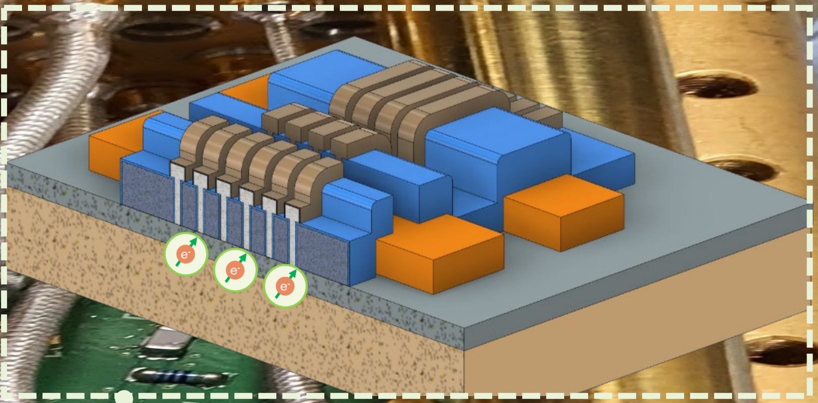
Dec.22.2022

2022 KIAS-SNU wintercamp



Basics of spin-based quantum computing circuits
Lecture 2 : spin qubit experiments

Dohun Kim

Department of Physics & Astronomy, SNU

Outline

Lecture 2. Basics of spin qubit experiments

- Background *Semiconductor quantum dot quantum computing*
- Approach *Recall lecture 1, Host materials*
- Single-spin qubit *1Q, 2Q gates*
- Single triplet qubits *Electric manipulation of spins*

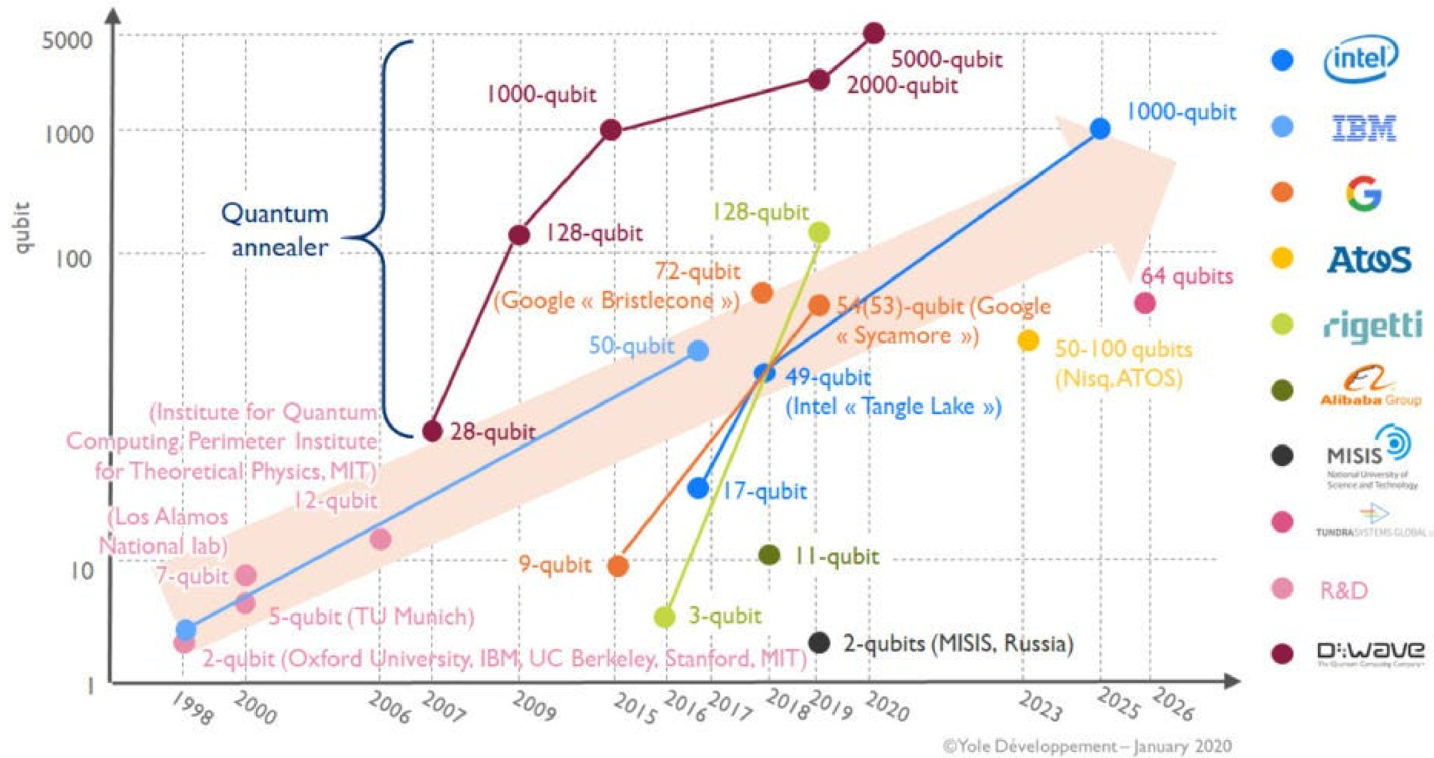
1

Background

양자컴퓨터 하드웨어 현황과 로드맵

Physical qubit roadmap for quantum computer

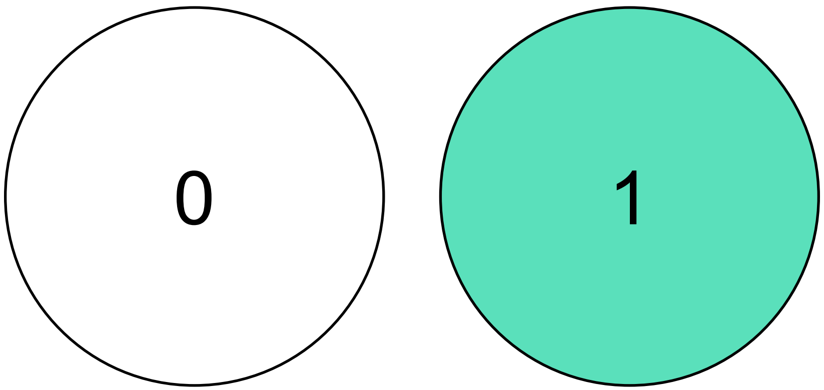
(Source: Quantum Technologies 2020 report, Yole Développement)



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

양자정보 : 중첩과 얽힘

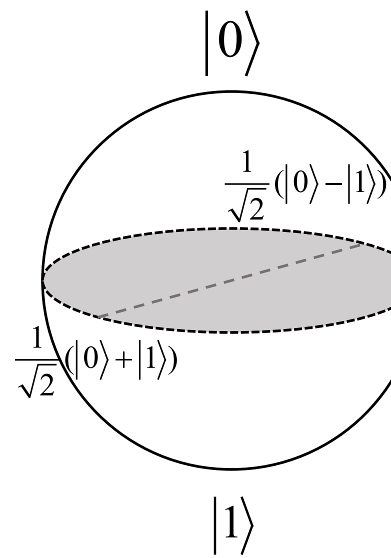
현대 컴퓨터의 bit



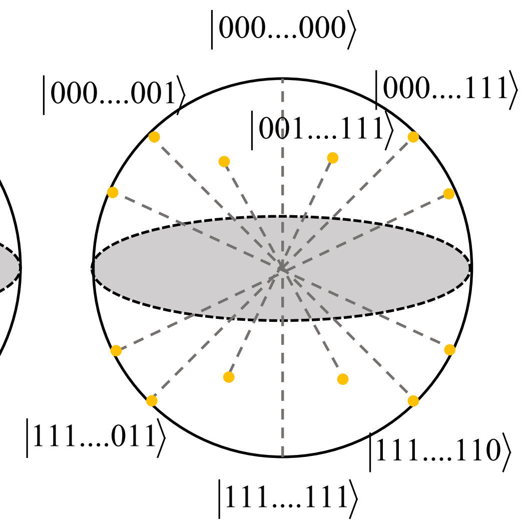
False = OFF

True = ON

양자 컴퓨터의 qubit



1 qubit

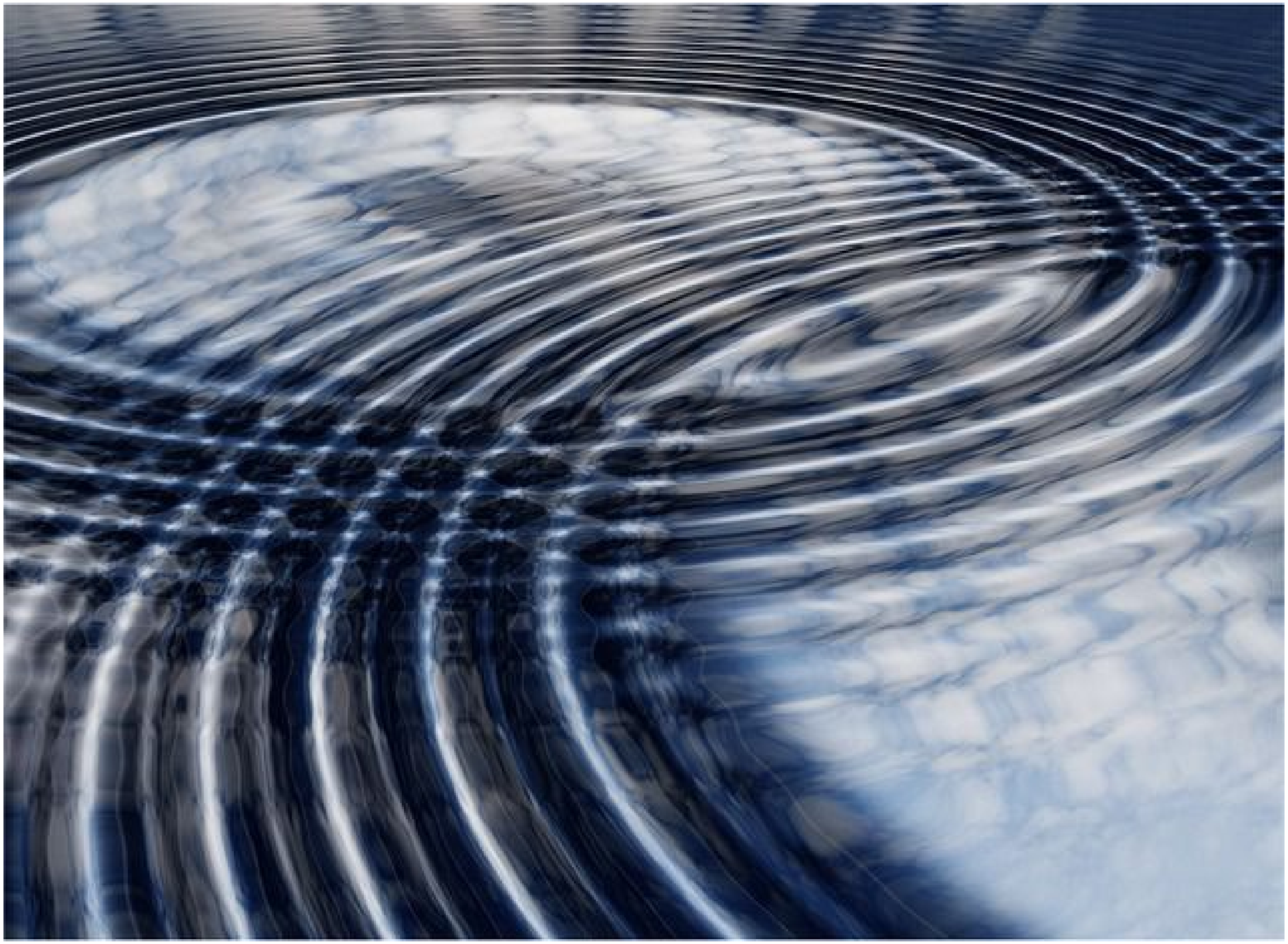


N qubit

1

Background

양자정보 : 중첩과 얽힘



1

Background

배경 : 확률적 계산

발견될 확률 high low

Step 1	Step 2	…	…	Final
3	3	3	3	3
5	5	5	5	5
7	7	7	7	7
11	11	11	11	11
…	…	…	…	…
15485863	15485863	15485863	15485863	15485863
…	…	…	…	…
239815173914273	239815173914273	239815173914273	239815173914273	239815173914273

239815173914273

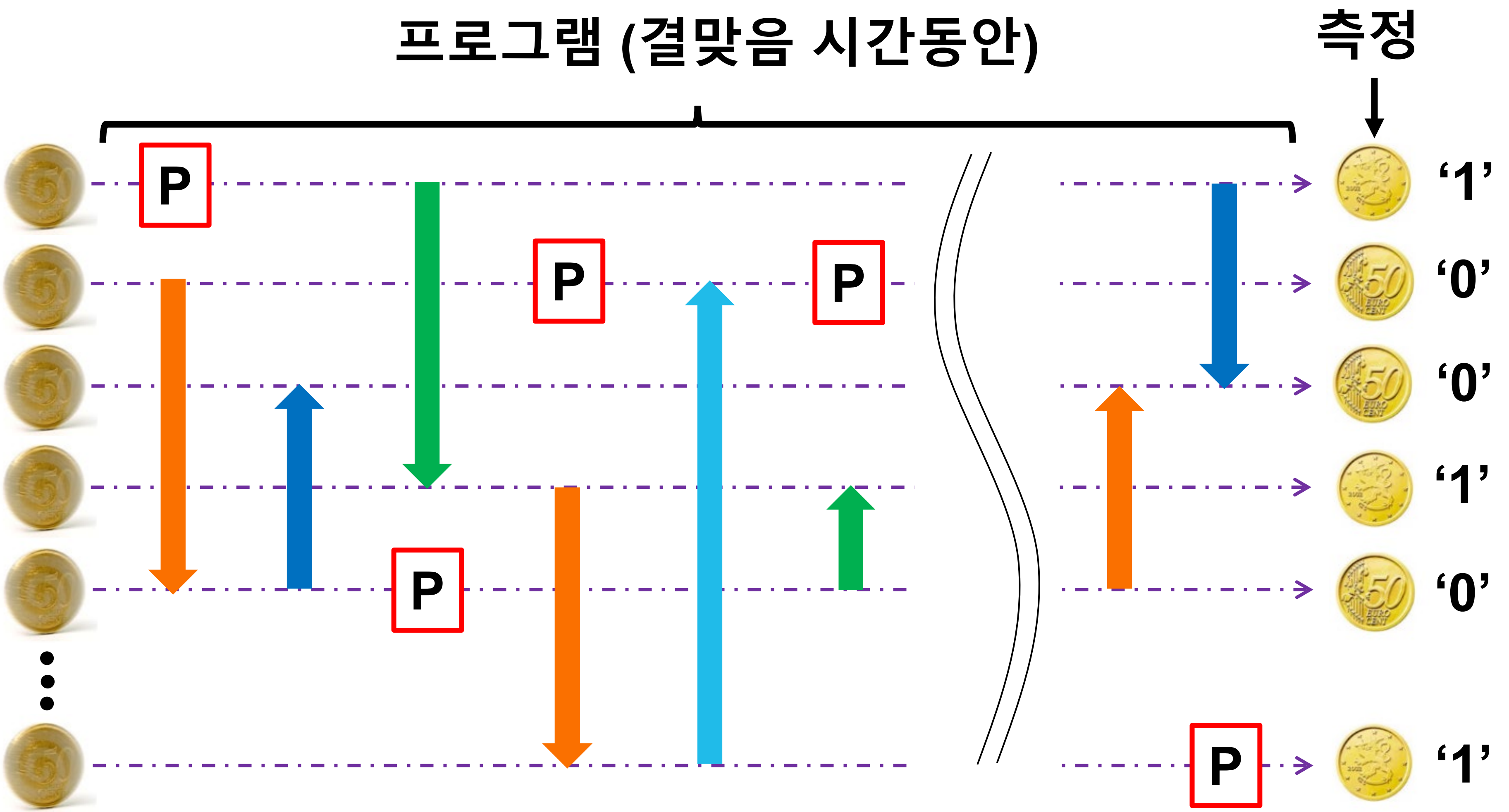
15485863

In a nutshell,

가능한 모든 경우를 동시에 준비하고, 단계마다
각 확률이 동시에 바뀌어 답에 확률을 몰아준다.

1 Background

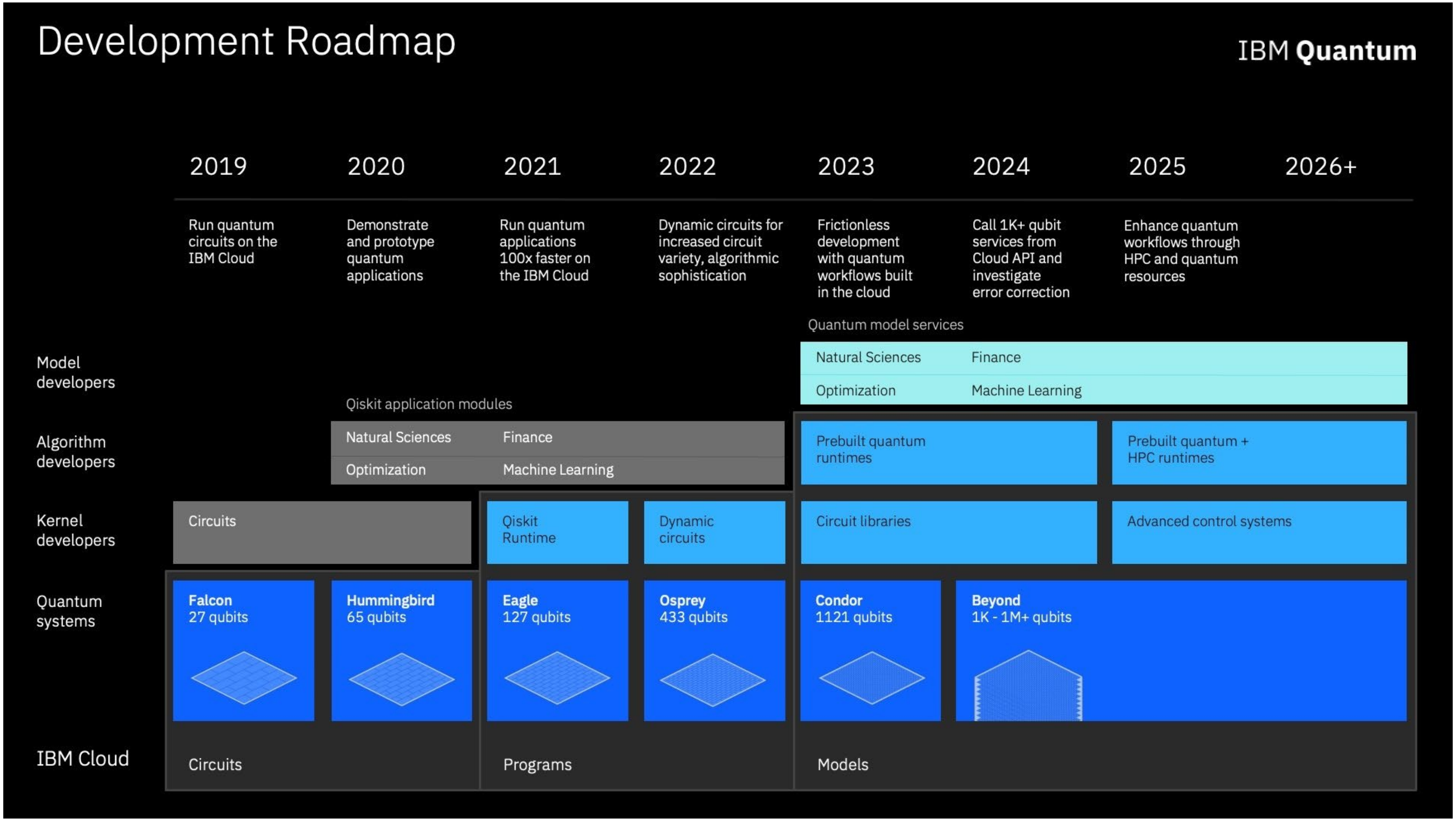
양자 컴퓨팅이란



P 중첩 확률변경 (단일 큐비트 게이트)

