

# 量子計算実験基礎

阿部英介

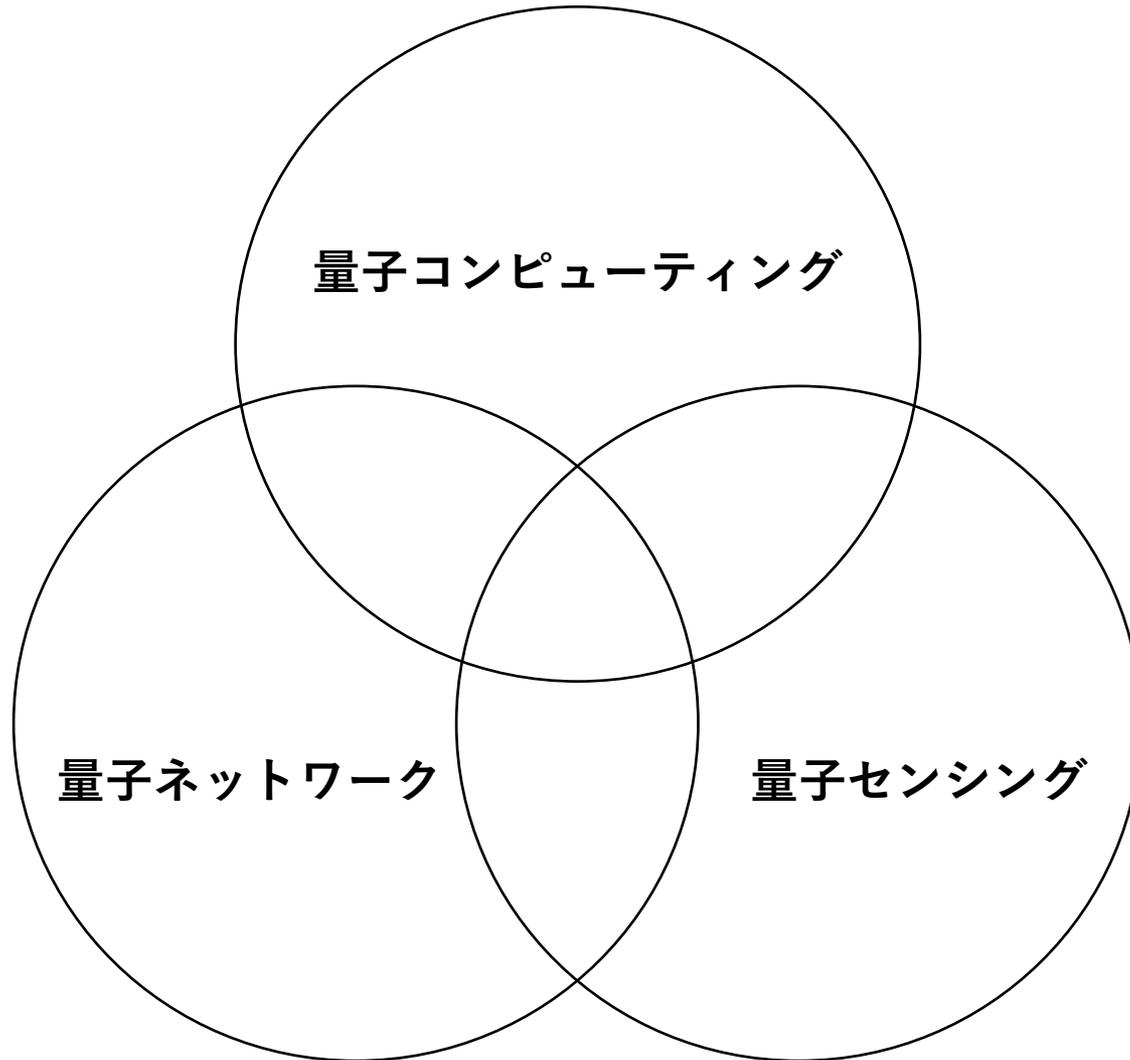
慶應義塾大学スピントロニクス研究センター

2018年7月31日@UT ISSP

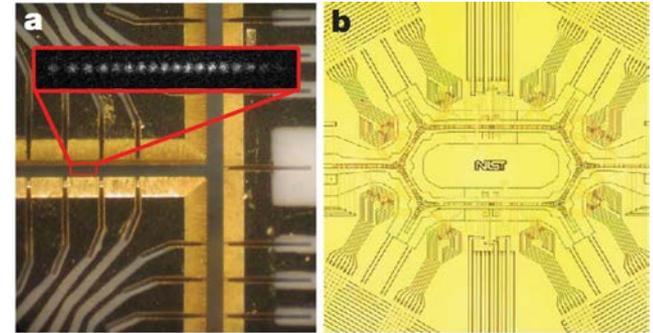
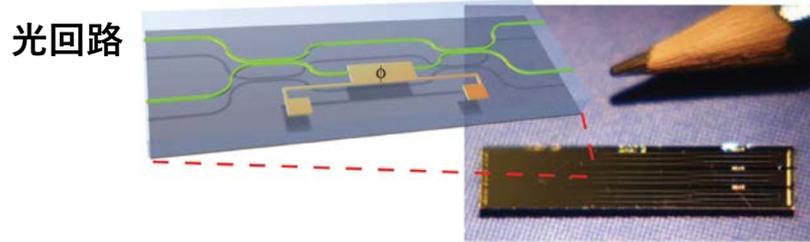
物性研究所短期研究会「量子情報・物性の新潮流」  
—量子技術が生み出す多様な物性と情報処理技術—



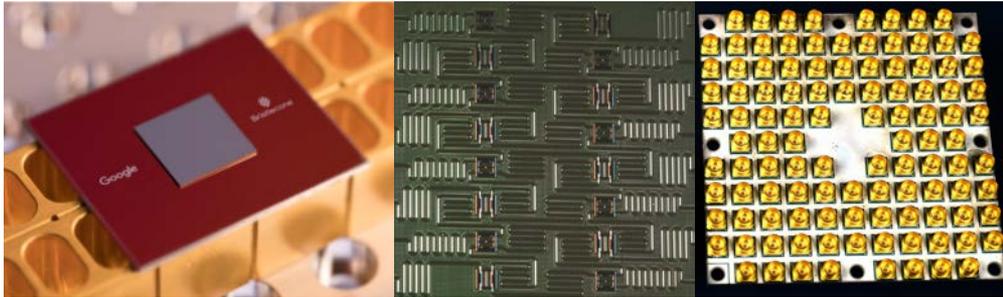
# 量子技術



# 量子技術のプラットフォーム



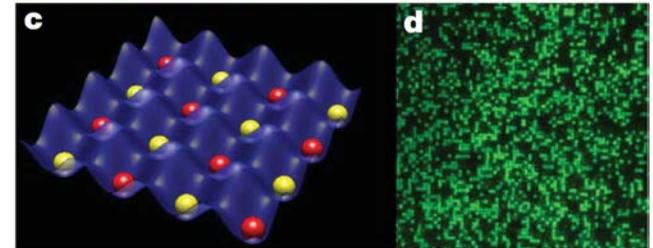
## 超伝導回路



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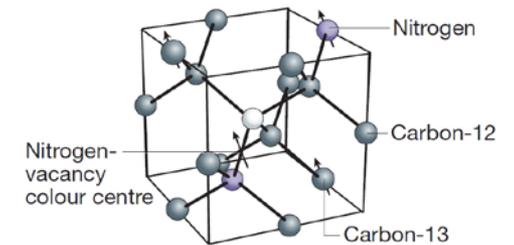
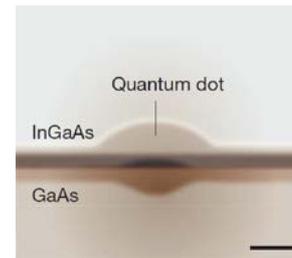
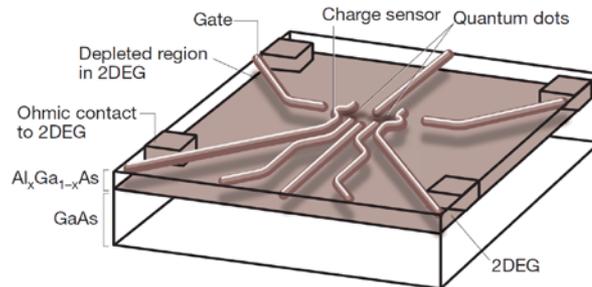
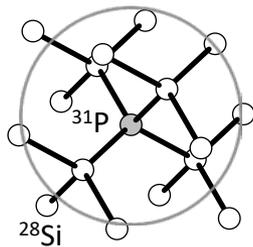
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捕捉イオン/冷却原子

## 半導体スピン

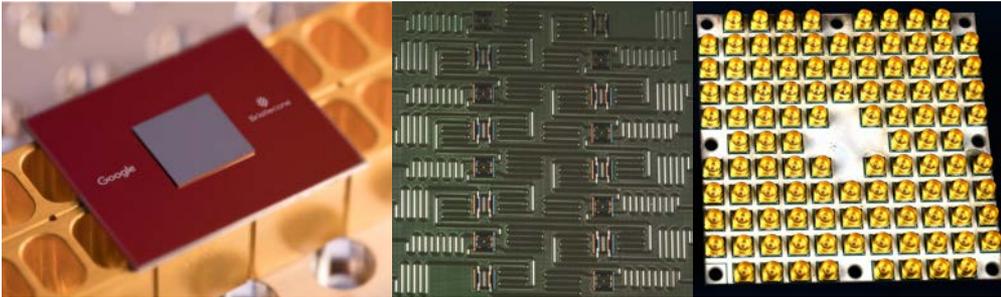


Nature **464**, 45 (2010) Ladd *et al.*

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

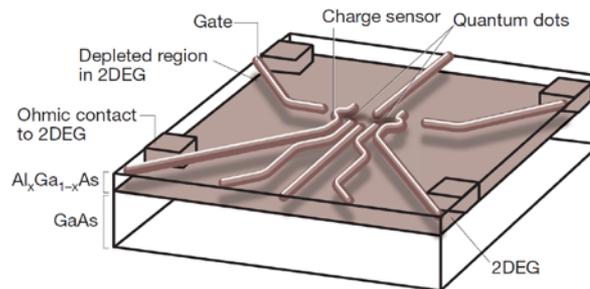
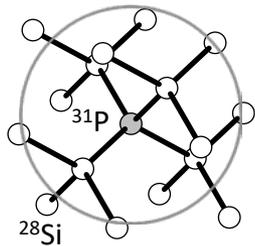


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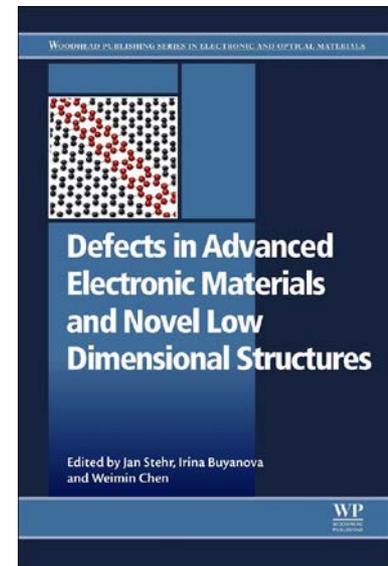
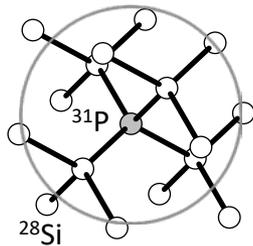
## 半導体スピン



*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)

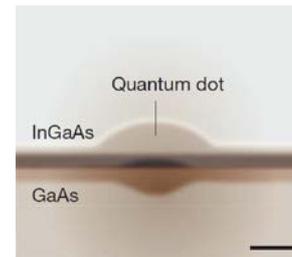
固体物理 **48 (11)**, 541 (2013) 山本 & 阿部

“光制御量子ドットスピンを用いた量子情報システムの  
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



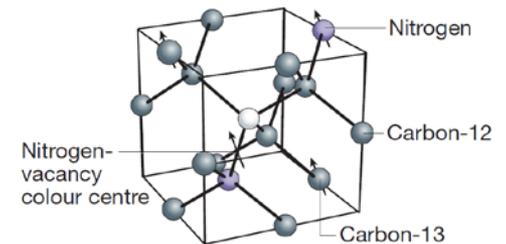
NEW DIAMOND **33 (2)**, 3 (2017) 阿部 & 伊藤

“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”

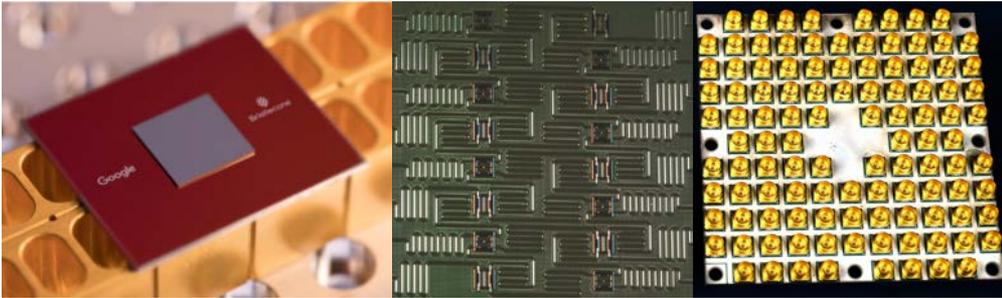
J. Appl. Phys. **123**, 161191 (2018) Abe & Sasaki

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

半導体スピン



## 超伝導回路

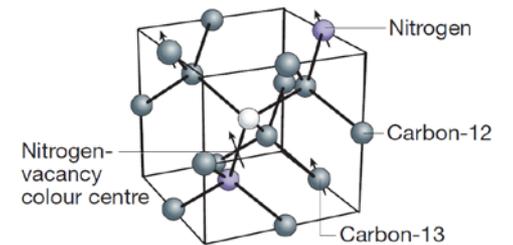
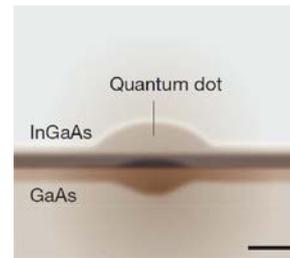
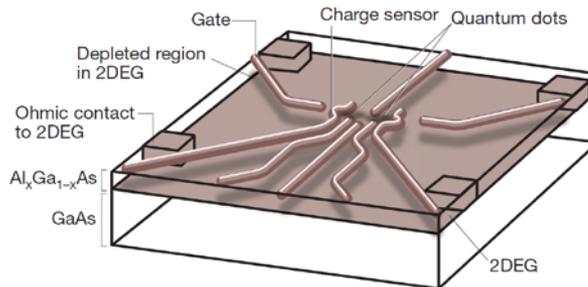
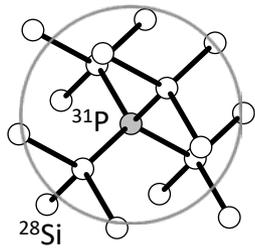


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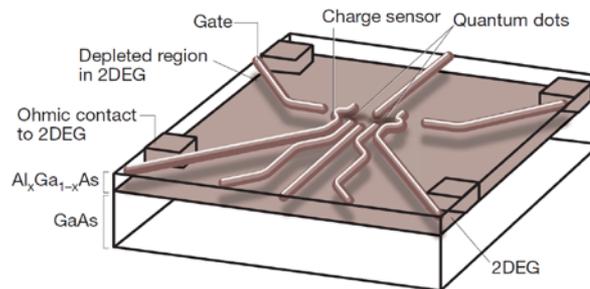
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## 半導体スピン



# 本チュートリアルでは シリコン量子ドット系について解説

## 半導体スピン



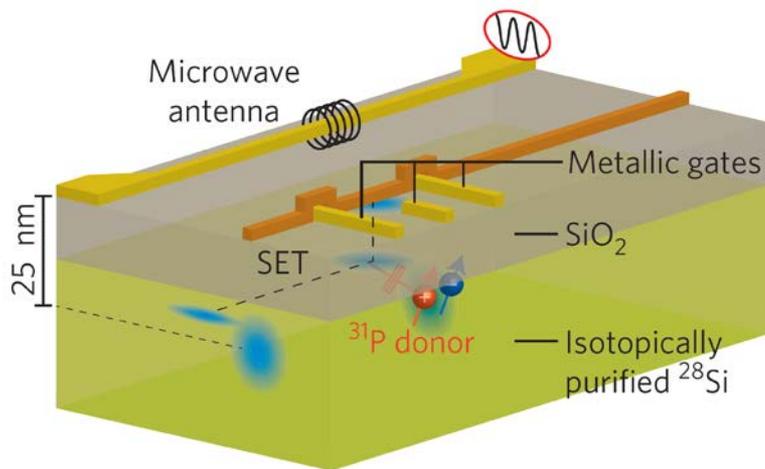
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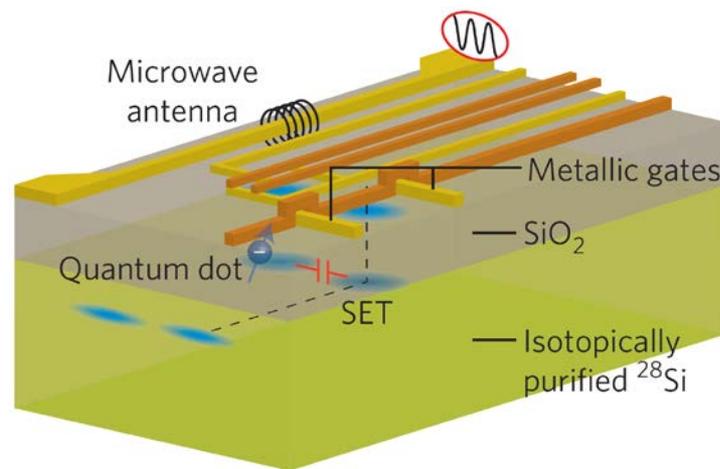
©Google Earth

- **2001.4 – 2006.3 慶應義塾大学**
  - シリコン(スピンコヒーレンス)
- **2006.4 – 2009.12 東京大学物性研究所**
  - 半導体&超伝導ナノ構造(量子輸送・マイクロ波分光)
- **2010.1 – 2011.6 オックスフォード大学**
  - ハイブリッド系(スピン-共振器強結合)
- **2011.7 – 2015.3 スタンフォード大学/理研**
  - 自己形成量子ドット(量子ネットワーク)
- **2015.4 – 現在 慶應義塾大学**
  - NV中心(量子センシング)

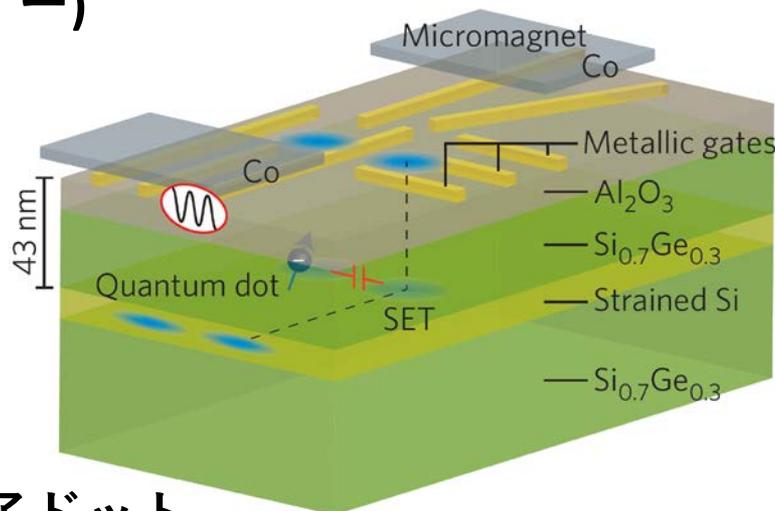
# シリコンスピン量子ビット



(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

→ ?

