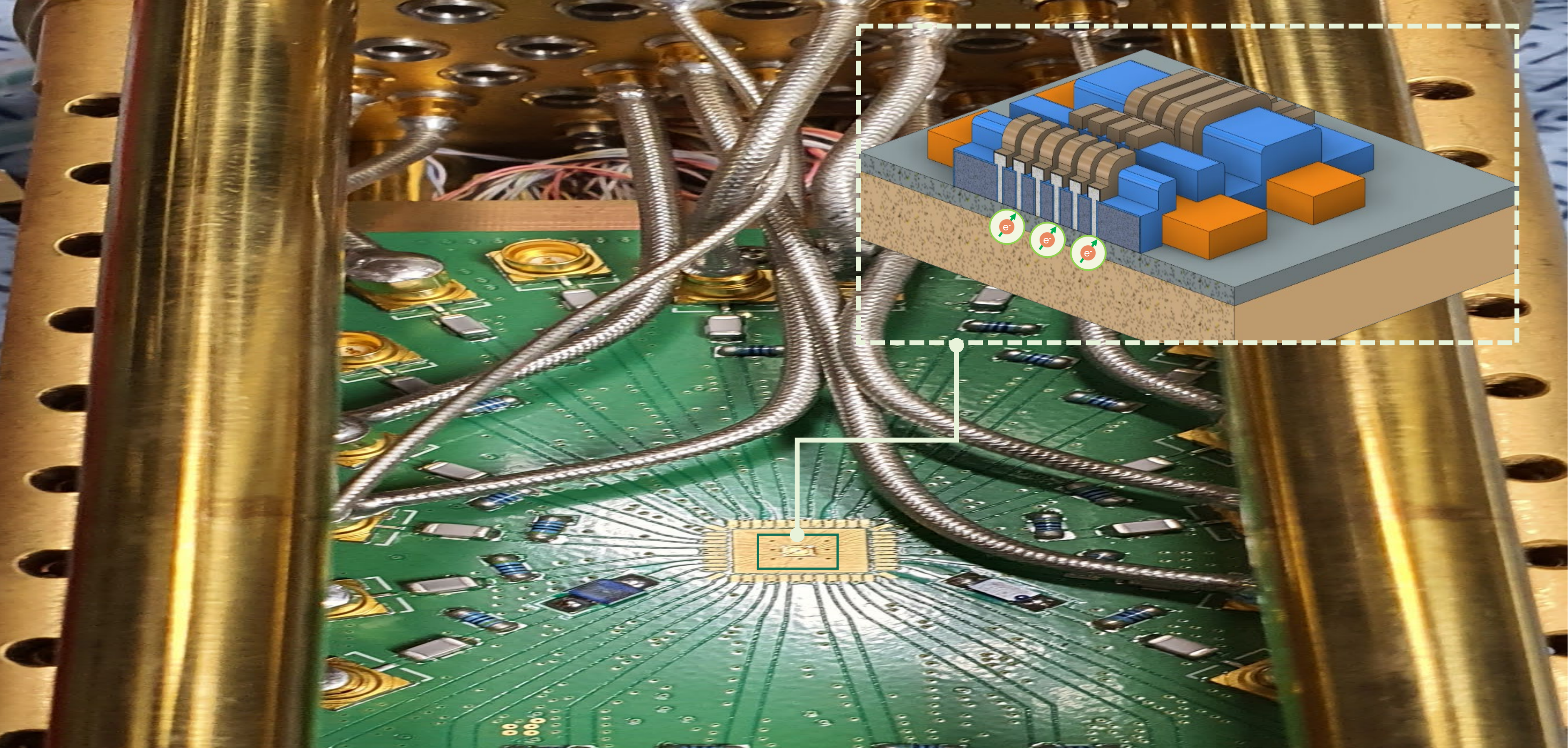
May/20/2022

2022 중시계 여름학교



Quantum dot spin qubits I: basic concepts

(Slide courtesy : 윤종인, 장원진)

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Outline

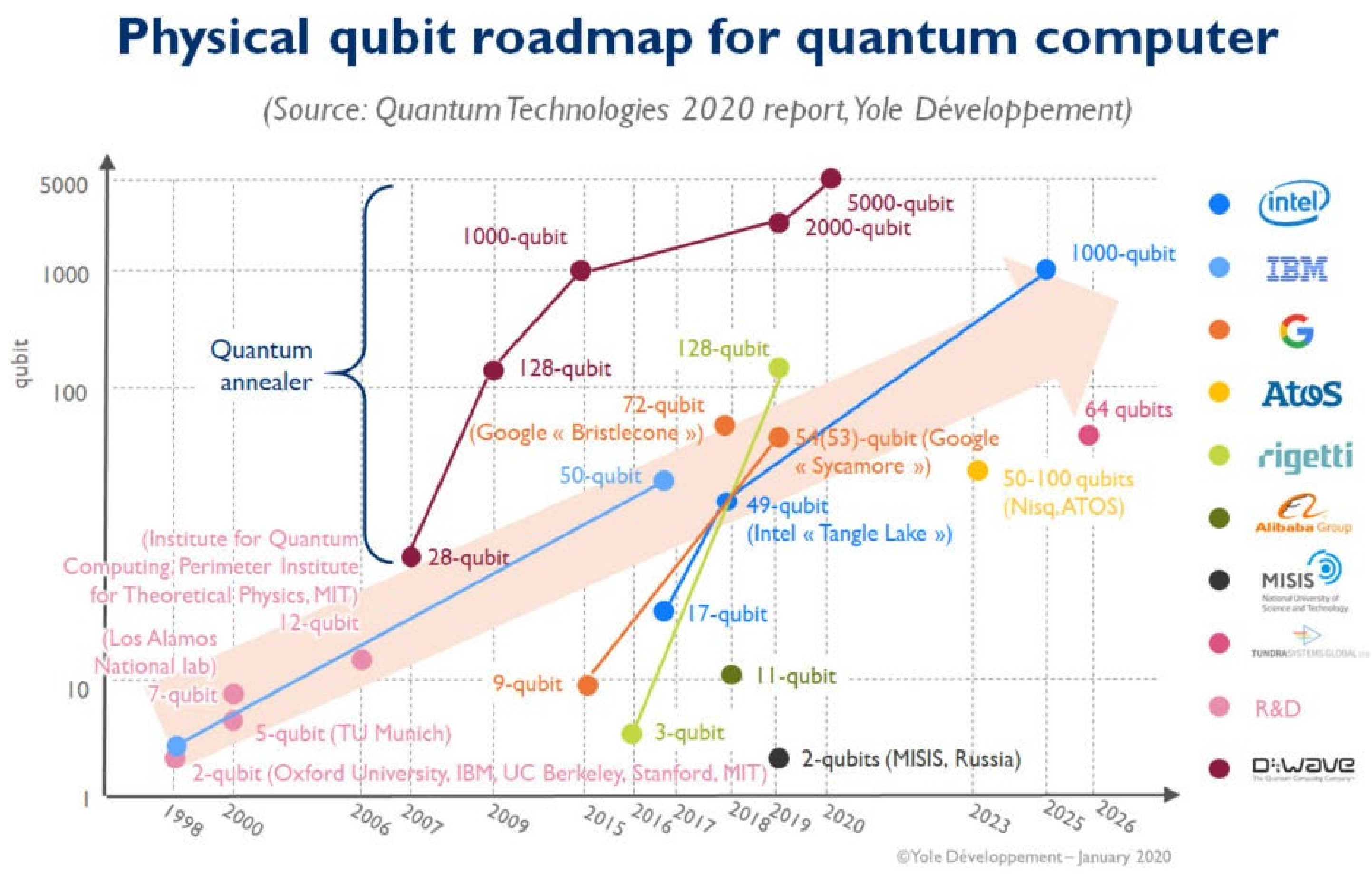
Lecture 1. Basics

- Background *Semiconductor quantum dot quantum computing*
- Approach *Basic concepts, experimental details*
- Single spin qubits *1Q, 2Q gates*
- Singlet-Triplet qubits *1Q, 2Q gates*

Lecture 2. More than two qubits

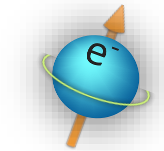
- Three, Four, Six qubit operations *Recent achievements*
- Coherent spin shuttling *Linking distant qubits*
- Scaling issue *Hot qubits, integration issue…*

양자컴퓨터 하드웨어 현황과 로드맵



See also: 주요 하드웨어 개발기관의 로드맵: https://research.ibm.com/blog/ibm-quantum-roadmap, https://ionq.com/posts/december-09-2020-scaling-quantum-computer-roadmap, https://www.eetimes.eu/cea-leti-details-silicon-based-quantum-computing-roadmap/ 등

Quantum mechanical phase coherence

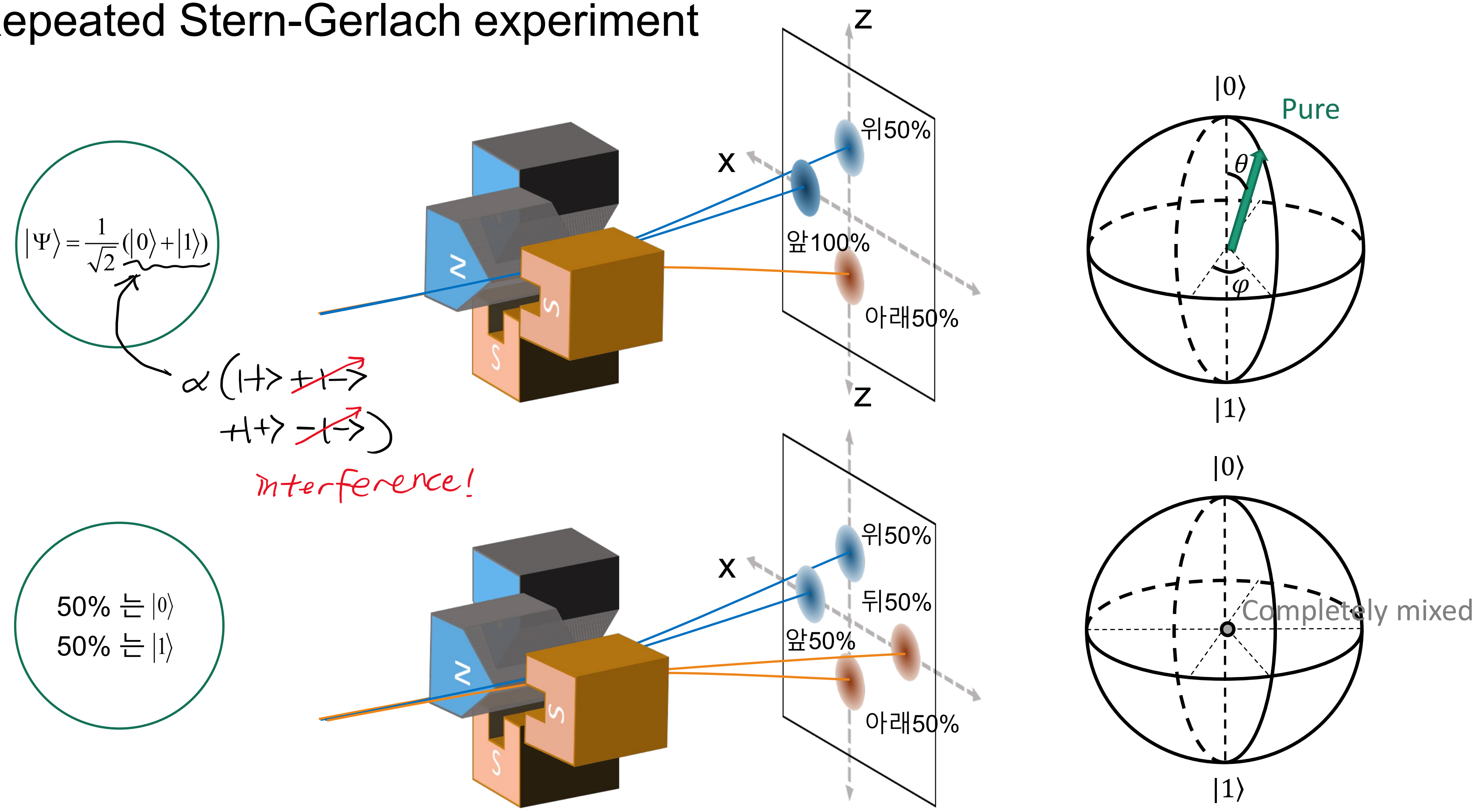


Superposition		Statistical Mixture
N개 집합 $$\|\Psi\rangle = \frac{1}{\sqrt{2}}(\|0\rangle + \|1\rangle)$$	$\neq$	N개 집합 50% 는 $\|0\rangle$ 50% 는 $\|1\rangle$

- 다른 점을 한단어로 ? *'coherence' : 간섭현상을 보일 수 있는 능력*
- 어떻게 구별 ?

Distinguishing superposition vs mixture

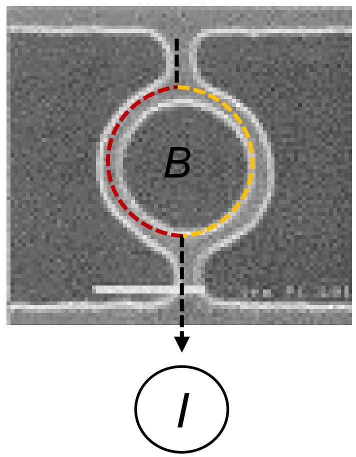
Repeated Stern-Gerlach experiment

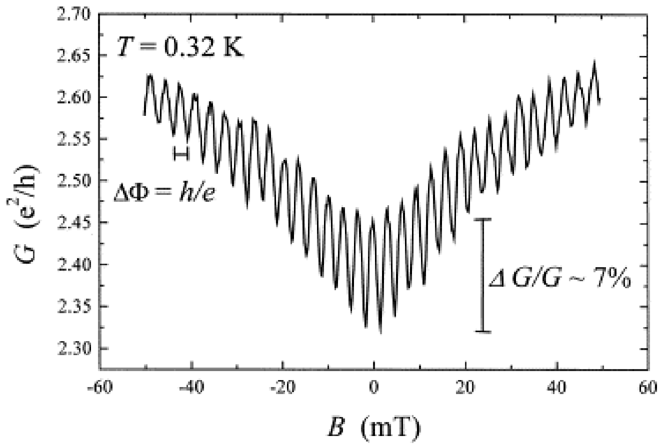


- 어떻게 구별 ? *토모그래피 : 모든 Measurement basis 에 대해 projection 해본다.*
- *Projective reconstruction – interference 는 어디에 ?*

What is *single-shot* measurement ?

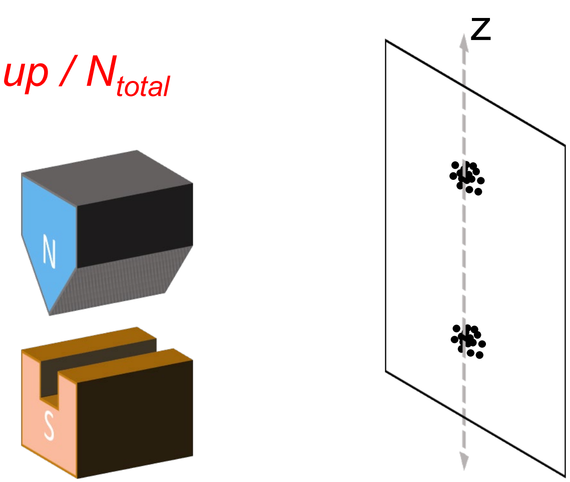
What is NOT single-shot experiment…





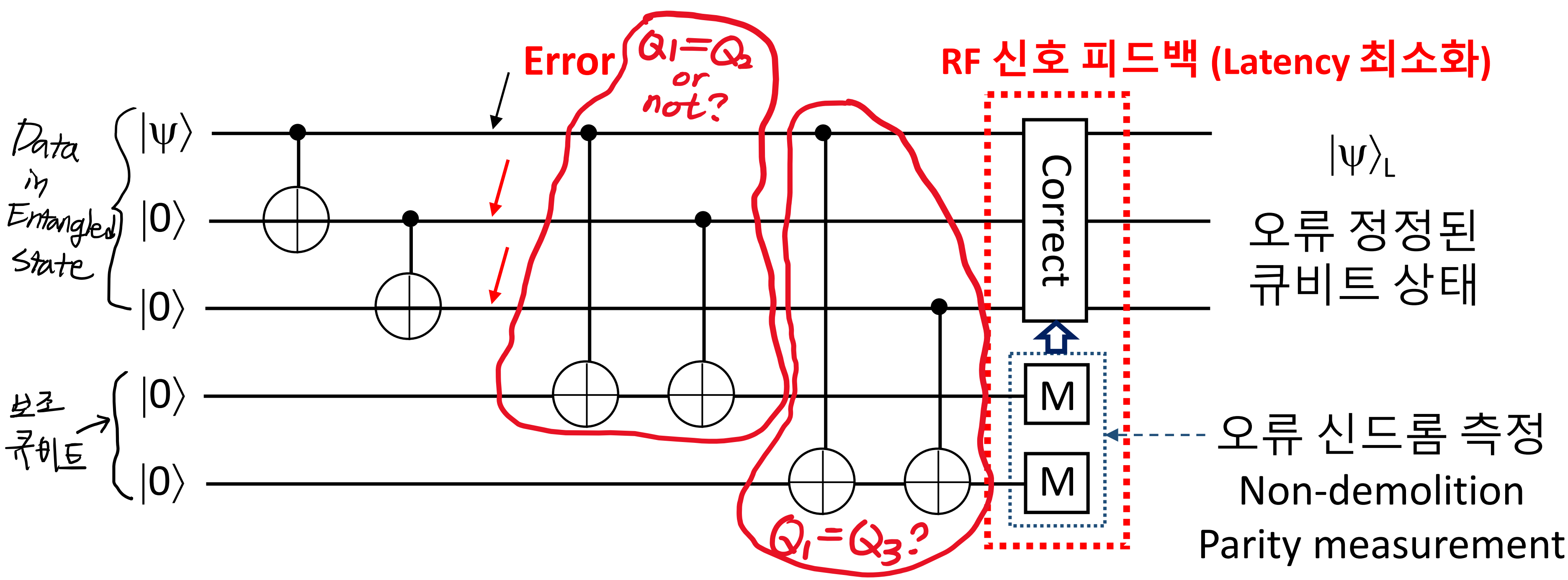
Really what QM textbook describes…

P_1 = #state up / N_{total}

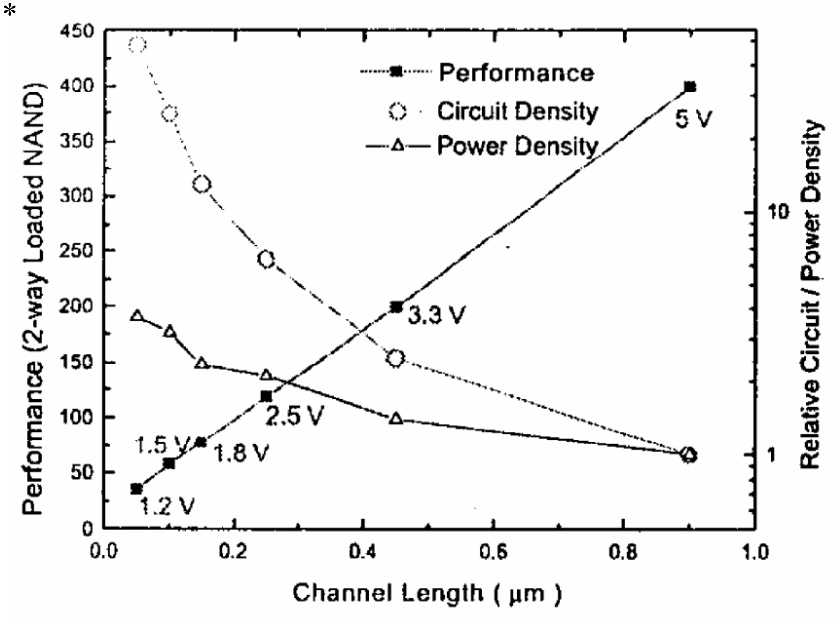


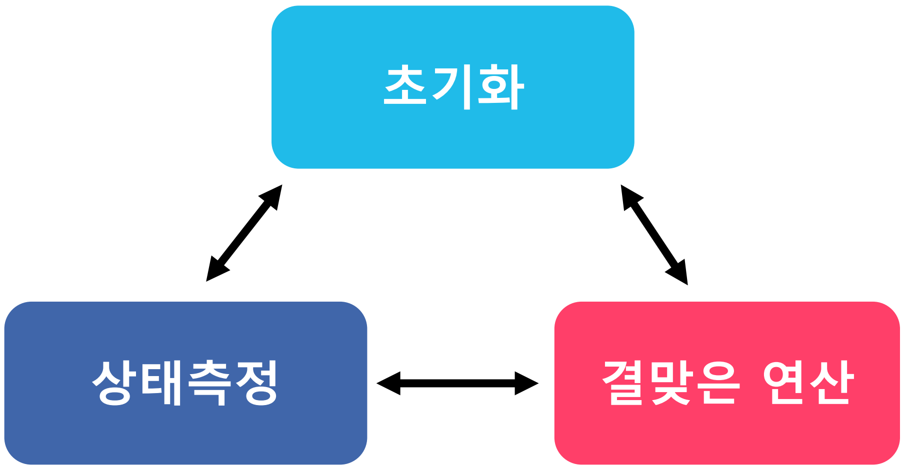
Why *single-shot* is important ?

- Ex. Quantum error correction
- 보조 큐비트의 오류 신드롬 측정 후 고속 피드백으로 실시간 오류 정정 (Single-shot !)



양자컴퓨터: 왜 만들기 어렵나?





고전 디지털 컴퓨터

(최근까지는) 트랜지스터를 30% 작게 만들면,

- *43% 동작속도 향상*
- *2x 집적도 향상*
- *30% 누설전류 감소*
- *65% 소모전력 감소*

작게: 어렵지만..

"일석다조"

양자 컴퓨터

- *So far : 극한환경 (극저온 and/or 초고진공)*

(원리적으로) 상충되는 목표,

- *상호작용 증가: 동작속도 향상, **but 결맞음 감소***
- *강한 상태 측정: SNR 증가, **but backaction***
- *다중큐비트: **crosstalk***

* G. G. Shahidi, "Challenges of CMOS scaling at below 0.1μm," The 12th International Conference on Microelectronics (2000)

Background

다양한 양자컴퓨팅 플랫폼

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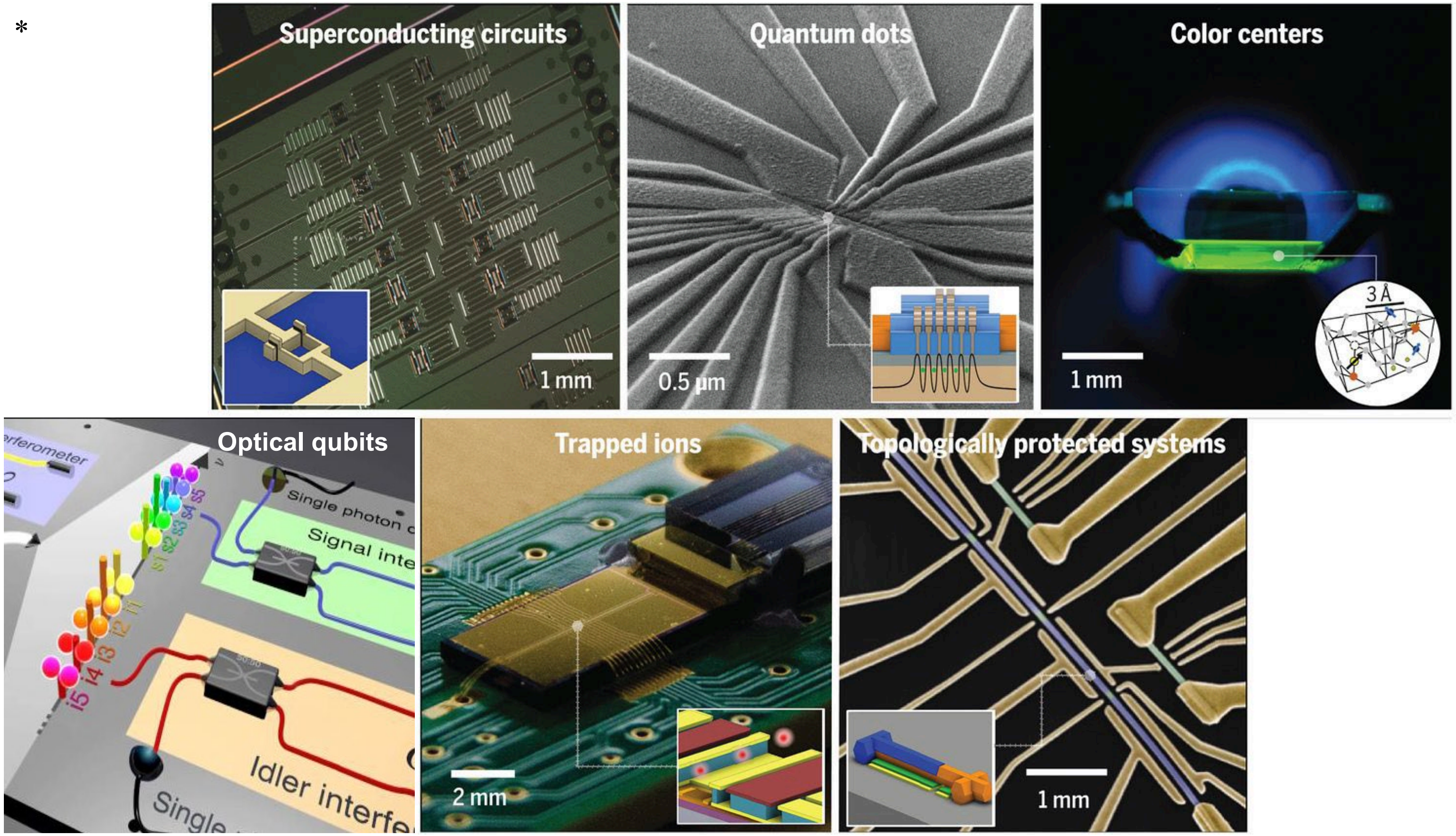

*Science. **372** 253 (2021)

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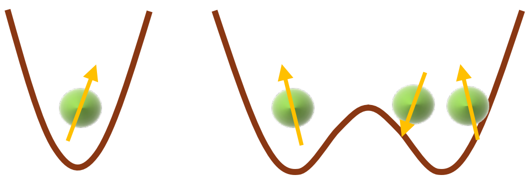
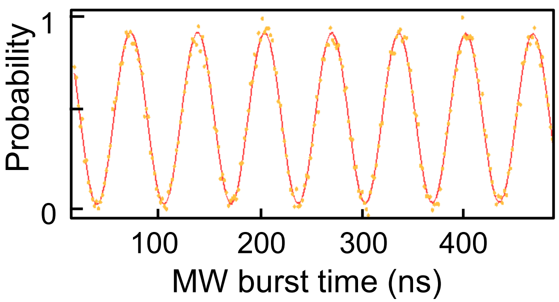
Background

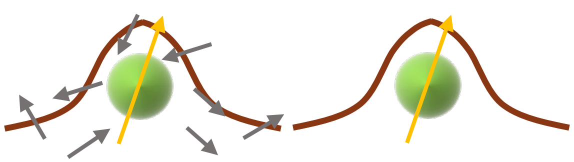
Why semiconductor QDQC?