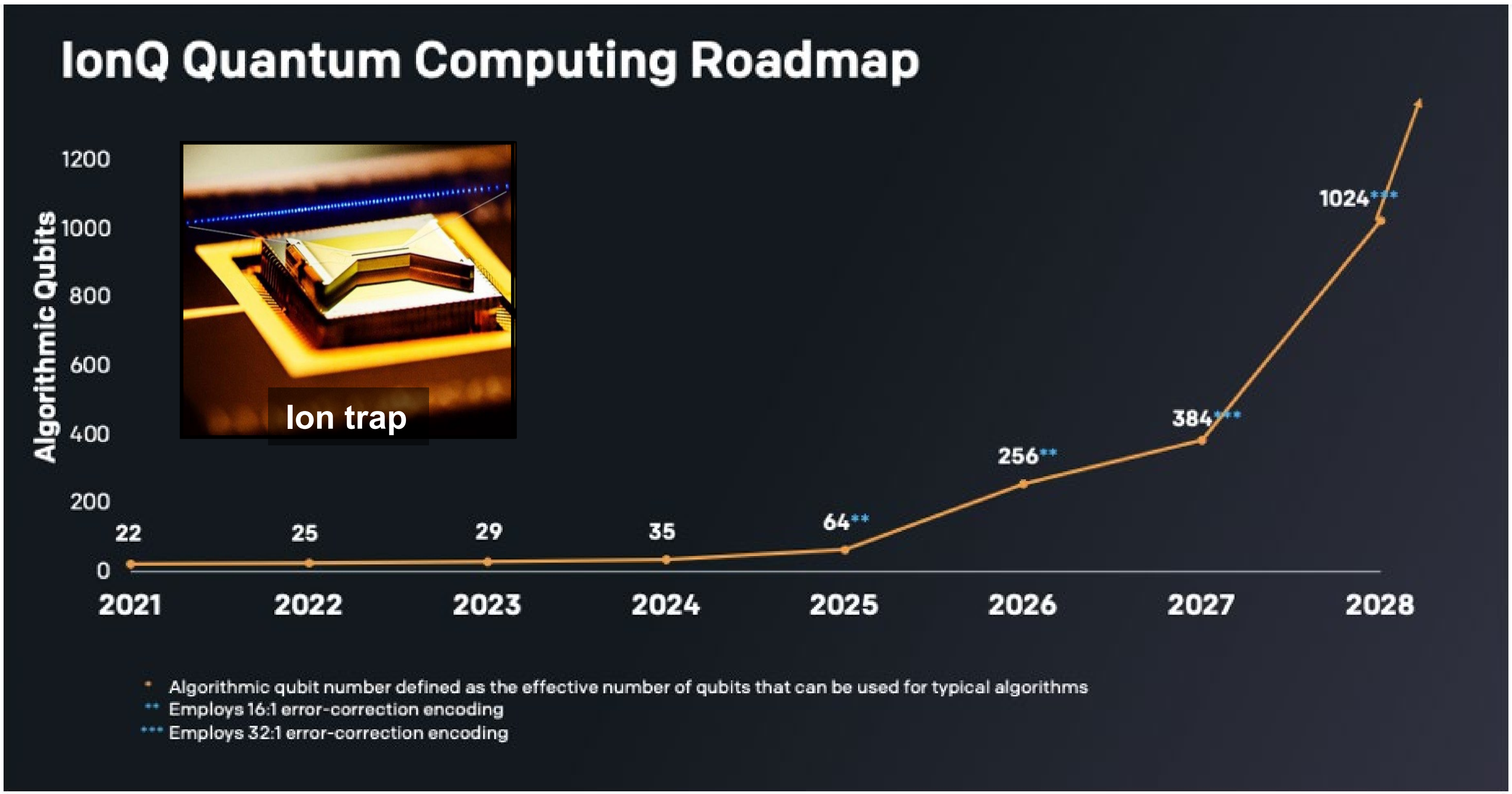
얽힘 제어 (이중 큐비트 게이트)

IBM, Google – 초전도 회로기반



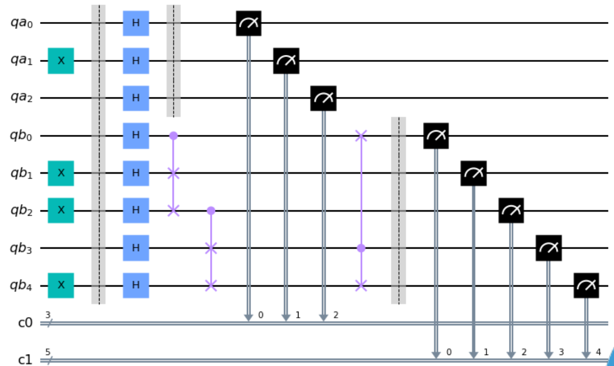
Leading groups

IonQ, Honeywell – 이온트랩 기반



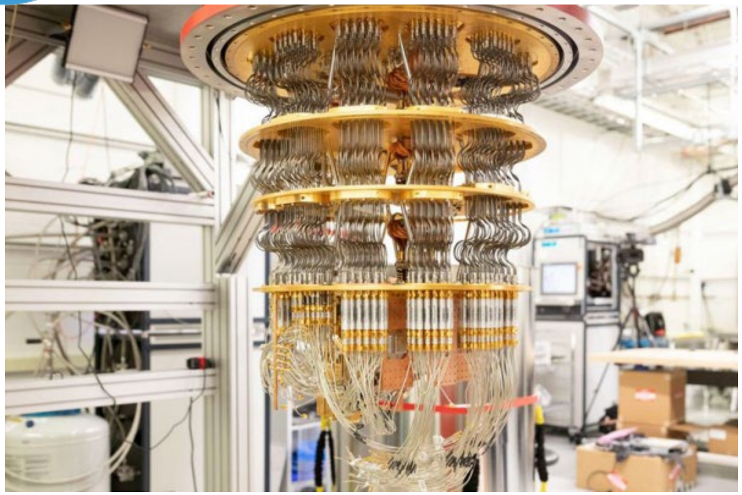
양자컴퓨터 구동 예

사용자가 프로그래밍 – Qiskit : python 기반



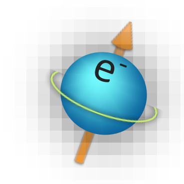
Job 순위 관리, 사용자 – 백엔드 간 통신 관리

양자 컴퓨터 하드웨어



1 Background

Quantum mechanical phase coherence



Superposition

N개 집합

$$|\Psi\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$$

$\neq$

Statistical Mixture

N개 집합

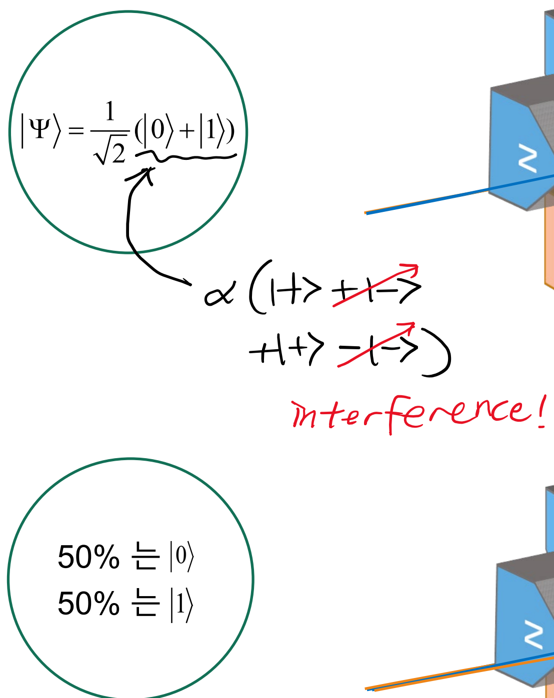
50% 는 $|0\rangle$

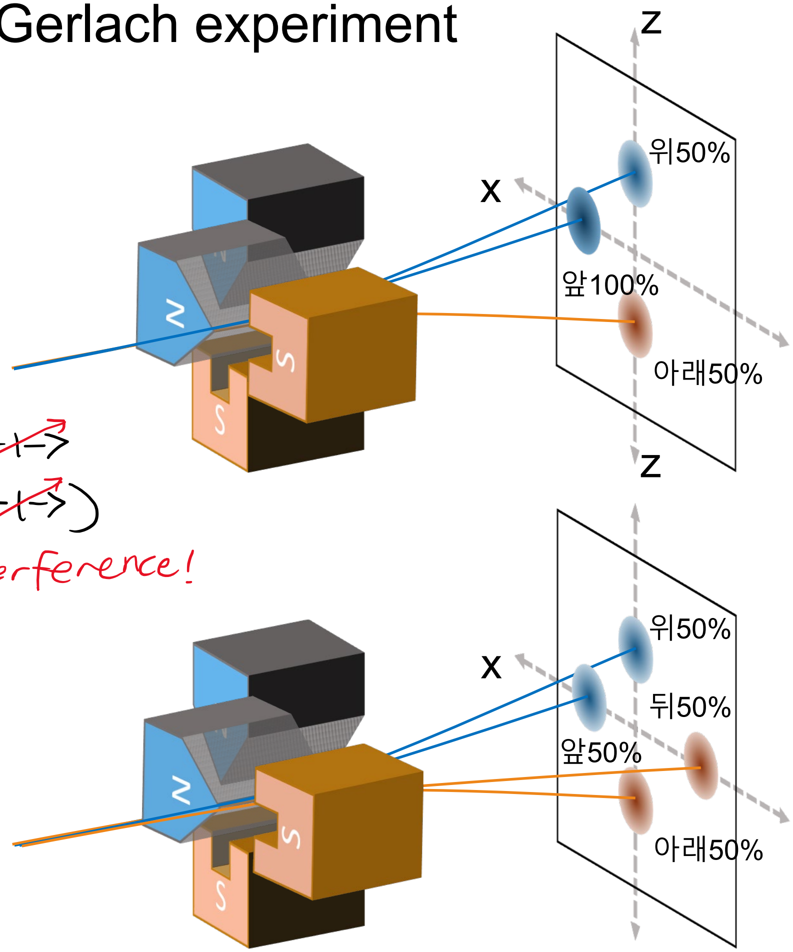
50% 는 $|1\rangle$

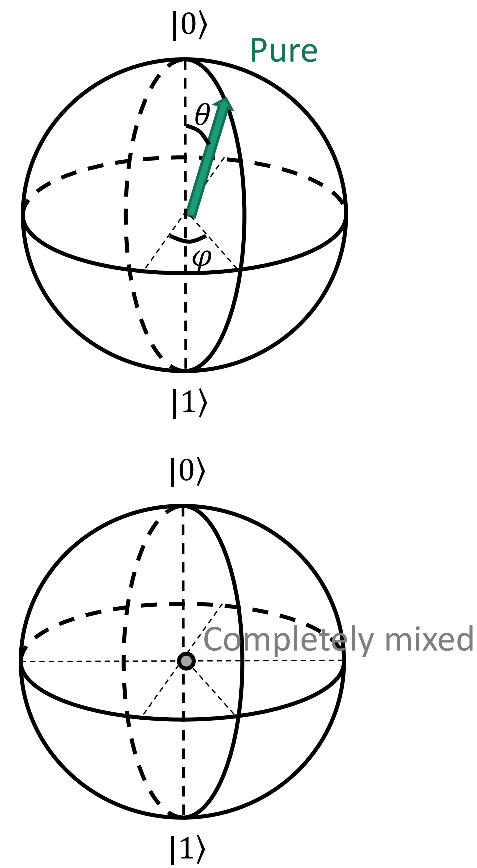
- 다른 점을 한단어로 ? *'coherence' : 간섭현상을 보일 수 있는 능력*
- 어떻게 구별 ?

Distinguishing superposition vs mixture

Repeated Stern-Gerlach experiment



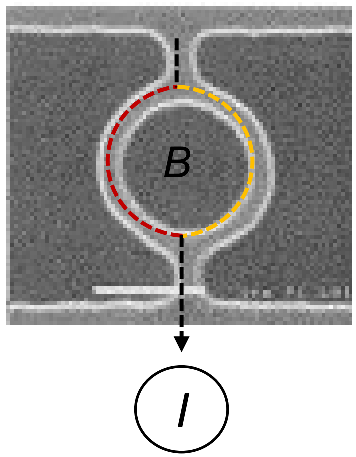


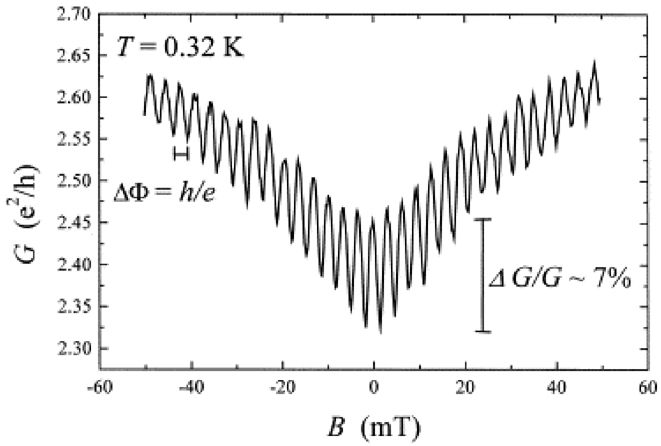


- 어떻게 구별 ? *토모그래피 : 모든 Measurement basis 에 대해 projection 해본다.*
- *Projective reconstruction – interference 는 어디에 ?*

What is *single-shot* measurement ?

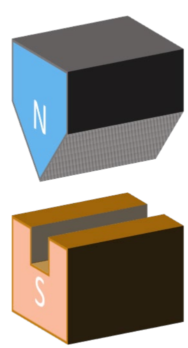
What is NOT single-shot experiment…

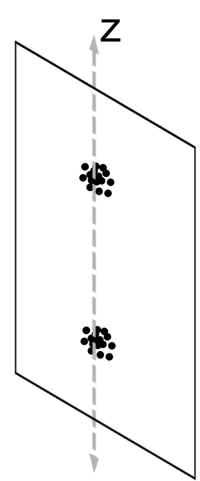




Really what QM textbook describes…

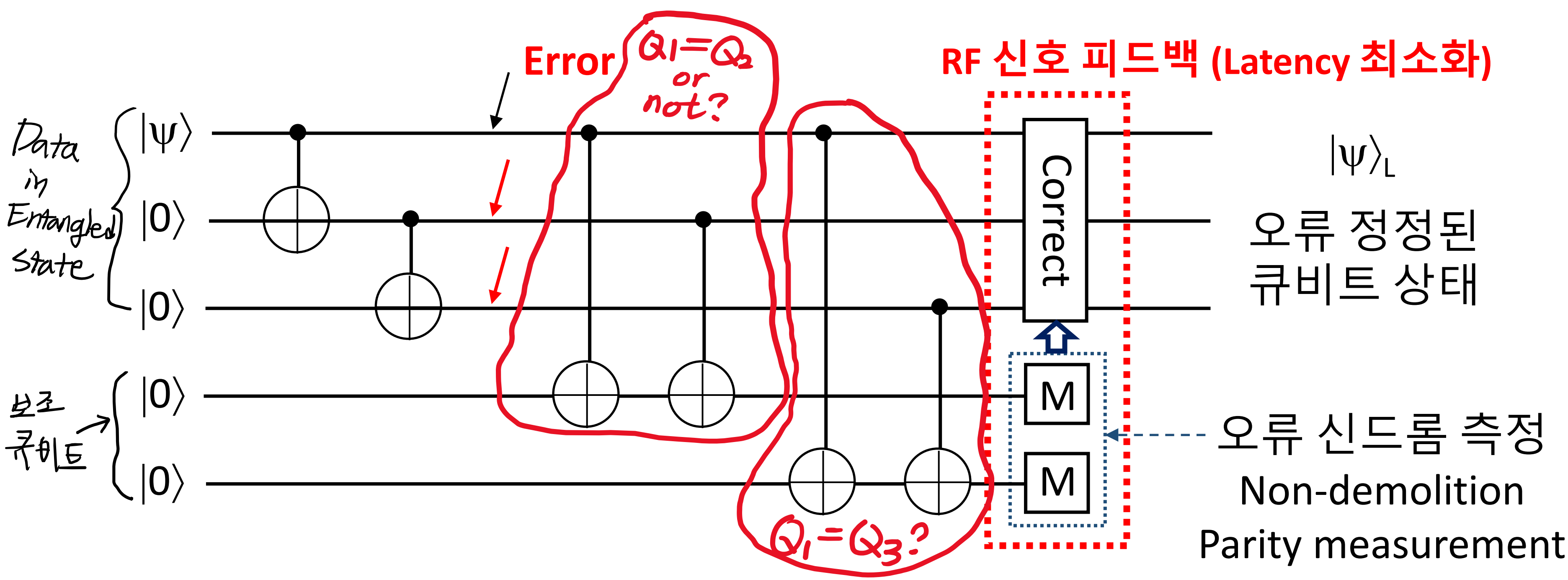
P_1 = #state up / N_{total}





Why *single-shot* is important ?