## 2. 初期化

→  $T_1$ , スピン依存トンネル

## 3. 長いコヒーレンス時間

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

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

## 4. ユニバーサル量子ゲート

→ 1,2量子ビット制御

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

## 5. 射影測定

→ スピン-電荷変換



D. DiVincenzo  
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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

→  $T_1$ , スピン依存トンネル

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

→ 1,2量子ビット制御

5. 射影測定

→ スピン-電荷変換



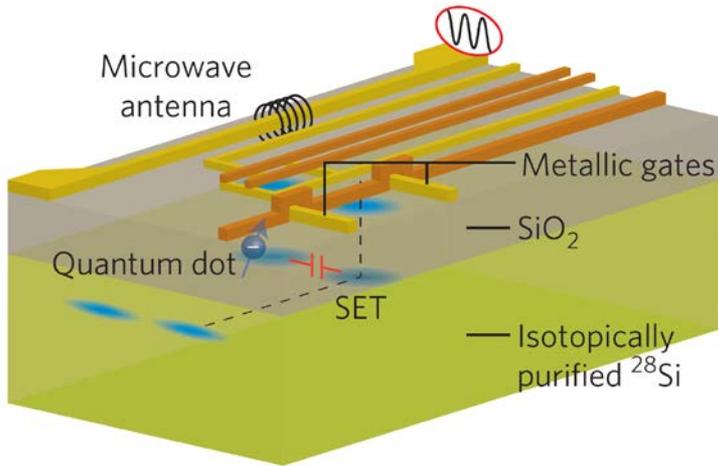
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フィデリティ > 99%

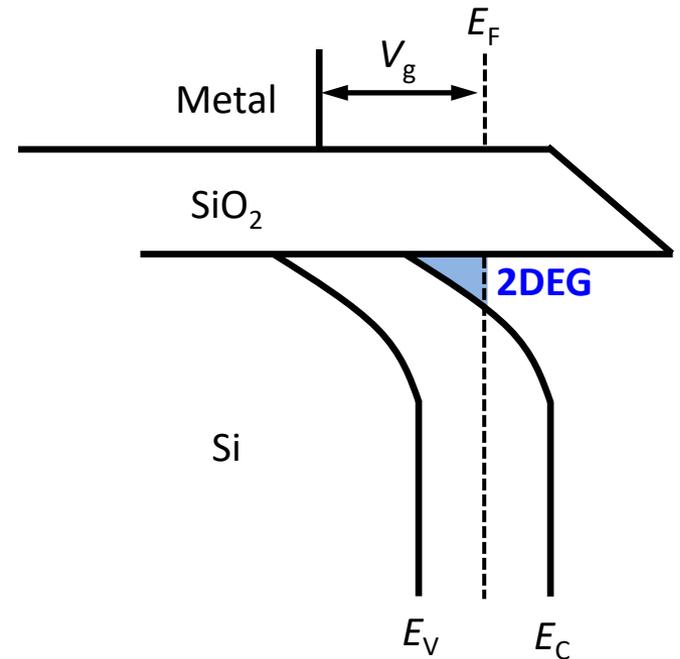
# 量子ゲート

- **1量子ビットゲート**
  - 電子スピン共鳴によるX,Yゲート
  - 電気双極子スピン共鳴によるX,Yゲート
  - (ソフトウェアによるZゲート)
  
- **2量子ビットゲート**
  - 電圧パルスによるCZゲート
  - マイクロ波パルスによるCROTゲート

# 界面MOS構造



## 反転層の形成

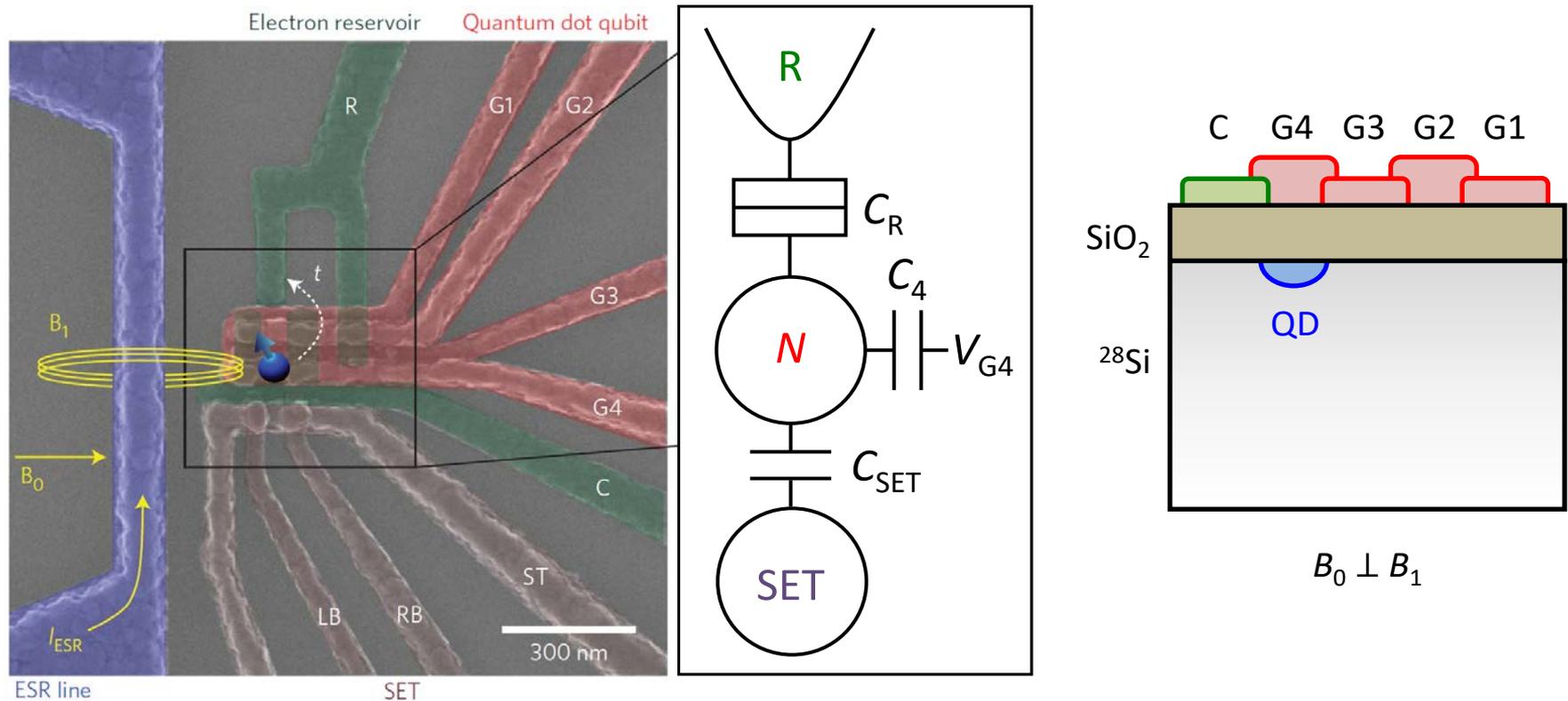


(L to R) J. Muhonen, A. Morello, M. Veldhorst, A. Dzurak

$^{28}\text{Si} : ^{29}\text{Si} (I = 1/2) : ^{30}\text{Si} = 92.2\% : 4.7\% : 3.1\%$   
 $\rightarrow ^{28}\text{Si} = 99.2\%$

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

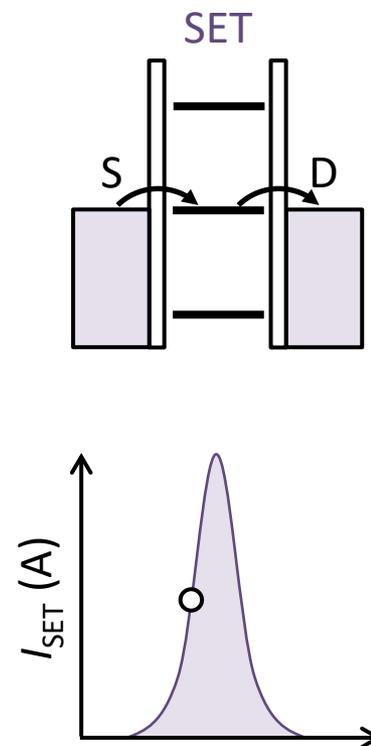
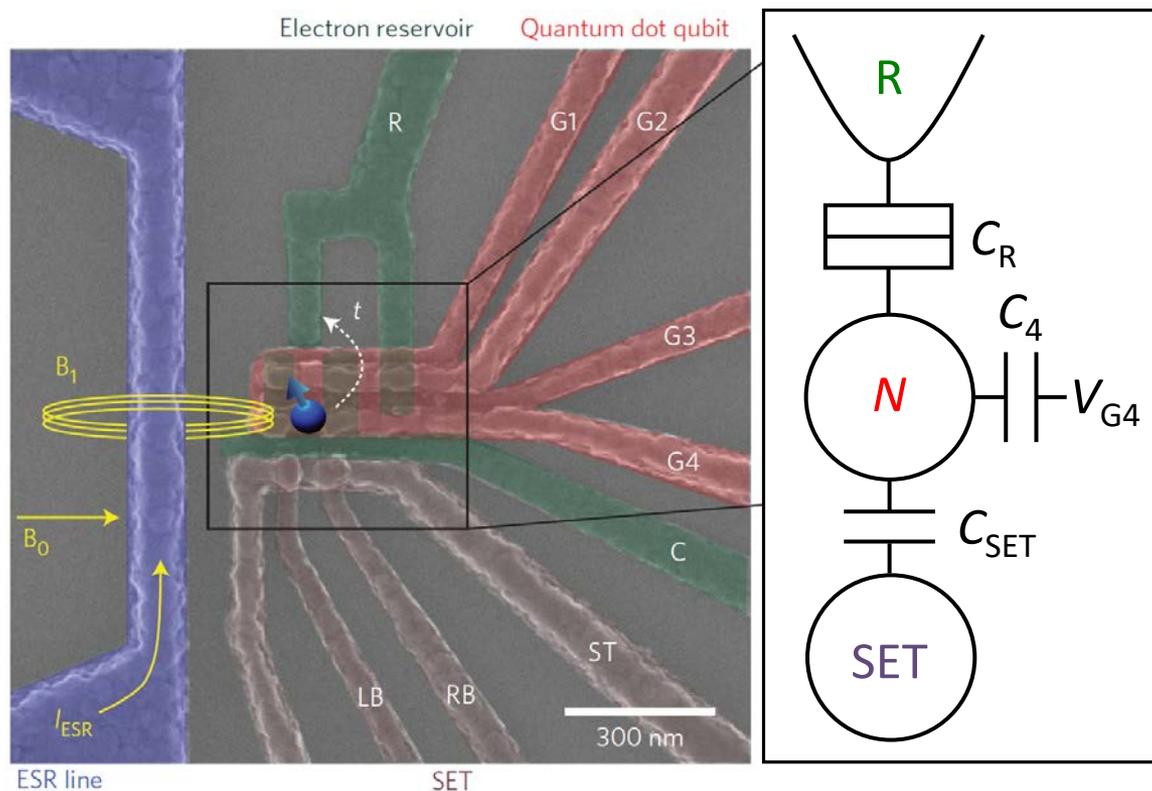
M. Veldhorst<sup>1\*</sup>, J. C. C. Hwang<sup>1</sup>, C. H. Yang<sup>1</sup>, A. W. Leenstra<sup>2</sup>, B. de Ronde<sup>2</sup>, J. P. Dehollain<sup>1</sup>, J. T. Muhonen<sup>1</sup>, F. E. Hudson<sup>1</sup>, K. M. Itoh<sup>3</sup>, A. Morello<sup>1</sup> and A. S. Dzurak<sup>1\*</sup>



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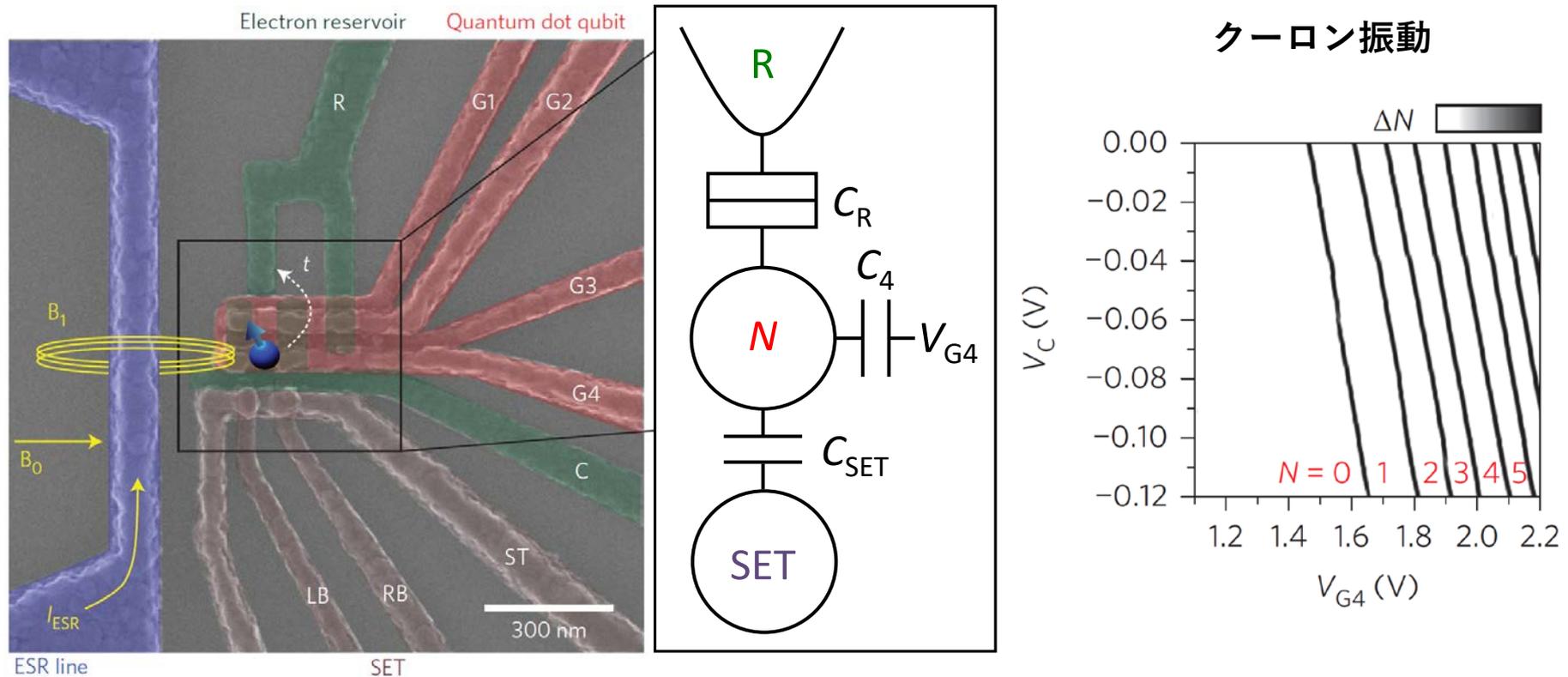
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SET電荷センサ  
QDの電子数変化に  
鋭敏に応答

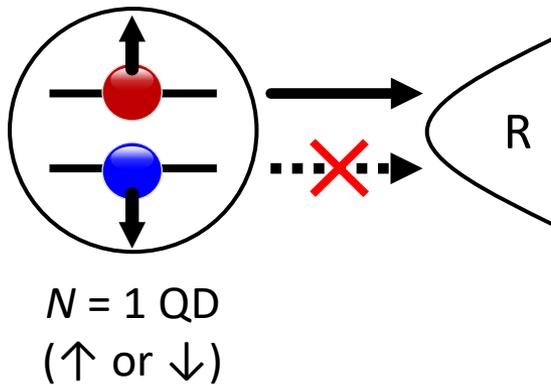


# An addressable quantum dot qubit with fault-tolerant control-fidelity

M. Veldhorst<sup>1\*</sup>, J. C. C. Hwang<sup>1</sup>, C. H. Yang<sup>1</sup>, A. W. Leenstra<sup>2</sup>, B. de Ronde<sup>2</sup>, J. P. Dehollain<sup>1</sup>, J. T. Muhonen<sup>1</sup>, F. E. Hudson<sup>1</sup>, K. M. Itoh<sup>3</sup>, A. Morello<sup>1</sup> and A. S. Dzurak<sup>1\*</sup>



# スピン-電荷変換



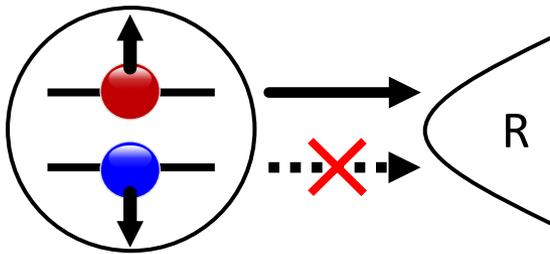
$$E_C \approx 1 \text{ meV}$$

$$E_{VS}(V_C) = 0.1\text{--}0.5 \text{ meV}$$

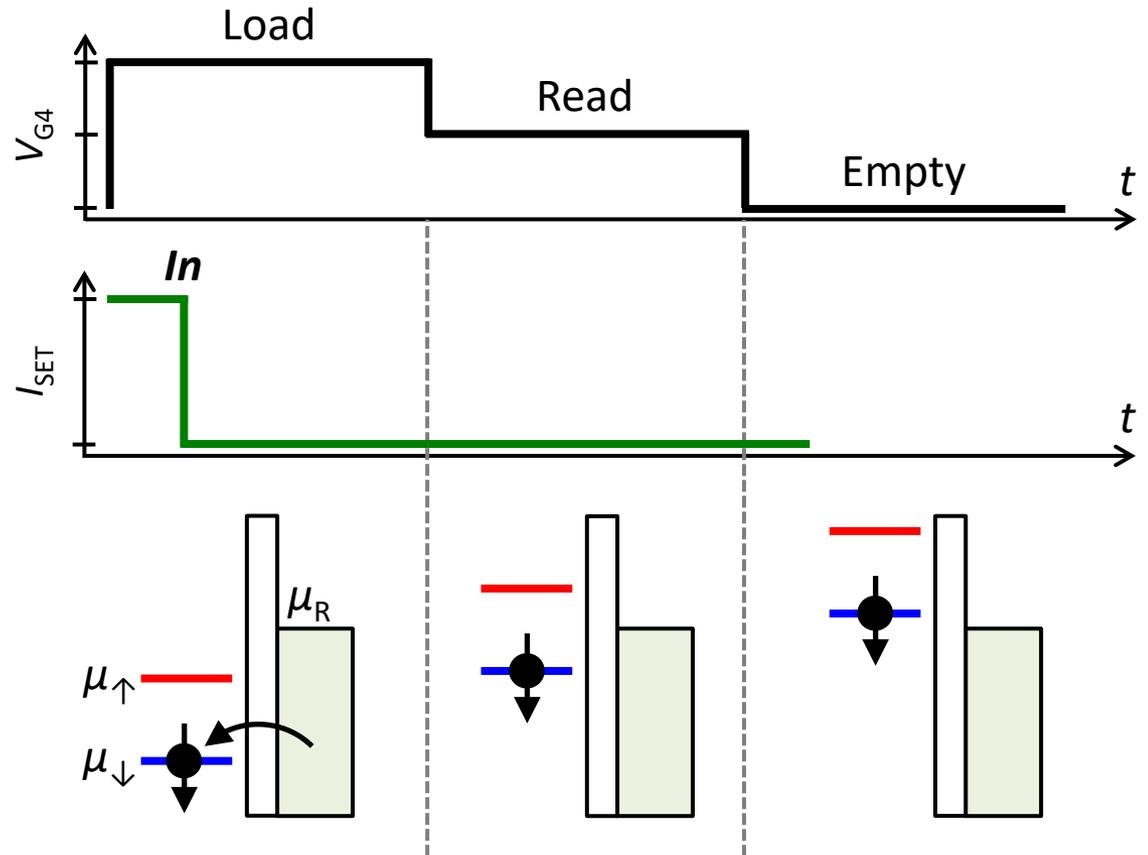
$$E_z = 39 \text{ GHz} = 160 \text{ } \mu\text{eV} @ B_0 = 1.4 \text{ T}$$

$$T_{\text{base}} = 50 \text{ mK} = 4 \text{ } \mu\text{eV}$$

# スピン測定(↓)



$N = 1$  QD  
( $\uparrow$  or  $\downarrow$ )



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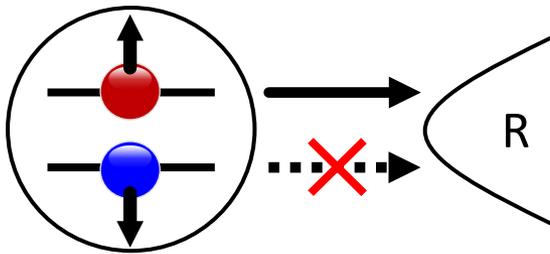
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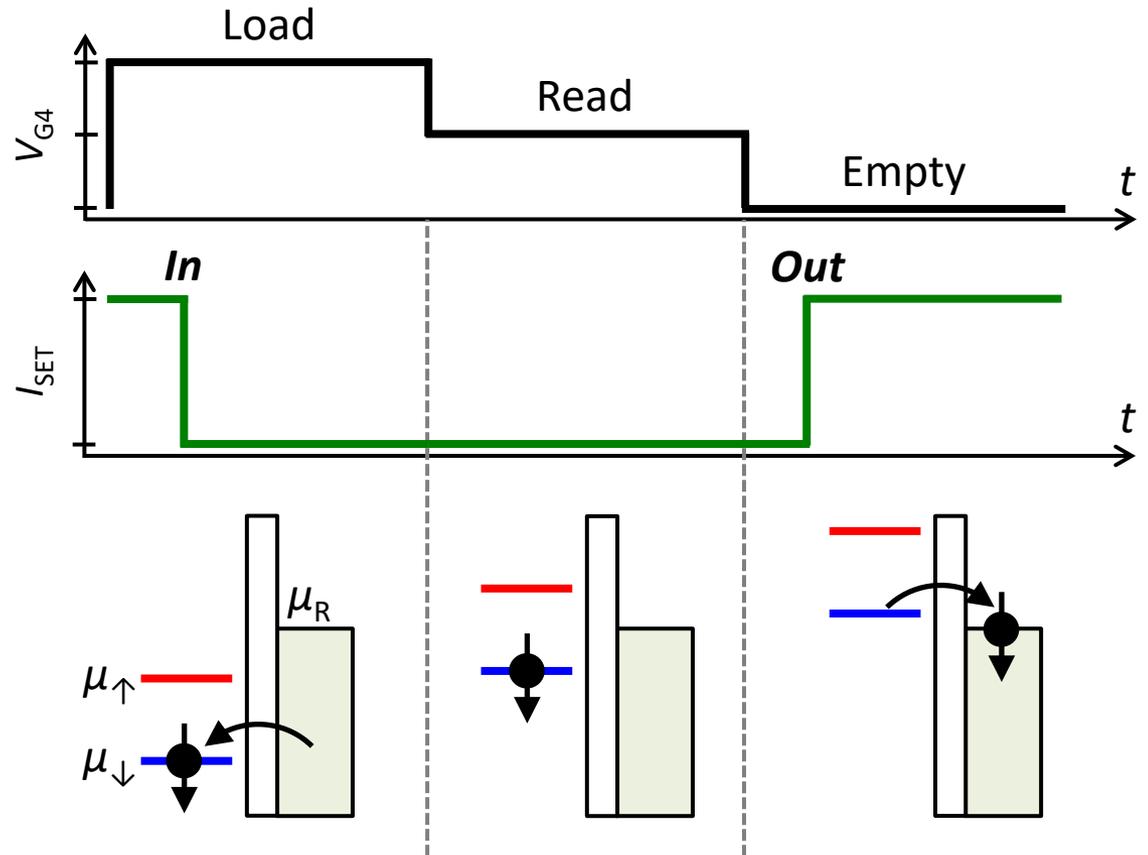
(GaAs QD) Nature **430**, 431 (2004) Elzerman *et al.*