Coherence



- Long-lived spins in semiconductors
- Canonical 2-level system
- Small leakage errors





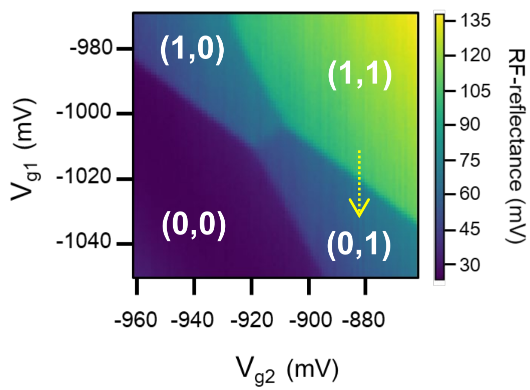
GaAs $T_2^{cpmg} > 350\ us$

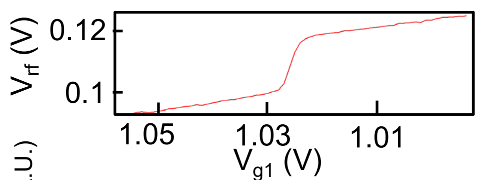
^{28}Si $T_2^* > 120\ us$

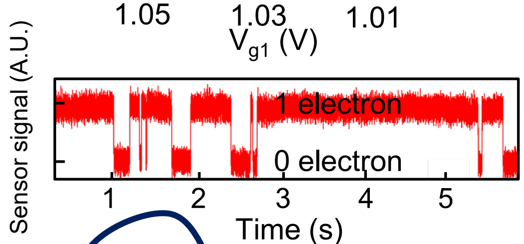
Nuclear bath spin polarization in GaAs

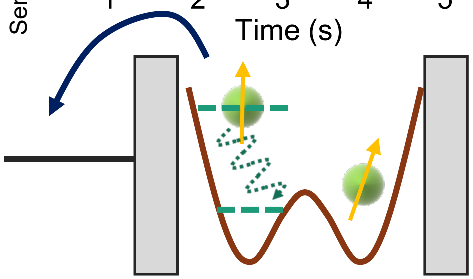
Small spin-orbit coupling & Small hyperfine interaction in purified ^{28}Si

Measurement



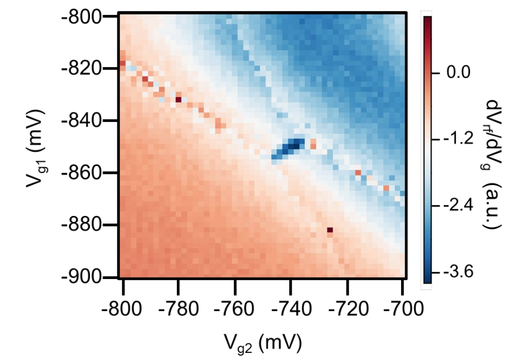


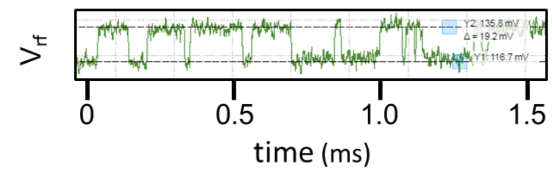


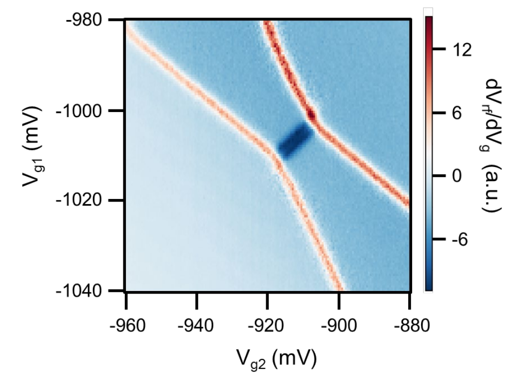


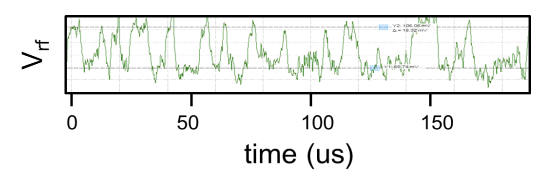
Long T_1 time → Single-shot measurement straightforward

Tunability









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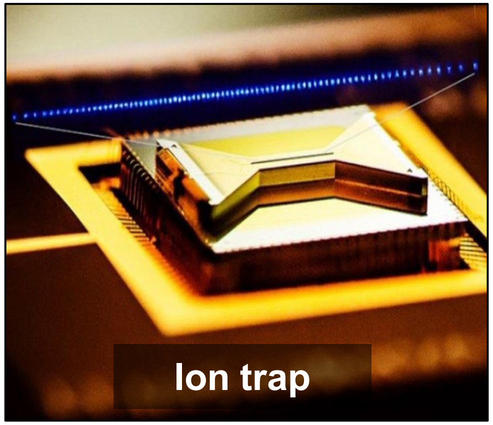
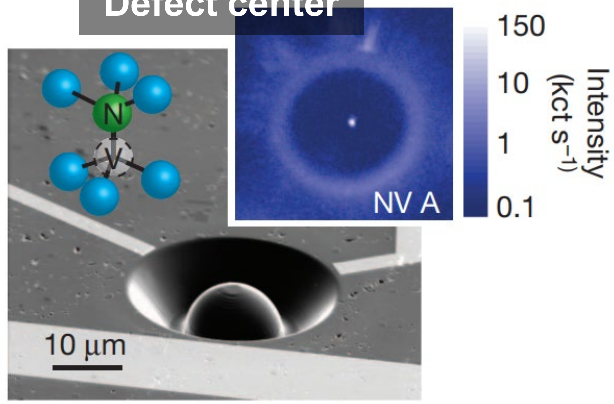
Approach : detailed description of experiments

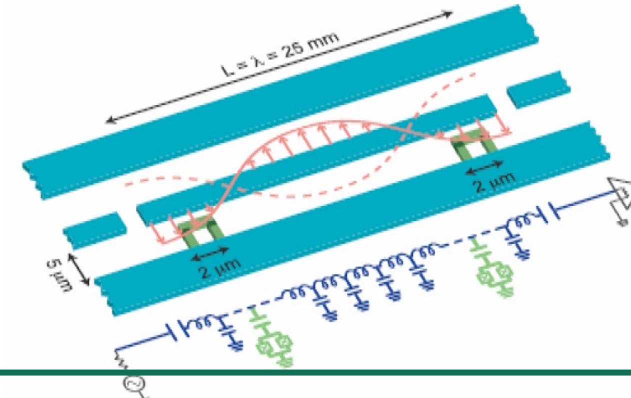
Single-shot measurements in physical systems



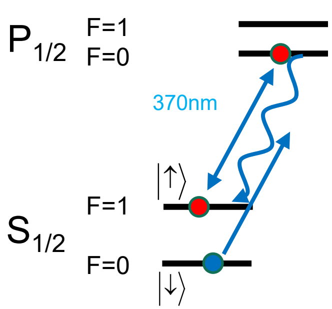
Defect center

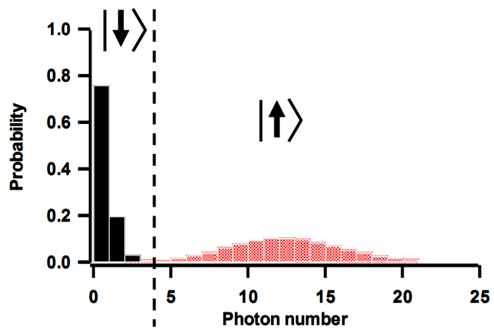


SC qubits

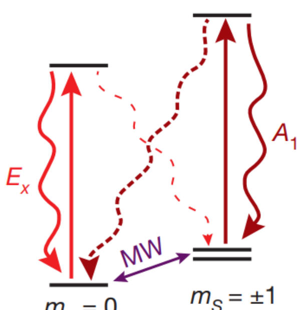


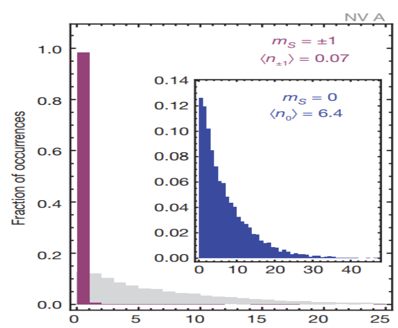
$^{171}Yb^{+}$



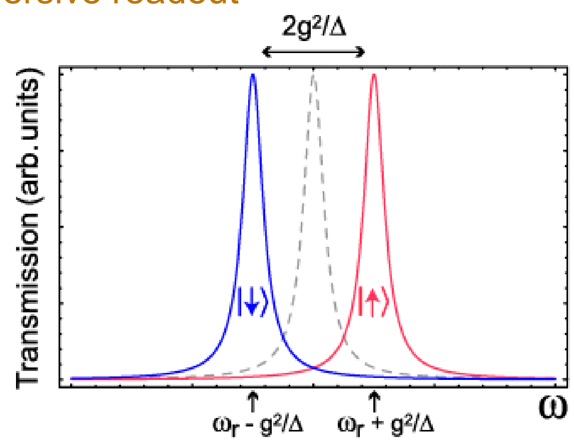


Nitrogen-Vacancy color center





Dispersive readout



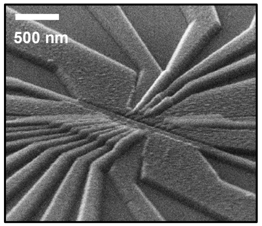
SNR > 1 in a few us integration time

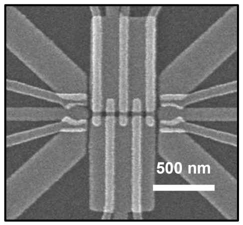
K.Kim group, (Tsinghua univ.)
M.Lee group (POSTECH ERC)
R.Hanson group, (quTech)
IBM, Google.. Etc.

Approach : detailed description of experiments

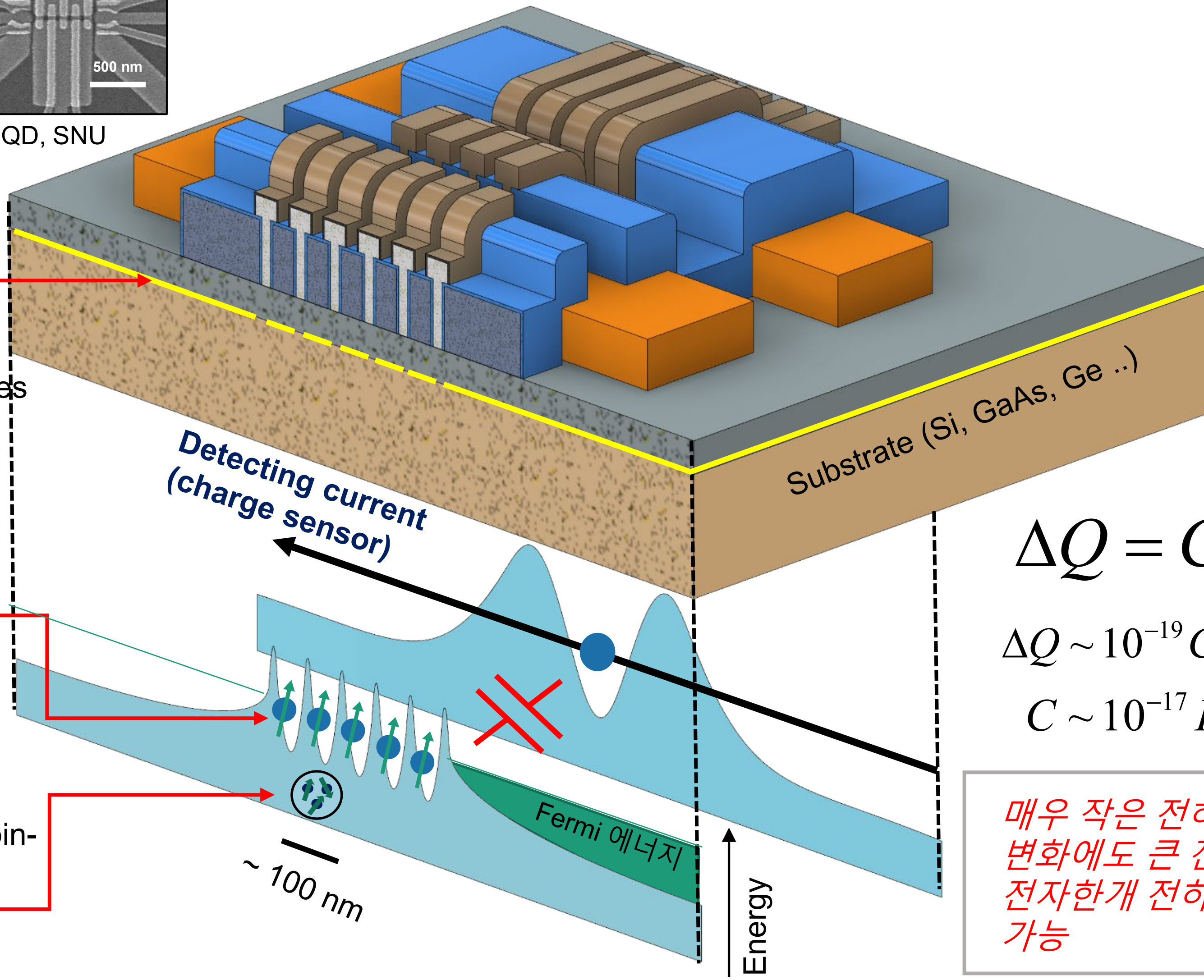
The semiconductor quantum chip

Si QD, Eriksson group, UW





Si QD, SNU



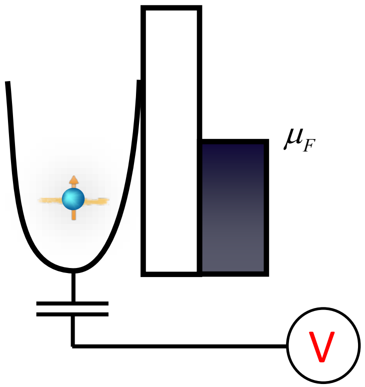
$$\Delta Q = C\Delta V$$

$$\Delta Q \sim 10^{-19}\,Coulomb$$

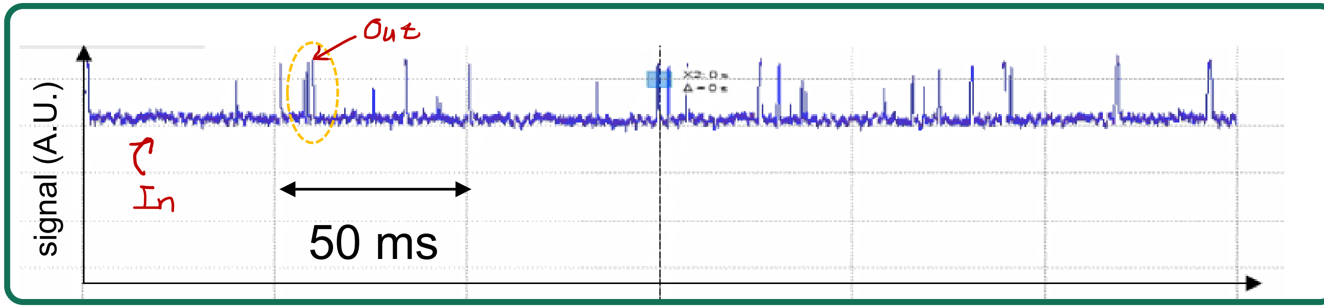
$$C \sim 10^{-17}\,Farad$$

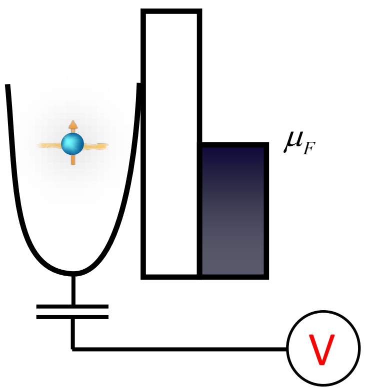
매우 작은 전하량 변화에도 큰 전압변화 전자한개 전하량 측정 가능

Typical example : watching electron tunneling

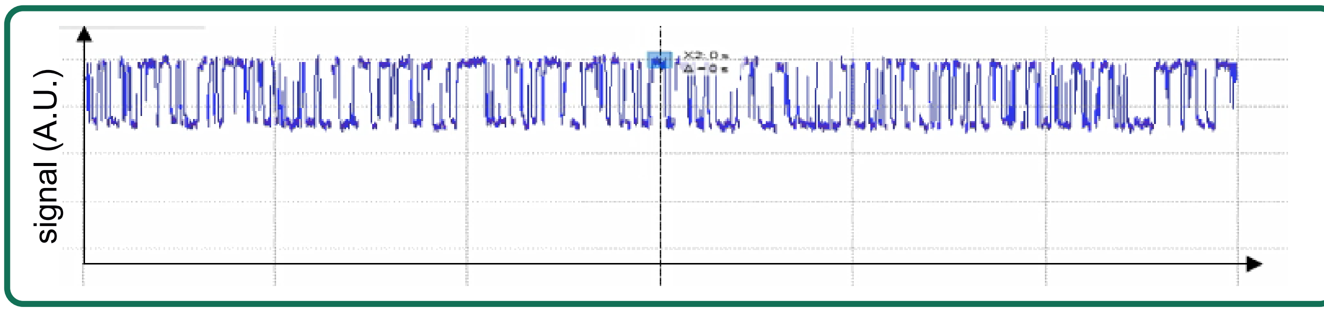


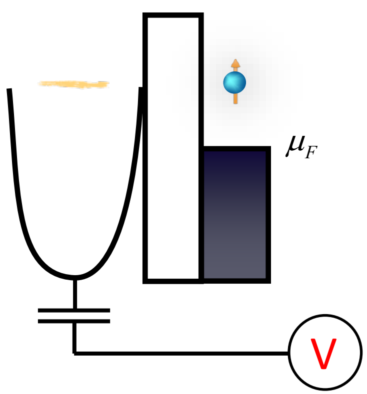
Mostly occupied



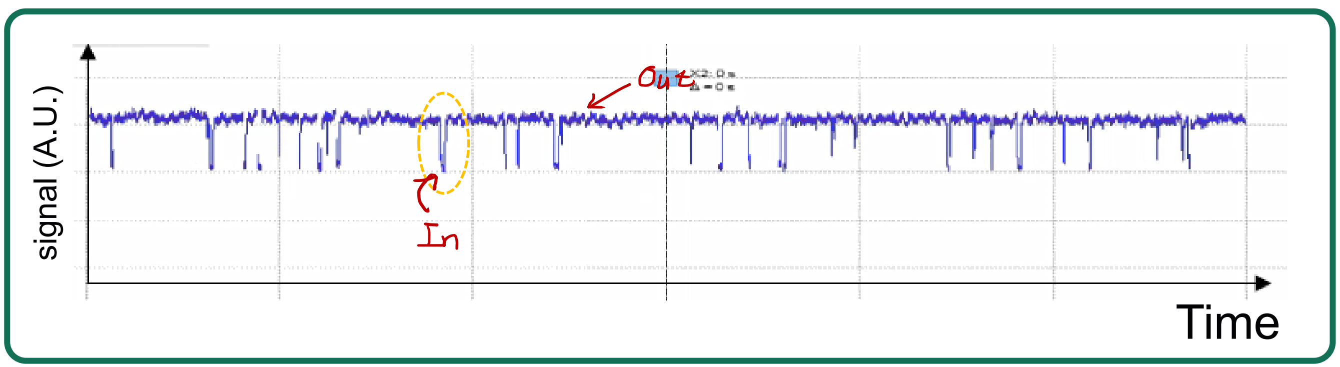


Half the time occupied, half the time empty





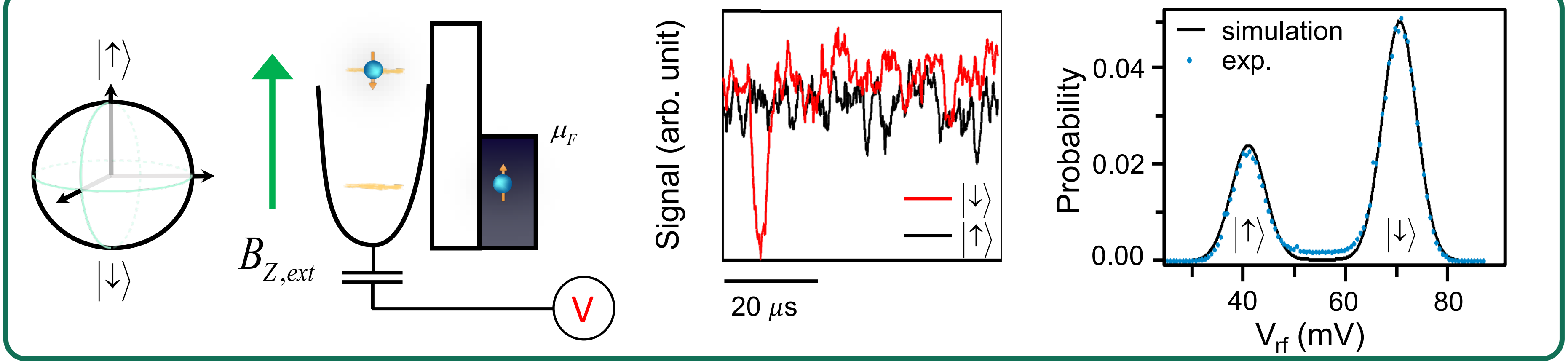
Mostly empty



2 Fast single-shot measurements

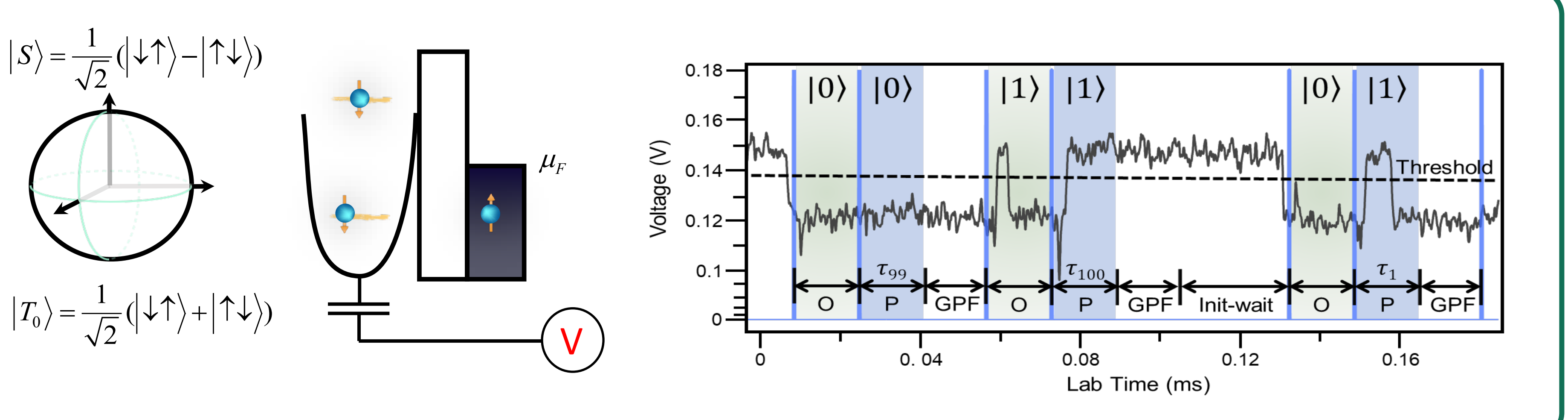
Something (mostly spin) to charge conversion

Single electron spin up-down qubit



Two electron singlet-triplet qubit

W. Jang et al, npj Quant. Inf. , APL, Nano Letter.. Etc.

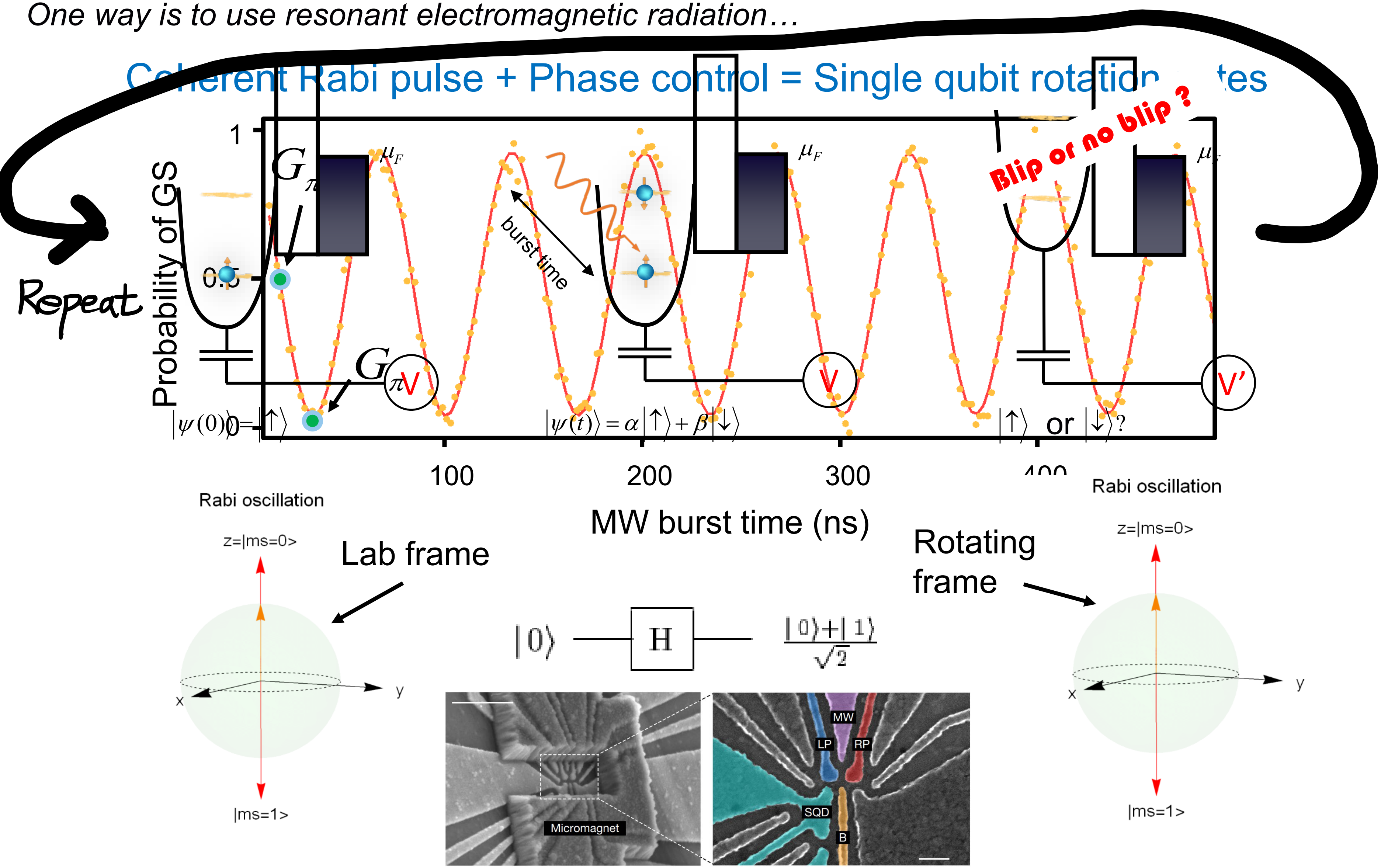


Current state of the art : SNR ~ 10 @ t_{int} =100 ns, F_{meas} > 99.5 % (T_1 / T_{meas} > 500) - SNU

Missing component : coherent manipulation

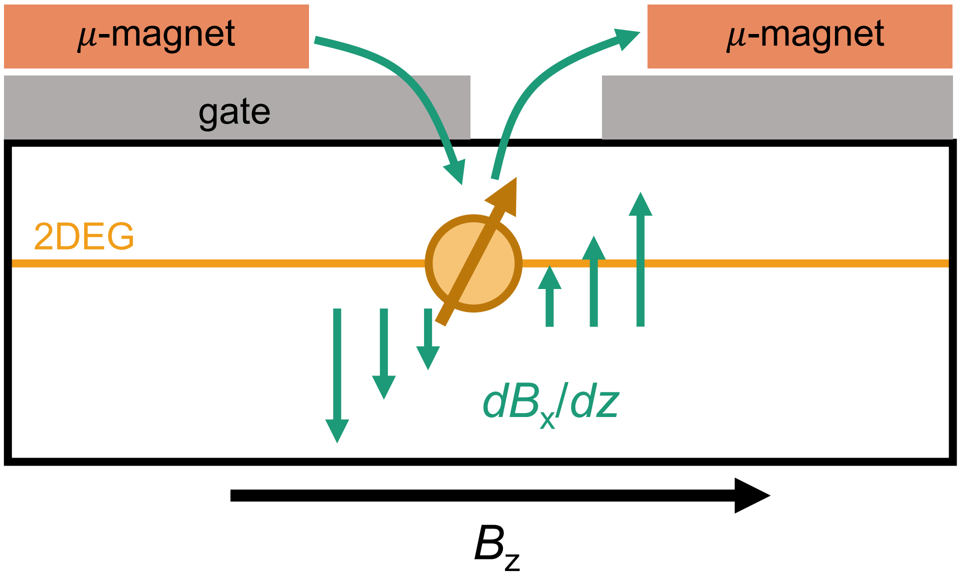
One way is to use resonant electromagnetic radiation…

Coherent Rabi pulse + Phase control = Single qubit rotation gates



Role of micromagnet

Single spin electric dipole spin resonance (EDSR)



Single spin Hamiltonian
$H = \mathbf{B \cdot S}$

$$H = B_z{}^*\sigma_z = \begin{bmatrix} B_z/2 & 0 \\ 0 & -B_z/2 \end{bmatrix}$$

$$H = B_z{}^*\sigma_z + B_x(z)*\sigma_x = \begin{bmatrix} B_z/2 & B_x(z)/2 \\ B_x(z)/2 & -B_z/2 \end{bmatrix}$$

Electric driving of the electron wavefunction (f_{mw} ~ *zeeman splitting*, B_z)

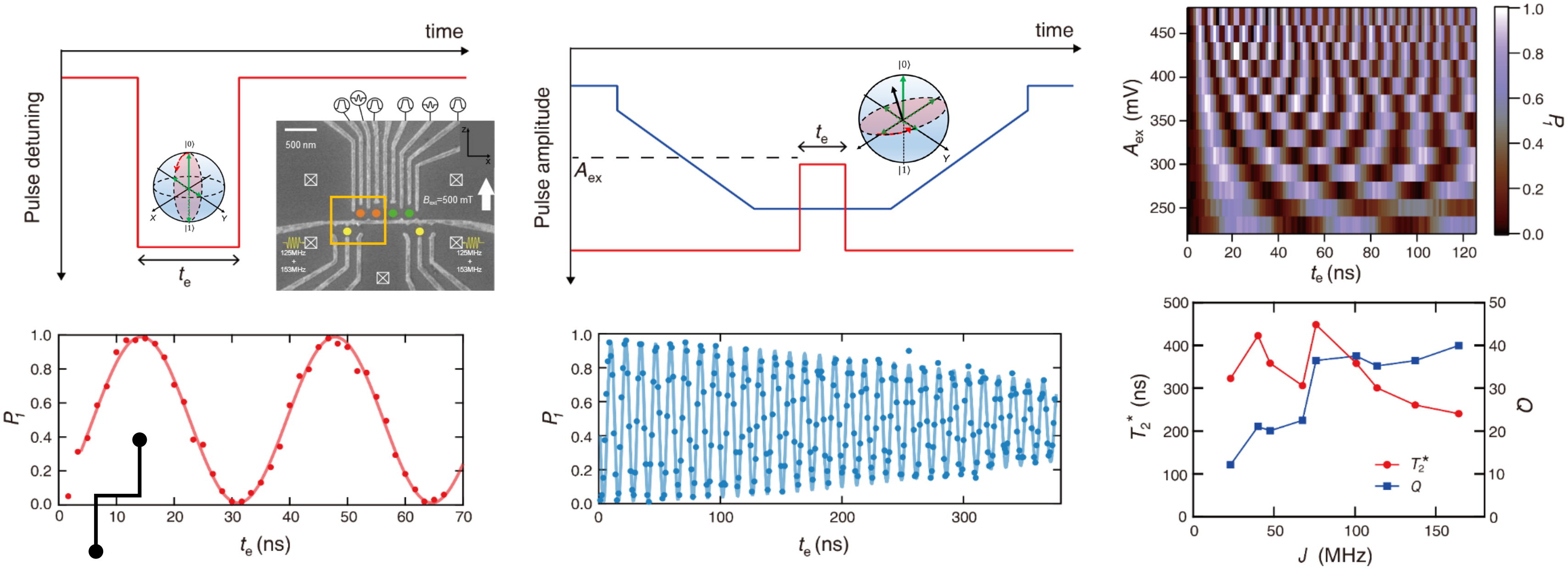
$$H = B_z{}^*\sigma_z + \delta B_x * \cos(2\pi f_{mw}) * \sigma_x = \begin{bmatrix} B_z/2 & \delta B_x * \cos(2\pi f_{mw}) \\ \delta B_x * \cos(2\pi f_{mw}) & -B_z/2 \end{bmatrix}$$

With the rotating wave approximation…
$H_{rot} = \delta B_x * \sigma_x + (B_z - f_{mw}) * \sigma_z$
@ Resonance, $H_{rot} = \delta B_x * \sigma_x$ → Rotation about the x-axis on the Bloch sphere

