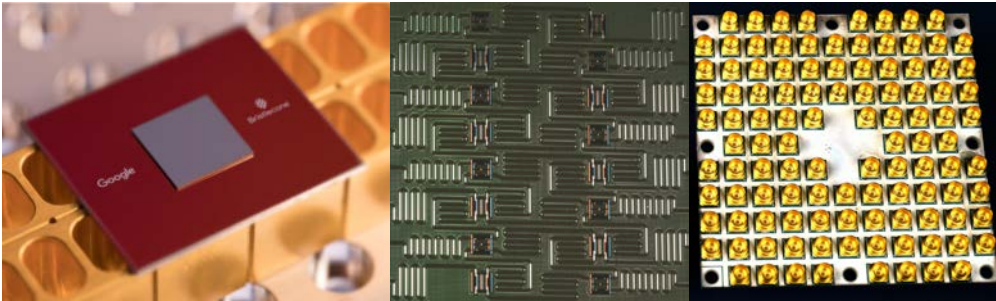


Nature **464**, 45 (2010) Ladd *et al.*

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.)

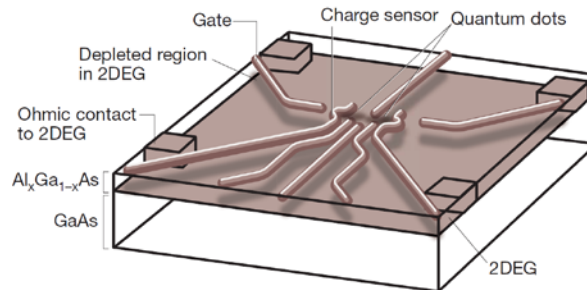
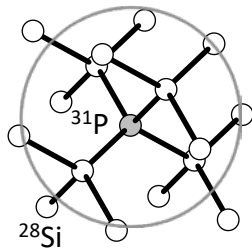


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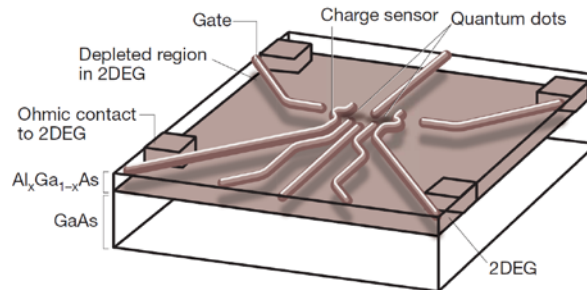
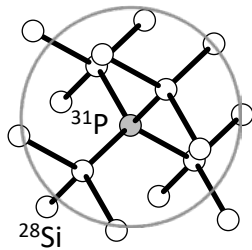
半導体スピン



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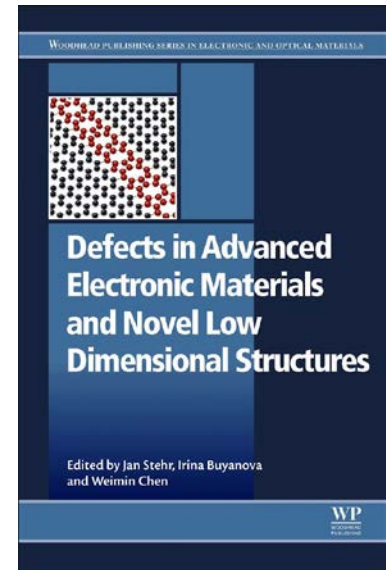
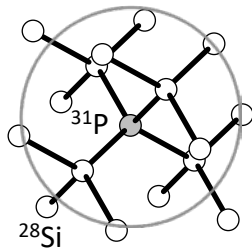
半導体スピン



Defects in Advanced Electronic Materials and Novel Low Dimensional Structures, Chap. 9, Abe & Itoh

“Defects for quantum information processing in silicon”

半導体スピン



(June, 2018)

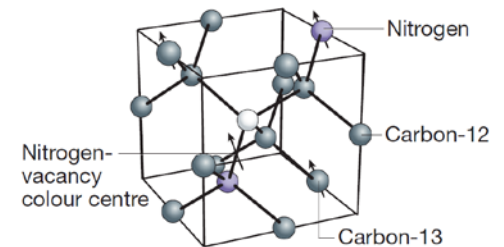
NEW DIAMOND **33 (2)**, 3 (2017) 阿部 & 伊藤

“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



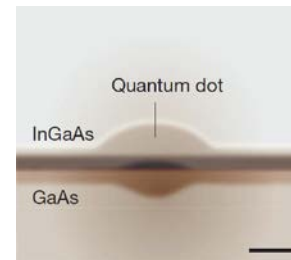
固体物理 **48 (11)**, 541 (2013) 山本 & 阿部

“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



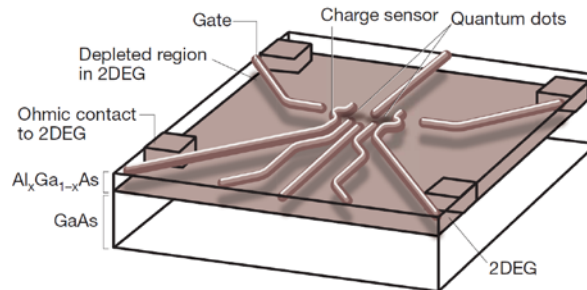
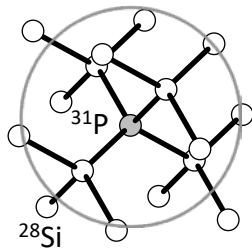
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それでも全部は話せません...

→ Encyclopedia of Modern Optics (2nd ed.) 1, 467 (2018) Ladd & Carroll “Silicon Qubits”

半導体スピン



講演内容

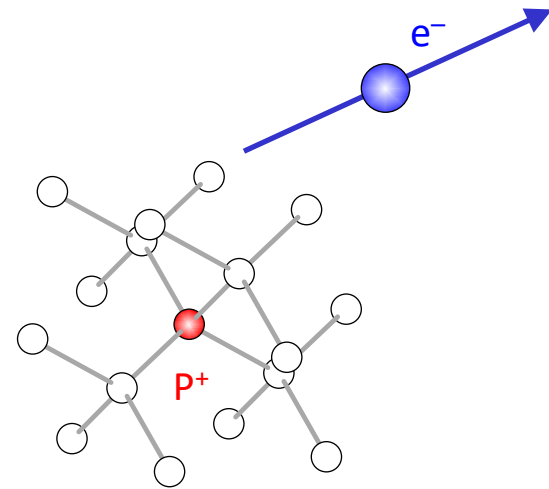
- **磁気共鳴と量子コヒーレンス**
 - アンサンブルリンドナー
- **シリコンスピン量子コンピュータ**
 - 単一リンドナー
 - MOS量子ドット
 - Si/SiGe量子ドット
- **多量子ビット化への道**
 - スピン-マイクロ波光子結合
 - アーキテクチャ

講演内容

- **磁気共鳴と量子コヒーレンス**
 - アンサンブルリンドナー
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 - アーキテクチャ

シリコン中のリンドナー

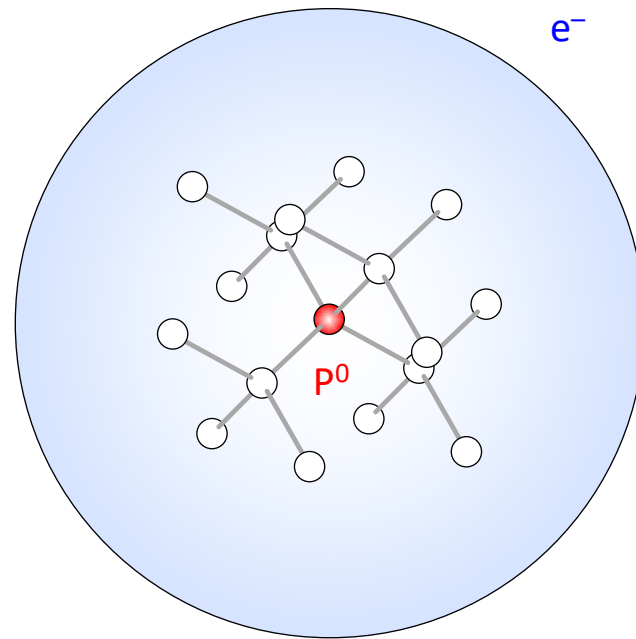
| III (13) | IV (14) | V (15) |
|-------------|------------|-----------|
| B | C | N |
| Al | Si | P |
| Ga | Ge | As |



高温(室温)下: 余剰電子はイオン化して伝導電子に

シリコン中のリンドナー

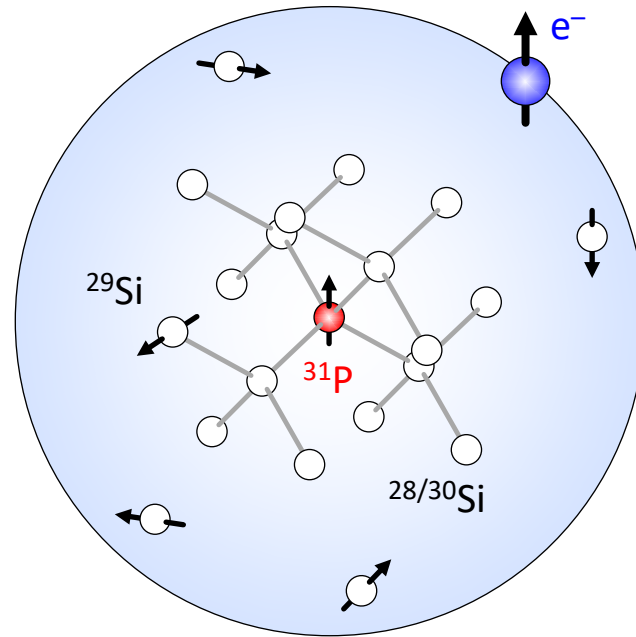
| III (13) | IV (14) | V (15) |
|-------------|------------|-----------|
| B | C | N |
| Al | Si | P |
| Ga | Ge | As |



低温下(< 10 K): 電子はリンに束縛される

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 |



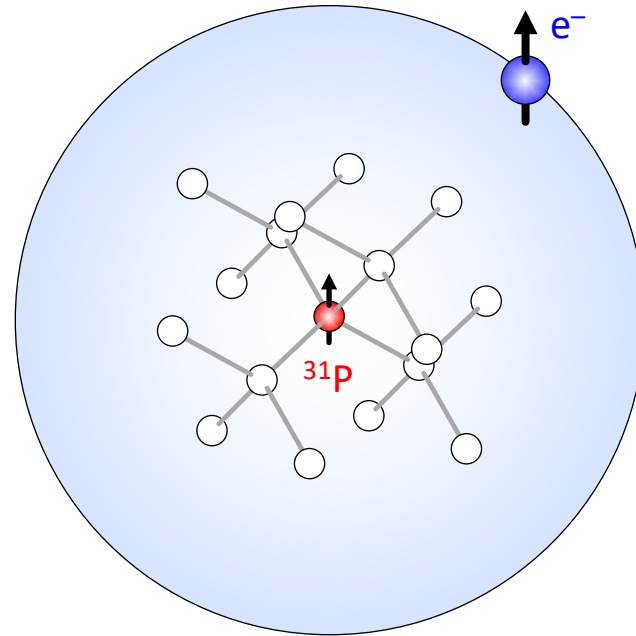
磁気環境

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

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

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

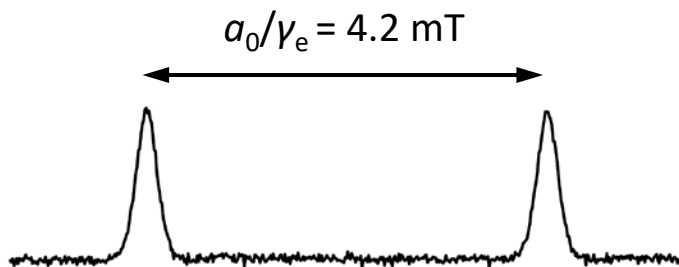
$$H_0 = \gamma_e B_0 S_z - \gamma_P B_0 I_z + a_0 S_z I_z$$

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

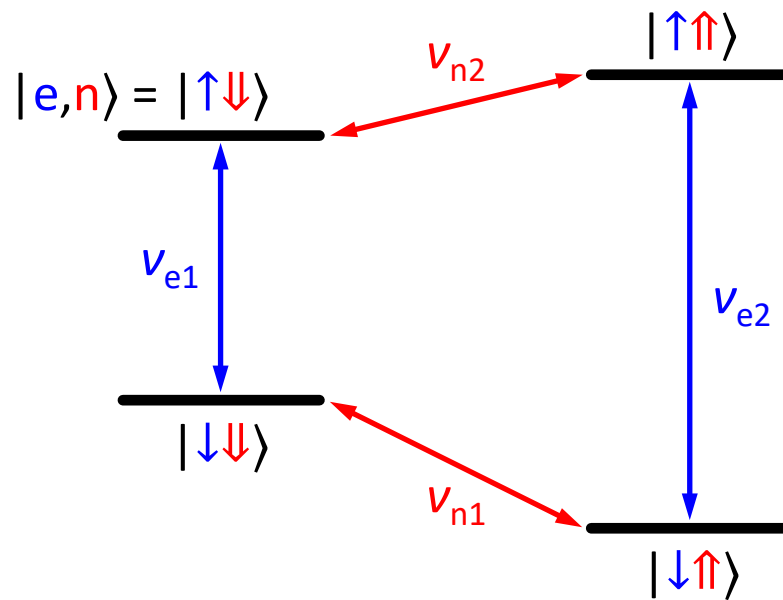
$$\gamma_e = 27.97 \text{ GHz/T}$$

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

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



アンサンブル電子スピン共鳴(磁場掃引)



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

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

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

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

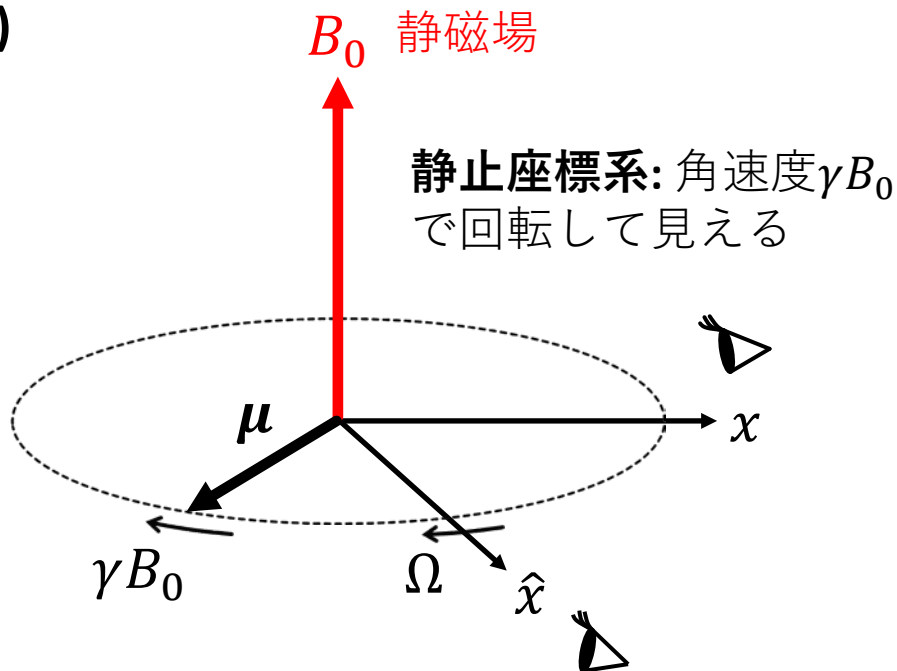
磁気共鳴

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

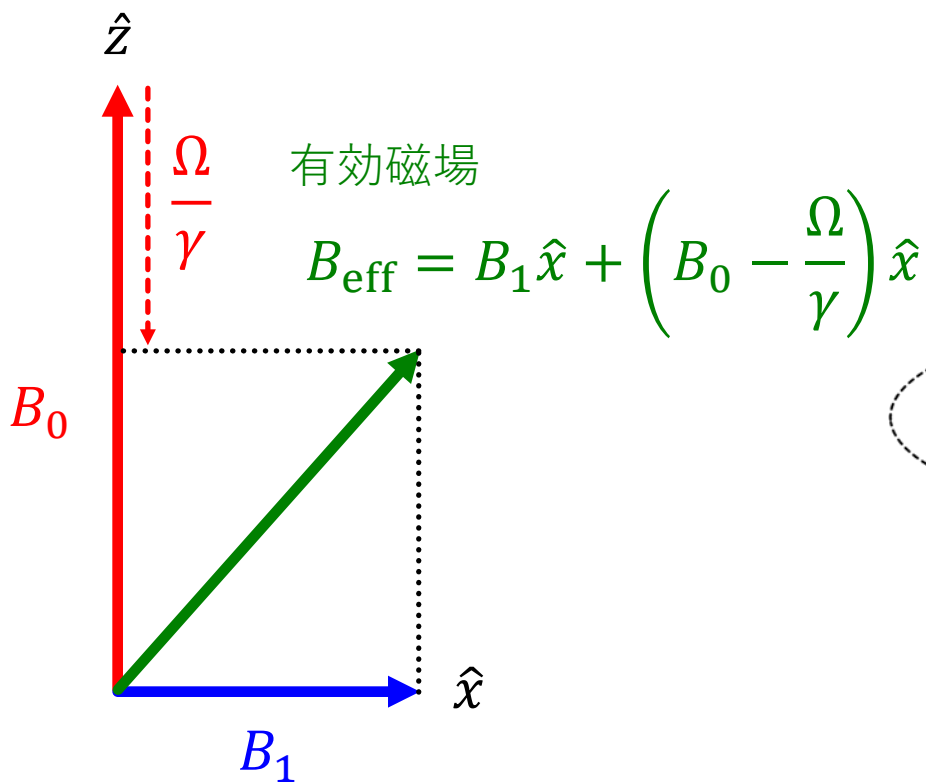


角速度 Ω で回転する座標系:
遅くなって見える. なぜ??

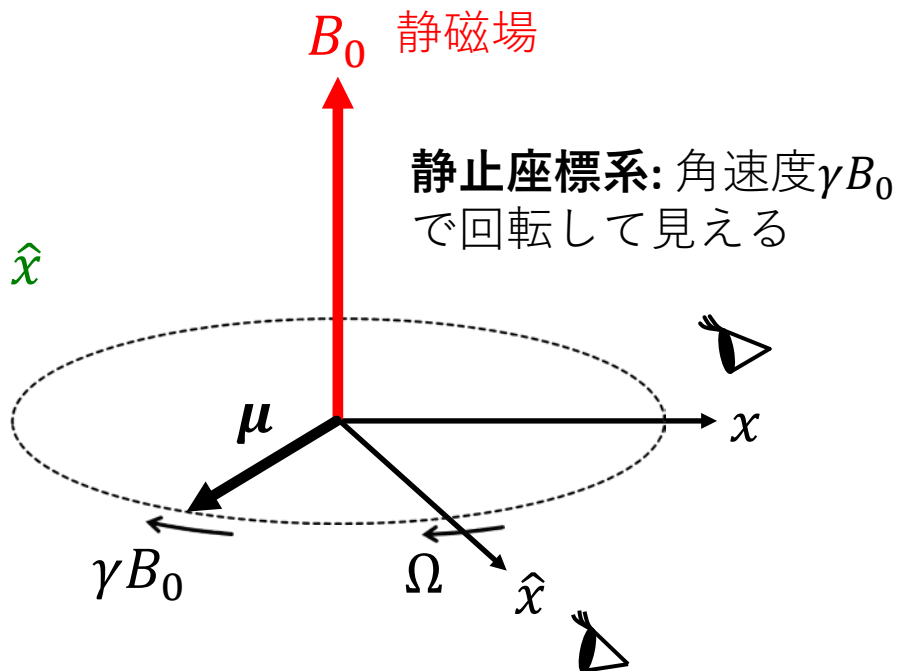


z 方向の磁場が弱くなったから

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??



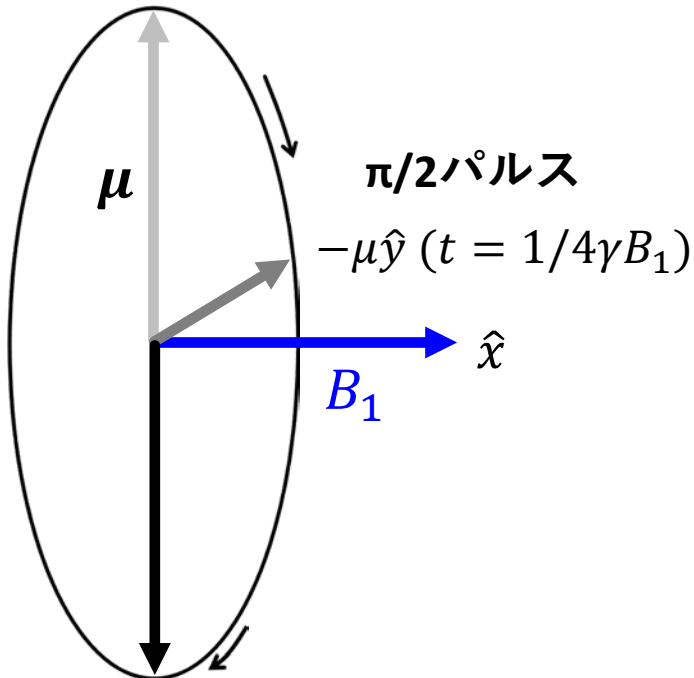
z 方向の磁場が弱くなったから

磁気共鳴 = 1量子ビット操作

$\Omega = \gamma B_0$ で回転する座標系

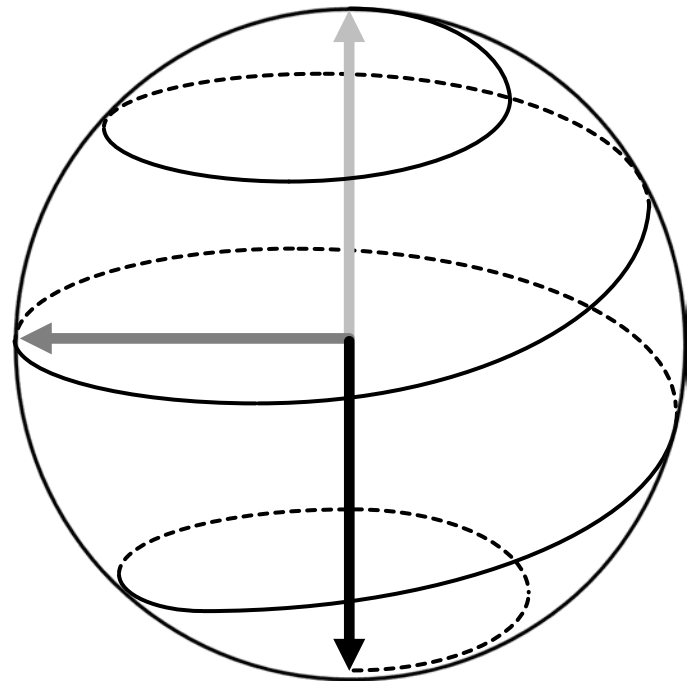
静止座標系

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



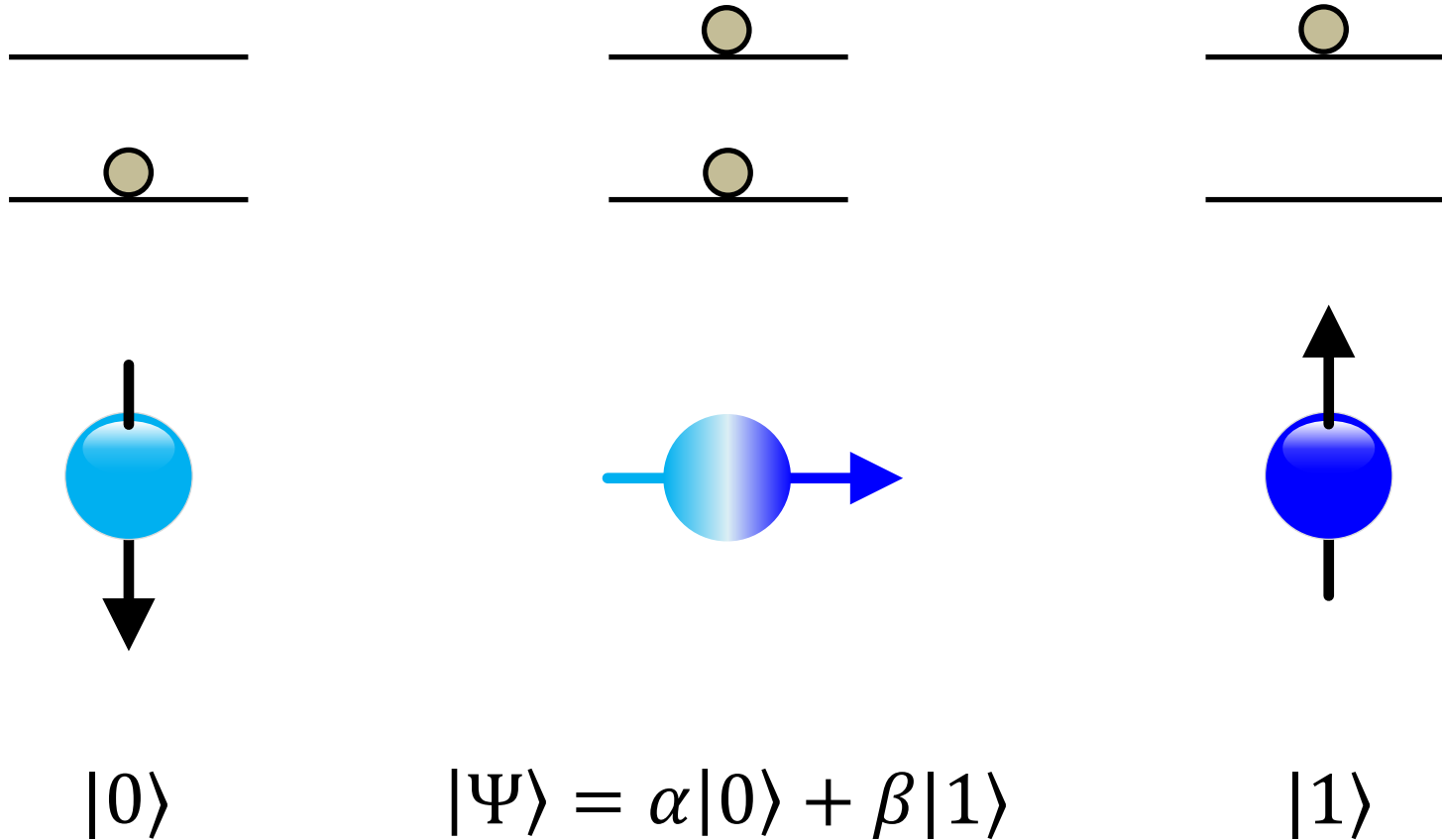
$-\mu\hat{z} (t = 1/2\gamma B_1)$

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

量子コヒーレンス



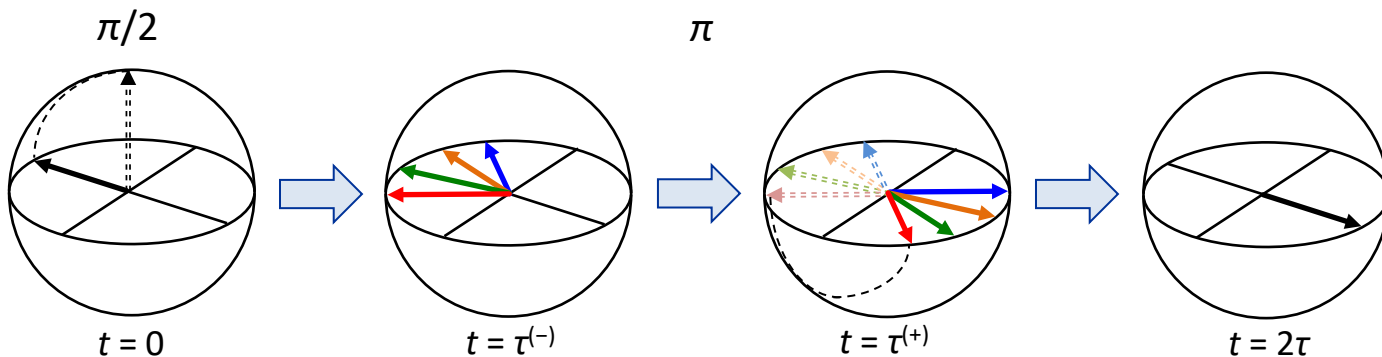
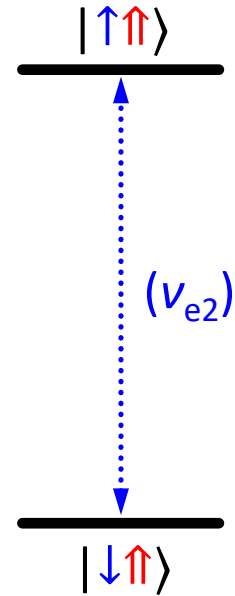
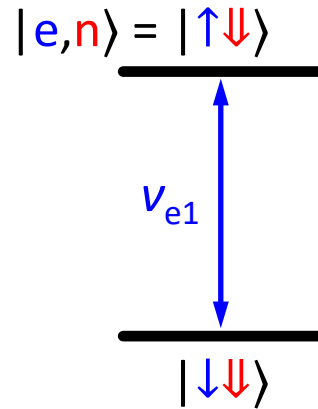
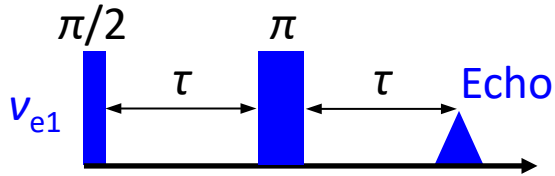
τ_2 : 重ね合わせ状態の持続時間

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)

電子スピンのコヒーレンス: T_{2e}

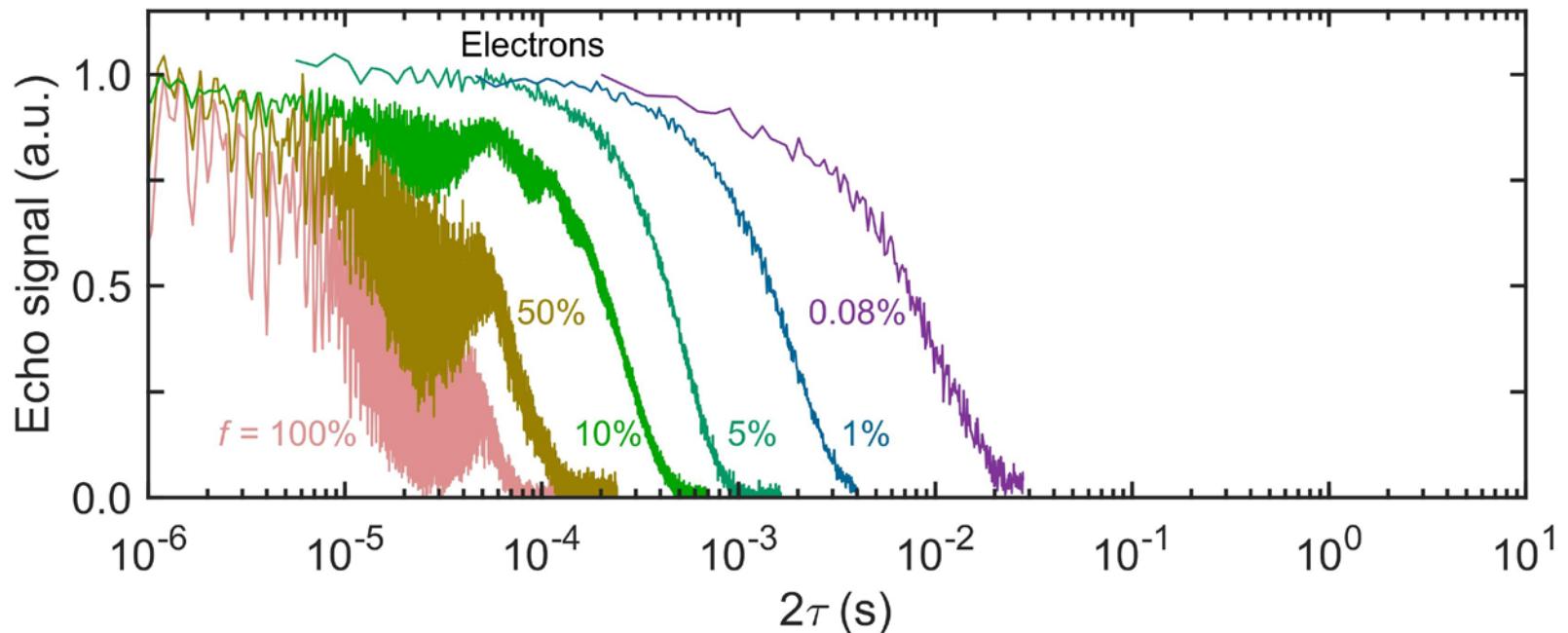
スピンエコー



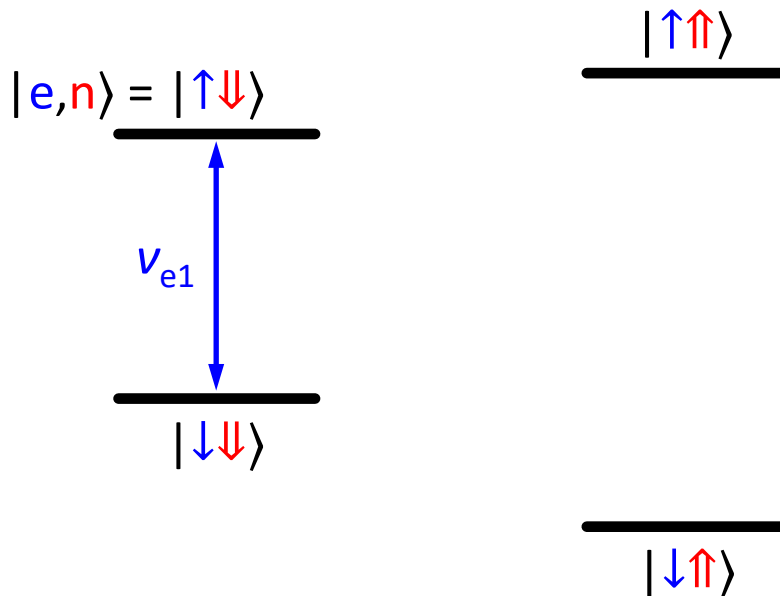
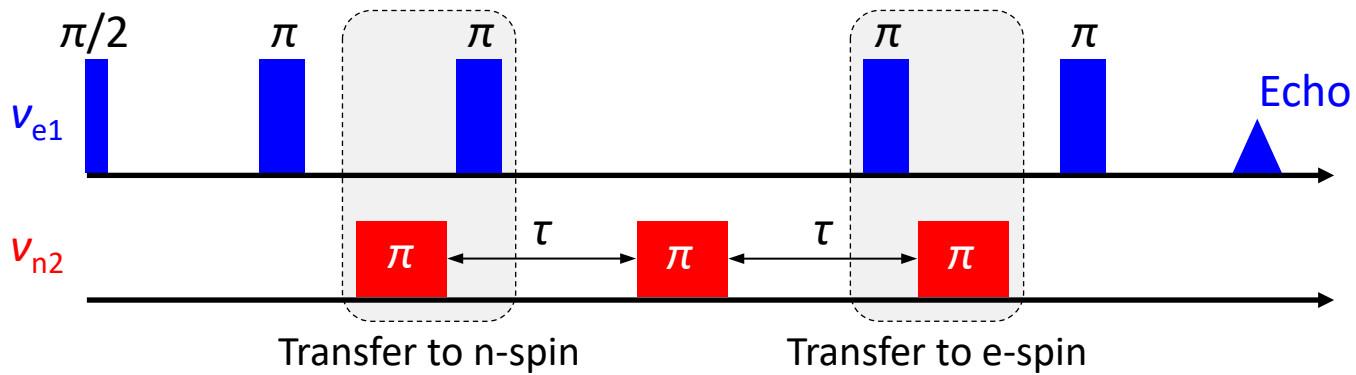
電子スピンコヒーレンス: T_{2e}