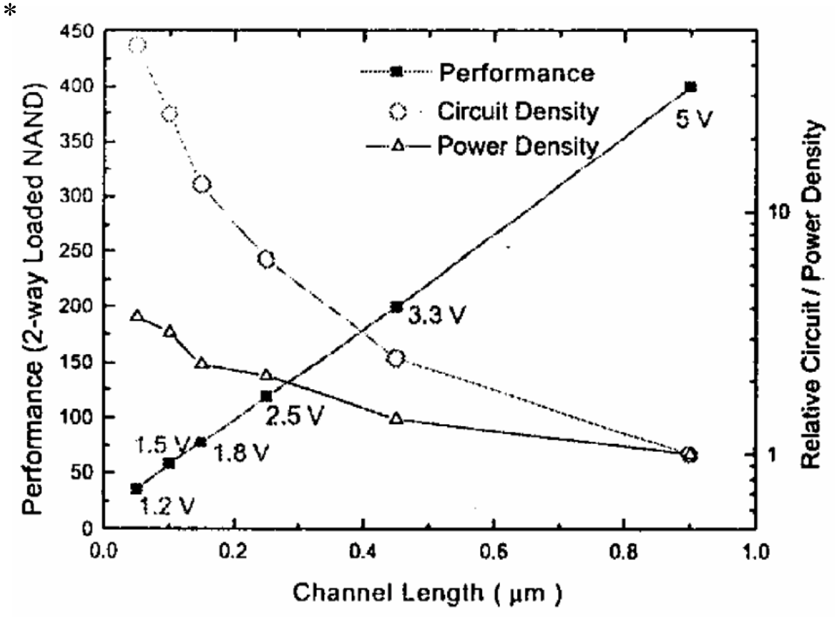
- **Ex. Quantum error correction**
- **보조 큐비트의 오류 신드롬 측정 후 고속 피드백으로 실시간 오류 정정 (Single-shot !)**

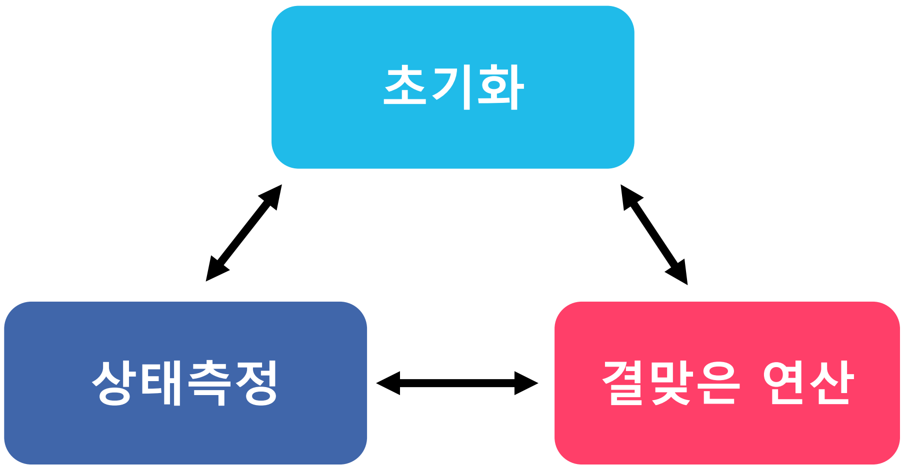


Challenges

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***

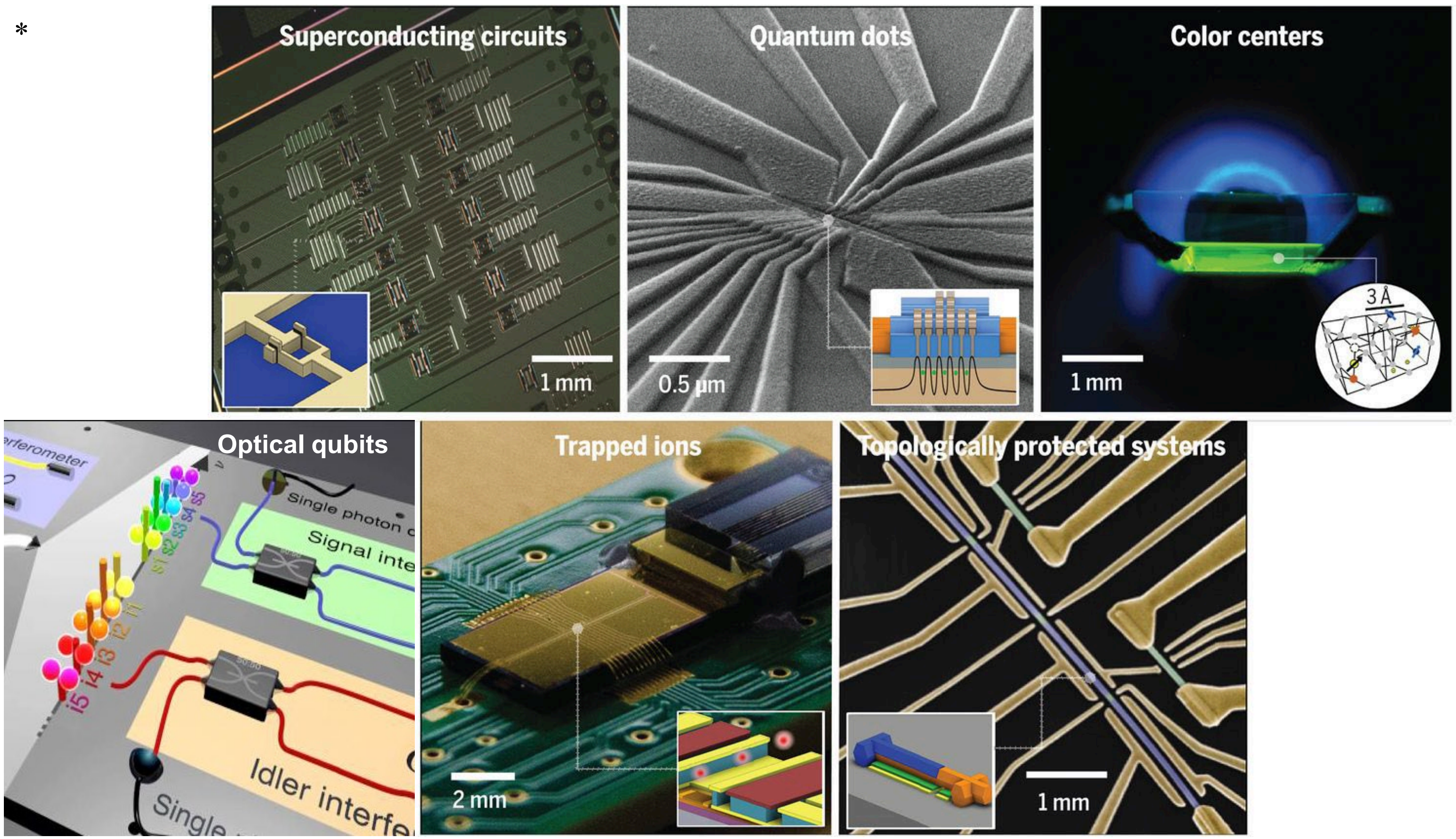
* G. G. Shahidi, "Challenges of CMOS scaling at below 0.1μm," The 12th International Conference on Microelectronics (2000)

1

Background

다양한 양자컴퓨팅 플랫폼

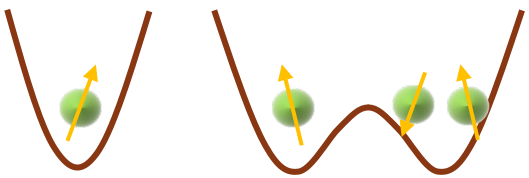
*



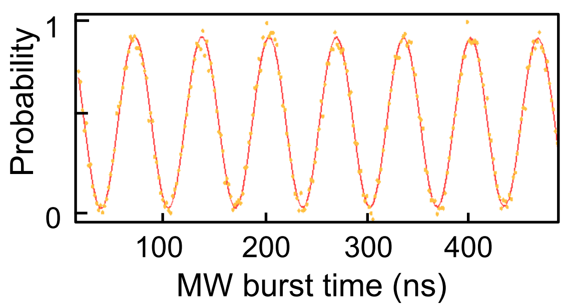
*Science. **372** 253 (2021)

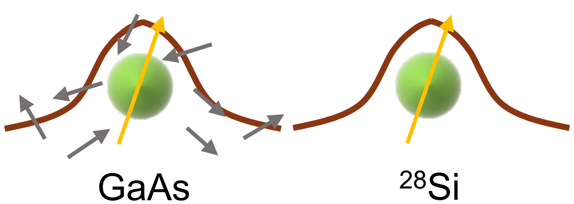
Why semiconductor QDQC?

Coherence



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



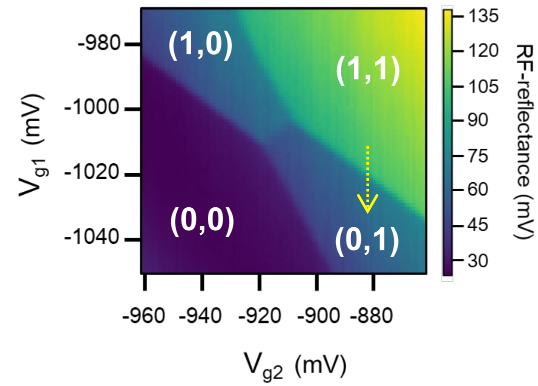


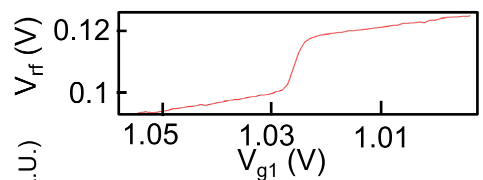
T_2^{cpmg} > 350 *us* T_2^* > 120 *us*

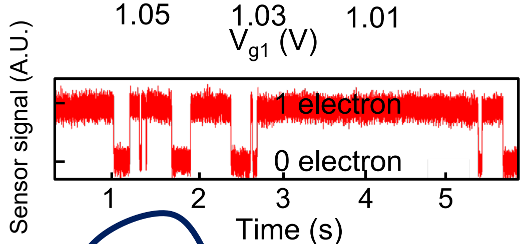
Nuclear bath spin polarization in GaAs

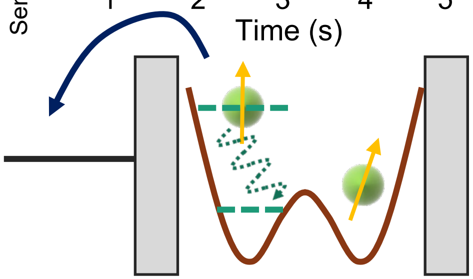
Small spin-orbit coupling & Small hyperfine interaction in purified ^{28}Si

Measurement



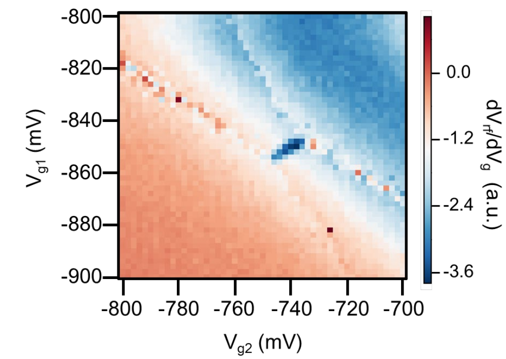


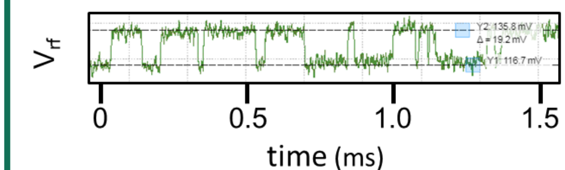


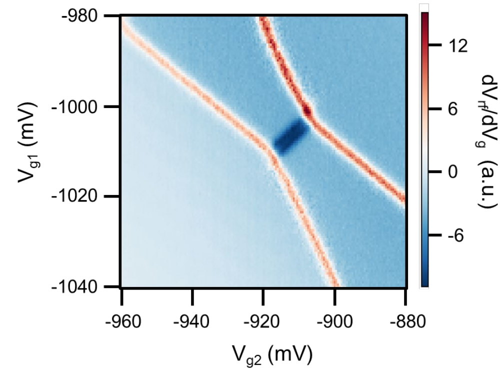


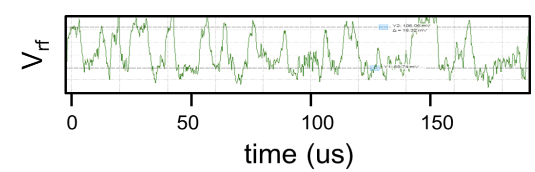
Long T_1 time → Single-shot measurement straightforward

Tunability





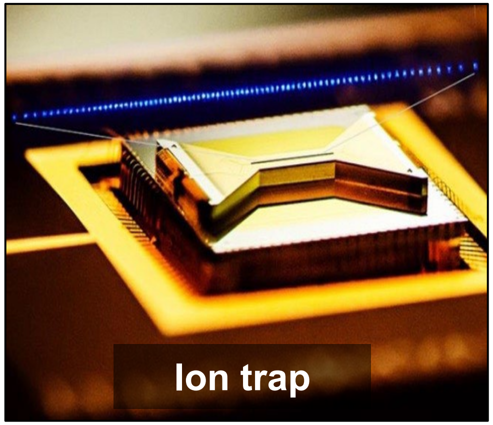


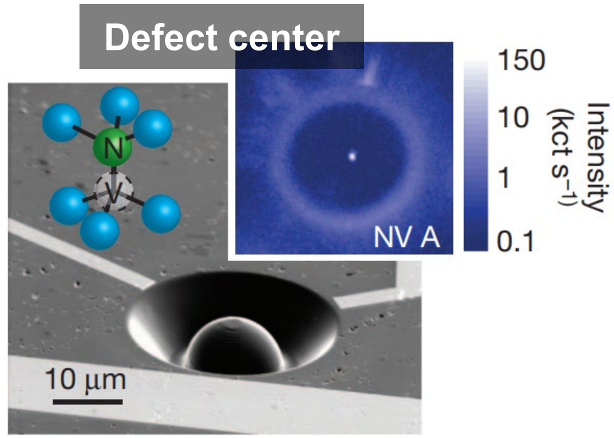


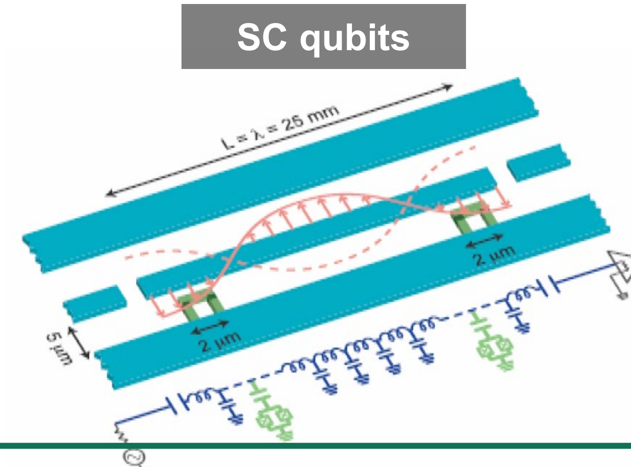
2

Approach

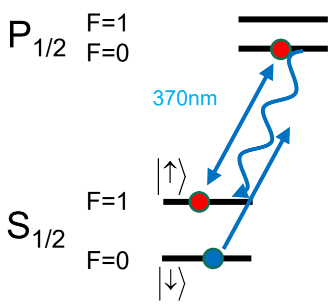
Single-shot measurements in physical systems

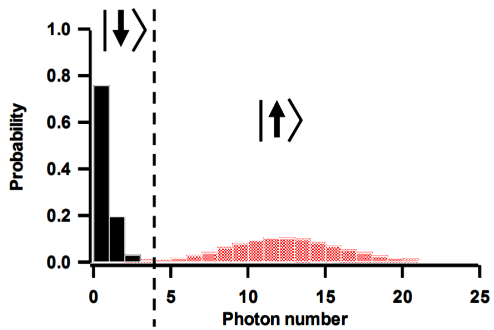




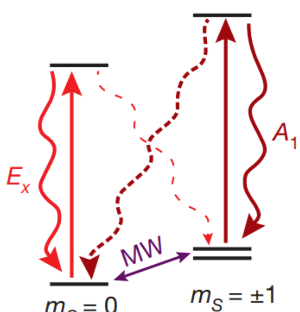


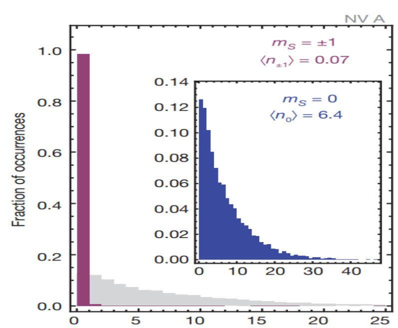
$^{171}Yb^{+}$



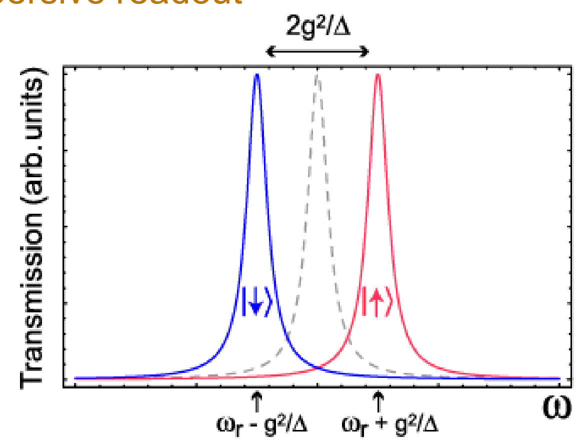


Nitrogen-Vacancy color center





Dispersive readout



SNR > 1 in a few us integration time

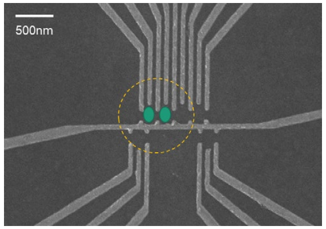
K.Kim group, (Tsinghua univ.)
M.Lee group (POSTECH ERC)
R.Hanson group, (quTech)
IBM, Google.. Etc.