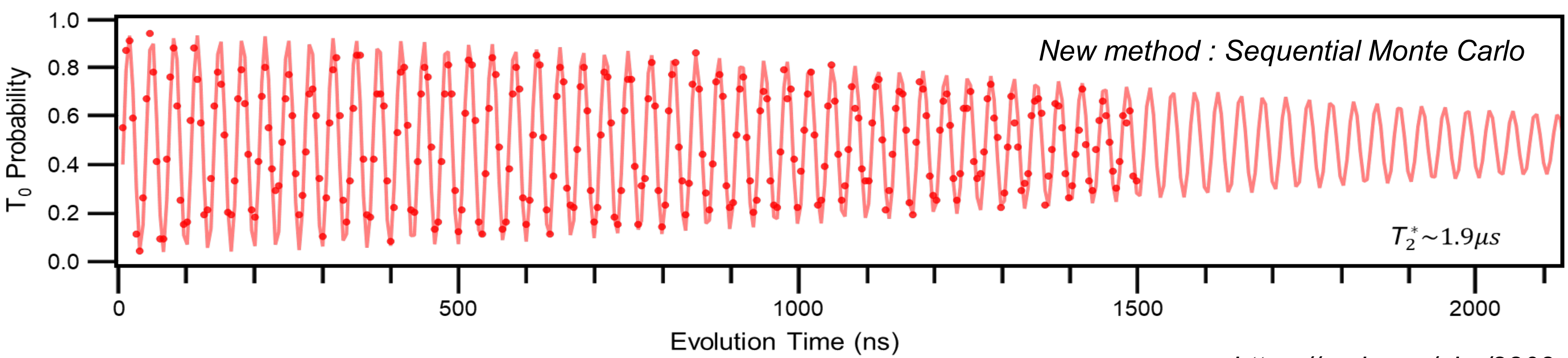
2

Fast single-shot measurements

SNU contribution : record high visibility



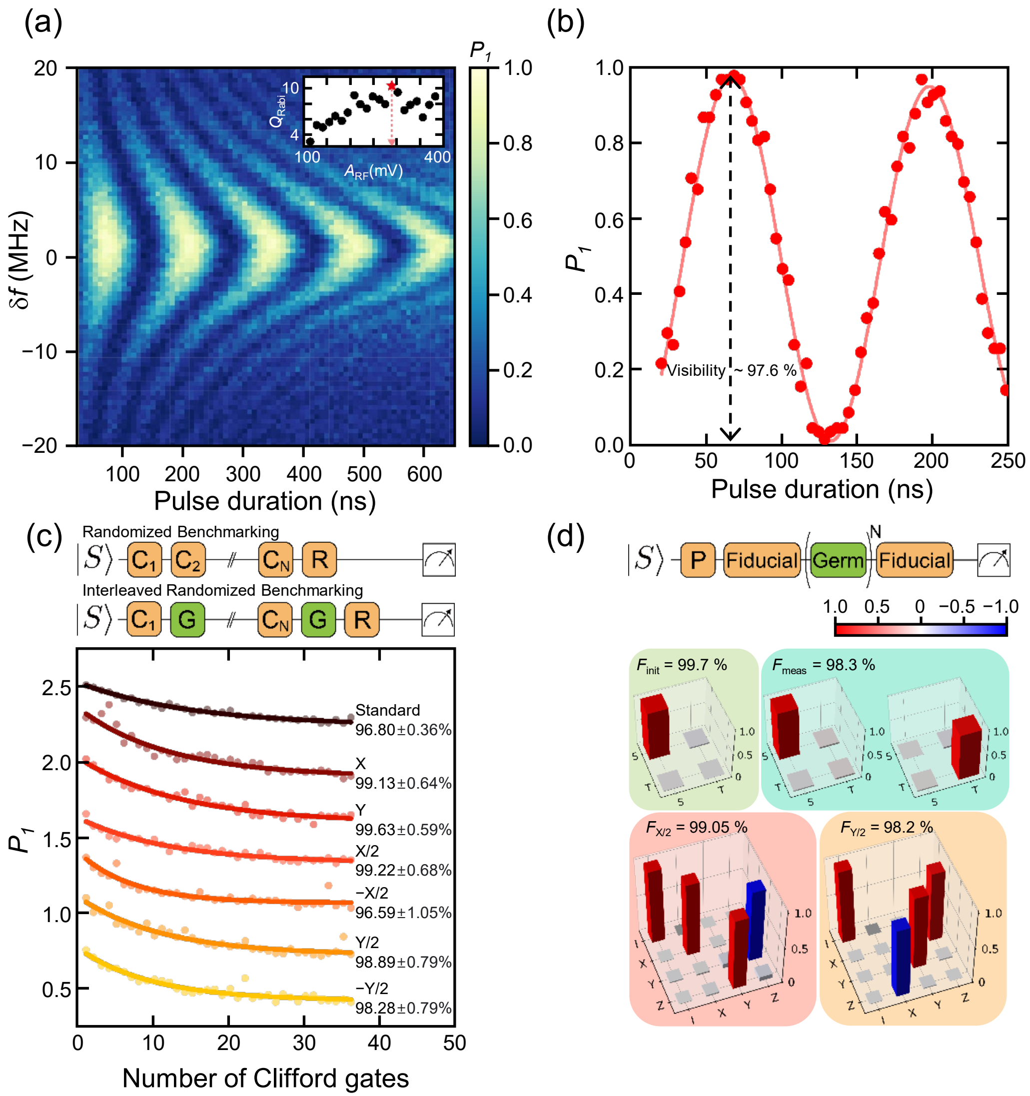
Record high 98% visibility: > 99% 1Q gate (Bayesian), > 99.9% I, > 99.5 % M



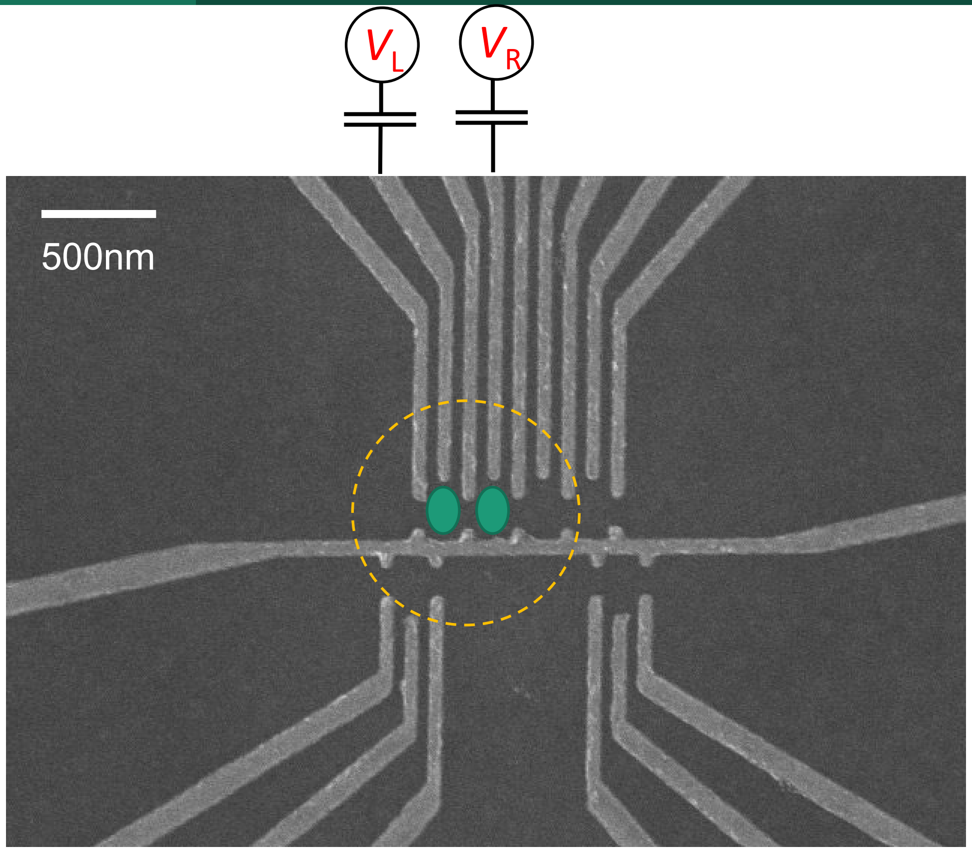
https://arxiv.org/abs/2203.01101

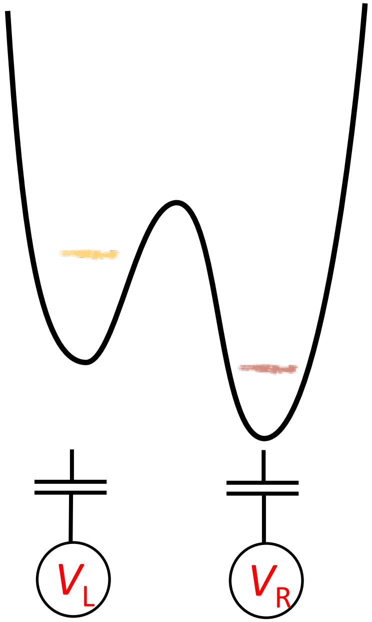
Fast single-shot measurements

SNU contribution : record high fidelity

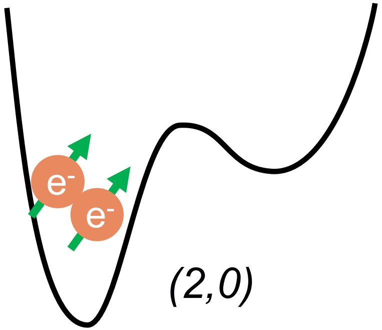


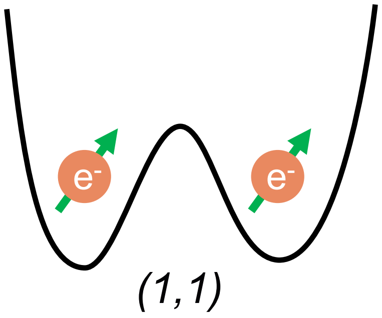
Two qubit gates





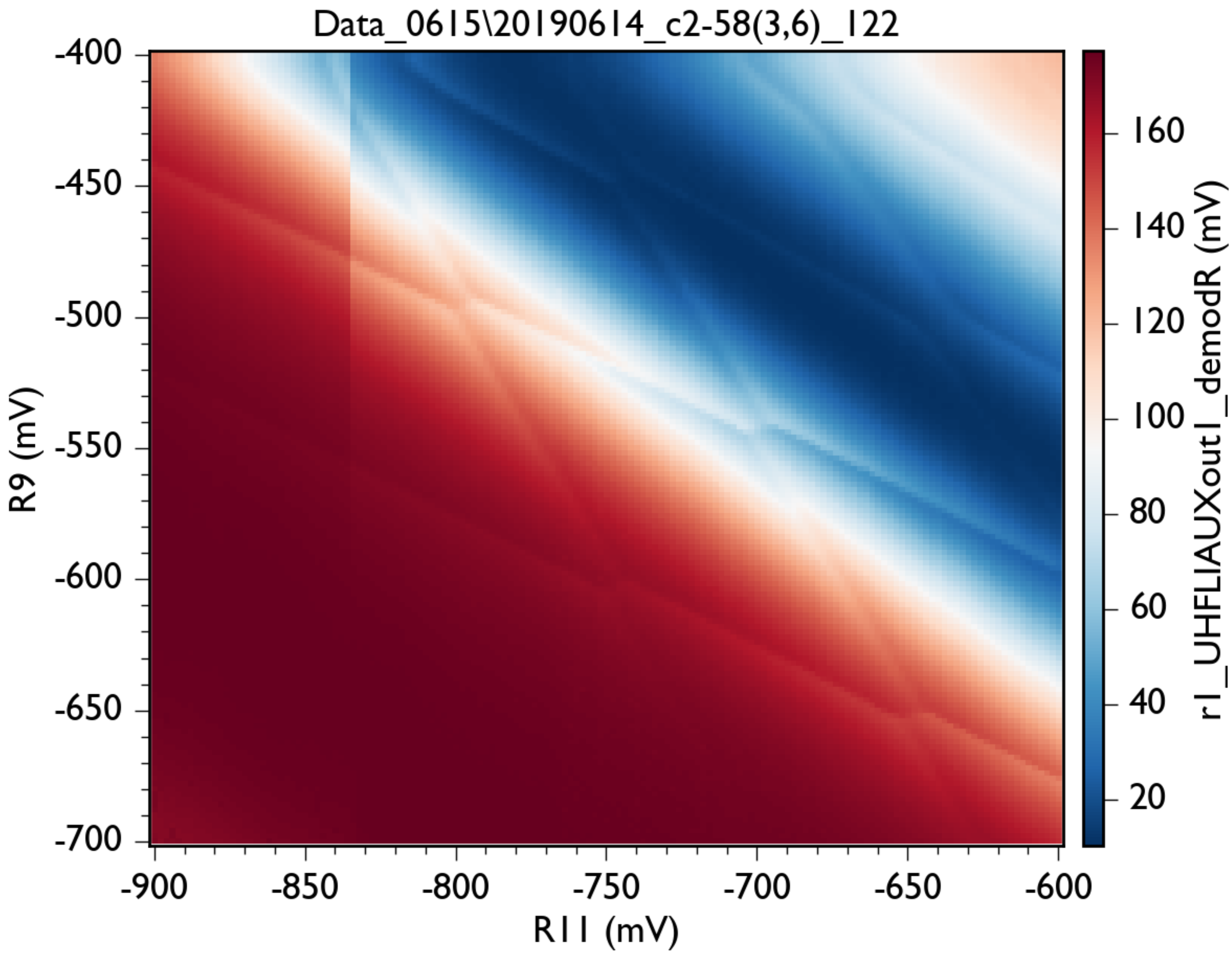
이중 양자점에 전자는 2개





2

Charge stability diagram



Two electron spin states & position pseudo-spin

Tunneling selection rule : $\Delta S = 0, \Delta S_z = 0$, start with $|0\rangle_{(2,0)}$

Clebsch – Gordan coeff.

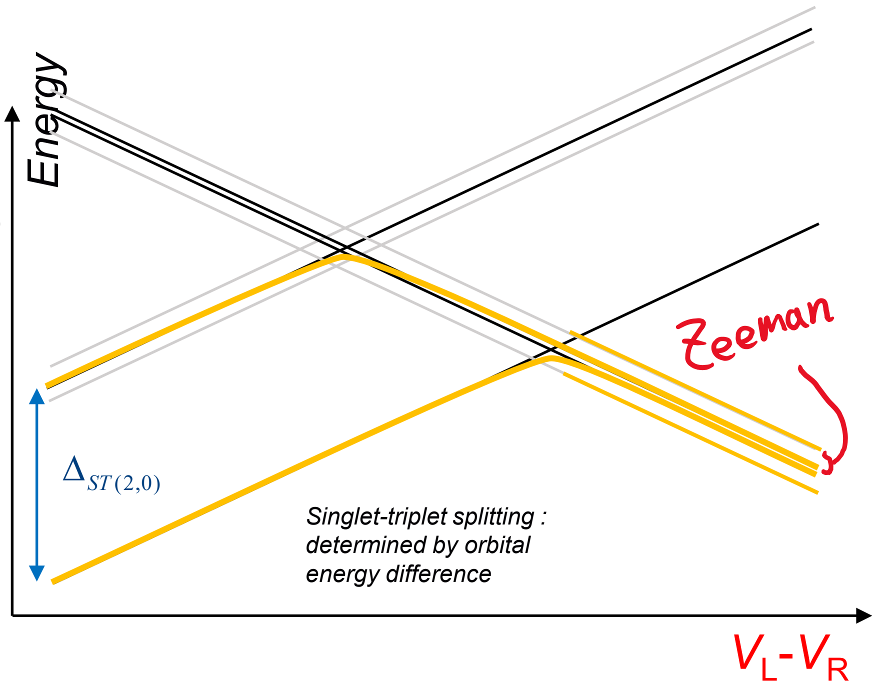
$$|3\rangle_{(2,0)} = |T_-\rangle = |\uparrow\uparrow\rangle$$

$$|2\rangle_{(2,0)} = |T_0\rangle = \frac{1}{\sqrt{2}}(|\downarrow\uparrow\rangle + |\uparrow\downarrow\rangle)$$

$$|1\rangle_{(2,0)} = |T_+\rangle = |\downarrow\downarrow\rangle$$

$$|0\rangle_{(2,0)} = |S\rangle = \frac{1}{\sqrt{2}}(|\downarrow\uparrow\rangle - |\uparrow\downarrow\rangle)$$

$S_z = 0$

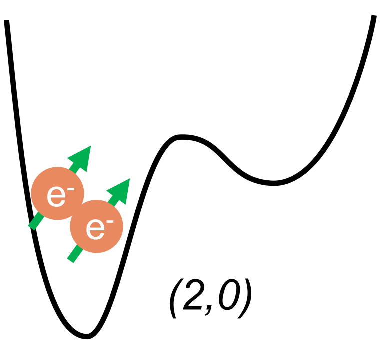


$$|3\rangle_{(1,1)} = |T_-\rangle = |\uparrow\uparrow\rangle$$

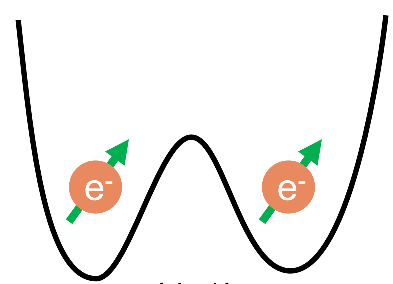
$$|2\rangle_{(1,1)} = |T_0\rangle = \frac{1}{\sqrt{2}}(|\downarrow\uparrow\rangle + |\uparrow\downarrow\rangle)$$

$$|1\rangle_{(1,1)} = |S\rangle = \frac{1}{\sqrt{2}}(|\downarrow\uparrow\rangle - |\uparrow\downarrow\rangle)$$

$$|0\rangle_{(1,1)} = |T_+\rangle = |\downarrow\downarrow\rangle$$



(2,0)

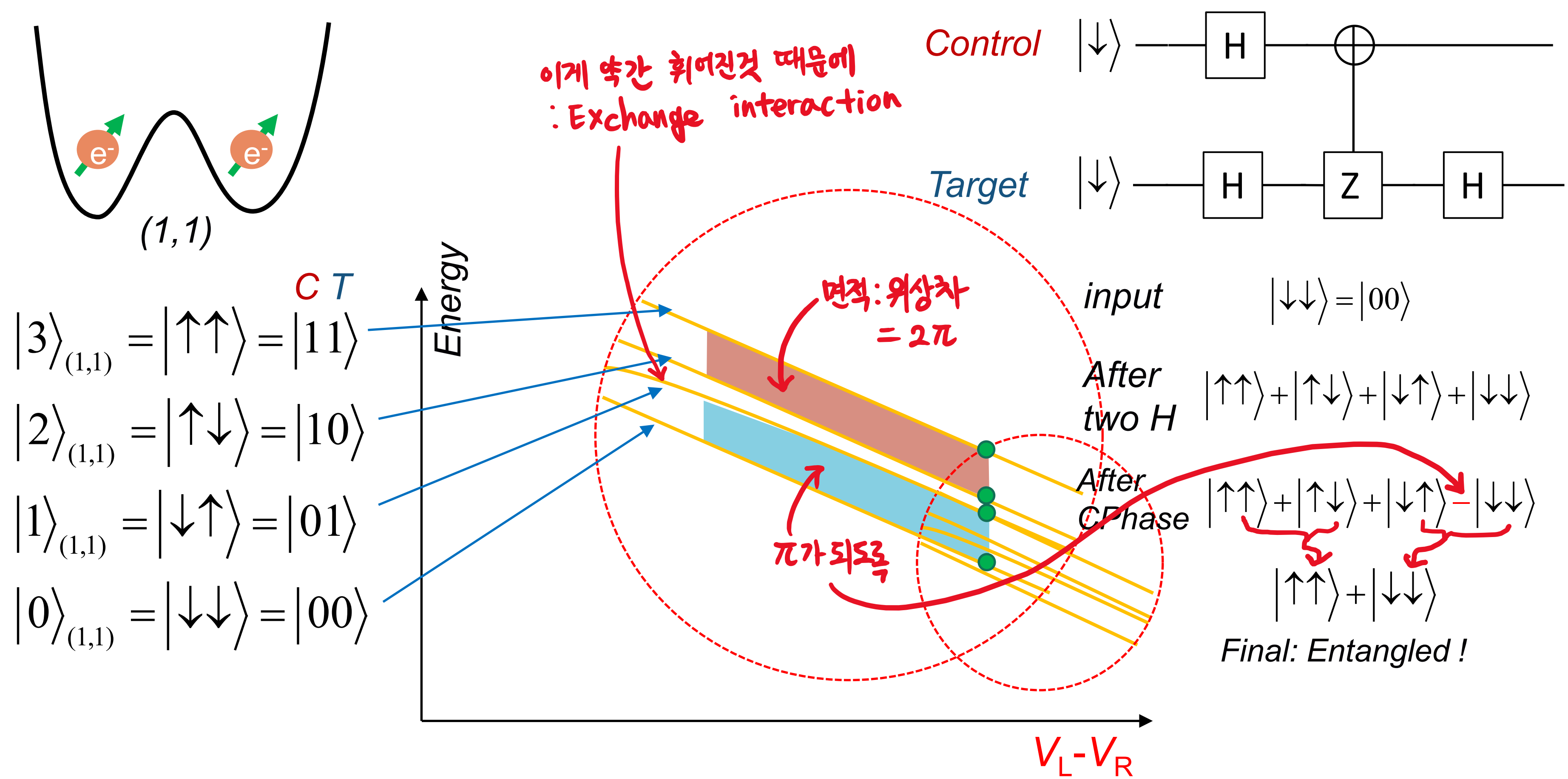


(1,1)

2

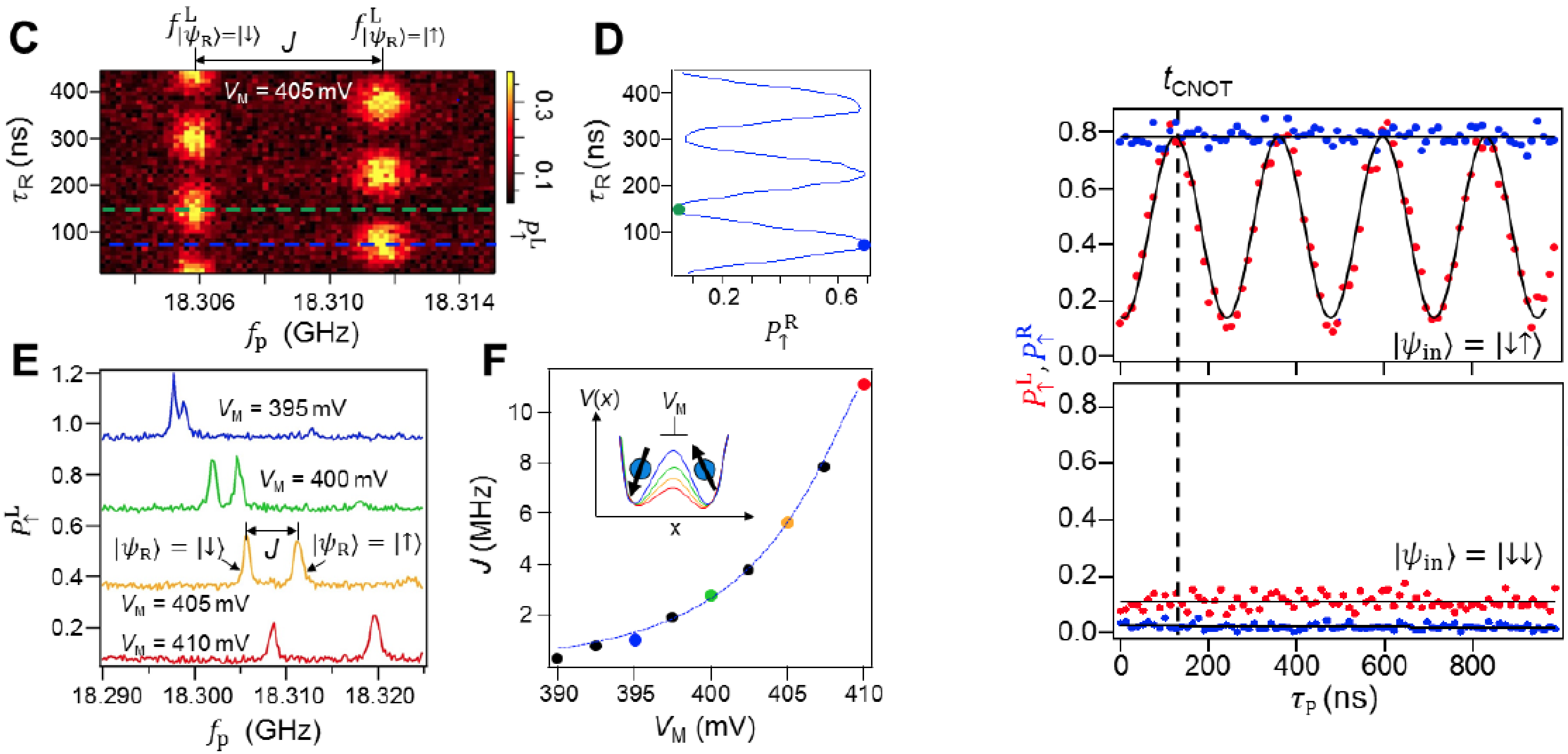
Approach: detailed description of experiments

Essential physics for a QD-based QC



Take home message : 1Q gate 는 자기공명 (Rabi oscillation) 으로, 2Q gate 는 exchange interaction or capacitive coupling 에 의한 controlled phase 로
= Universal gate set for arbitrary quantum operation

Another way : Controlled rotation gate



Another way : Controlled rotation gate

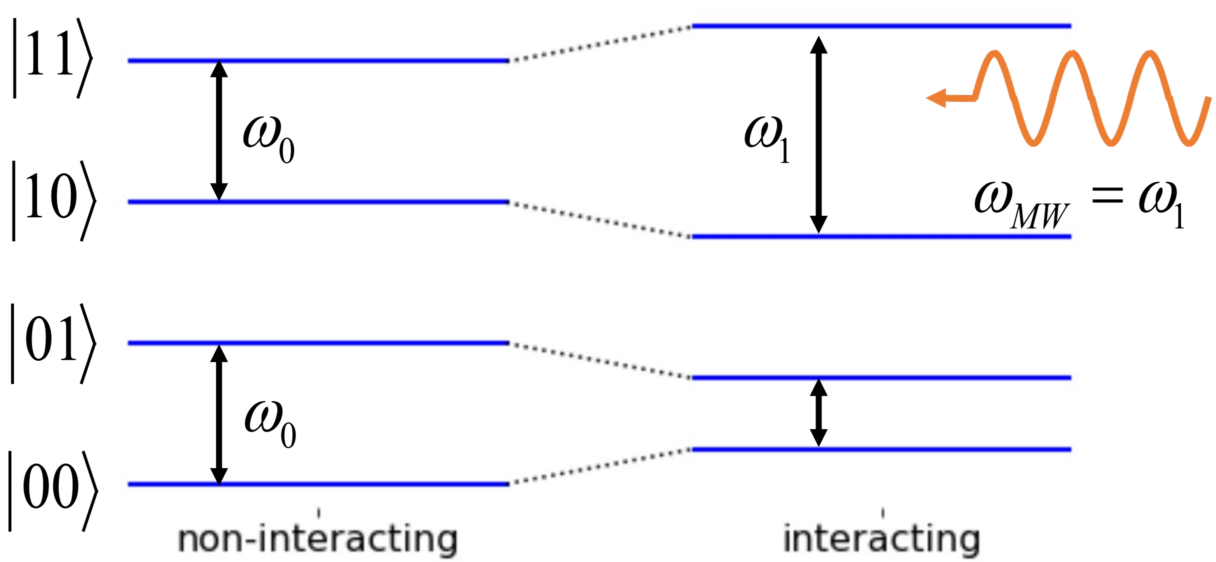
Two qubit gate

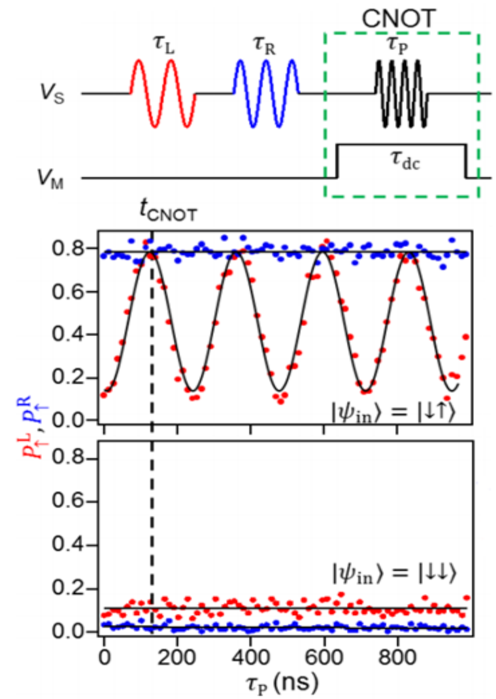
Ex. Calibrated Rabi π pulse under two body interaction = CNOT

$$\hat{H} = \frac{\hbar\omega_0}{2}(2\hat{\sigma}_{z1} \otimes I + I \otimes \hat{\sigma}_{z2}) + \hbar g(\hat{\sigma}_{z1} \otimes \hat{\sigma}_{z2})$$