(P donor) Nature **497**, 687 (2010) Morello *et al.*

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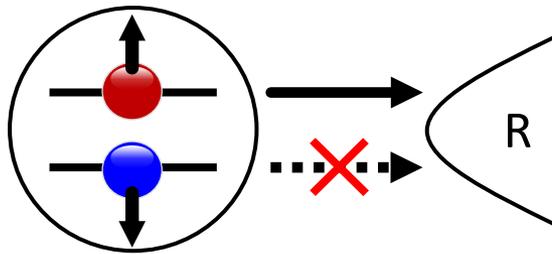
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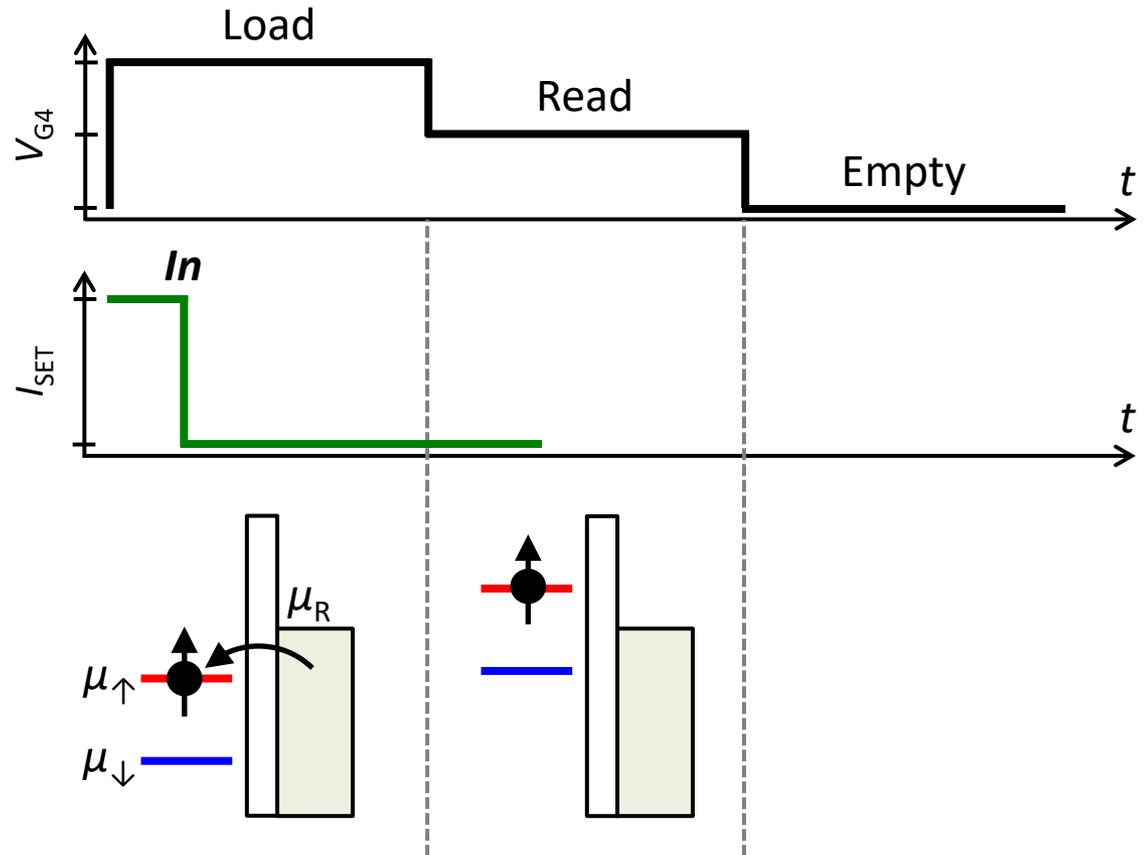
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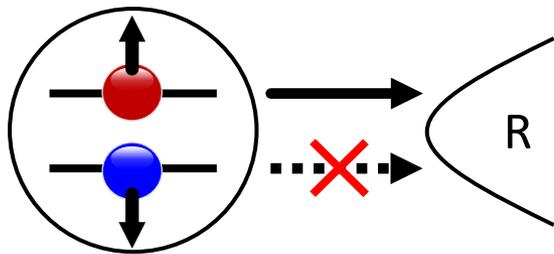
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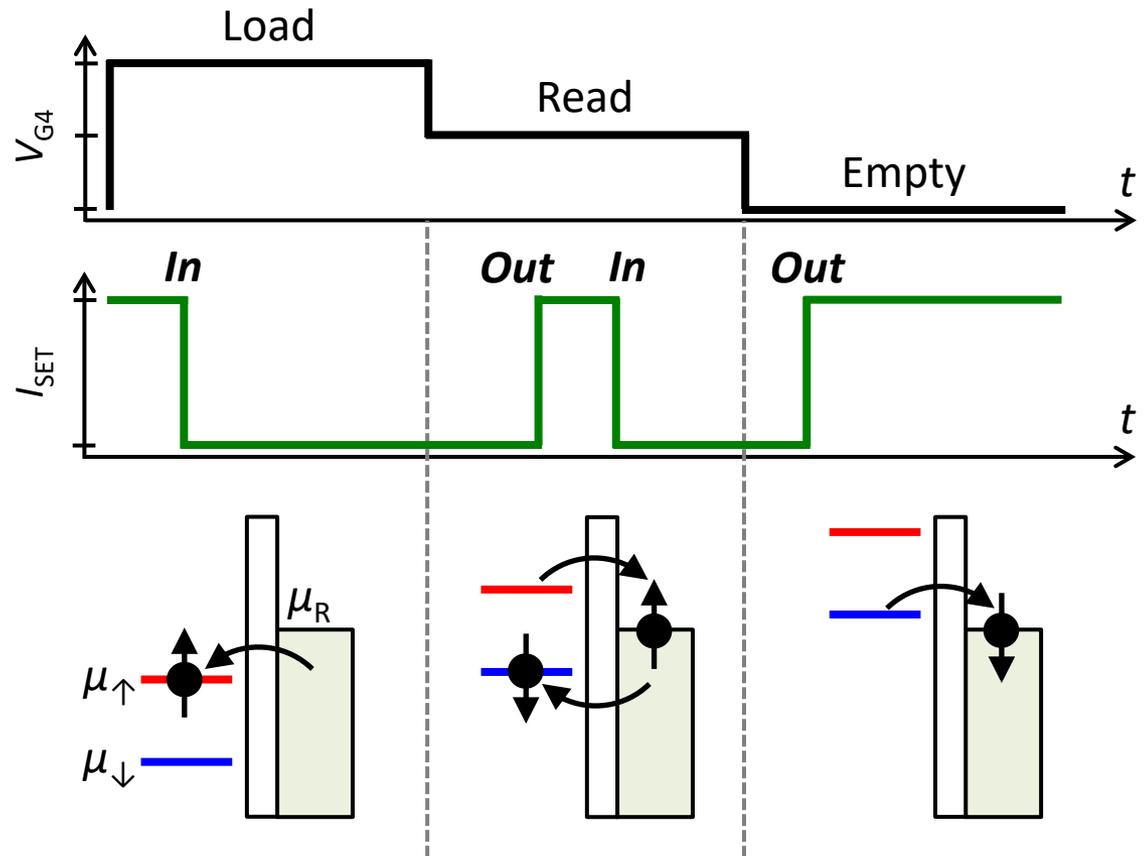
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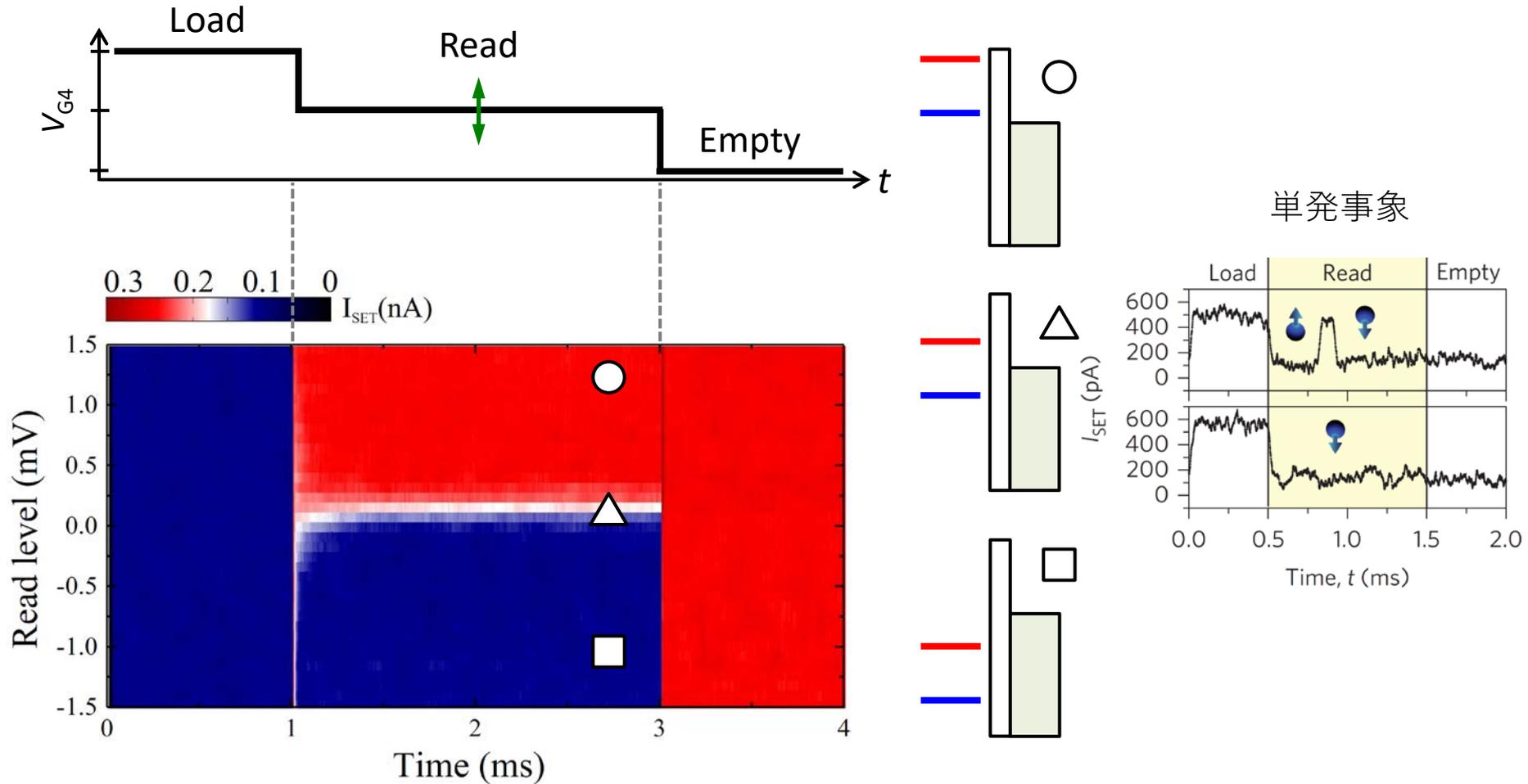
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(GaAs QD) Nature **430**, 431 (2004) Elzerman *et al.*

(P donor) Nature **497**, 687 (2010) Morello *et al.*

# 電子スピン単発読み出し



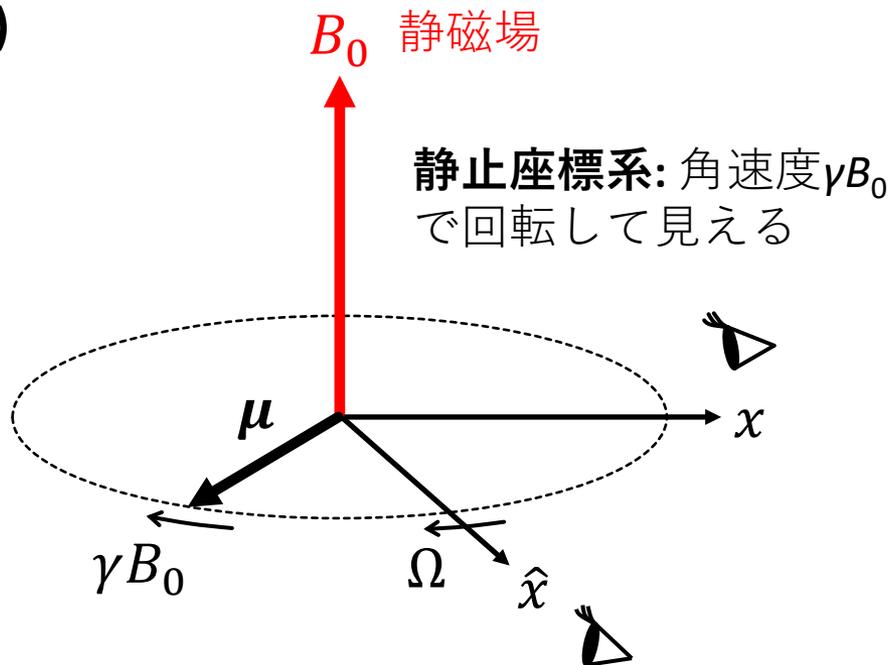
# 磁気共鳴

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:  $\boldsymbol{\mu} = \gamma \mathbf{J}$

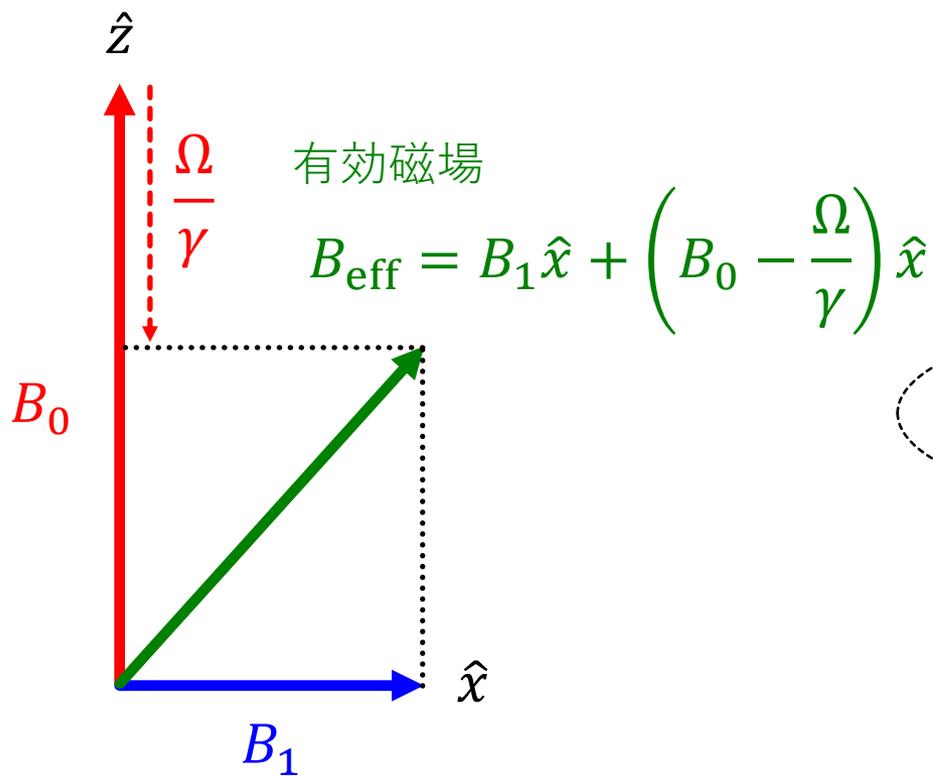
↙  
磁気回転比



静止座標系: 角速度  $\gamma B_0$  で回転して見える

角速度  $\Omega$  で回転する座標系: 遅くなって見える. なぜ??

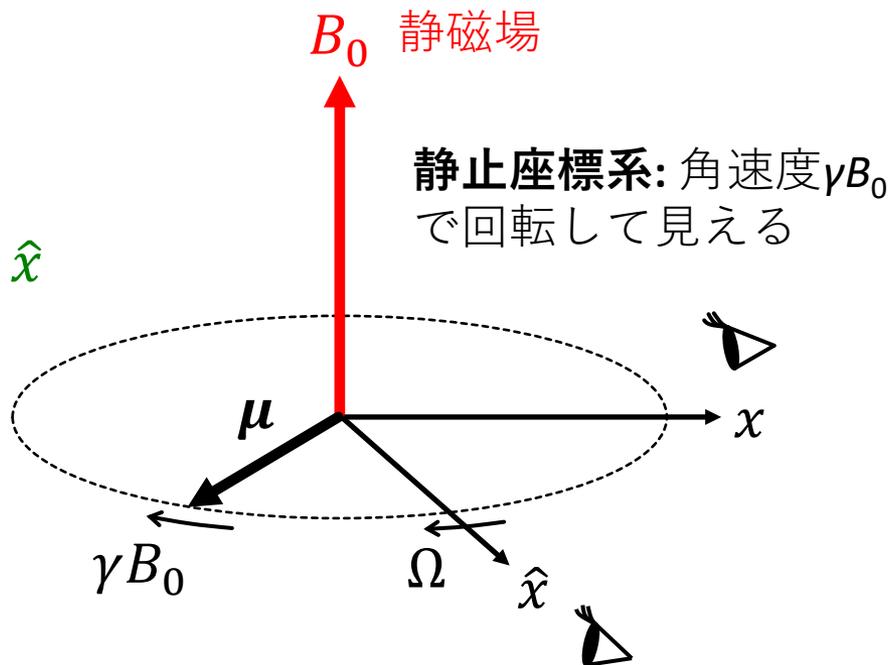
# 磁気共鳴



有効磁場

$$B_{\text{eff}} = B_1 \hat{x} + \left( B_0 - \frac{\Omega}{\gamma} \right) \hat{z}$$

$xy$ 平面を角速度 $\Omega$ で回転する交流磁場



静止座標系: 角速度 $\gamma B_0$ で回転して見える

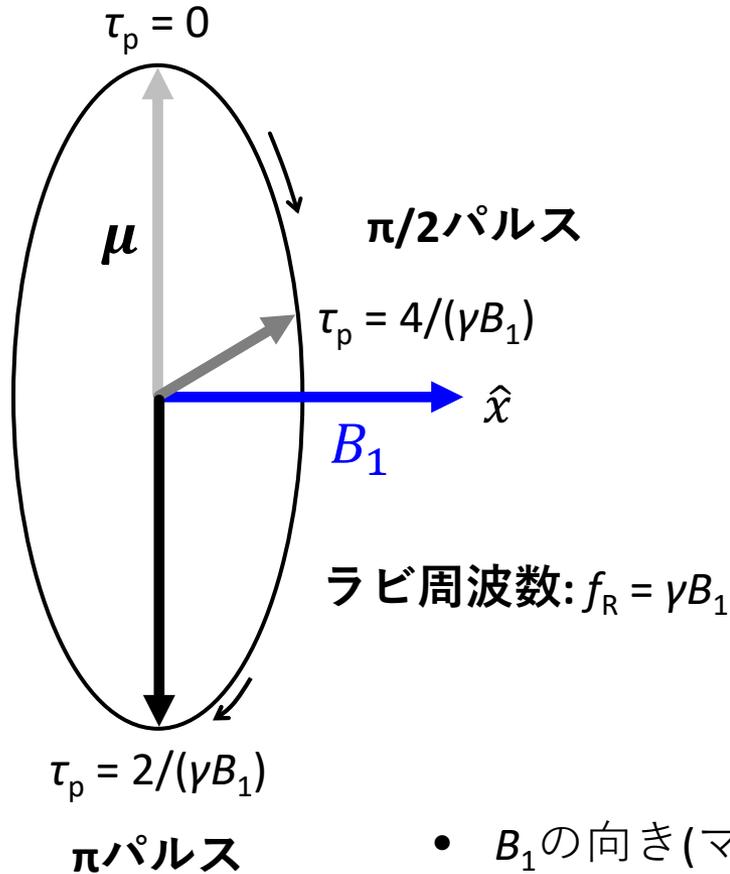
角速度 $\Omega$ で回転する座標系:  
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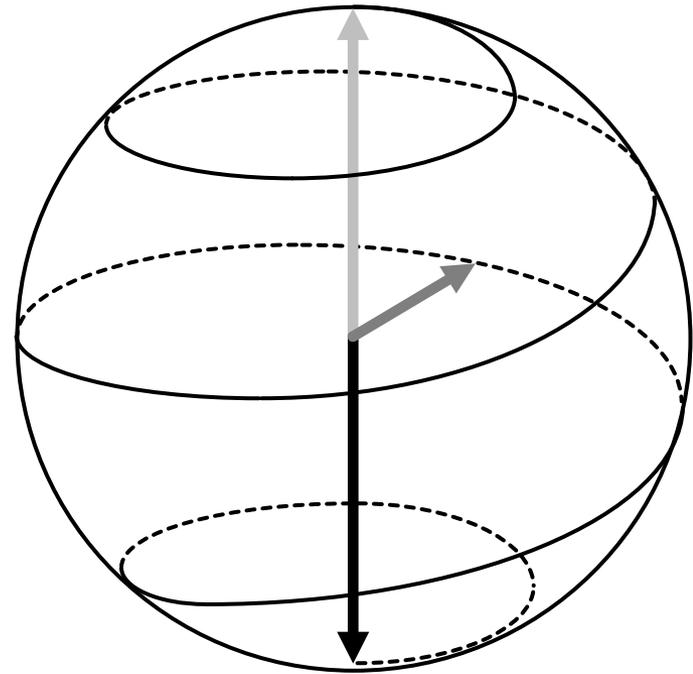
$z$ 方向の磁場が弱くなったから