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

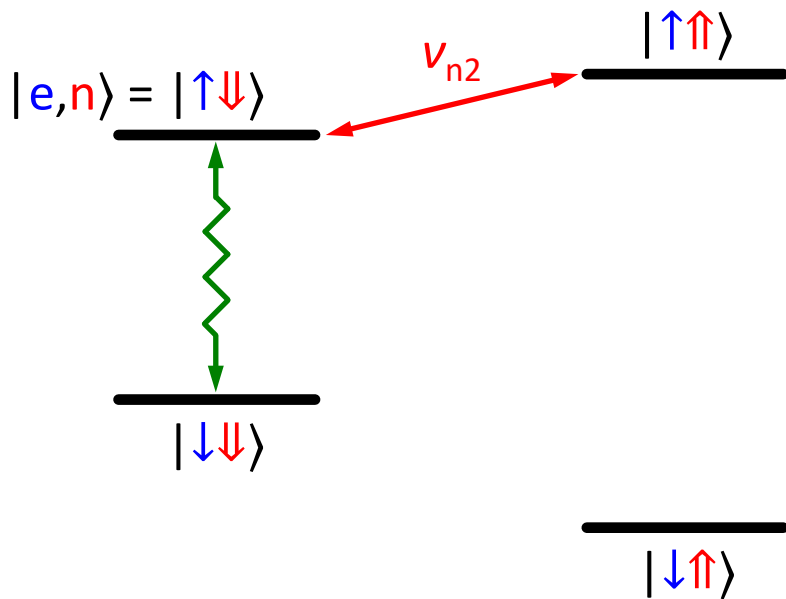
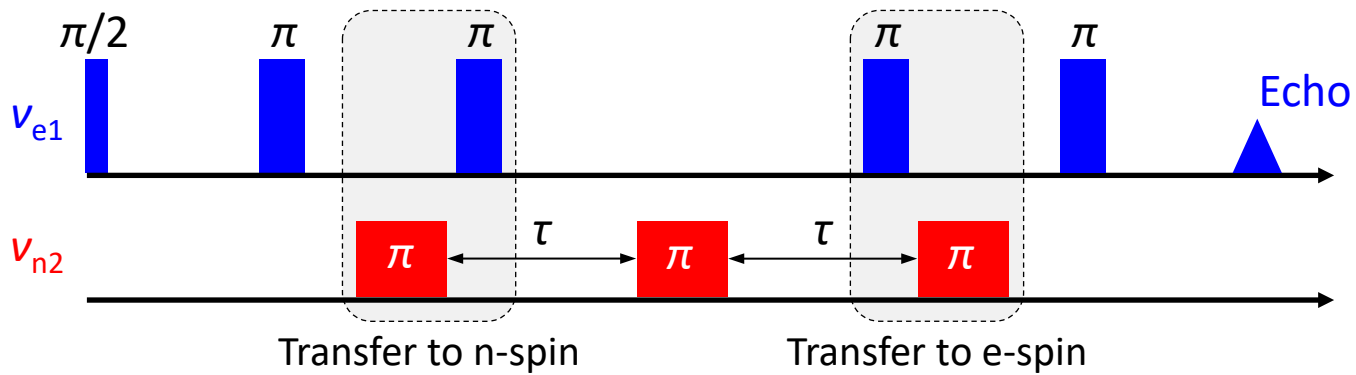
Eisuke Abe,^{1,2,*} Alexei M. Tyryshkin,³ Shinichi Tojo,² John J. L. Morton,^{1,4} Wayne M. Witzel,⁵ Akira Fujimoto,² Joel W. Ager,⁶ Eugene E. Haller,^{6,7} Junichi Isoya,⁸ Stephen A. Lyon,³ Mike L. W. Thewalt,⁹ and Kohei M. Itoh²



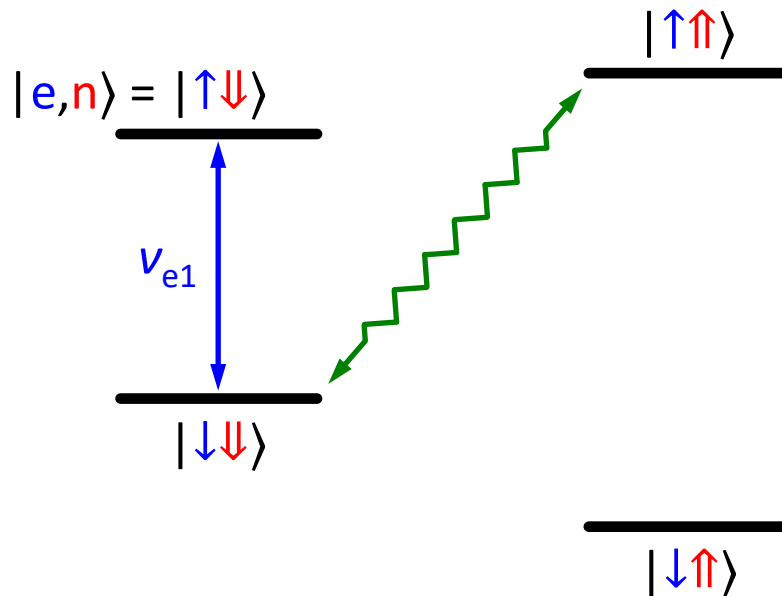
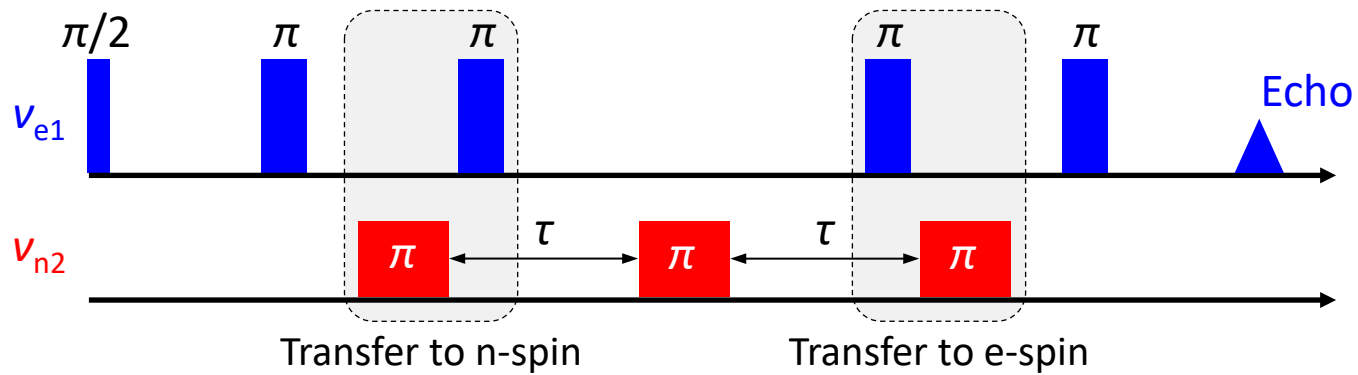
核スピンコヒーレンス: T_{2n0}



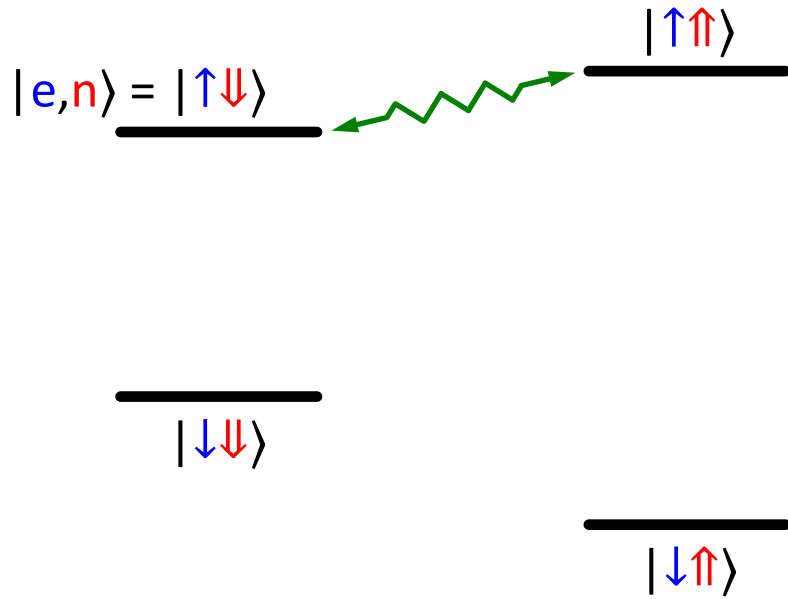
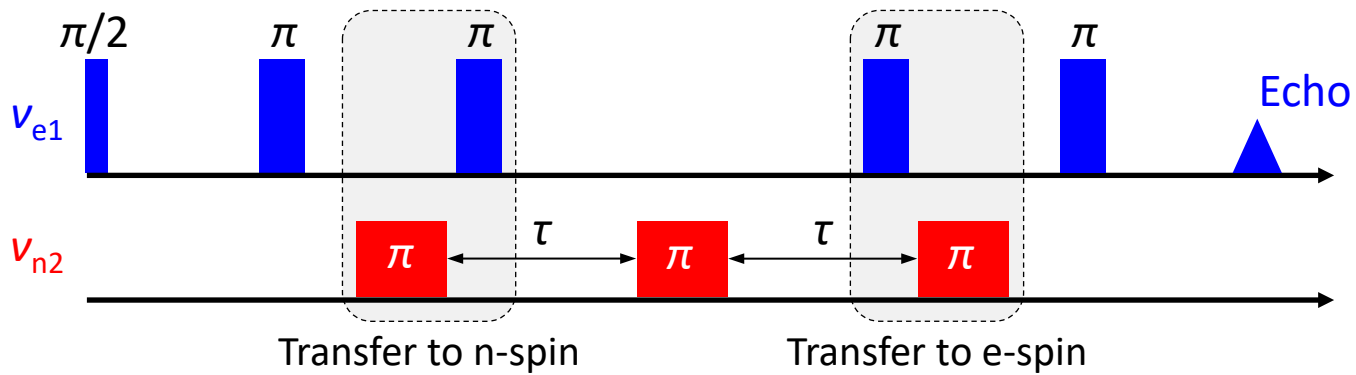
核スピンコヒーレンス: T_{2n0}



核スピンコヒーレンス: T_{2n0}



核スピンコヒーレンス: T_{2n0}



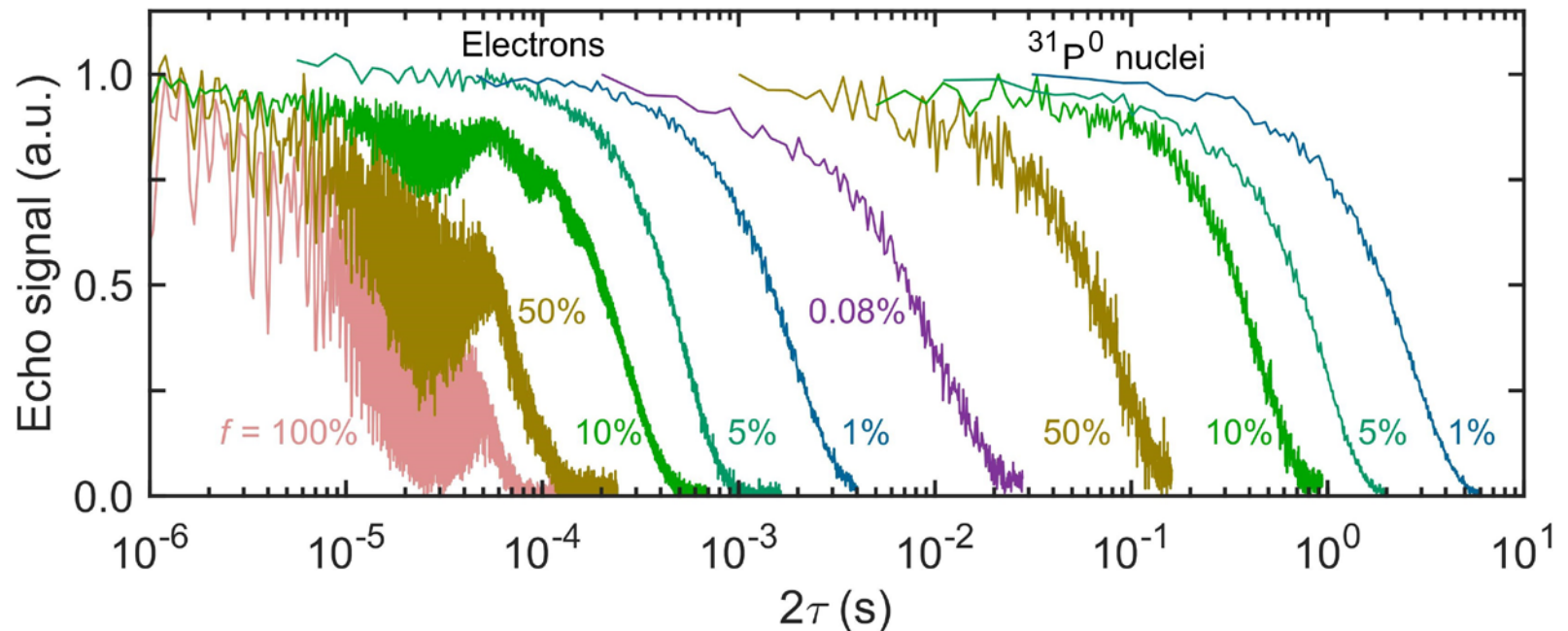
核スピンコヒーレンス: T_{2n0}

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

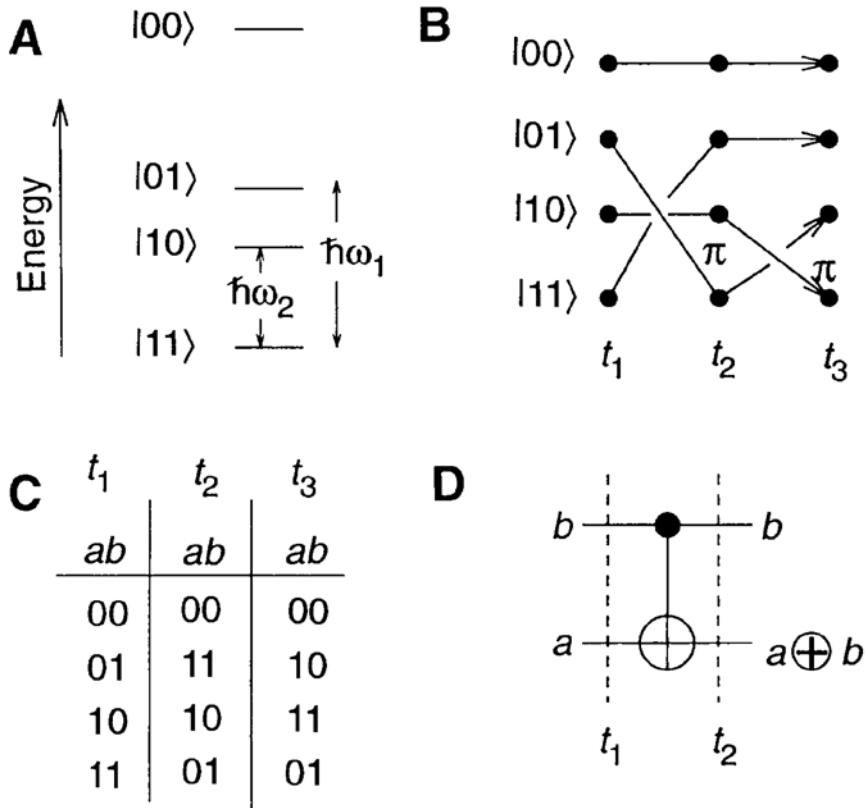
Nuclear spin decoherence of neutral ^{31}P donors in silicon: Effect of environmental ^{29}Si nuclei

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



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.

Electron Nuclear DOuble Resonance



G. Feher (©R.A. Icaacson)

“delighted to hear that EPR in Si is sill alive and doing well and has branched out into new and exciting areas” (e-mail to EA, Dec. 2016)

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

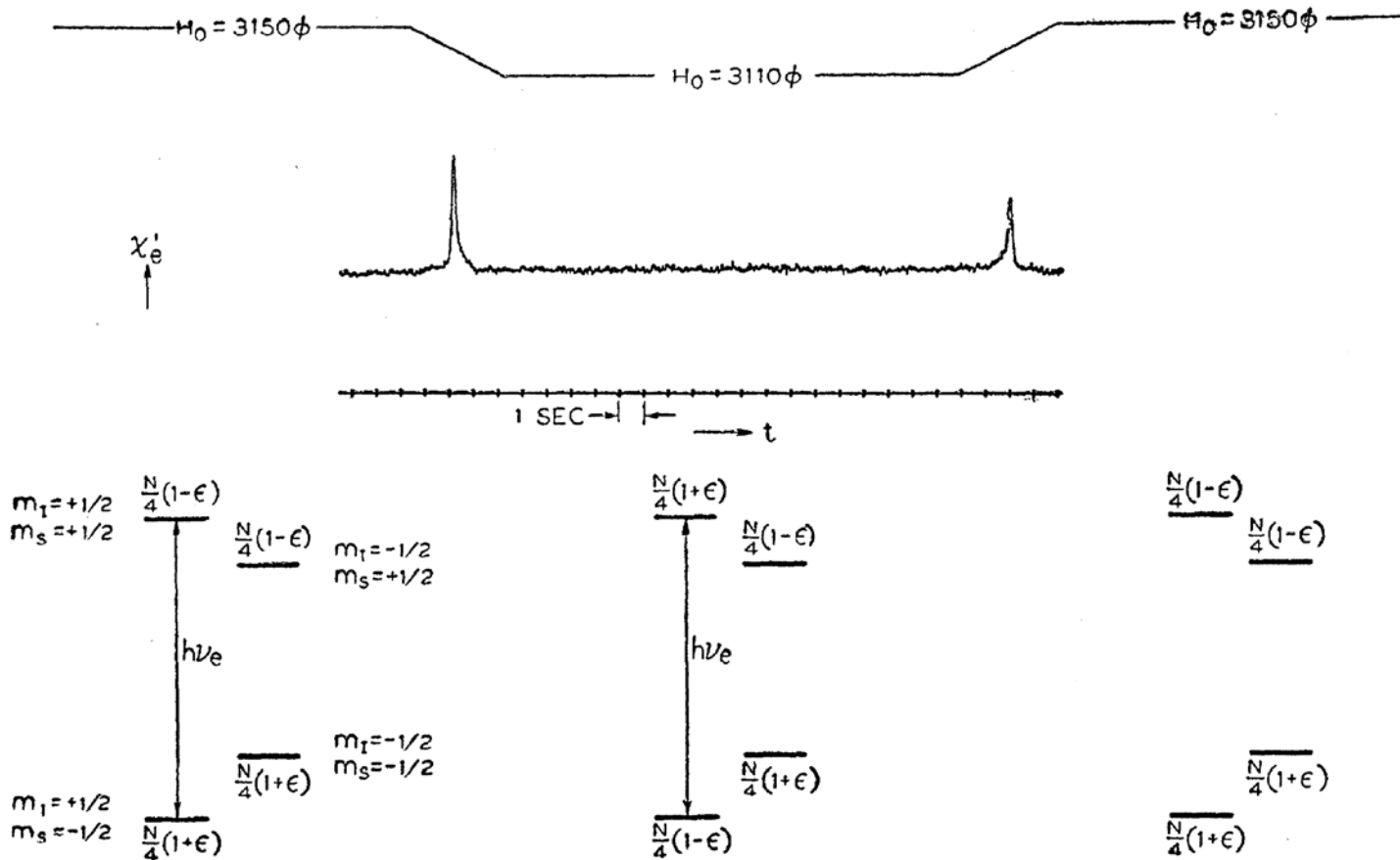
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(π -pulse on e -spin)

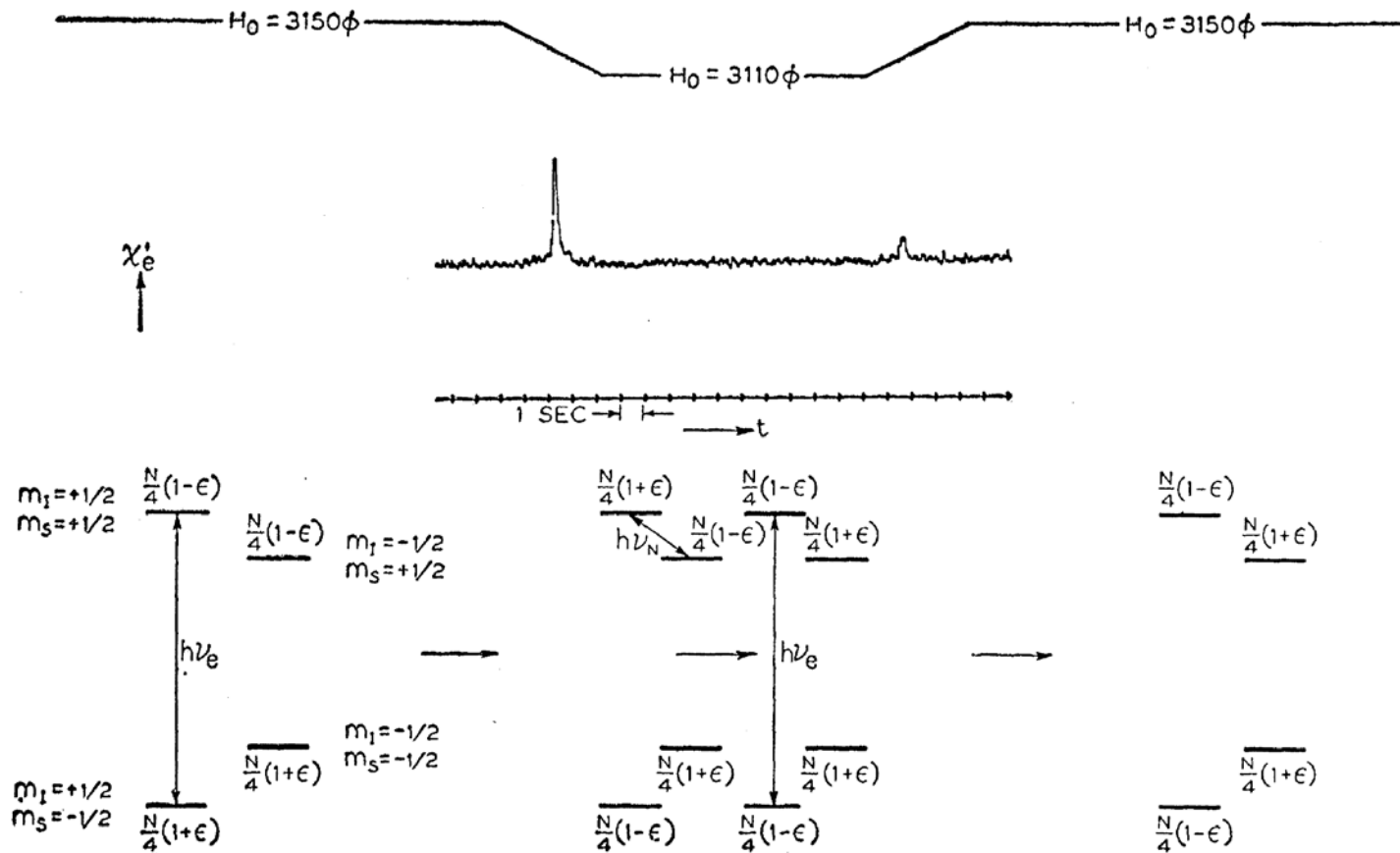
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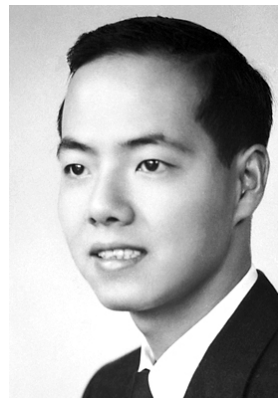
Phys. Rev. **103**, 501 (1956) Feher & Gere

ENDORとパリティ非保存

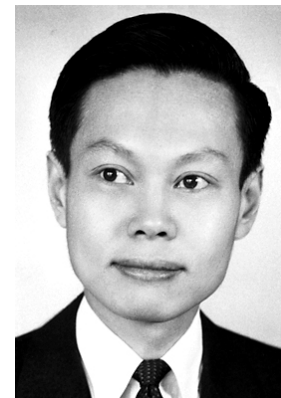
[...] In the fall of 1956, I gave a colloquium at Columbia University on the nuclear polarization scheme. After the colloquium, C. S. Wu and T. D. Lee excitedly tried to persuade me to measure the asymmetry of β -decay in a polarized sample of donor nuclei in silicon. T. D. Lee and C. N. Yang had circulated a preprint of an article in which they suggested that one of the conservation laws of physics, parity, did not hold in the case of weak interactions. [...] I listened politely with limited interest and promised them I would get to it as soon as I finished the ENDOR experiments [...]



C. S. Wu
(©AIP Emilio Segre
Visual Archives)



T. D. Lee
(©Nobel Foundation)



C. N. Yang
(©Nobel Foundation)

ENDORとパリティ非保存

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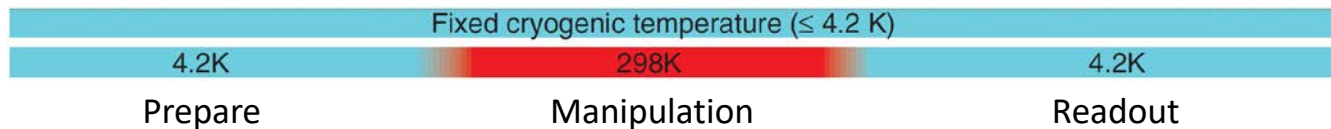
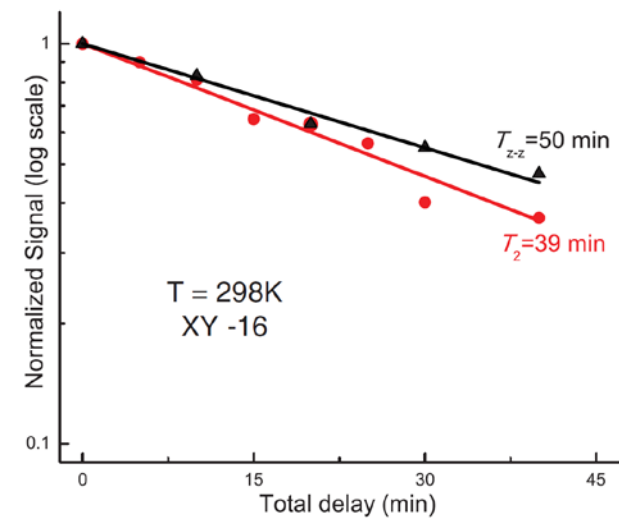
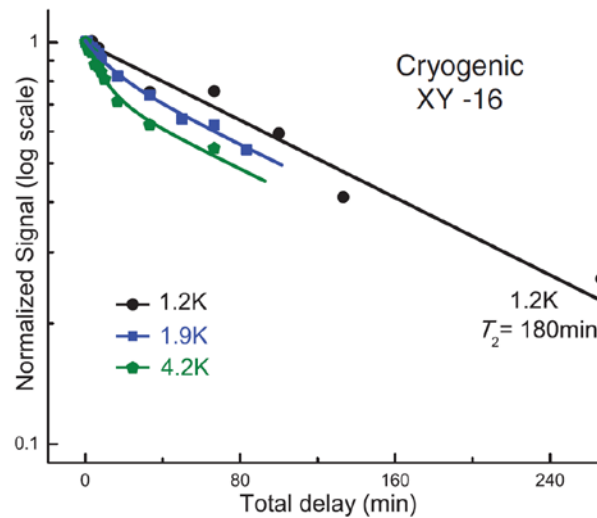
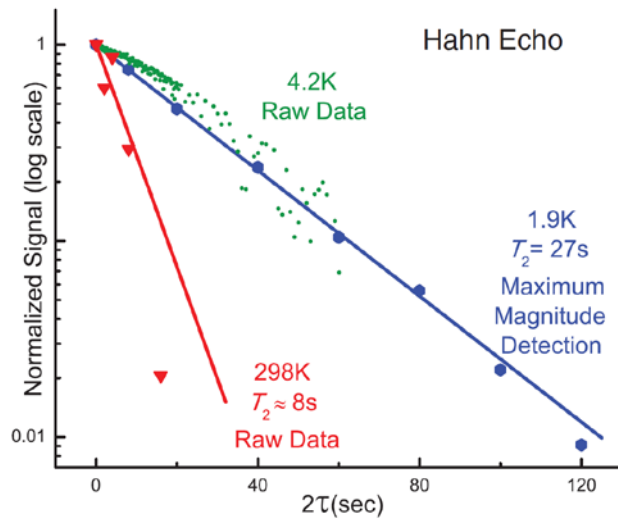
After finishing these at the end of 1956, I took an extended skiing vacation in the West. On the way back I stopped off at the University of Pittsburgh where I gave a colloquium [...] At the conclusion, I mentioned that I would like to test Lee & Yang's hypothesis of parity nonconservation. [...] it felt as if the temperature of the room had dropped by 10 degrees. Finally, G. C. Wick said, "But don't you know that parity nonconservation has already been proven by several groups?". Of course, I did not know; I had been skiing for a month.

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

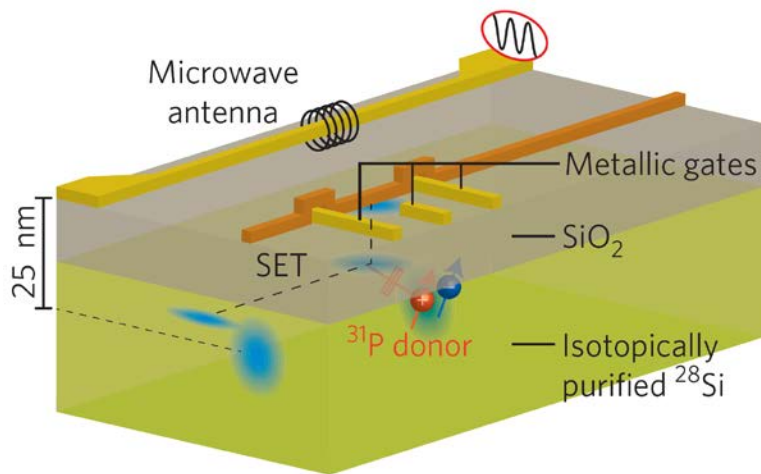
Kamyar Saeedi,¹ Stephanie Simmons,² Jeff Z. Salvail,¹ Phillip Dluhy,¹ Helge Riemann,³ Nikolai V. Abrosimov,³ Peter Becker,⁴ Hans-Joachim Pohl,⁵ John J. L. Morton,⁶ Mike L. W. Thewalt^{1*}



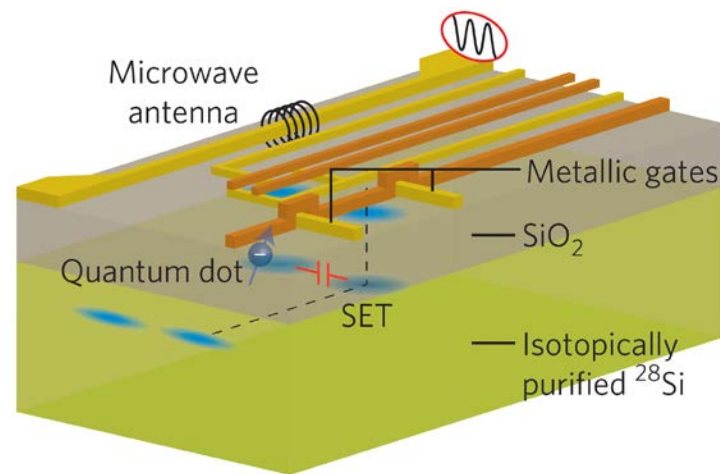
講演内容

- **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
- **多量子ビット化への道**
 - スピン-マイクロ波光子結合
 - アーキテクチャ

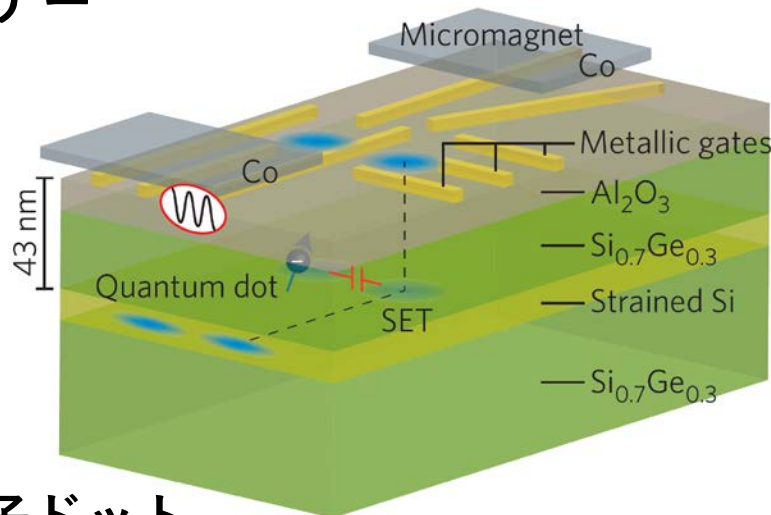
シリコンスピン量子ビット



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



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, 分散シフト



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, 分散シフト

フェデリティ > 99%



D. DiVincenzo
(©RWTH Aachen U.)

希釈冷凍機



超伝導量子回路実験との違い

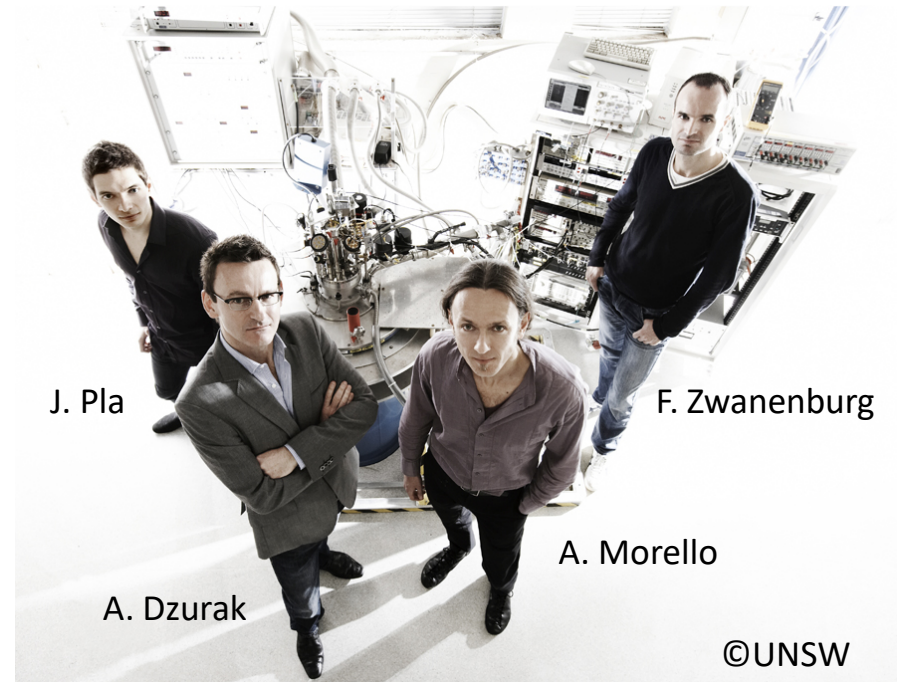
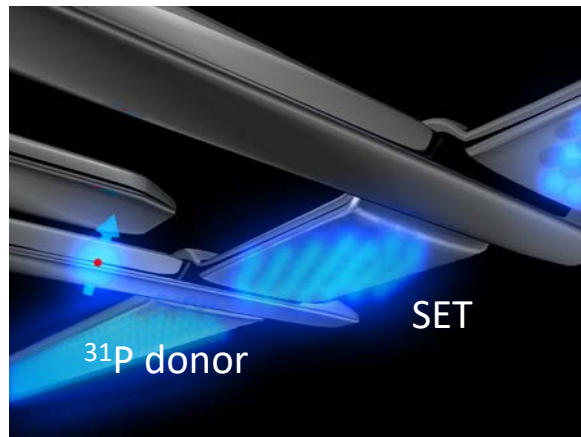
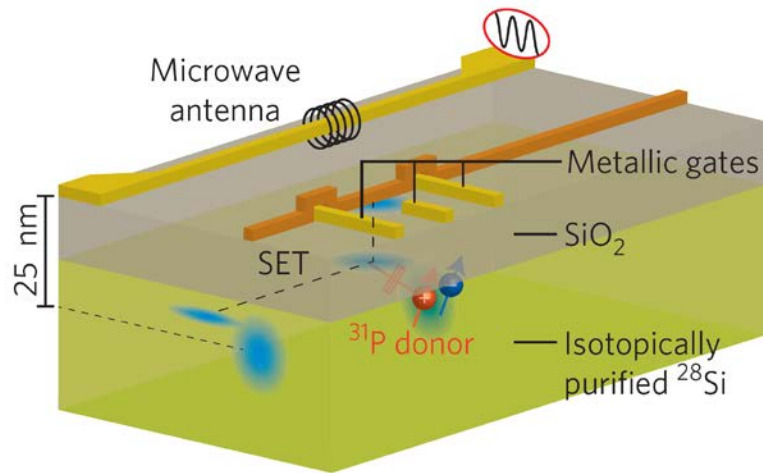
- しばしば強磁場が必要
- ゲート電極用のDCラインが多数必要

典型的なエネルギースケール

- $T_{\text{base}} = 10 \text{ mK} = 860 \text{ neV}$
- $T_{\text{elec}} \approx 100 \text{ mK} = 8.6 \text{ } \mu\text{eV}$
- $E_{\text{ion}} = 45 \text{ meV}$
- $E_{\text{C}} \approx 1 \text{ meV}$
- $E_{\text{valley}} = 35\text{--}270 \text{ } \mu\text{eV}$
- $E_z = 28 \text{ GHz} = 116 \text{ } \mu\text{eV} @ B_0 = 1 \text{ T}$

Single-shot readout of an electron spin in silicon

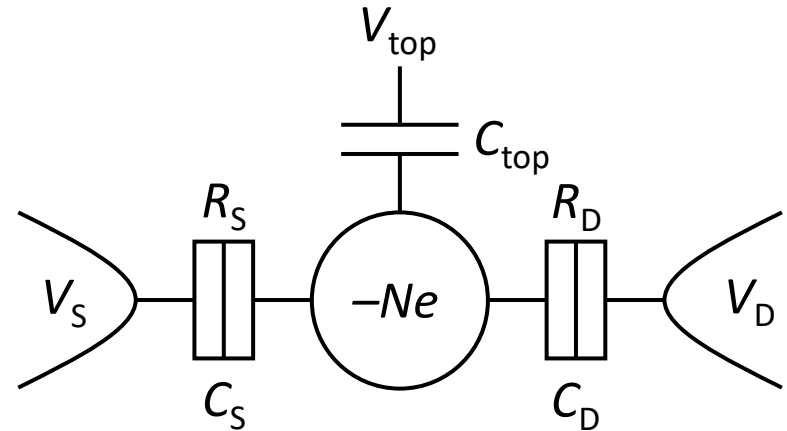
Andrea Morello¹, Jarryd J. Pla¹, Floris A. Zwanenburg¹, Kok W. Chan¹, Kuan Y. Tan¹, Hans Huebl^{1†}, Mikko Möttönen^{1,3,4}, Christopher D. Nugroho^{1†}, Changyi Yang², Jessica A. van Donkelaar², Andrew D. C. Alves², David N. Jamieson², Christopher C. Escott¹, Lloyd C. L. Hollenberg², Robert G. Clark^{1†}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