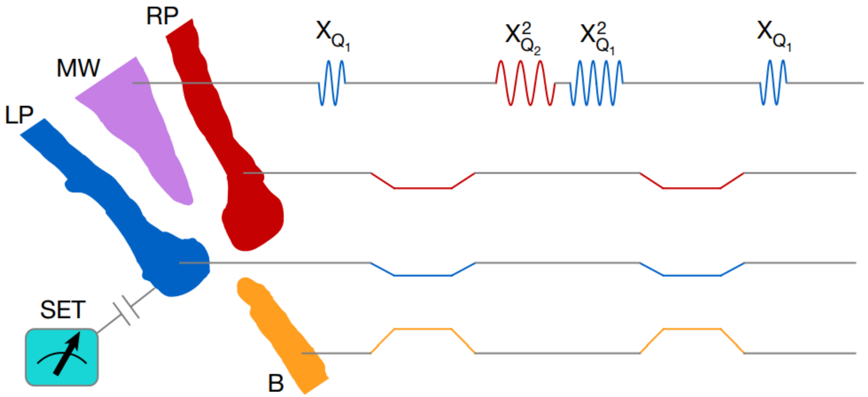
반도체 스핀 큐빗의 예

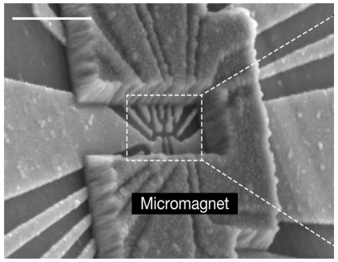
c t

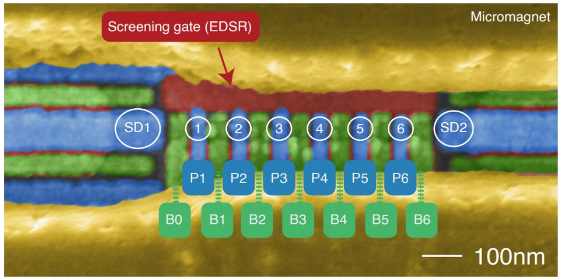




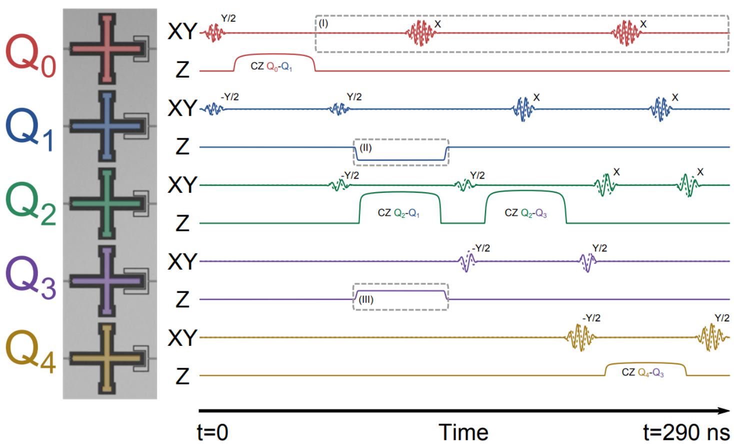
Current state of the art

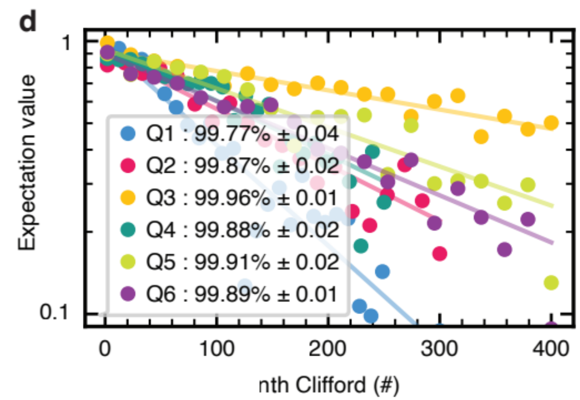






Cf. 5- SC qubit experiment (UCSB 2014, Nature)



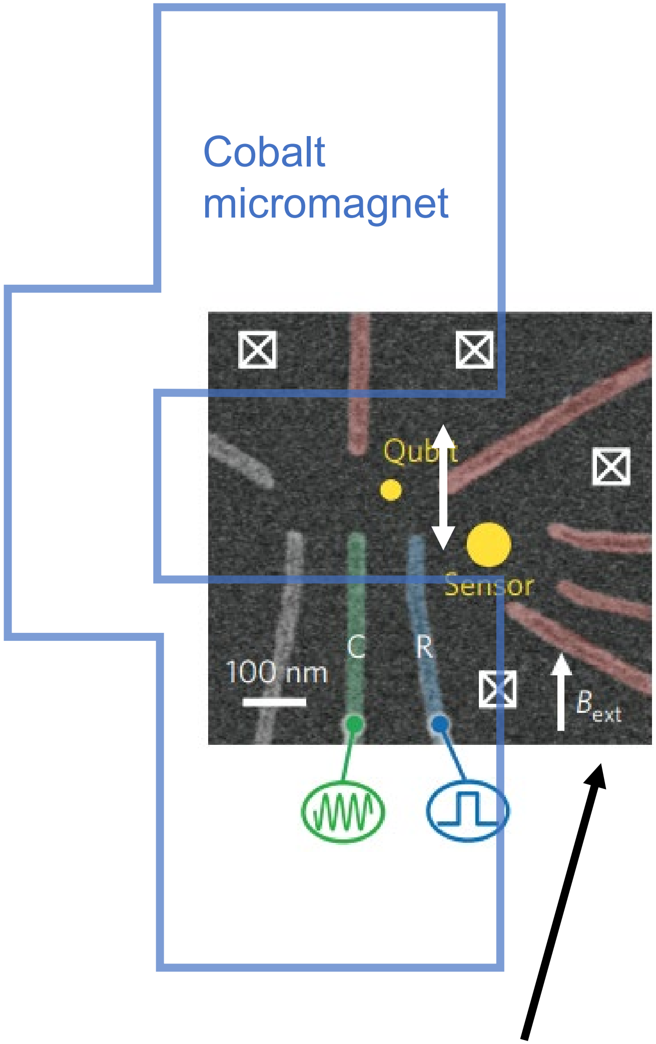


https://arxiv.org/abs/2202.09252

Both 1Q, 2Q gate fidelities exceed surface code error correction threshold.
멀티 큐비트 작동의 자세한 시퀀스 설명은 Lecture 2 에서..

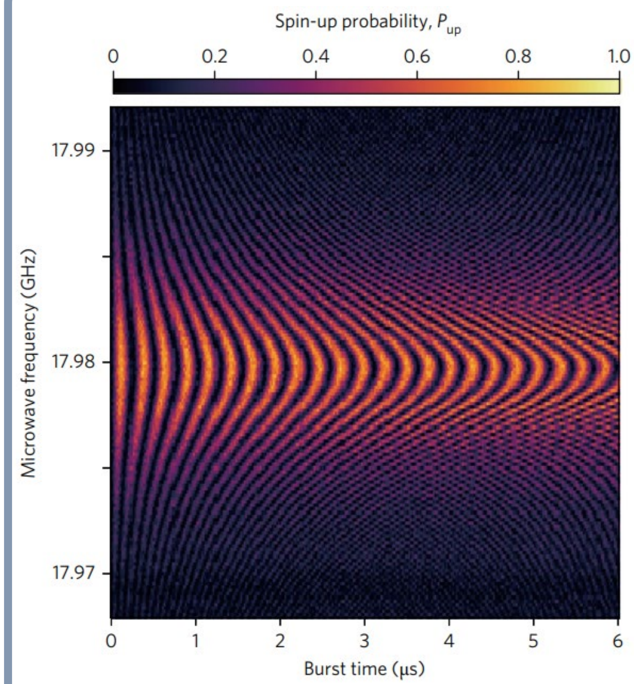
Approach: detailed description of experiments

Current state of the art



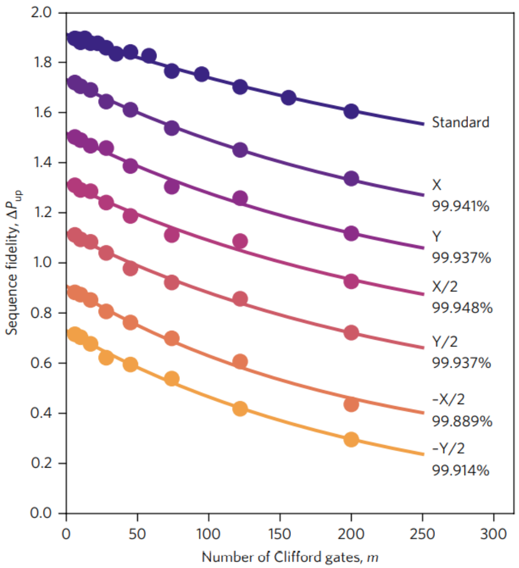
Purified ^{28}Si

Coherent Rabi Oscillation



Randomized Benchmarking

avg. fidelity > 99.9 %

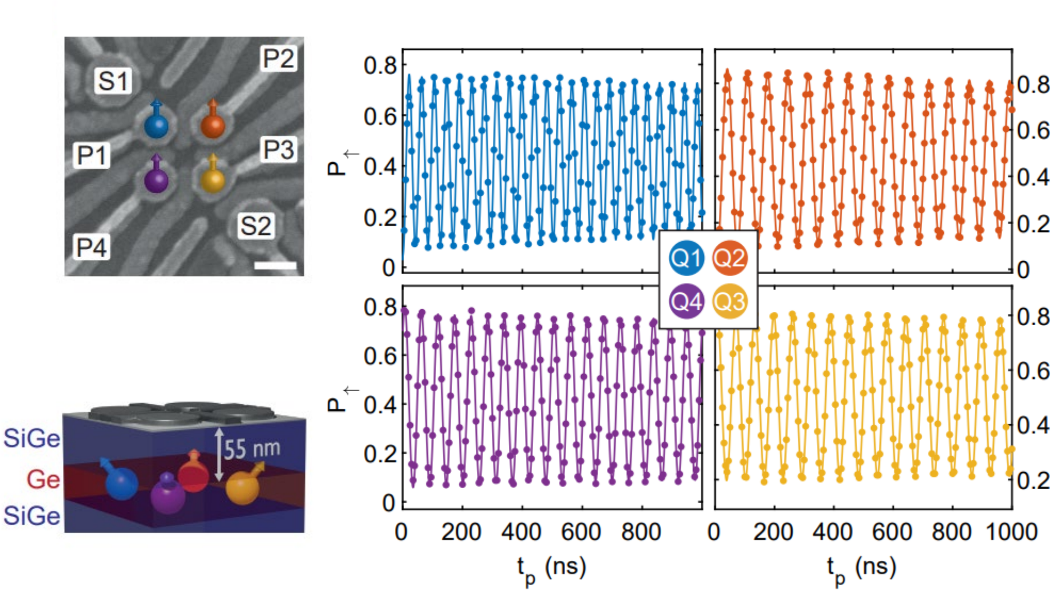


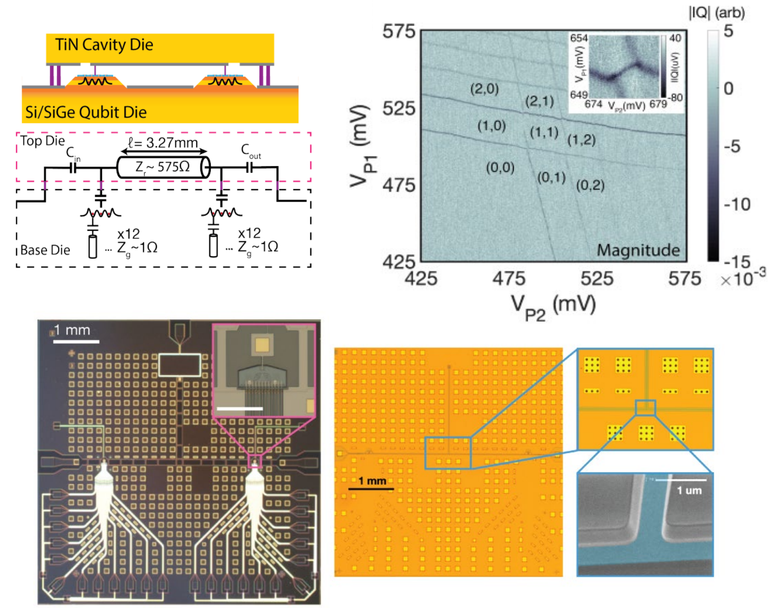
- **High fidelity single qubit control (> 99.9%,** confirmed by RB**)** in the purified ^{28}Si
- Charge noise limited coherence (CPMG, Ramsey measurement)

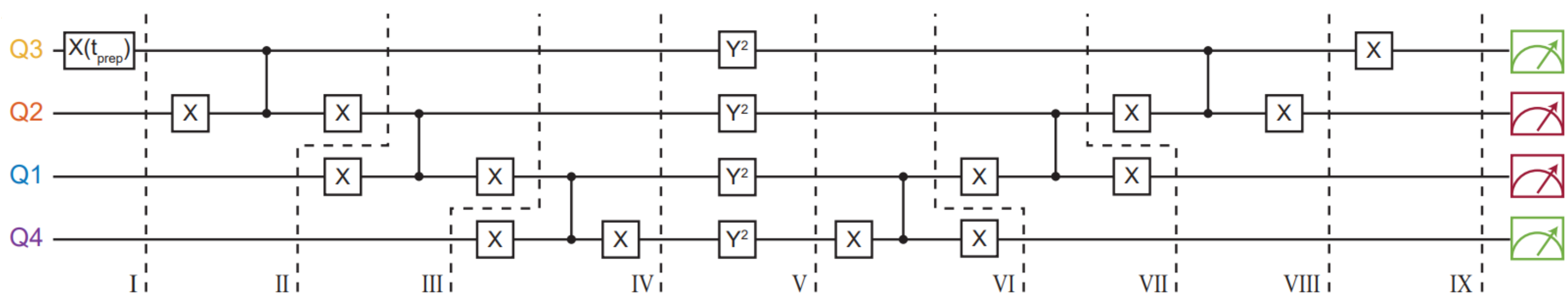
Nature Nanotech. **13**, 102 (2018)

Example: Si, GaAs, Ge.. Boosting up results

Most recent developments : Germanium 4 qubit processing & 3D integration



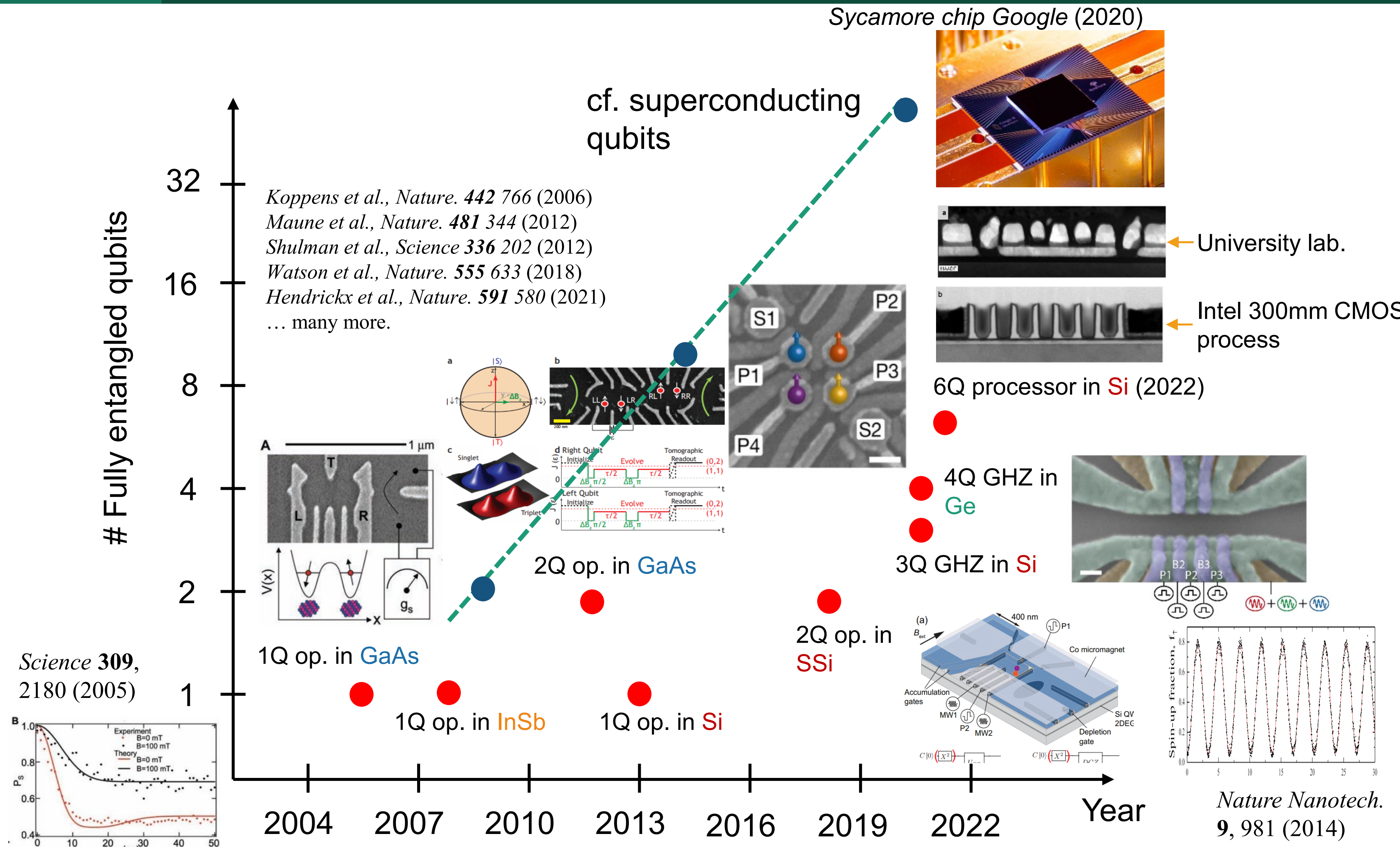




Again, 회로설명은 Lecture 2에서..

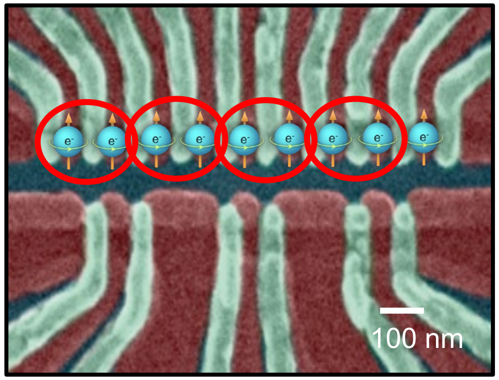
quTech, Delft Sep. 2020
M.Eriksson group UW Nov. 2020

Recent developments of QD-based QC

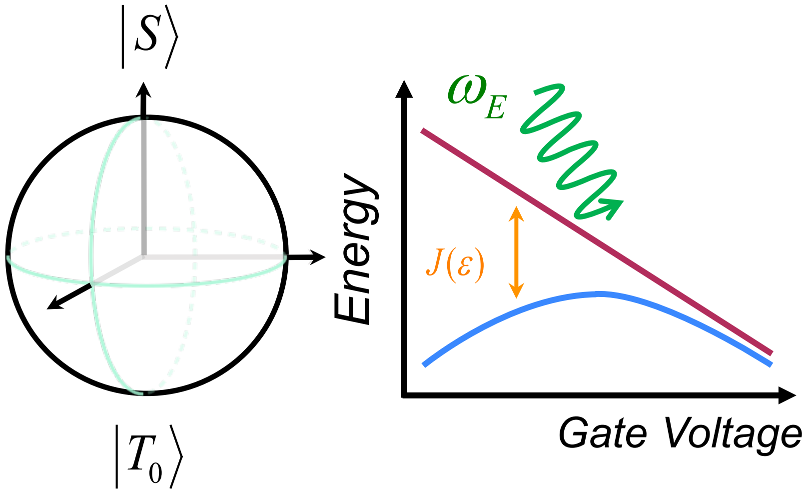


N. P. de Leon, Kohei M. Itoh, Dohun Kim, Karan K. Mehta, Tracy E. Northup, Hanhee Paik, B. S. Palmer, N. Samarth, Sorawis Sangtawesin, D. W. Steuerman "Material challenges and opportunities for quantum computing hardware" - *Science.* **372**, 253 (2021) Review paper

The type of qubit we focus



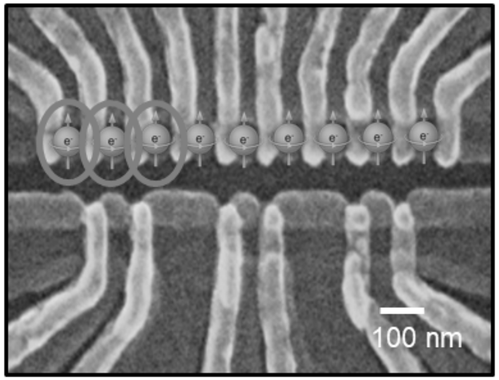
Two electron spin in DQD



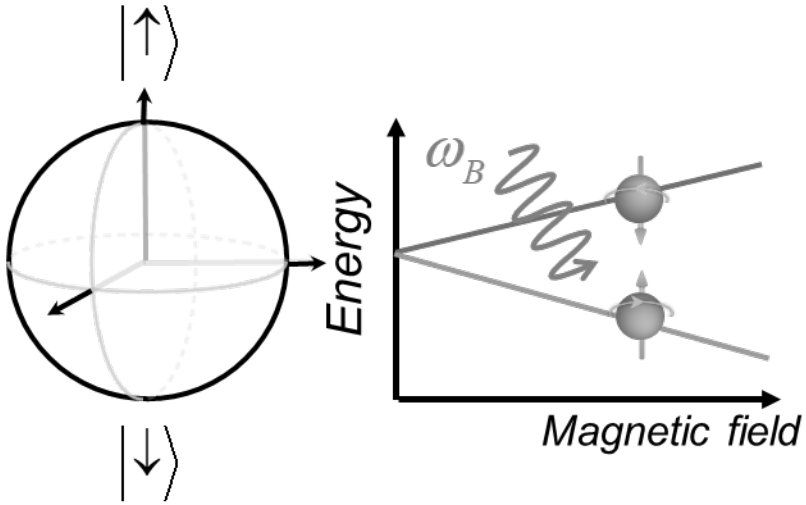
- *E-field control*
- *Fast ~ ns gate*
- *Nucl. polarization*
- *D or Ex coupling*
- *Complexity*
- *Less SNR (improvable)*

For GaAs system

cf. canonical type : single electron spin up-down qubit



Single electron spin



- *Simple*
- *Most coherent*
- *Higher SNR*
- *Exchange coupling*
- *B-field control*
- *slow ~ us gate*

For Si system

Different look at two-spin states

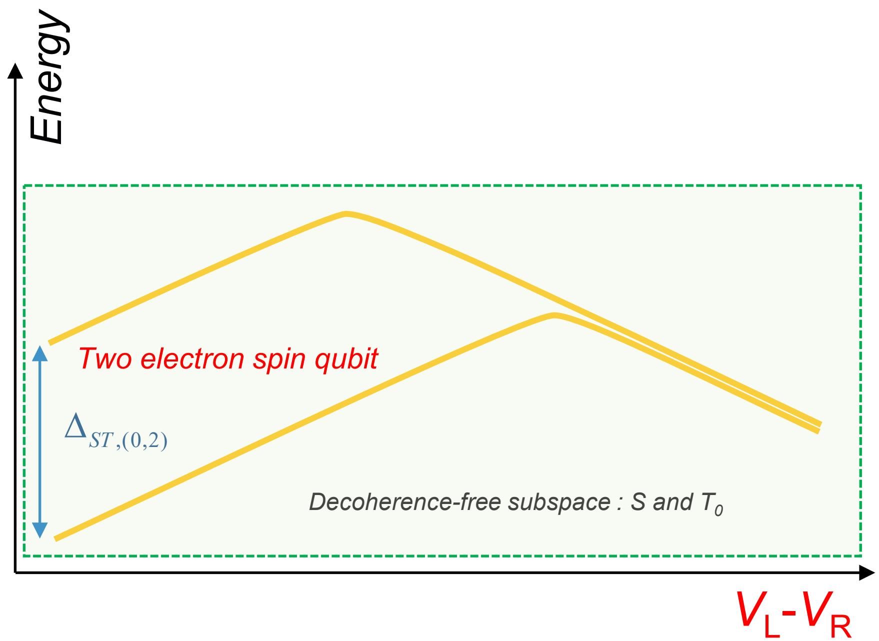
Clebsch-Gordan coeff.

$|3\rangle_{(2,0)} = |T_-\rangle = |\uparrow\uparrow\rangle$

$|2\rangle_{(2,0)} = |T_0\rangle = \frac{1}{\sqrt{2}}(|\downarrow\uparrow\rangle + |\uparrow\downarrow\rangle)$

$|1\rangle_{(2,0)} = |T_+\rangle = |\downarrow\downarrow\rangle$

$|0\rangle_{(2,0)} = |S\rangle = \frac{1}{\sqrt{2}}(|\downarrow\uparrow\rangle - |\uparrow\downarrow\rangle)$

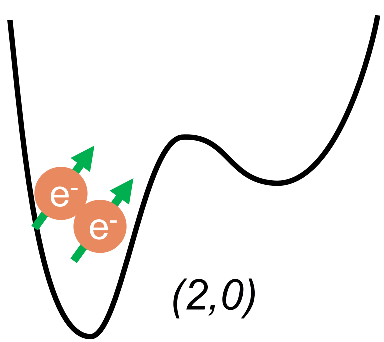


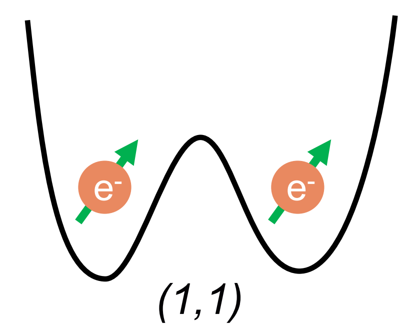
$|3\rangle_{(1,1)} = |T_-\rangle = |\uparrow\uparrow\rangle$

$|2\rangle_{(1,1)} = |T_0\rangle = \frac{1}{\sqrt{2}}(|\downarrow\uparrow\rangle + |\uparrow\downarrow\rangle)$

$|1\rangle_{(1,1)} = |S\rangle = \frac{1}{\sqrt{2}}(|\downarrow\uparrow\rangle - |\uparrow\downarrow\rangle)$

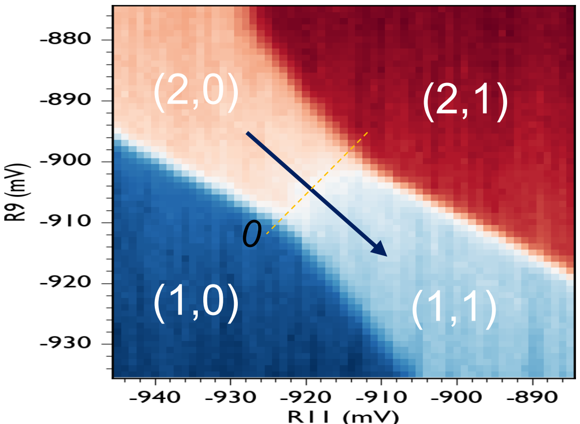
$|0\rangle_{(1,1)} = |T_+\rangle = |\downarrow\downarrow\rangle$

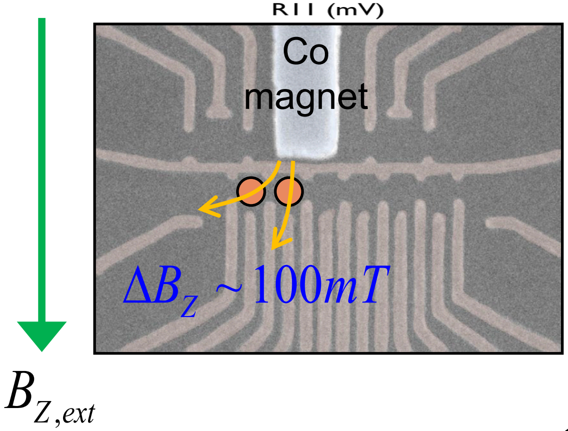


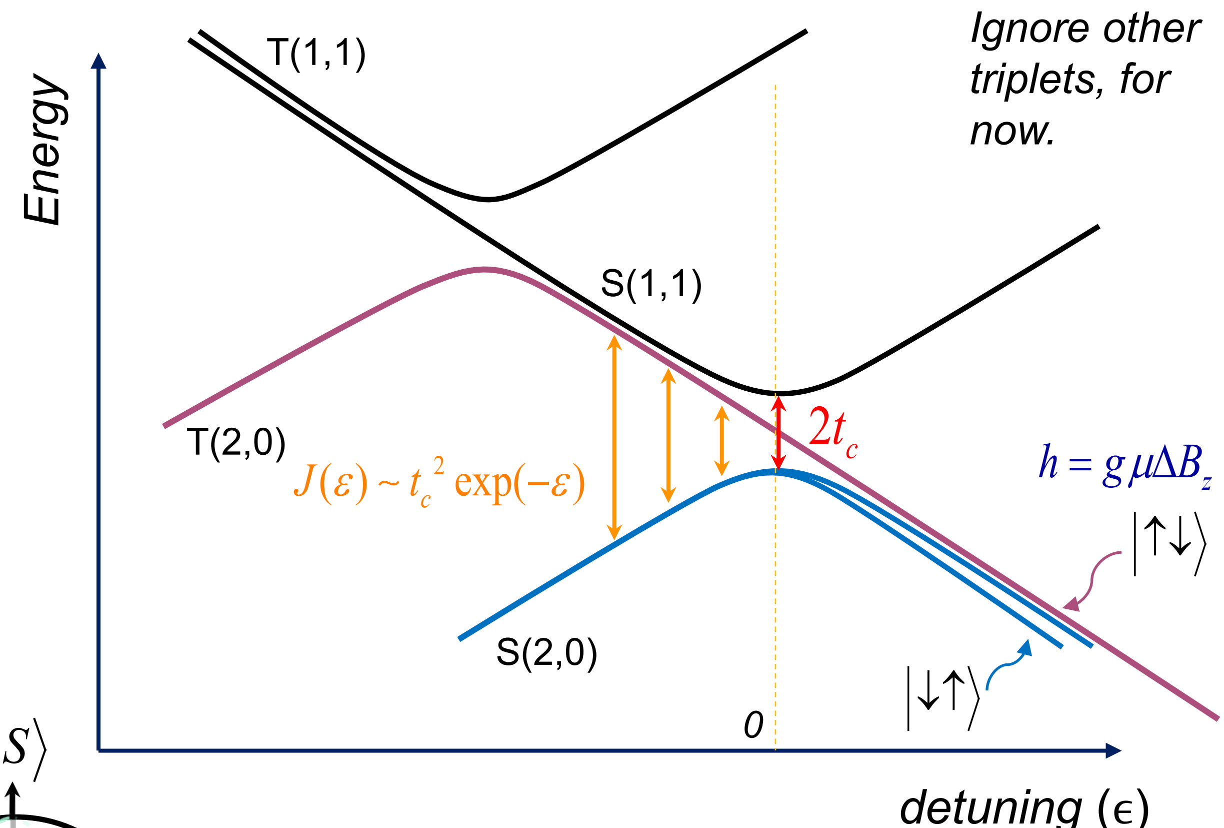


Approach : detailed description of experiments

Introduction to DQD - ST qubit

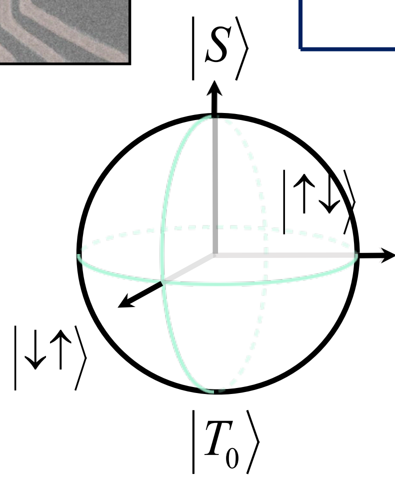






$$H = \begin{bmatrix} J(\varepsilon) & h \\ h & 0 \end{bmatrix}$$

$$h = g\mu\Delta B_z$$



Singlet -Triplet Qubit

- Two electrons in a DQD
- *Voltage dependent* Q energy
- *J & h* determines eigenaxes
- Typical values
  J : 0~30 GHz (0~120 μeV)
  h : 0~1 GHz (0~4 μeV)