2

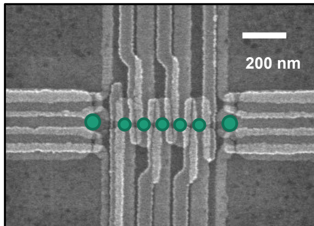
Approach

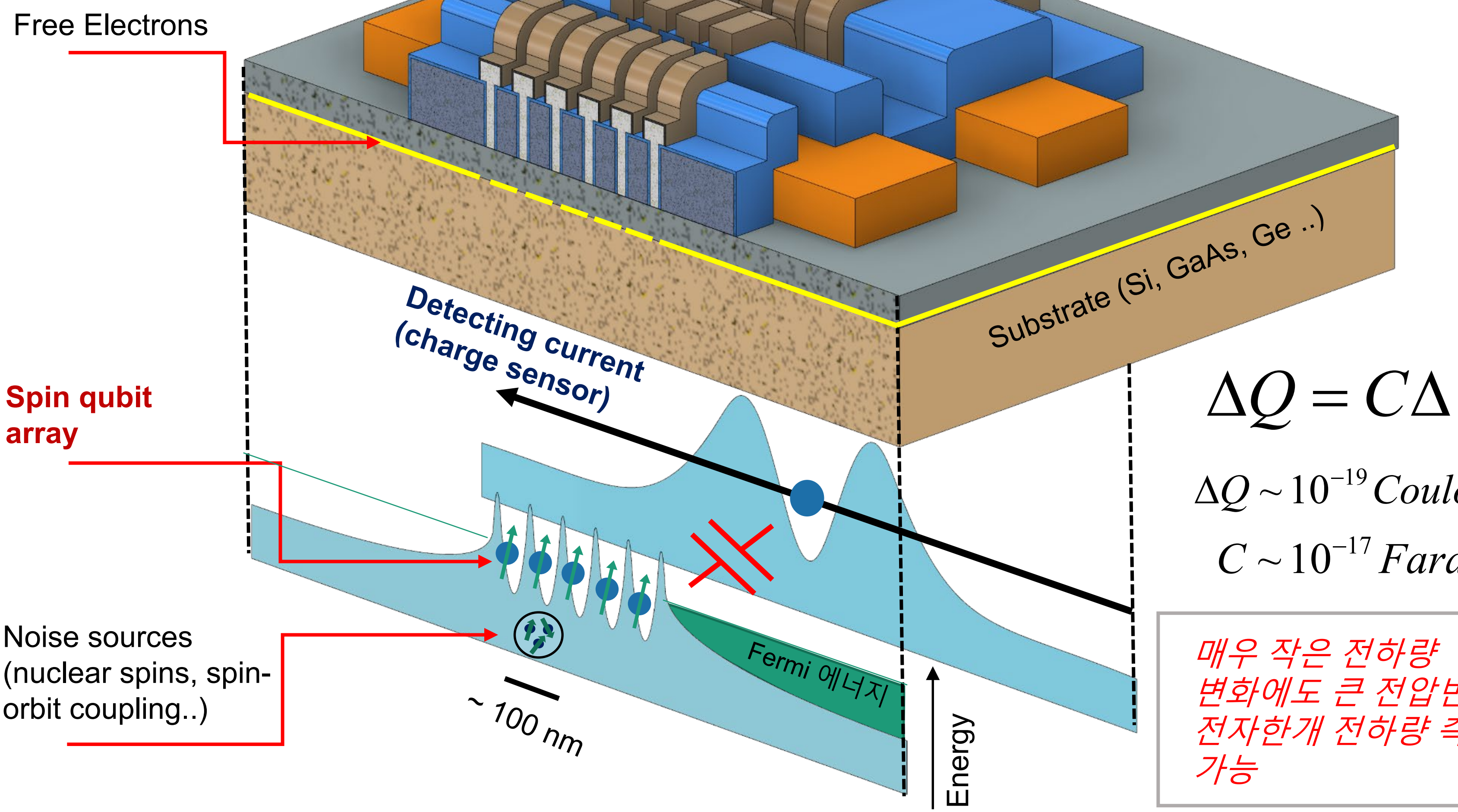
The semiconductor quantum chip

GaAs QD, SNU



^{28}Si QD, SNU





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

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

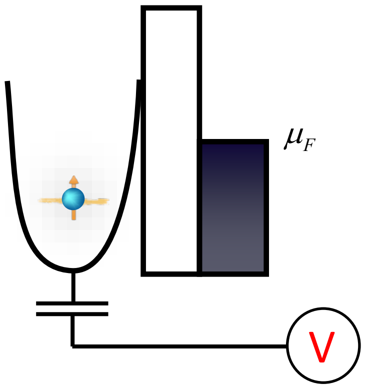
$$C \sim 10^{-17}\, Farad$$

매우 작은 전하량 변화에도 큰 전압변화
전자한개 전하량 측정 가능

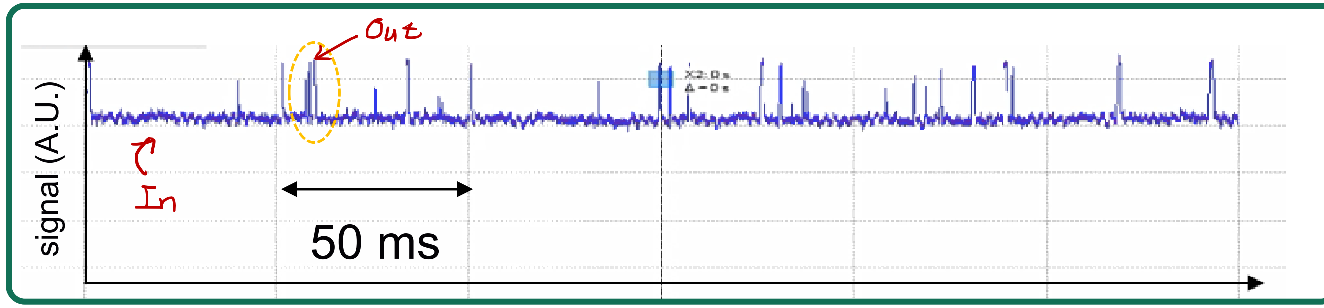
2

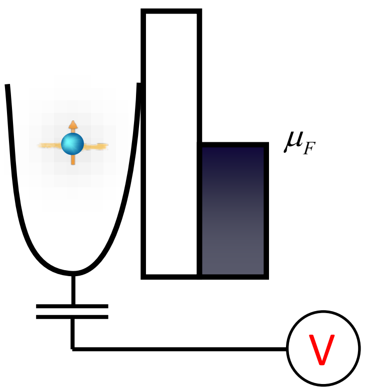
Approach : detailed description of experiments

Typical example : watching electron tunneling

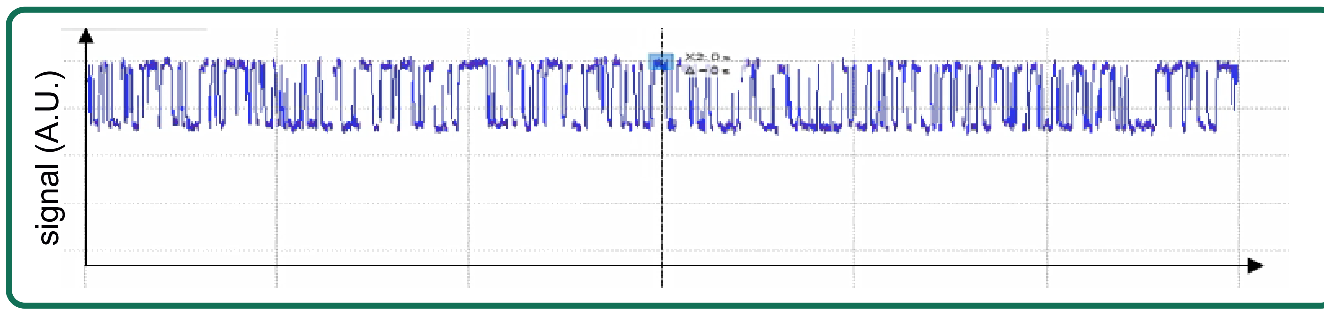


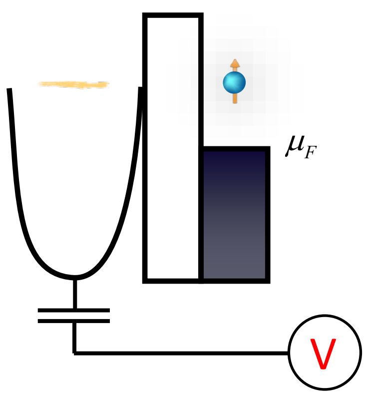
Mostly occupied



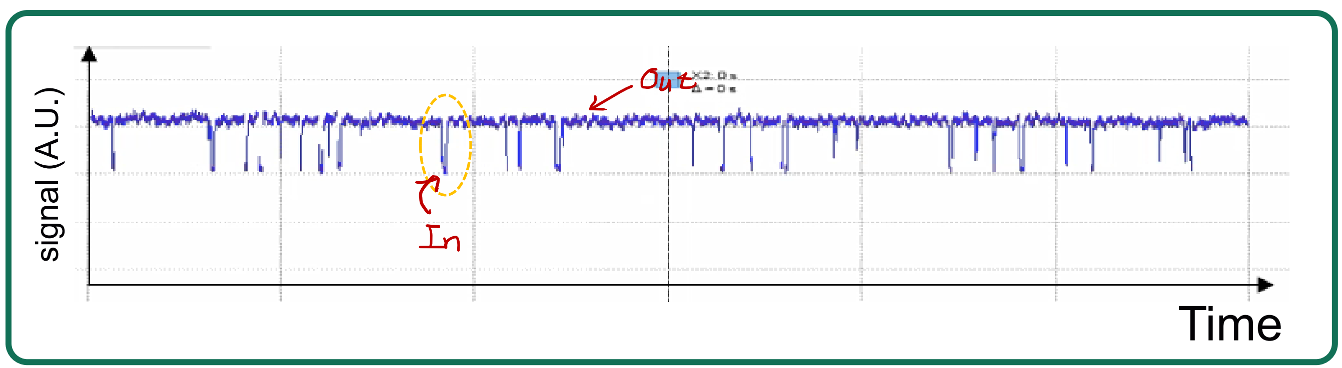


Half the time occupied, half the time empty





Mostly empty

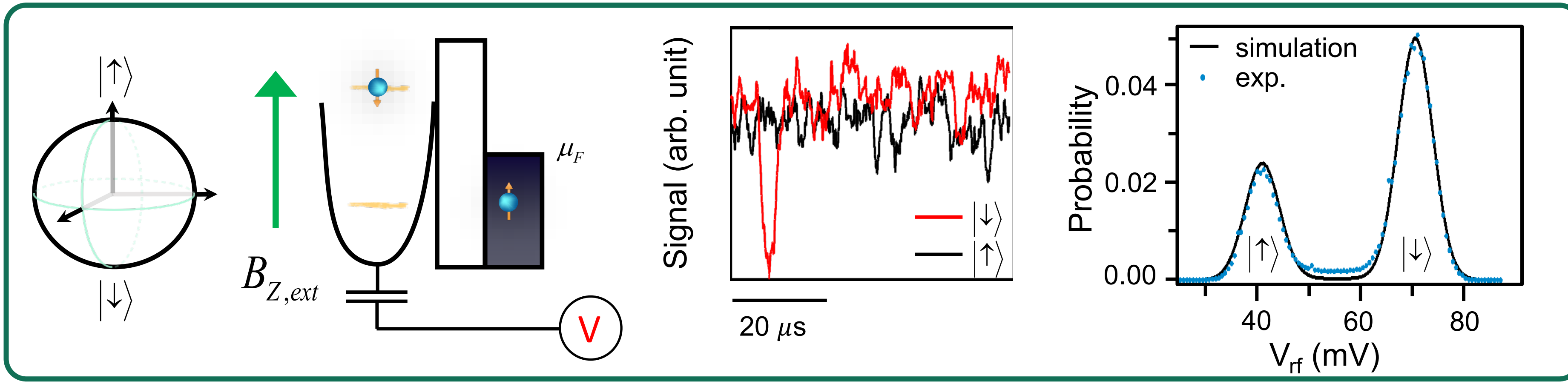


2

Fast single-shot measurements

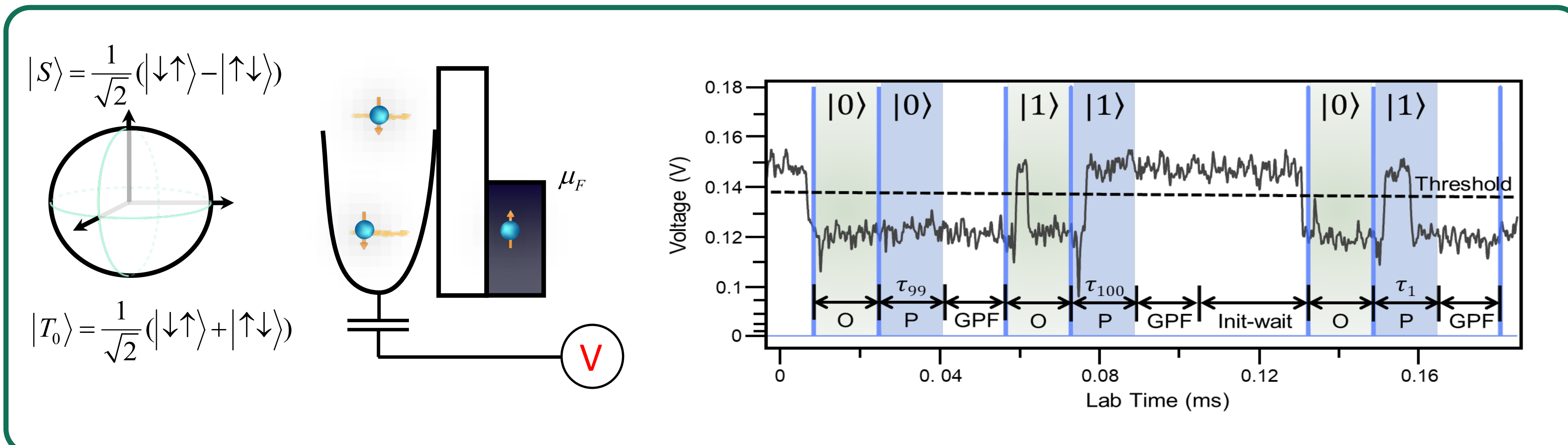
Something (mostly spin) to charge conversion

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

Control of quantum two level system

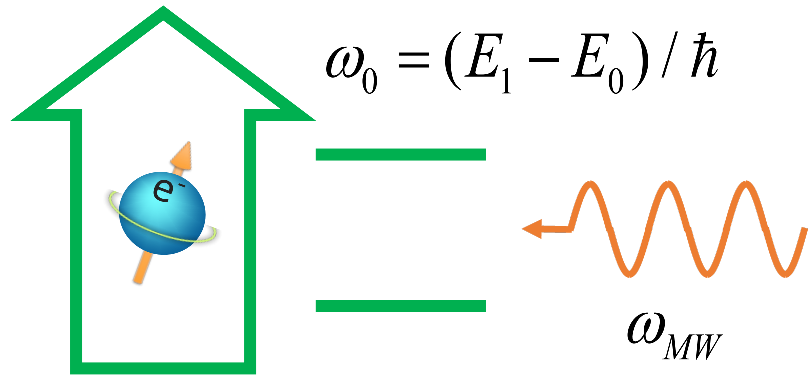
Rabi oscillation

Two level system, with

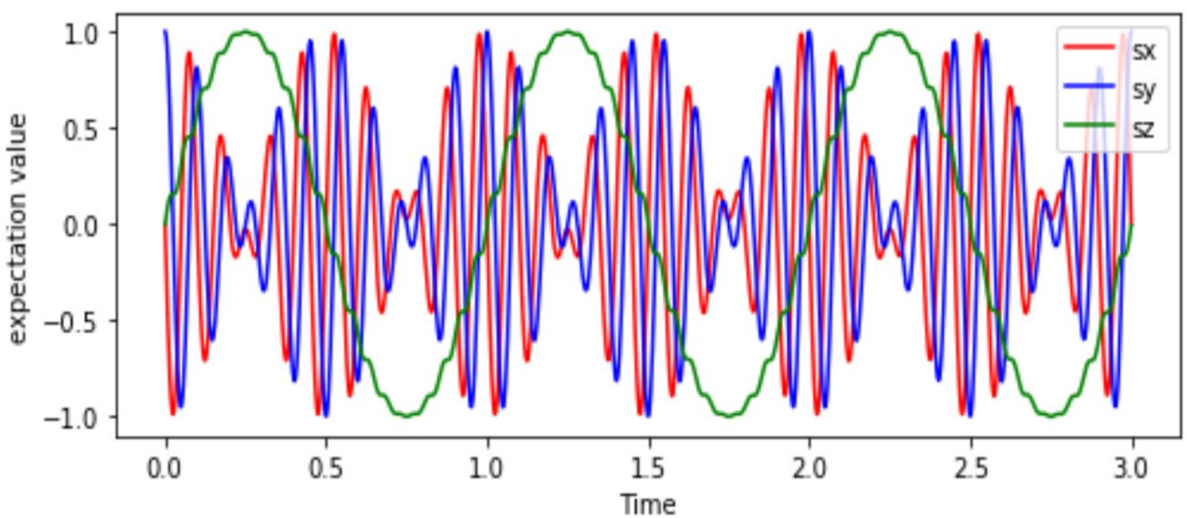
$$\hat{H} = \frac{\hbar\omega_0}{2}\hat{\sigma}_z + \hbar\eta(\hat{\sigma}_x \cos\omega_{MW} t)$$

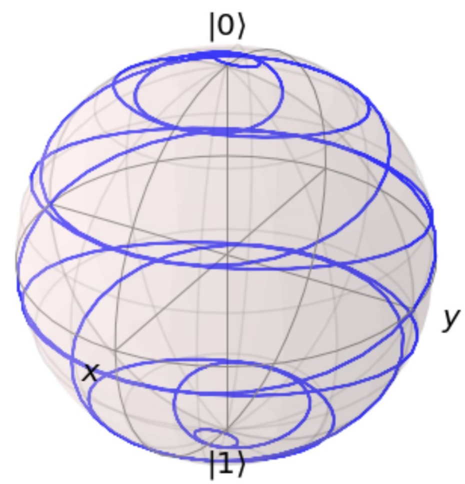
Apply harmonic radiation

$$\omega_0 = (E_1 - E_0)/\hbar$$



On resonance, $\omega_0 = \omega_{MW}$





Control of quantum two level system

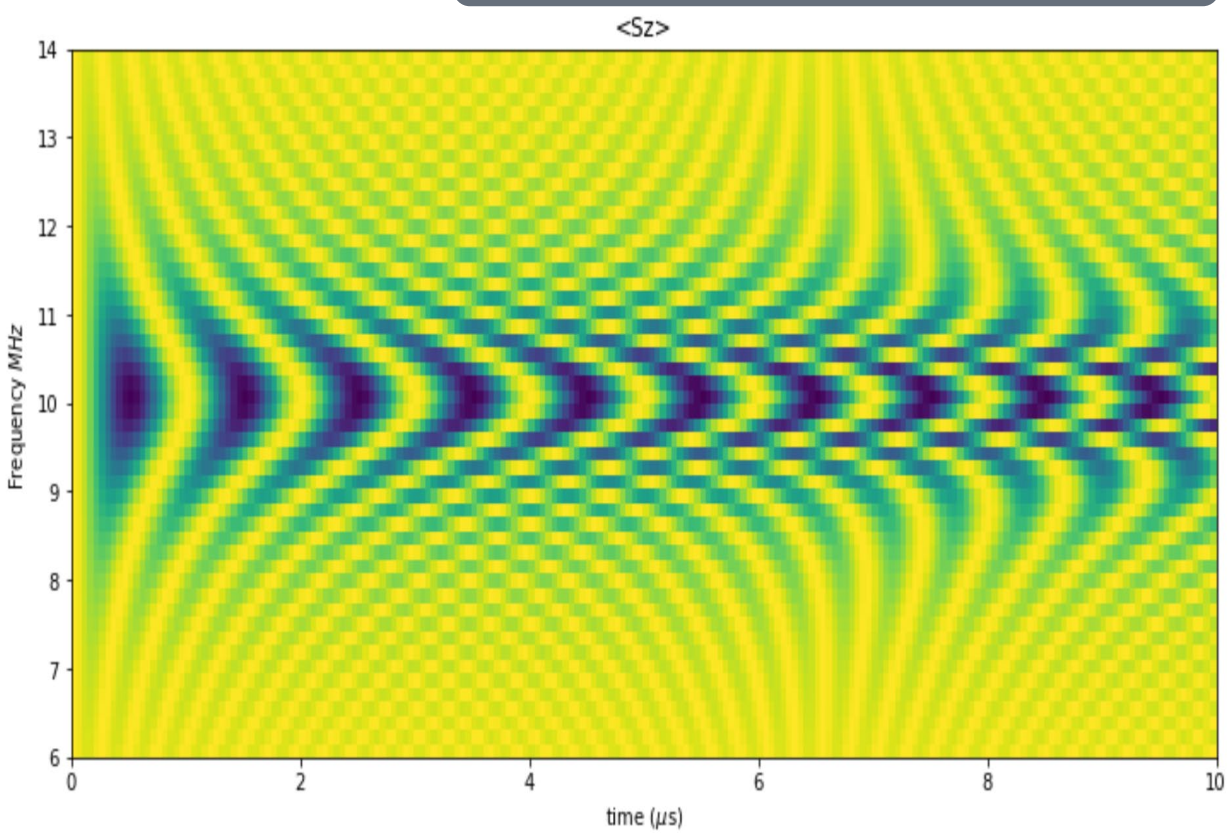
Rotating frame: RWA approximation

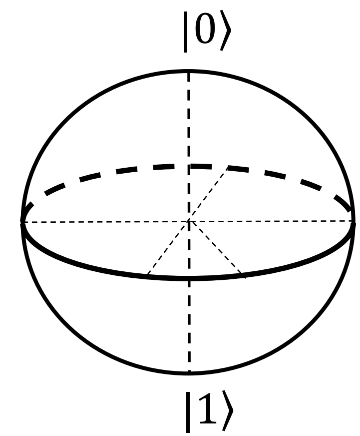
$$\hat{H}_{rot} = \frac{\hbar}{2}(\omega_0 - \omega_{MW})\hat{\sigma}_z + \frac{\hbar\eta}{2}\hat{\sigma}_x$$

$$\delta = \omega_0 - \omega_{MW}$$

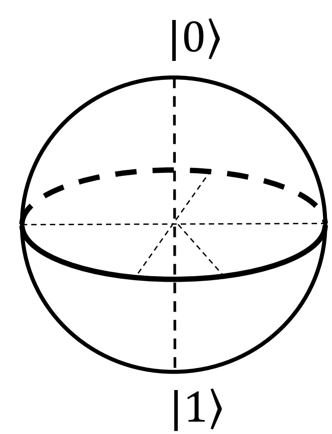
ω_0 의 intrinsic rot. 사라짐
$\hat{\sigma}_z, \hat{\sigma}_x$ 성분의 벡터합이 도는 축을 결정

Q : Hadamard Gate ?