単電子トランジスタ



定相互作用モデル



電気化学ポテンシャル

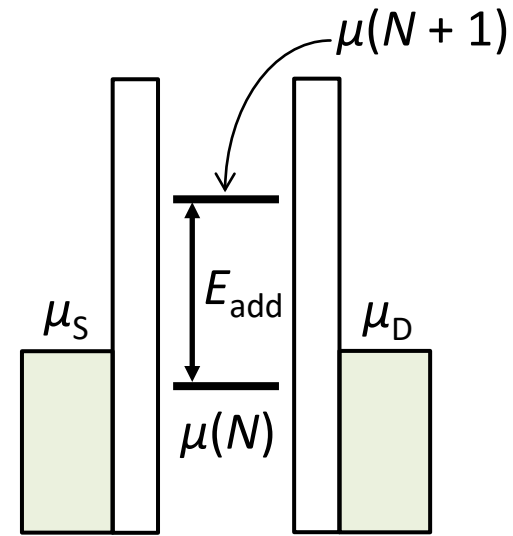
Rev. Mod. Phys. **79**, 1217 (2007) Hanson *et al.*

$$\mu(N) = E_C \left(N - N_0 - \frac{1}{2} \right) - \frac{E_C}{e} (C_S V_S + C_{\text{top}} V_{\text{top}} + C_D V_D) + E_N$$

付加エネルギー

$$E_{\text{add}}(N) = \mu(N + 1) - \mu(N) = E_C + \Delta E \quad E_C = \frac{e^2}{C_\Sigma} : \text{帯電エネルギー}$$

単電子トランジスタ



SET準位, ソース, ドレインの μ の
相対位置で伝導を理解する

電気化学ポテンシャル

$$\mu(N) = E_C \left(N - N_0 - \frac{1}{2} \right) - \frac{E_C}{e} (C_S V_S + C_{\text{top}} V_{\text{top}} + C_D V_D) + E_N$$

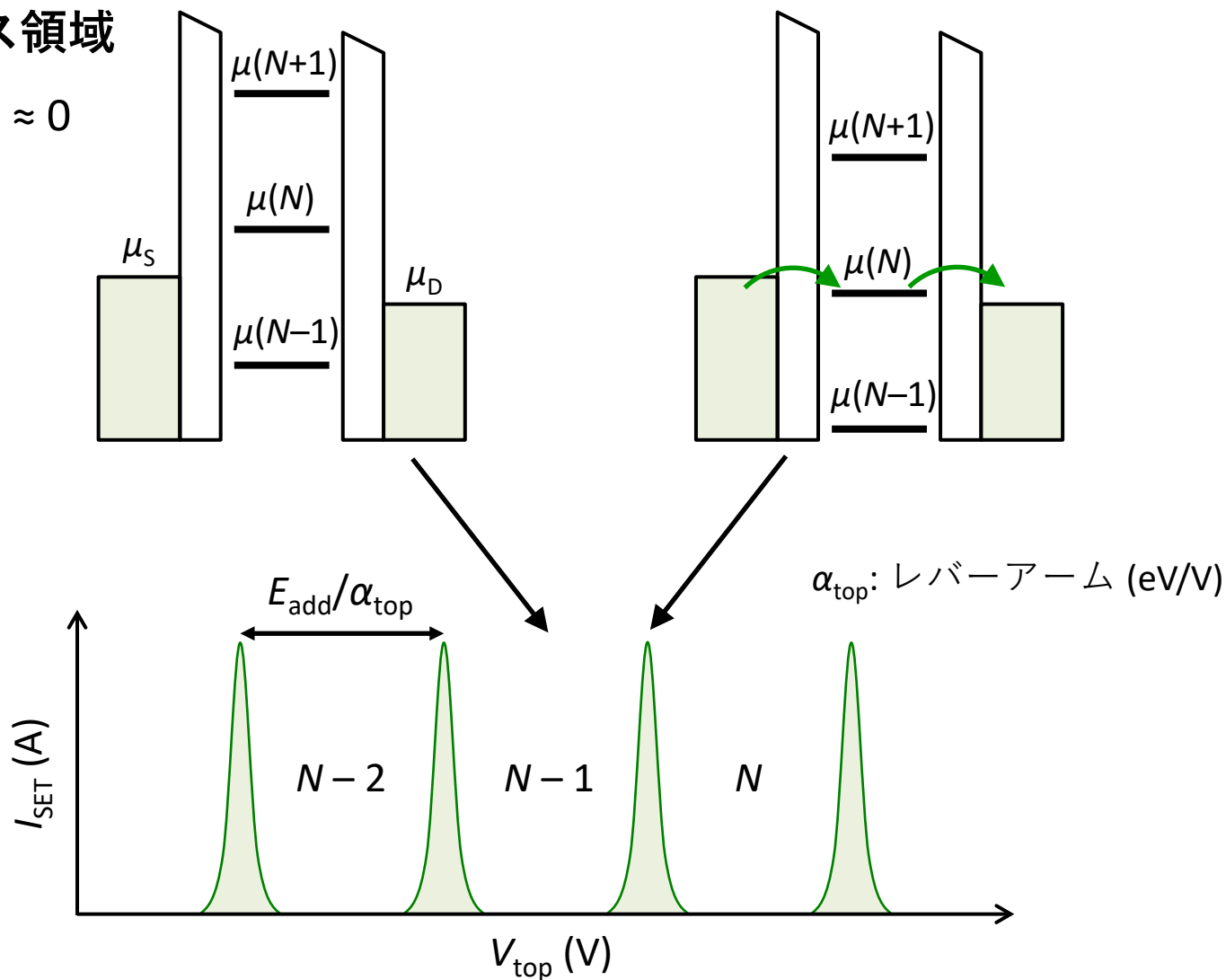
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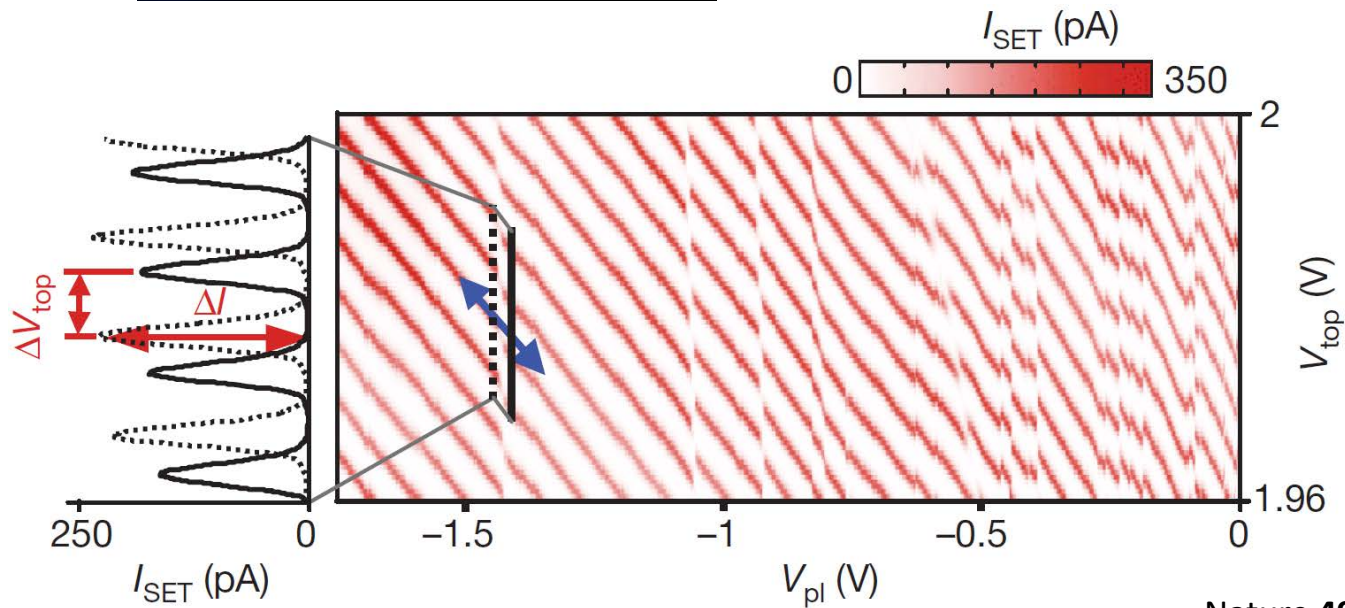
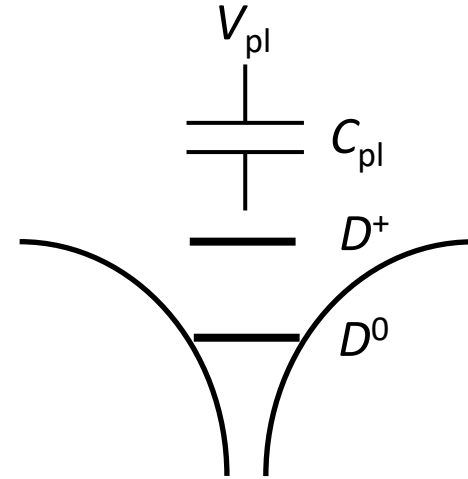
クーロン振動

低バイアス領域

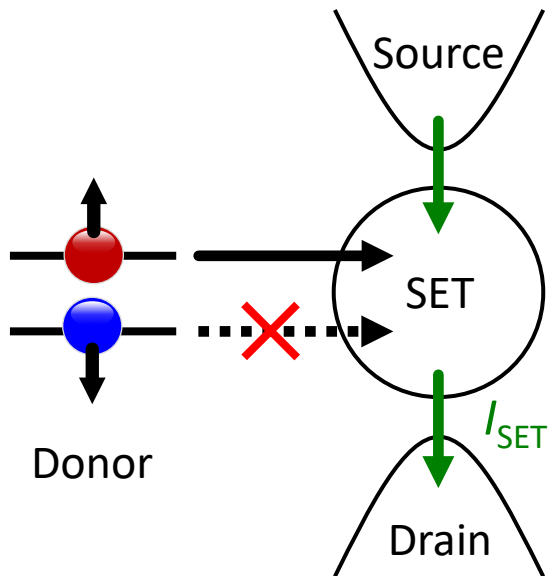
$$|\mu_S - \mu_D| \approx 0$$



ドナー-SETハイブリッド



スピン-電荷変換



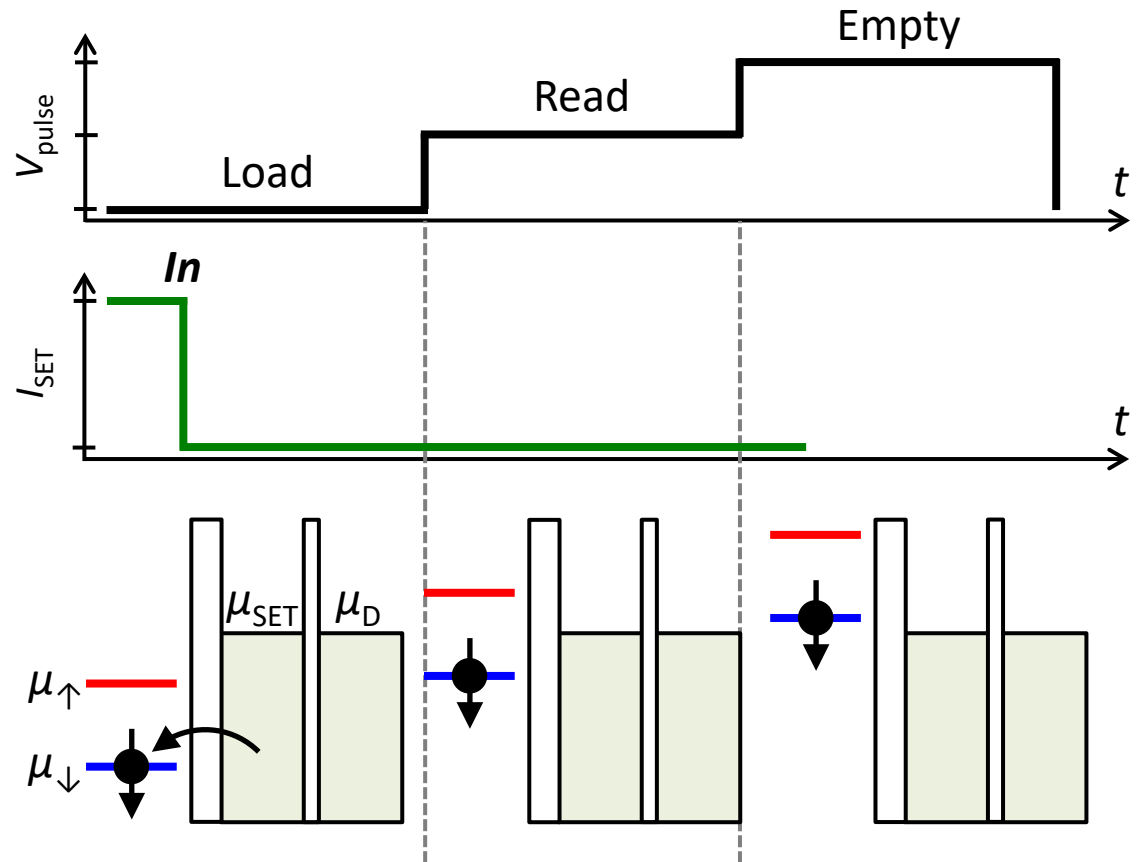
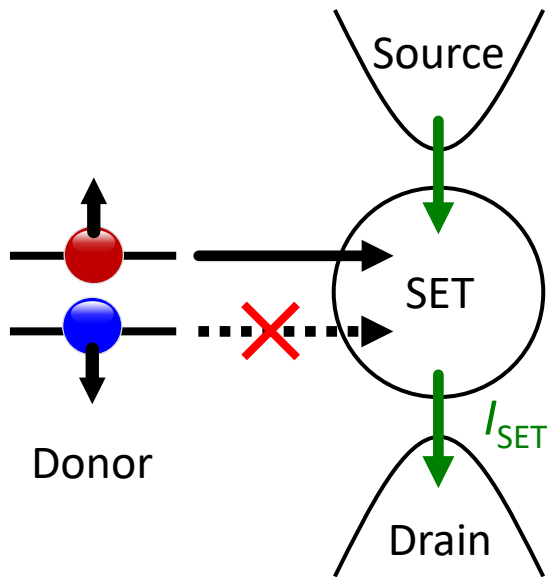
$$E(D^+) - E(D^0) = 45 \text{ meV}$$

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

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

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

スピン測定(↓)



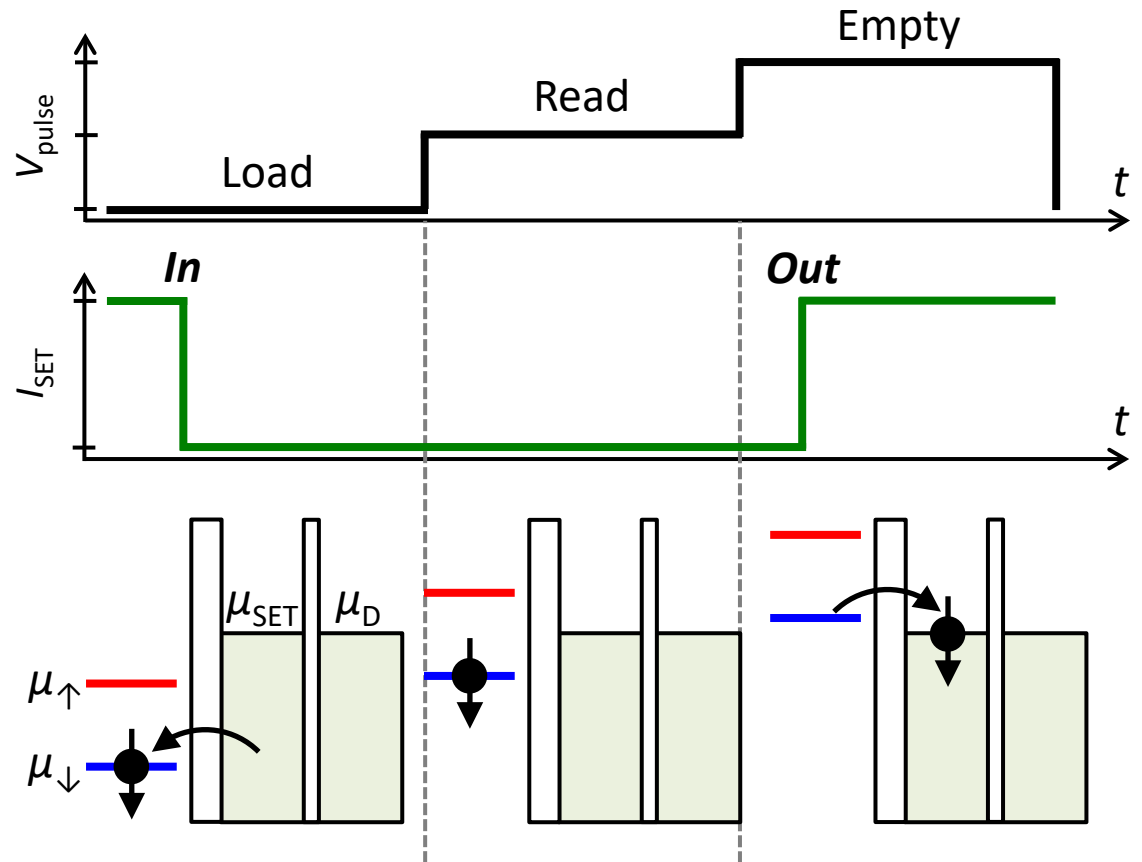
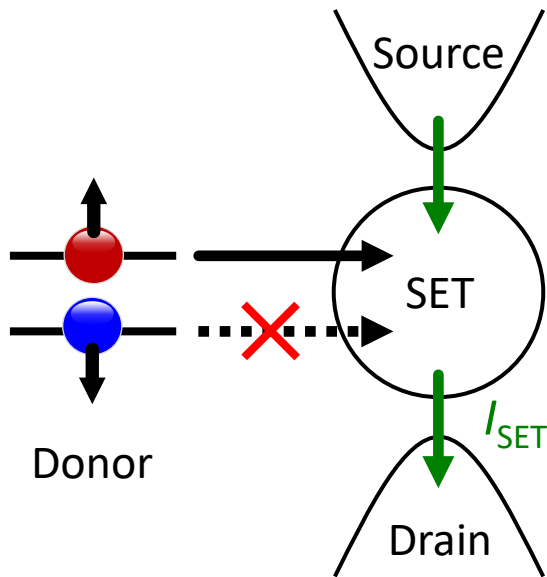
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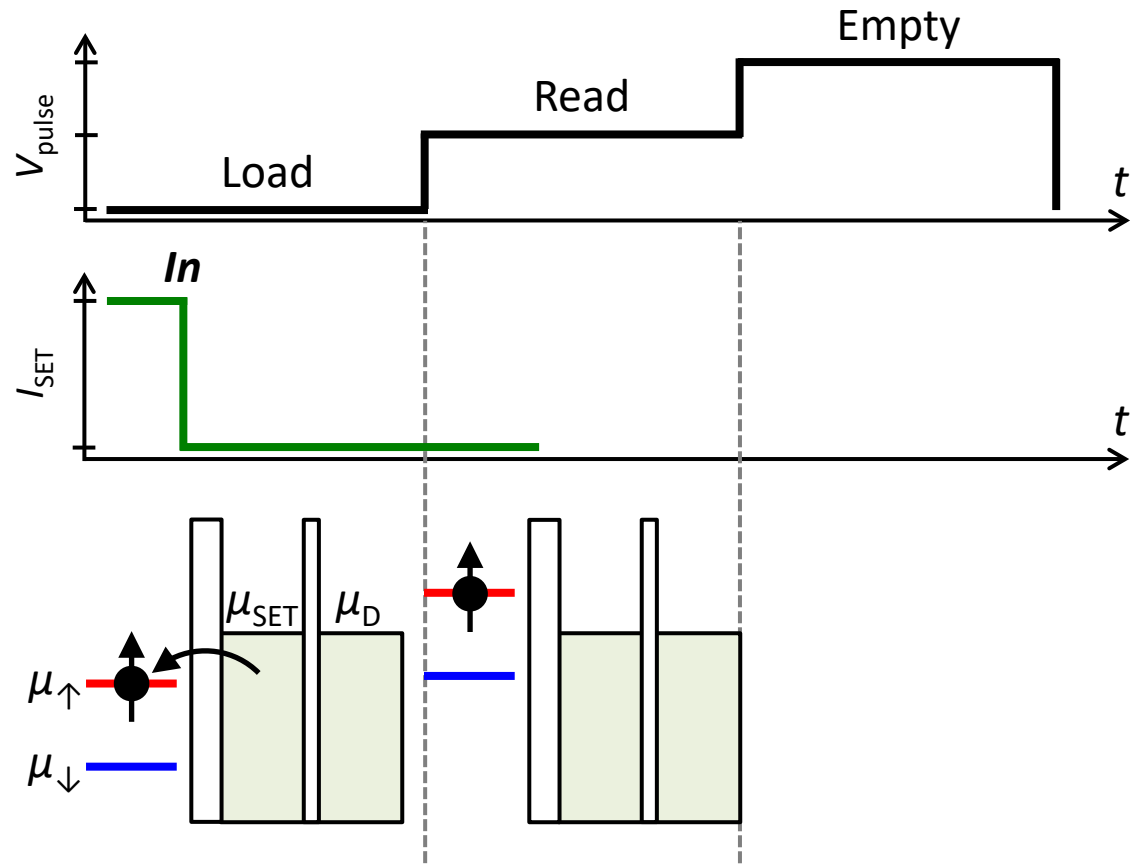
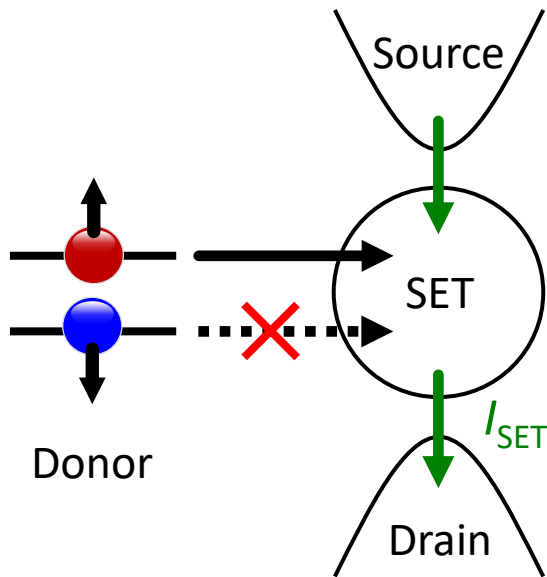
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スピン測定(↑)



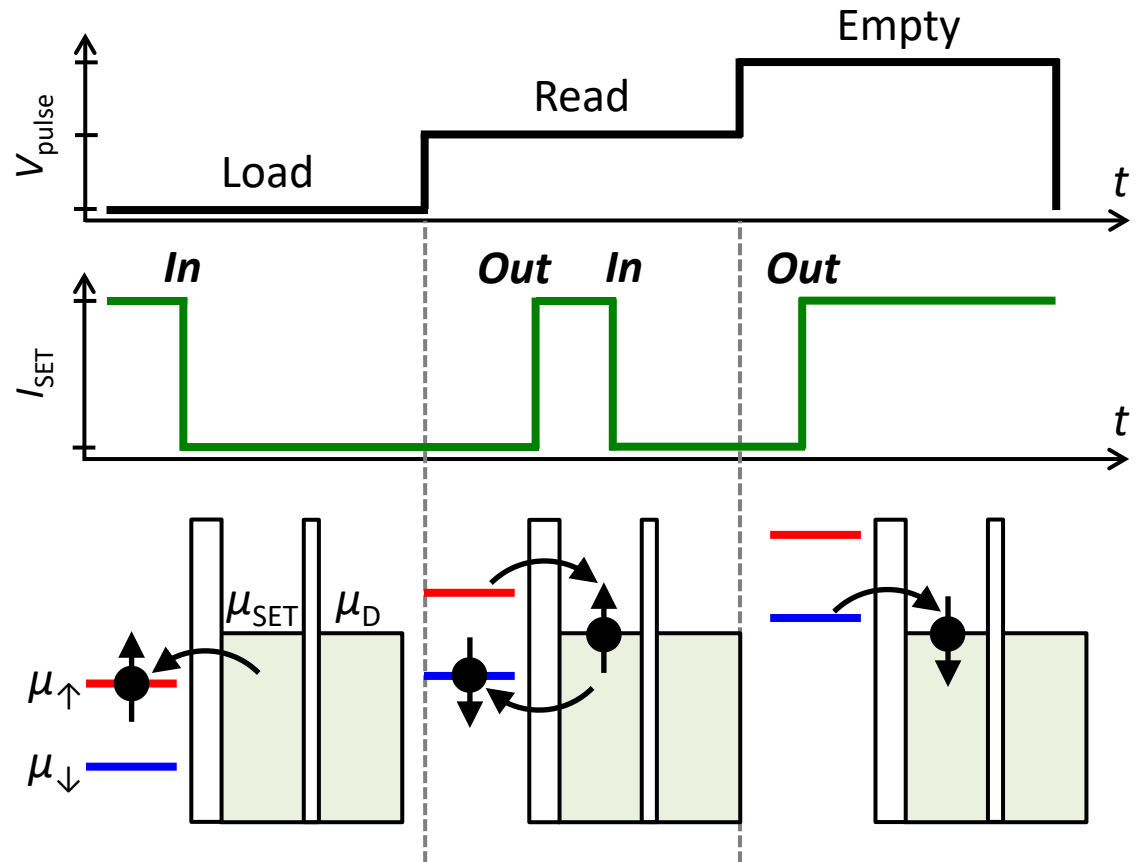
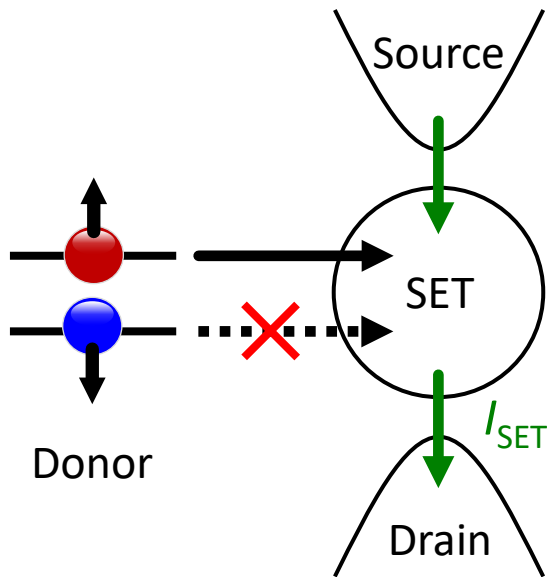
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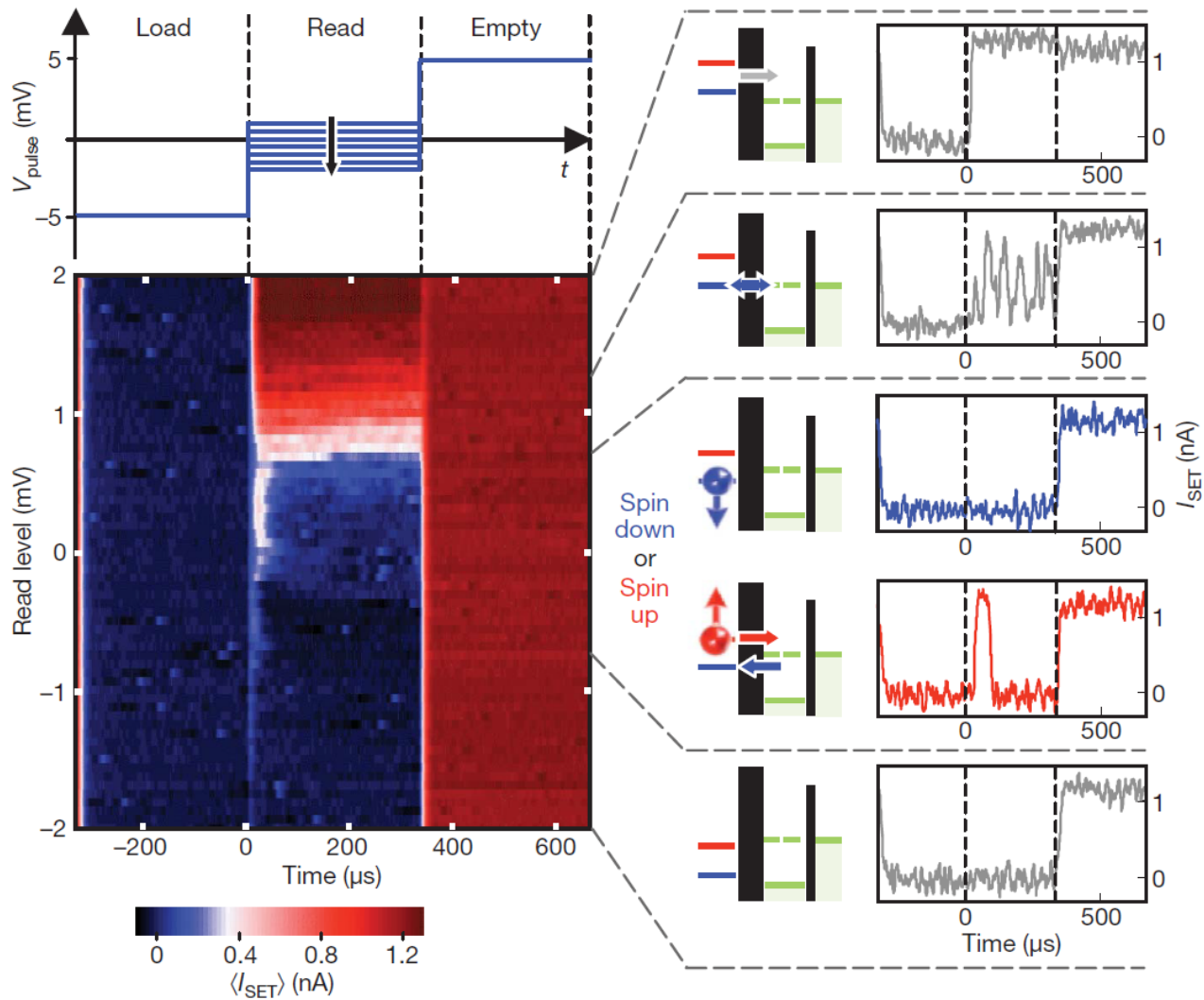
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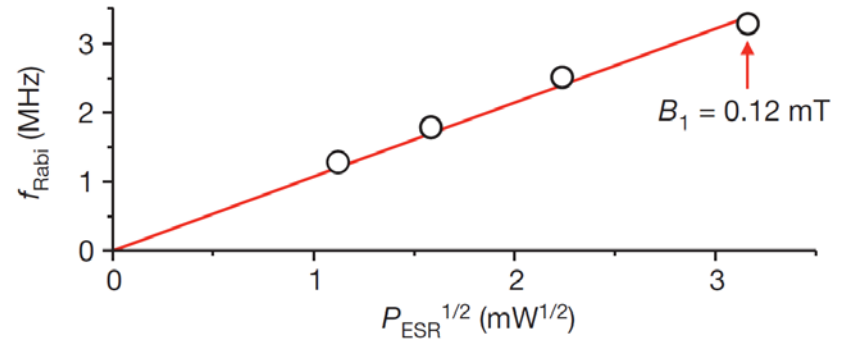
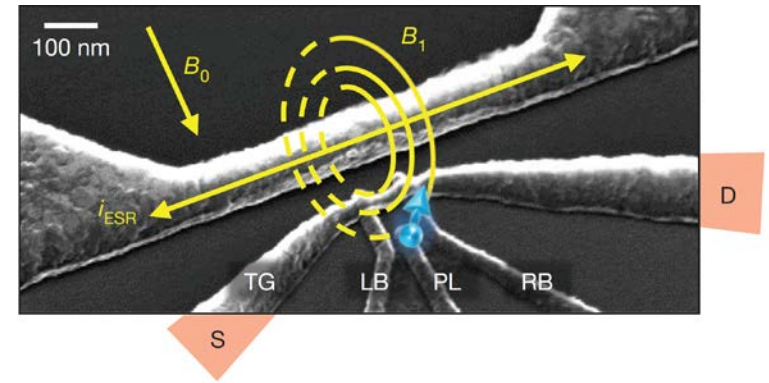
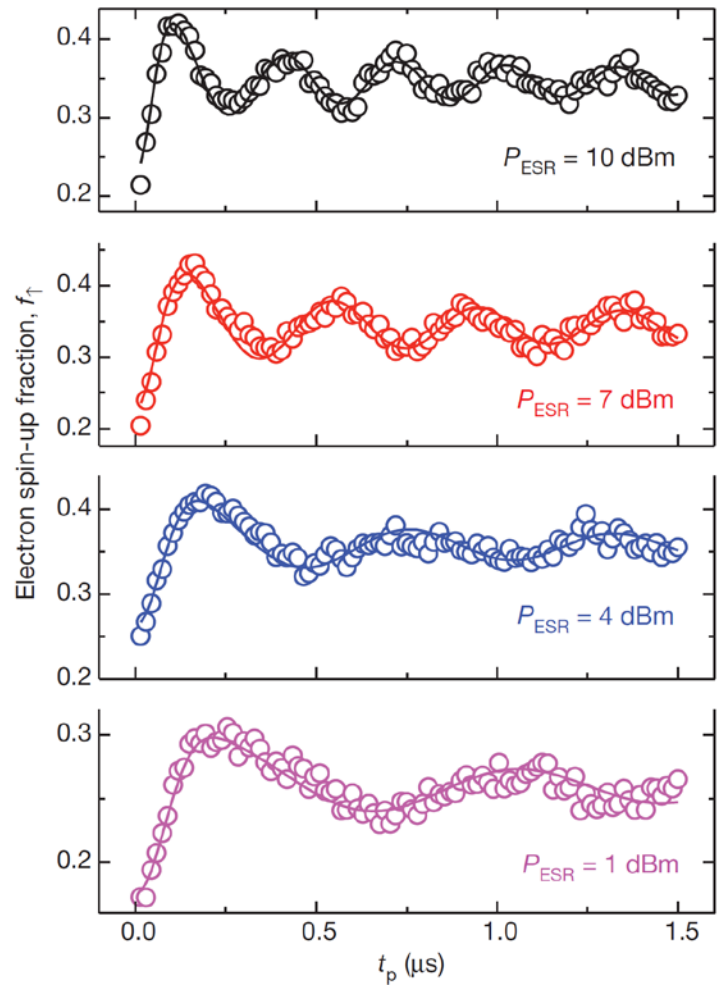
$$T_{\text{elec}} = 200 \text{ mK} = 17 \text{ } \mu\text{eV}$$

電子スピン単発読み出し



A single-atom electron spin qubit in silicon

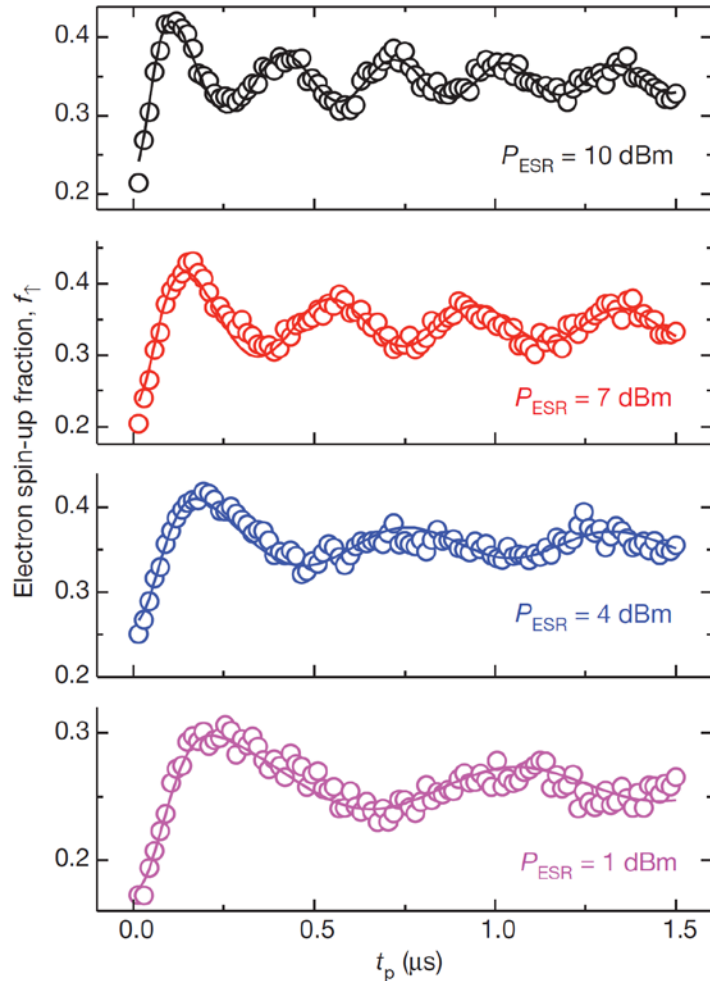
Jarryd J. Pla¹, Kuan Y. Tan^{1†}, Juan P. Dehollain¹, Wee H. Lim¹, John J. L. Morton^{2†}, David N. Jamieson³, Andrew S. Dzurak¹ & Andrea Morello¹