3

Singlet-Triplet qubits

Field-gradient-based two electron spin qubits

주요 스펙

- 큐비트 주파수: 수백 MHz
- 검출 주파수: 수백 MHz
- T_1 시간 > 최소 수백 μs
- T_2 시간: 재료에 크게 의존 (뒤에서…)
- 이중 큐비트 속도 : 수~수십 MHz (뒤에서…)

디자인 철학을 공유: operation 때는 잘 숨기고, readout 때는 큰 상호작용

Cf. 초전도 트랜스몬

- 큐비트 주파수: 수 GHz
- 검출 주파수: 수 GHz
- Dispersive readout

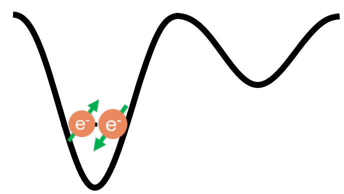
Practicality

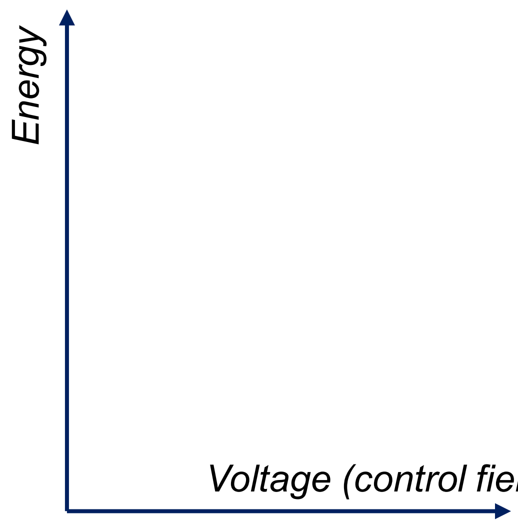
- 전기적인 spin 제어
- 큰 튜너빌리티
- < 1 GHz 의 낮은 제어라인 bandwidth 요구도

Qubit 초기화, 측정 영역

빠른 초기화, 스핀-전하 변환

(2,0)

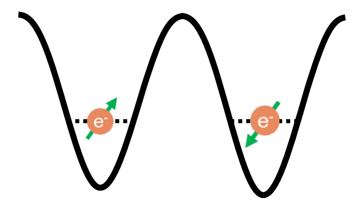




Qubit Operation 영역

긴 결맞음

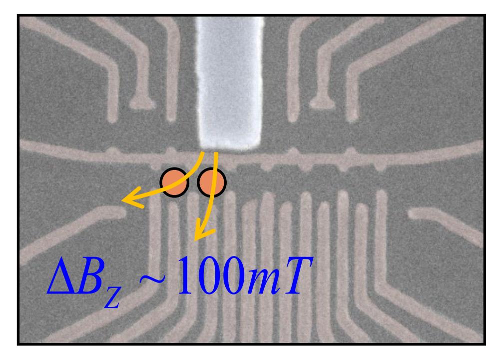
(1,1)



$|1\rangle = |\uparrow\downarrow\rangle$

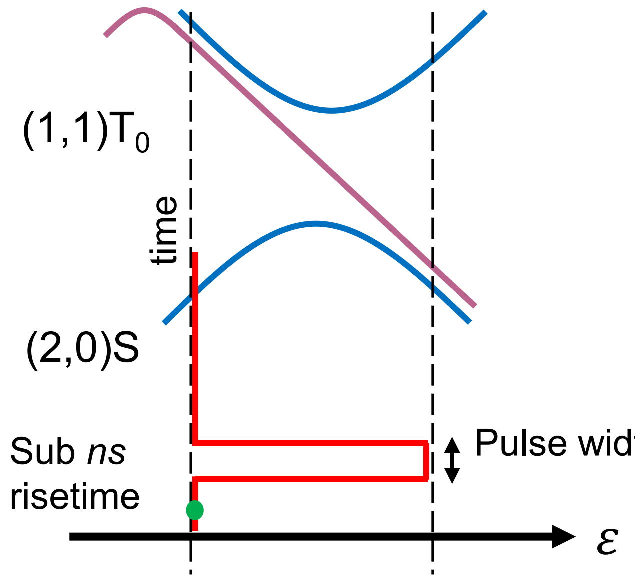
ΔB_Z 에만 의존 (전하잡음 무관)

$|0\rangle = |\downarrow\uparrow\rangle$

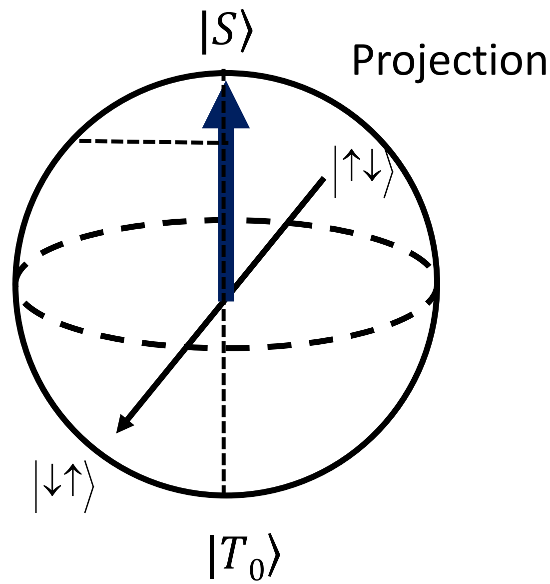


Initialization, Operation & Measurement of STQ

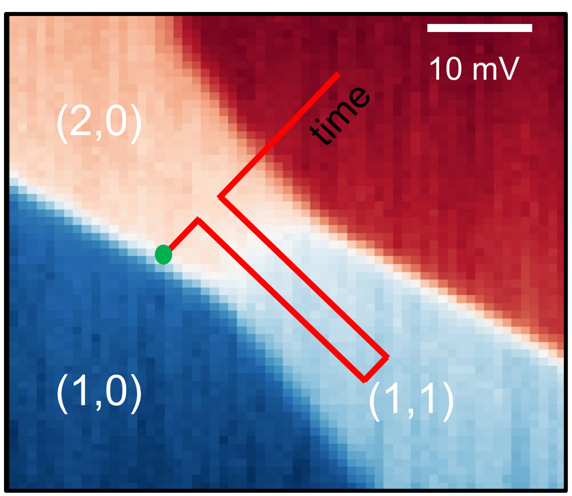
Operation: Voltage pulsing



$$H = \begin{bmatrix} J(\varepsilon) & \Delta B \\ \Delta B & 0 \end{bmatrix}$$

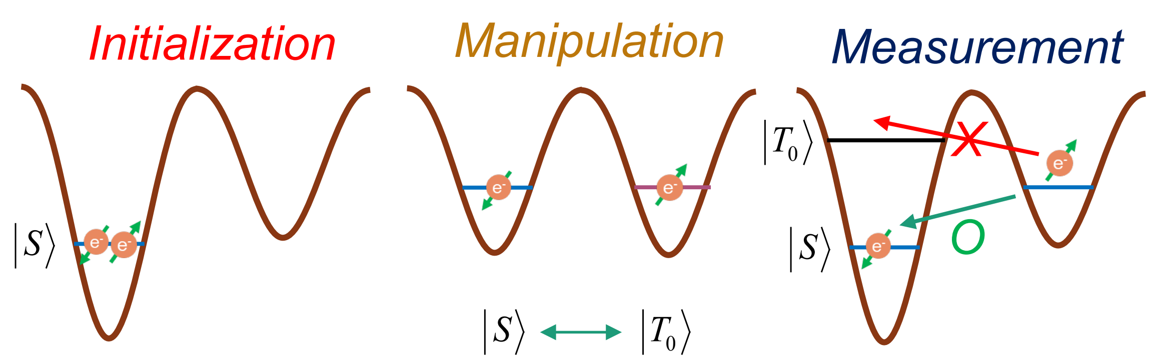


Initialization: ST relaxation (μs to *ms* – also voltage dependent)



Measurement: How to distinguish $|S\rangle$ from $|T_0\rangle$?
Pauli Spin Blockade

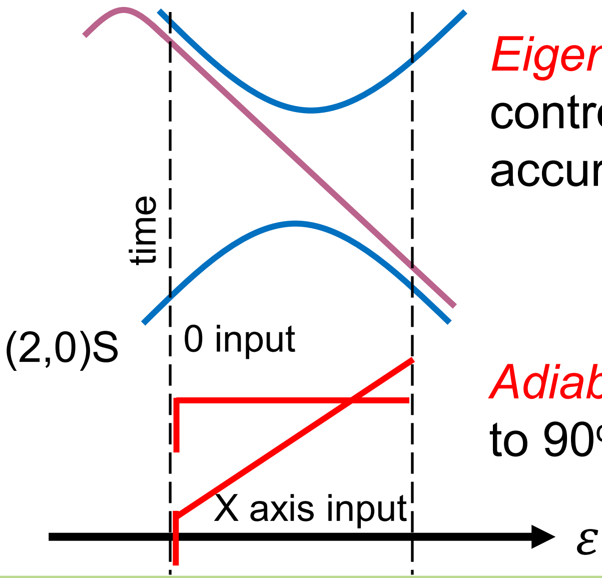
Spin to charge conversion
$|S\rangle$ becomes (2,0)
$|T_0\rangle$ remains in (1,1)



Approach : detailed description of experiments

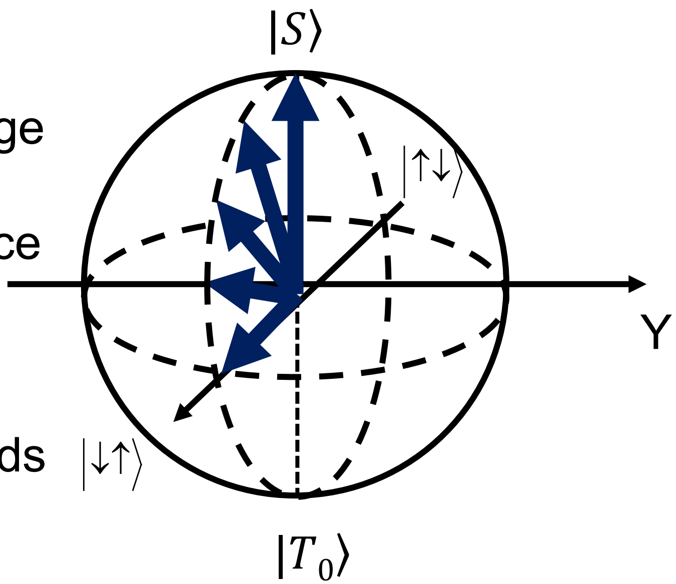
Tomographic sequence of STQ

High fidelity preparation of various input states



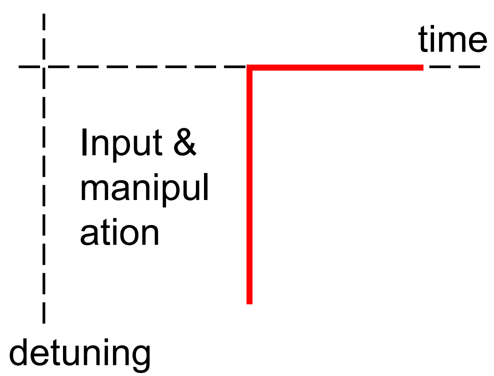
Eigenaxis controllability: Voltage controlled splitting allows accurate tomographic sequence

Adiabatic in & out : Corresponds to 90º rotation around Y axis

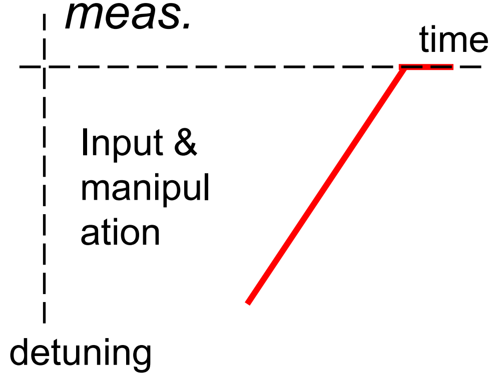


Versatile measurement axis rotation

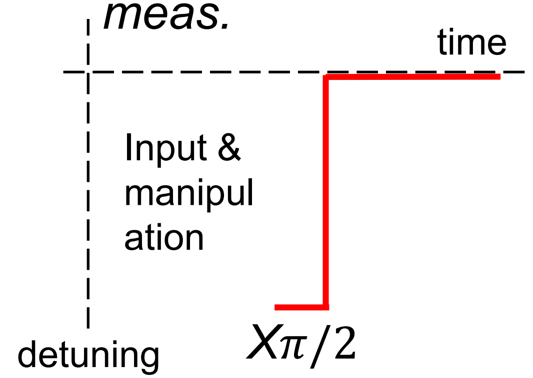
Z-projection meas.



$Y\pi/2$ Z = X-projection meas.

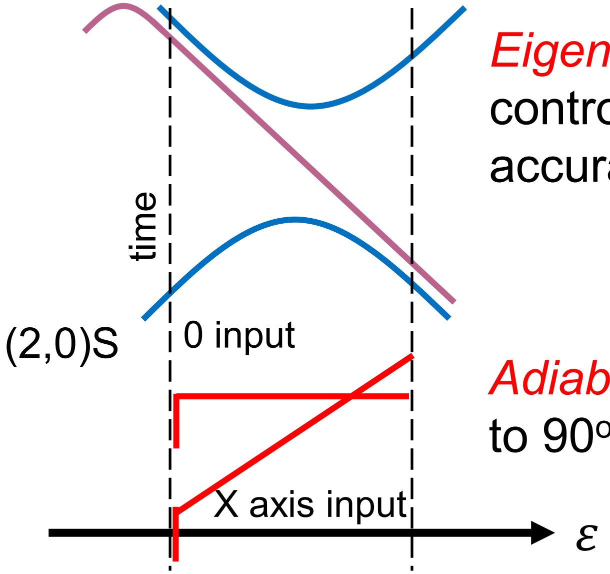


$X\pi/2$ Z = Y-projection meas.



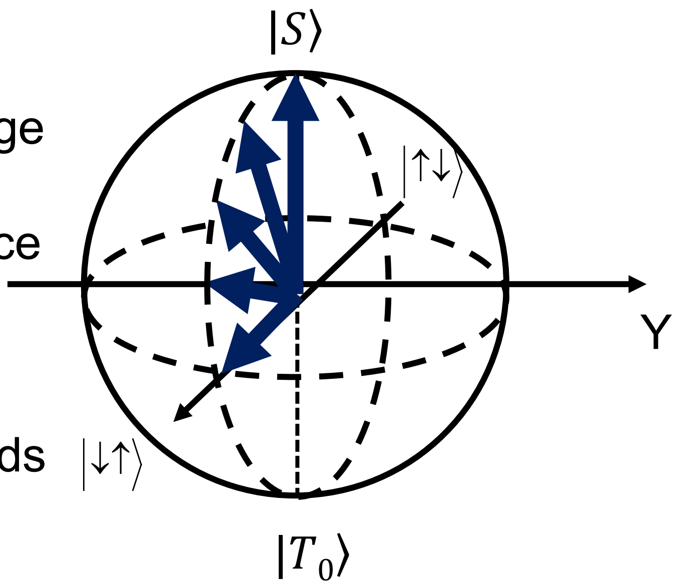
Resonant control of ST qubits

High fidelity preparation of various input states



Eigenaxis controllability: Voltage controlled splitting allows accurate tomographic sequence

Adiabatic in & out : Corresponds to 90º rotation around Y axis



그림그리기:

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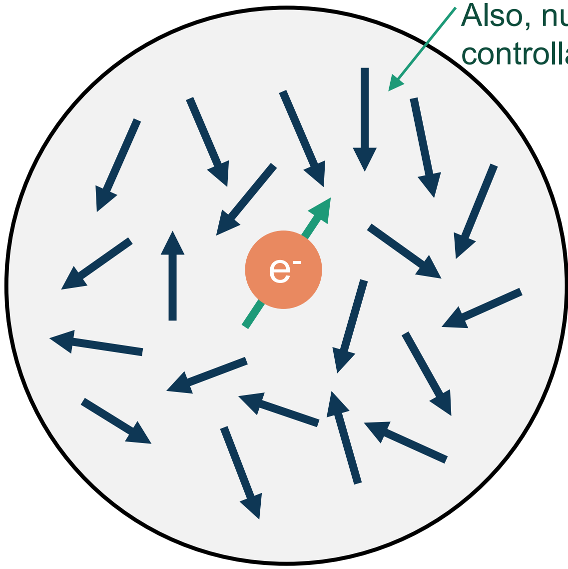
Approach: detailed description of experiments

Materials for QD qubits

GaAs

Fluctuating, but slow enough to keep track
Also, nuclear controllability



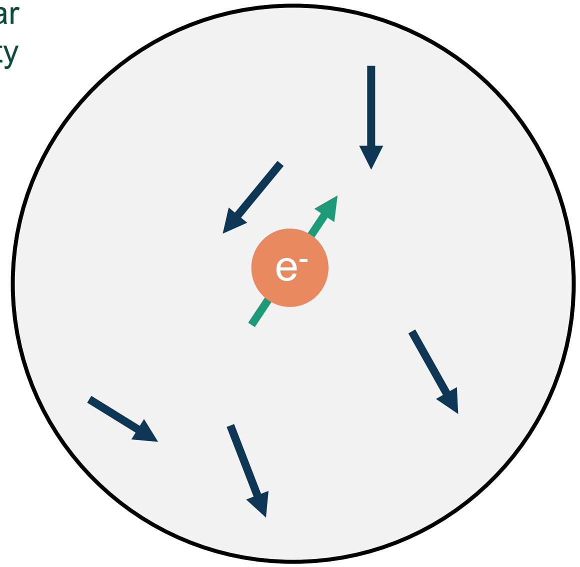
Material advantage

- *Mature growth, Ultra-stability*
- Clean QD formation
- Direct Band-gap – single valley

Major huddle

- *Nuclear control overhead*

^{Nat}Si or ^{28}Si



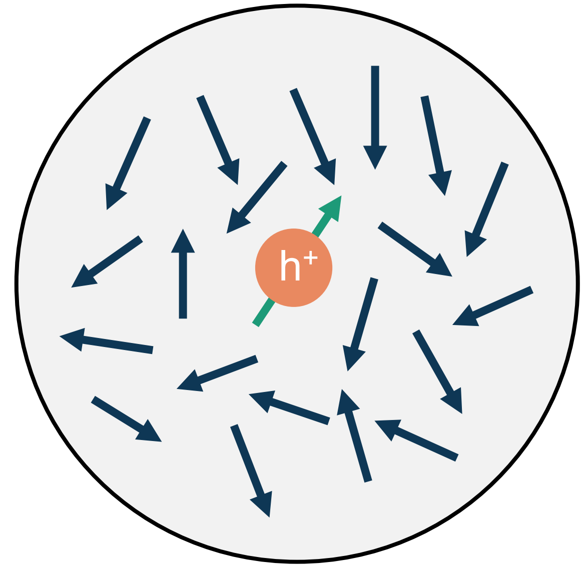
Material advantage

- *Small nuclear spin density*

Major huddle

- *Stringent fab. Req.*
- Unstable charge-traps
- Complicated valley physics

Ge (hole)



Material advantage

- *Hole spin less susceptible to nuclear noise*
- *Electric spin control (spin-orbit)*

Major huddle

- *Charge noise susceptibility (spin-orbit coupling)*

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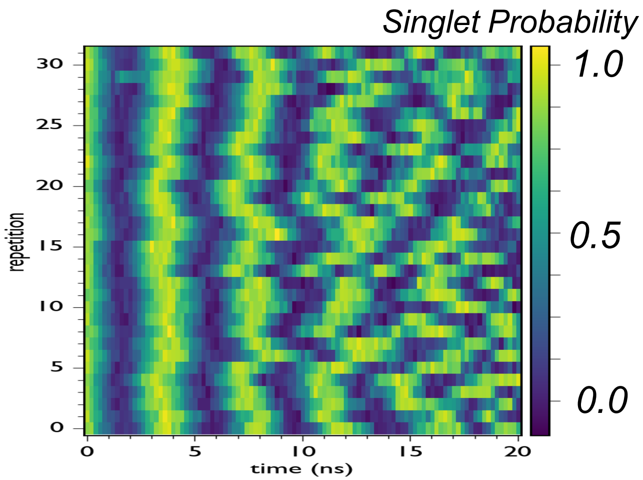
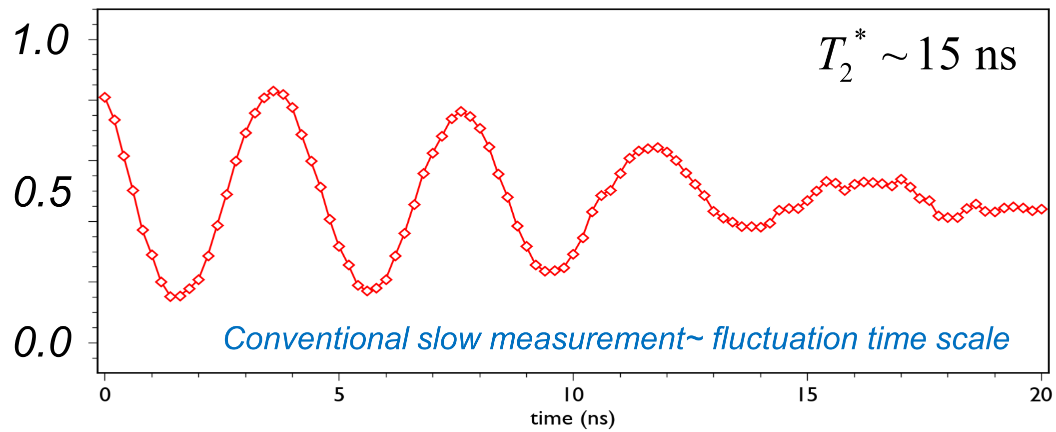
Singlet-Triplet qubits

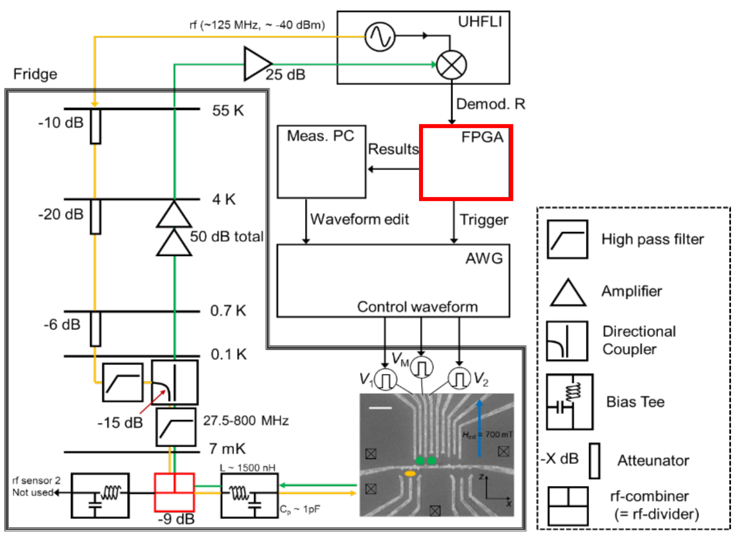
Real time Hamiltonian Parameter estimation



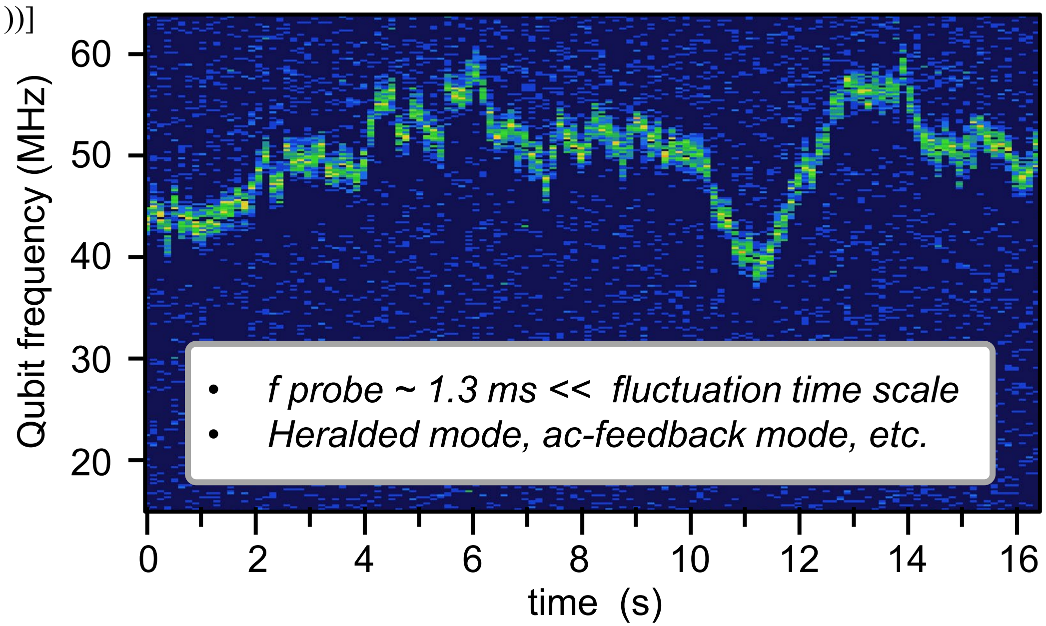


Bayesian inference with FPGA M.D. Shulman et al., *Nature Comm.* **5** 5156 (2013)

$$P(\Delta B_z | m_N, m_{N-1}, \ldots m_1) = P_0(\Delta B_z) \prod_{k=1}^{N} \frac{1}{2}[1 + r_k(\alpha + \beta \cos(2\pi \Delta B_z t_k))]$$



Real-time Qubit frequency tracking

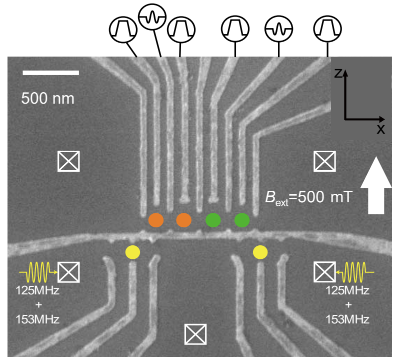


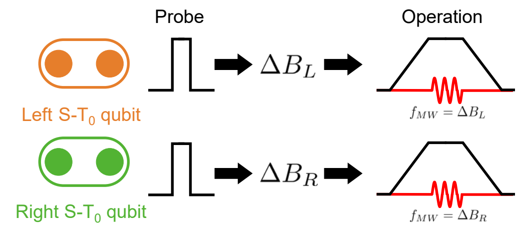
3

Recent contributions by SNU group

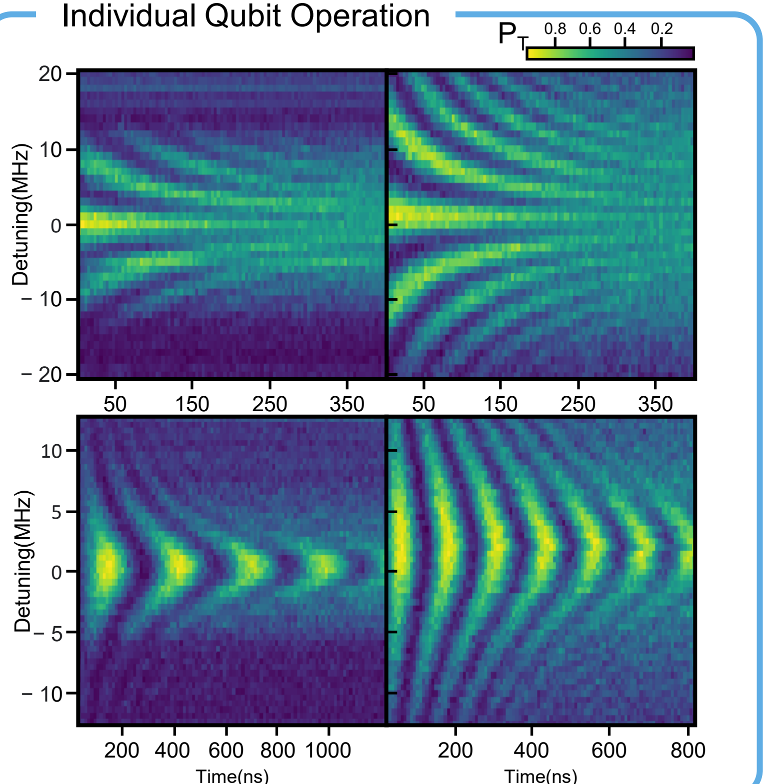
Two ST_0 qubits: Simultaneous Hamiltonian Parameter Estimation