# 磁気共鳴

$\Omega = \gamma B_0$ で回転する座標系

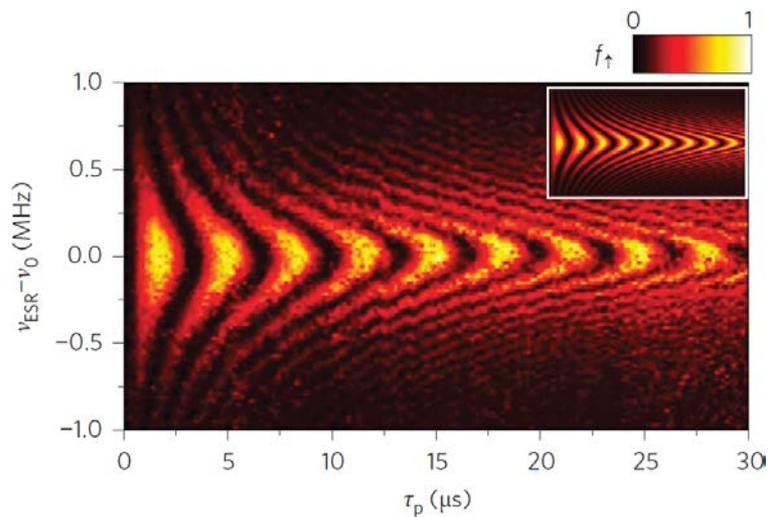
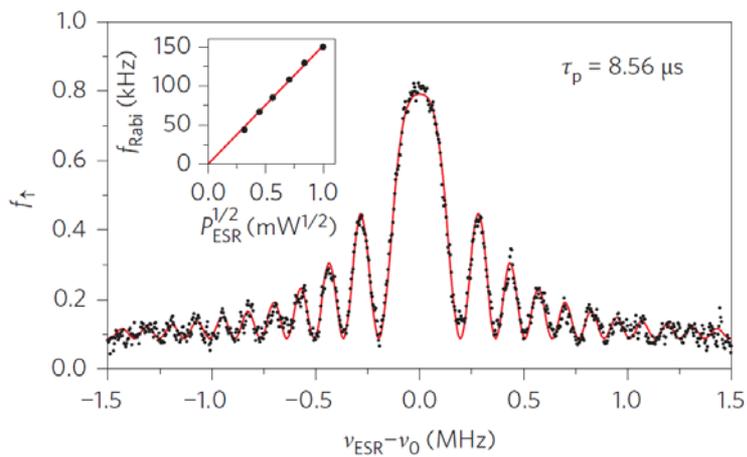
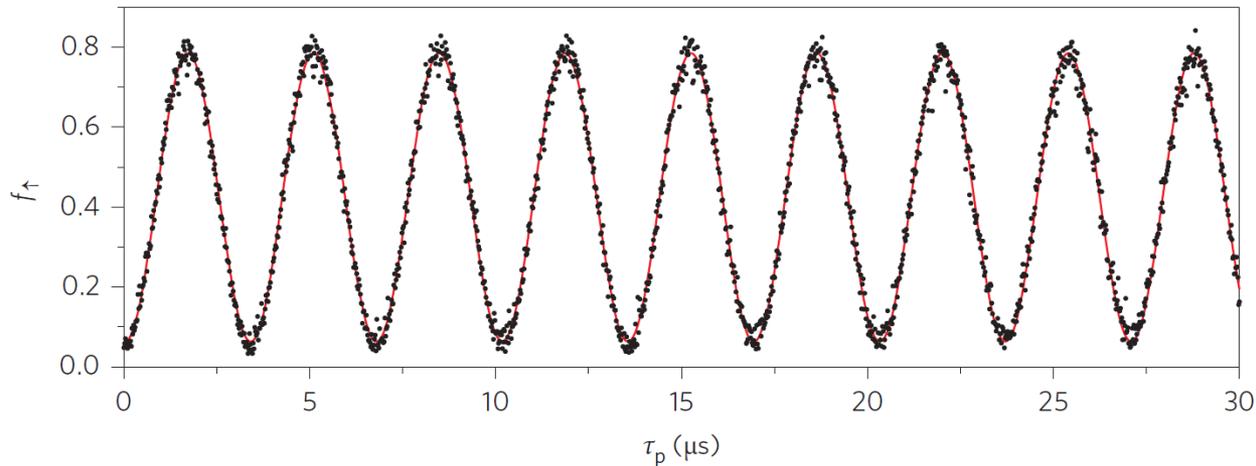


$\Omega \neq \gamma B_0$



- $B_1$ の向き(マイクロ波位相)により回転軸を調整
- 位相の定義を変えれば実効的なz軸回転が加わる

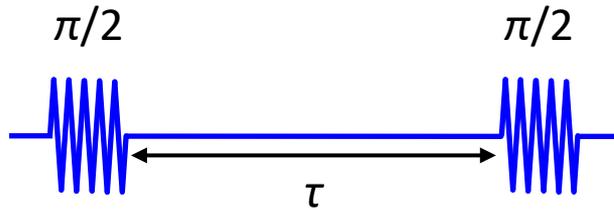
# ラビ振動



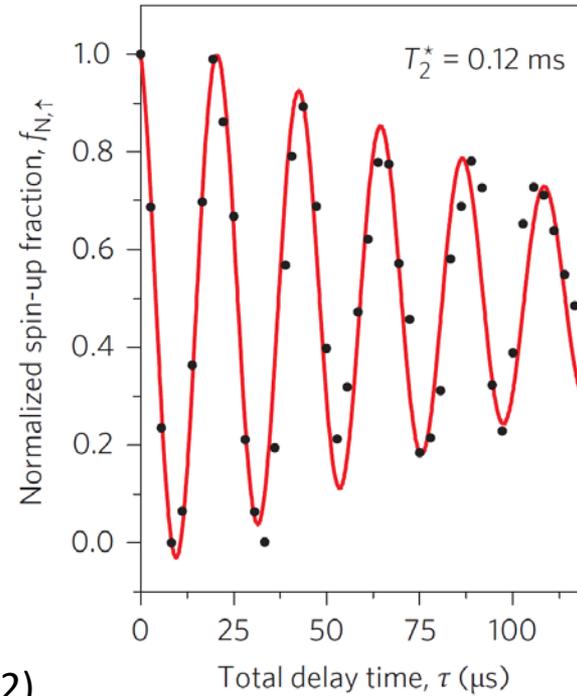
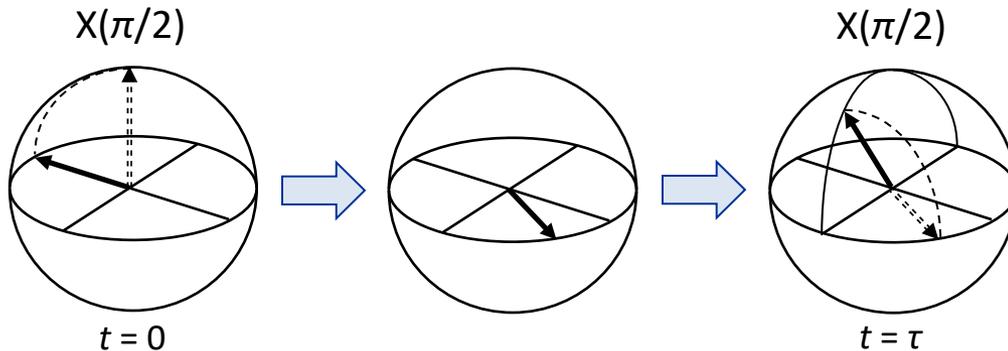
$\nu_0 = 39.14 \text{ GHz @ } B_0 = 1.4 \text{ T}$

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

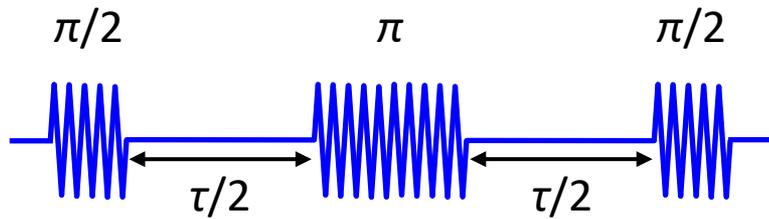
# ラムゼー干渉: $T_2^*$



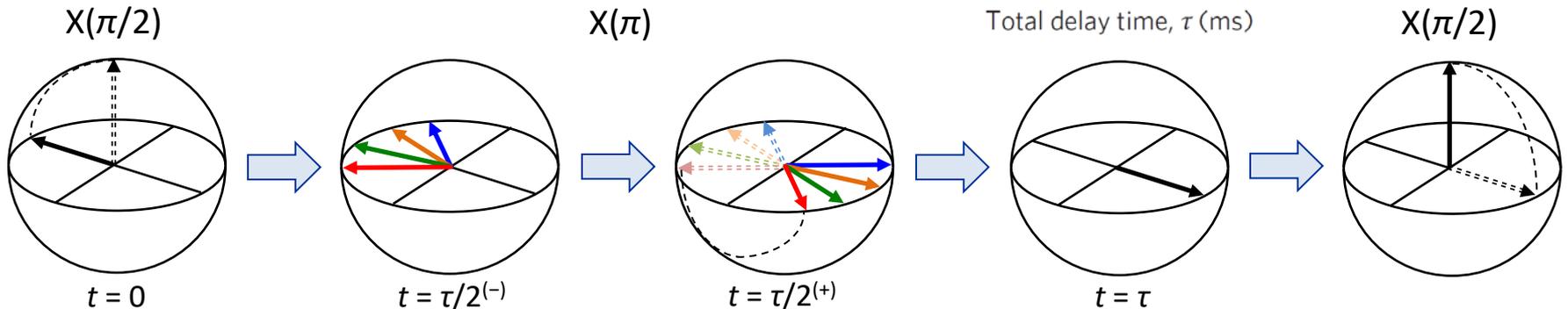
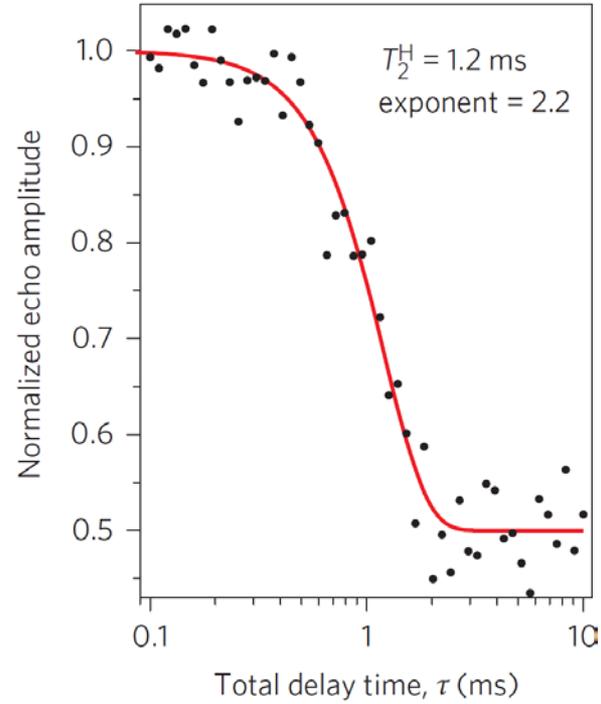
(共鳴から少し外れた回転系)



# スピンエコー: $T_2$

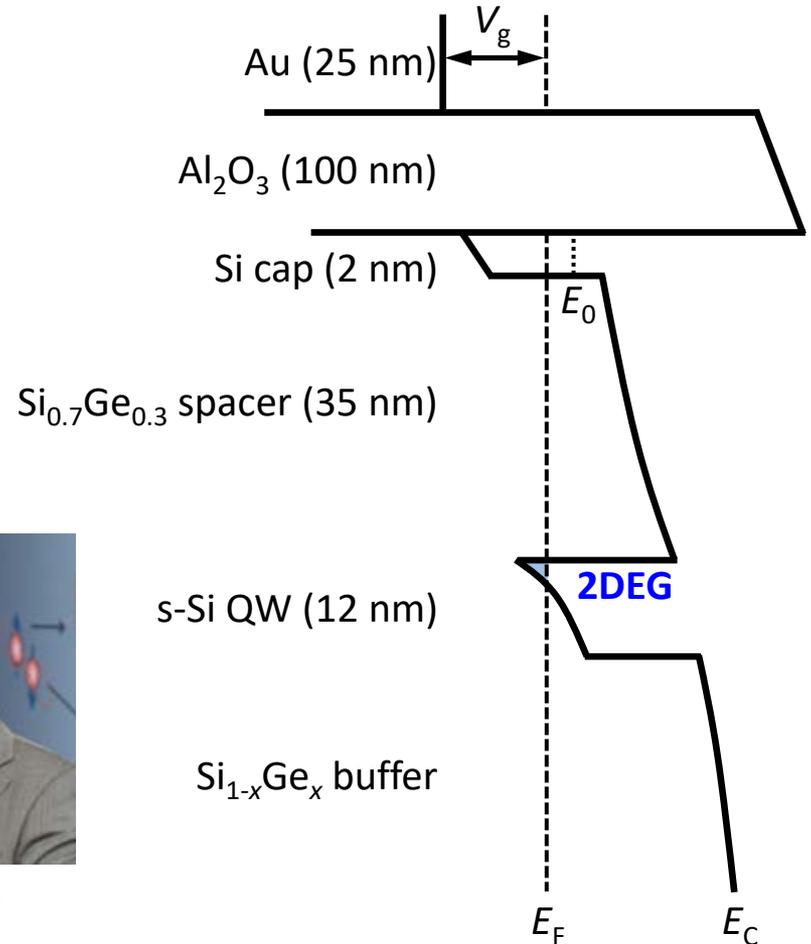
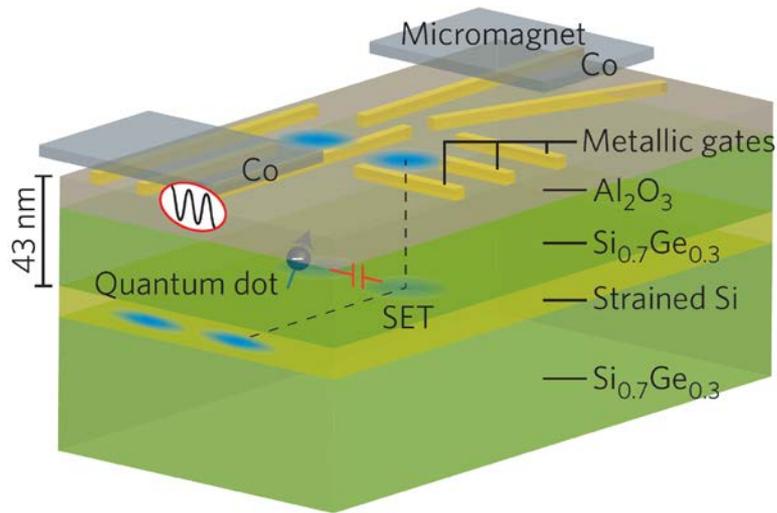


(共鳴周波数の回転系)



# 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)



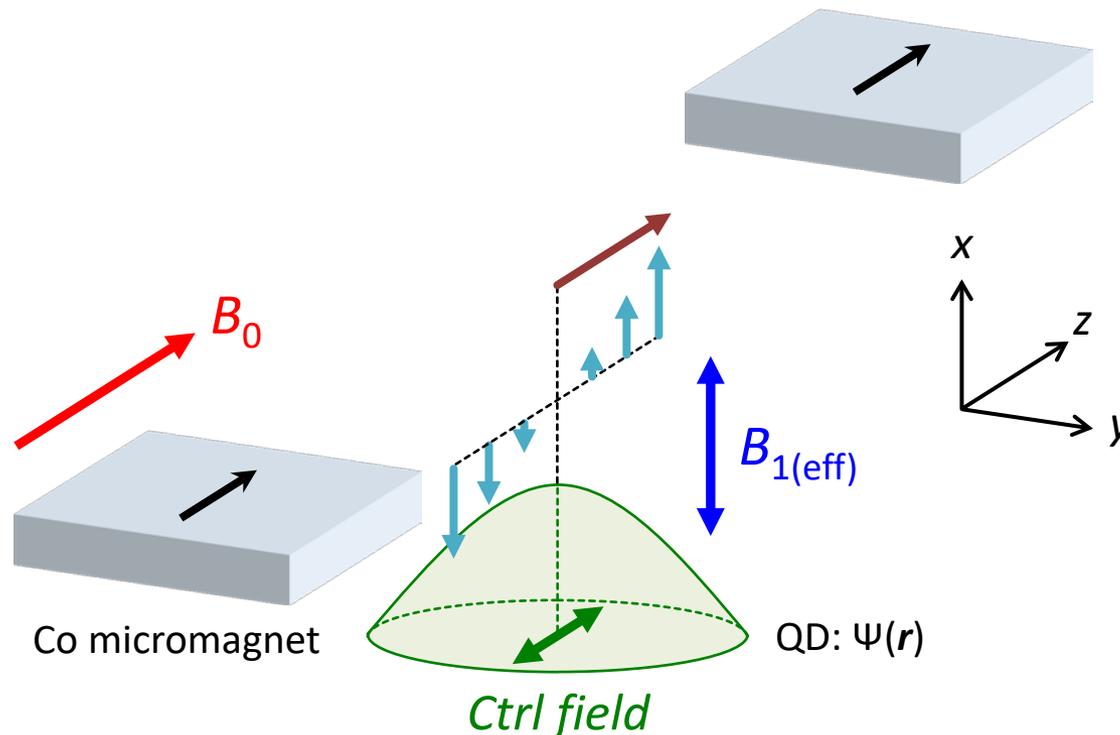
J. Petta  
(©Princeton)



S. Tarucha  
(©RIKEN)

# 電気双極子スピン共鳴

- $\pm z$ 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

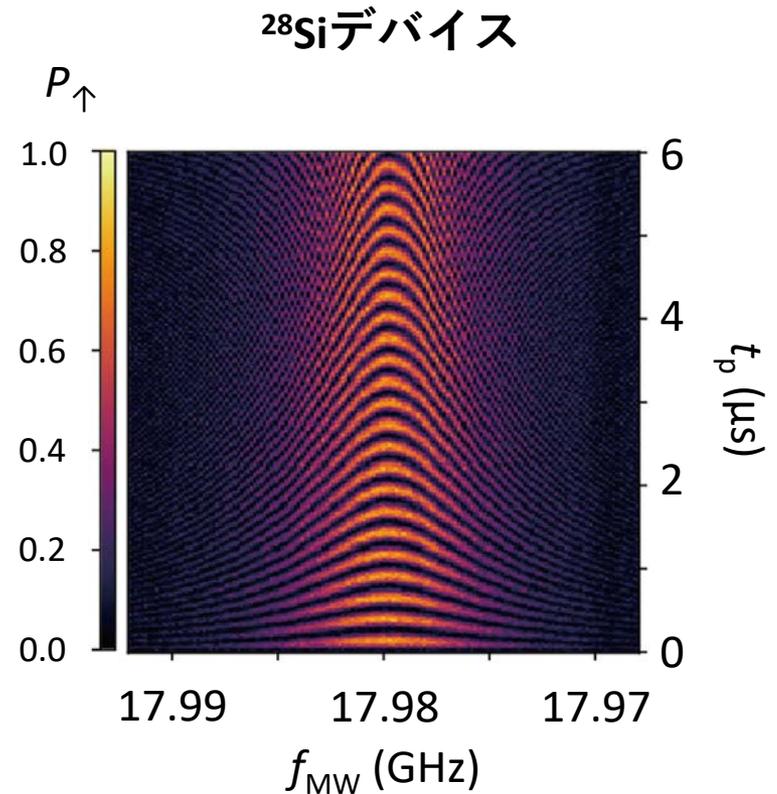
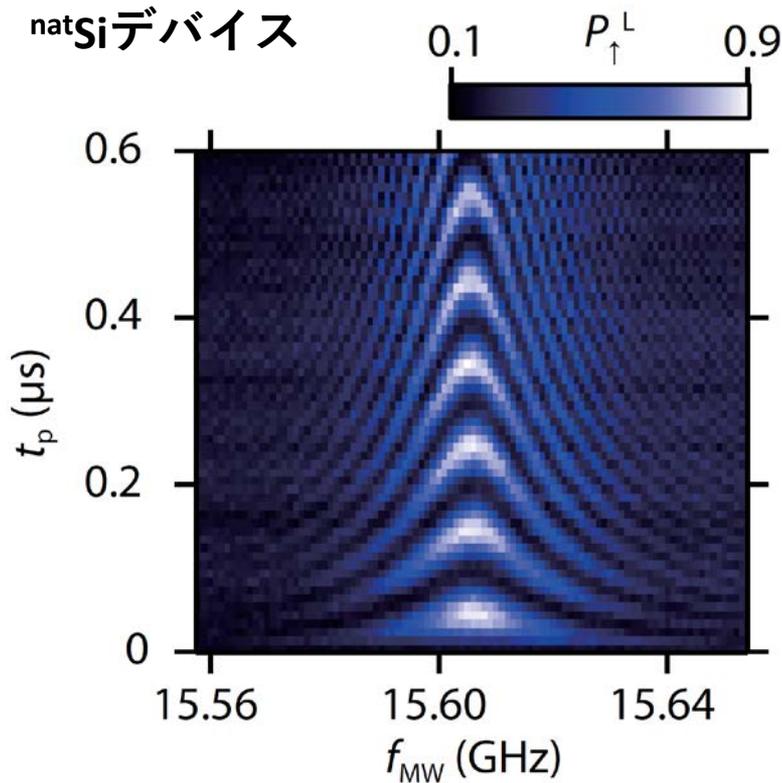