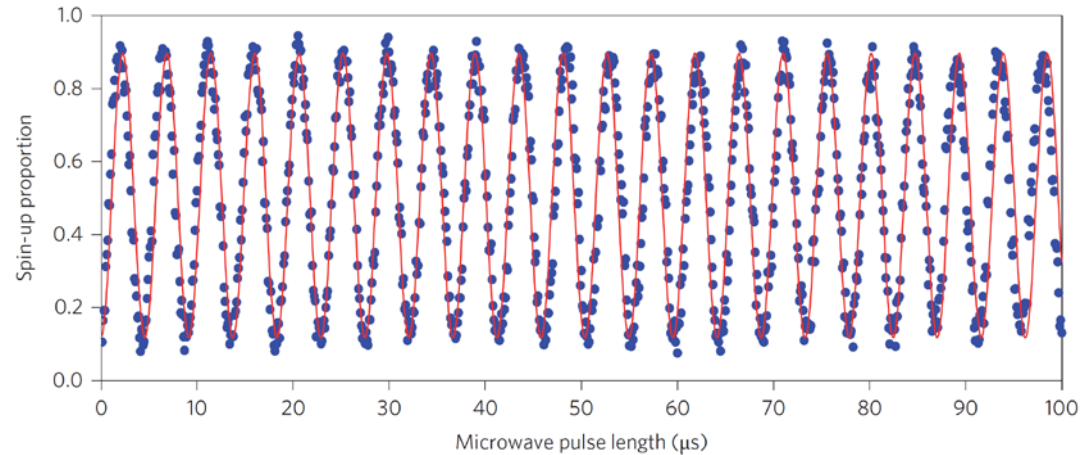
ラビ振動: natSiデバイス

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

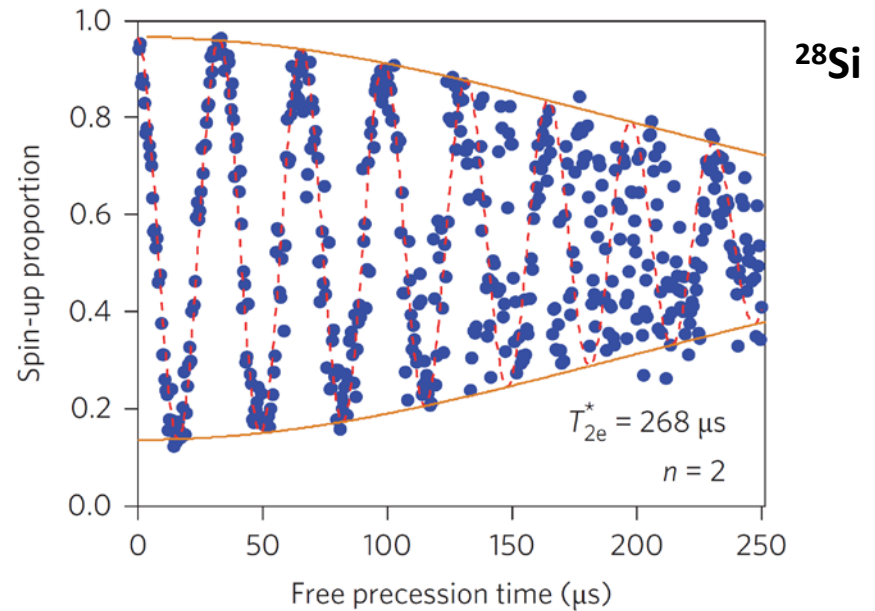
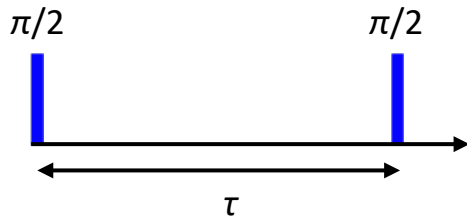


Nature Nano. **9**, 986 (2014) Muhonen *et al.*

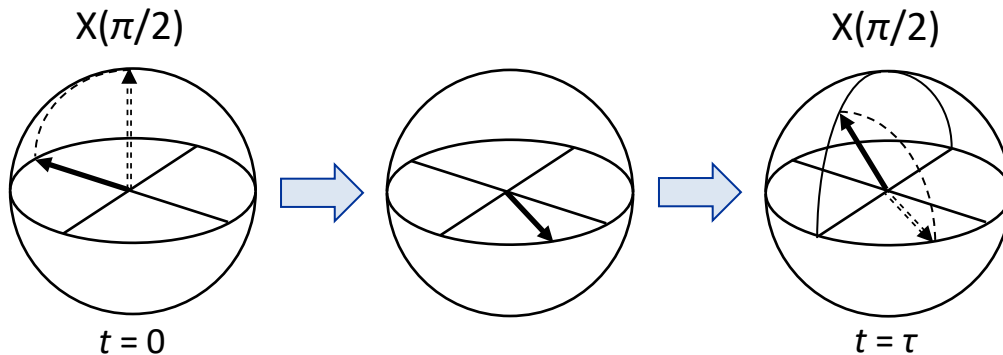
ラビ振動: natSiデバイス

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

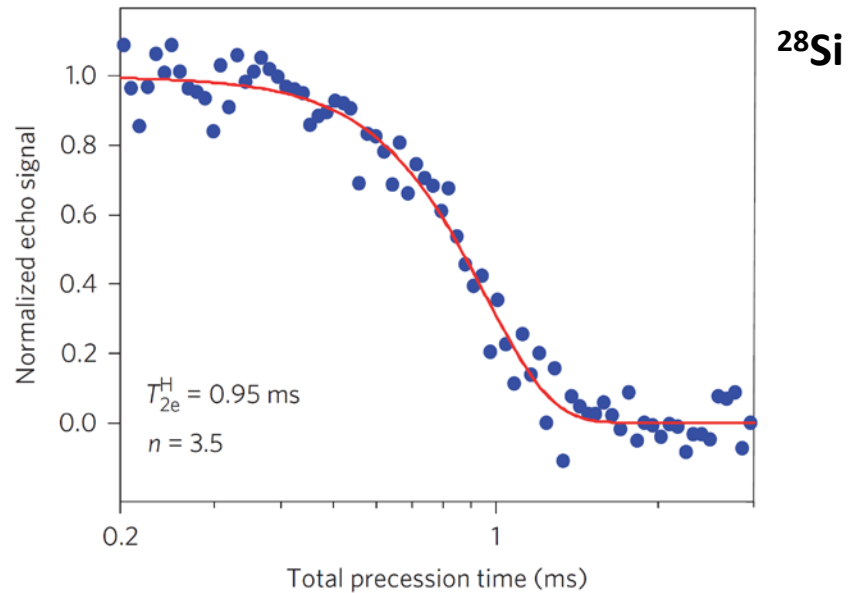
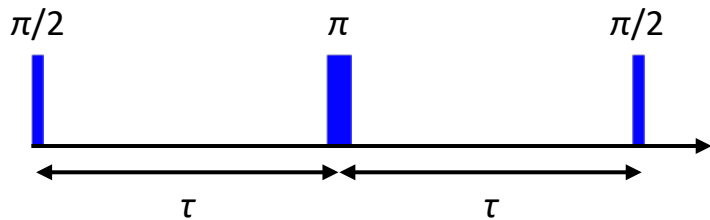
ラムゼー干渉: T_{2e}^*



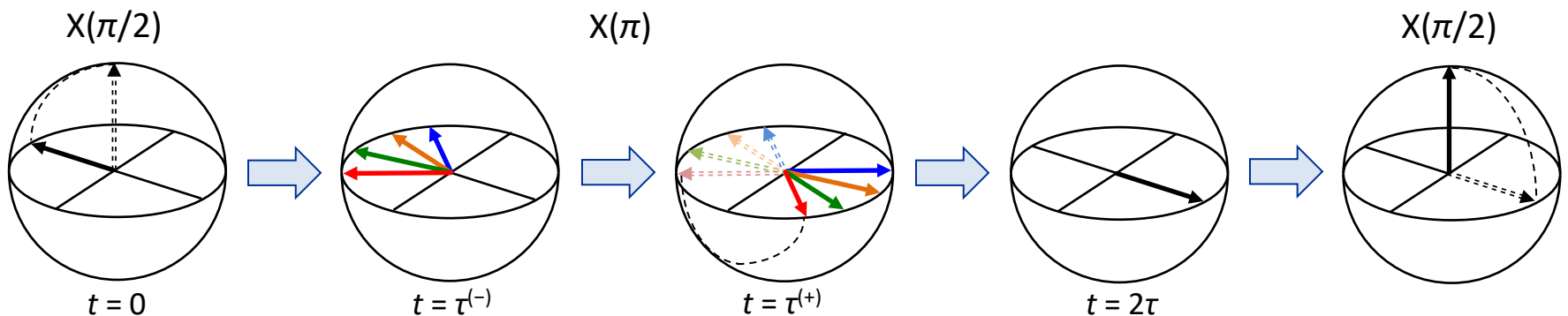
(共鳴から少し外れた回転系)



スピンエコー: T_{2e}

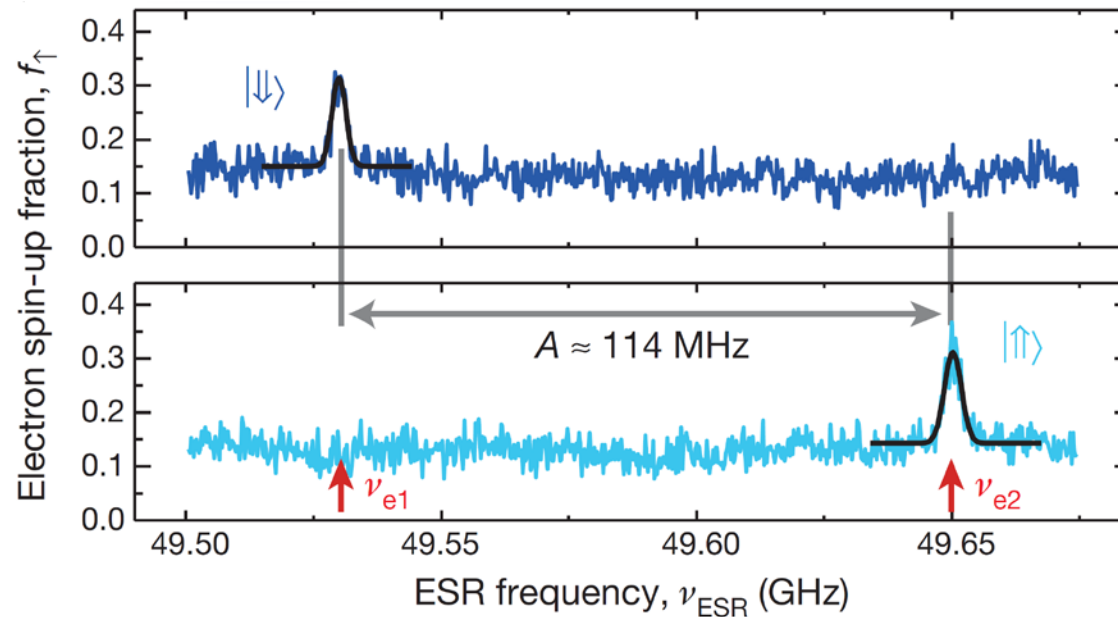


(共鳴周波数の回転系)



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

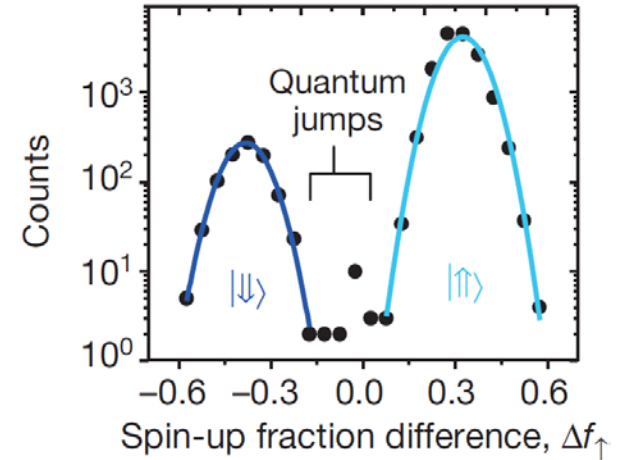
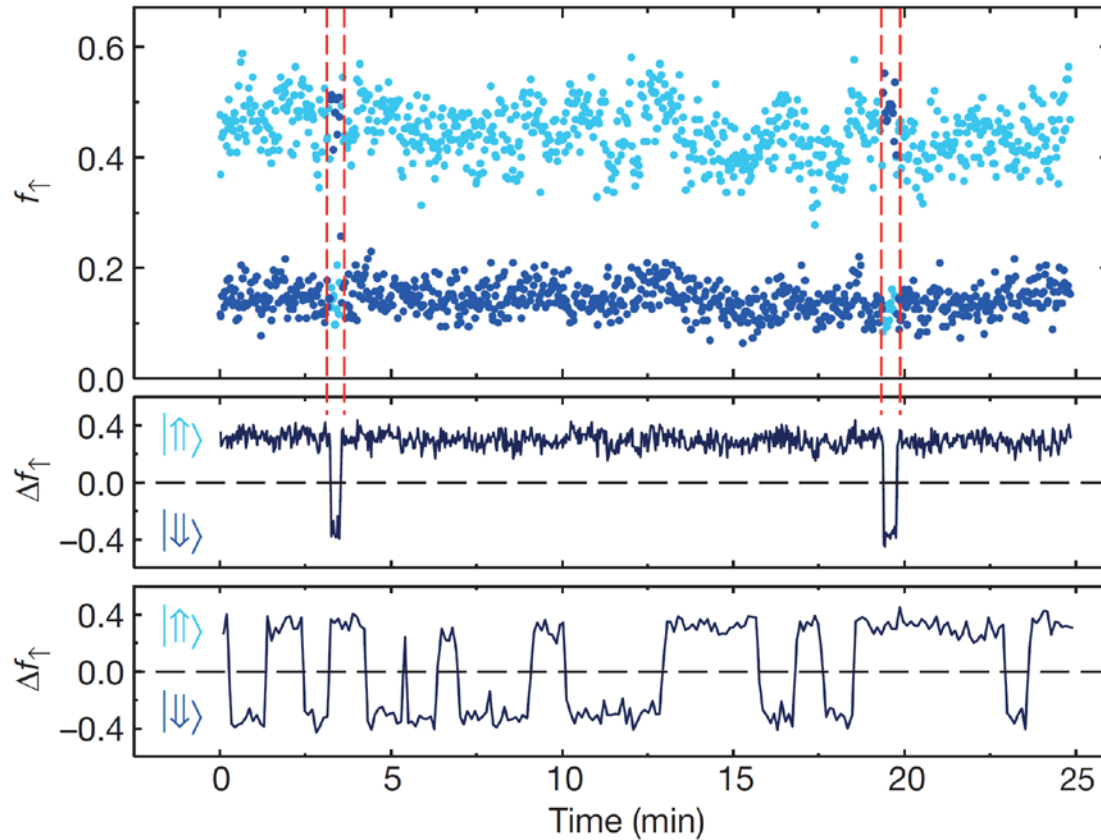
Jarryd J. Pla¹, Kuan Y. Tan^{1†}, Juan P. Dehollain¹, Wee H. Lim^{1†}, John J. L. Morton², Floris A. Zwanenburg^{1†}, David N. Jamieson³, Andrew S. Dzurak¹ & Andrea Morello¹



- 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

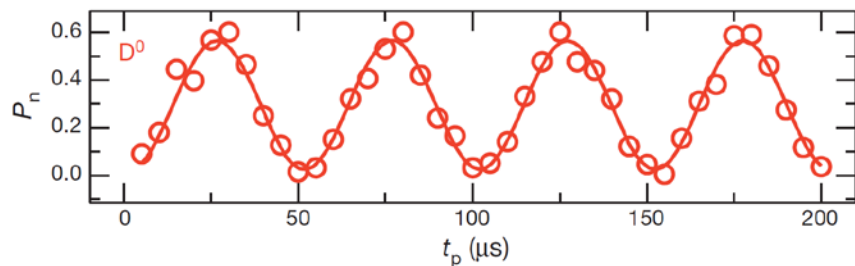
High-fidelity readout and control of a nuclear spin qubit in silicon

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

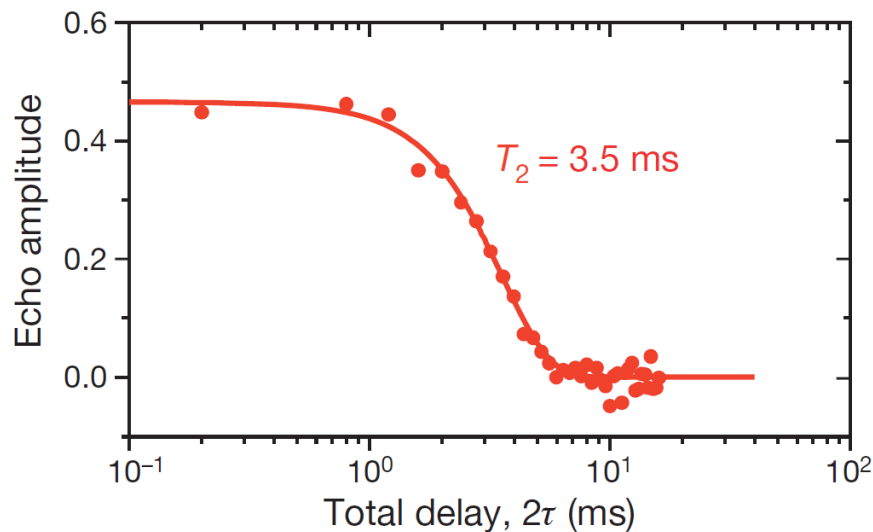
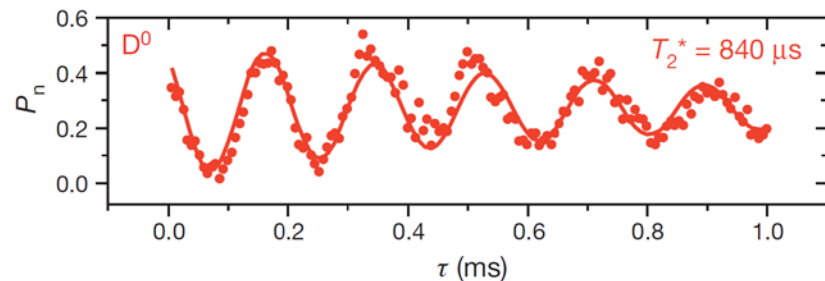


単一核スピンコヒーレント制御

ラビ振動(^{nat}Si)



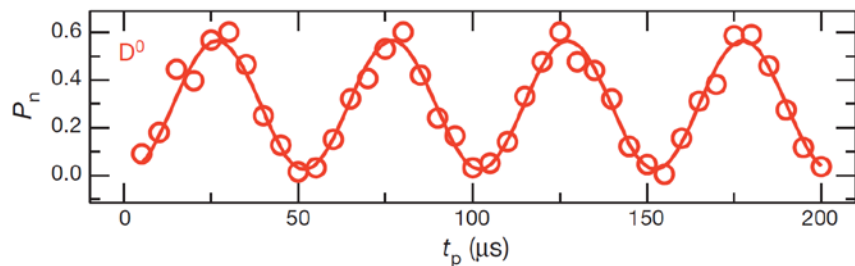
ラムゼー干渉(^{nat}Si)



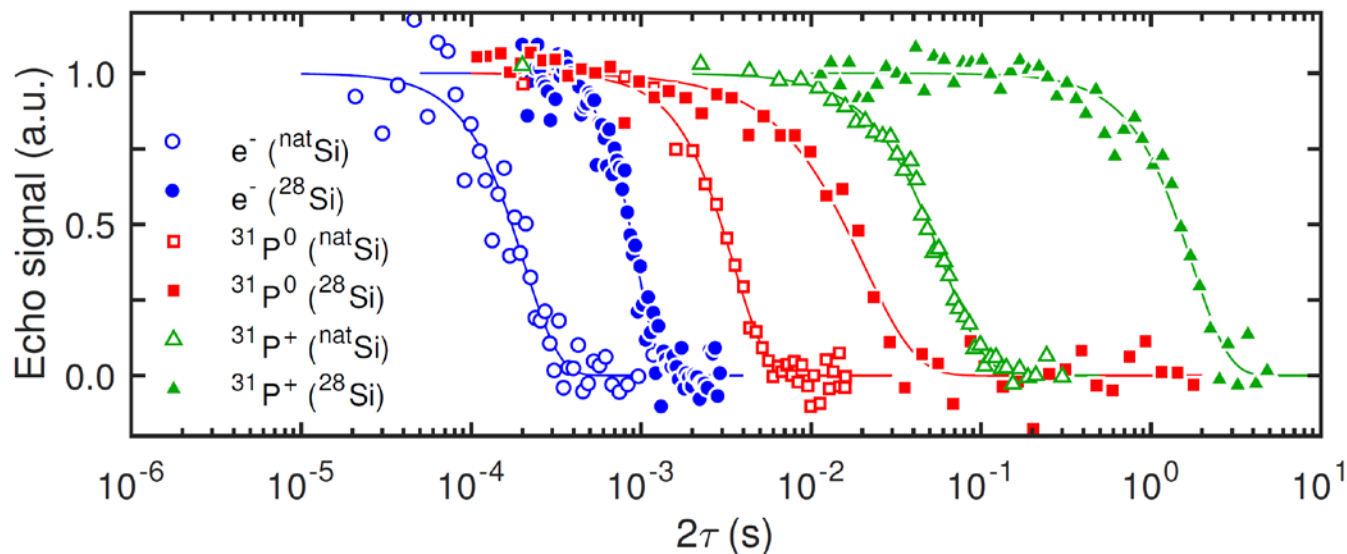
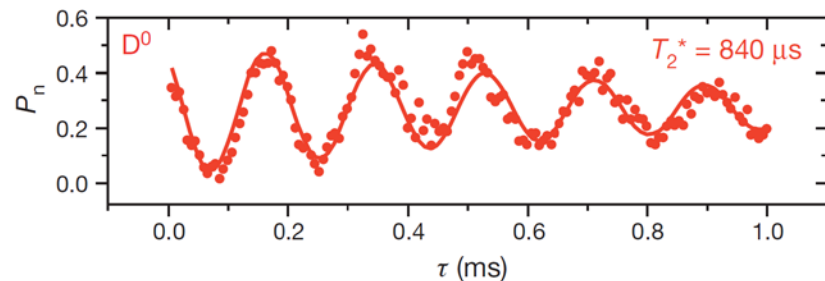
エコー(^{nat}Si)

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.*

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

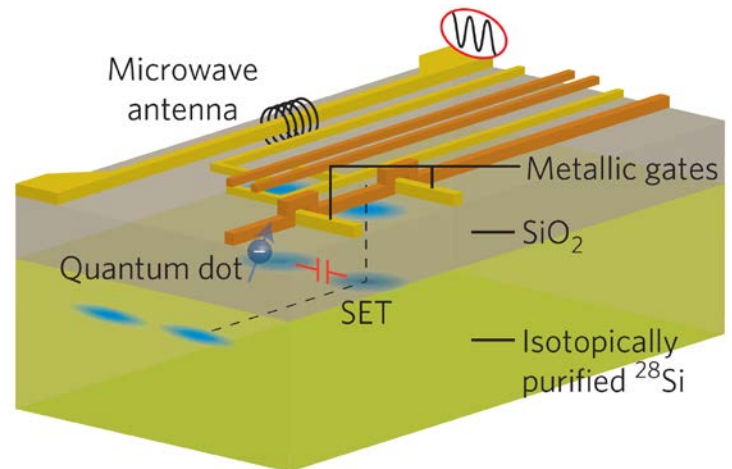
doi:10.1038/nature15263

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



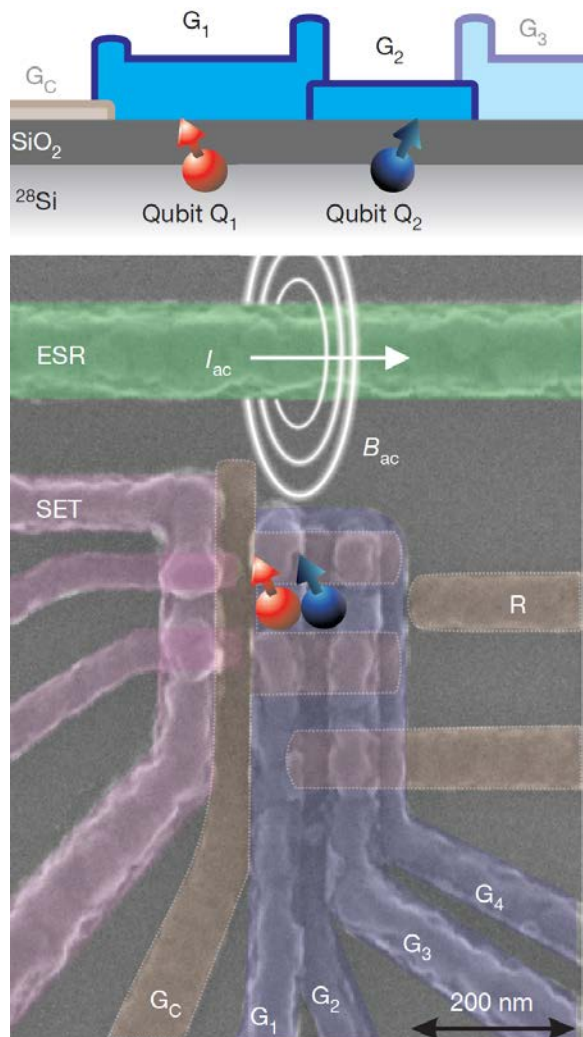
(L to R) J. Muhonen, A. Morello, M. Veldhorst, A. Dzurak



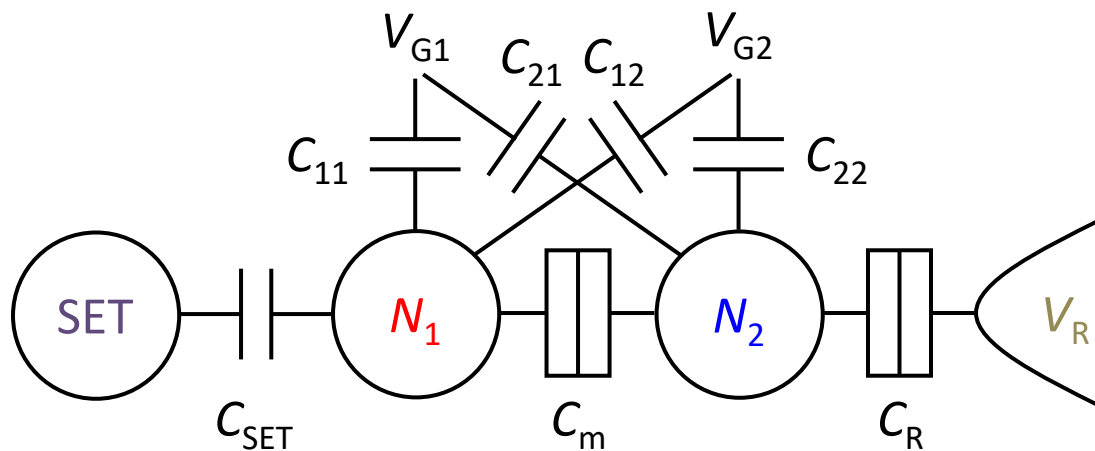
Nature Nano. **9**, 981 (2014) Veldhorst *et al.*

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

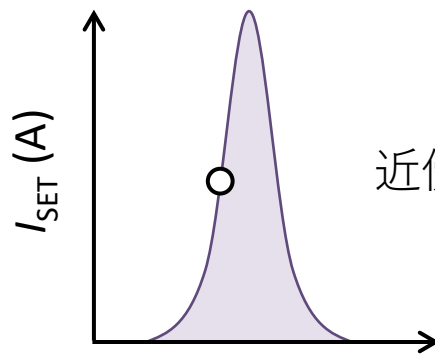
MOS型2重量子ドット



クロストーク

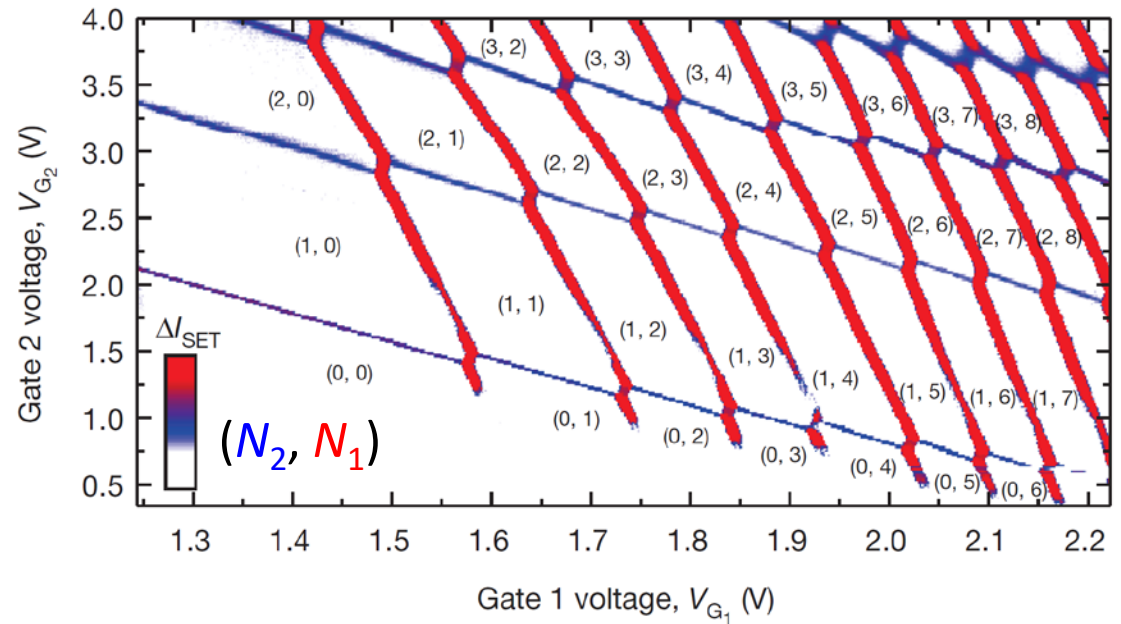
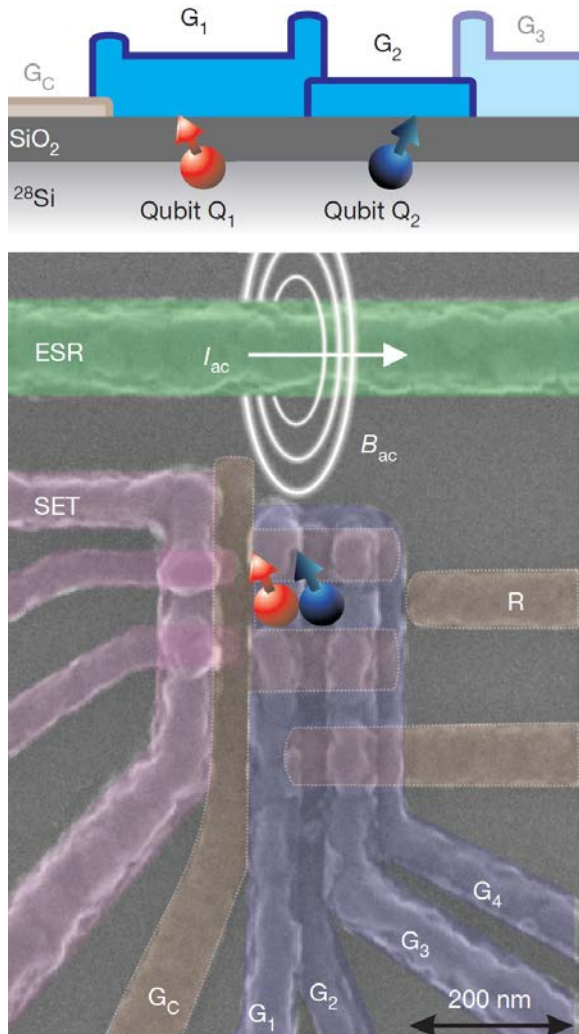