Manuscript in preparation

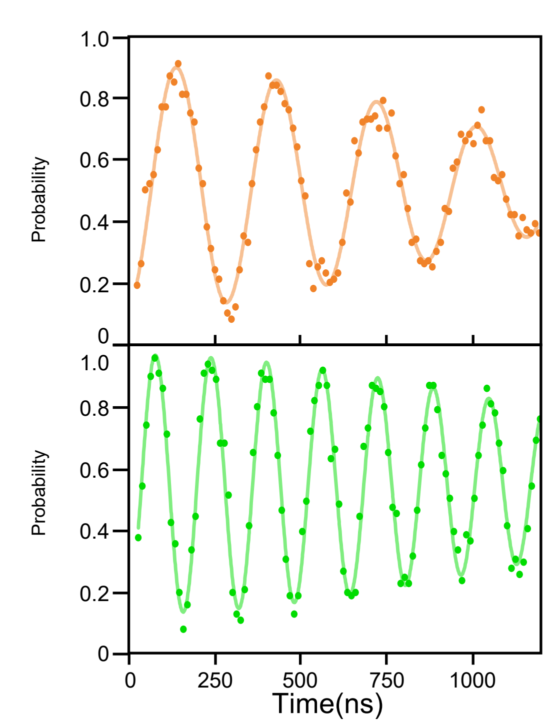




Individual Qubit Operation



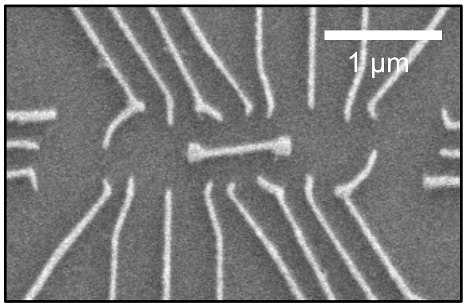
Simultaneous Qubit Driving



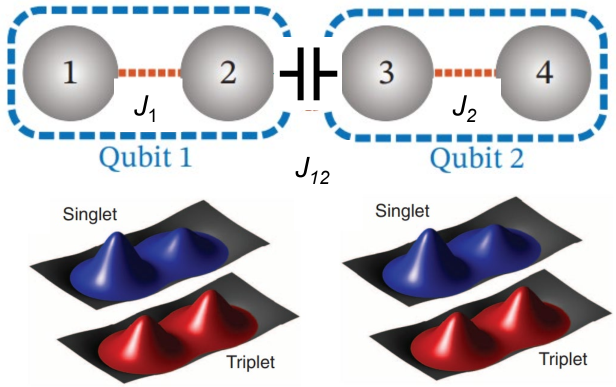
Two qubit interaction

Two qubit gate in two STQs

1. Dipolar interaction - Capacitive : possible but often slow



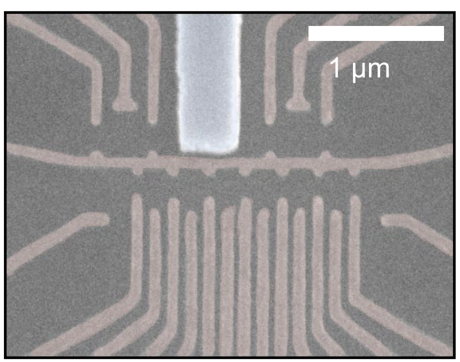
Harvard, *npj. Quant. Inf.* (2017)

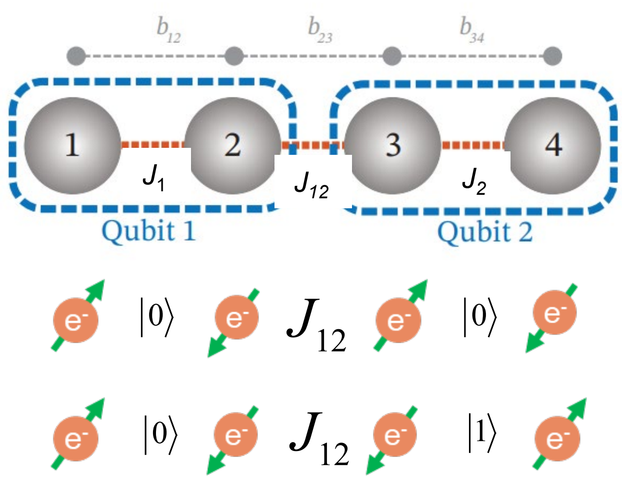


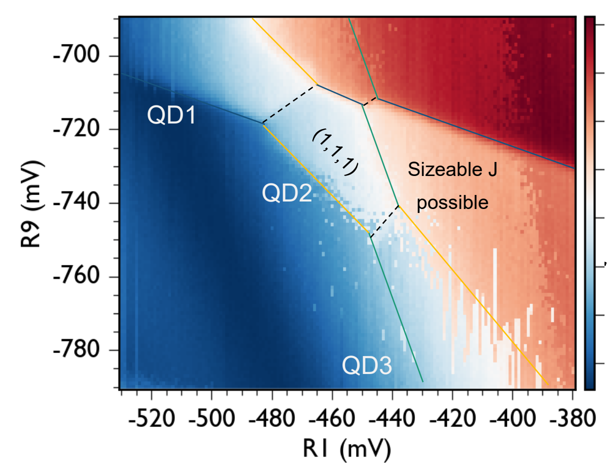
Interaction assumed to be small $\propto A(r)J_{12}J_{34}$

Previously ~3 MHz 2Q coupling demonstrated with spin-echo

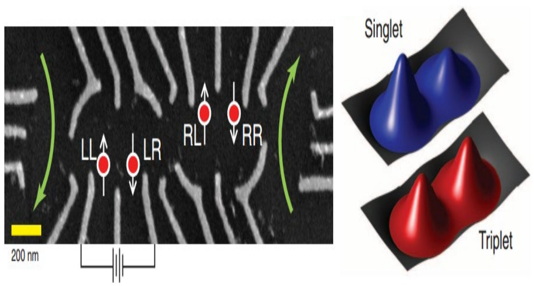
2. Inter Q exchange coupling : intrinsically fast, but leakage

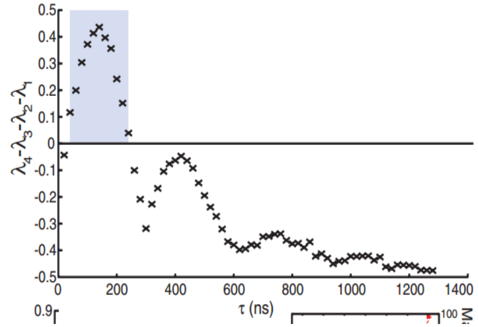


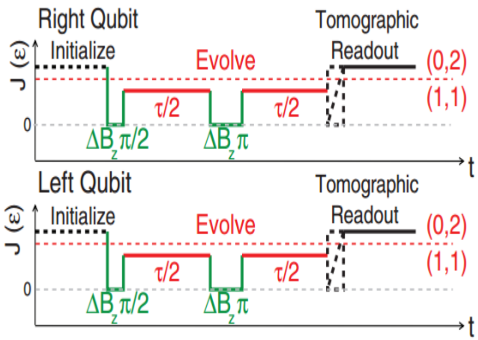


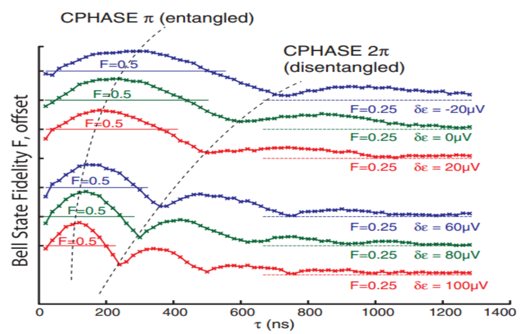


Previous entanglement demonstration



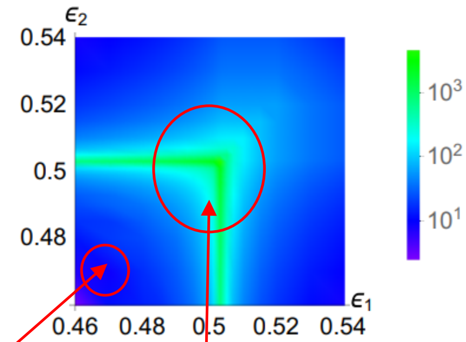






vs.

Theory of J_{12}/J_1J_2



Unexplored area

M. D. Shulman, et al., *Science* **336** 202 (2012)
D. Buterakos, S. Das Sarma, Physical Review B **100**, 075411 (2019)

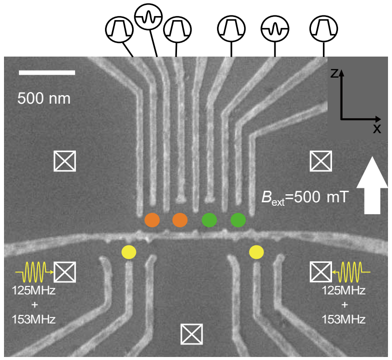
Previous : only at weak dipole-coupling regime

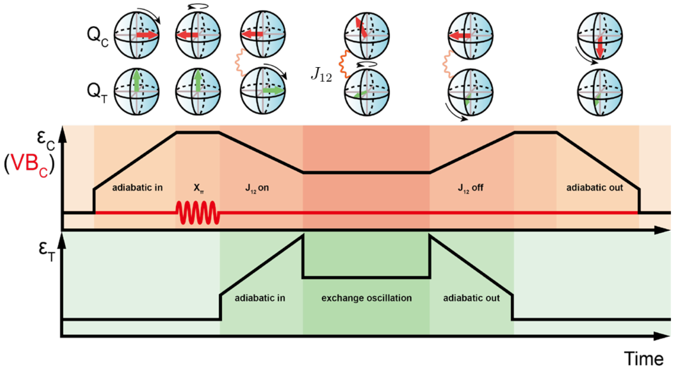
J_{12} ~ 3 MHz @ J_1, J_2 = 300 MHz ($J_{12} \sim J_1J_2$, bilinear), CZ gate fidelity ~ 70 %

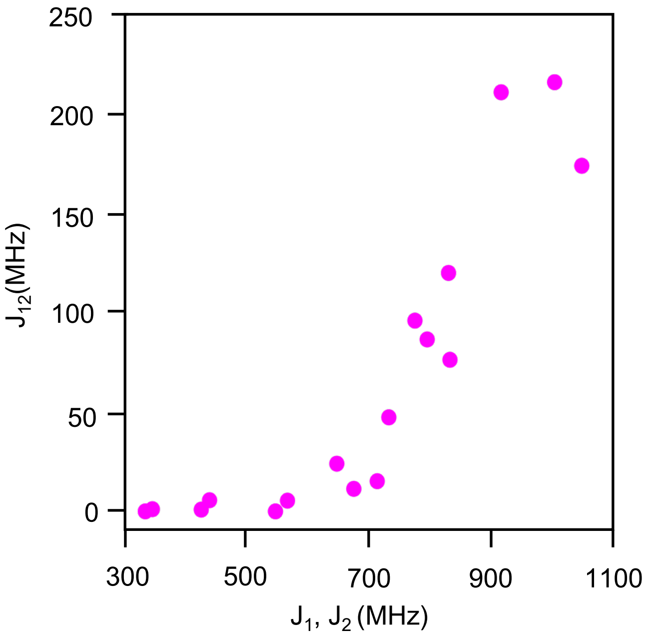
Recent contributions by SNU group

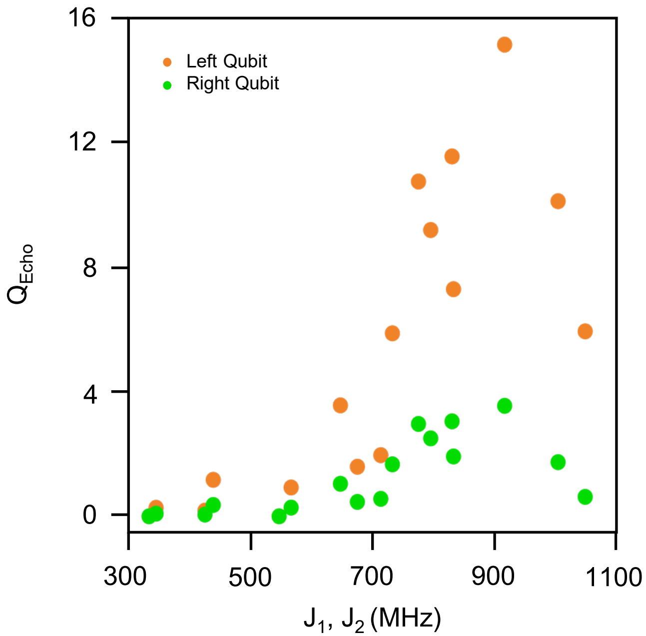
Strong capacitive coupling regime

Manuscript in preparation







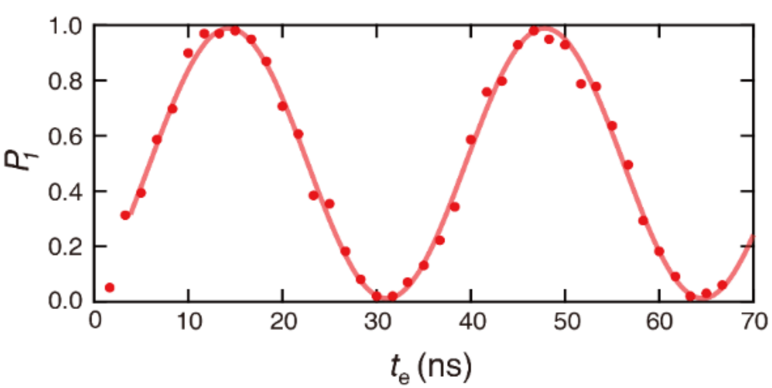


J_{12} ~ 220 MHz (> 20% of J_1, beyond bilinear regime, CZ gate fidelity > 90 %

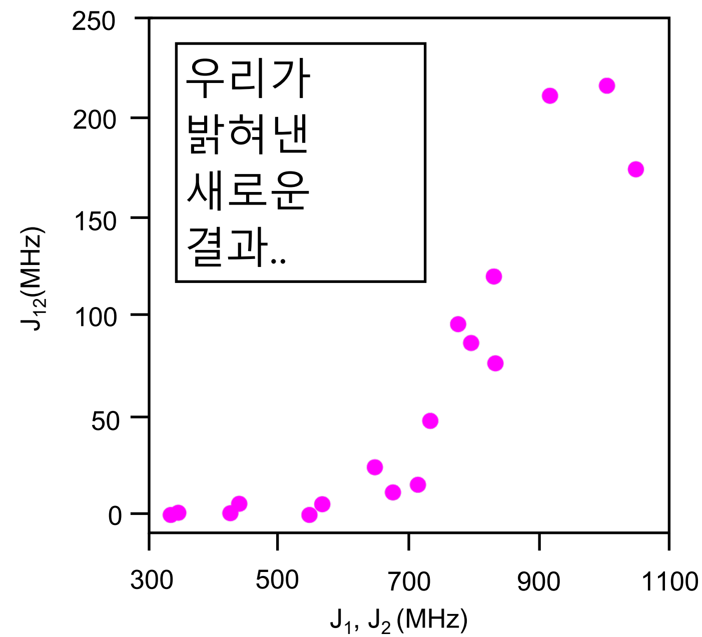
Summary of Lecture 1

Single spin qubit, Singlet-Triplet qubit

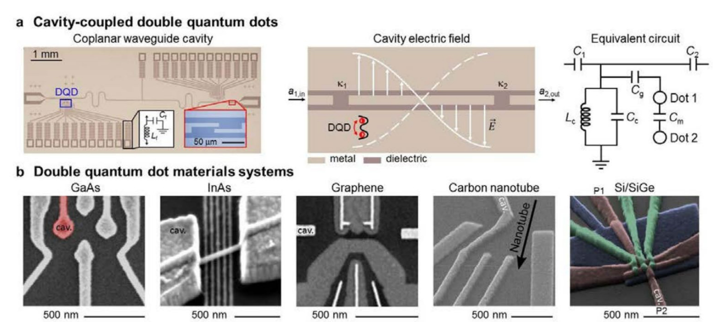
반도체 큐비트의 quality 도 이제는 다른 플랫폼에 못지 않게….



Capacitive coupling can be strong.



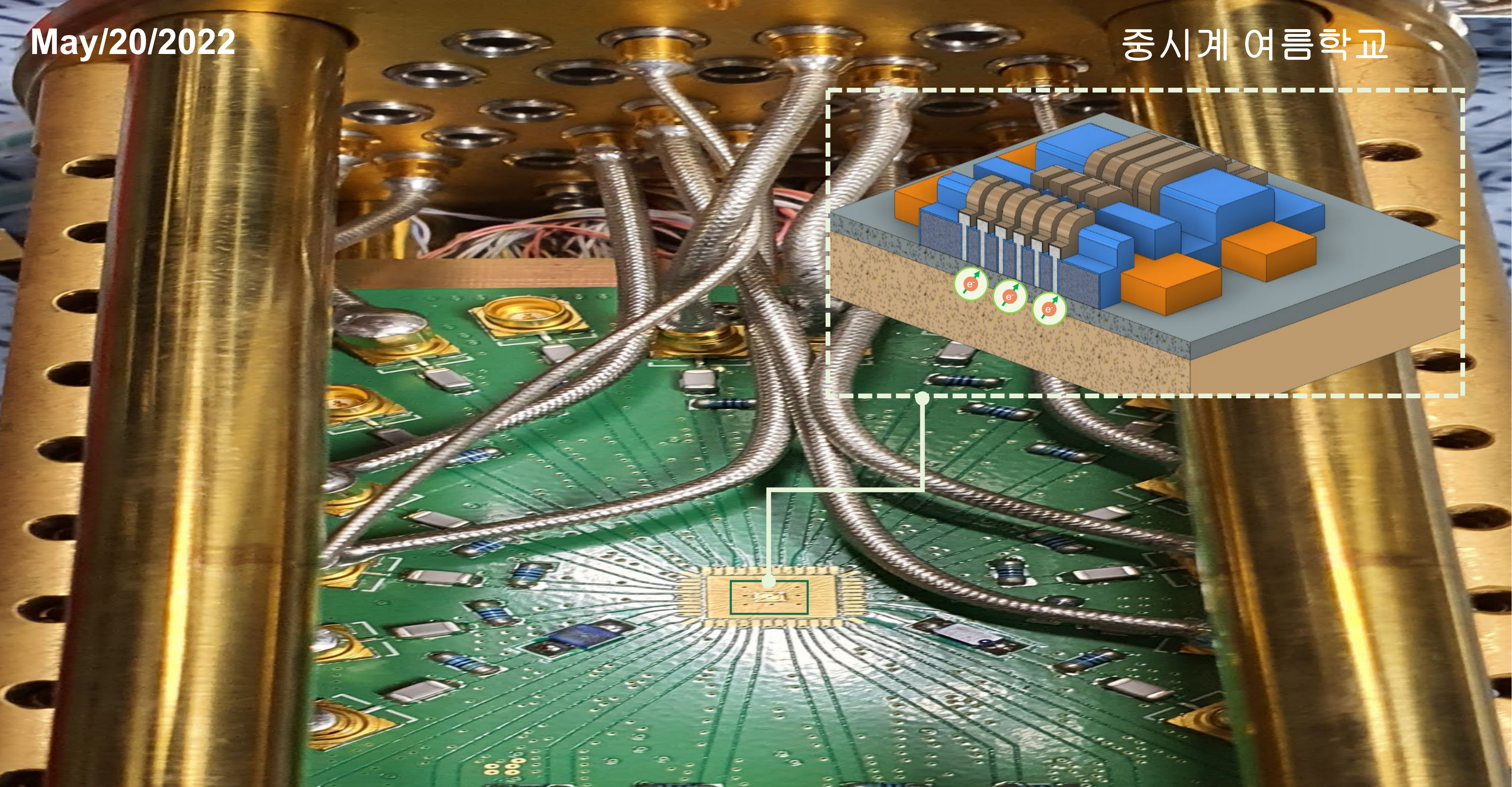
다음시간: 1. 구체적으로 3,4,6 큐비트 등은 어떻게 제어하나요? Ex. 아까 그림 보니 센서는 2개까지 밖에 없던데…
2. 멀리 떨어진 큐비트들은 어떻게 연결하나요?
3. Scaling 하는데 이슈는 ?



Nature Rev. Physics **2**, 129 (2020)

May/20/2022

중시계 여름학교



Quantum dot spin qubits II: multi-qubits and shuttling

(Slide courtesy : 윤종인, 장원진)

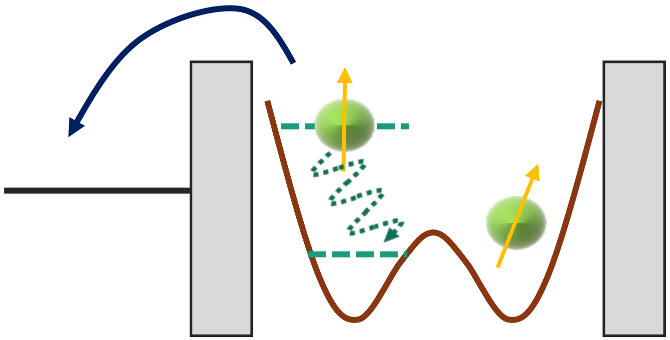
Dohun Kim

Department of Physics & Astronomy, SNU

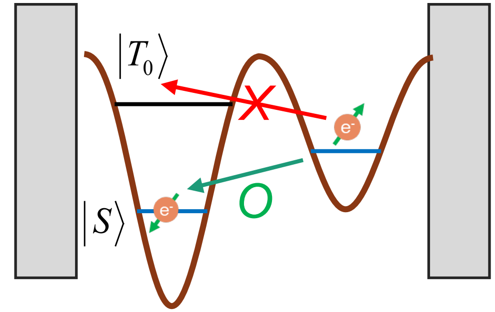
Outline

- Background *Recall EST & PSB, non-demolition measurements*
- Approach *Multi qubit initialization, manipulation, measurement*
- Some recent achievements *Shuttling-based long-distance connection, High-temperature operations*

Recall RSB & EST



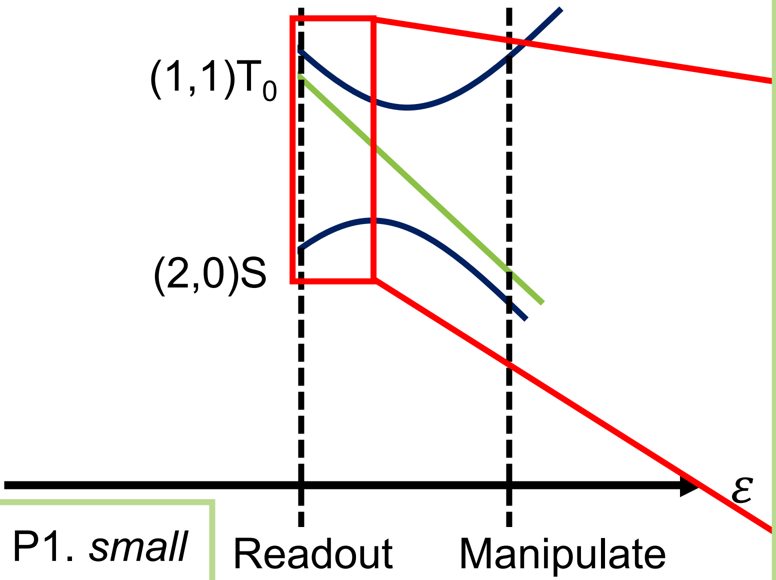
Measure one electron charge change



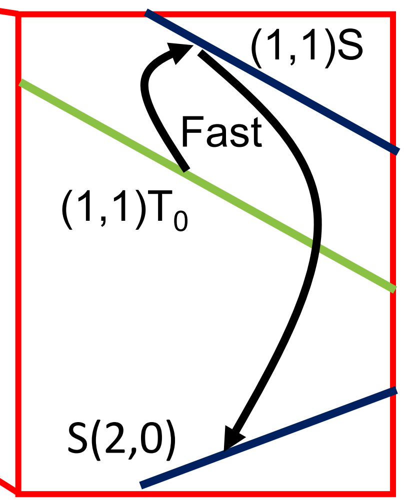
Measure relative position

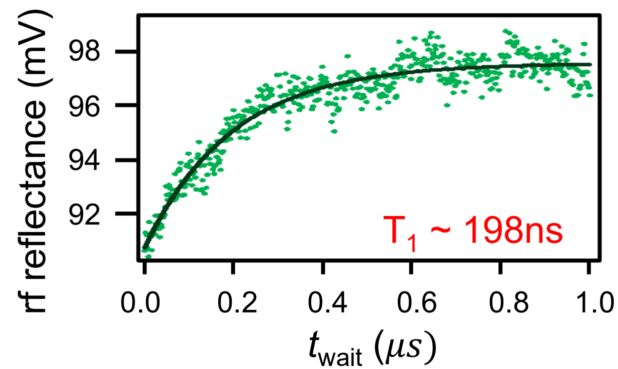
Typical signal : 그리기

Problem of conventional Read-out of STQ



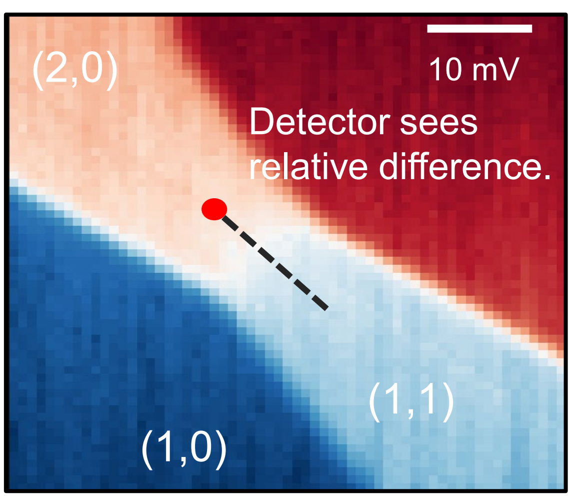
P2. *fast relaxation*



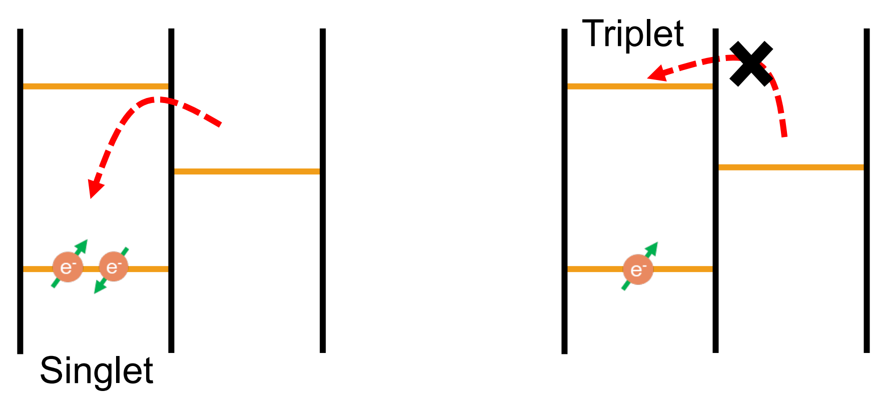


At PSB detuning, ΔB mixes S & T_0: (1,1)T_0 relax to S(2,0) – fast at *large* ΔB

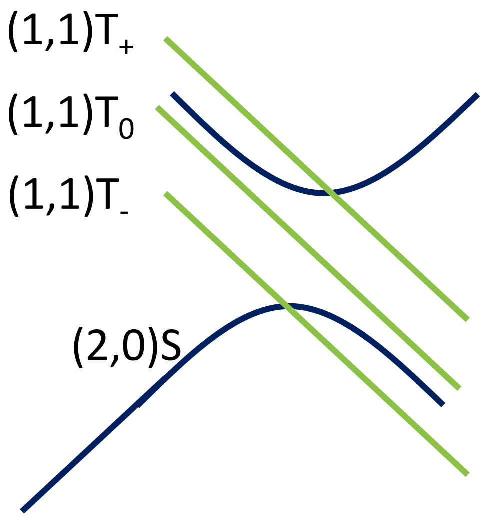
P1. *small Signal*



At the Readout point : *spin blockade*



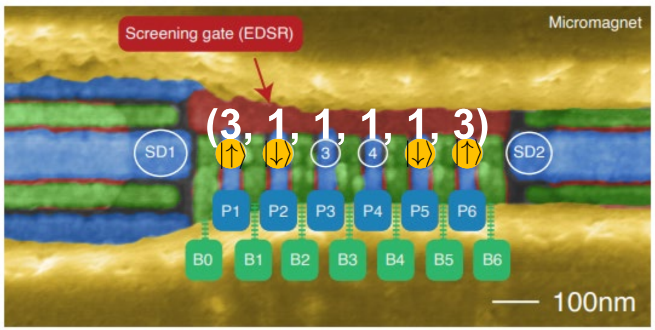
Really a problem ? Parity readout

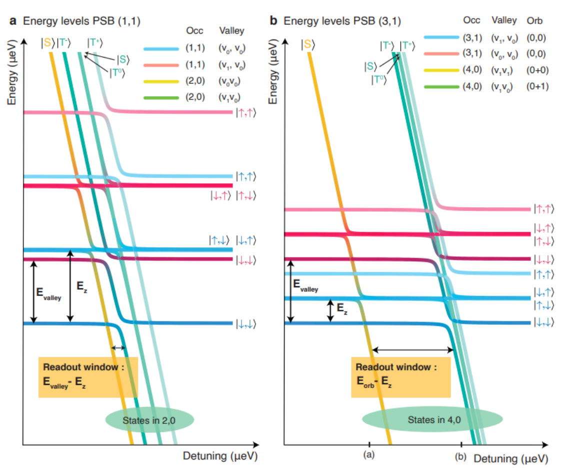


Typical signal : Readout 방법 그리기

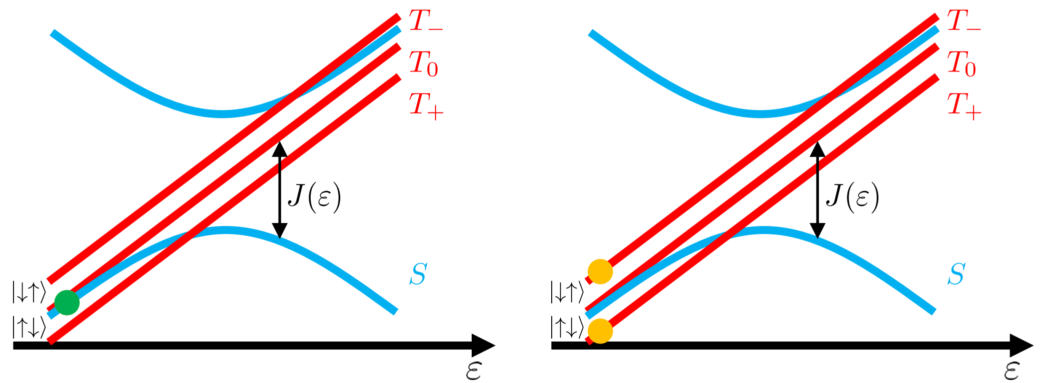
Six qubit operation : initialization

Initialization of the Spin State





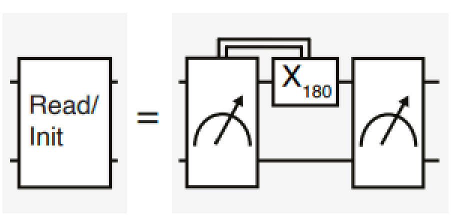
1. Parity based initialization of qubit 1-2 (5-6)



Odd Parity: T_0 relaxes **well before the 10μs readout window** at PSB regime

➡ Readout of state parity using PSB

Real-time feedback initialization

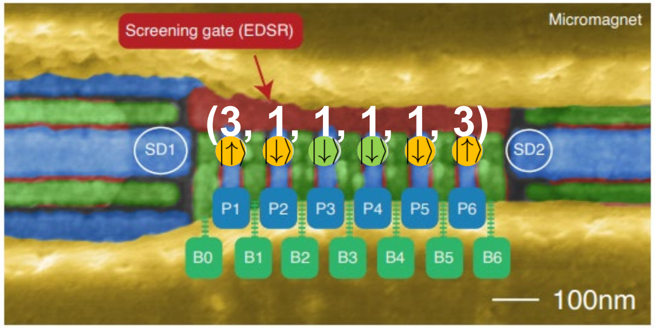


1. First parity measurement
2. Burst a π-pulse on qubit 1 when even parity
3. Second Parity Measurement
4. $|\uparrow\downarrow\rangle$ state is prepared

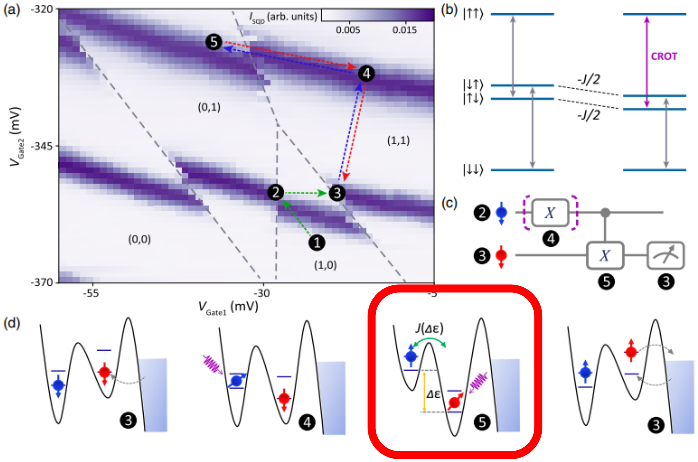
https://arxiv.org/abs/2202.09252

Six qubit operation : initialization

Initialization of the Spin State



2. Quantum-Non-Demolition readout of inner spin qubits



Physical Review A 32.4 (1985): 2287.