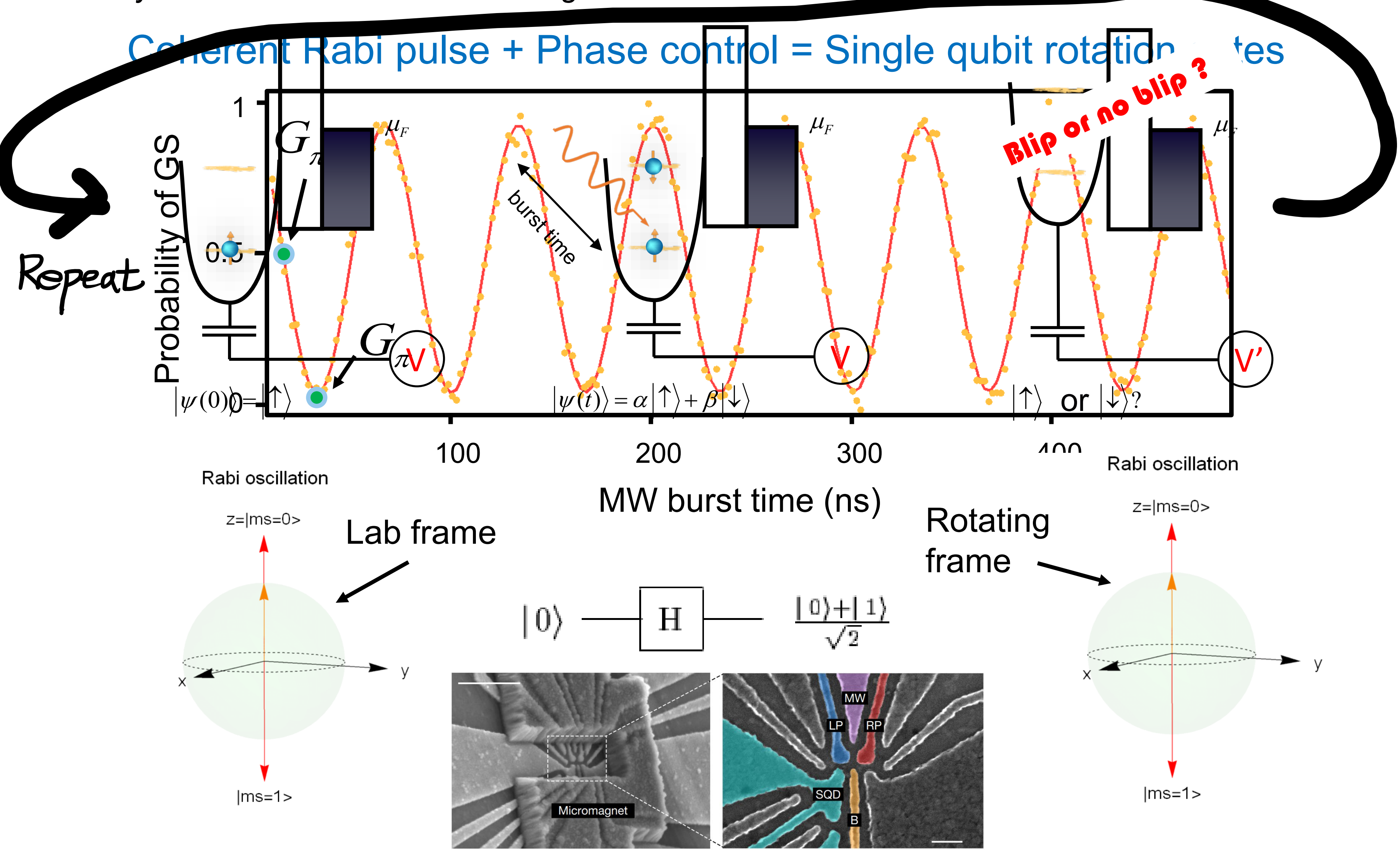


낙서



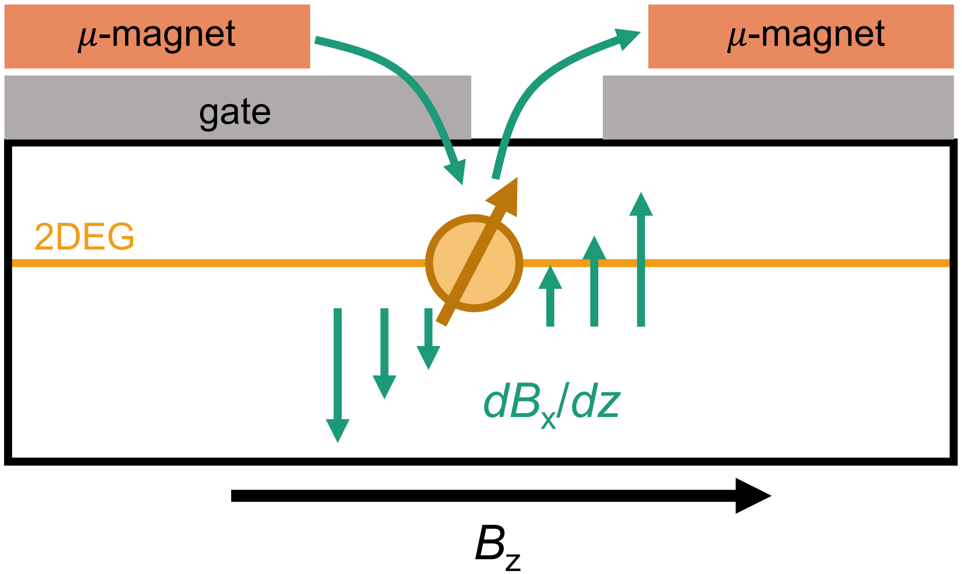
Missing component : coherent manipulation

One way is to use resonant electromagnetic radiation…



Role of micromagnet

Single spin electric dipole spin resonance (EDSR)



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

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

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

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

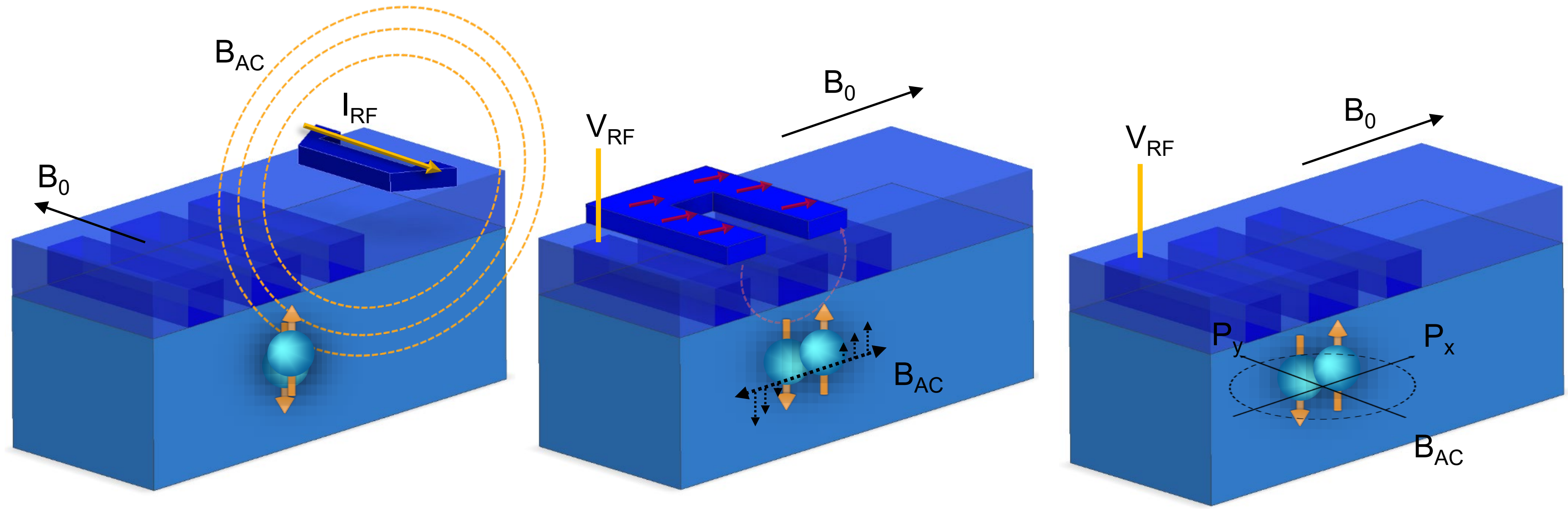
$$H = B_z{}^*\sigma_z + \delta B_x*\cos(2\pi f_{mw})*\sigma_x = \begin{bmatrix} B_z/2 & \delta B_x*\cos(2\pi f_{mw}) \\ \delta B_x*\cos(2\pi f_{mw}) & -B_z/2 \end{bmatrix}$$

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

3

Spin qubit principle

Different qubit driving methods



Stripline

Koppens et al. *Nature* 2006
Veldhorst et al. *Nature Nano* 2014
Muhonen et al. *Nature Nano* 2014

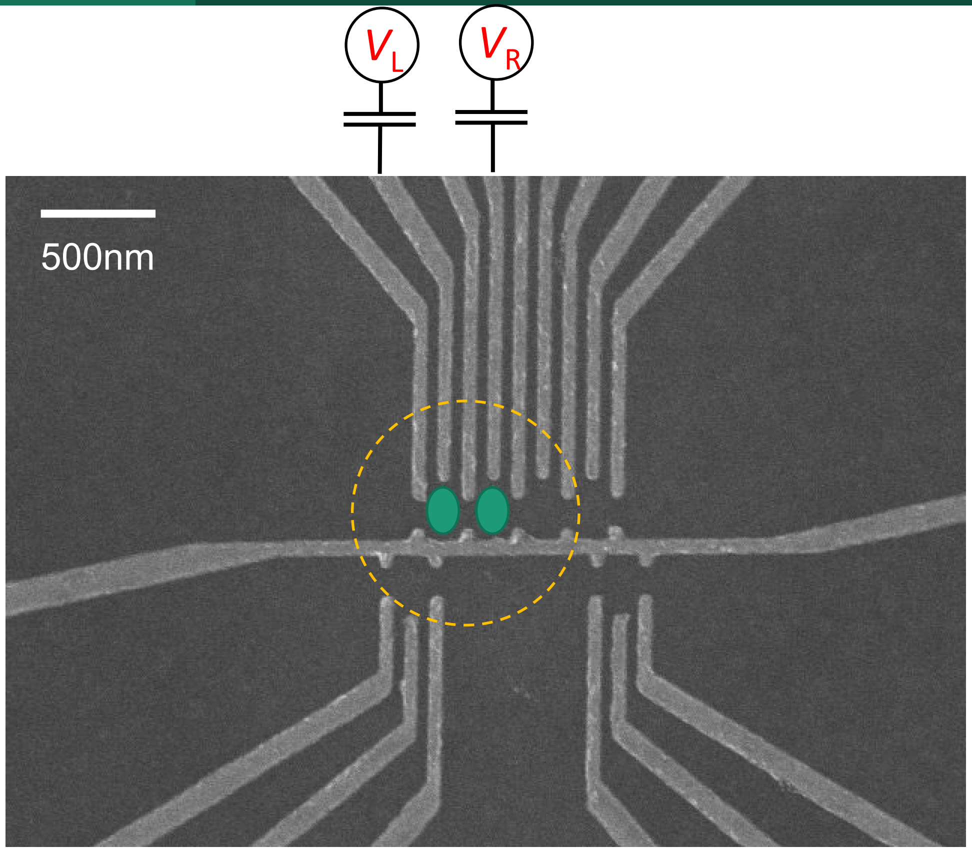
Nanomagnet

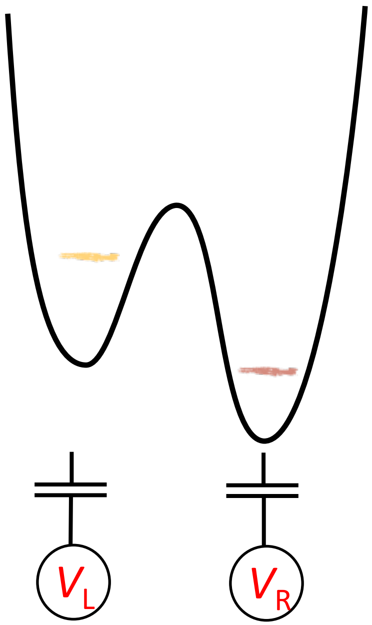
Pioro-Ladriere et al. *Nature Phys.* 2008
Kawakami et al. *Nature Nano* 2014

Spin-orbit coupling

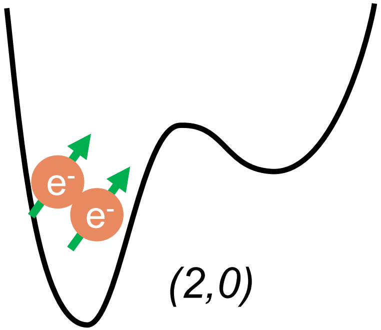
Nowack et al. *Science* 2007
Nadj-Perge et al. *Nature* 2010
Maurand et al. *Nature comm.* 2016
Watzinger el al. *Nature comm.* 2018

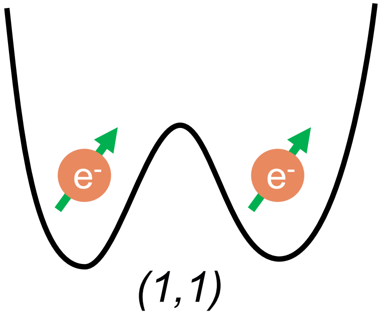
Two qubit gates





이중 양자점에 전자는 2개

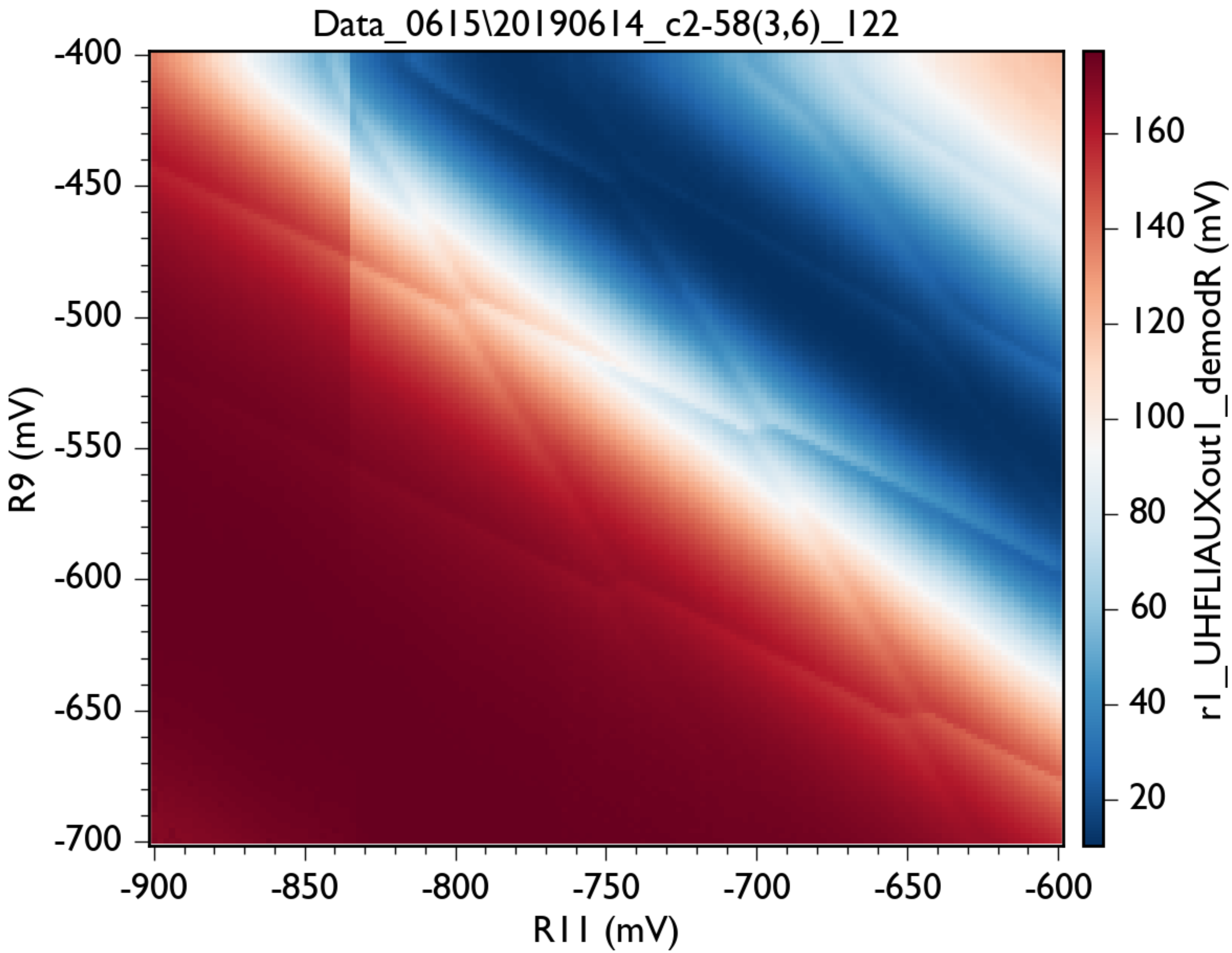




3

1Q, 2Q gates

Charge stability diagram



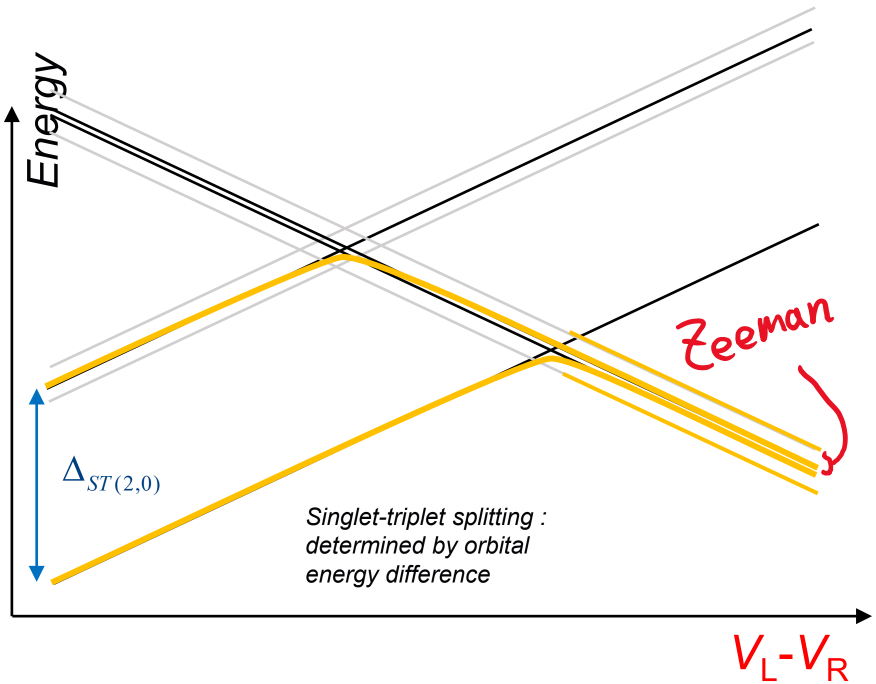
Two electron spin states & position pseudo-spin