SET電荷センサ



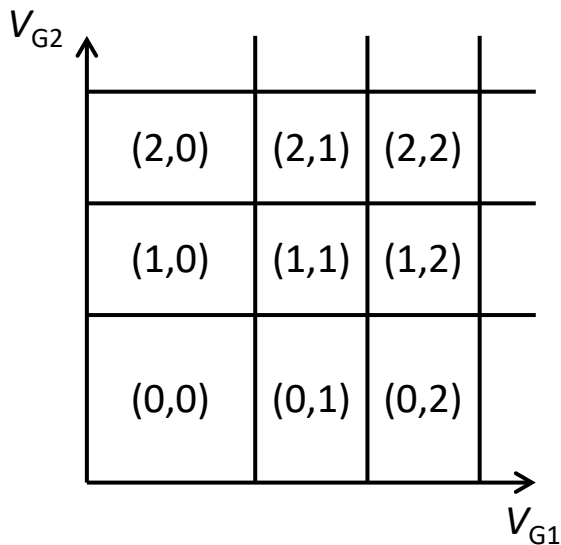
近傍のQDsの電子数変化に
鋭敏に応答

MOS型2重量子ドット



スタビリティダイアグラム

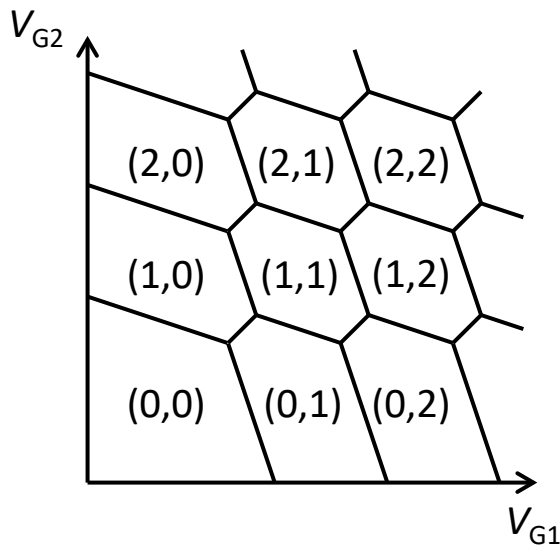
$$C_m \rightarrow 0$$



弱結合

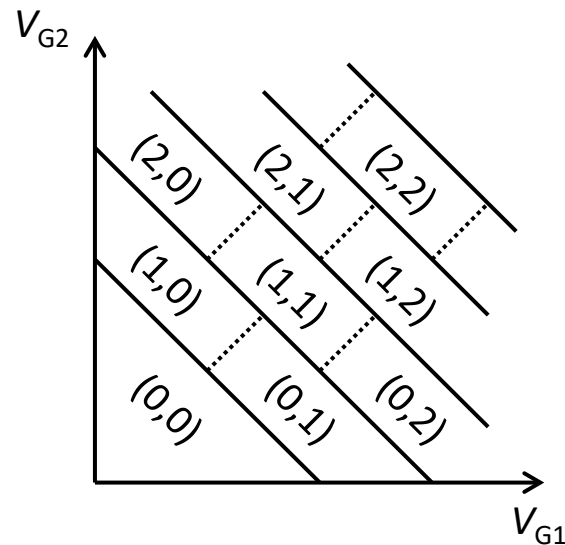
独立のドットとして
振る舞う

$$\frac{C_m}{C_{1,2}} \rightarrow 1$$



ハニカム構造

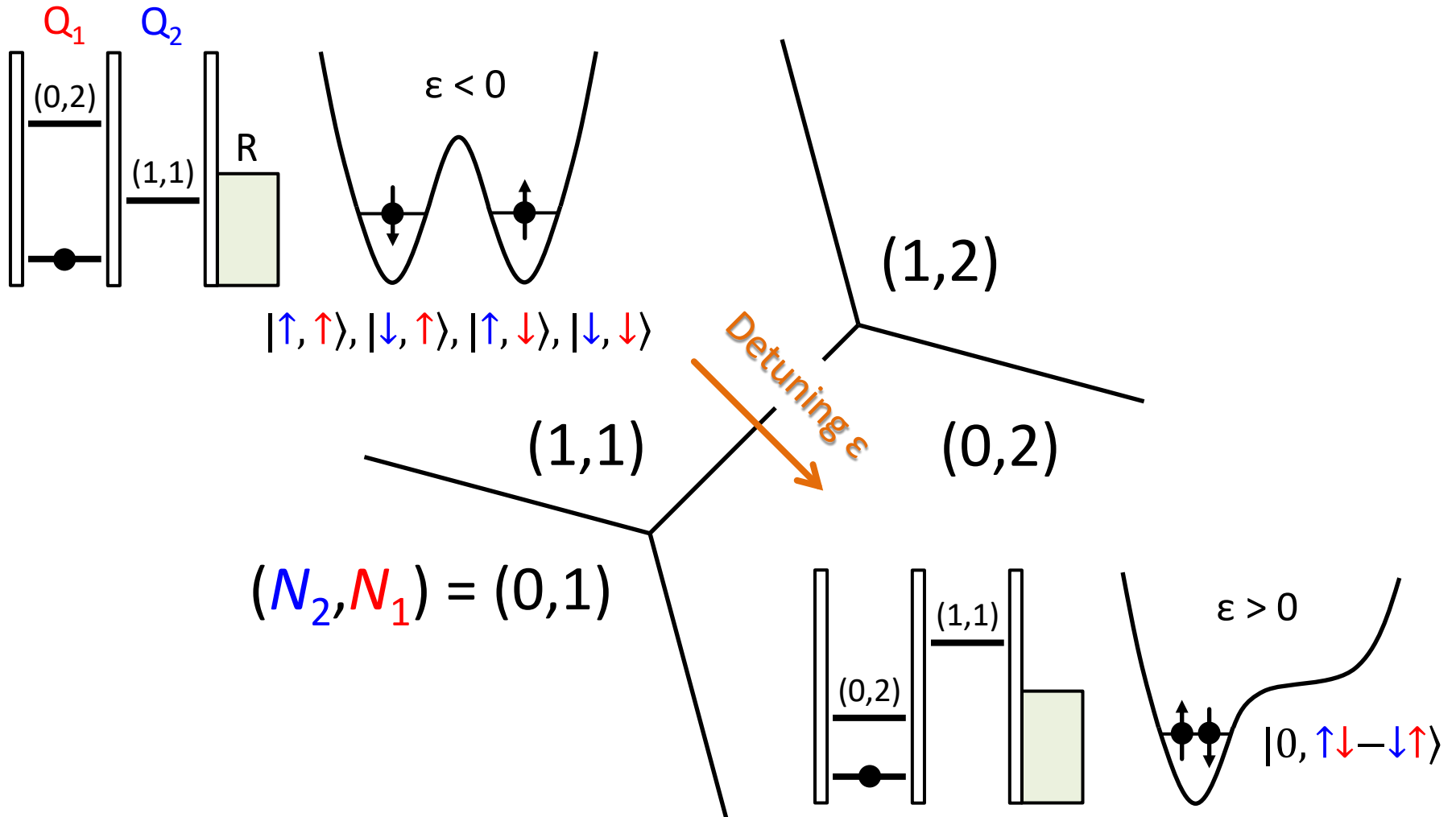
相互に影響しあう



強結合

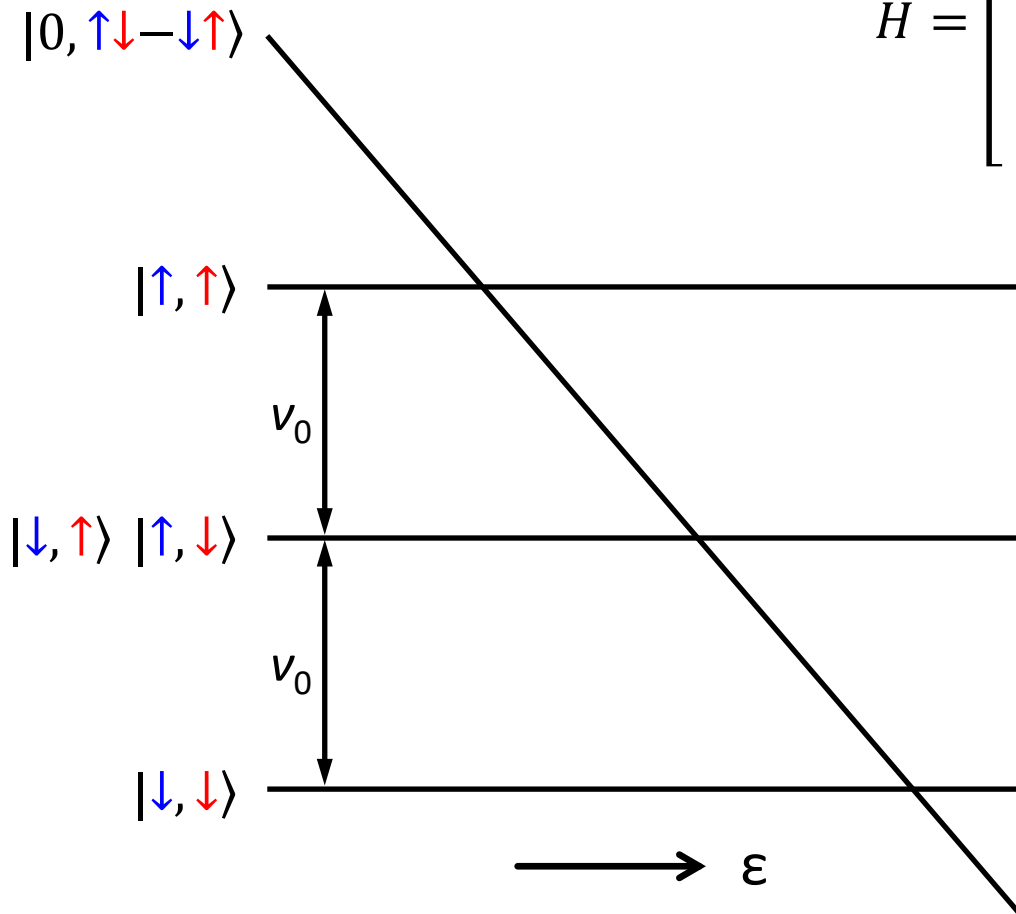
1つのドットとして
振る舞う

2電子状態



2電子状態

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

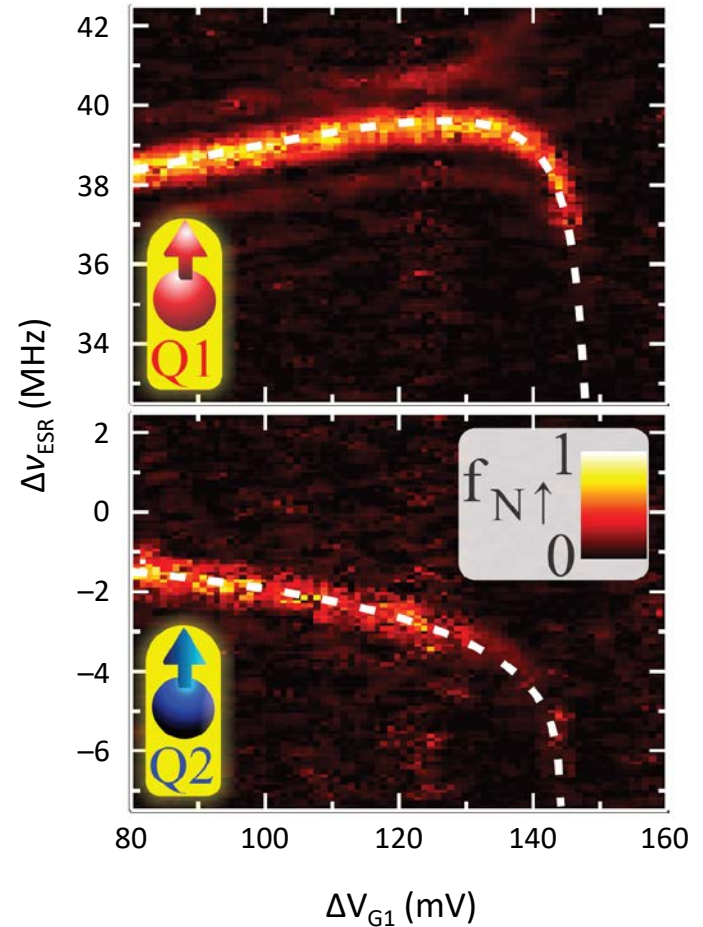
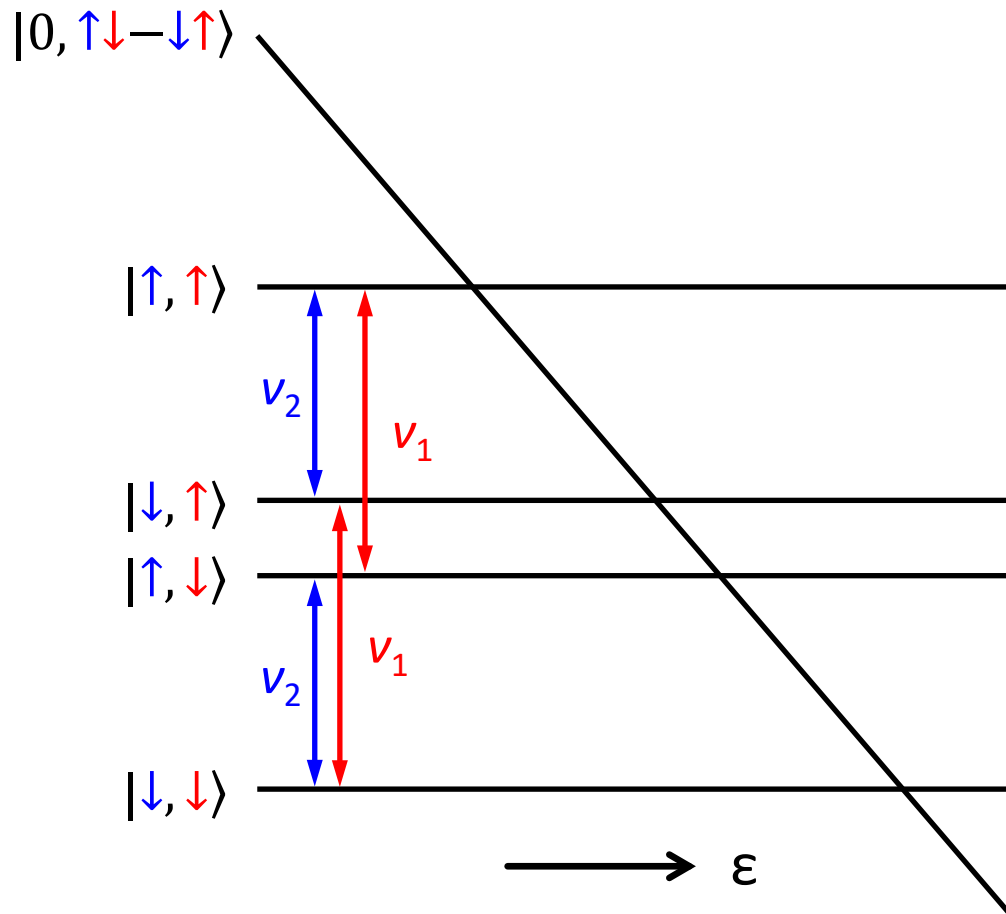


$$E_z = \gamma_e B_0 = h\nu_0$$

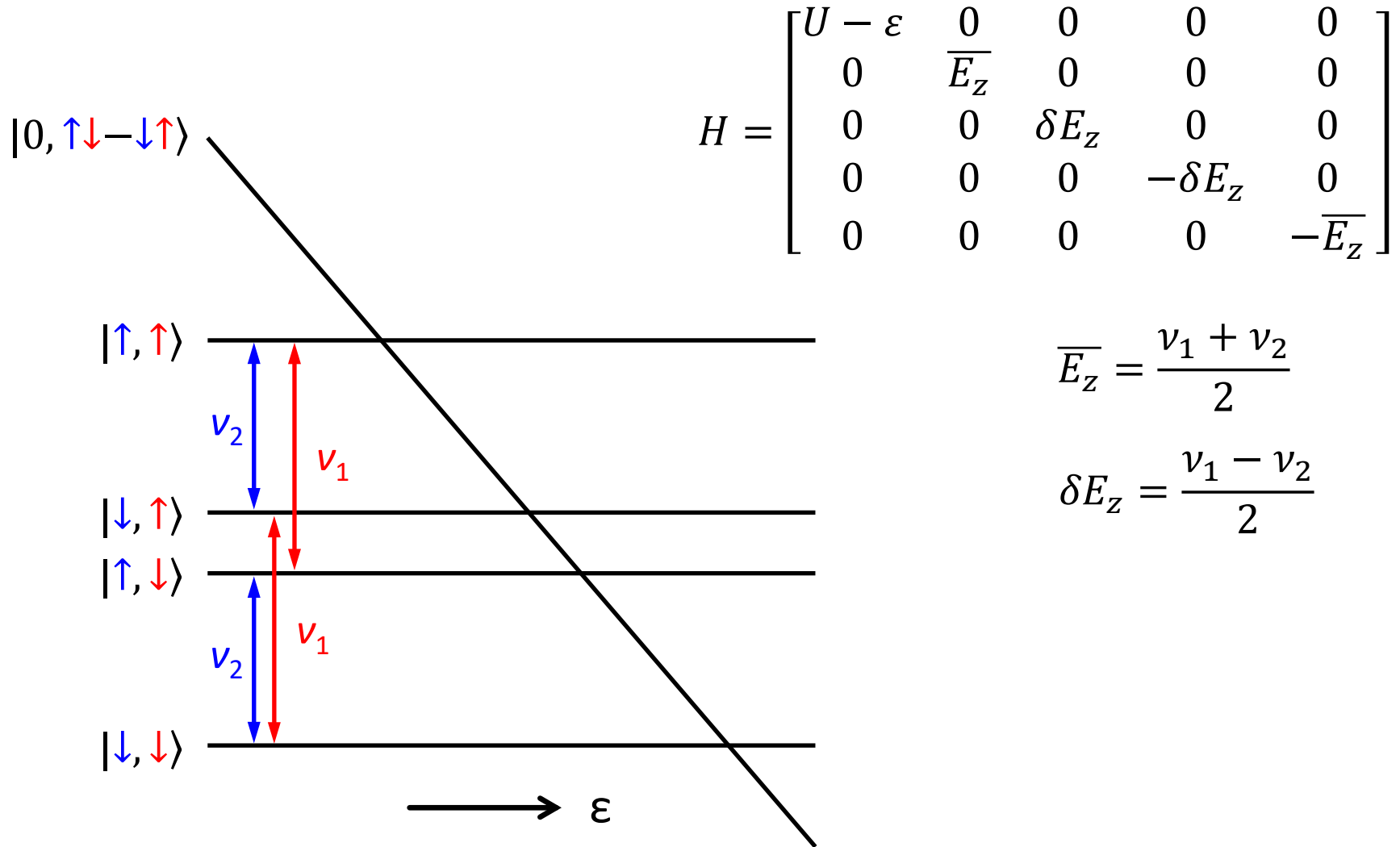
$$\nu_0 = 39.14 \text{ GHz @ } B_0 = 1.4 \text{ T}$$

2電子状態

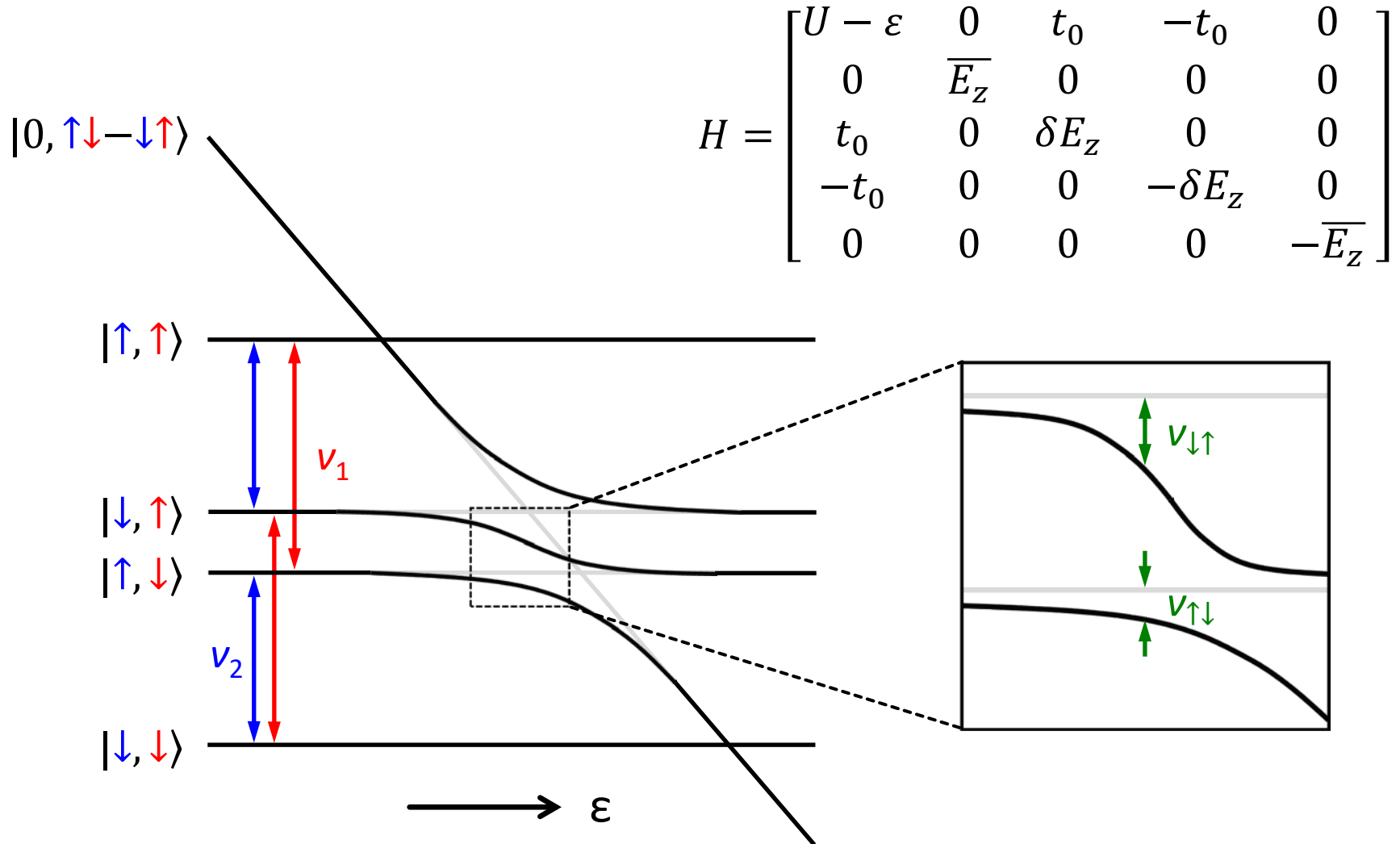
電場によるESR周波数制御: シュタルク効果



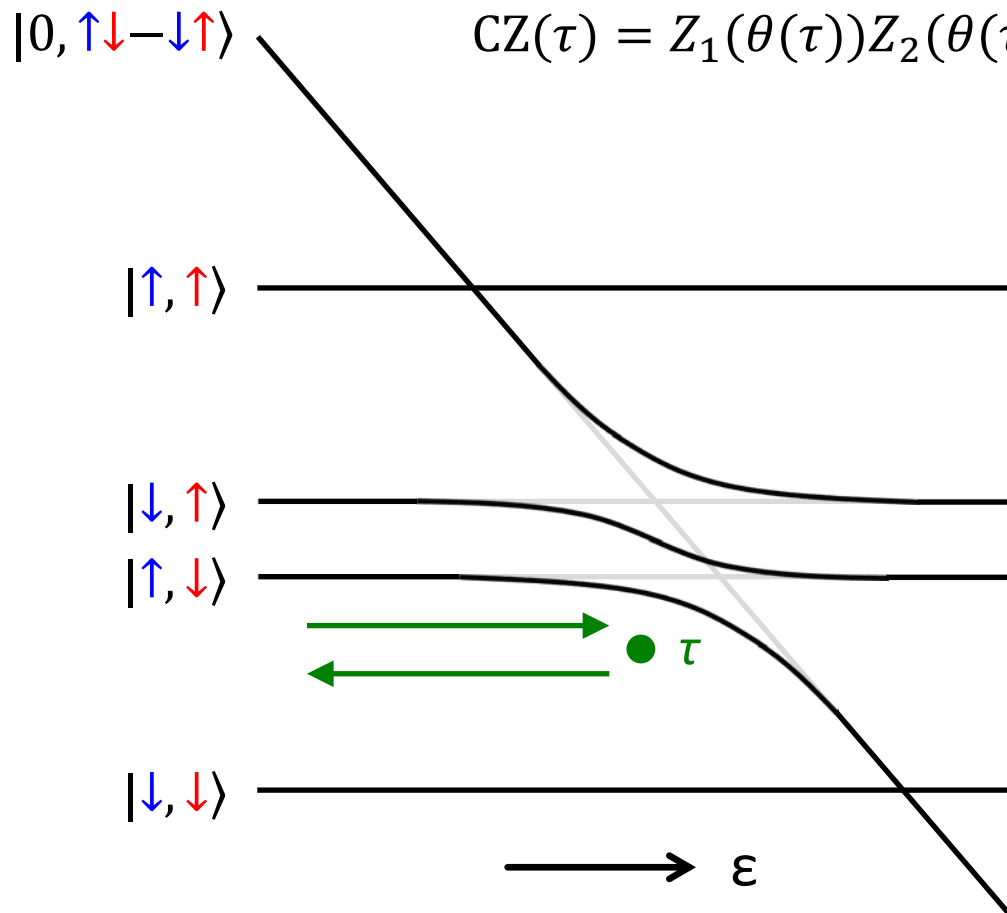
2電子状態



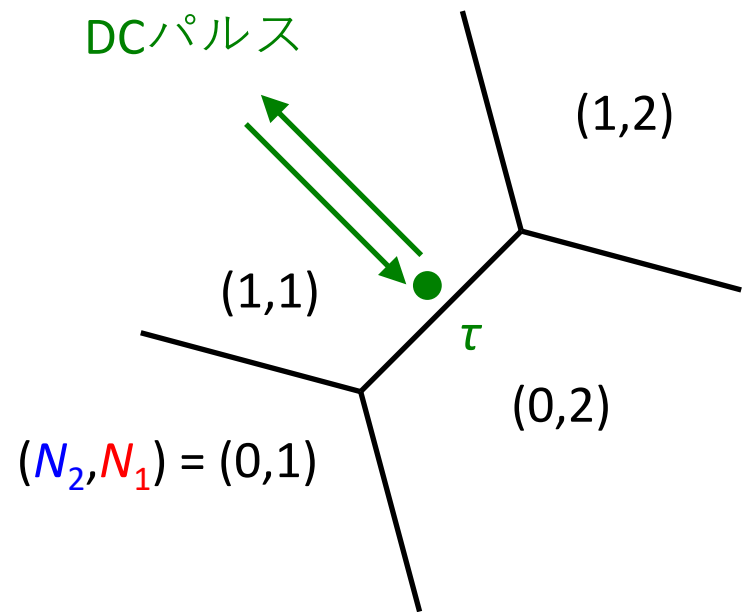
2電子状態



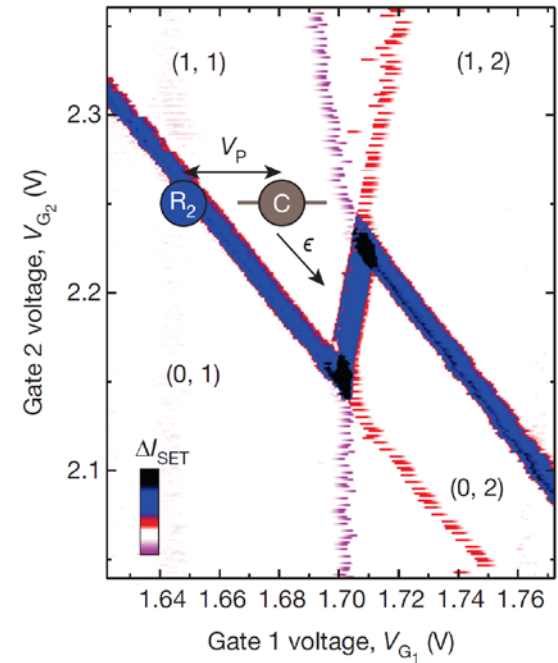
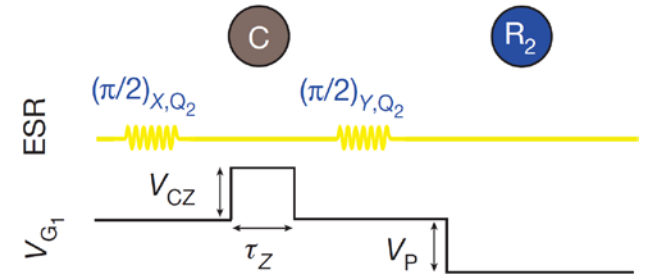
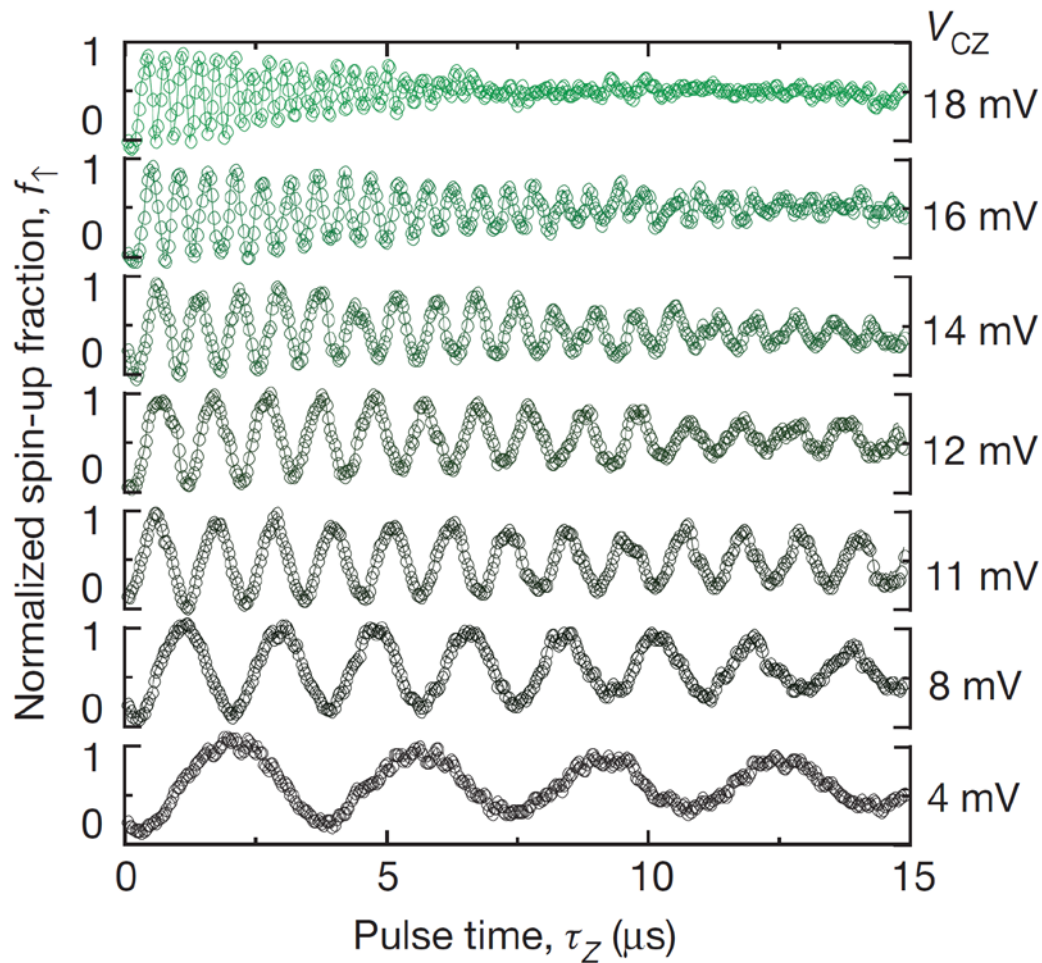
CZゲート



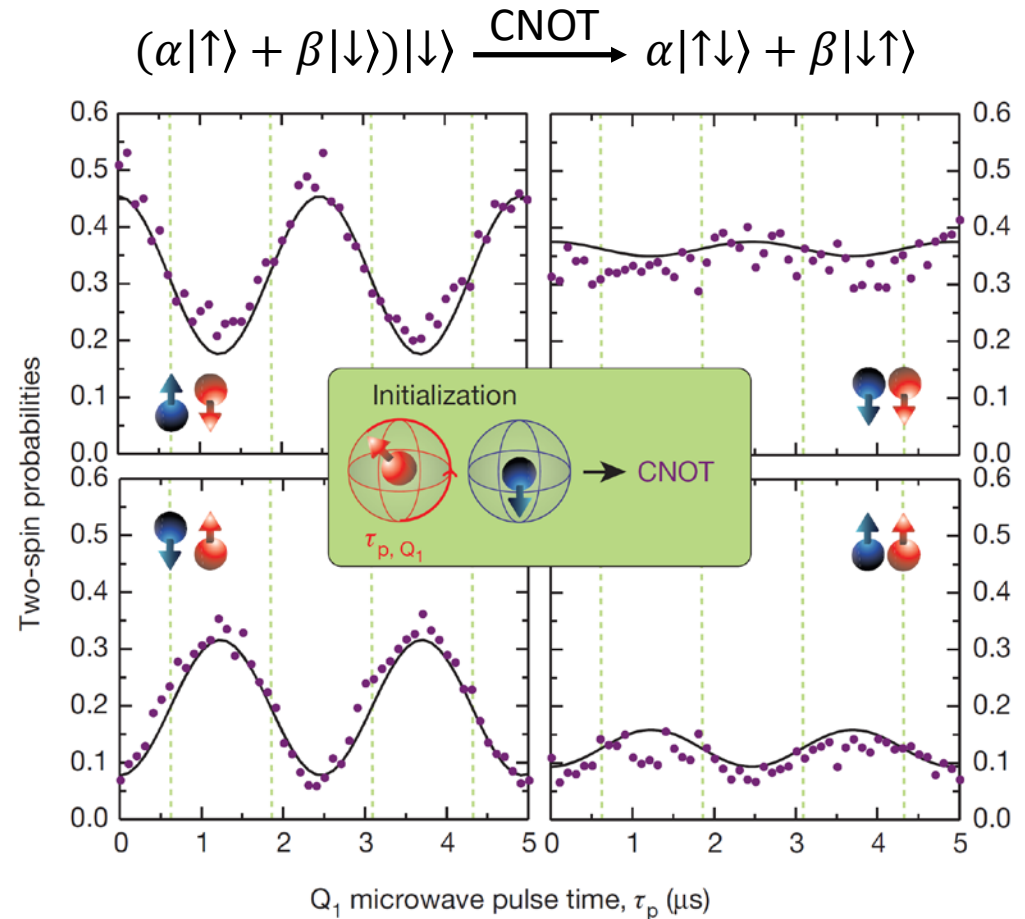
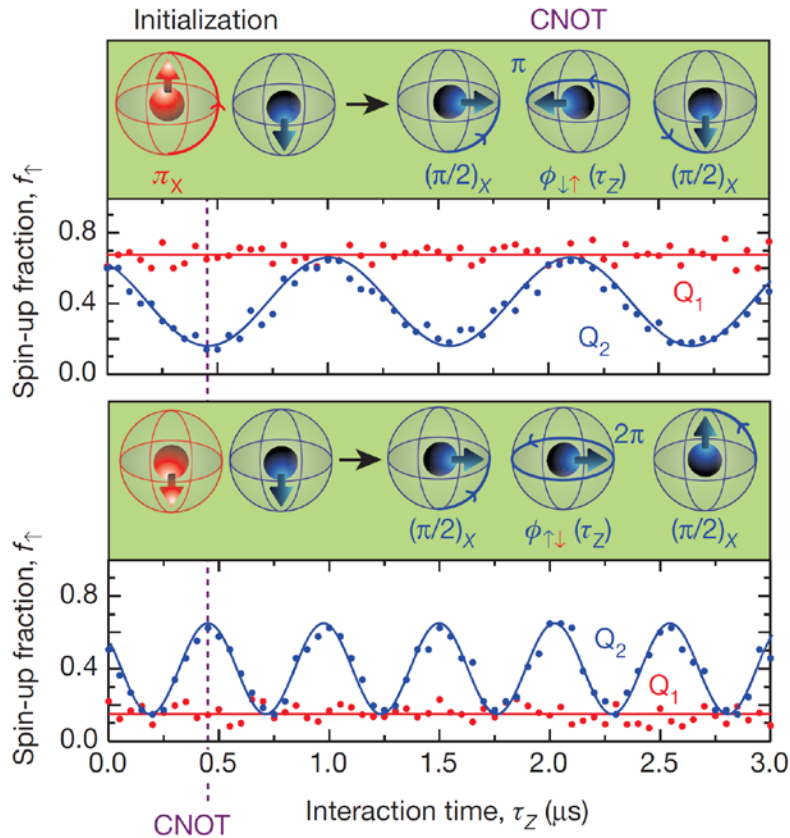
$$CZ(\tau) = Z_1(\theta(\tau))Z_2(\theta(\tau)) \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & e^{-i2\pi\nu_{\downarrow\uparrow}\tau} & 0 & 0 \\ 0 & 0 & e^{-i2\pi\nu_{\uparrow\downarrow}\tau} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$



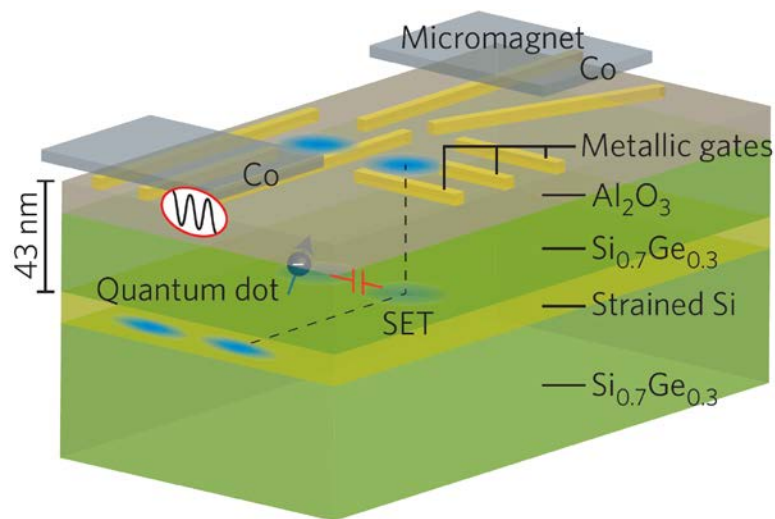
CZゲート



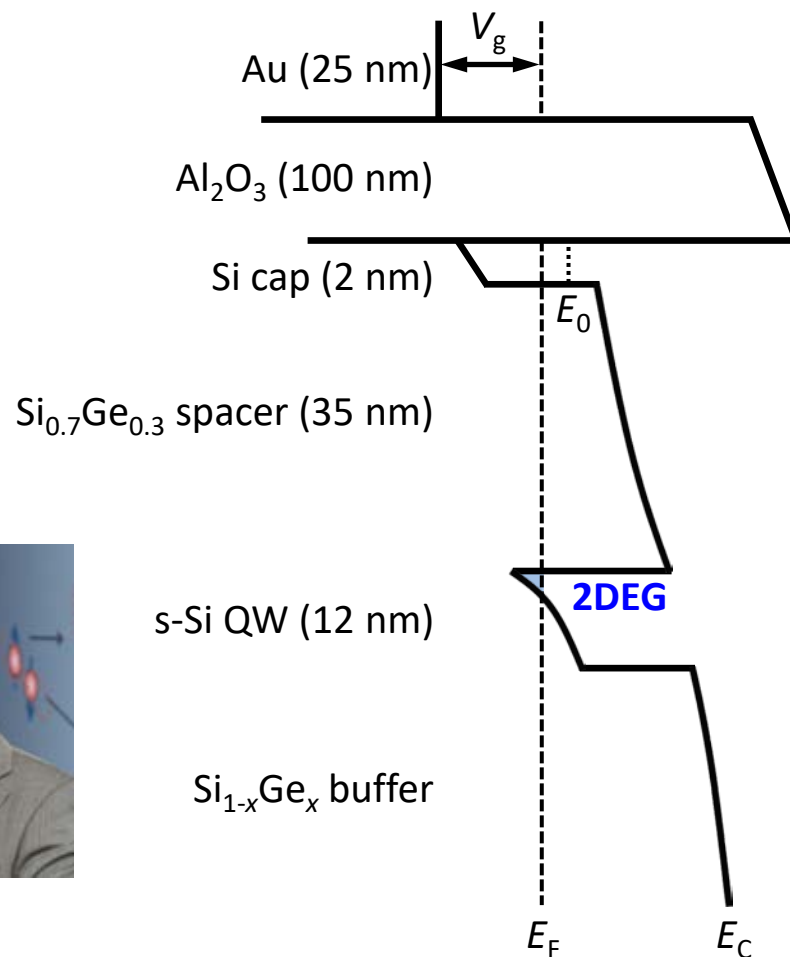
CNOTゲート



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)