1. The uncertainty introduced by the measurement should not affect the motion of the observable

$$[A_S, H_S] \approx [\sigma_z, \sigma_z] = 0$$

2. The interaction with the ancilla should not affect the motion of the observable

$$[A_S, H_{int}] \approx [\sigma_z, (\sigma_z \otimes \sigma_z - 1)] = 0$$

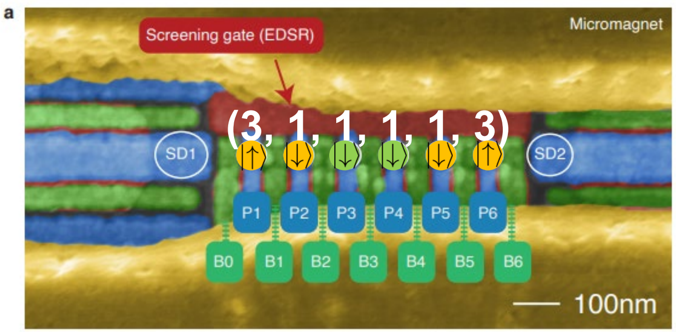
Physical Review X 10.2 (2020): 021006.

용어의 모호함 ?

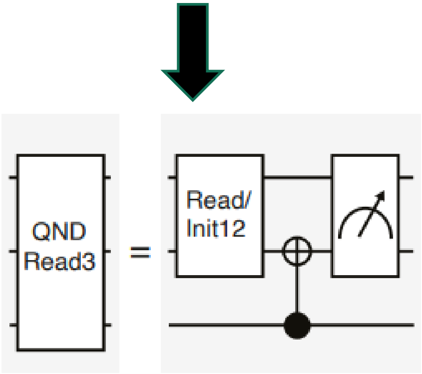
2 Approach

Six qubit operation : initialization

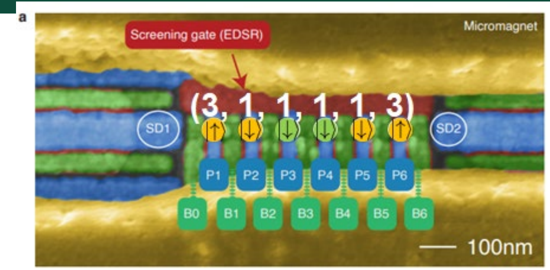
Initialization of the Spin State



2. Quantum-Non-Demolition readout of inner spin qubits
   1. Initialize the ancilla qubit to the spin-down state
   2. Turn on J_{int} by pulsing a virtual barrier gate and perform a CNOT gate
   3. Pulse to (4,0) and perform the single-shot measurement of the ancilla qubit
   4. Parity measurement prepares the desired initial states for qubit 1 and 2
   5. If qubit 3 is spin-up, flip it using the π-pulsing microwave

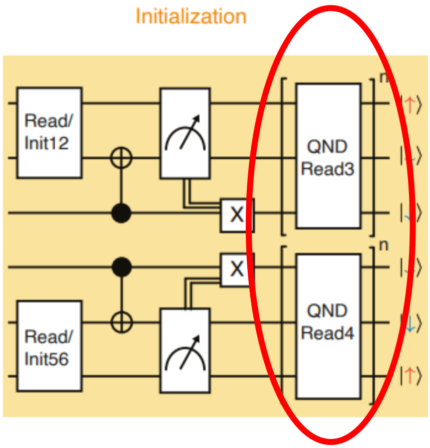


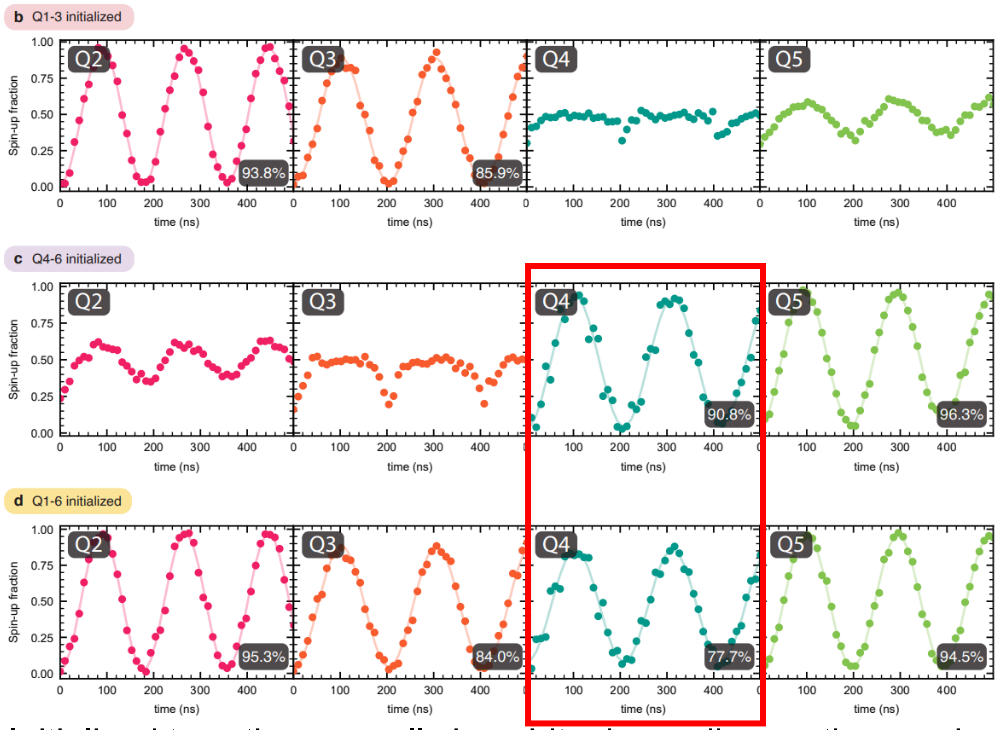
Six qubit operation : initialization



Initialization of the Spin State

1. Parity based initialization of qubit 1-2 (5-6)
2. Quantum-Non-Demolition readout of inner spin qubits





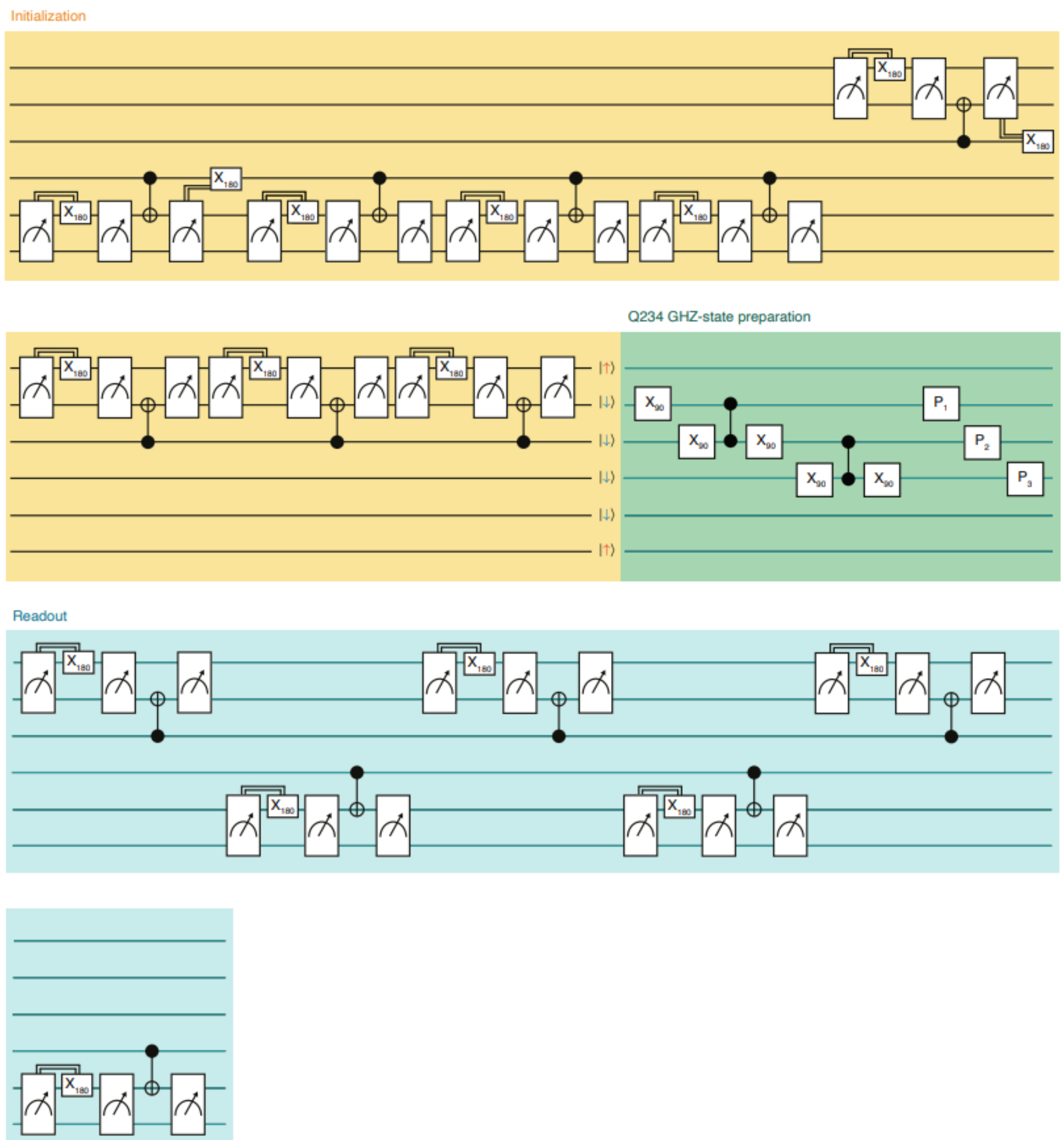
Run QND measurement three times and **post-select** runs with three identical QND readout outcome
(except for GHZ state preparation and tomography, where the **majority vote** is used)

Initialized two, three, or all six qubits depending on the requirement of the specific quantum circuit

2

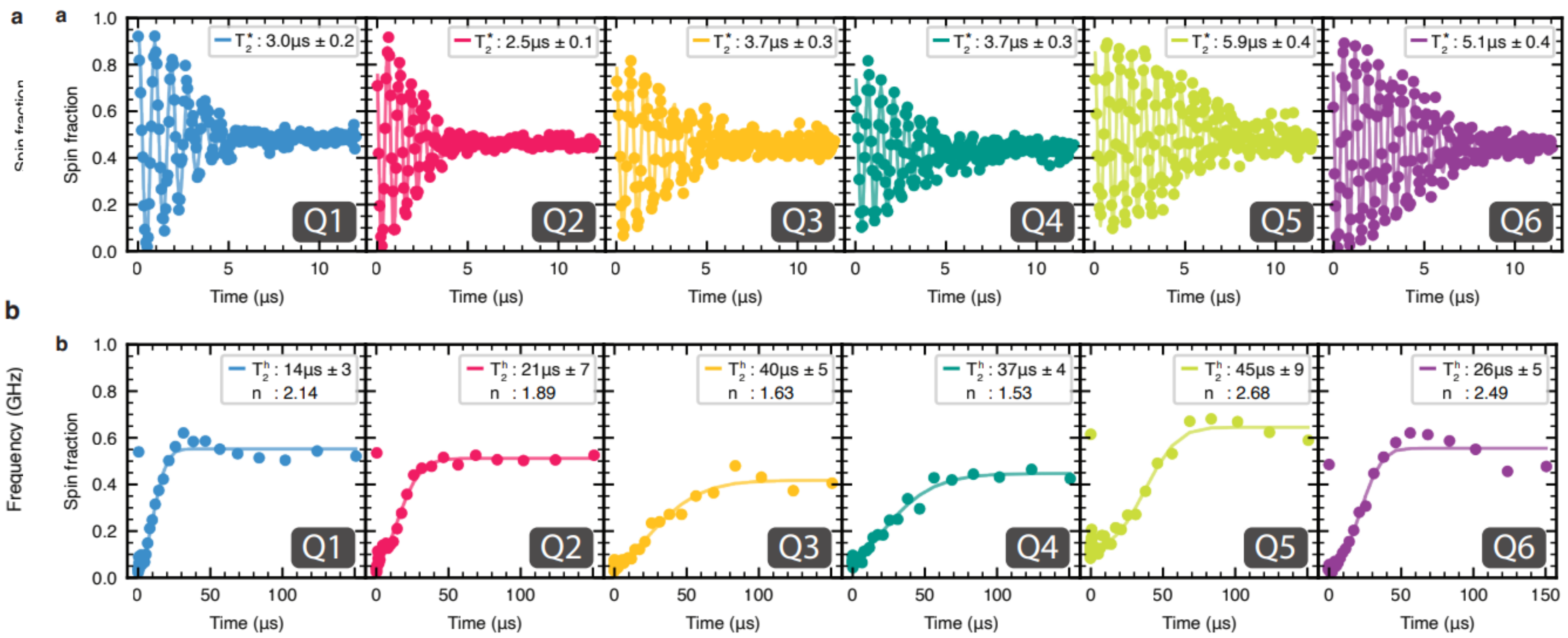
Approach

Six qubit operation : readout



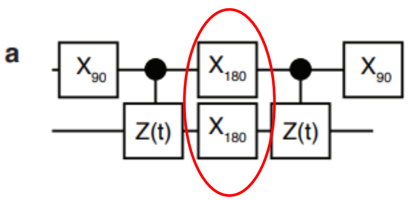
Six qubit operation : operation

1. EDSR Based Rabi Oscillation

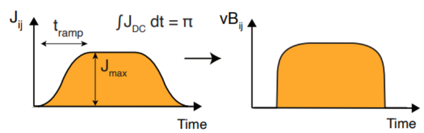


Six qubit operation : operation

2. Two Qubit Gate (C-Phase) by Virtual Barrier Gate Pulse



Apply π to both Q1 and Q2, which offsets the oscillation by J_s and J_A yet preserves the oscillation by J_{int}



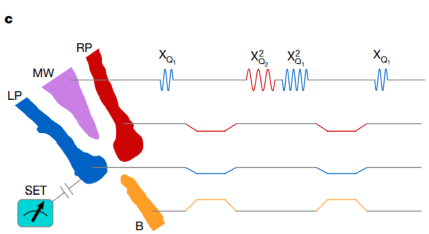
$$W(t,r)=\begin{cases}\frac{1}{2}\left[1-\cos\left(\frac{2\pi t}{r t_p}\right)\right] & 0\le t\le \frac{r t_p}{2}\\ 1 & \frac{r t_p}{2}<t<t_p-\frac{r t_p}{2},\\ \frac{1}{2}\left[1-\cos\left(\frac{2\pi (t_p-t)}{r t_p}\right)\right] & t_p-\frac{r t_p}{2}\le t\le t_p\end{cases}$$

Nature 601.7893 (2022): 343-347.

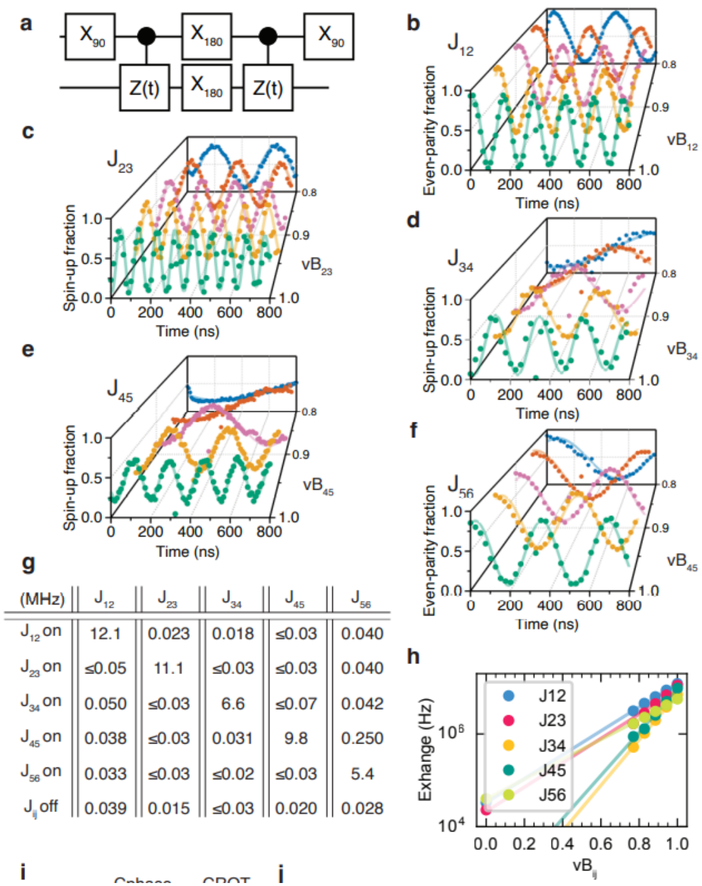
Tukey window with a ramp time of

$$t_{ramp}=\frac{3}{\sqrt{\delta B^2+J_{max}^2}}$$

Physical Review A 90.2 (2014): 022307.



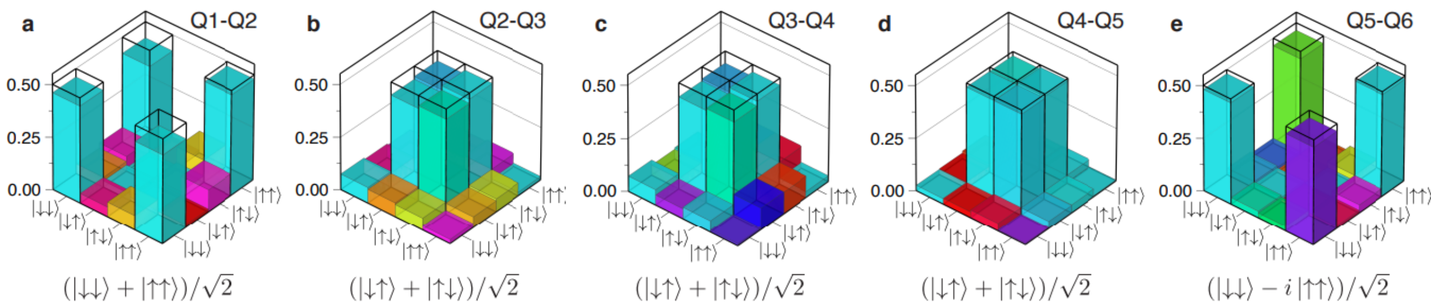
Nature 601.7893 (2022): 343-347.

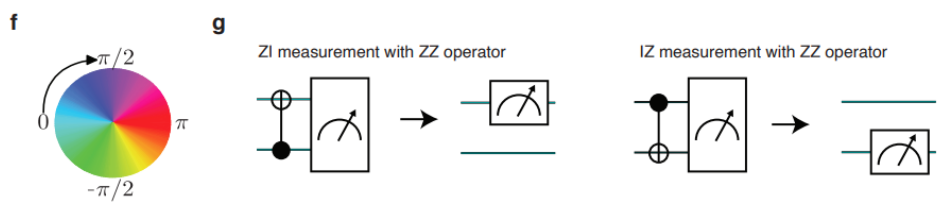


(MHz)	J_{12}	J_{23}	J_{34}	J_{45}	J_{56}
J_{12} on	12.1	0.023	0.018	≤0.03	0.040
J_{23} on	≤0.05	11.1	≤0.03	≤0.03	0.040
J_{34} on	0.050	≤0.03	6.6	≤0.07	0.042
J_{45} on	0.038	≤0.03	0.031	9.8	0.250
J_{56} on	0.033	≤0.03	≤0.02	≤0.03	5.4
J_{ij} off	0.039	0.015	≤0.03	0.020	0.028

Six qubit operation : operation

3. Bell State Tomography/GHZ State Tomography



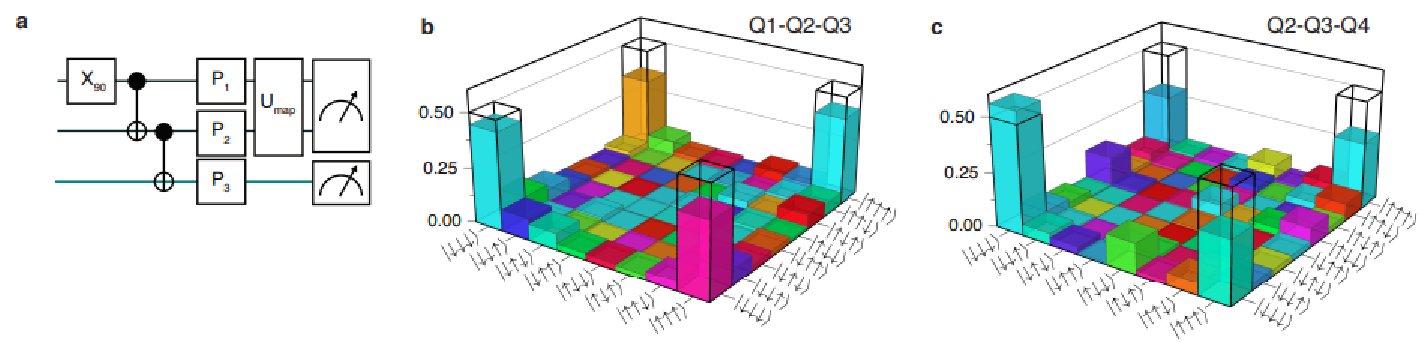


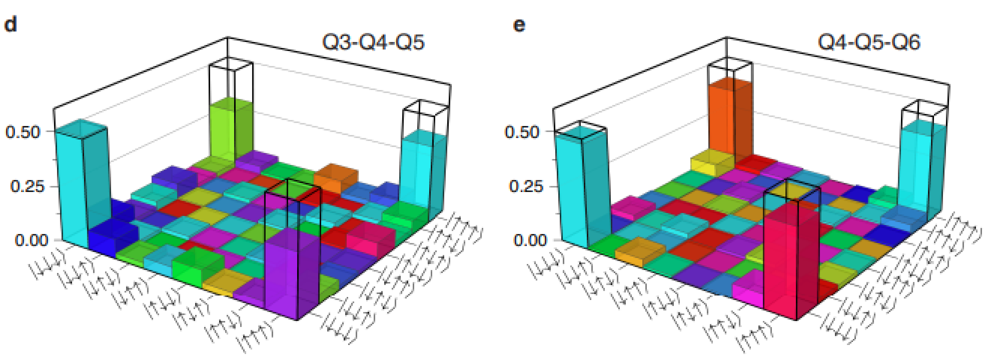
h

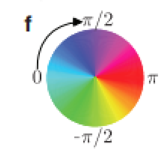
Qubits	Fidelity (%)	Concurence (%)
1-2	89.2 ± 2.2	86.7 ± 3.2
2-3	90.1 ± 2.2	83.9 ± 3.8
3-4	88.3 ± 3.6	87.9 ± 5.0
4-5	95.6 ± 2.0	94.9 ± 3.2
5-6	94.1 ± 1.4	90.6 ± 3.6

Six qubit operation : operation

4. GHZ State Tomography







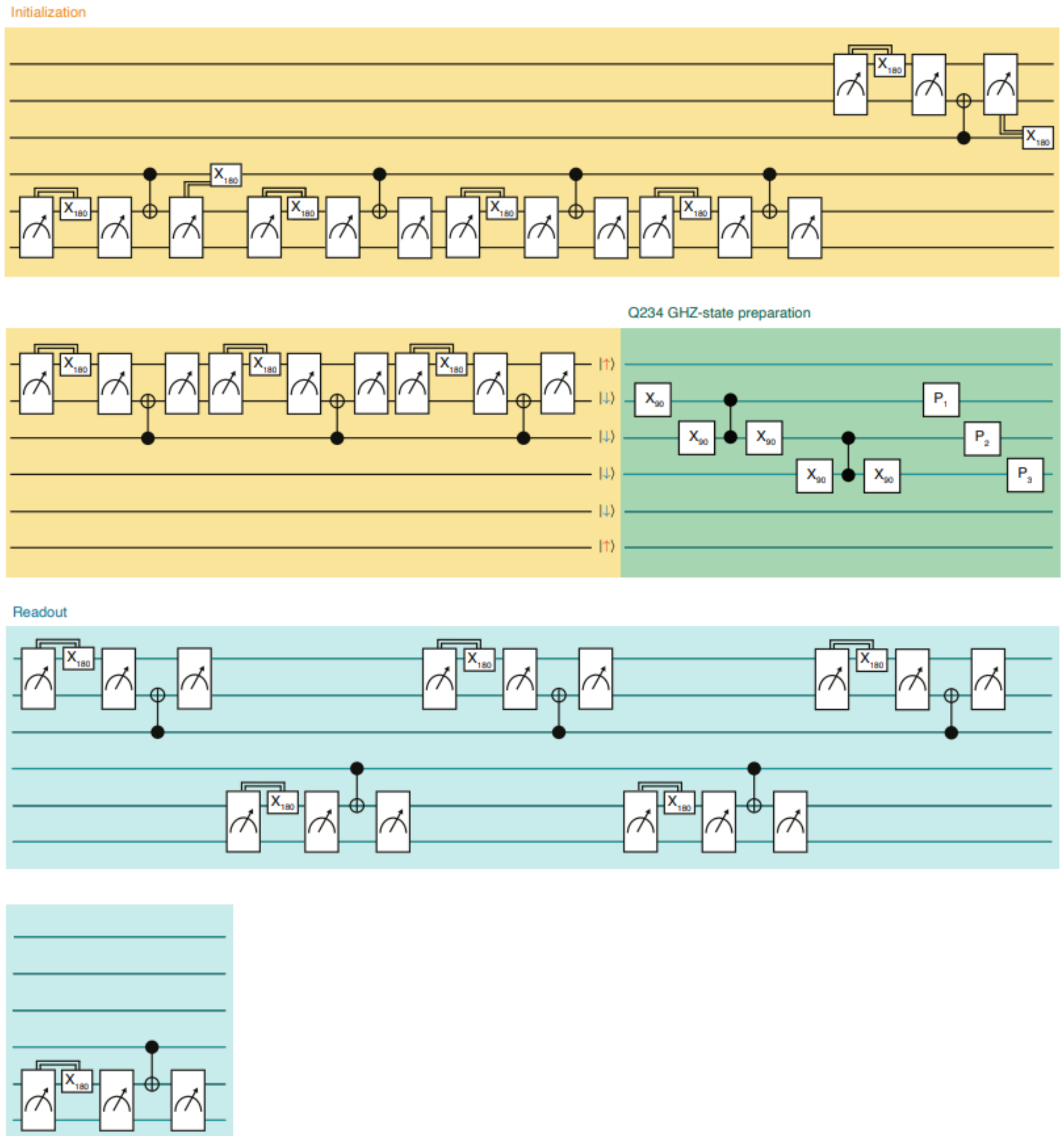
g

Qubits	Φ (rad)	Fidelity (%)	Witness
1-2-3	2.41	76.8 ± 2.2	-0.327 ± 0.022
2-3-4	-0.32	71.4 ± 3.2	-0.297 ± 0.038
3-4-5	1.67	72.2 ± 4.0	-0.291 ± 0.036
4-5-6	2.68	83.6 ± 2.2	-0.380 ± 0.024