(Theory) Phys. Rev. Lett. **96**, 047202 (2006) Tokura *et al.*

(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



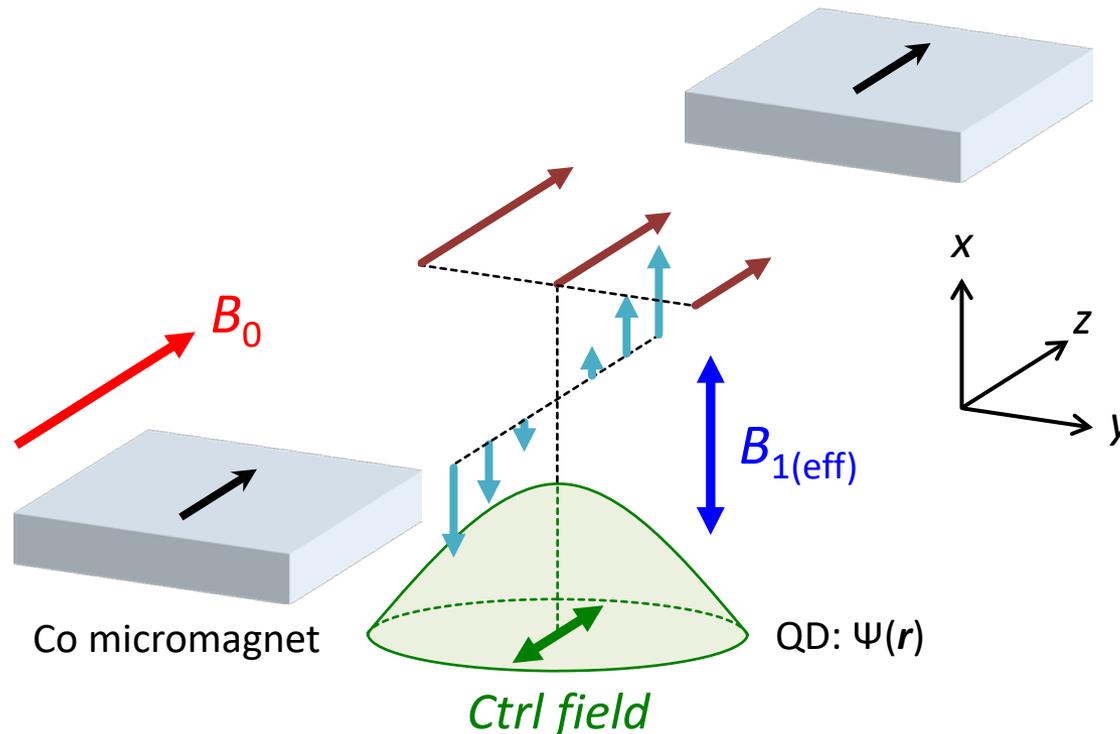
- ラビ周波数  $f_R \approx 30$  MHz
- フィデリティ  $F^{RB} = 99.6\% \rightarrow > 99.9\%$
- $T_2^* = 2 \mu\text{s} \rightarrow 20 \mu\text{s}$ ,  $T_2^{\text{CPMG}} = 3.1$  ms

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

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

# 電気双極子スピン共鳴

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

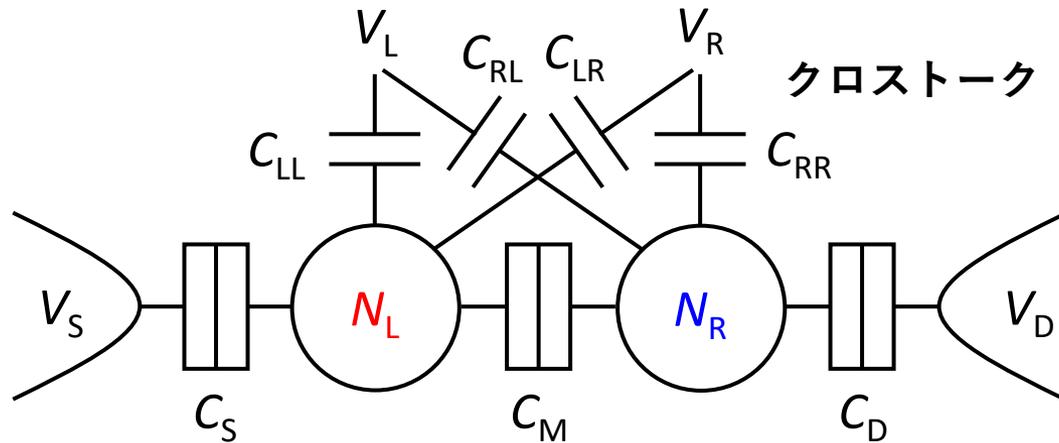
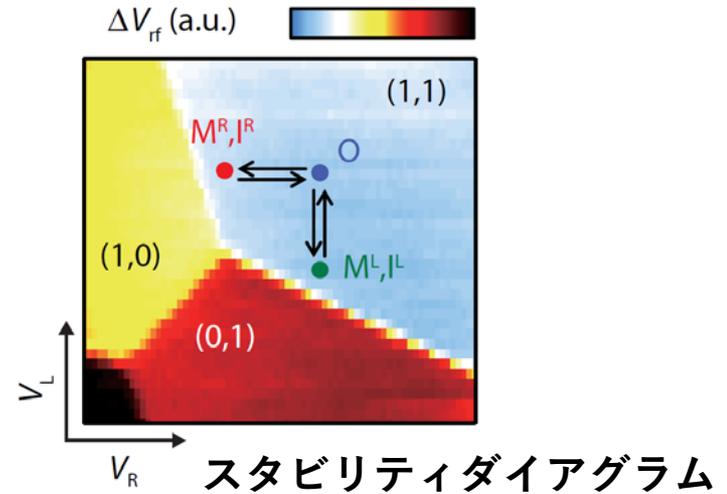
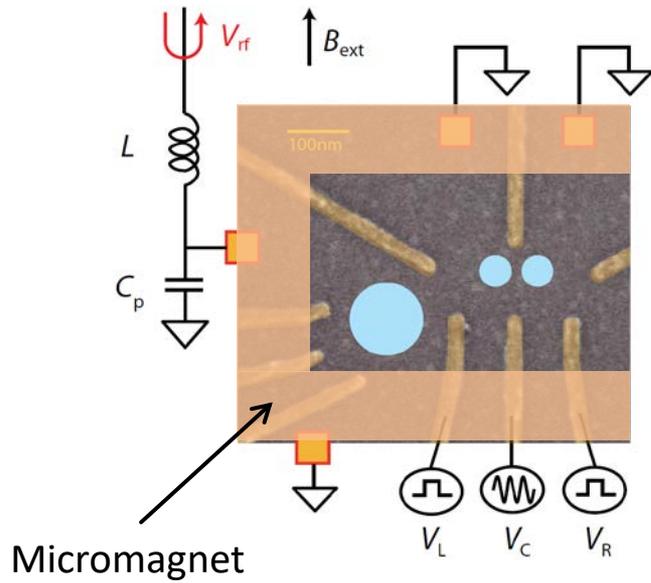


(Theory) Phys. Rev. Lett. **96**, 047202 (2006) Tokura *et al.*

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

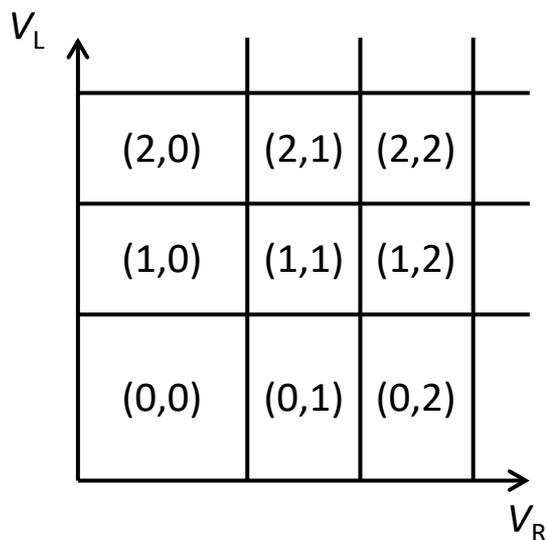
(Magnet design) Appl. Phys. Express **8**, 084401 (2015) Yoneda *et al.*

# 2重量子ドット



# スタビリティダイアグラム

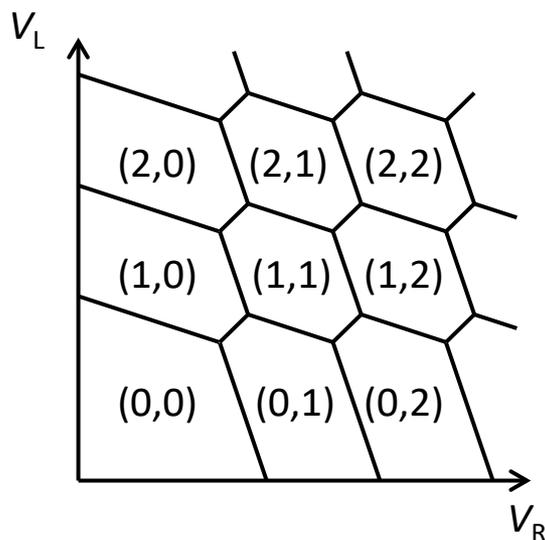
$$C_M \rightarrow 0$$



弱結合

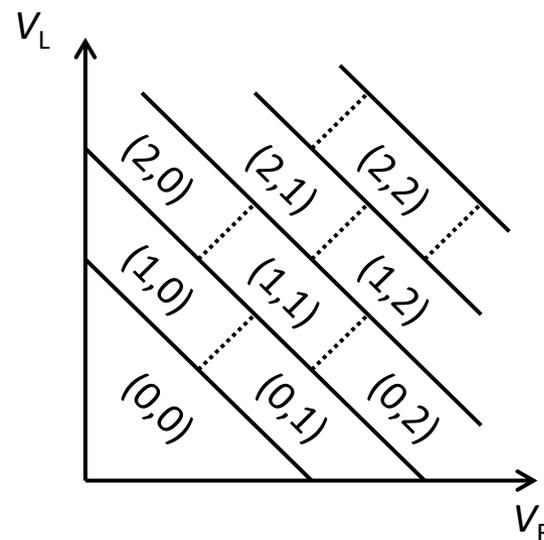
独立のドットとして  
振る舞う

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



ハニカム構造

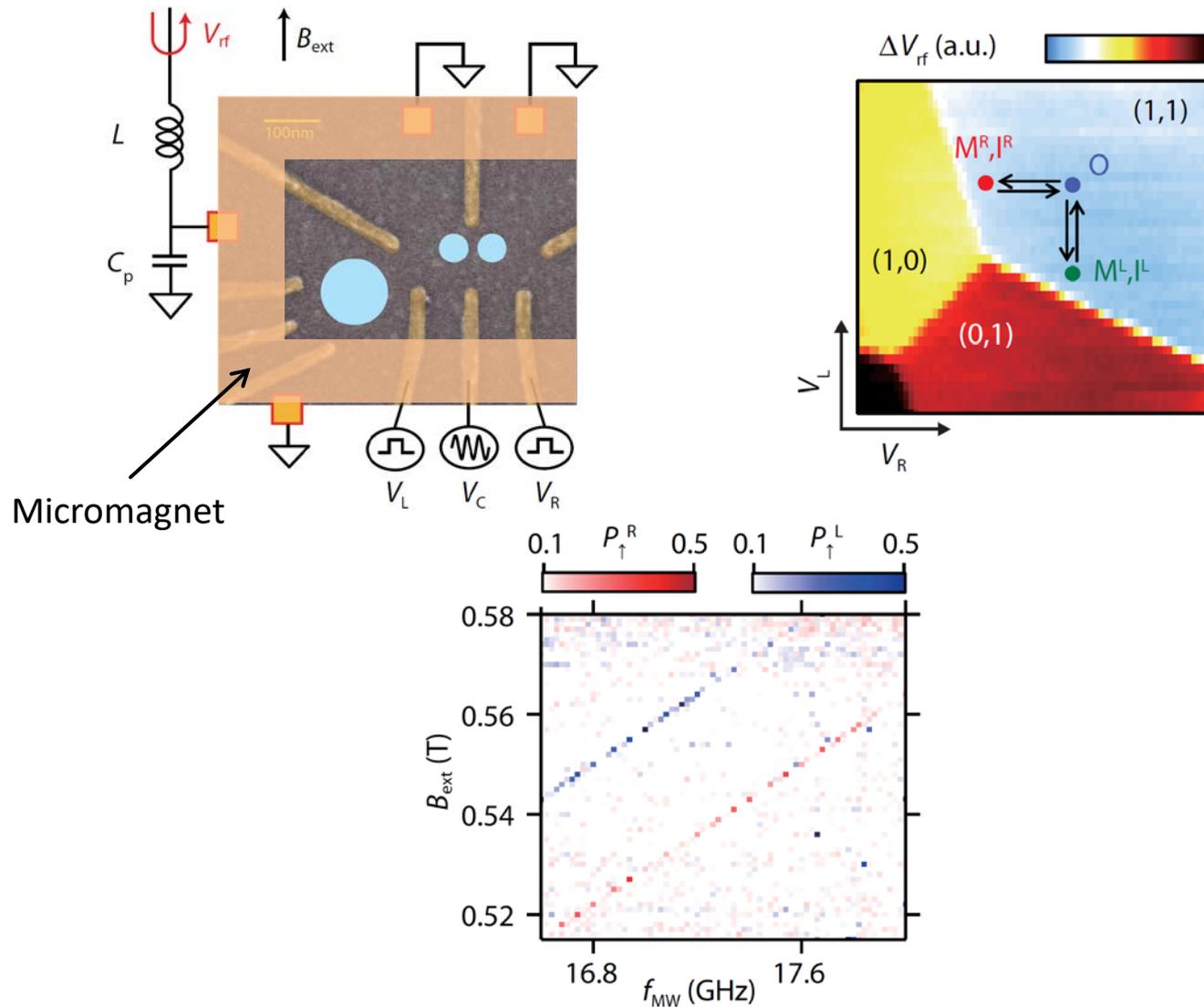
相互に影響しあう



強結合

1つのドットとして  
振る舞う

# 共鳴周波数の分離



## A programmable two-qubit quantum processor in silicon

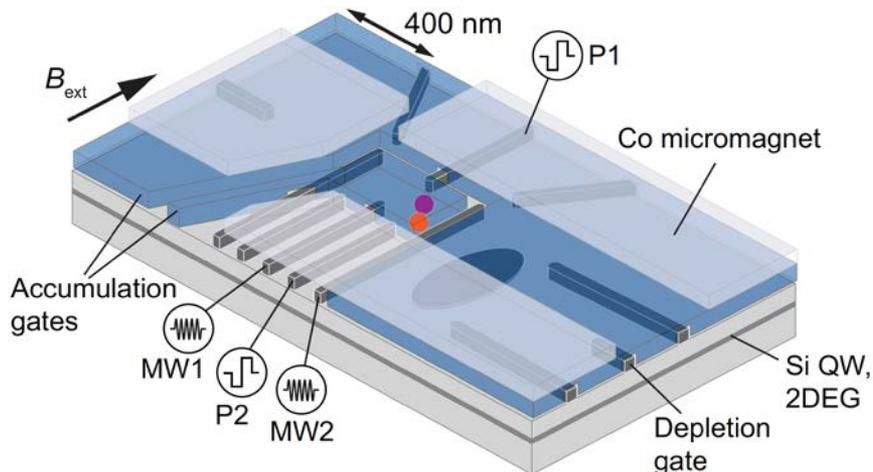
T. F. Watson<sup>1</sup>, S. G. J. Philips<sup>1</sup>, E. Kawakami<sup>1</sup>, D. R. Ward<sup>2</sup>, P. Scarlino<sup>1</sup>, M. Veldhorst<sup>1</sup>, D. E. Savage<sup>2</sup>, M. G. Lagally<sup>2</sup>, Mark Friesen<sup>2</sup>, S. N. Coppersmith<sup>2</sup>, M. A. Eriksson<sup>2</sup> & L. M. K. Vandersypen<sup>1</sup>

量子ドット系ではじめてドイツ・ジョザ、グローバーのアルゴリズムを実行

### Experimental realization of a quantum algorithm

Isaac L. Chuang<sup>\*</sup>, Lieven M. K. Vandersypen<sup>†</sup>, Xinlan Zhou<sup>†</sup>, Debbie W. Leung<sup>‡</sup> & Seth Lloyd<sup>§</sup>

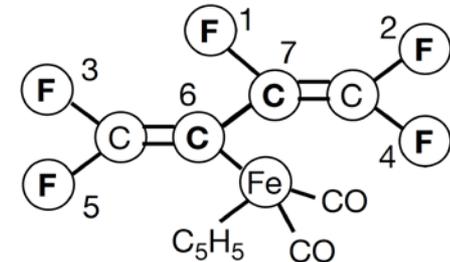
Nature **393**, 143 (1998) Chuang *et al.*



### Experimental realization of Shor's quantum factoring algorithm using nuclear magnetic resonance

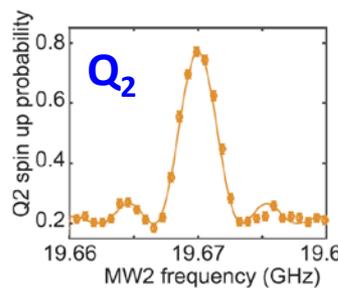
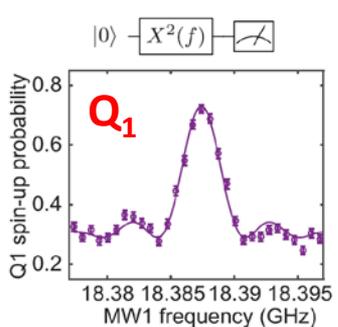
Lieven M. K. Vandersypen<sup>\*†</sup>, Matthias Steffen<sup>\*†</sup>, Gregory Breyta<sup>\*</sup>, Costantino S. Yannoni<sup>\*</sup>, Mark H. Sherwood<sup>\*</sup> & Isaac L. Chuang<sup>\*†</sup>

Nature **414**, 883 (2001) Vandersypen *et al.*

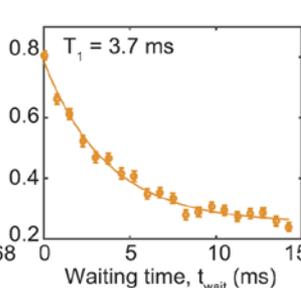
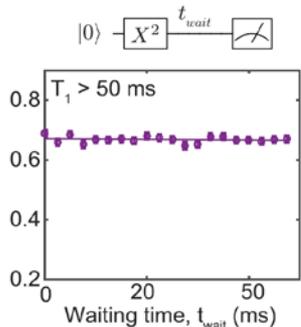


Nature **555**, 633 (2018) Watson *et al.*

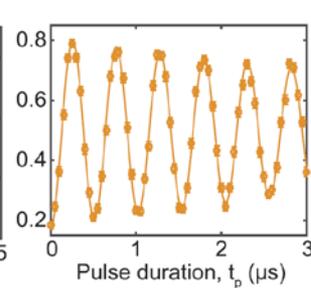
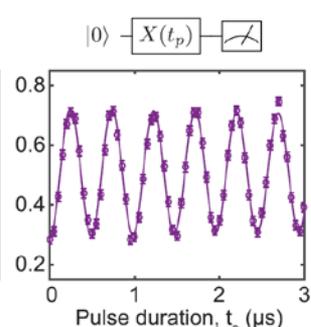
## Spectroscopy



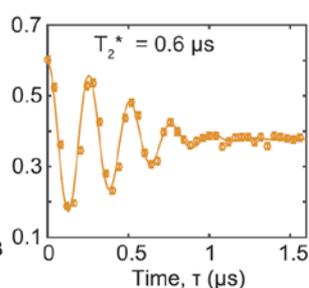
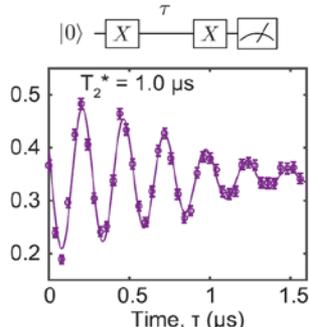
## $T_1$



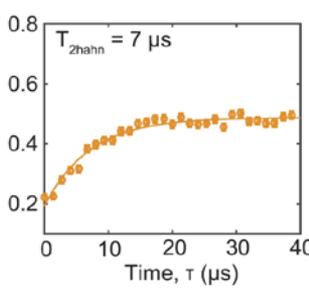
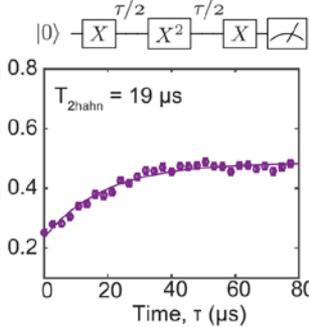
## Rabi



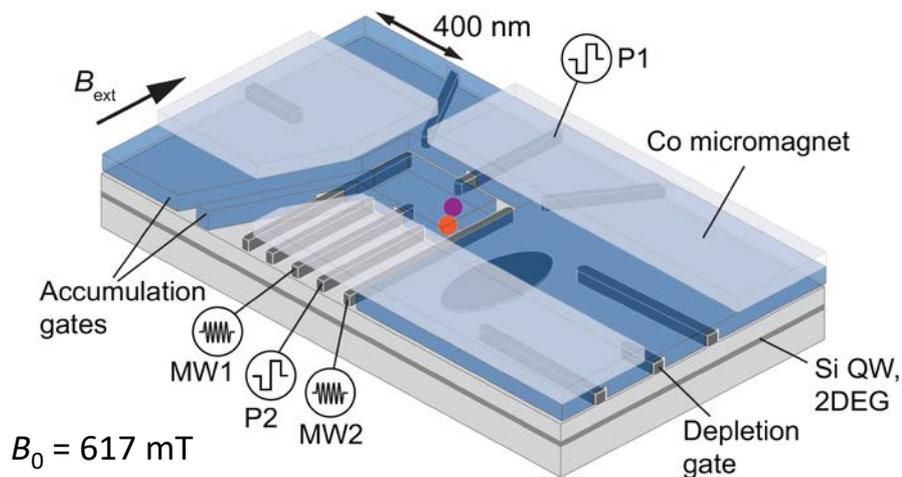
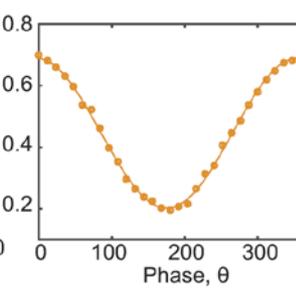
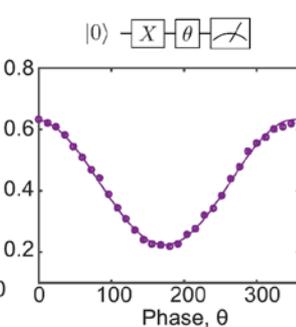
## Ramsey