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

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

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

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

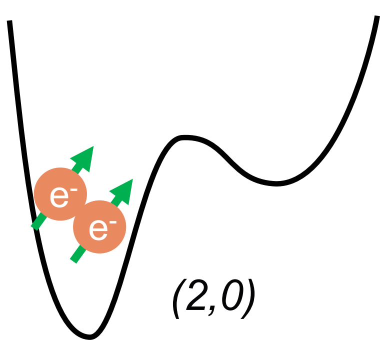


$|3\rangle_{(1,1)} = |\uparrow\uparrow\rangle = |11\rangle$

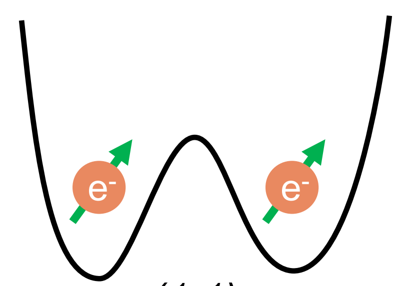
$|2\rangle_{(1,1)} = |\uparrow\downarrow\rangle = |10\rangle$

$|1\rangle_{(1,1)} = |\downarrow\uparrow\rangle = |01\rangle$

$|0\rangle_{(1,1)} = |\downarrow\downarrow\rangle = |00\rangle$



(2,0)

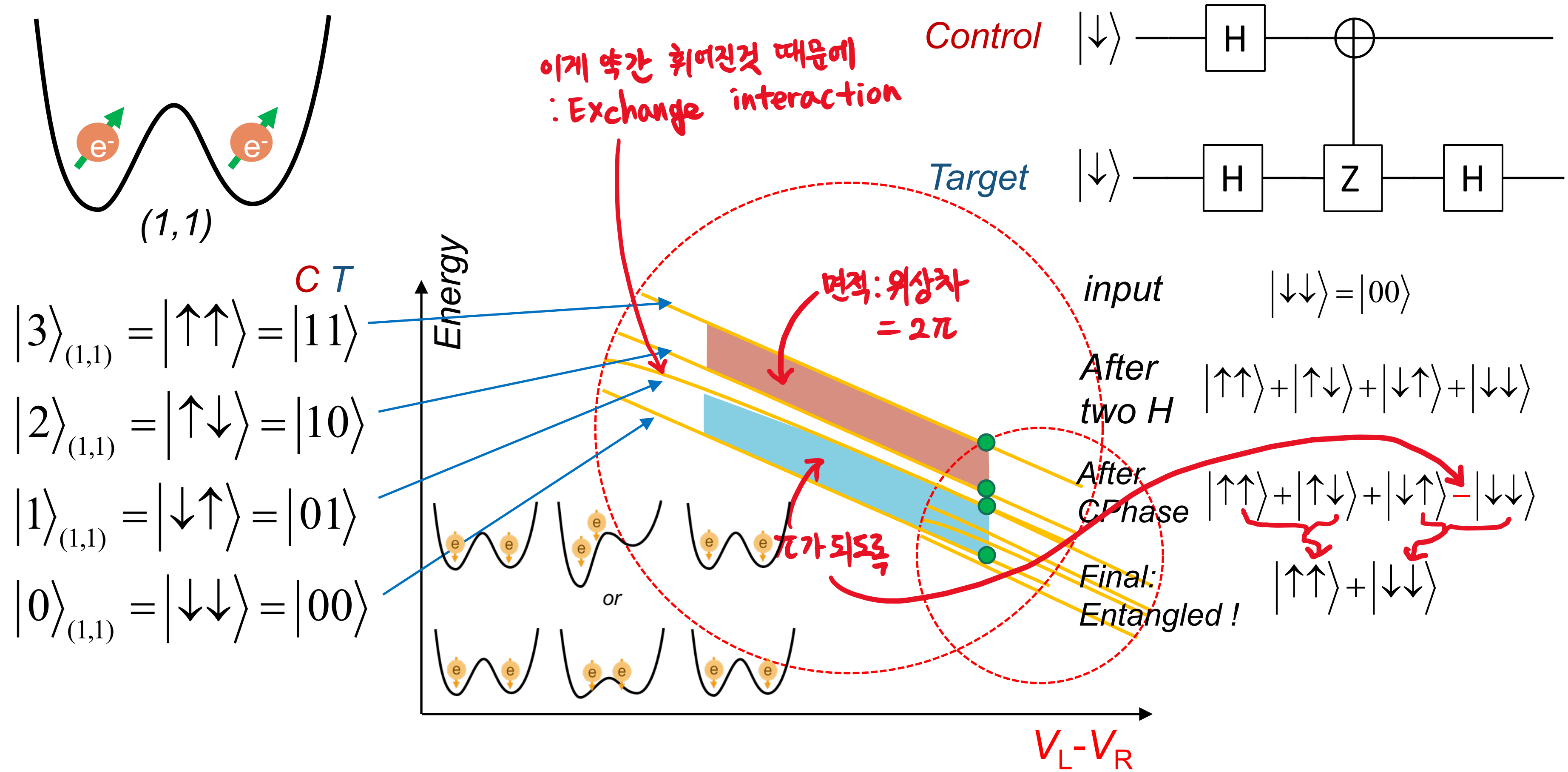


(1,1)

3

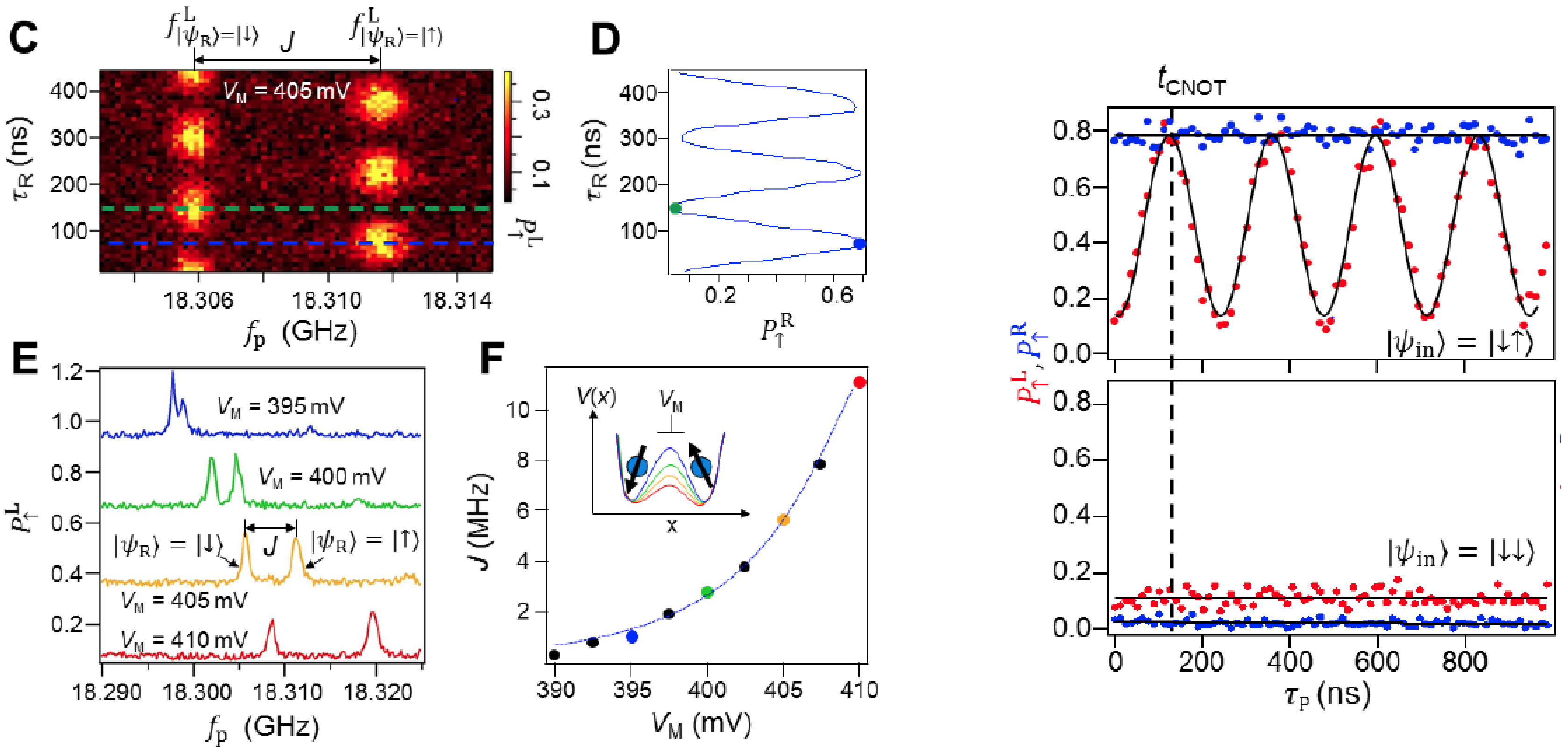
1Q, 2Q gates

Essential physics for a QD-based QC



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

Another way : Controlled rotation gate



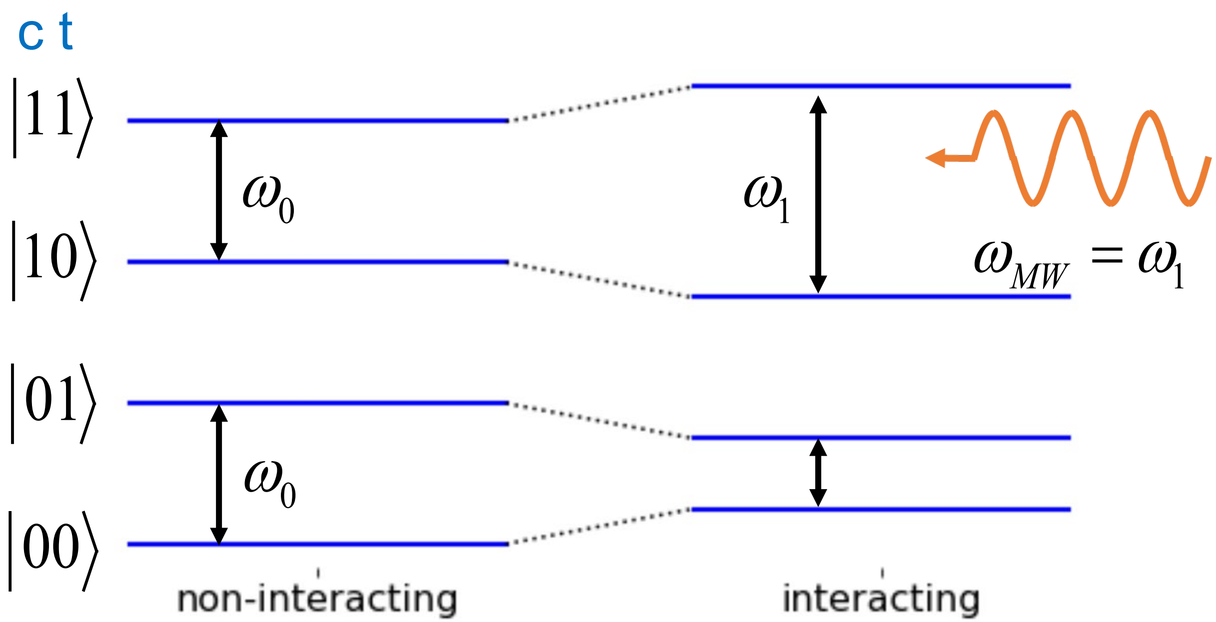
Another way : Controlled rotation gate

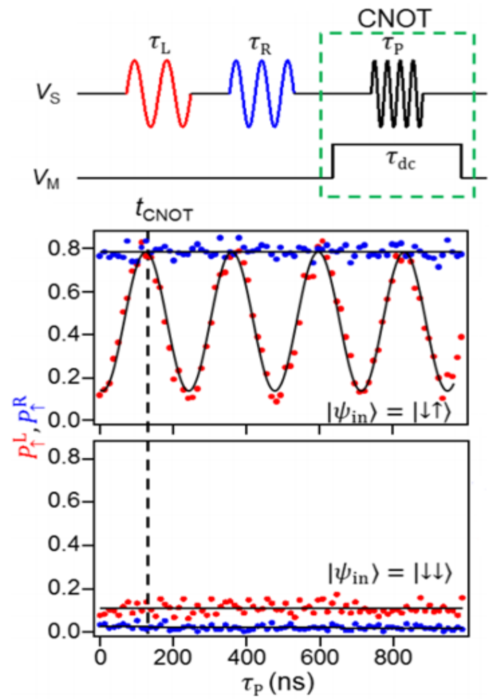
Two qubit gate – 관련 팀 프로젝트 문제 3, 4 번

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

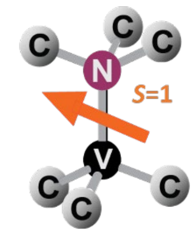




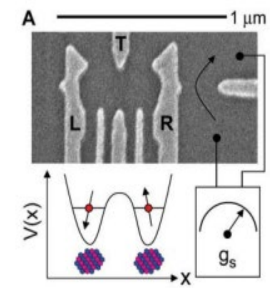
Host materials : semiconductors

					2 He Helium 4
5 B Boron 11	6 C Carbon 12	7 N Nitrogen 14	8 O Oxygen 16	9 F Fluorine 19	10 Ne Helium 20
13 Al Aluminum 27	14 Si Helium 4	15 P Helium 4	16 S Helium 4	17 Cl Helium 4	18 Ar Helium 4
31 Ga Gallium 70	32 Ge Germanium 73	33 As Arsenic 75	34 Se Selenium 79	35 Br Bromine 80	36 Kr Krypton 84
48 In Indium 115	50 Sn Tin 119	51 Sb Antimony 122	52 Te Tellurium 128	53 I Iodine 127	54 Xe Xenon 131
81 Ti Thallium 204	82 Pb Lead 207	83 Bi Bismuth 209	84 Po Polonium 210	85 At Astatine 210	86 Rn Radon 222

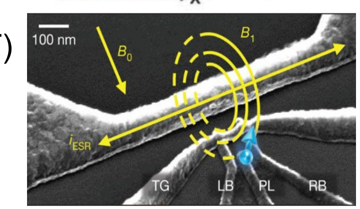
- 2004 – Nitrogen-vacancy in diamond (Stuttgart)

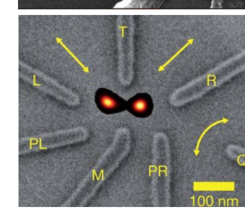


- 2005 – GaAs singlet-triplet (Stuttgart)

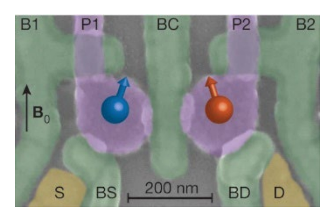


- 2012 – Si:P donor electron spin (CQC2T) Si/SiGe singlet-triplet (HRL)





- 2020 – Germanium hole spins (Delft)



Physical properties

III	IV	V			2 He Helium 4
5 B Boron 11	6 C Carbon 12	7 N Nitrogen 14	8 O Oxygen 16	9 F Fluorine 19	10 Ne Helium 20
13 Al Aluminum 27	14 Si Helium 4	15 P Helium 4	16 S Helium 4	17 Cl Helium 4	18 Ar Helium 4
31 Ga Gallium 70	32 Ge Germanium 73	33 As Arsenic 75	34 Se Selenium 79	35 Br Bromine 80	36 Kr Krypton 84
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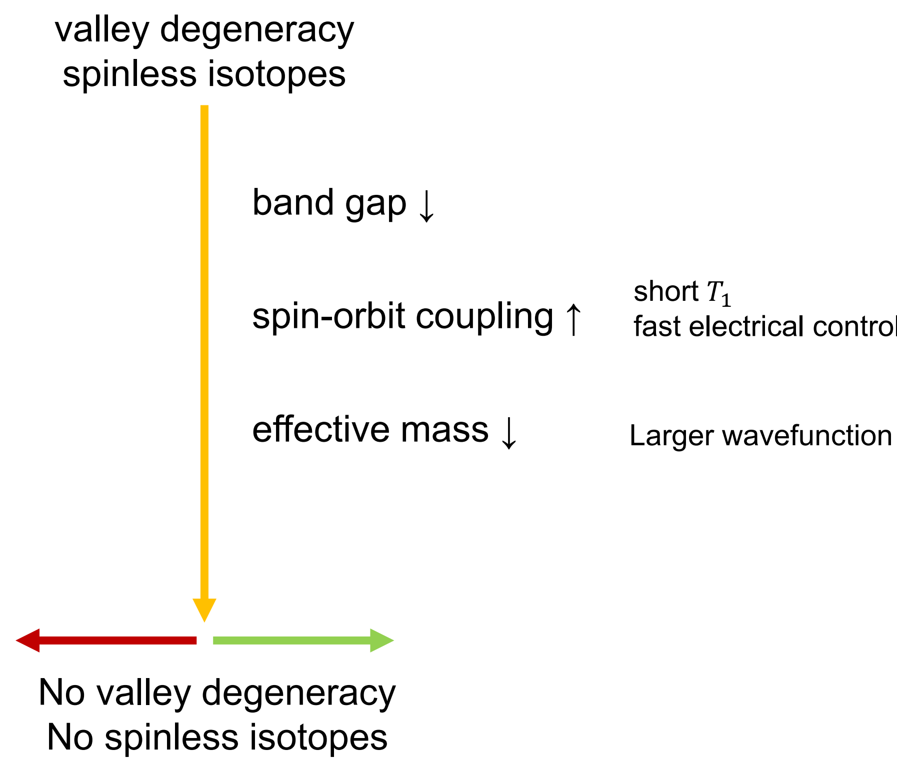
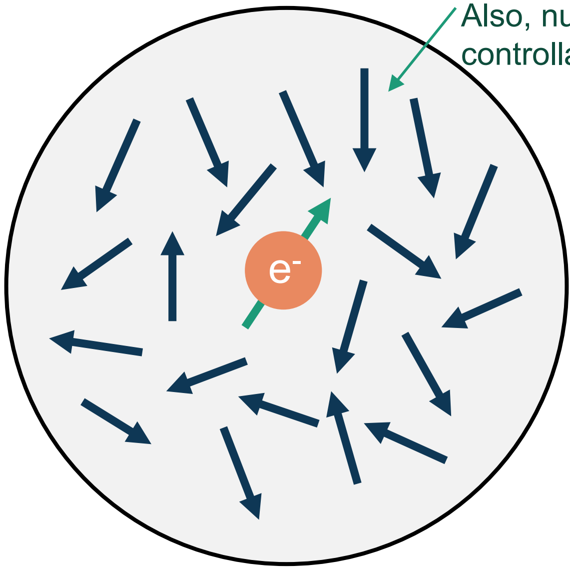