2

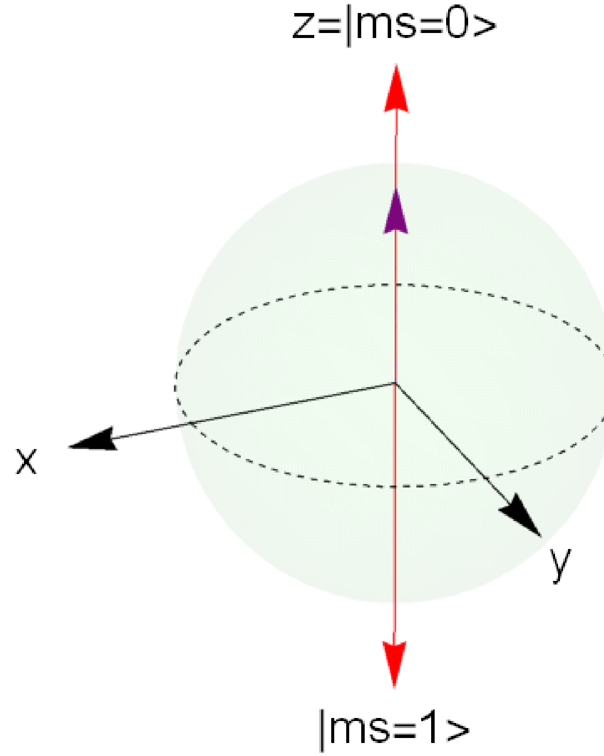
Approach

Six qubit operation : 전체회로 recall



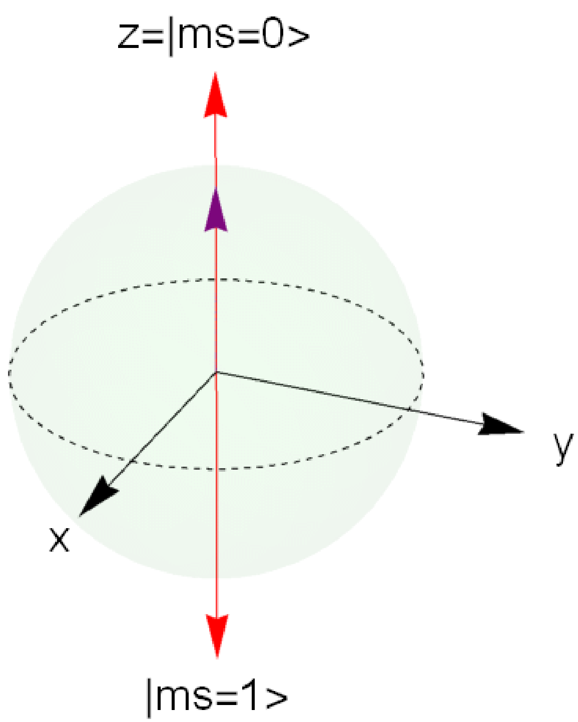
One more technique : Spin-echo

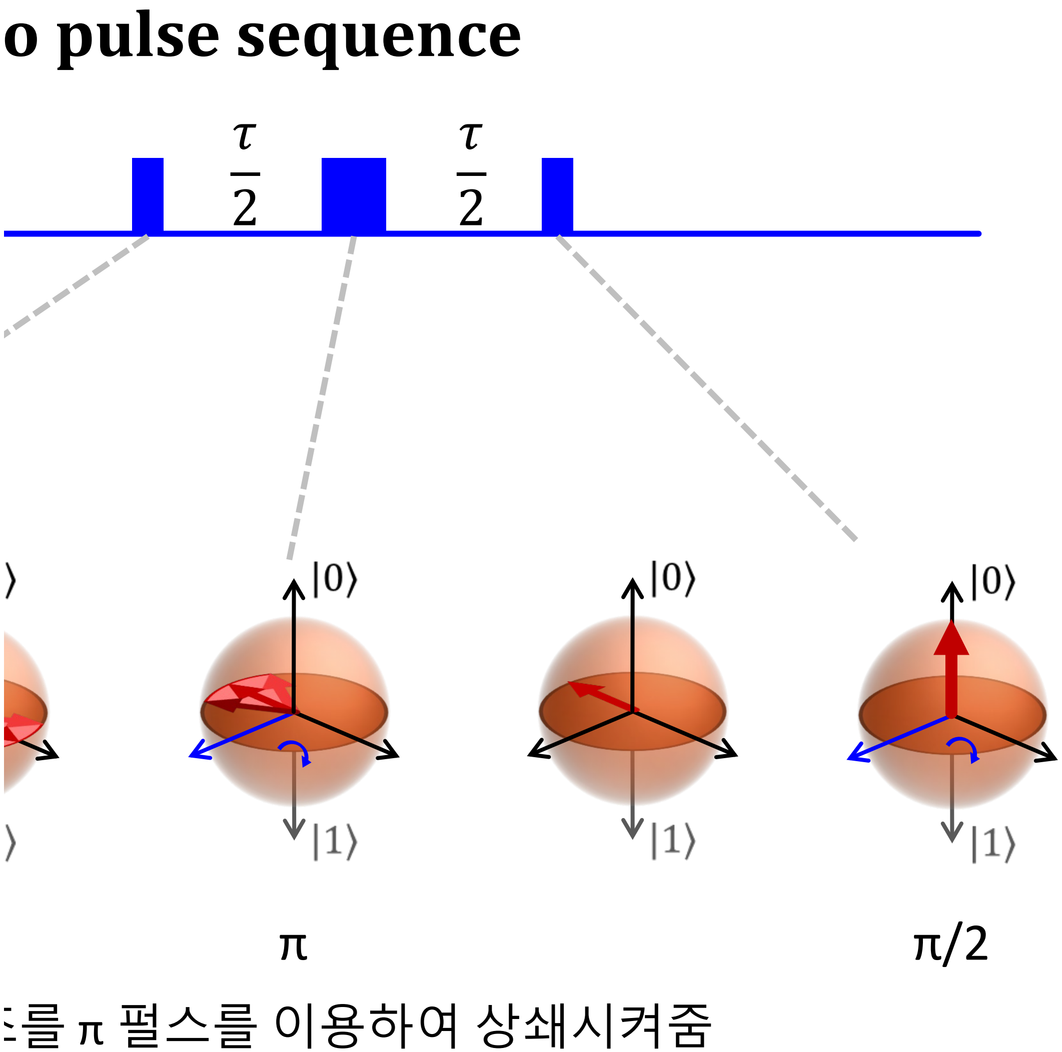
Ramsey sequence



One more technique : Spin-echo

Spin echo

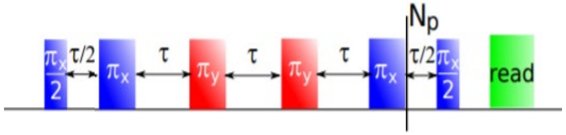




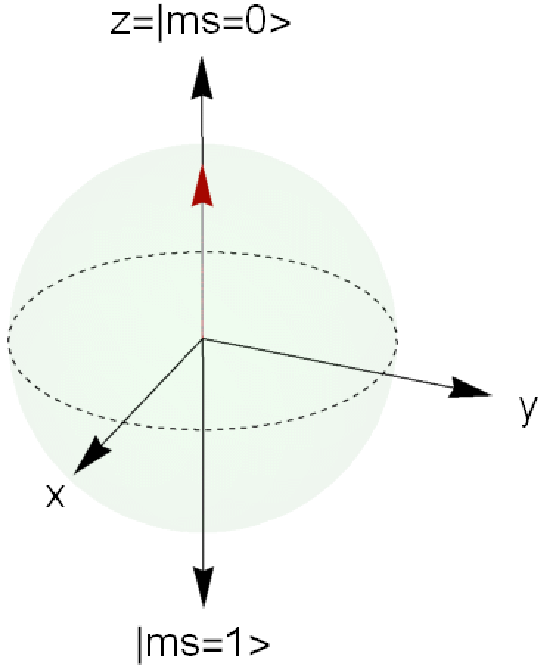
One more technique : Spin-echo

Ex: CPMG (Carr-Purcell-Mieboom-Gill) pulse

Cpmg sequence



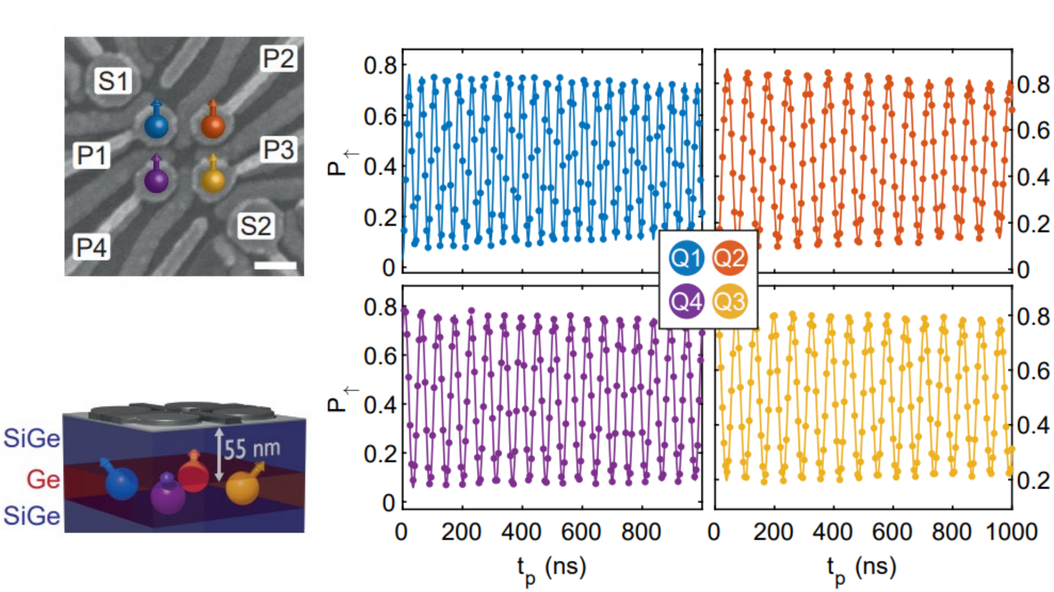
CPMG XY4

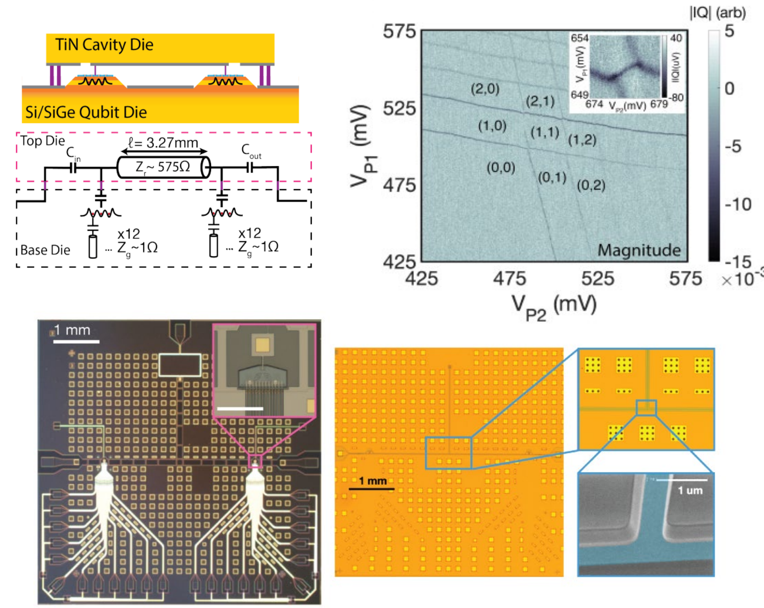


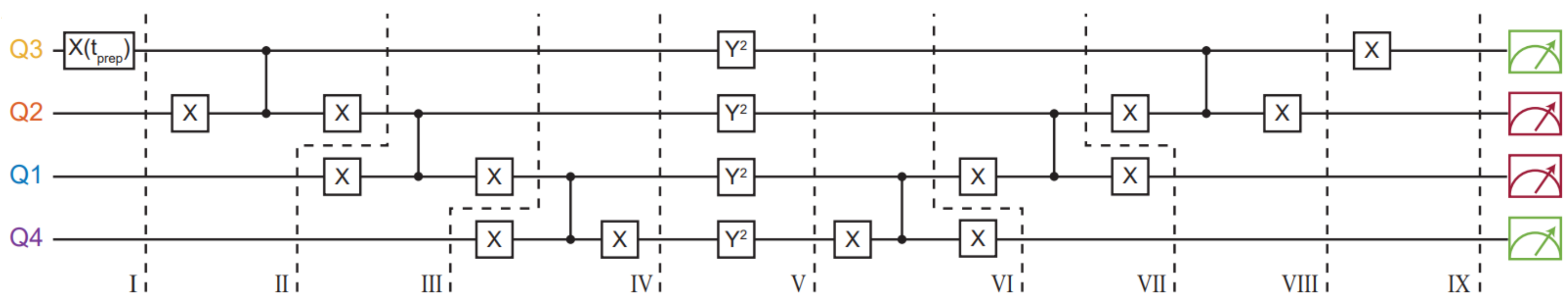
Dynamic decoupling 의 핵심 : dynamic decoupling pulse sequence 는 frequency filter, 이를 이용하면 environment 의 noise spectrum 측정 가능 – 좀 더 advanced course 에서…

Example: Si, GaAs, Ge.. Boosting up results

Most recent developments : Germanium 4 qubit processing & 3D integration

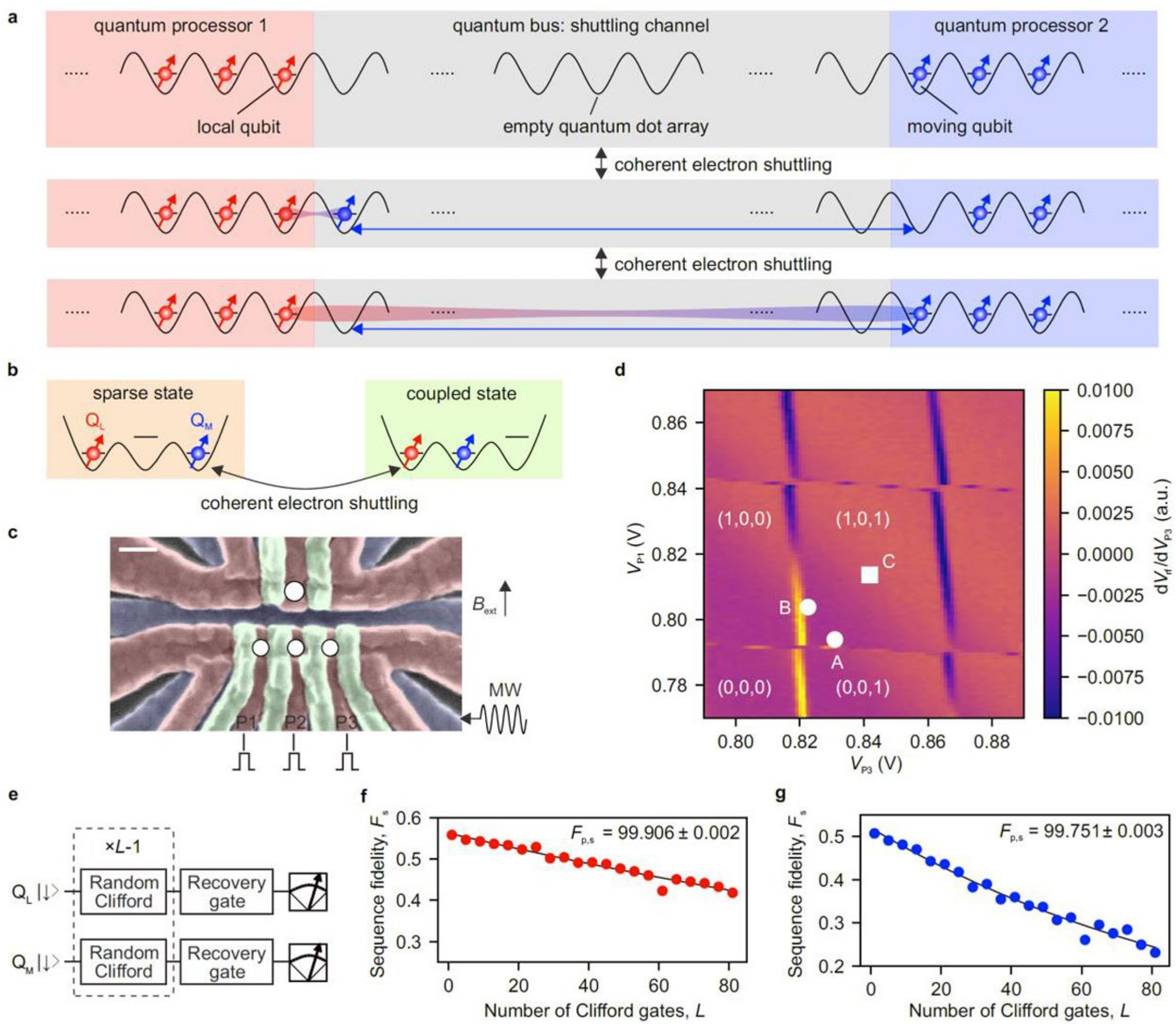






quTech, Delft Sep. 2020
M.Eriksson group UW Nov. 2020

Coherent Shuttling

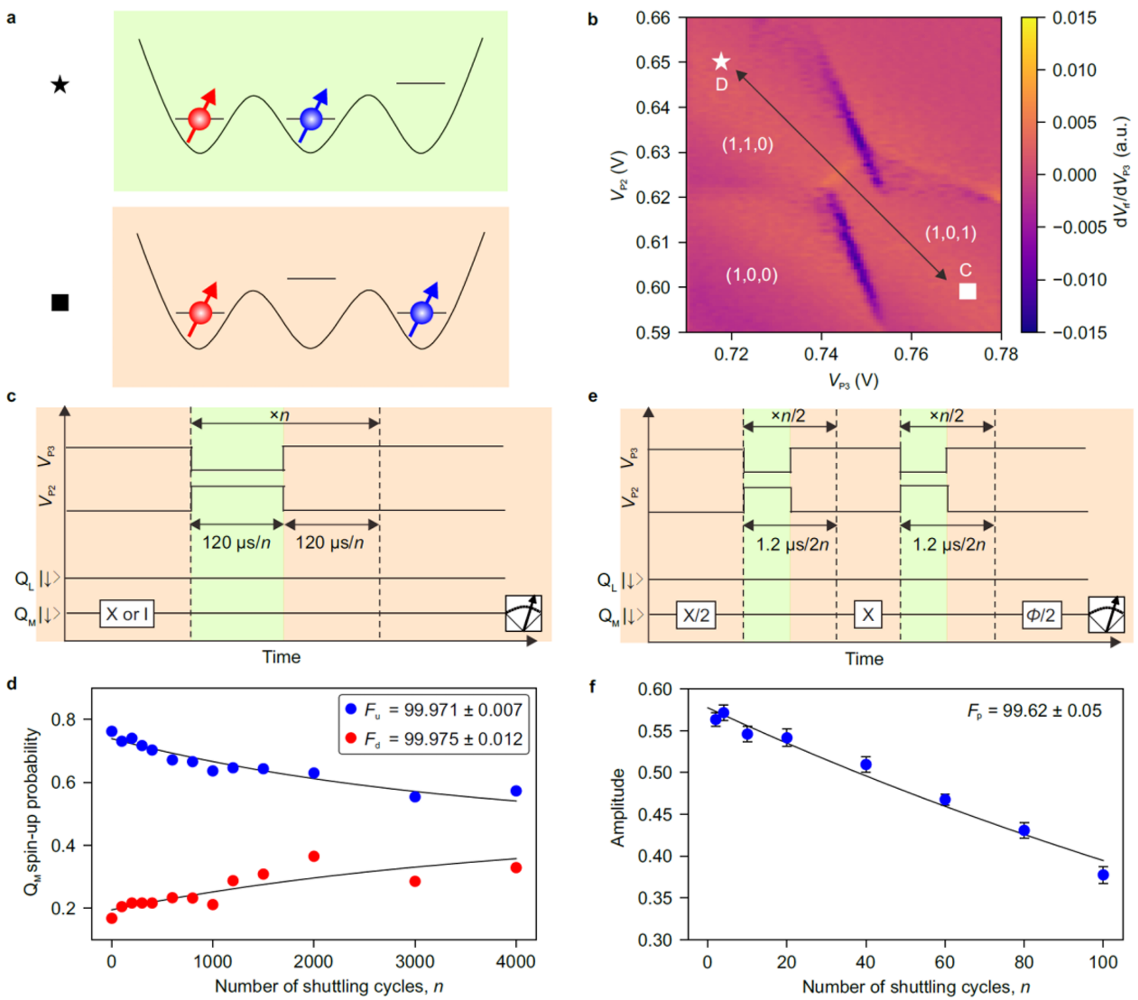


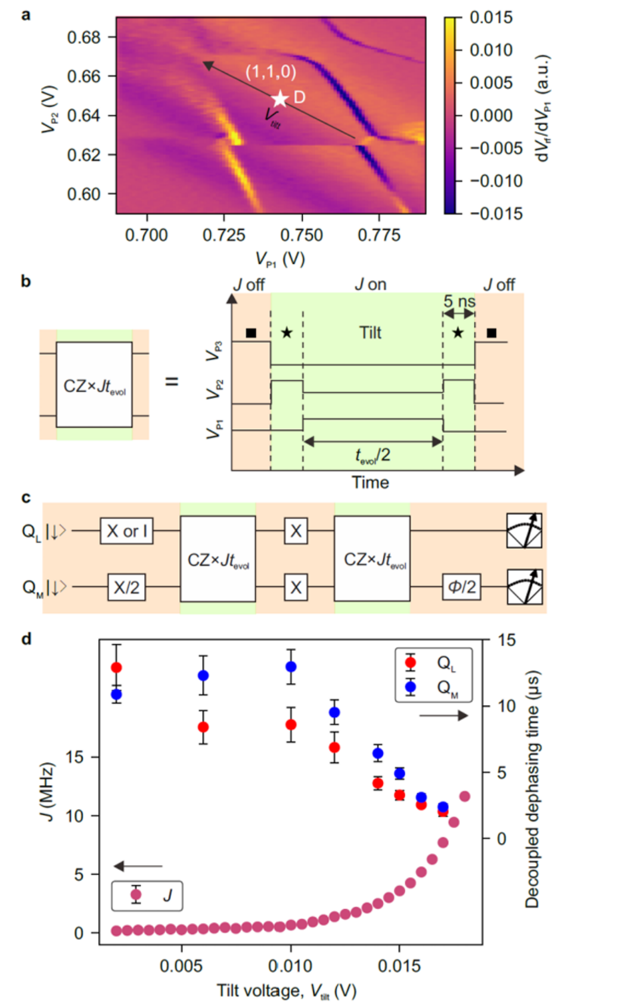
https://arxiv.org/abs/2202.01357

3

Recent developments

Coherent Shuttling





https://arxiv.org/abs/2202.01357

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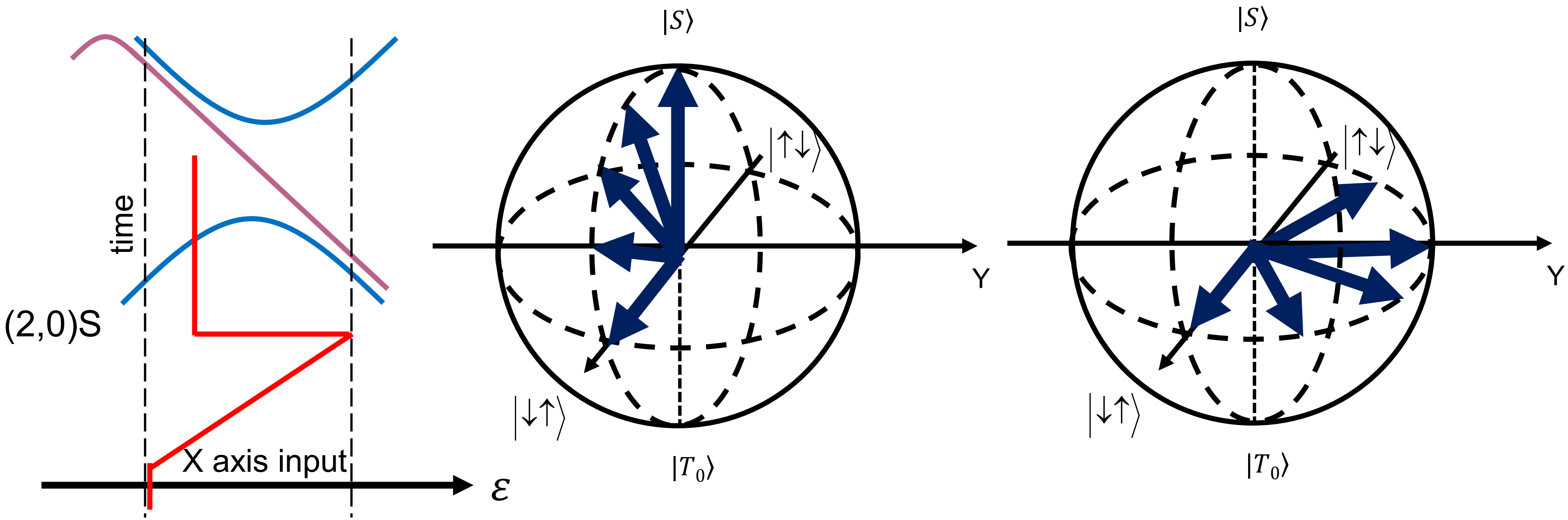
Recent developments

Other than shuttling : spin exchange without moving

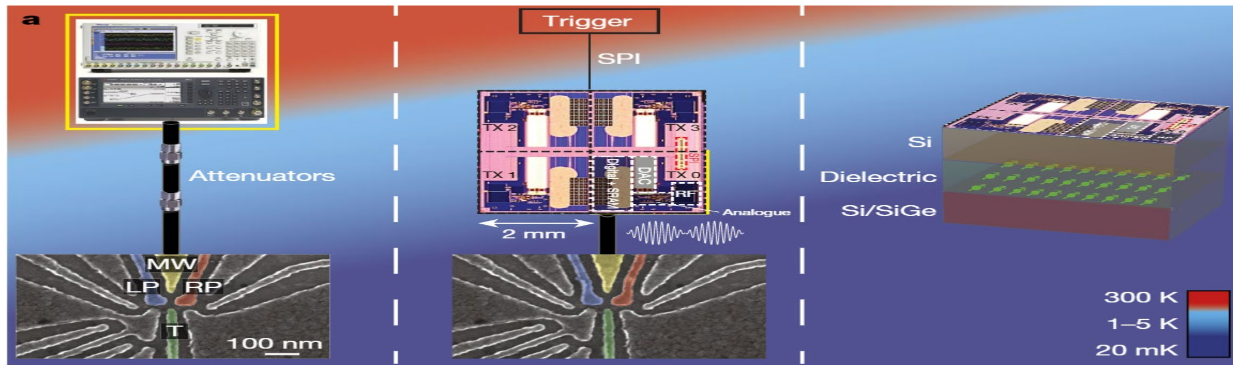


few K operation = Integration with Classical CMOS

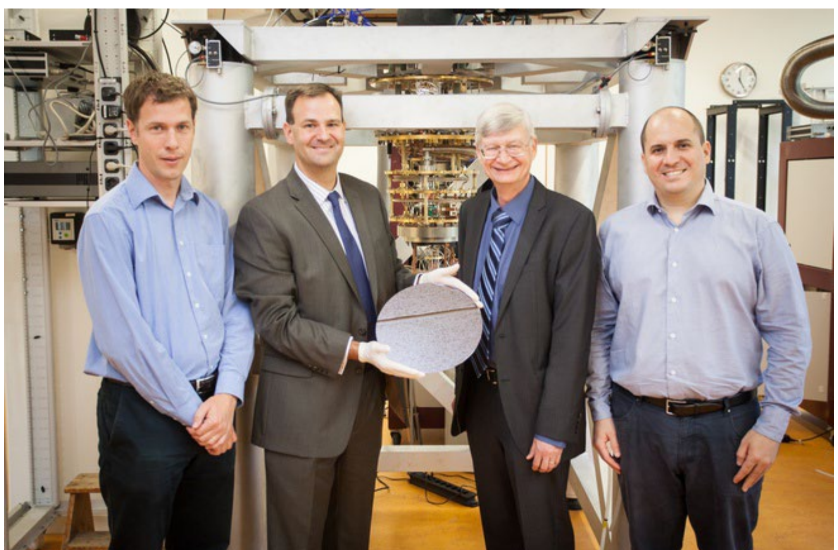
Article

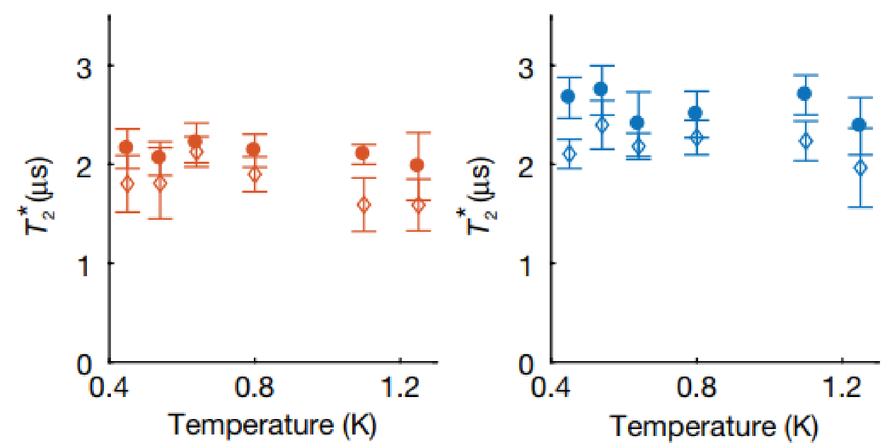
Universal quantum logic in hot silicon qubits

L. Petit et al, *Nature* **580**, 355 (2020)



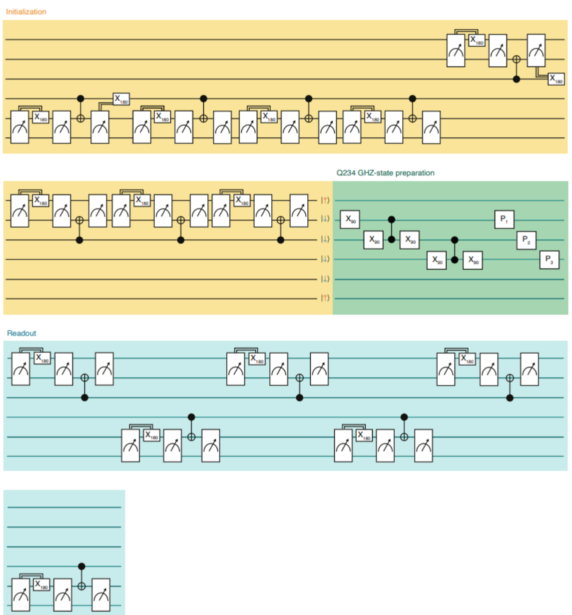
QuTech / Intel.



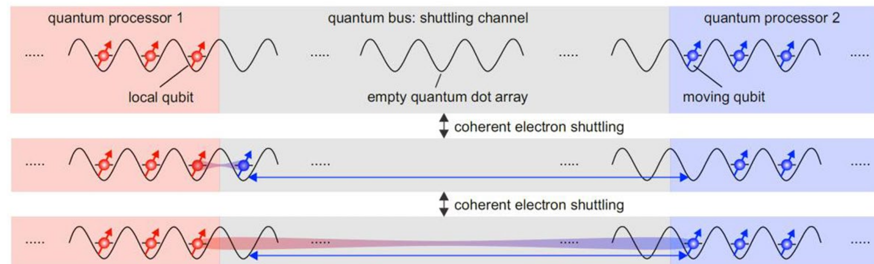


Summary of Lecture 2

Multi qubit operation : 종합선물세트



Toward larger array: shuttling, exchange



결론: 반도체 양자컴퓨팅 – 어렵지만 promising developments