## $T_2$



## 2-axis control

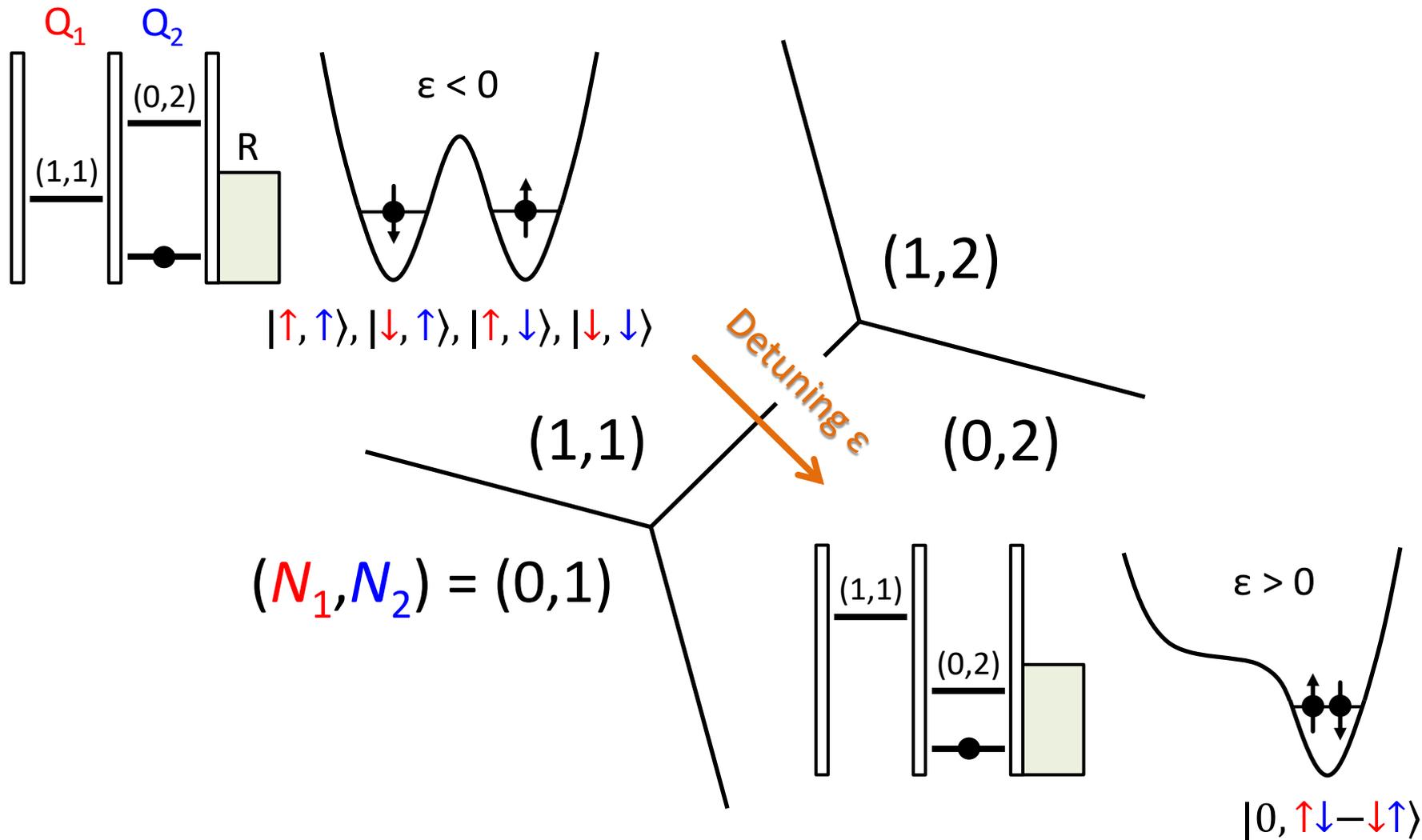


Encode

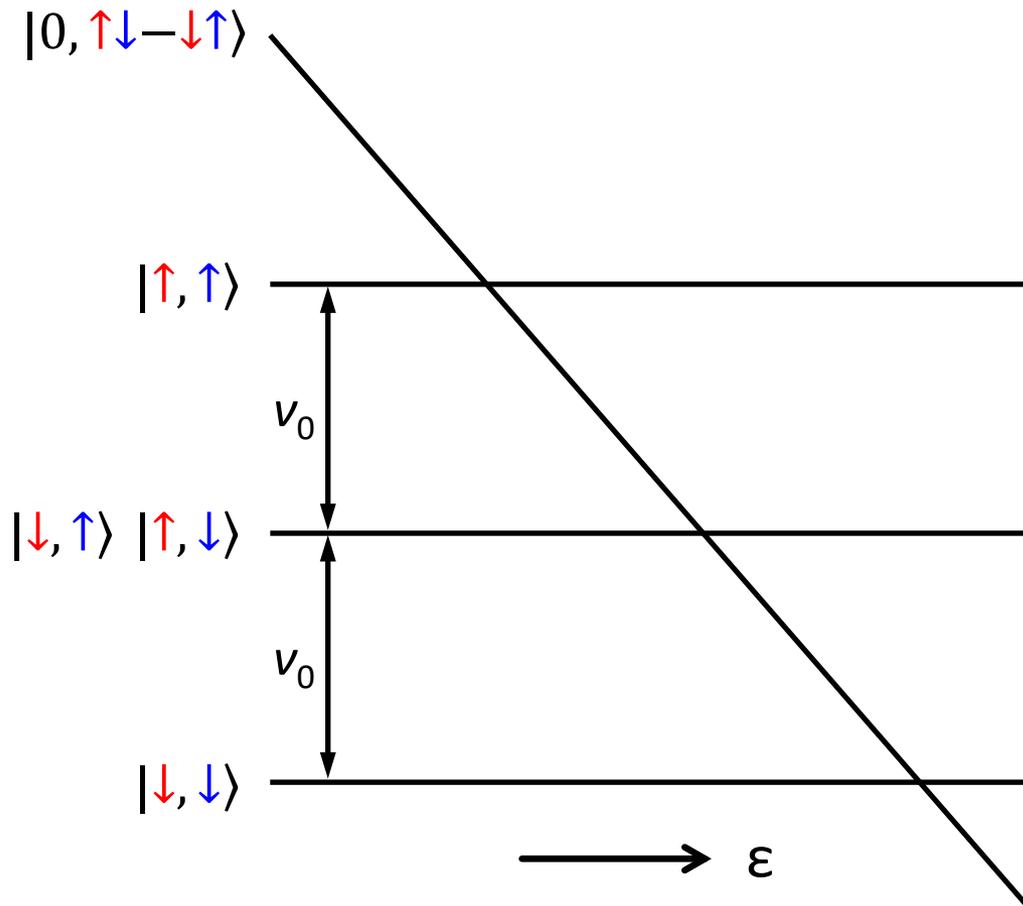
$$|\downarrow\rangle \equiv |0\rangle$$

$$|\uparrow\rangle \equiv |1\rangle$$

# 2電子状態



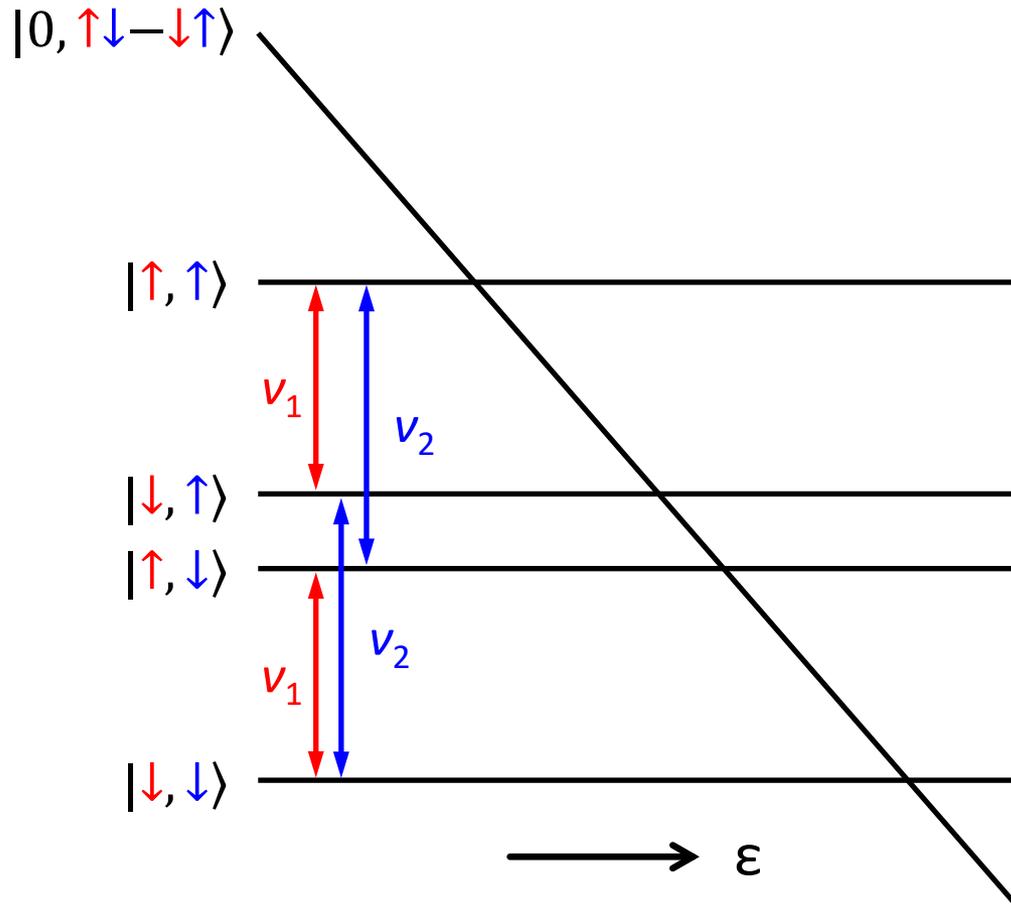
# 2電子状態



ゼーマン効果のみの場合

$$\nu_0 \approx 17.3 \text{ GHz @ } B_0 = 617 \text{ mT}$$

# 2電子状態



マイクロマグネットあり

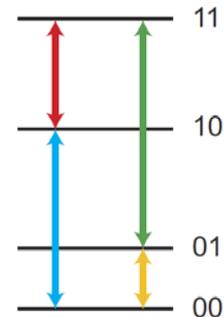
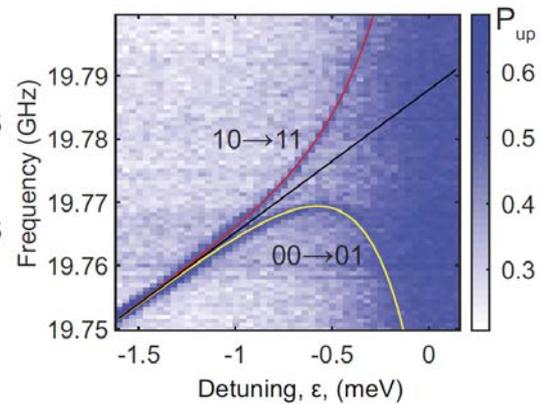
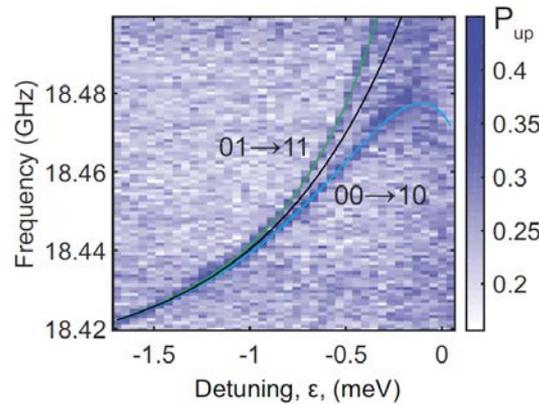
- $\nu_1 = 18.4 \text{ GHz}$
- $\nu_2 = 19.7 \text{ GHz}$

他にも

- 閉じ込め
- シュタルク効果
- 異方性
- 歪 etc

# 2電子状態

$|0, \uparrow\downarrow - \downarrow\uparrow\rangle$

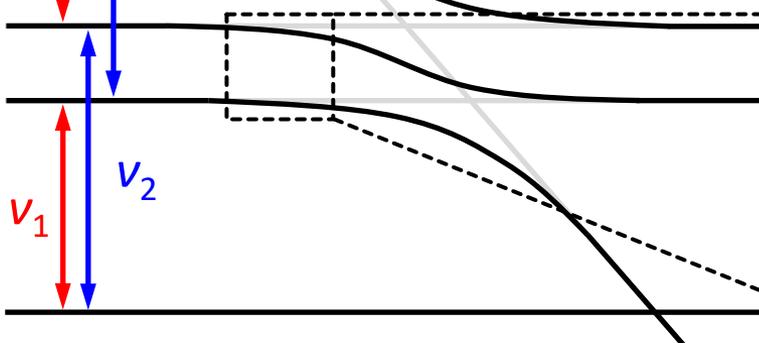


$|\uparrow, \uparrow\rangle$



$|\downarrow, \uparrow\rangle$

$|\uparrow, \downarrow\rangle$

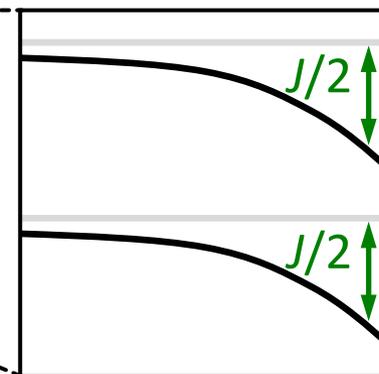


$|\downarrow, \downarrow\rangle$

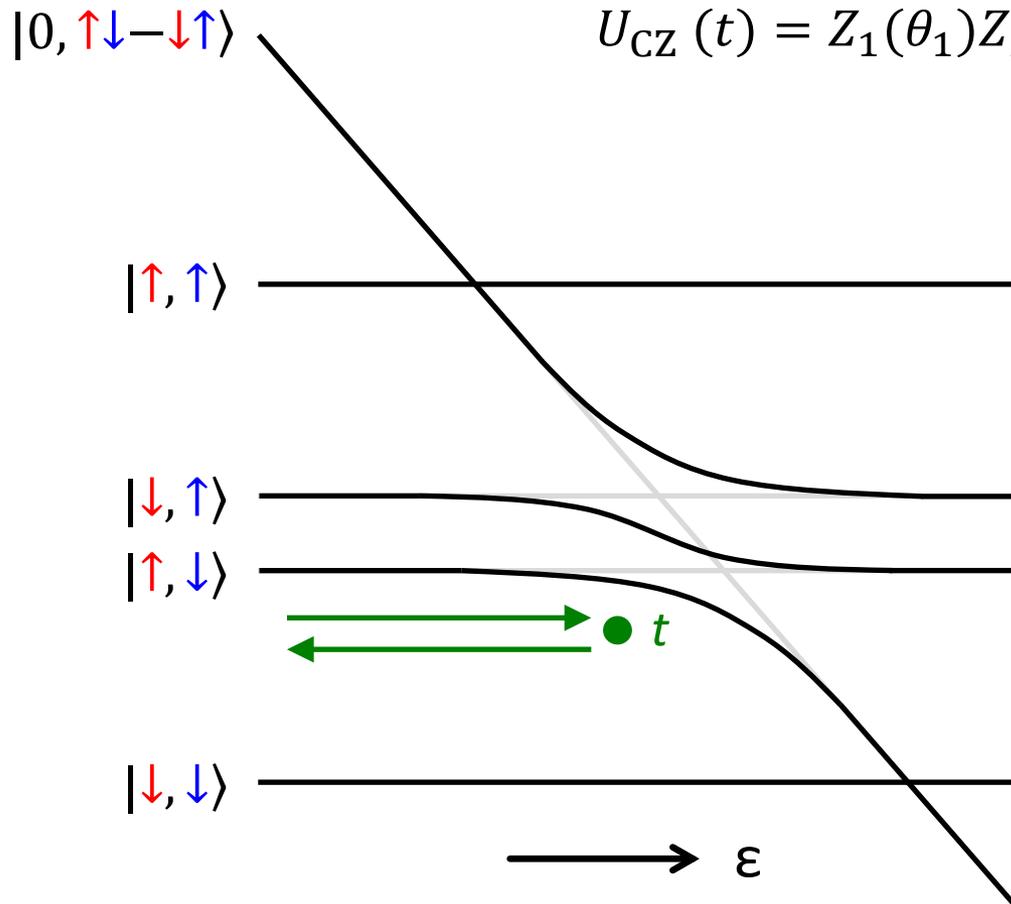
$\rightarrow \epsilon$

交換相互作用

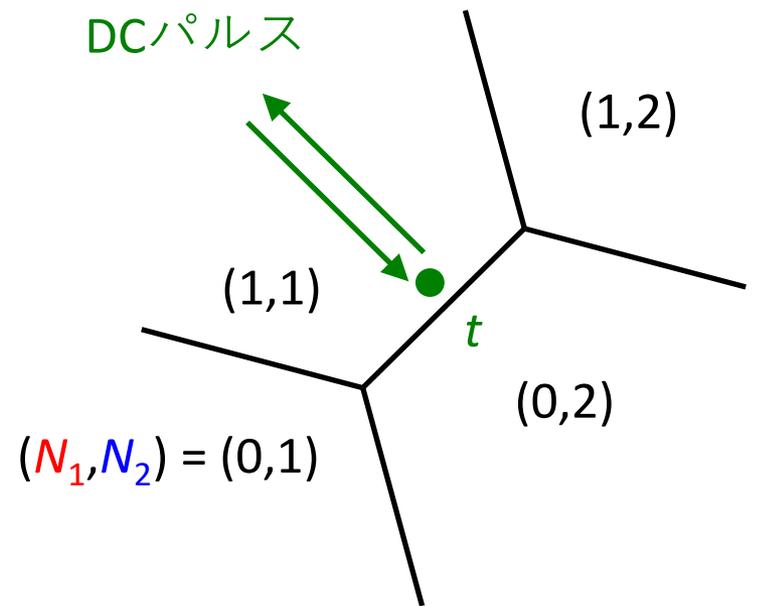
$$J(\epsilon) \approx 10 \text{ MHz}$$



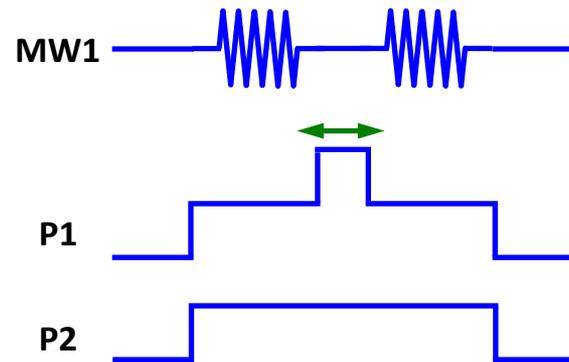
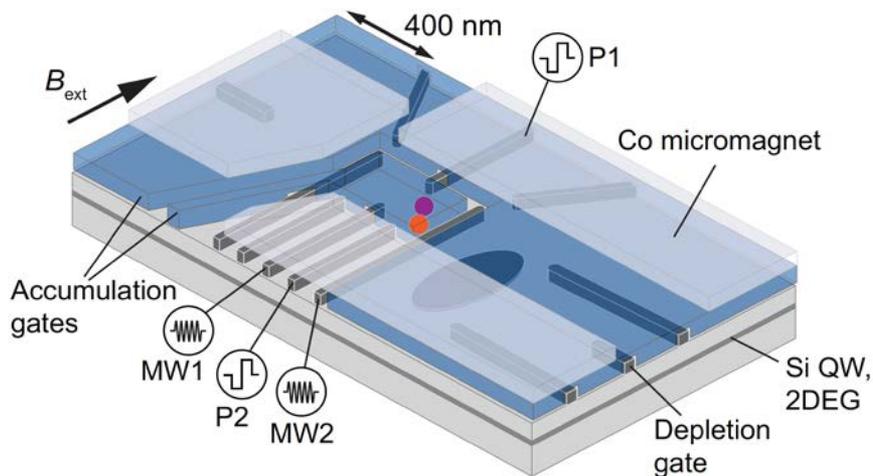
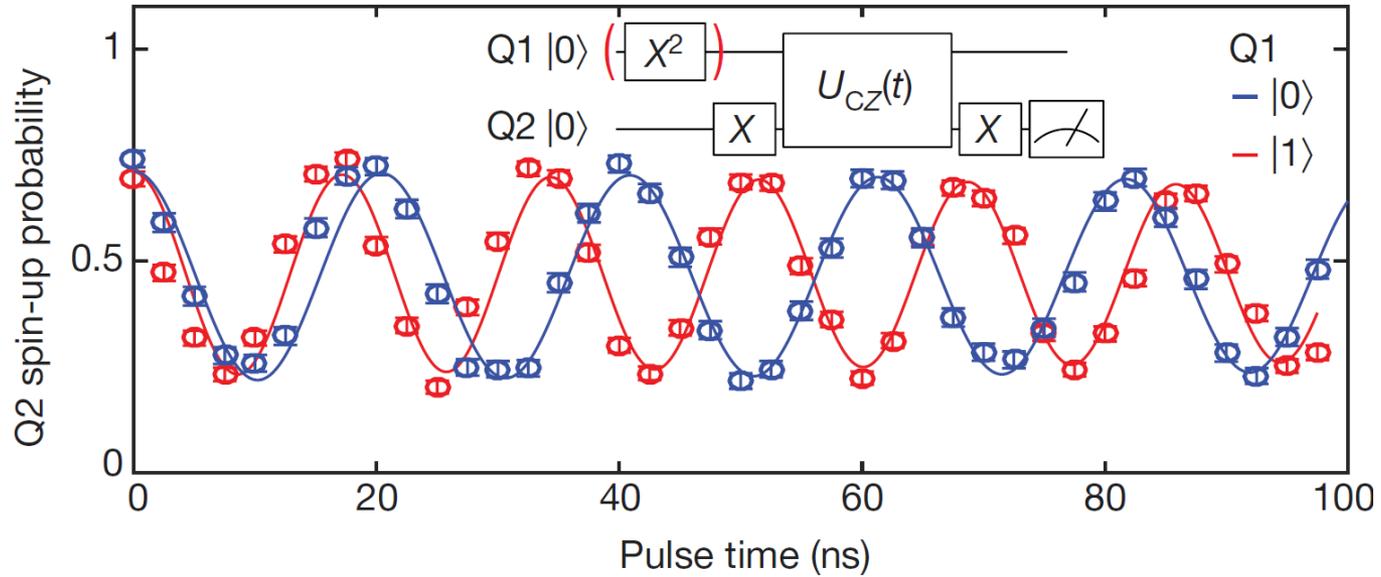
# CZゲート



$$U_{\text{CZ}}(t) = Z_1(\theta_1)Z_2(\theta_2) \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & e^{i\pi Jt/2} & 0 & 0 \\ 0 & 0 & e^{i\pi Jt/2} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