Materials for QD qubits

GaAs



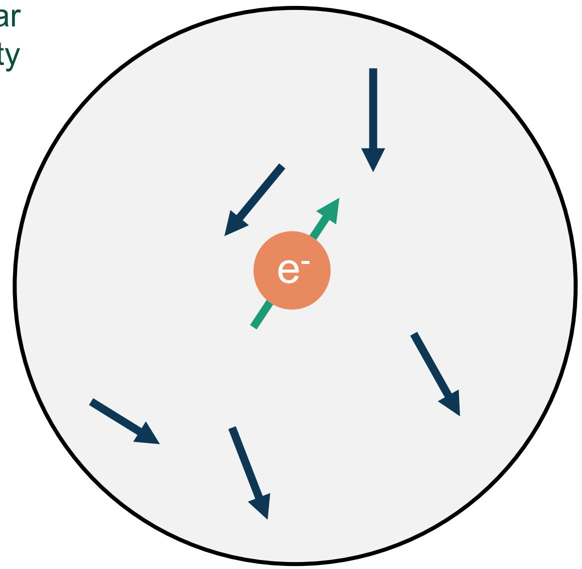
Material advantage

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

Major huddle

- *Nuclear control overhead*

^{Nat}Si or ^{28}Si



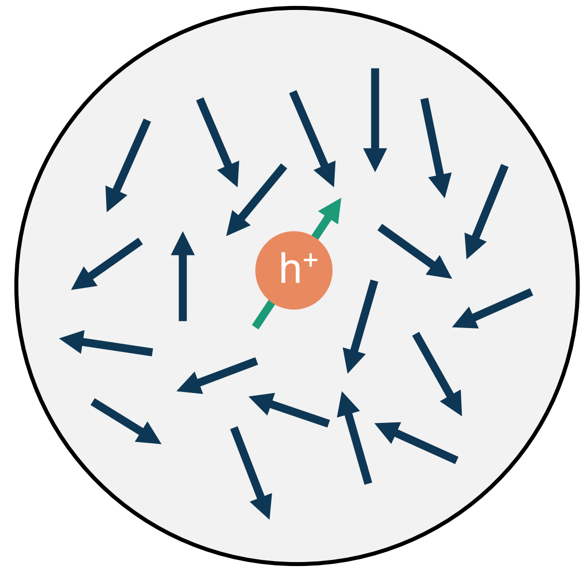
Material advantage

- *Small nuclear spin density*

Major huddle

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

Ge (hole)



Material advantage

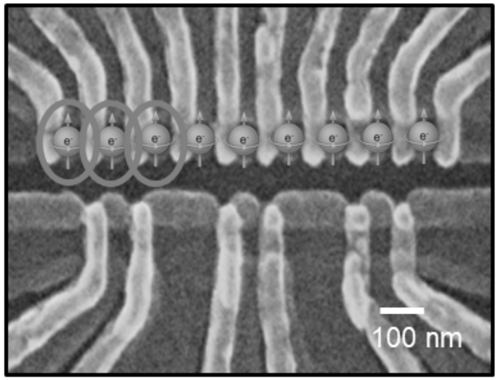
- *Hole spin less susceptible to nuclear noise*
- *Electric spin control (spin-orbit)*

Major huddle

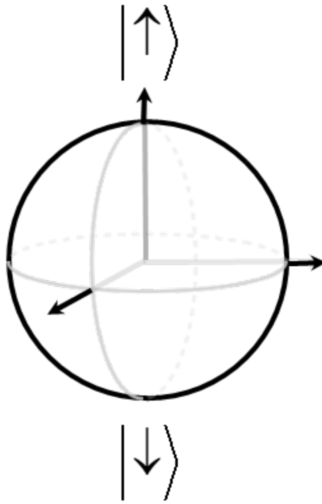
- *Charge noise susceptibility (spin-orbit coupling)*

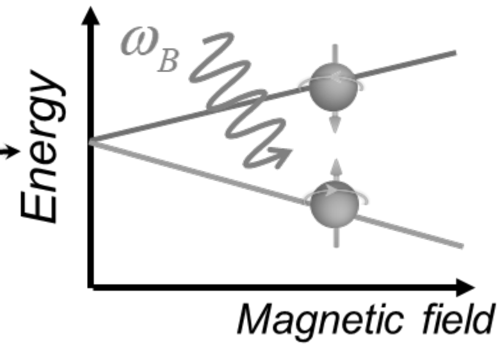
Encoded spin qubit : Two-electron spin qubit

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

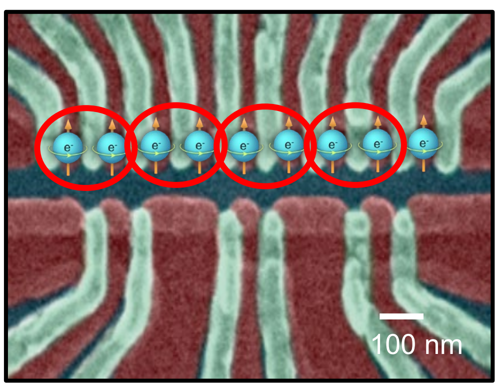


Single electron spin

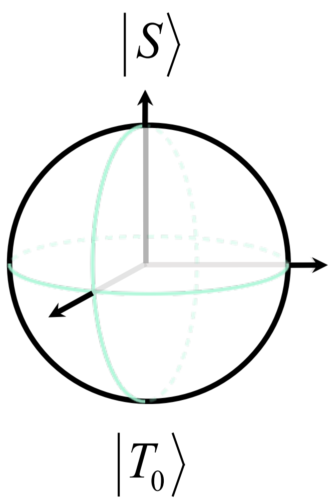


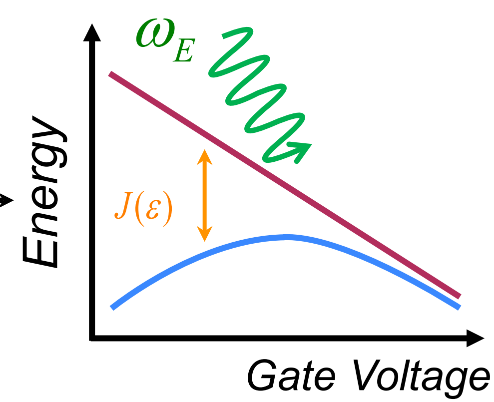


- *Simple*
- *Most coherent*
- *Higher SNR*
- *Exchange coupling*
- *B-field control*
- *slow ~ us gate*



Two electron spin in DQD

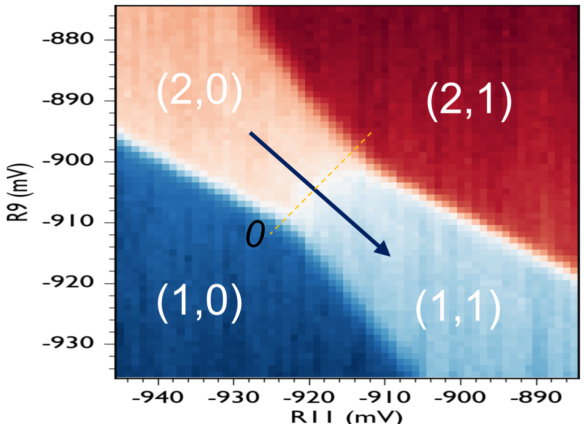


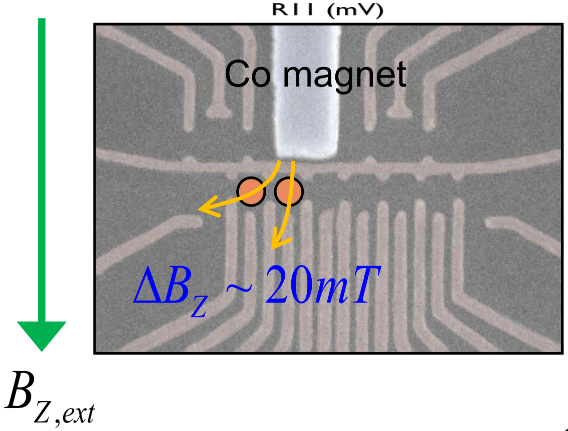


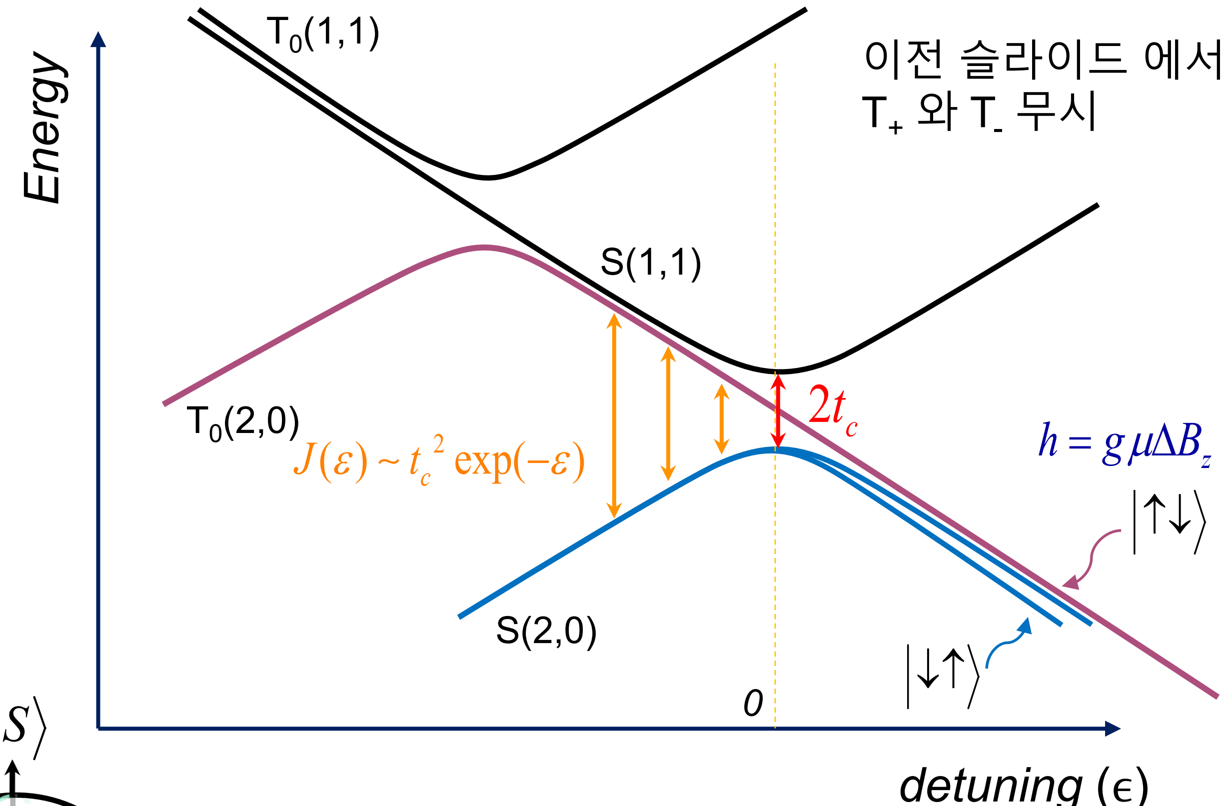
- *E-field control*
- *Fast ~ ns gate*
- *Nucl. polarization*
- *D or Ex coupling*
- *Complexity*
- *Less SNR (improvable)*

Two electron spin qubit

Introduction to DQD – ST_0 qubit



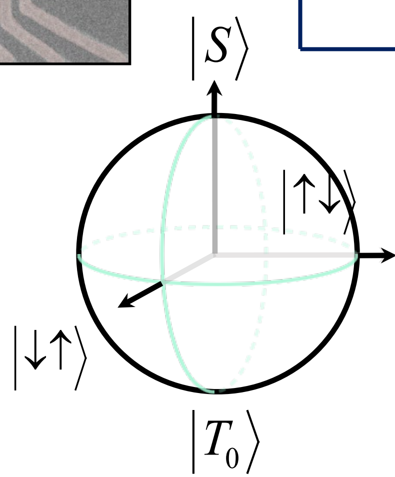




이전 슬라이드 에서
T_+ 와 T_- 무시

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

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



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 : 0~0.2 GHz (0~1 μeV)

4 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

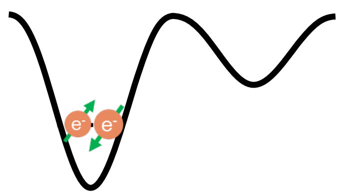
Cf. 초전도 트랜스몬
- 큐비트 주파수: 수 GHz
- 검출 주파수: 수 GHz
- Dispersive readout

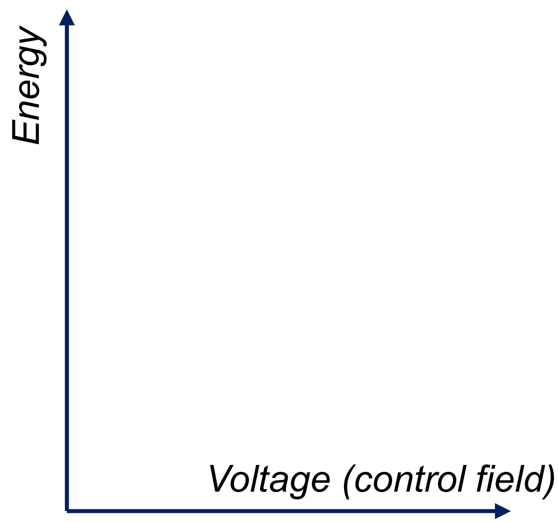
Practicality

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

Qubit 초기화, 측정 영역
빠른 초기화, 스핀-전하 변환

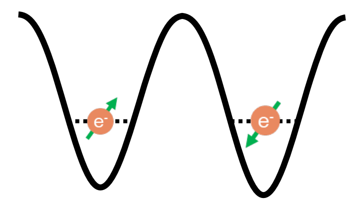
(2,0)

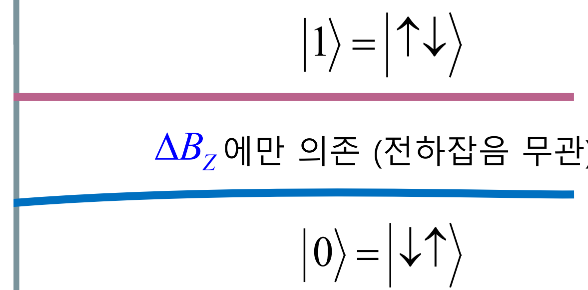


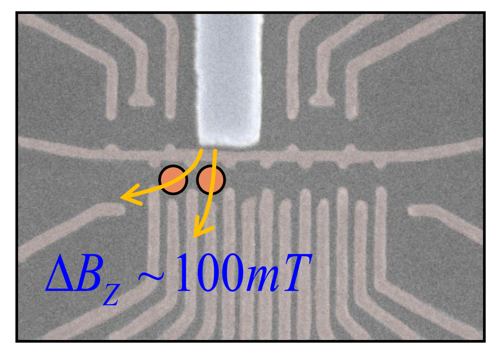


Qubit Operation 영역
긴 결맞음

(1,1)

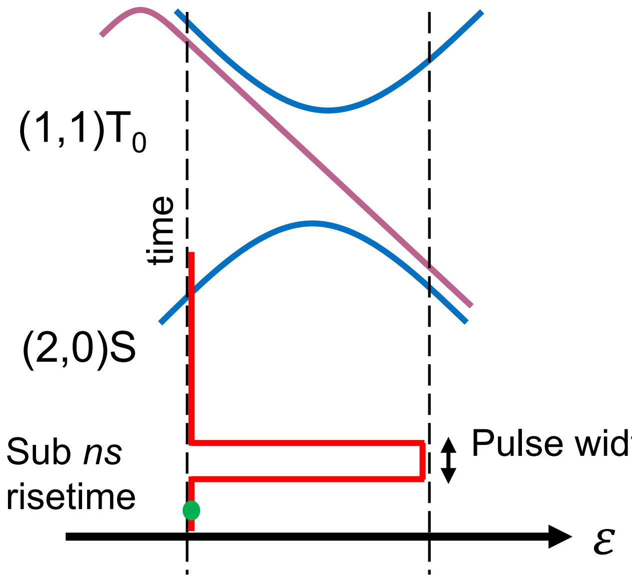




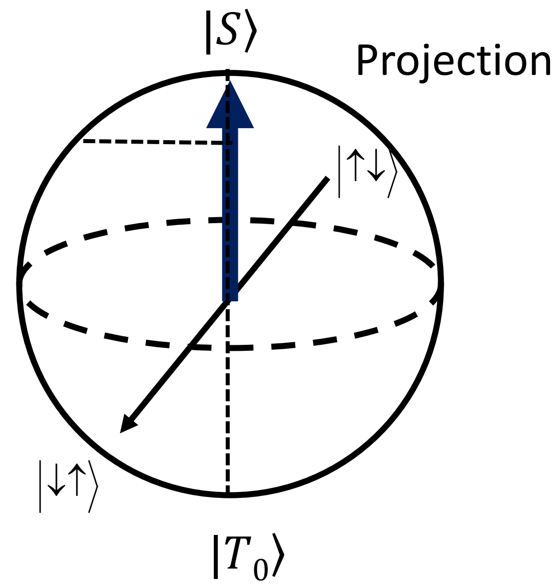


Initialization, Operation & Measurement of STQ

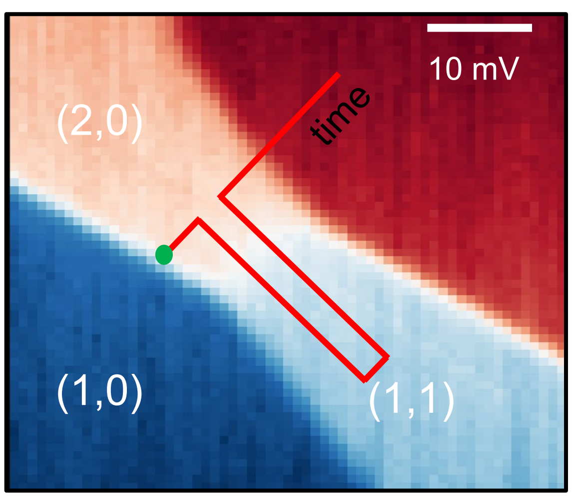
Operation: Voltage pulsing



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

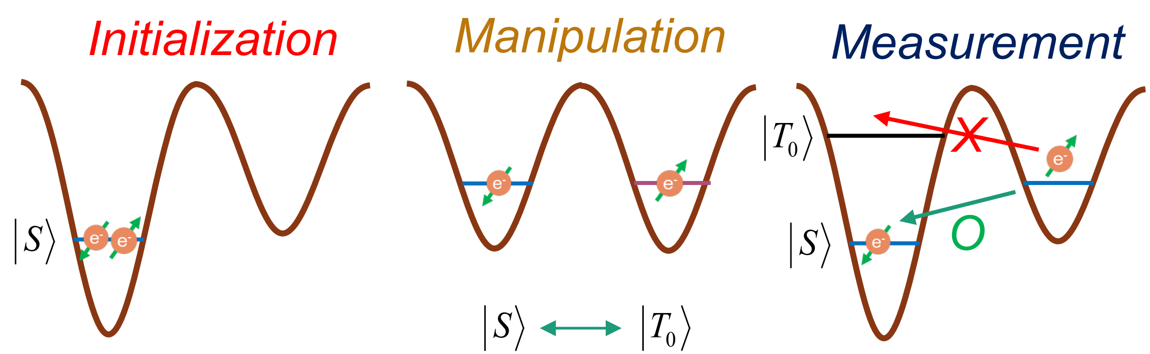


Initialization: ST relaxation (μs to *ms* – also voltage dependent)