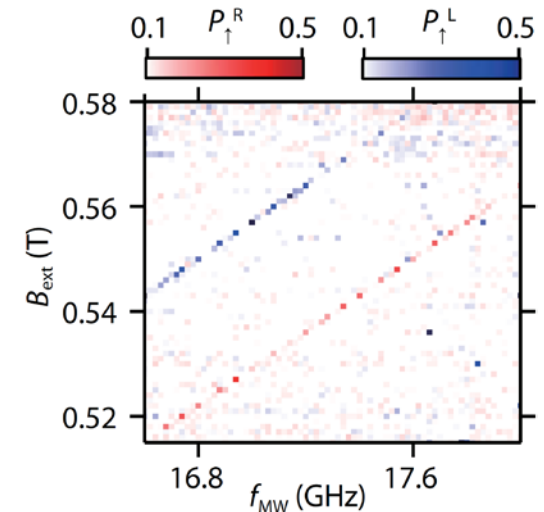
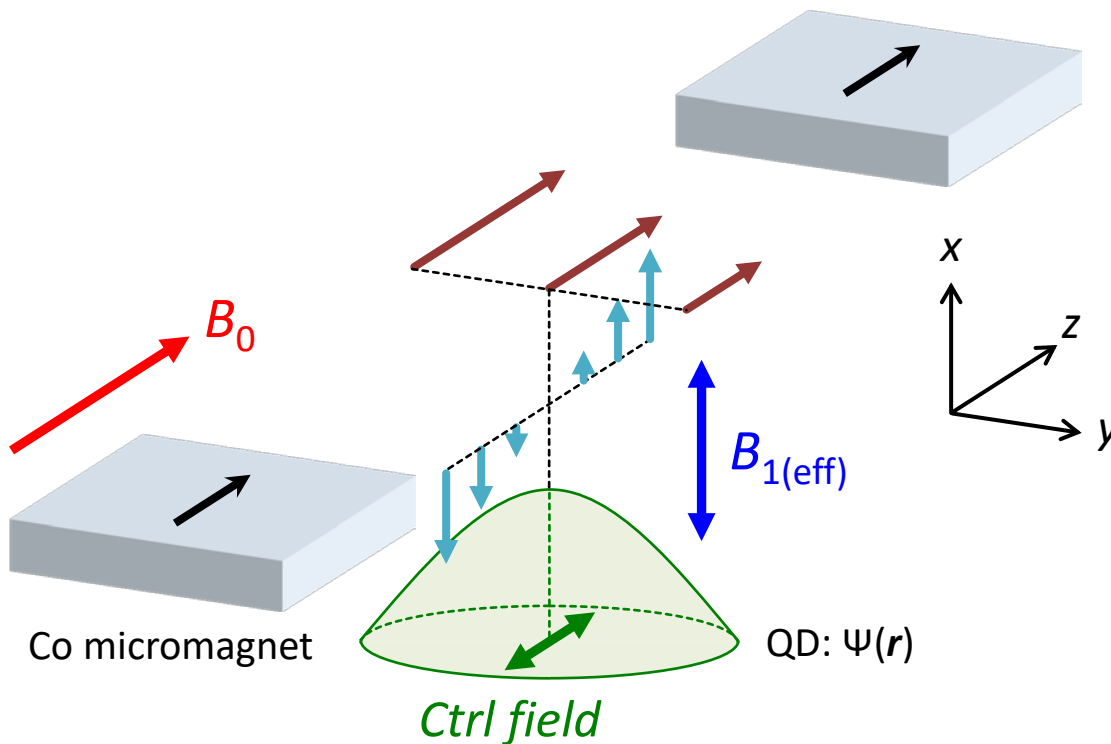
J. Petta
(©Princeton)



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



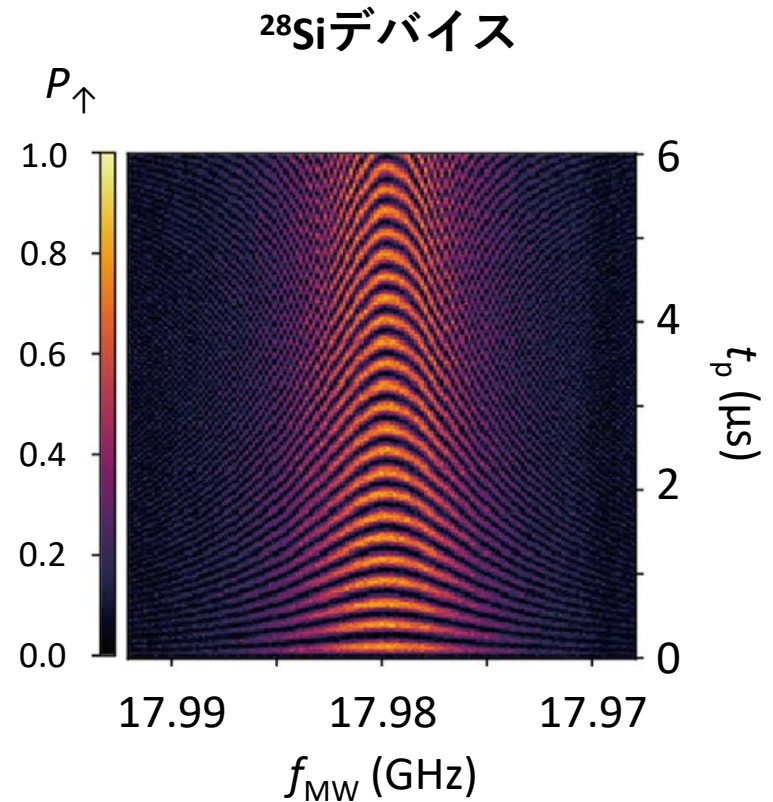
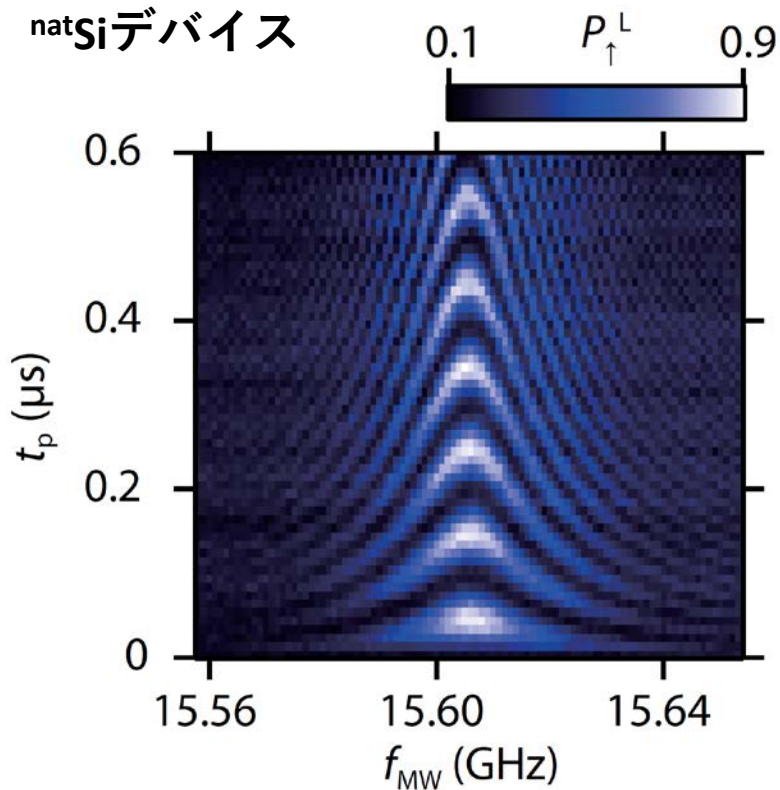
Sci. Adv. **2**, e1600694 (2016) Takeda *et al.*

(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

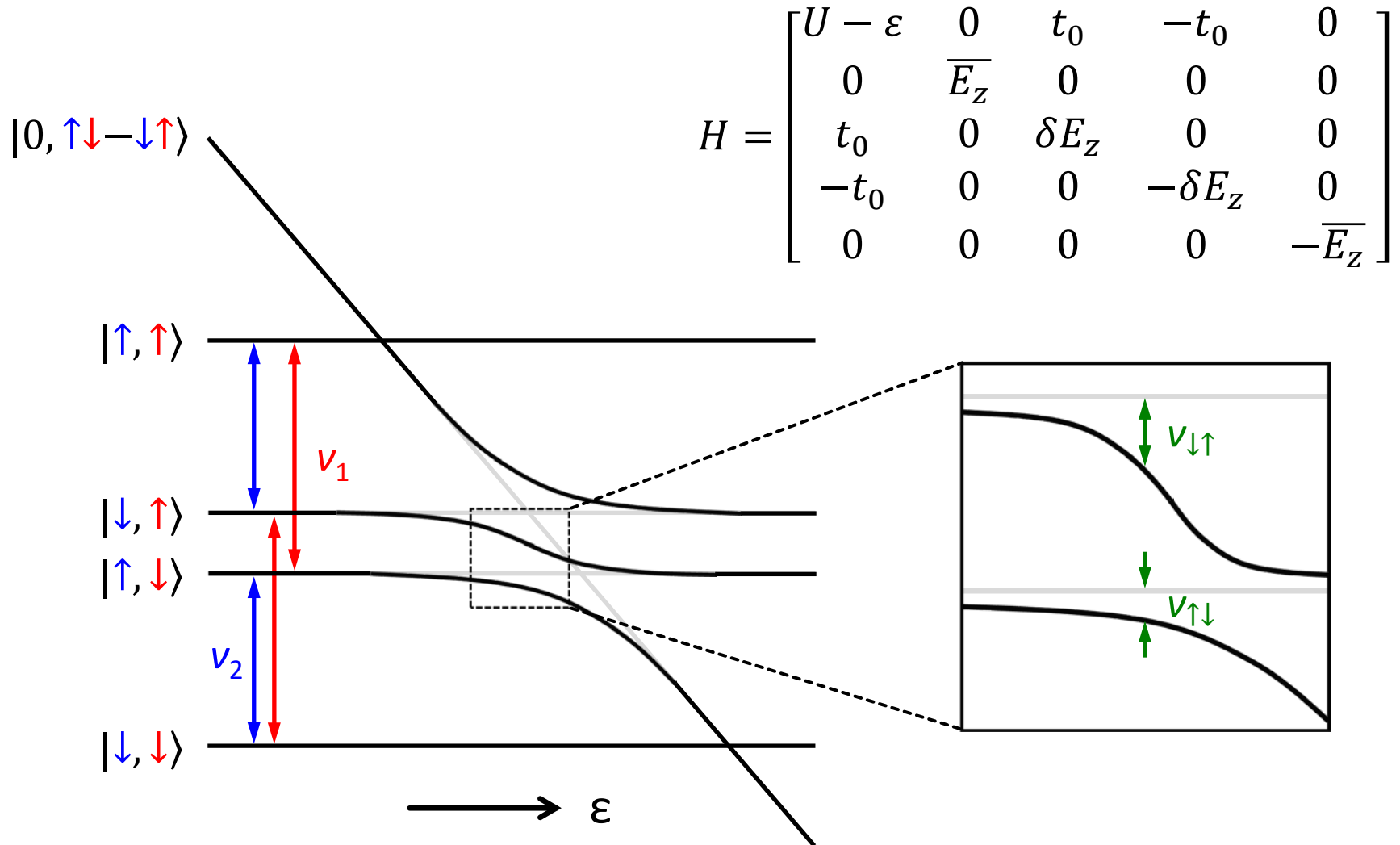


- ラビ周波数 $f_R \approx 30$ MHz
- フィデリティ $F^{\text{RB}} = 99.6\% \rightarrow > 99.9\%$
- $T_2^* = 2 \mu\text{s} \rightarrow 20 \mu\text{s}$, $T_2^{\text{CPMG}} = 3.1$ ms

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

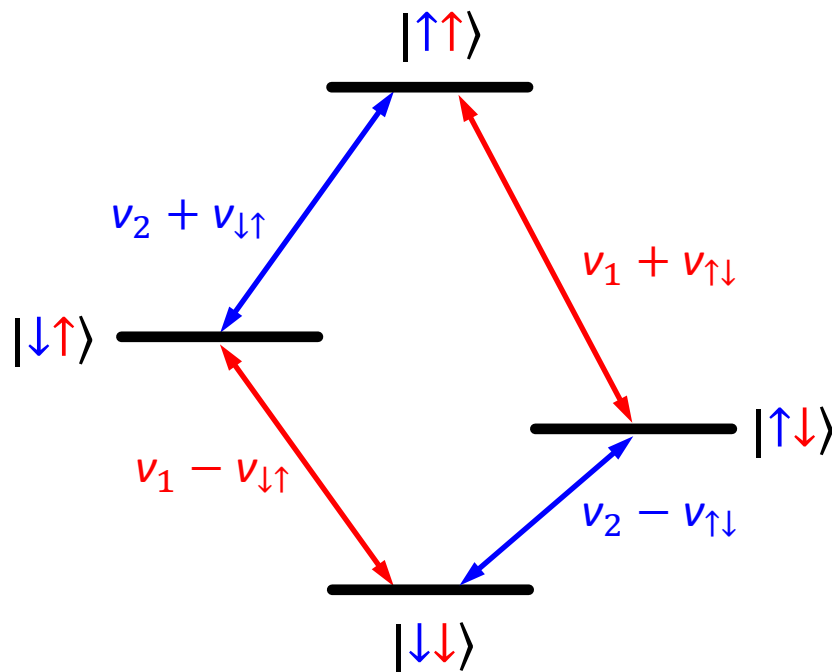
Nature Nano. **13**, 102 (2018) Yoneda *et al.*

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

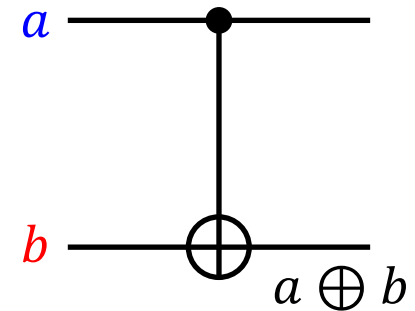
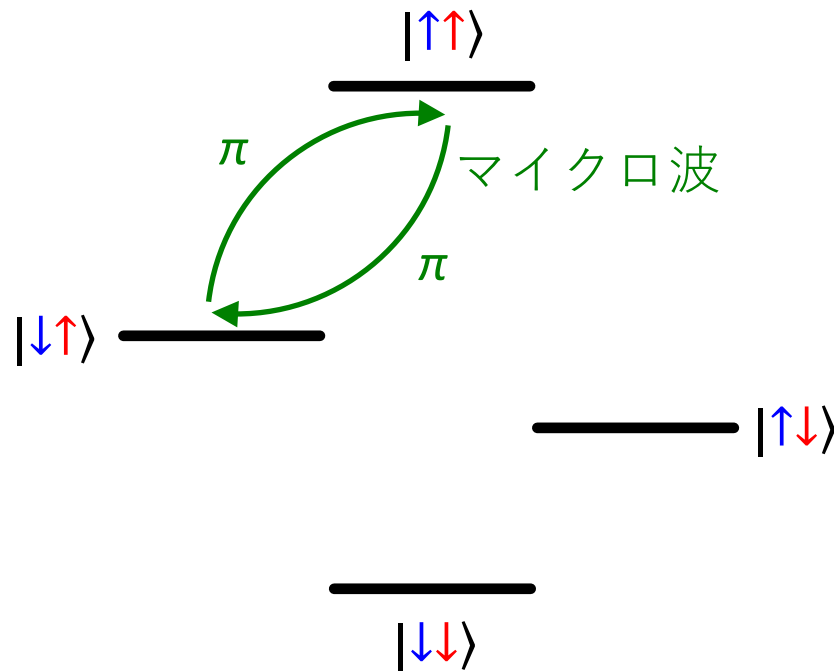
e.g. CNOTゲート

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

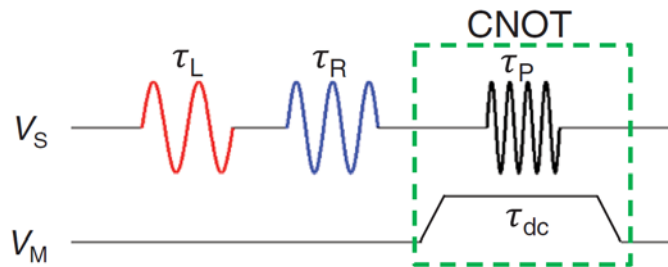
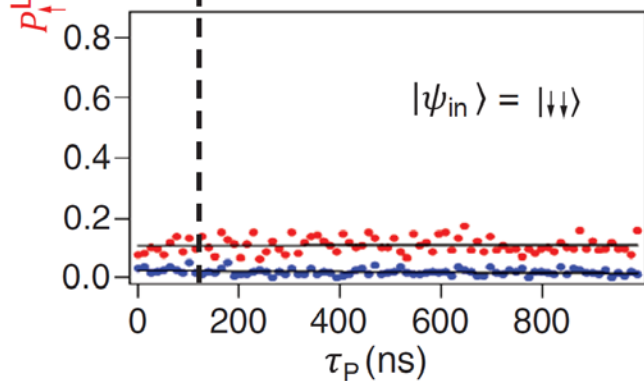
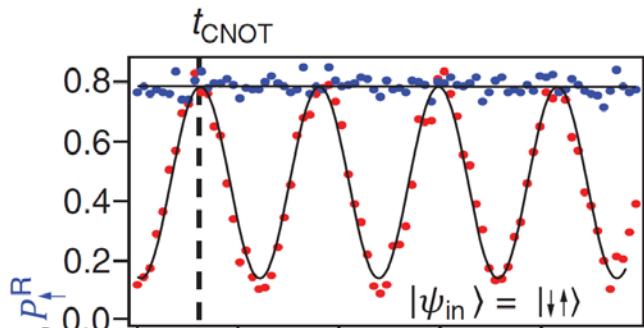
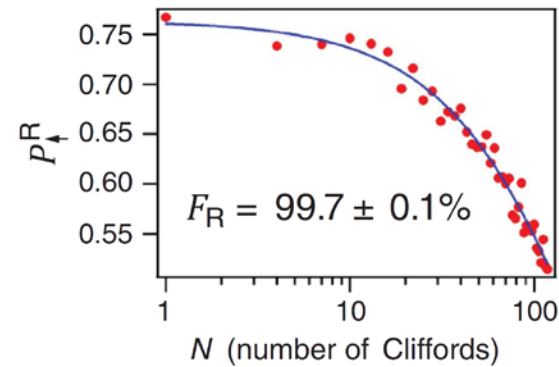
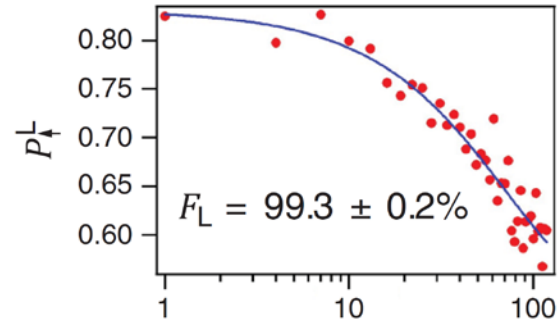
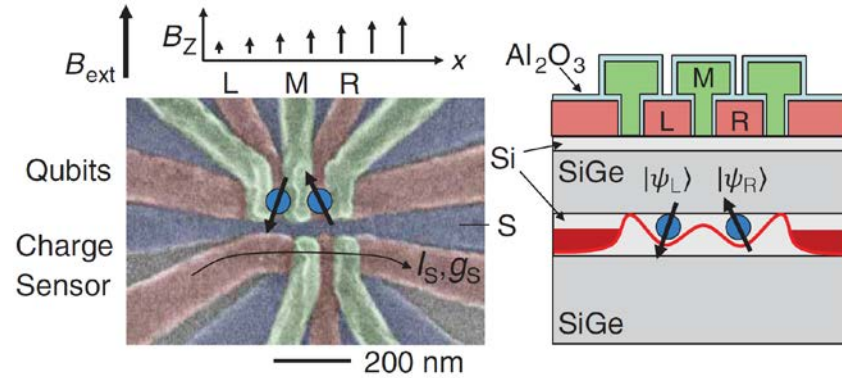
$$|\uparrow\downarrow\rangle = |10\rangle \longrightarrow |11\rangle$$

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

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

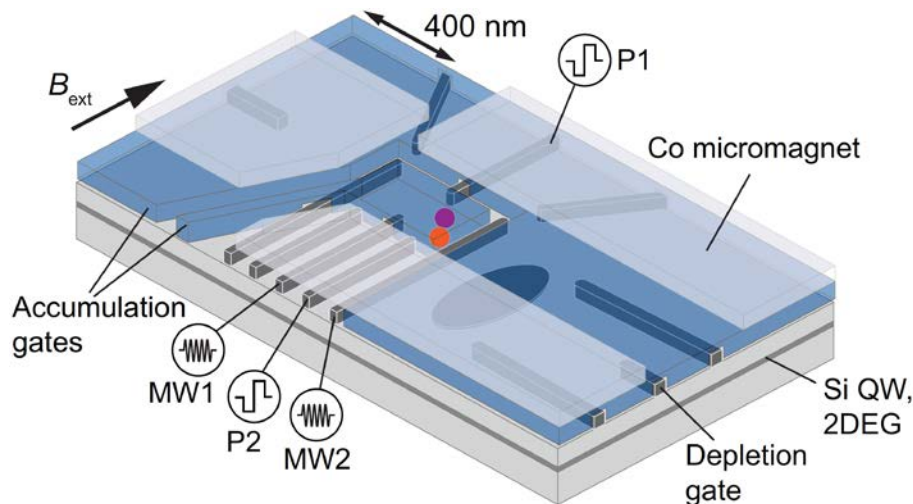
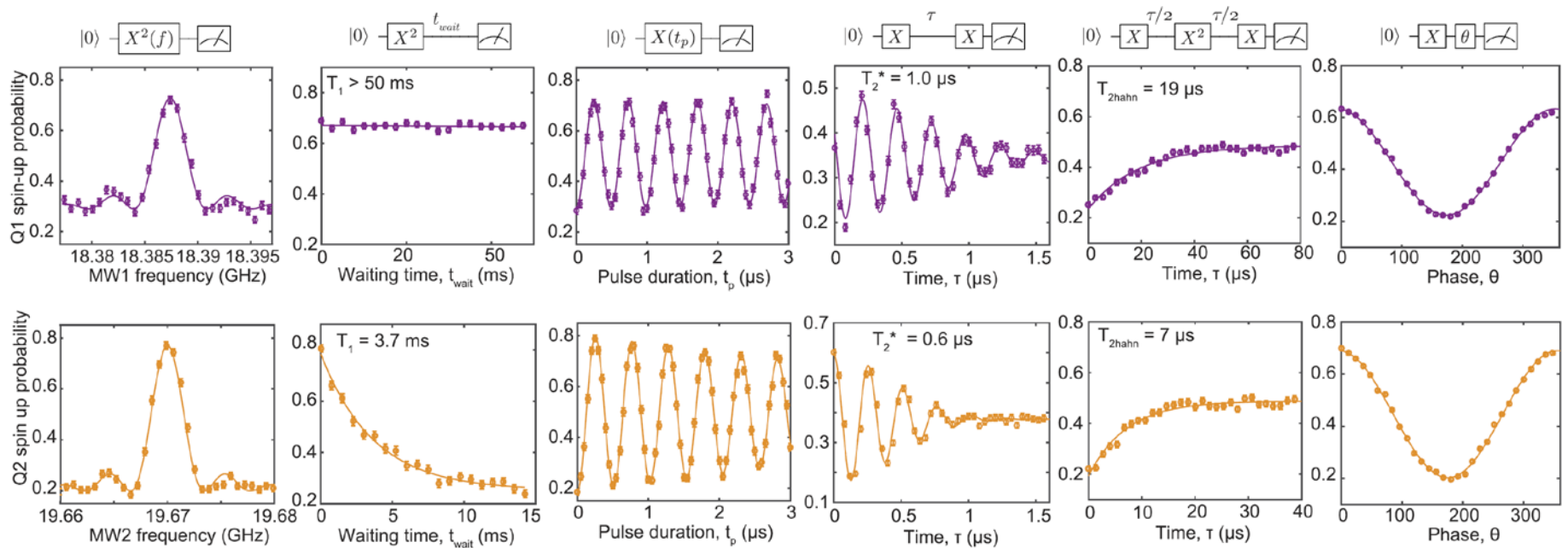


CNOTゲート



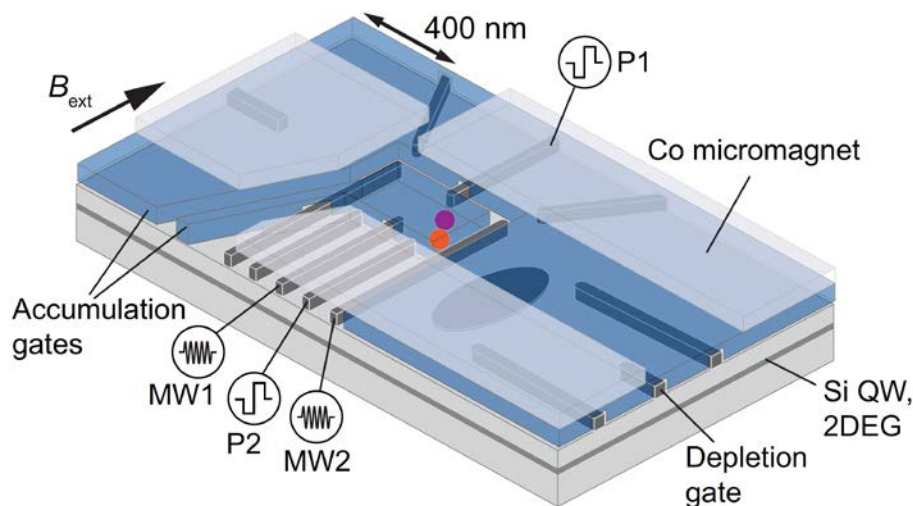
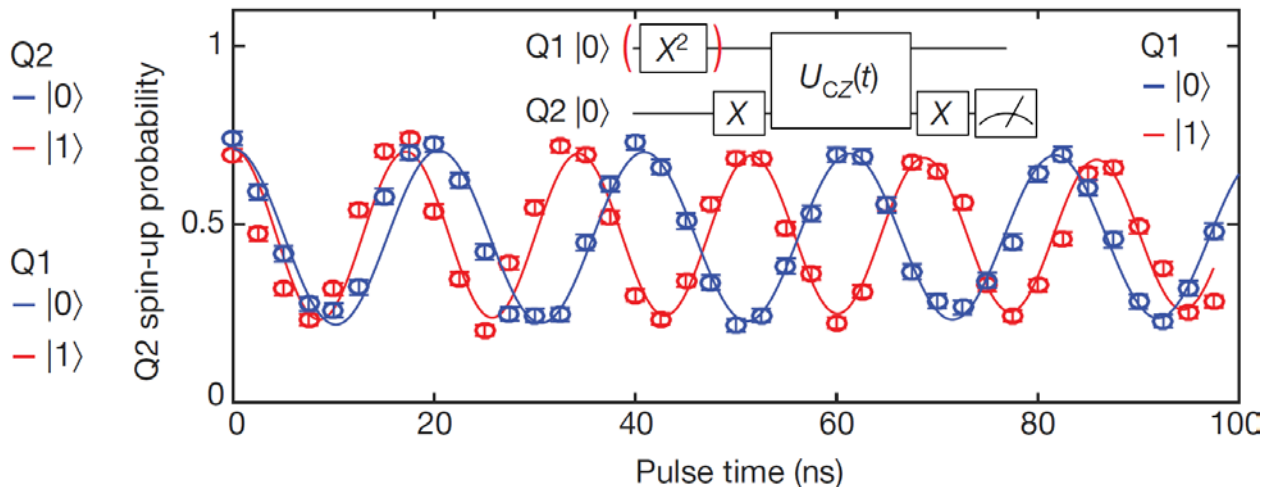
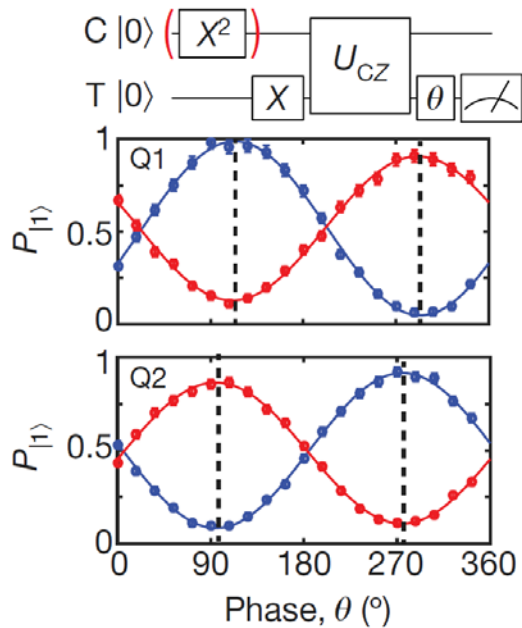
$$F^{Bell} = 78\%$$

2量子ビットプロセッサ

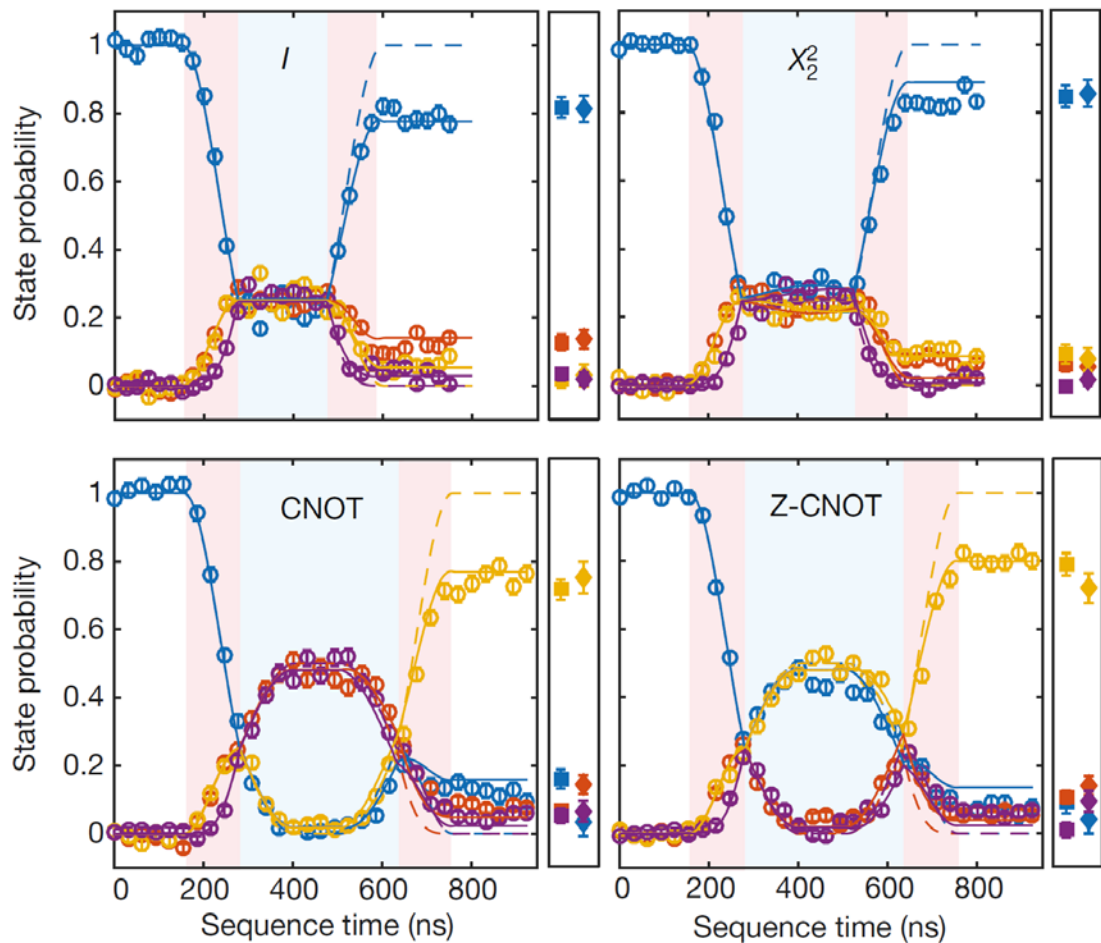


Nature **555**, 633 (2018) Watson *et al.*

2量子ビットプロセッサ

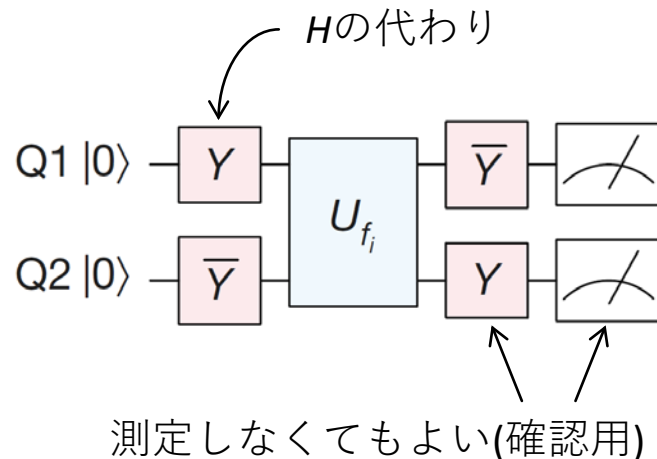


ドイチュ・ジョザアルゴリズムの実行



○ Experiment - - - Ideal ——— With noise

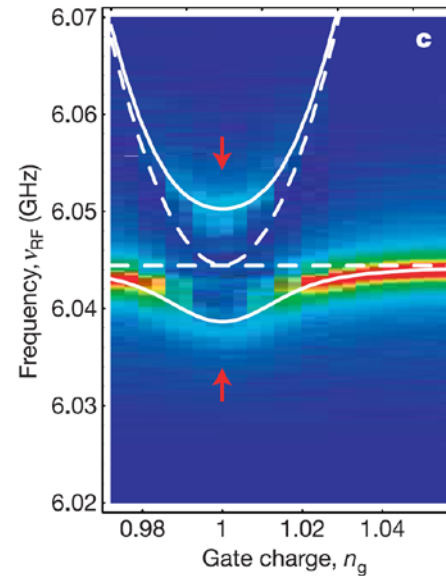
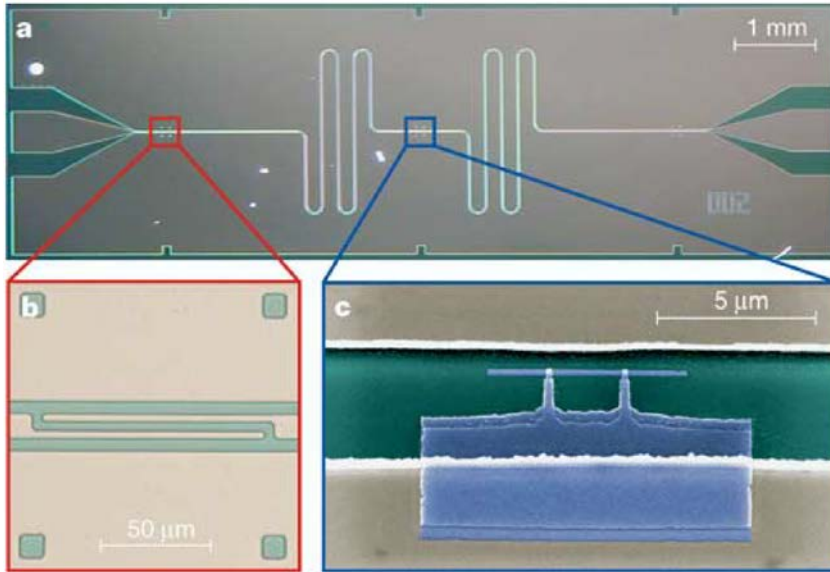
● |00> ● |01> ● |10> ● |11>



講演内容

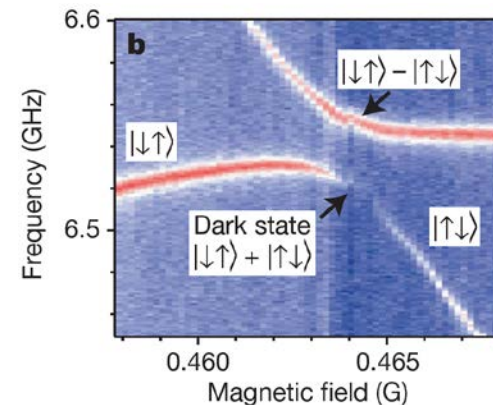
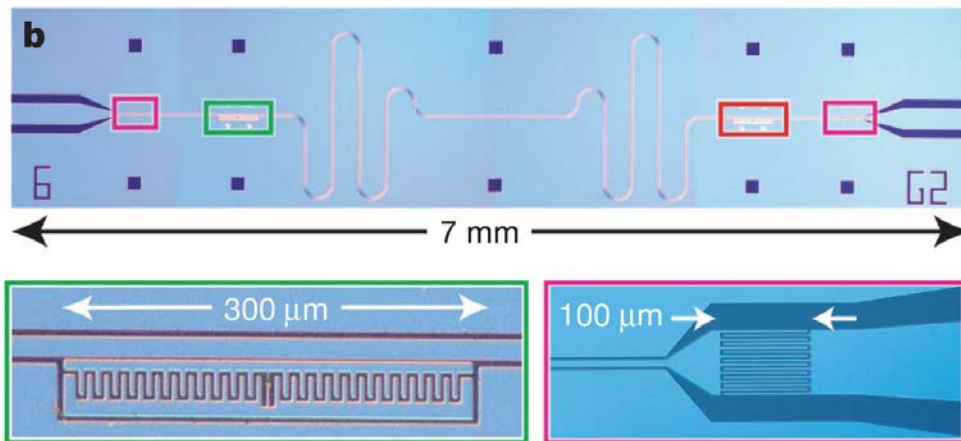
- **磁気共鳴と量子コヒーレンス**
 - － アンサンブルリンドナー
- **シリコンスピン量子コンピュータ**
 - － 単一リンドナー
 - － MOS量子ドット
 - － Si/SiGe量子ドット
- **多量子ビット化への道**
 - － スピン-マイクロ波光子結合
 - － アーキテクチャ