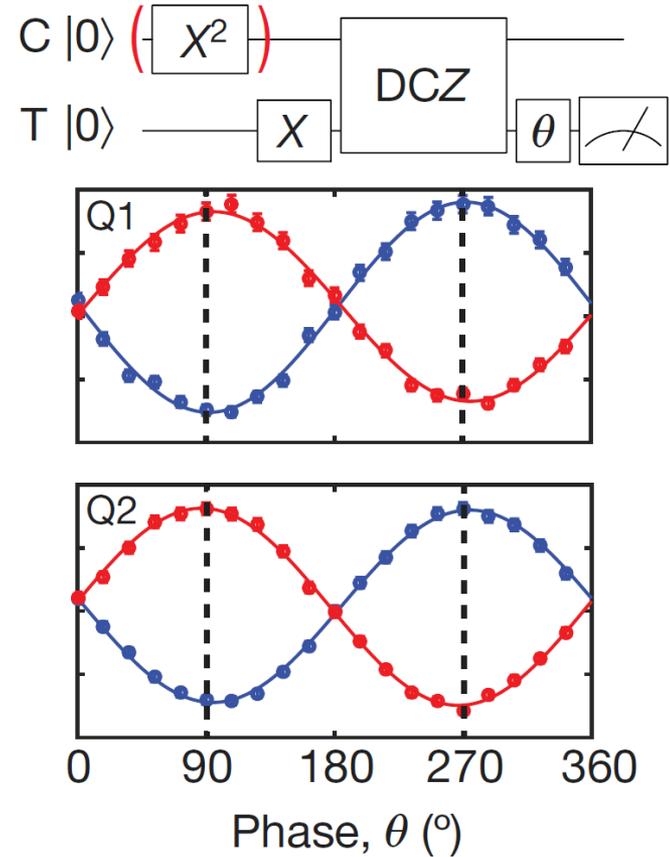
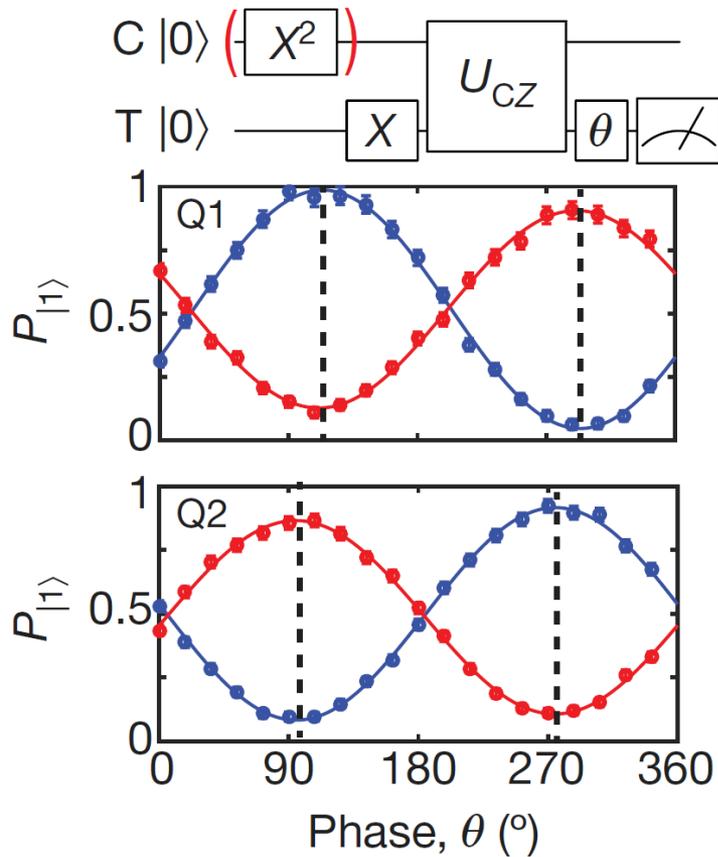


# CZゲート



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

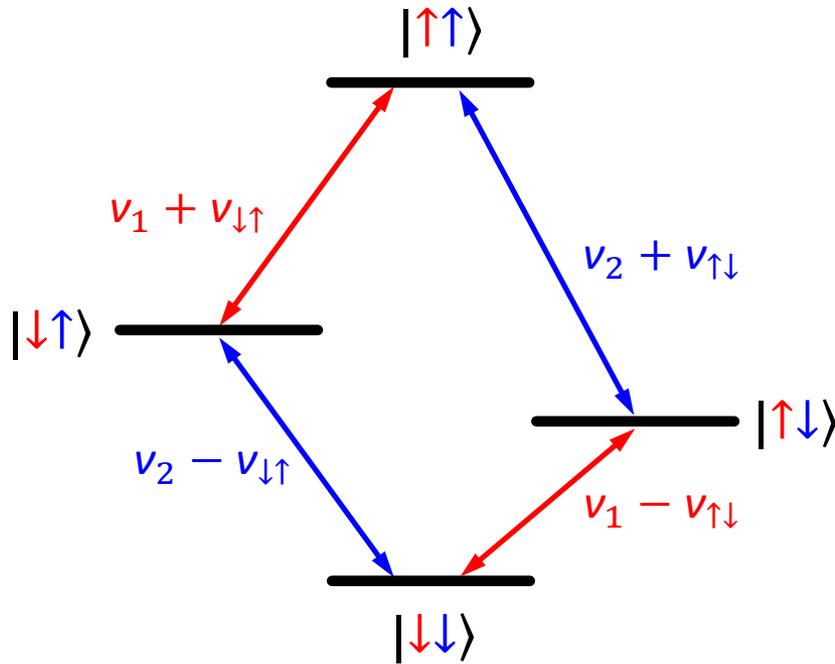
# CZゲート



$$DCZ = U_{CZ} (1/2J) X_1^2 X_2^2 U_{CZ} (1/2J)$$

# 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 $\pi$ パルスにより2量子ビットゲートが実現可能

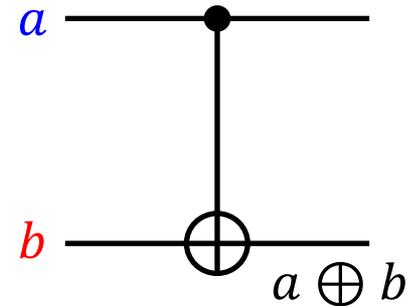
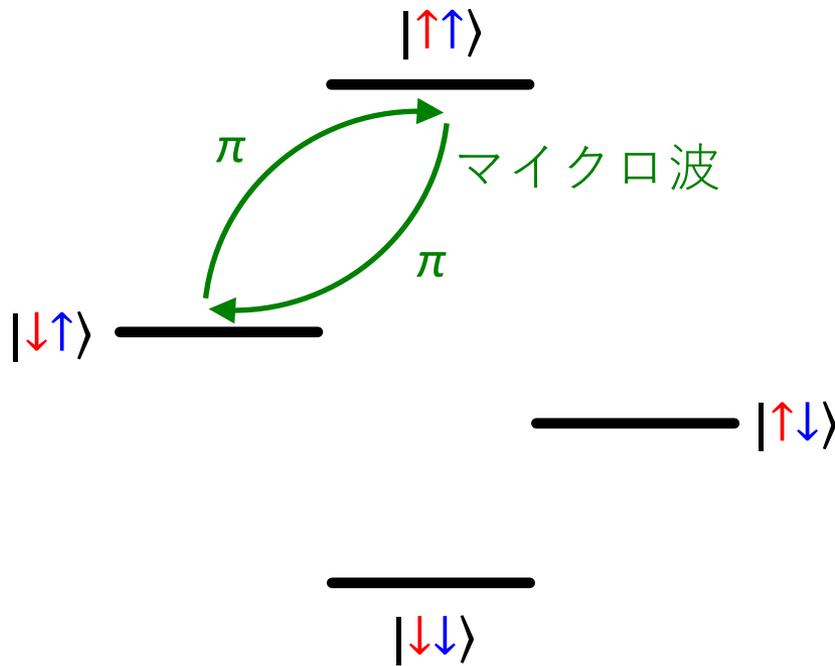
e.g. CNOTゲート

$$|TC\rangle = |\uparrow\uparrow\rangle = |11\rangle \longrightarrow |01\rangle$$

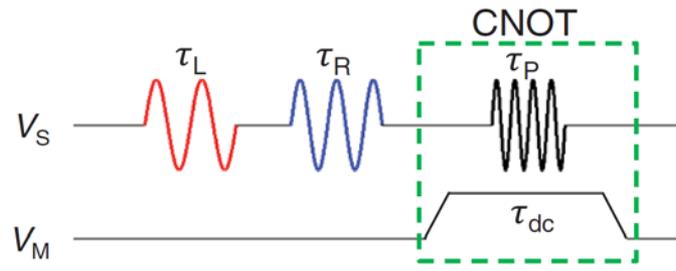
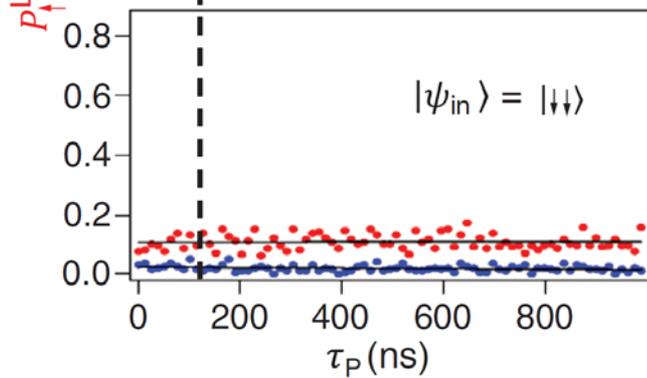
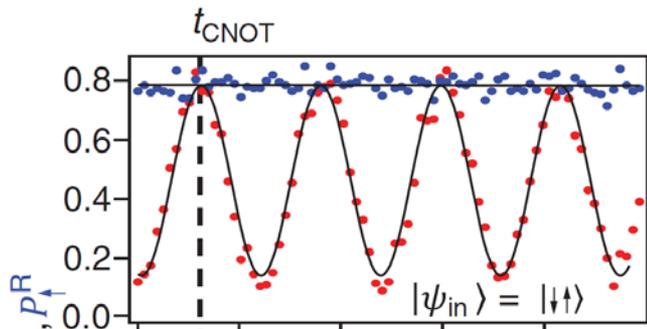
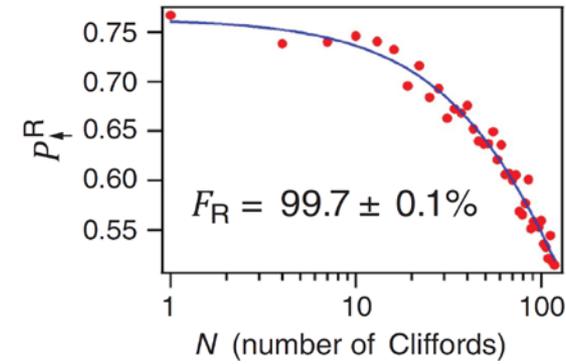
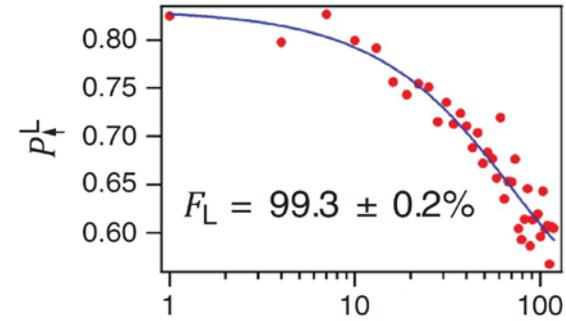
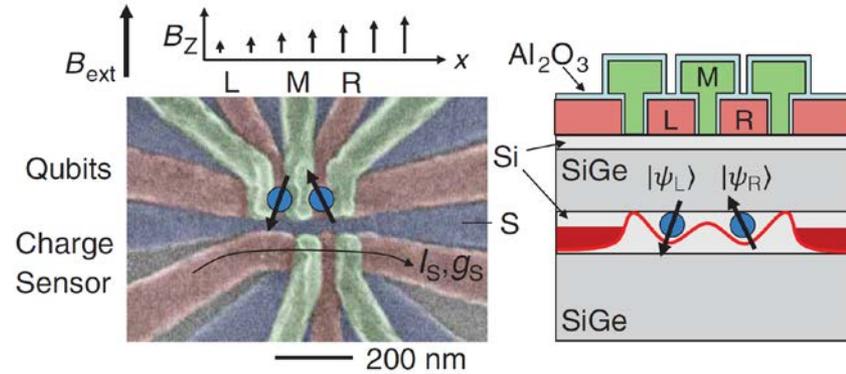
$$|\uparrow\downarrow\rangle = |10\rangle \longrightarrow |10\rangle$$

$$|\downarrow\uparrow\rangle = |01\rangle \longrightarrow |11\rangle$$

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

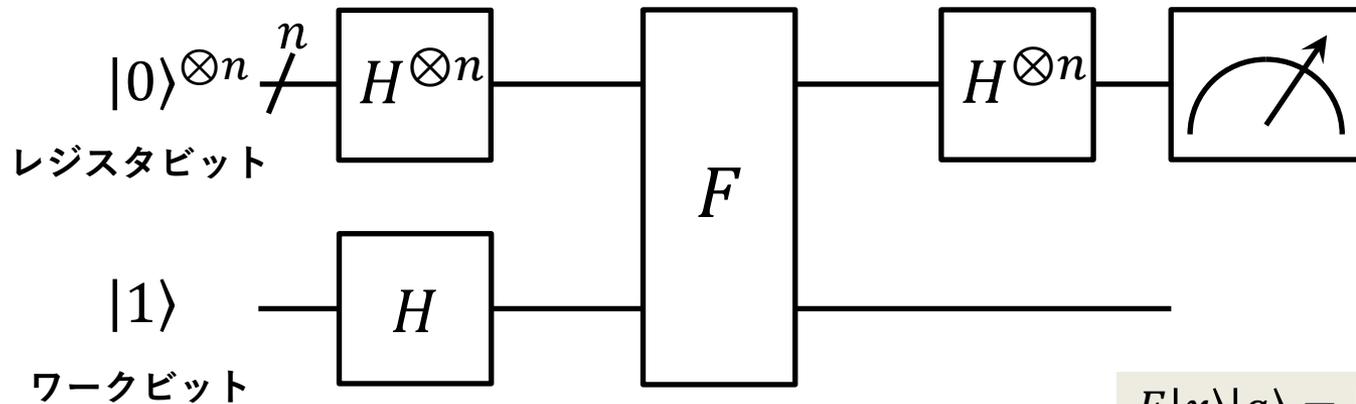


# CNOTゲート



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

# ドイチェ・ジヨザのアルゴリズム



$$F|x\rangle|a\rangle = |x\rangle|a \oplus f(x)\rangle$$

$$|0 \oplus f(x)\rangle - |1 \oplus f(x)\rangle = (-1)^{f(x)}(|0\rangle - |1\rangle)$$

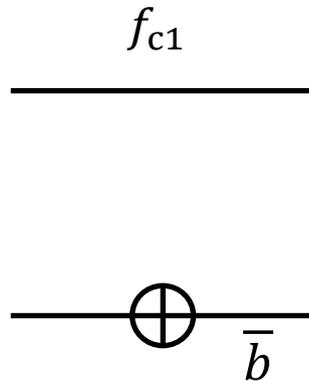
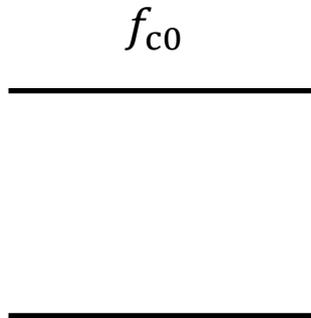
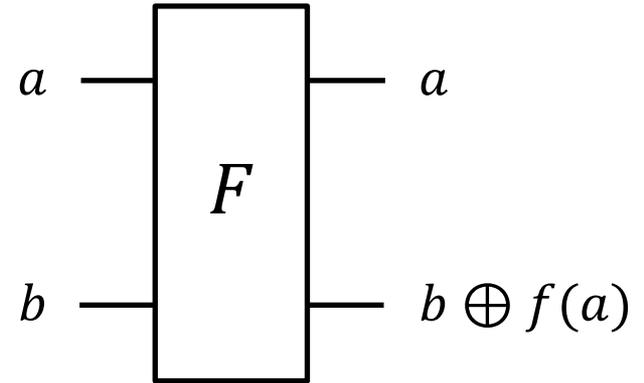
$$\frac{1}{\sqrt{2^n}} \sum_x |x\rangle \left( \frac{|0\rangle - |1\rangle}{\sqrt{2}} \right) \xrightarrow{F} \frac{1}{\sqrt{2^n}} \sum_x (-1)^{f(x)} |x\rangle \left( \frac{|0\rangle - |1\rangle}{\sqrt{2}} \right)$$

$$(H^{\otimes n}) \otimes I \xrightarrow{\quad} \sum_{x,y} \frac{(-1)^{f(x)+x \cdot y}}{2^n} |y\rangle \left( \frac{|0\rangle - |1\rangle}{\sqrt{2}} \right)$$

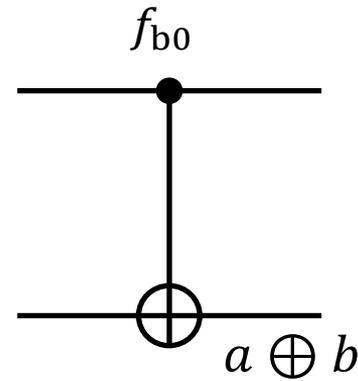
$f(x)$ がconstantのときRB  
は確率1で $|0\rangle^{\otimes n}$ に戻る

# 1ビットのFゲート

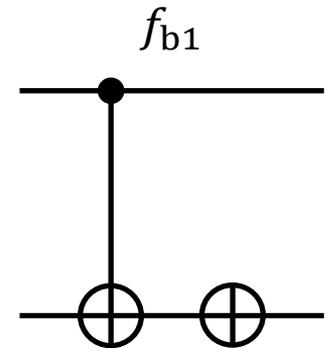
$a$	constant		balanced	
	$f_{c0}$	$f_{c1}$	$f_{b0}$	$f_{b1}$
0	0	1	0	1
1	0	1	1	0



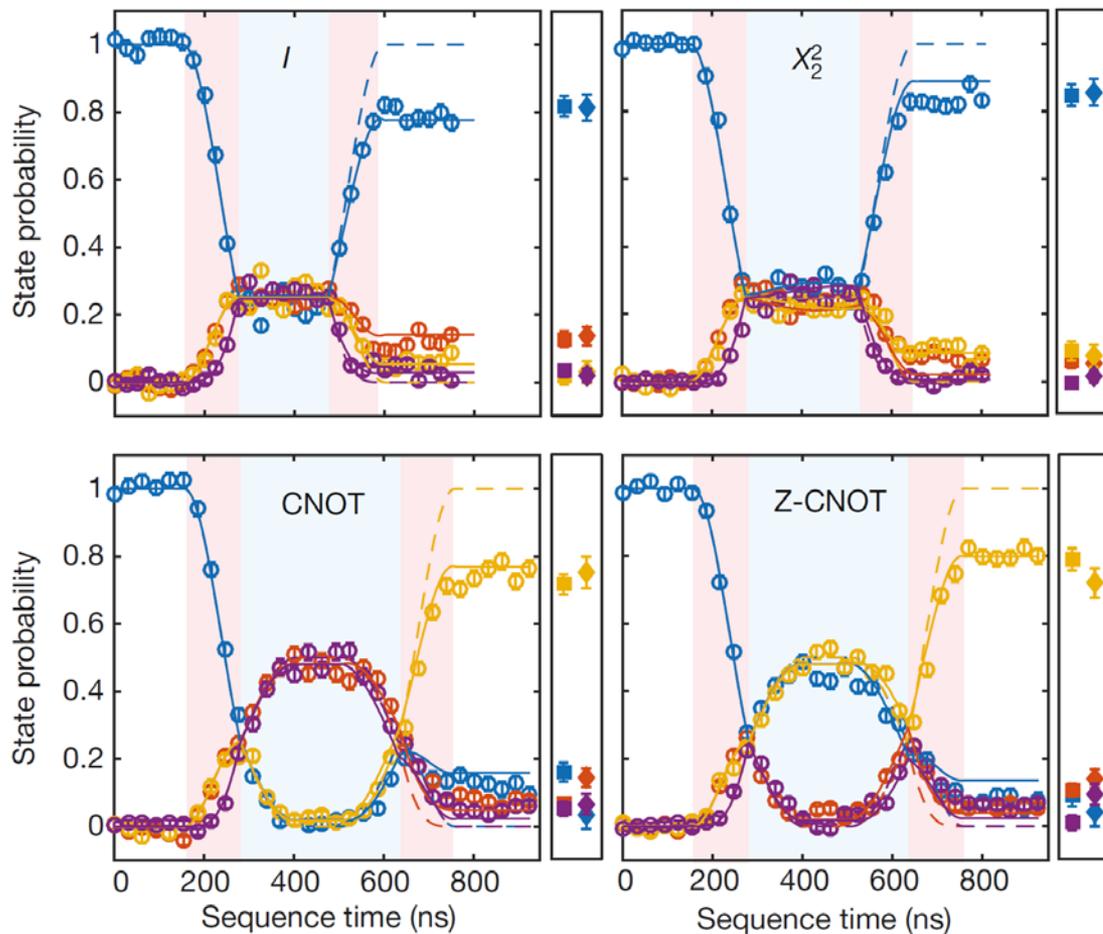
NOTゲート



制御NOTゲート

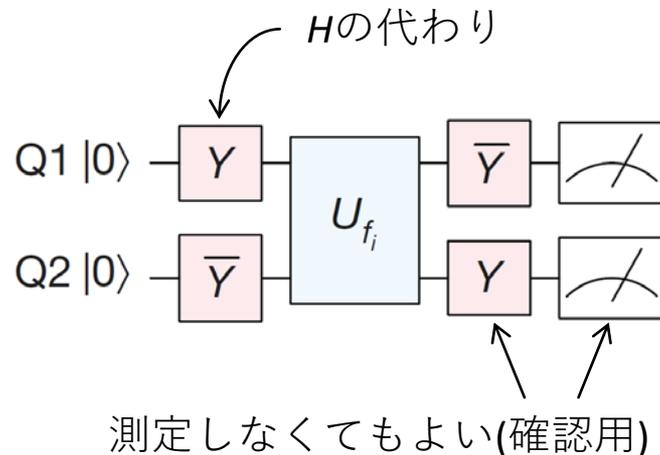


# ドイチュ・ジョザアルゴリズムの実行



○ Experiment    - - - Ideal    ——— With noise

● |00>    ● |01>    ● |10>    ● |11>



# シリコンスピン系実験の現状

方式	1量子ビット	2量子ビット	多量子ビット化
単一ドナー	$T_{2e}^{\text{CPMG}} = 559 \text{ ms}$ $T_{2n+}^{\text{CPMG}} = 35.6 \text{ s}$ $F_{2n+} = 99.99\% (*1)$	$F^{e-e} = \text{N/A}$ 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	$T_2^{\text{CPMG}} = 28 \text{ ms} (*2)$ $F^{\text{RB}} = 99.957\% (*3)$	$F^{\text{Bell}} = 89\%$ $F^{\text{RB}} = 98\% (*6)$	CMOS/DRAM技術 との融合 (*9,10)
Si/SiGe量子ドット	$T_2^{\text{CPMG}} = 3.1 \text{ ms}$ $F^{\text{RB}} = 99.926\% (*4)$	$F^{\text{Bell}} = 89\% (*7)$	スピン-MW光子結合 による回路QED (*11,12)