量子ビット間の結合: 回路QED



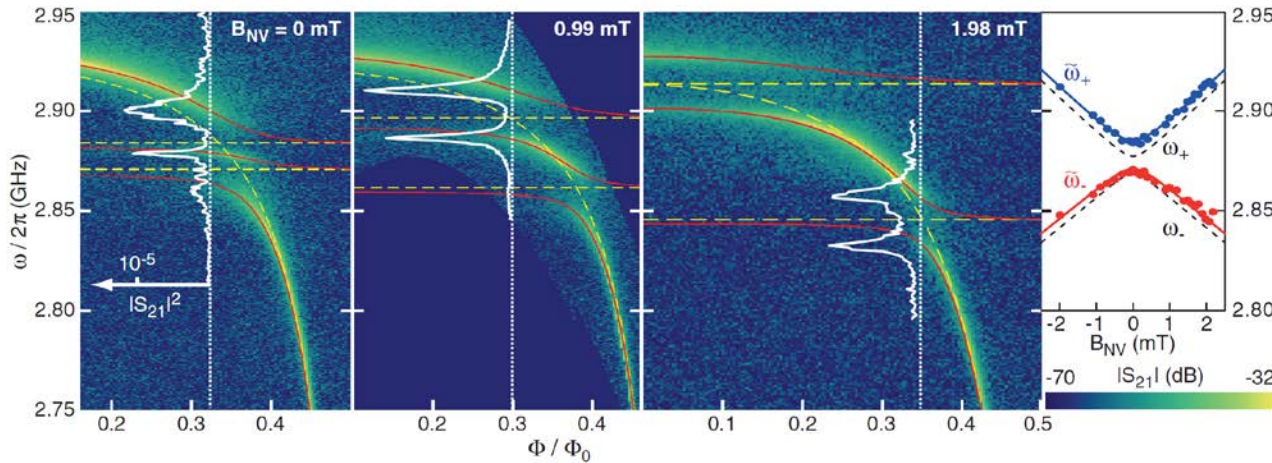
超伝導: 電荷(g_c)

Nature **431**, 162 (2004) Wallraff *et al.*



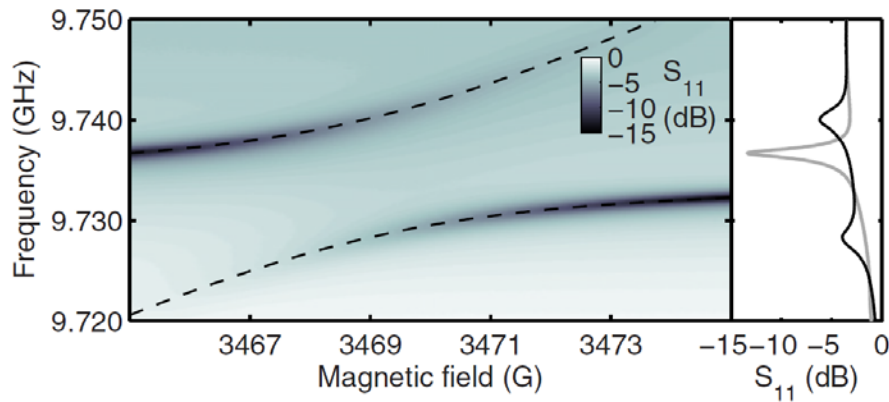
Nature **449**, 443 (2007) Majer *et al.*

スピン系の共振器QED

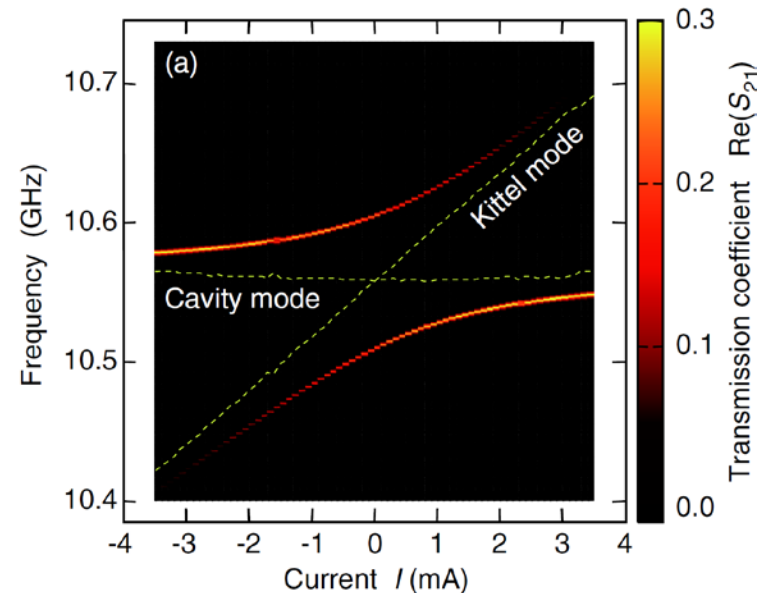


$$g_{s,ens} \propto g_s \sqrt{N}$$

(2D + NV centers) Phys. Rev. Lett. **105**, 140502 (2010) Kubo *et al.*



(3D + radical) Appl. Phys. Lett. **98**, 251108 (2011) Abe *et al.*

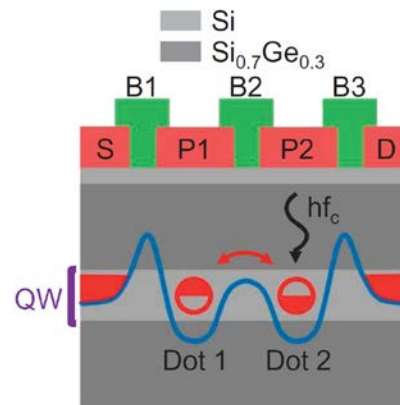
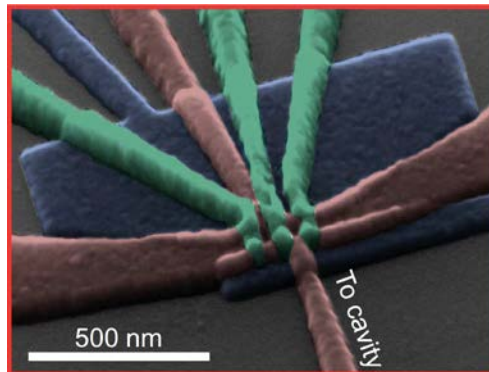
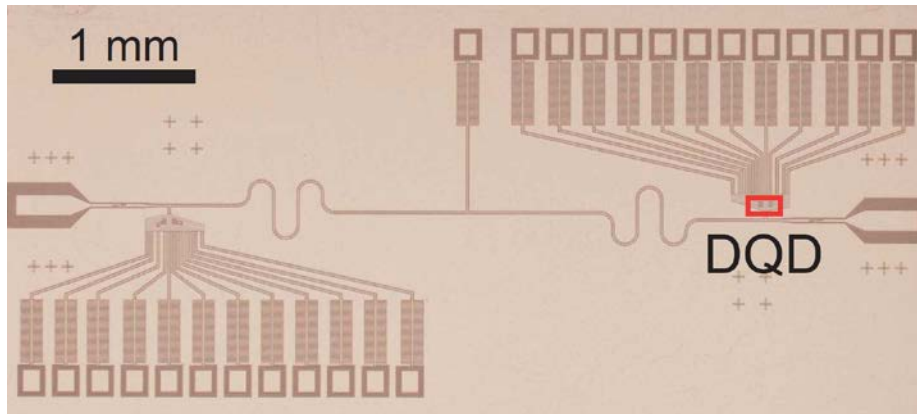


(3D + magnon) Phys. Rev. Lett. **113**, 083603 (2014) Tabuchi *et al.*

Strong coupling of a single electron in silicon to a microwave photon

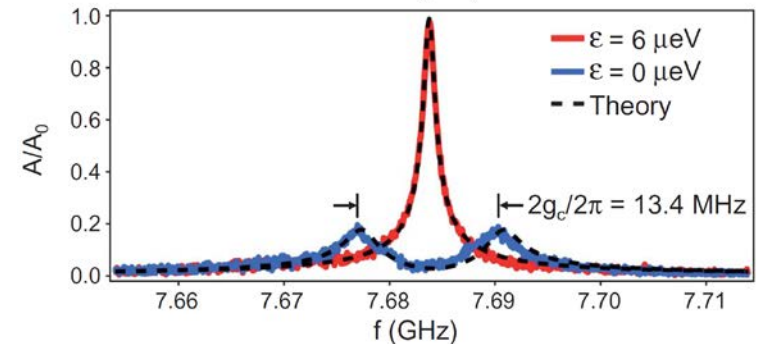
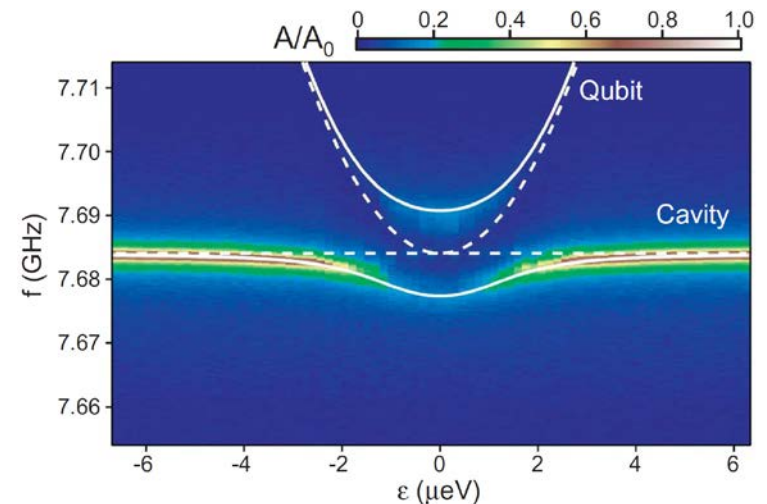
X. Mi,¹ J. V. Cady,^{1*} D. M. Zajac,¹ P. W. Deelman,² J. R. Petta^{1†}

電荷



$$2t_c/h = f_c = 7.68 \text{ GHz}$$

$$(g_c, \kappa, \gamma_c)/2\pi = (6.7, 1.0, 2.6) \text{ MHz}$$



A coherent spin–photon interface in silicon

X. Mi¹, M. Benito², S. Putz¹, D. M. Zajac¹, J. M. Taylor³, Guido Burkard² & J. R. Petta¹

$$g_s \propto g_c \propto \sqrt{Z_c}$$

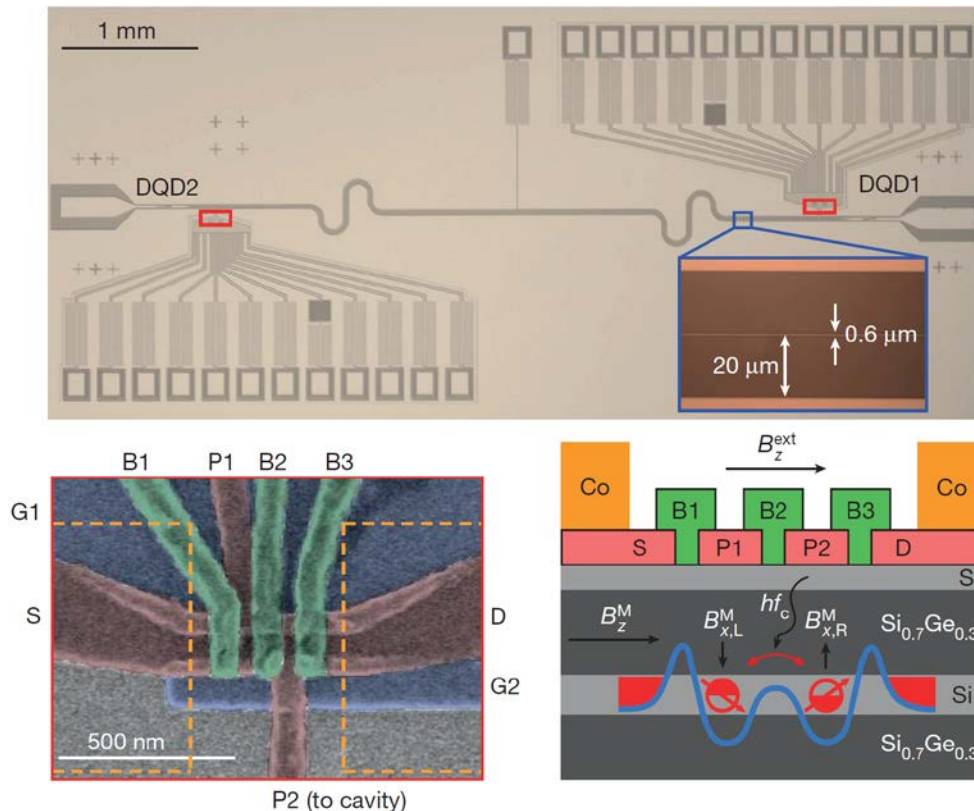
スピ–電荷ハイブリダイゼーション

Science **349**, 408 (2015) Viennot *et al.*

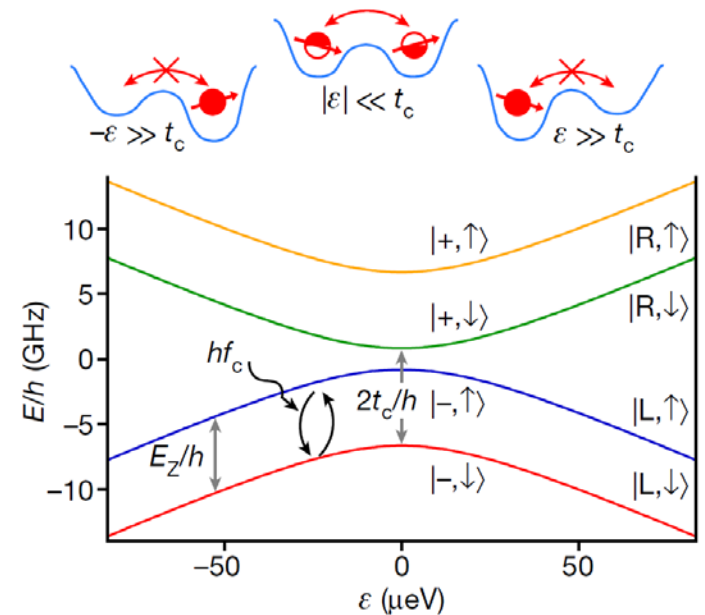
高インピーダンス回路

Phys. Rev. X **7**, 011030 (2017) Stockklauser *et al.*

Ann. Phys. **16**, 767 (2007) Devoret *et al.*



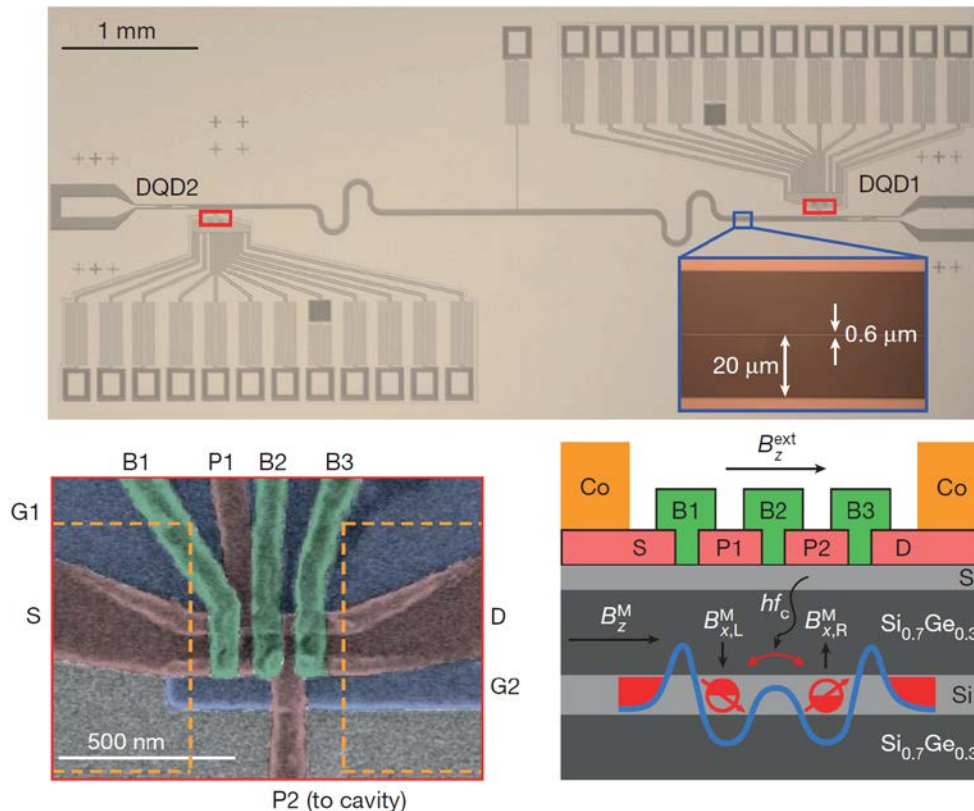
$$g_c/2\pi = 40 \text{ MHz} @ B_z^{\text{ext}} = 0 \text{ mT}$$



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

A coherent spin–photon interface in silicon

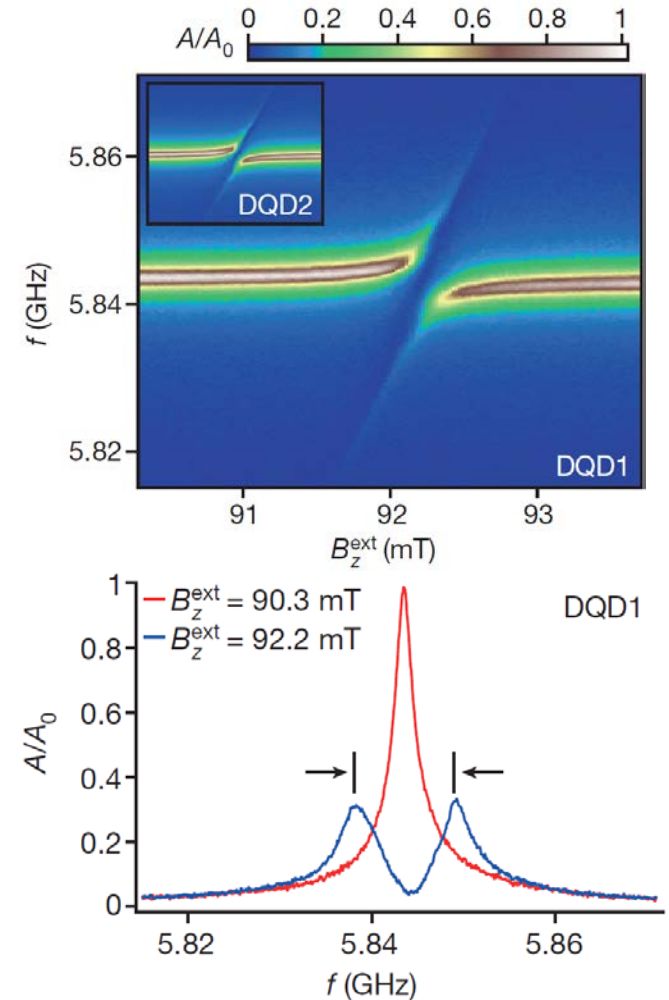
X. Mi¹, M. Benito², S. Putz¹, D. M. Zajac¹, J. M. Taylor³, Guido Burkard² & J. R. Petta¹



$$g_c/2\pi = 40 \text{ MHz} @ B_z^{\text{ext}} = 0 \text{ mT}$$

$$2t_c/h = 7.4 \text{ GHz}$$

$$(g_s, \kappa, \gamma_s)/2\pi = (5.5, 1.8, 2.4) \text{ MHz}$$

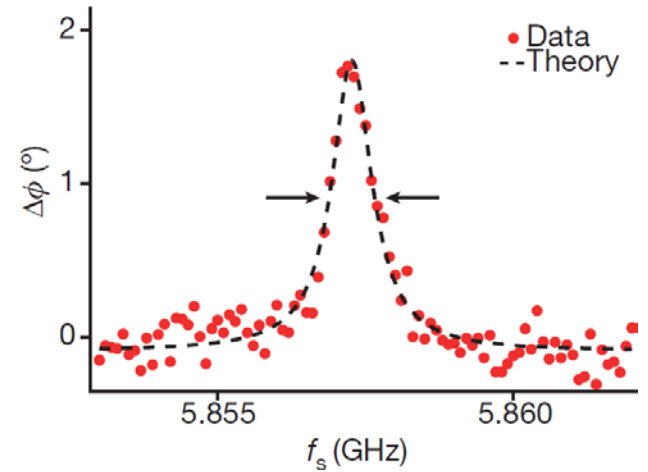
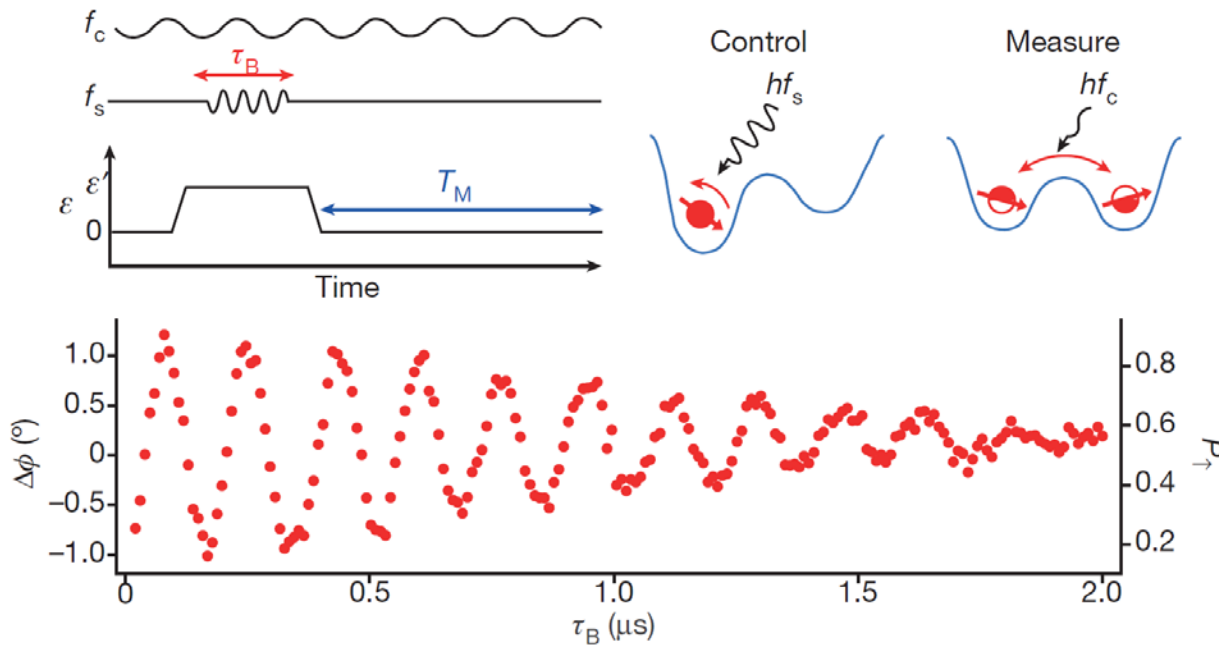


Nature **555**, 599 (2018) Mi *et al.*

A coherent spin–photon interface in silicon

X. Mi¹, M. Benito², S. Putz¹, D. M. Zajac¹, J. M. Taylor³, Guido Burkard² & J. R. Petta¹

分散シフトによる単一スピンの読み出し

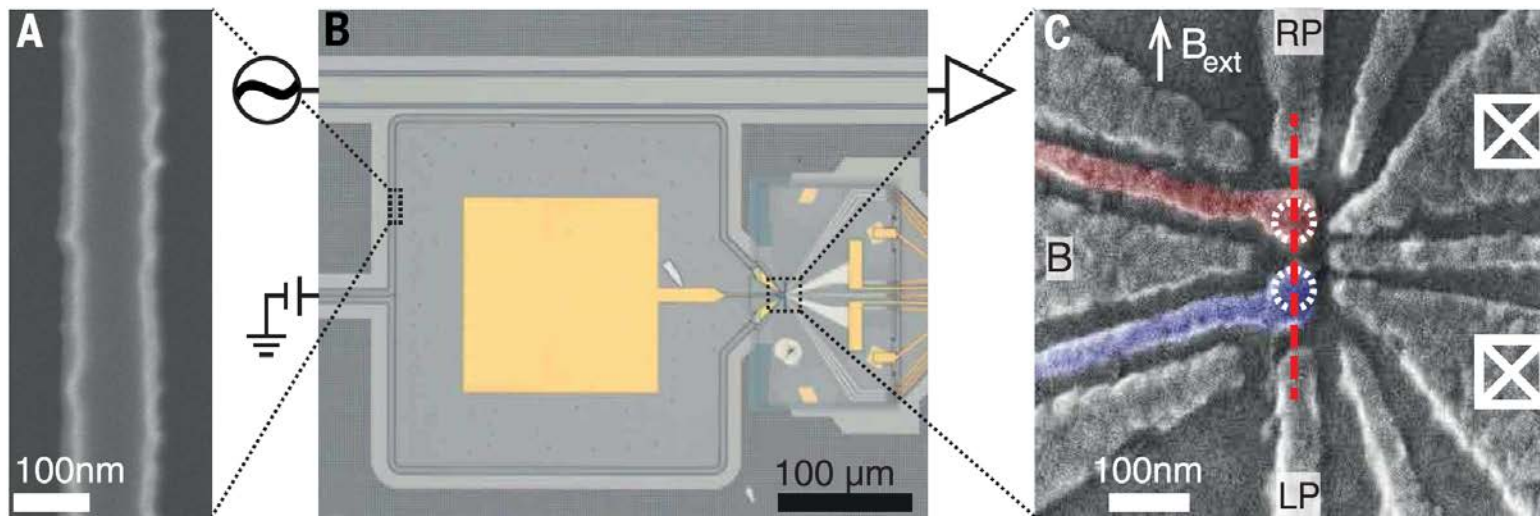
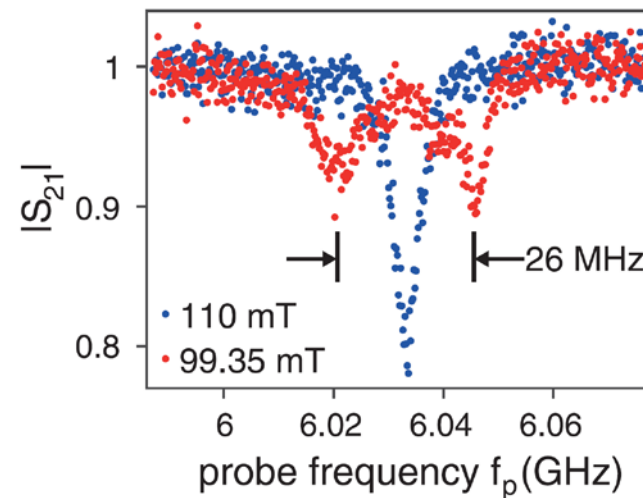


分散領域: $|\Delta| \gg g_s$
 $(\Delta, g_s)/2\pi = (14, 1.4)$ MHz
 $2t_c/h = 11.1$ GHz, $\varepsilon = 0$ μeV

$2t_c/h = 11.1$ GHz
 $\varepsilon' = 70$ μeV

Strong spin-photon coupling in silicon

N. Samkharadze,^{1*} G. Zheng,^{1*} N. Kalhor,¹ D. Brousse,² A. Sammak,² U. C. Mendes,³
A. Blais,^{3,4} G. Scappucci,¹ L. M. K. Vandersypen^{1†}



アーキテクチャ

- **インターフェイス**

- npj Quant. Info. **1**, 15011 (2015) Reilly: **“Engineering the quantum-classical interface of solid-state qubits”**
- npj Quant. Info. **3**, 34 (2017) Vandersypen *et al.*: **“Interfacing spin qubits in quantum dots and donors—hot, dense, and coherent”**

- **単一リンドナー**

- Nature Commun. **8**, 450 (2017) Tosi *et al.*: **“Silicon quantum processor with robust long-distance qubit couplings”**

- **MOS量子ドット**

- Nature Commun. **8**, 1766 (2017) Veldhorst *et al.*: **“Silicon CMOS architecture for a spin-based quantum computer”**
- arXiv:1711.03807 Li *et al.*: **“A crossbar network for silicon quantum dot qubits”**

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arXiv:1803.01774 Petit *et al.*

- **単一リンドナー**

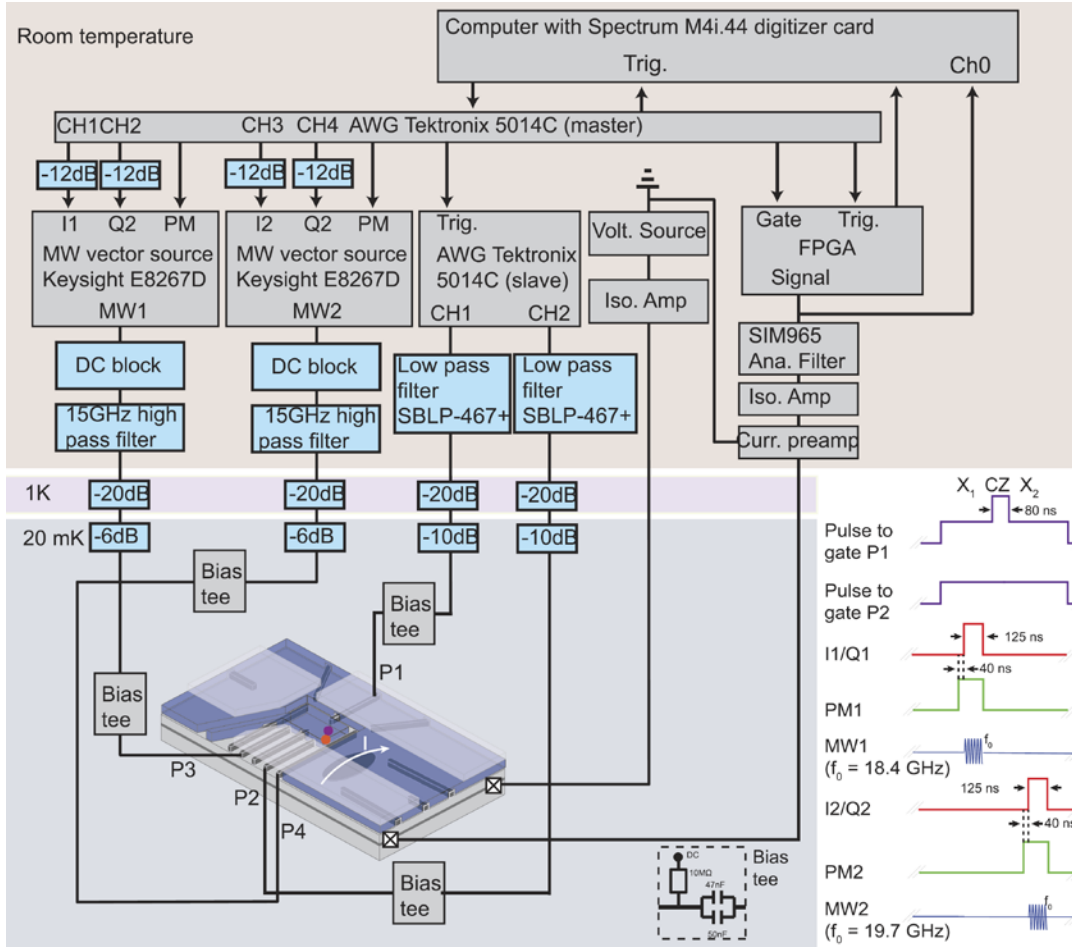
- Nature Commun. **8**, 450 (2017) Tosi *et al.*: **“Silicon quantum processor with robust long-distance qubit couplings”**

arXiv:1804.03364 Ono *et al.*

- **MOS量子ドット**

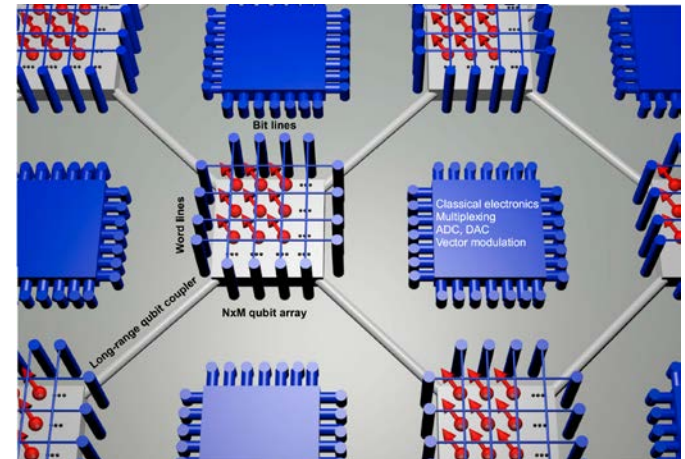
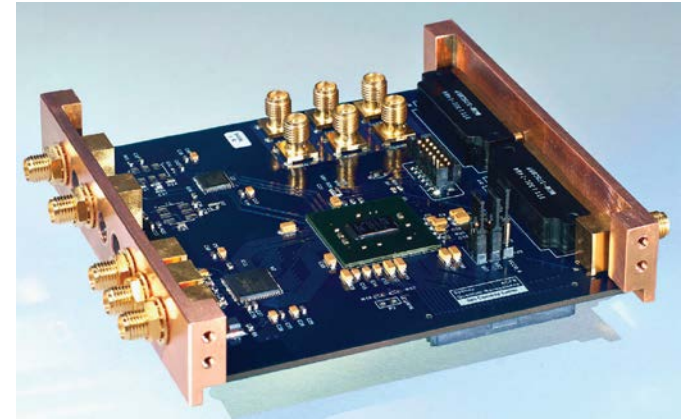
- Nature Commun. **8**, 1766 (2017) Veldhorst *et al.*: **“Silicon CMOS architecture for a spin-based quantum computer”**
- arXiv:1711.03807 Li *et al.*: **“A crossbar network for silicon quantum dot qubits”**

インターフェイス



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

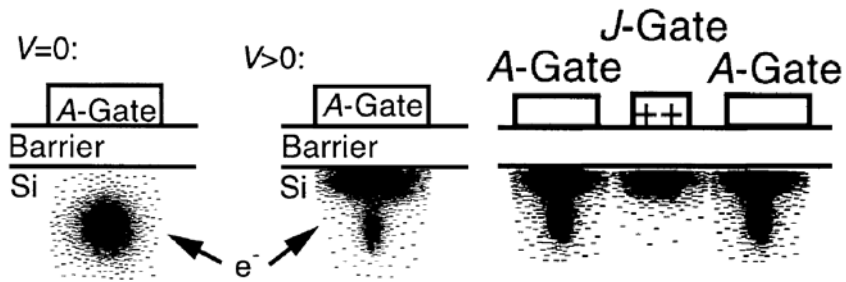
+ RF-SET, JPA, on-chip elements... \leftrightarrow Op. Temp.



npj Quant. Info. **1**, 15011 (2015) Reilly

npj Quant. Info. **3**, 34 (2017) Vandersypen *et al.*

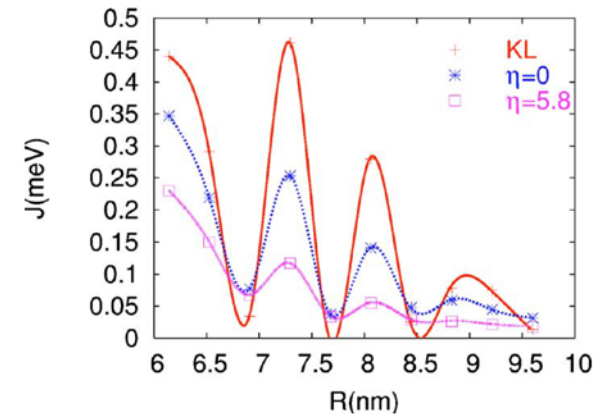
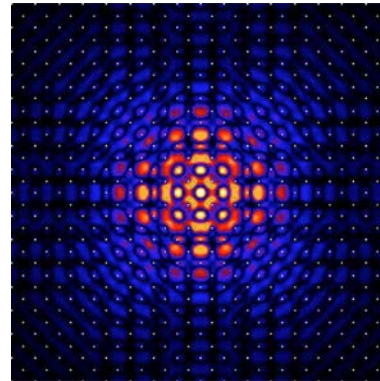
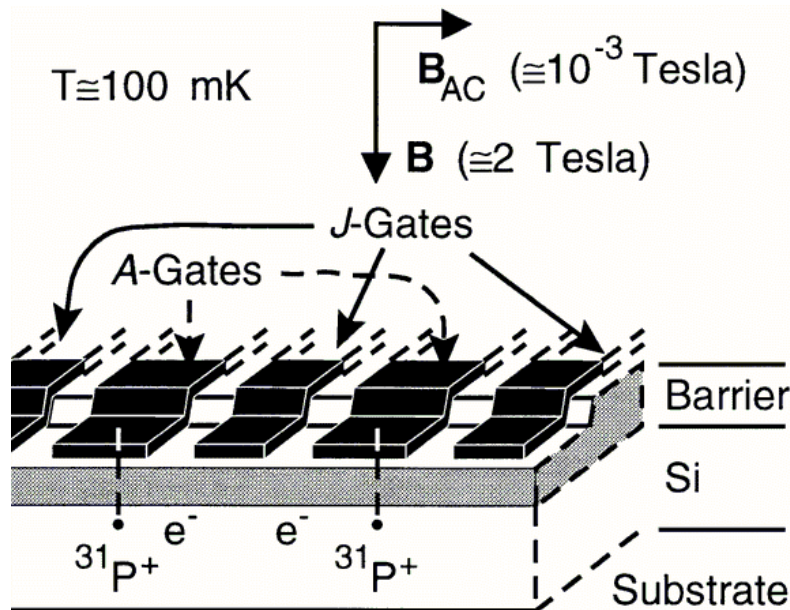
単一リンドナー



- 超微細相互作用(a_0)の電場制御は可能

Sci. Adv. **1**, e1500022 (2015) Laucht *et al.*

- 交換相互作用の精密制御は**絶望的**



Phys. Rev. B **72**, 085202 (2005) Wellard *et al.*

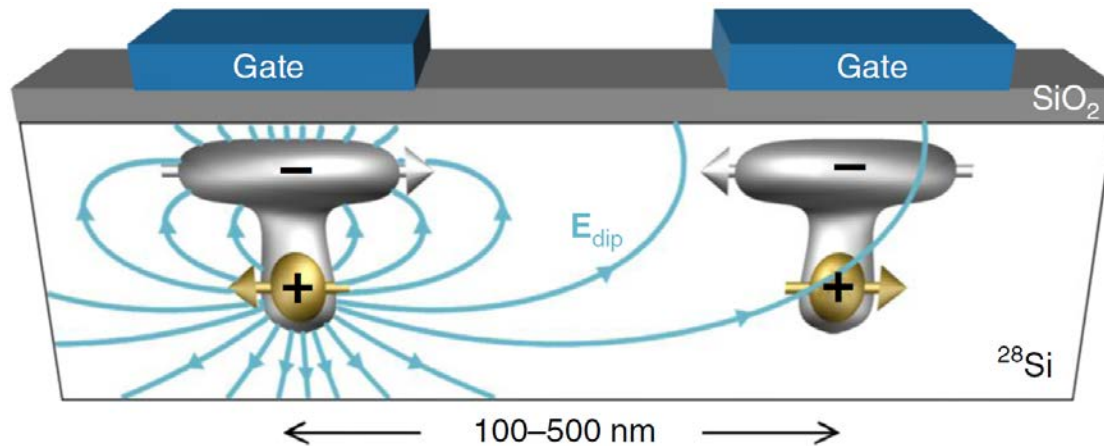
Phys. Rev. B **68**, 195209 (2003) Wellard *et al.*

Phys. Rev. Lett. **88**, 027903 (2002) Koiller *et al.*

Nature **393**, 133 (1998) Kane

Silicon quantum processor with robust long-distance qubit couplings

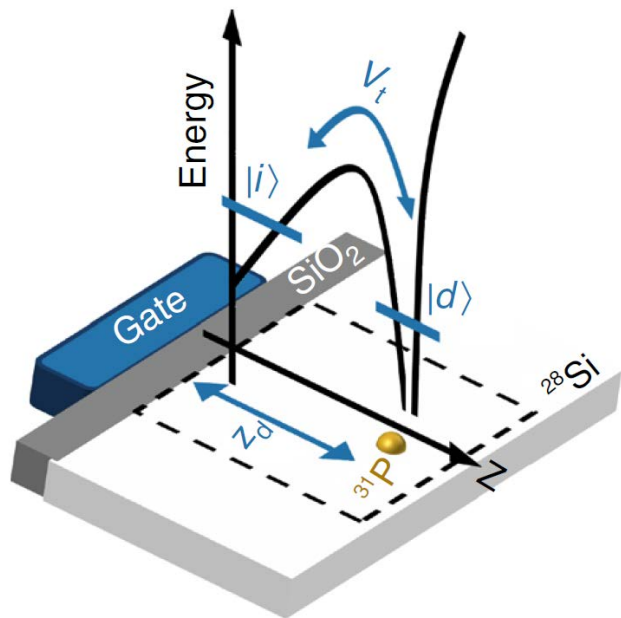
Guilherme Tosi¹, Fahd A. Mohiyaddin^{1,3}, Vivien Schmitt¹, Stefanie Tenberg¹, Rajib Rahman², Gerhard Klimeck² & Andrea Morello¹



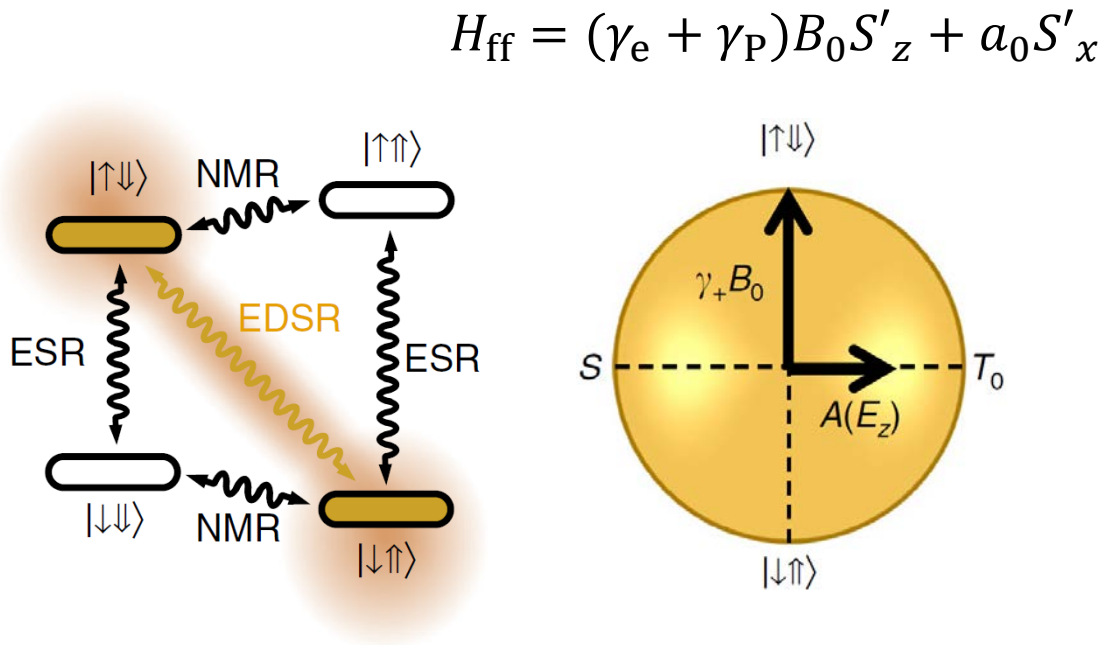
- 長距離結合に**電気双極子相互作用**を利用
- スピン-電荷ハイブリッドだが,**時計遷移**条件で高コヒーレンス保持
- ドナー位置の**ばらつきを補償**可能

Silicon quantum processor with robust long-distance qubit couplings

Guilherme Tosi¹, Fahd A. Mohiyaddin^{1,3}, Vivien Schmitt¹, Stefanie Tenberg¹, Rajib Rahman², Gerhard Klimeck² & Andrea Morello¹



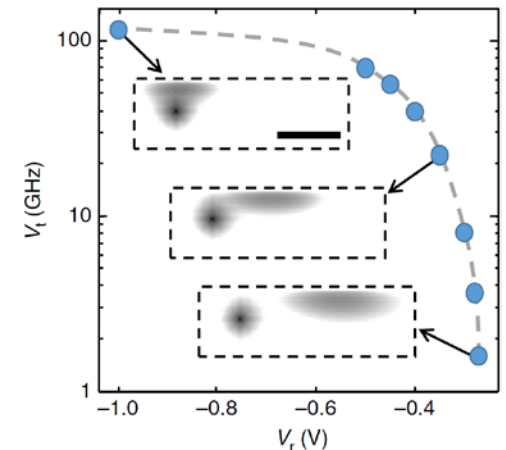
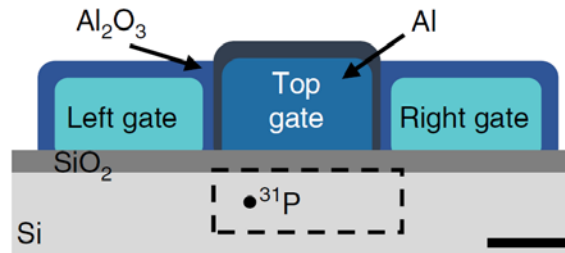
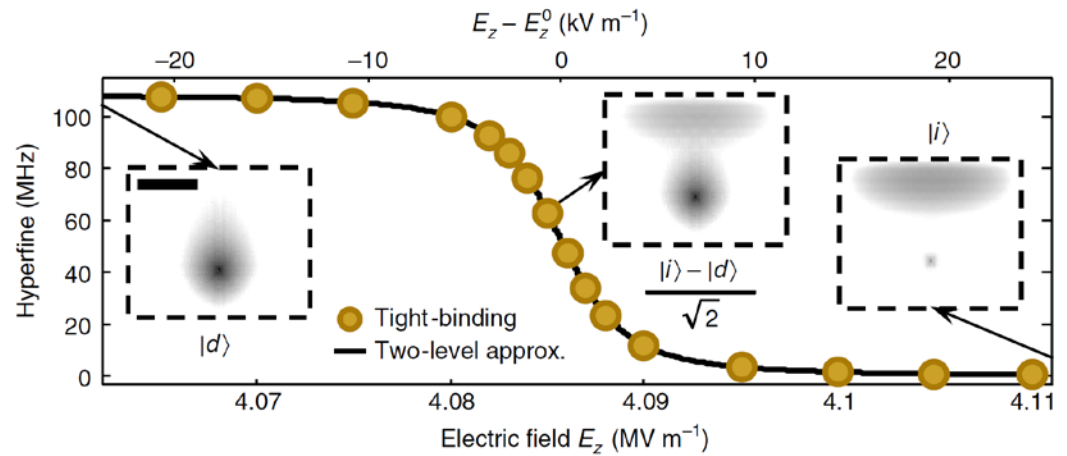
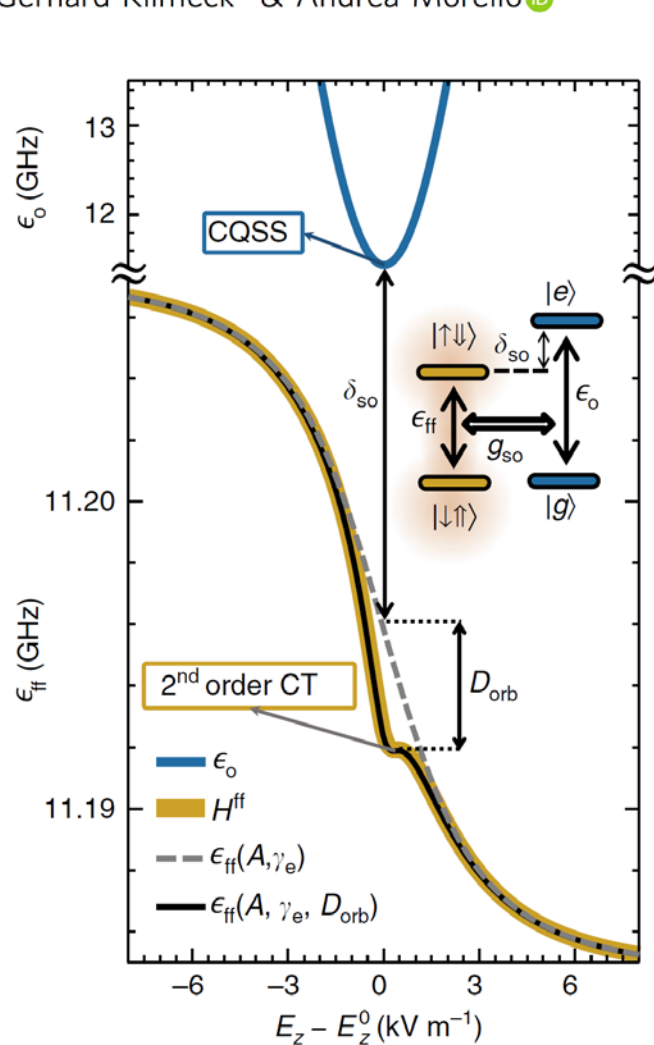
界面-ドナー電荷量子ビット





“フリップフロップ”量子ビット

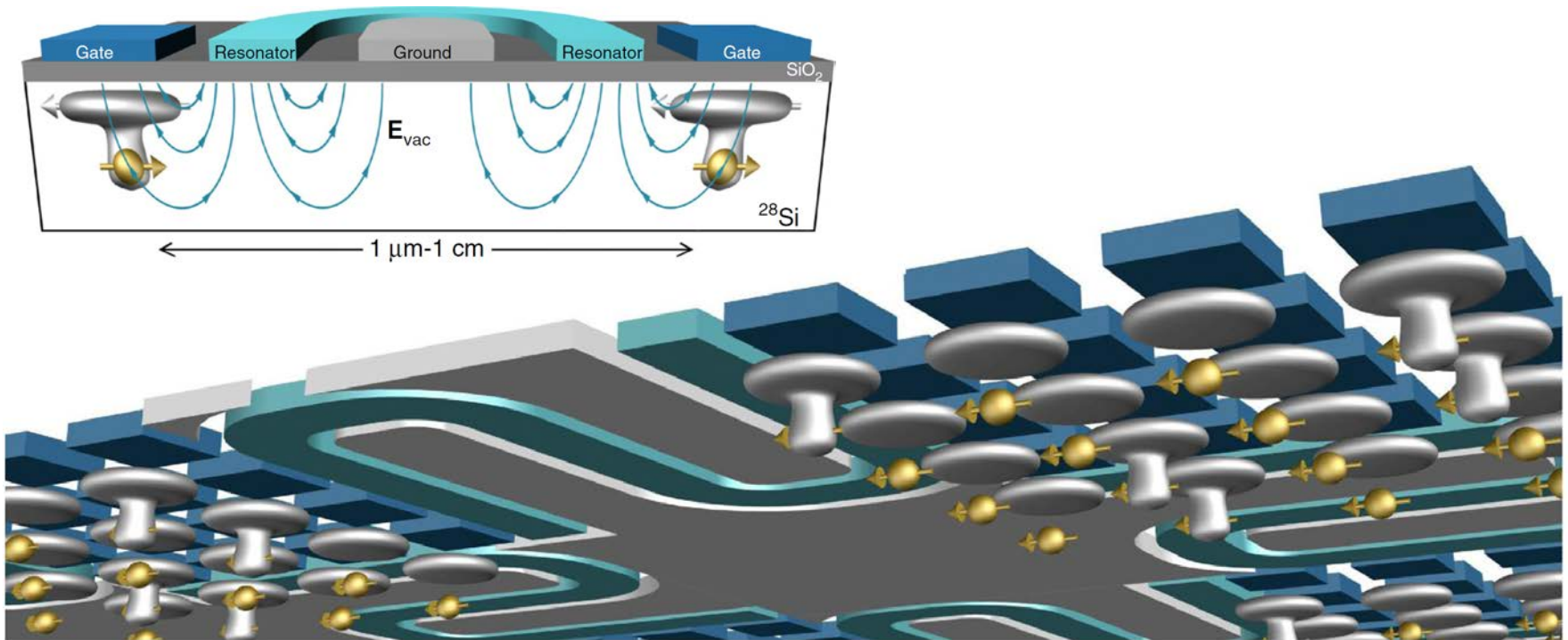
Silicon quantum processor with robust long-distance qubit couplings

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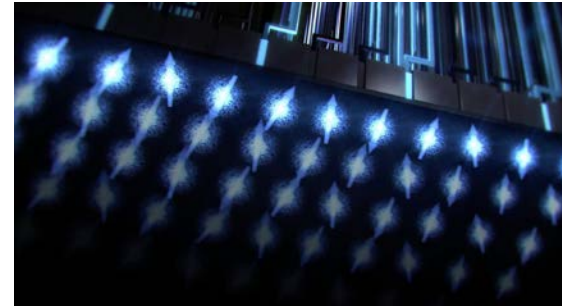
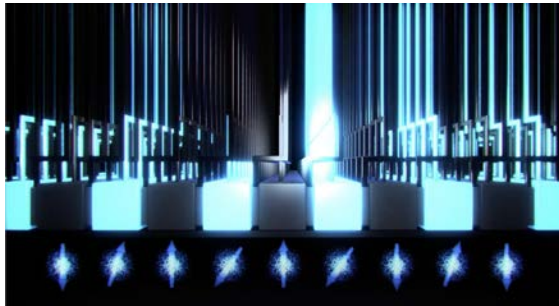
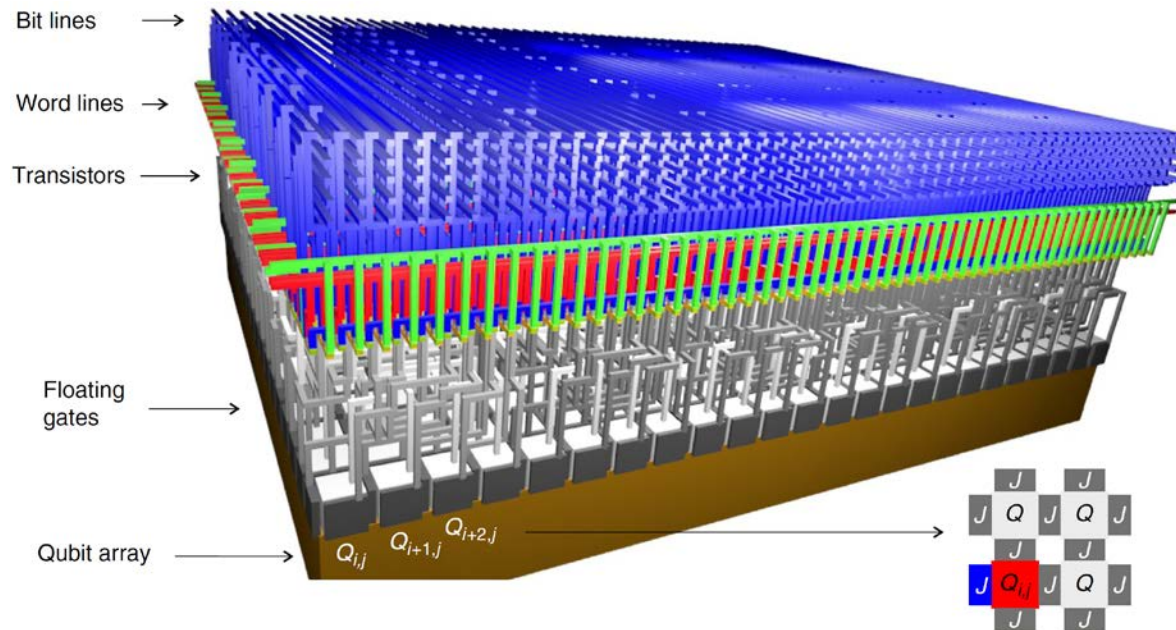


| z-gates | | x(y)-gates | | | 2-qubit \sqrt{i} SWAP gates | | | Photonic link |
|------------|-----------|----------------|-------|-----------|-------------------------------|------------------------------|-----------------------|---------------------------|
| τ_π | Error | $\tau_{\pi/2}$ | Power | Error | Distance | $\tau_{\sqrt{i}\text{SWAP}}$ | Error | Coupling |
| 70 ns | 10^{-4} | 30 ns | <1 pW | 10^{-3} | 100–500 nm | 40 ns | 10^{-2} – 10^{-3} | $g_E^{\text{ff}} = 3$ MHz |

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

Silicon CMOS architecture for a spin-based quantum computer

M. Veldhorst^{1,2}, H.G.J. Eenink^{1,2}, C.H. Yang² & A.S. Dzurak²

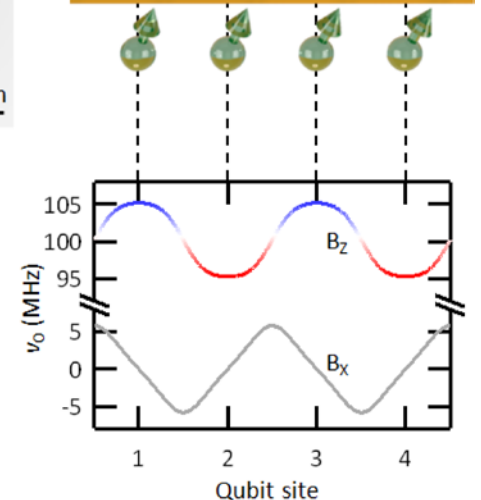
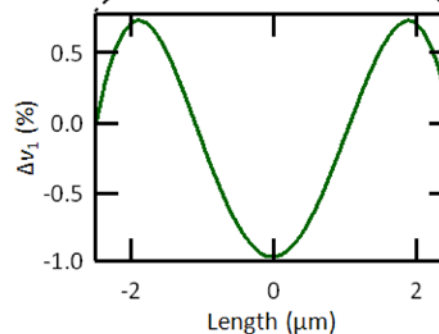
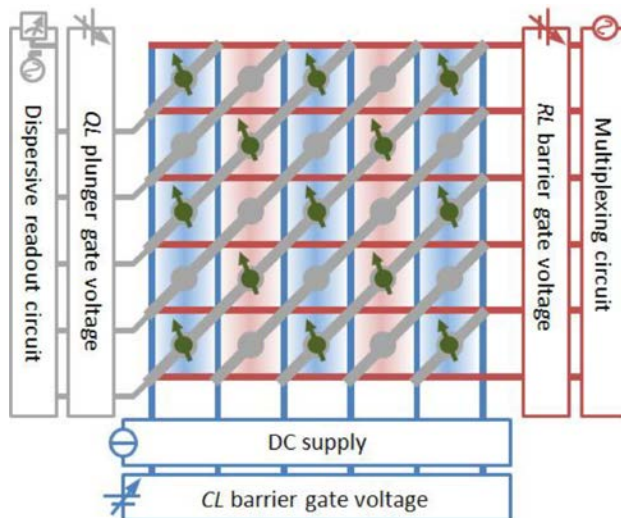
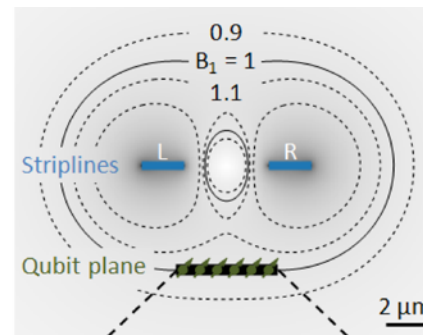
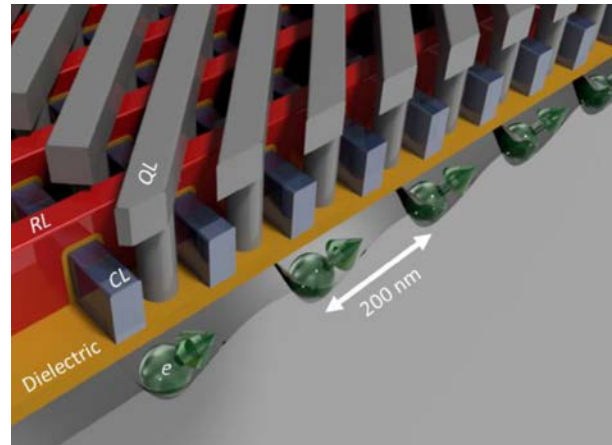


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Nature Commun. **8**, 1766 (2017) Veldhorst *et al.*

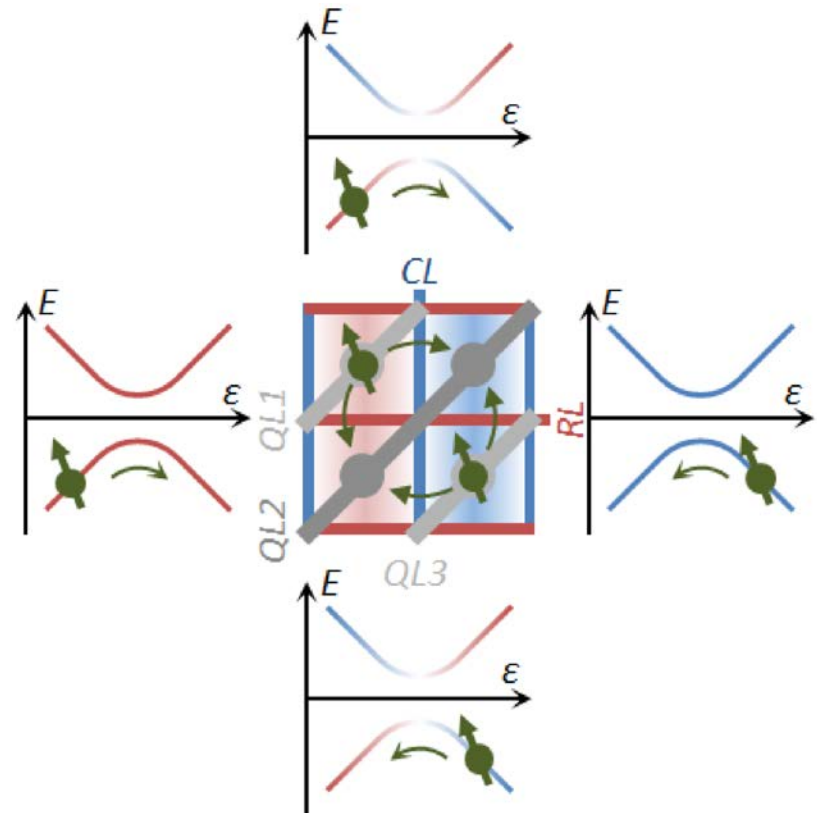
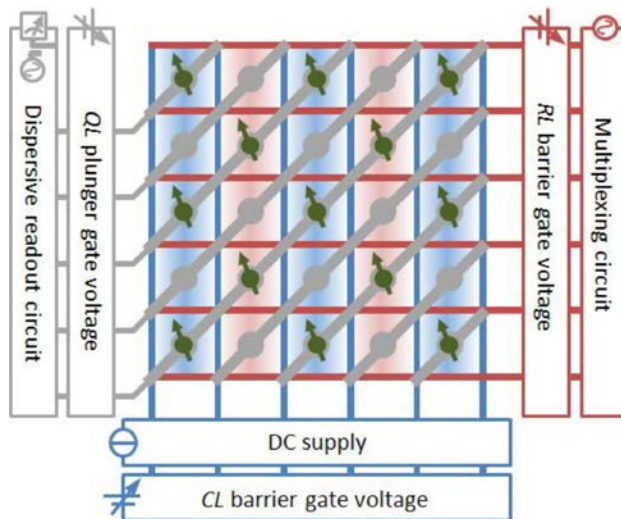
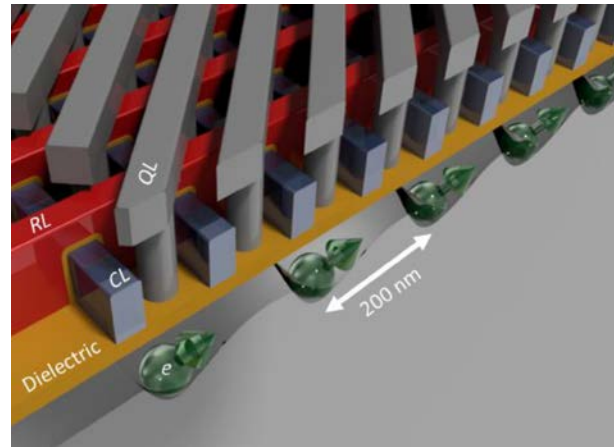
A Crossbar Network for Silicon Quantum Dot Qubits

R. Li^{1,2}, L. Petit^{1,2}, D.P. Franke^{1,2}, J.P. Dehollain^{1,2}, J. Helsen¹, M. Steudtner^{3,1}, N.K. Thomas⁴, Z.R. Yoscovits⁴, K.J. Singh⁴, S. Wehner¹, L.M.K. Vandersypen^{1,2,4}, J.S. Clarke⁴, and M. Veldhorst^{1,2*}



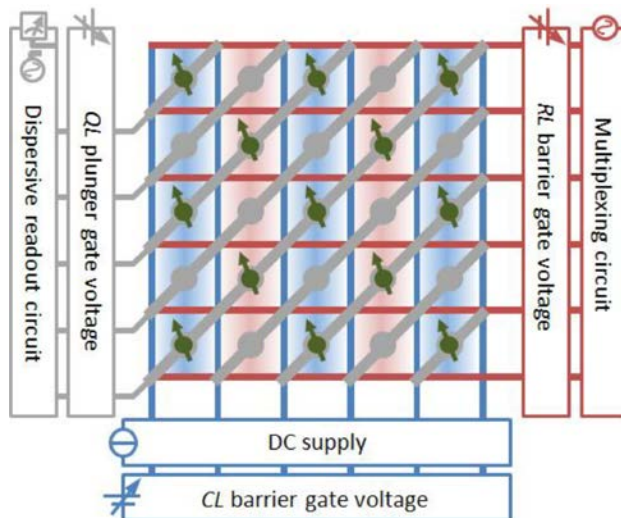
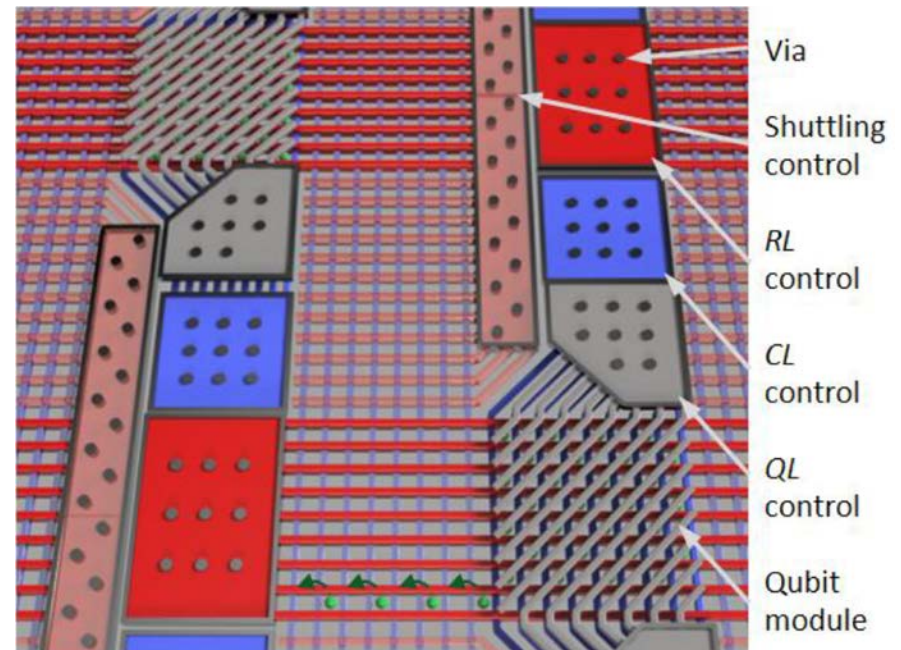
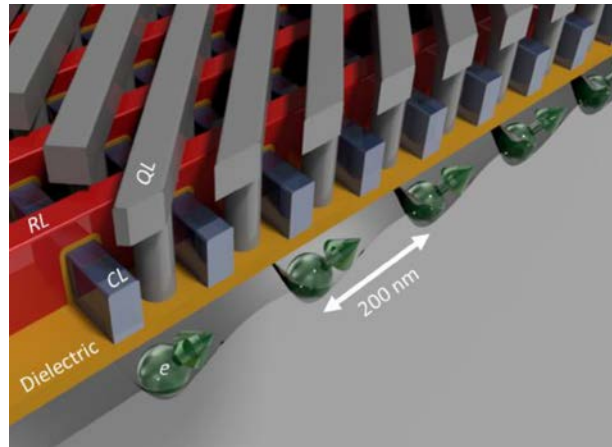
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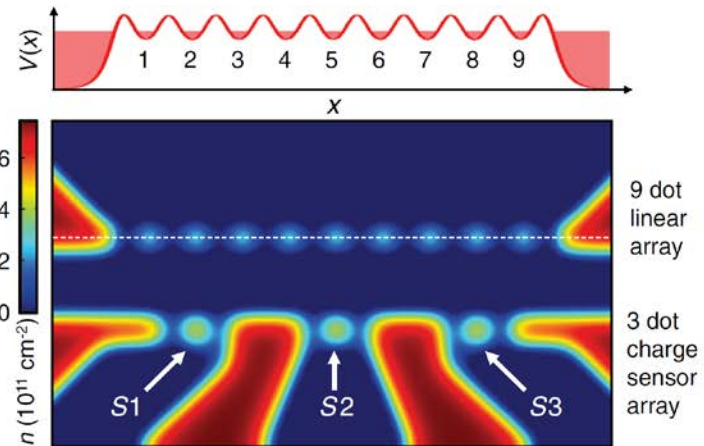
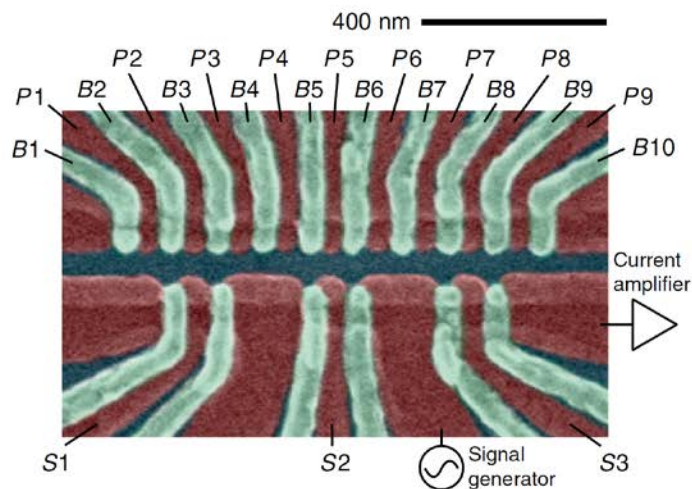
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アーキテクチャ

- アーキテクチャの提案は, 量子ビットを**2次元に配列**することがデフォルトとなっている
 - **表面符号**による量子誤り訂正が**2次元正方格子**上で実装されるため

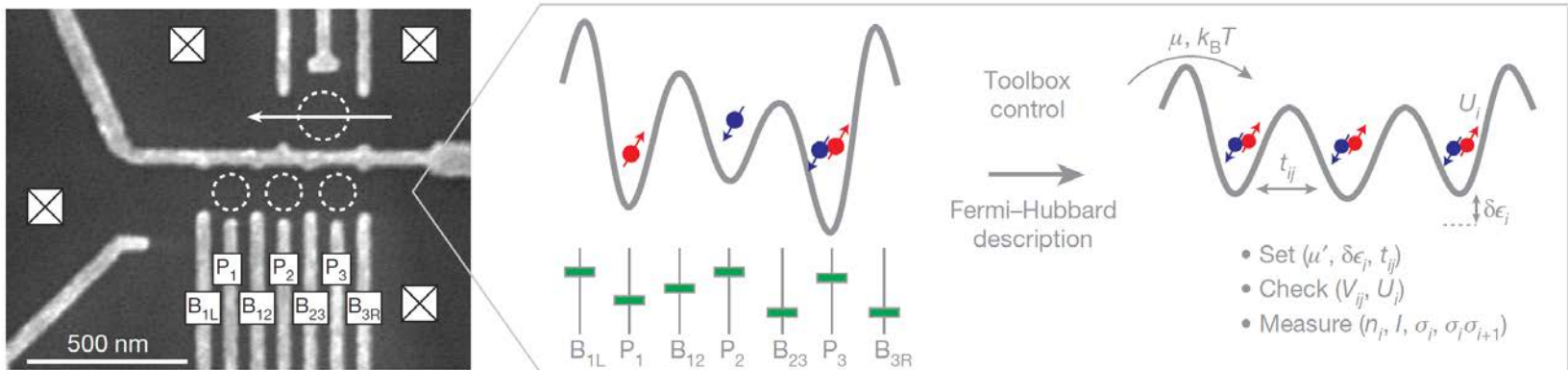
作りやすさだけなら1次元



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フェルミオン系の量子シミュレーション

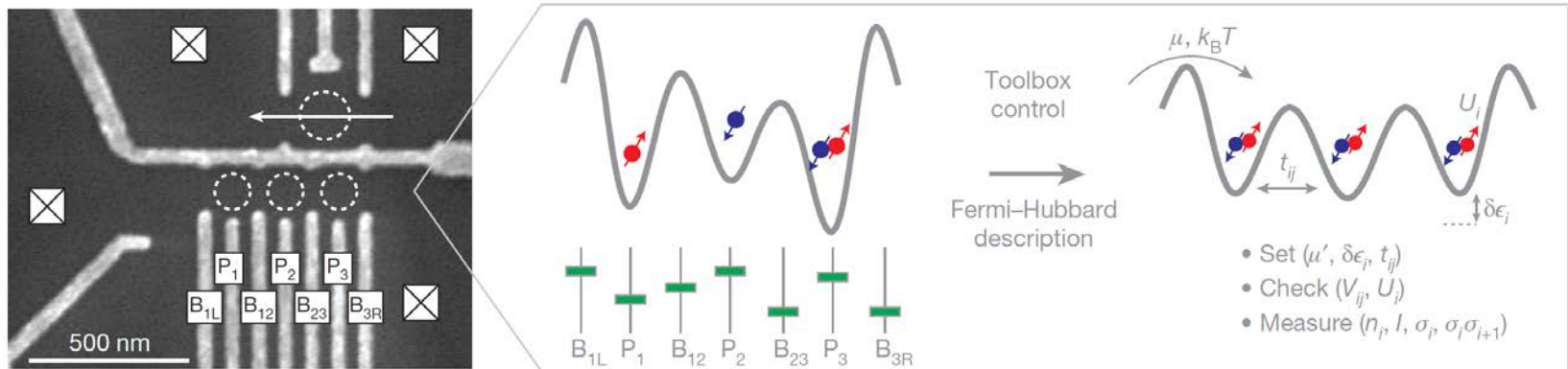


アーキテクチャ

- 現在開発中の量子コンピュータのほとんどは量子誤り訂正の実装を前提としていない
 - 量子シミュレーション, (小規模)量子化学計算 etc に適したデザインとは?
 - “シリコン系では一足飛びに万能量子コンピュータを実現する”という意欲の現れかもしれない

cf. Xmon, Gmon & Fluxmon by Google

フェルミオン系の量子シミュレーション



まとめ

| 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. $F^{\text{Bell}(e-n)} = 97\% (*2)$ | “フリップフロップ” 量子ビット |
| MOS量子ドット | $T_2^{\text{CPMG}} = 28 \text{ ms}$ $F^{\text{RB}} = 99.6\% (*3)$ | CNOT (*4) | CMOS/DRAM技術 との融合 |
| Si/SiGe量子ドット | $T_2^{\text{CPMG}} = 3.1 \text{ ms}$ $F^{\text{RB}} > 99.9\% (*5)$ | $F^{\text{Bell}} = 89\% (*6)$ | スピン-MW光子結合 (回路QED) |

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

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

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

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

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

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