$T_{2e, 2n+}$ :  $T_2$  of the electron spin bound to the donor ( $^{31}\text{P}^0$ ) or of the nuclear spin of the ionized donor ( $^{31}\text{P}^+$ )

$F^{\text{RB(Bell)}}$ : Fidelity deduced from randomized benchmarking (state tomography of a Bell state)

$F^{\text{Bell}, e-n}$ : Fidelity of a Bell state between electron and nuclear spins within the same donor

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

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

\*3: arXiv:1807.09500 Yang *et al.*

\*4: Nature Nano. **13**, 102 (2018) Yoneda *et al.*

\*5: Nature Nano. **11**, 242 (2016) Dehollain *et al.*

\*6: arXiv:1805.05027 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: arXiv:1711.03807 Li *et al.*

\*11: Nature **555**, 599 (2018) Mi *et al.*

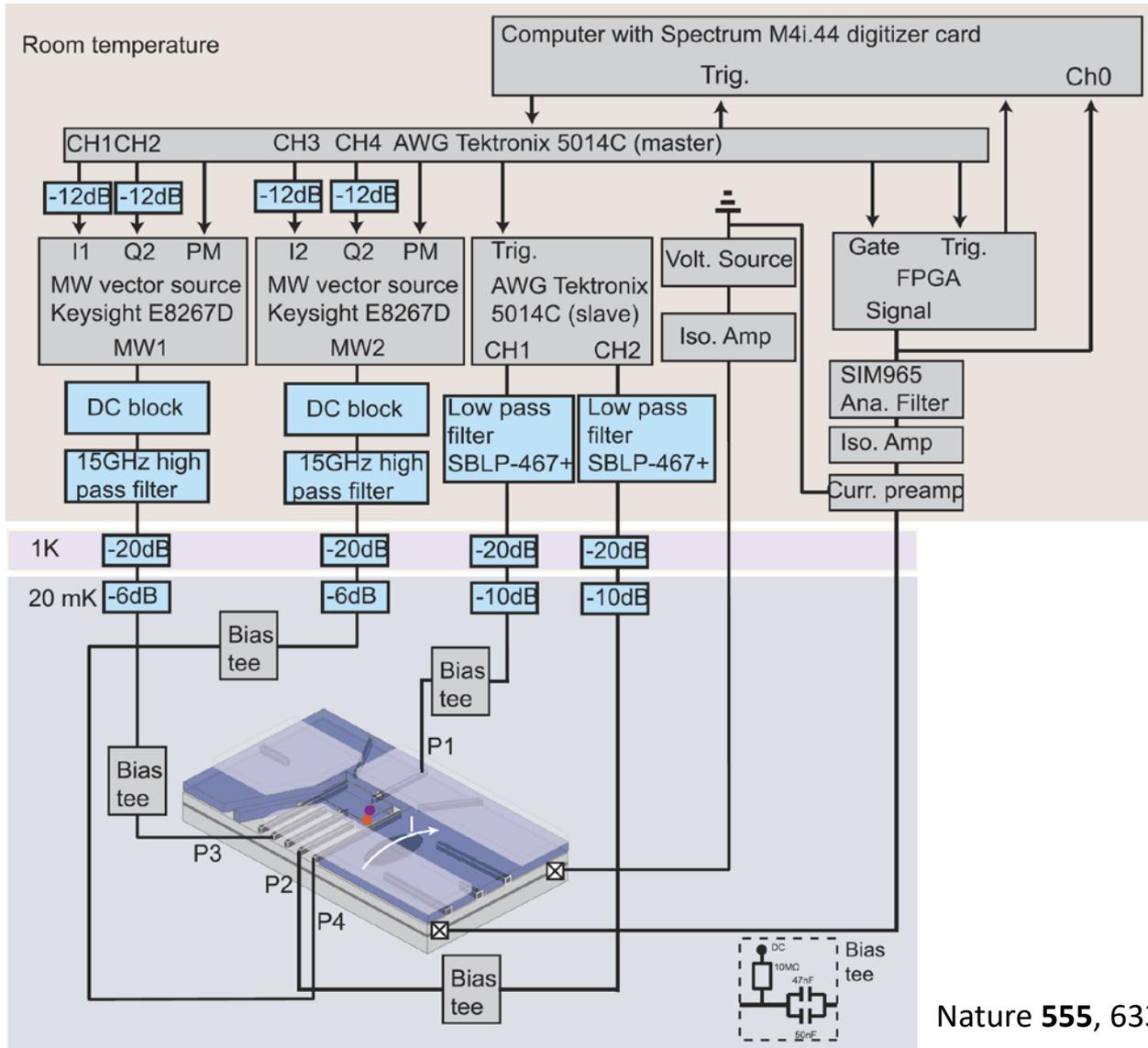
\*12: Science **359**, 1123 (2018) Samkharadze *et al.*

# シリコンスピン系実験の現状

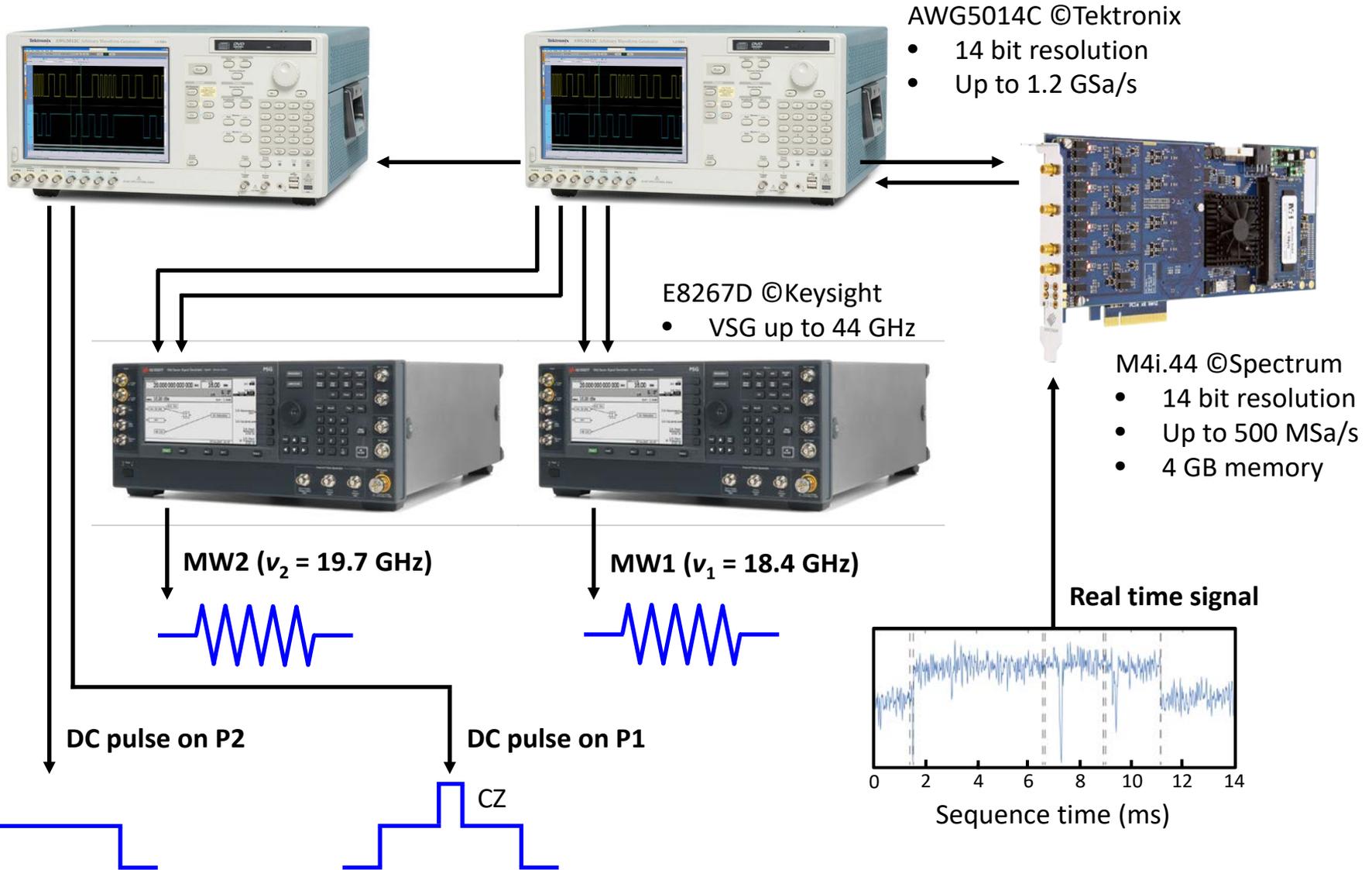
方式	1量子ビット	2量子ビット	多量子ビット化
単一リンドナー	$T_{2e}^{\text{CPMG}} = 559 \text{ ms}$ $T_{2n+}^{\text{CPMG}} = 35.6 \text{ s}$ $F_{2n+} = 99.99\% (*1)$	$F^{e-e} = \text{N/A}$ cf. $F^{\text{Bell}, e-n} = 97\% (*5)$	“フリップフロップ” 量子ビット (*8)
MOS量子ドット	$T_2^{\text{CPMG}} = 28 \text{ ms} (*2)$ $F^{\text{RB}} = 99.957\% (*3)$	$F^{\text{Bell}} = 89\%$ $F^{\text{RB}} = 98\% (*6)$	CMOS/DRAM技術 との融合 (*9,10)
Si/SiGe量子ドット	$T_2^{\text{CPMG}} = 3.1 \text{ ms}$ $F^{\text{RB}} = 99.926\% (*4)$	$F^{\text{Bell}} = 89\% (*7)$	スピン-MW光子結合 による回路QED (*11,12)

とはいえ、数字だけに囚われないようにしましょう

# セットアップ



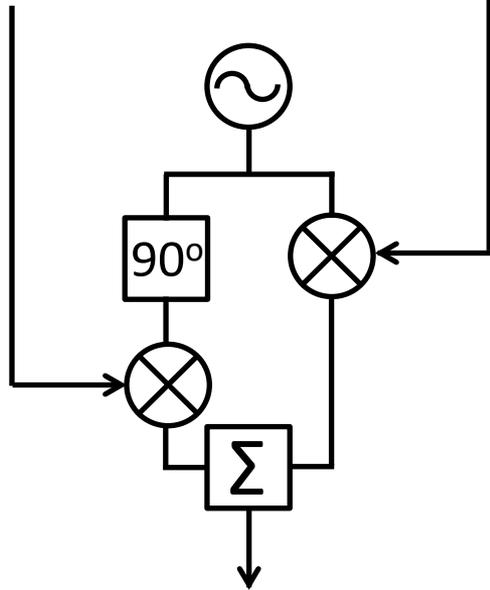
# セットアップ(室温)



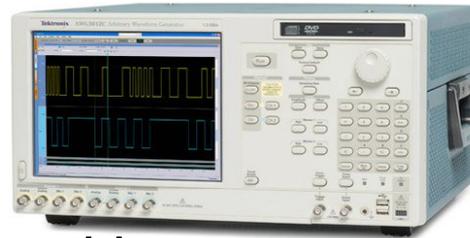
# IQ変調によるパルス生成

$$I(t) = A(t) \cos(2\pi\nu_m t + \theta)$$

$$Q(t) = A(t) \sin(2\pi\nu_m t + \theta)$$



$$I(t) \cos(2\pi\nu_{LO}t) - Q(t) \sin(2\pi\nu_{LO}t) = A(t) \cos[2\pi(\nu_{LO} + \nu_m)t + \theta]$$



AWG5014C ©Tektronix

- 14 bit resolution
- Up to 1.2 GSa/s

E8267D ©Keysight

- VSG up to 44 GHz



MW1 ( $\nu_1 = 18.4$  GHz)



# 今後は…



M9383A etc ©Keysight

- VSG up to 40 GHz



M3302A etc ©Keysight

- 500 MSa/s, 16bit AWG
- 500 MSa/s, 14 bit digitizer

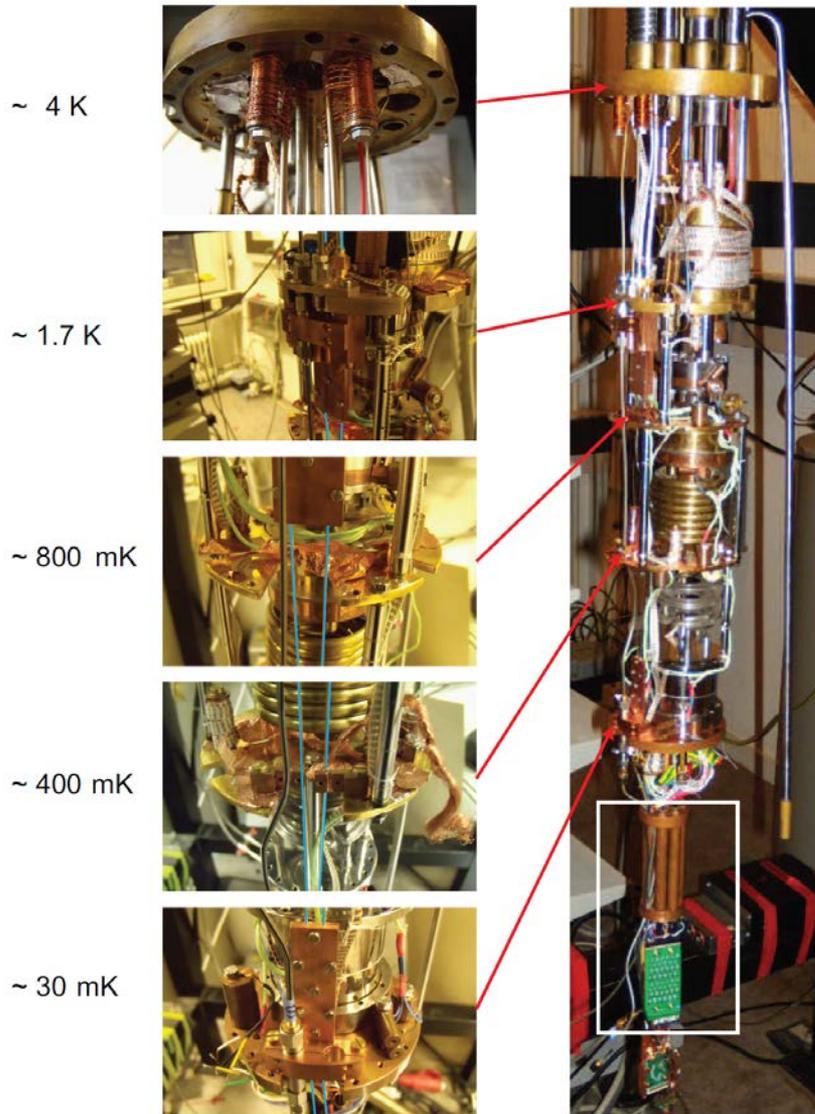


M9019A ©Keysight

- 18-slot chassis

**量子技術の発展のためには既存エレクトロニクスの発展も重要**  
(Keysightの回し者ではありません)

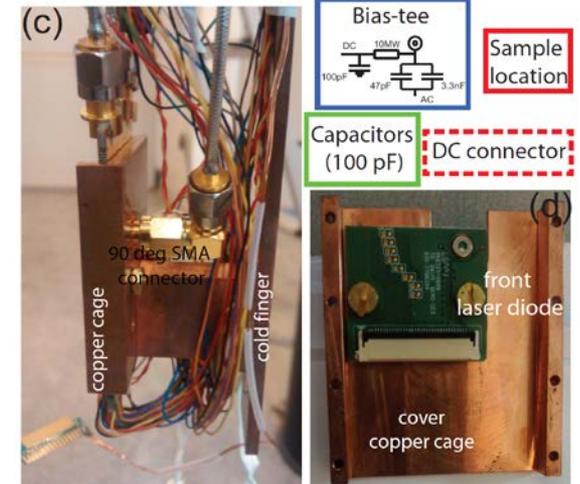
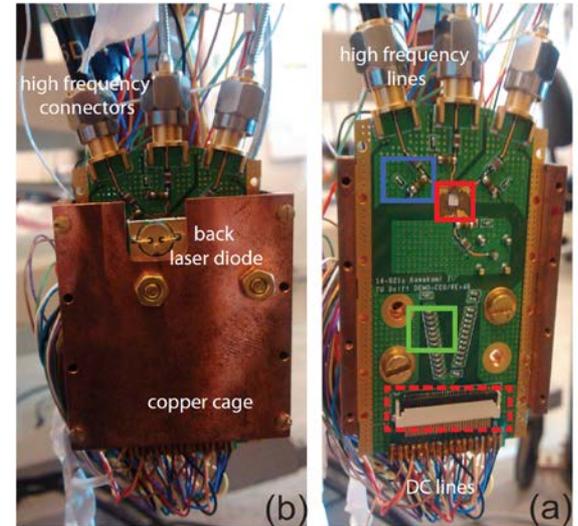
# セットアップ(低温)



cold finger



copper powder filters



# 希釈冷凍機

← “見慣れた”無冷媒型

## 超伝導量子回路実験との違い

- 磁場高め・周波数高め
- ゲート電極用のDCラインが多数必要

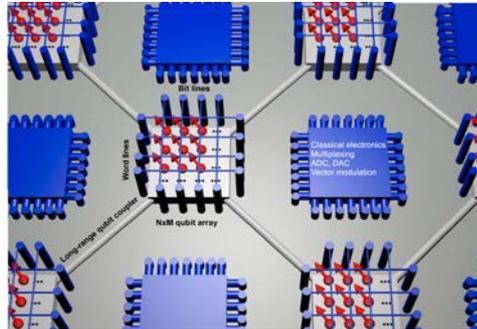
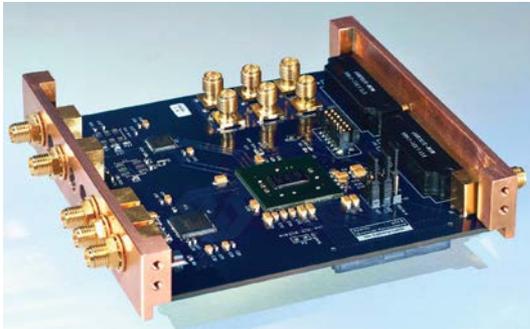


“現場希望者”は  
ご一読を...

(これに高周波技術を足した  
本があると素晴らしい...)

# (スピン系に特有の)展望

エレクトロニクスの高低温動作 and/or 量子ビットの高低温動作



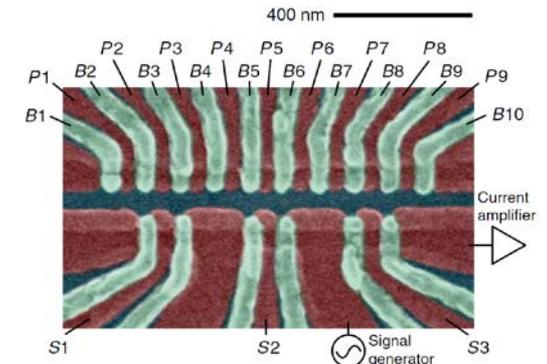
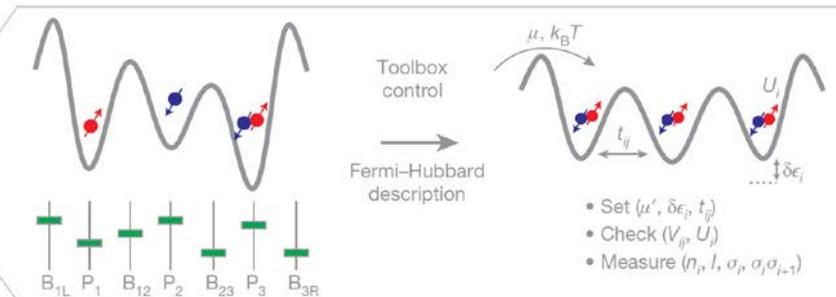
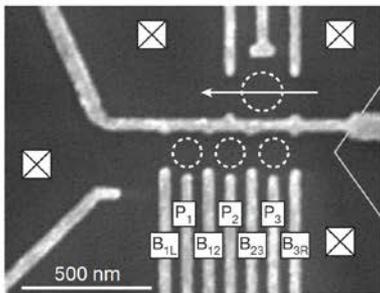
arXiv:1803.01774 Petit *et al.*

arXiv:1804.03364 Ono *et al.*

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

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

## フェルミオン系の量子シミュレーション



Nature **548**, 70 (2017) Hensgens *et al.*

Phys. Rev. Appl. **6**, 054013 (2016) Zajac *et al.*