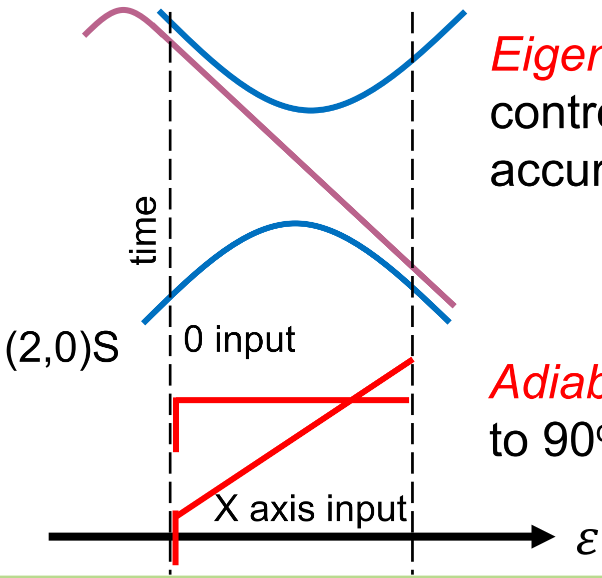
Measurement: How to distinguish $|S\rangle$ from $|T_0\rangle$?
Pauli Spin Blockade

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



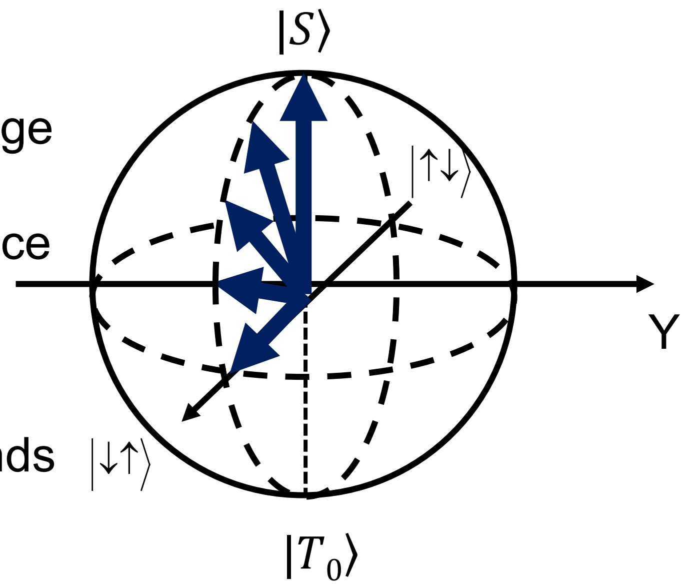
Tomographic sequence of STQ

High fidelity preparation of various input states



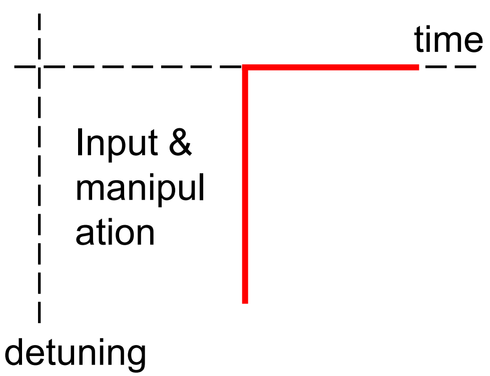
Eigenaxis controllability: Voltage controlled splitting allows accurate tomographic sequence

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

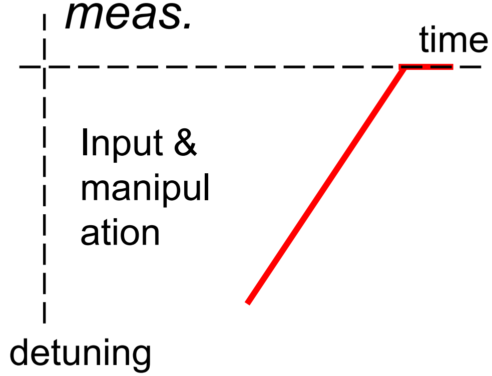


Versatile measurement axis rotation

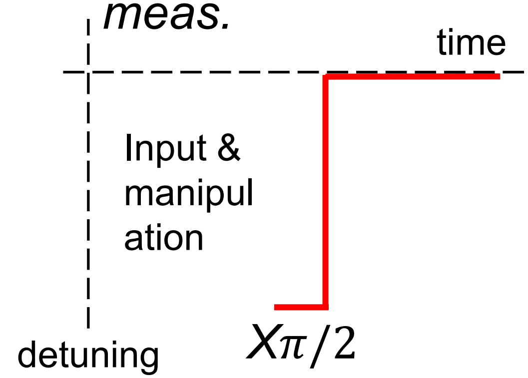
Z-projection meas.



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

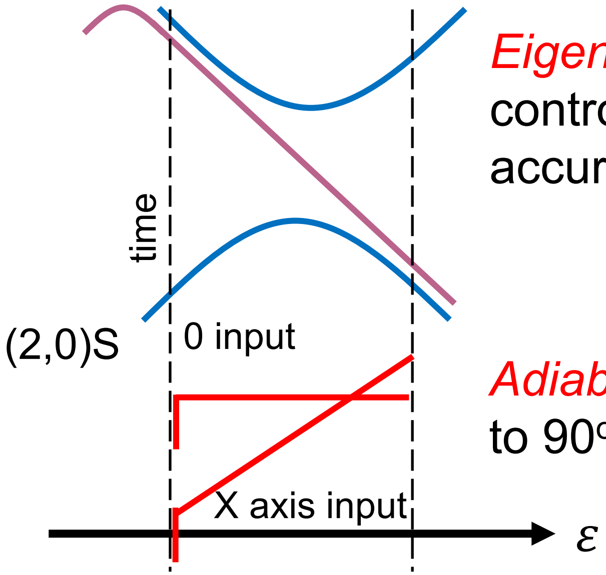


$X\pi/2$ Z = Y-projection meas.



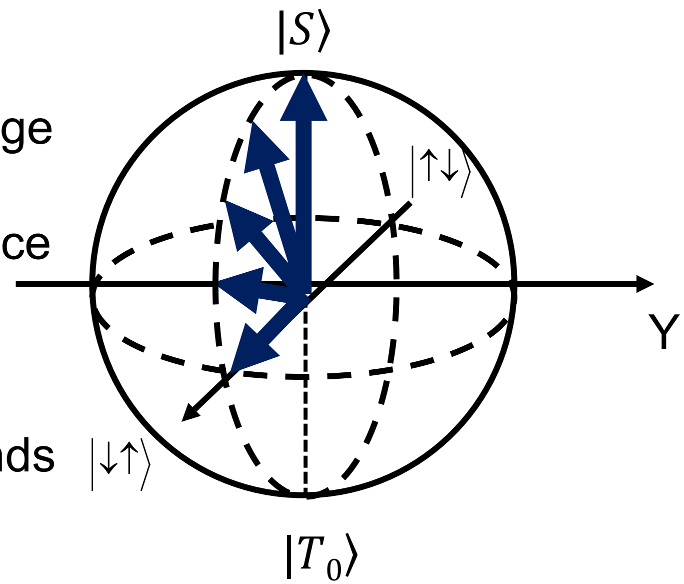
Resonant control of ST qubits

High fidelity preparation of various input states



Eigenaxis controllability: Voltage controlled splitting allows accurate tomographic sequence

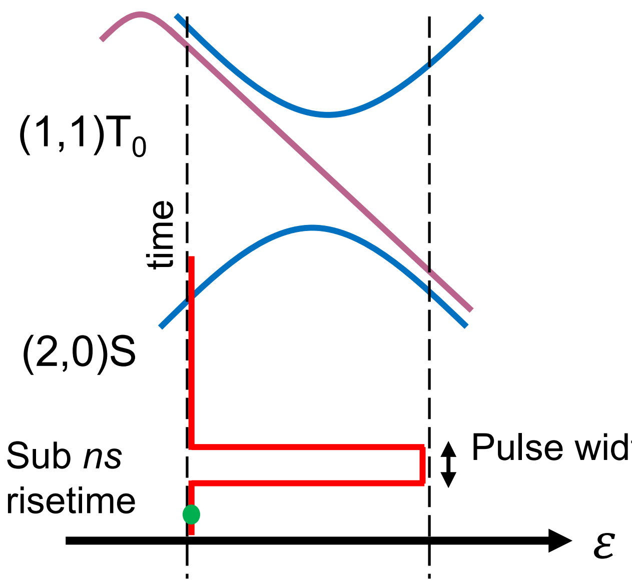
Adiabatic in & out : Corresponds to 90º rotation around Y axis



그림그리기:

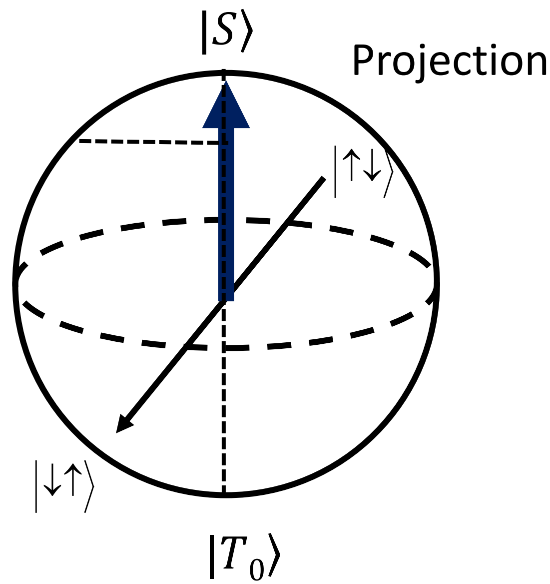
Initialization, Operation & Measurement of STQ

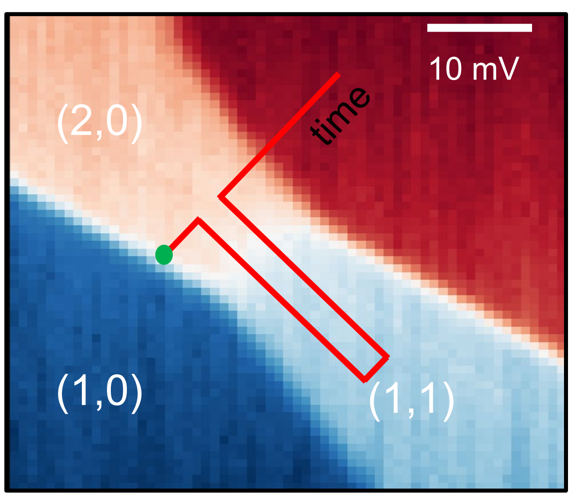
Operation: Voltage pulsing

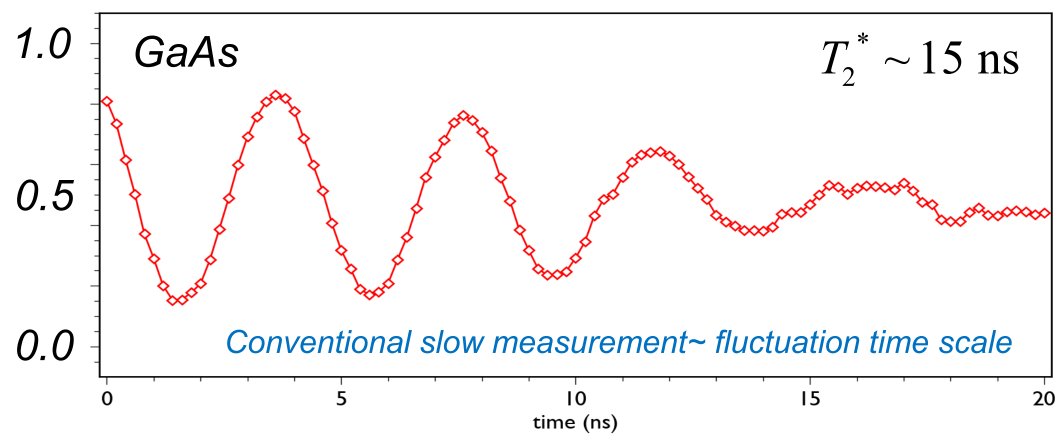


$$H = \begin{bmatrix} J(\varepsilon) & \Delta B \\ \Delta B & 0 \end{bmatrix}$$

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

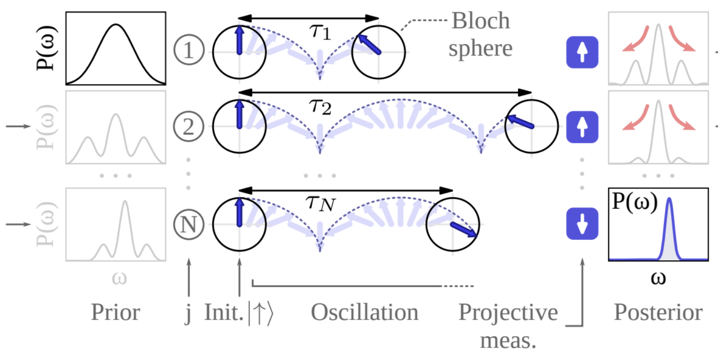






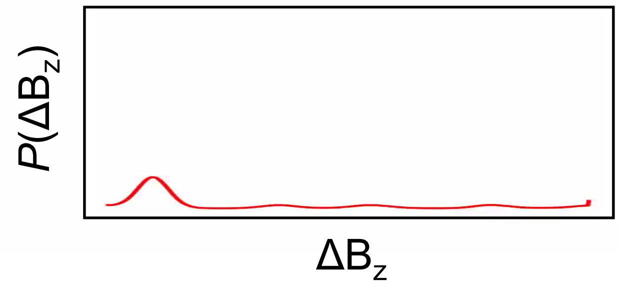
Results: Bayesian Hamiltonian estimation

Real time Hamiltonian Parameter estimation



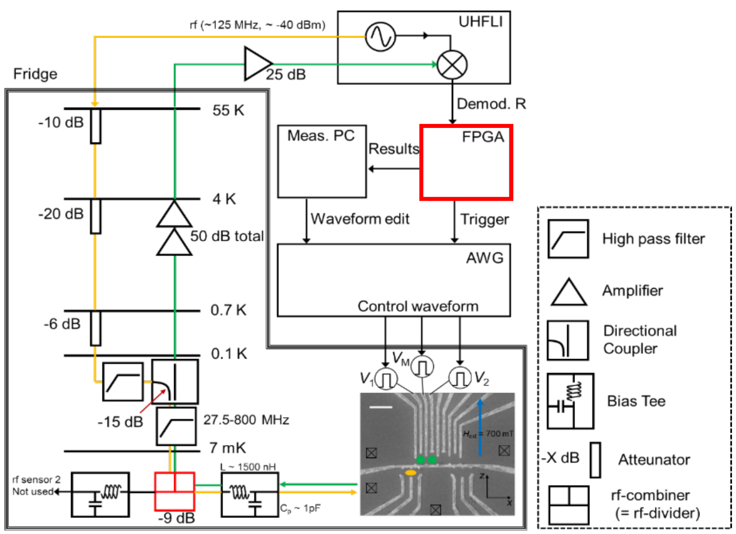
$$P(\Delta B_z \,|m_N, m_{N-1}, \ldots m_1) = P_0(\Delta B_z) \prod_{k=1}^{N} \frac{1}{2}[1 + r_k(\alpha + \beta \cos(2\pi \Delta B_z t_k))]$$

posterior initial Likelihood

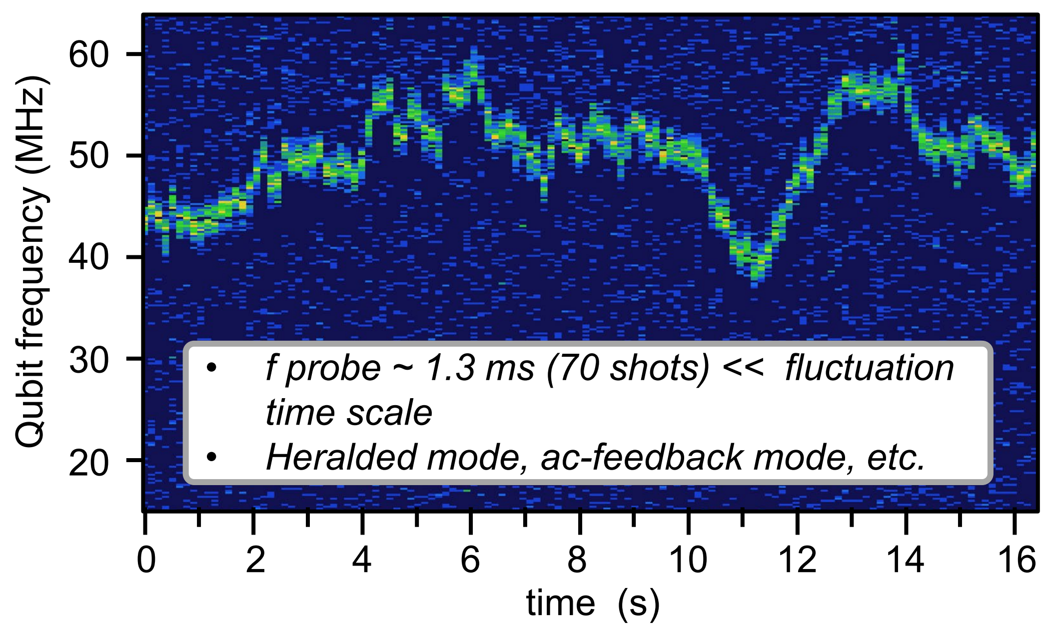


Bayesian inference with FPGA

M.D. Shulman et al., *Nature Comm.* **5** 5156 (2013)



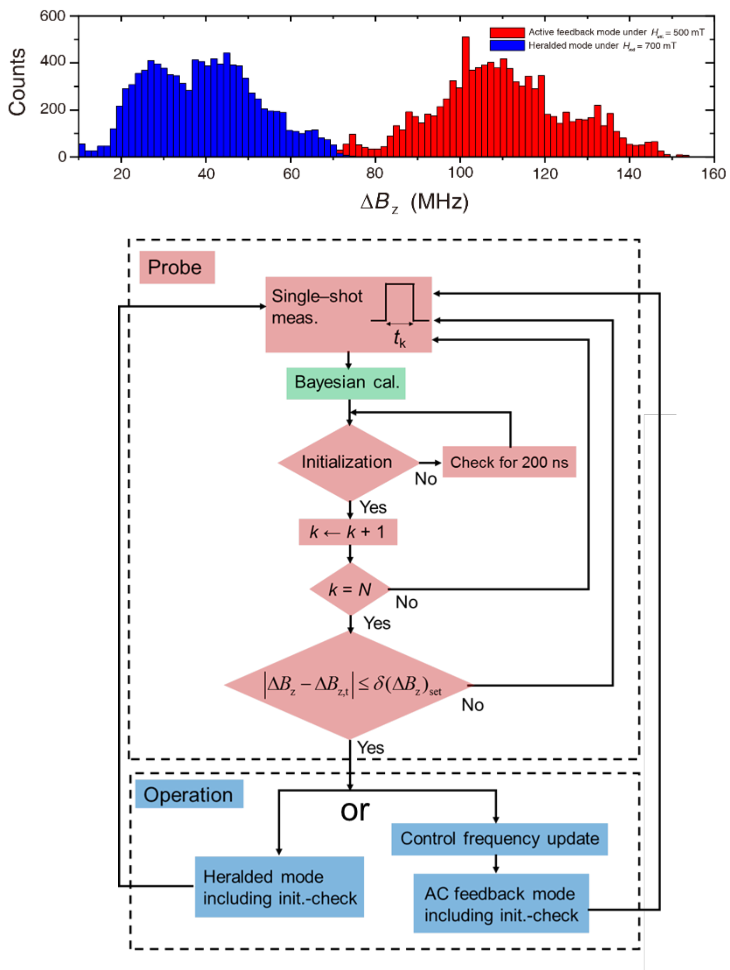
Real-time Qubit frequency tracking

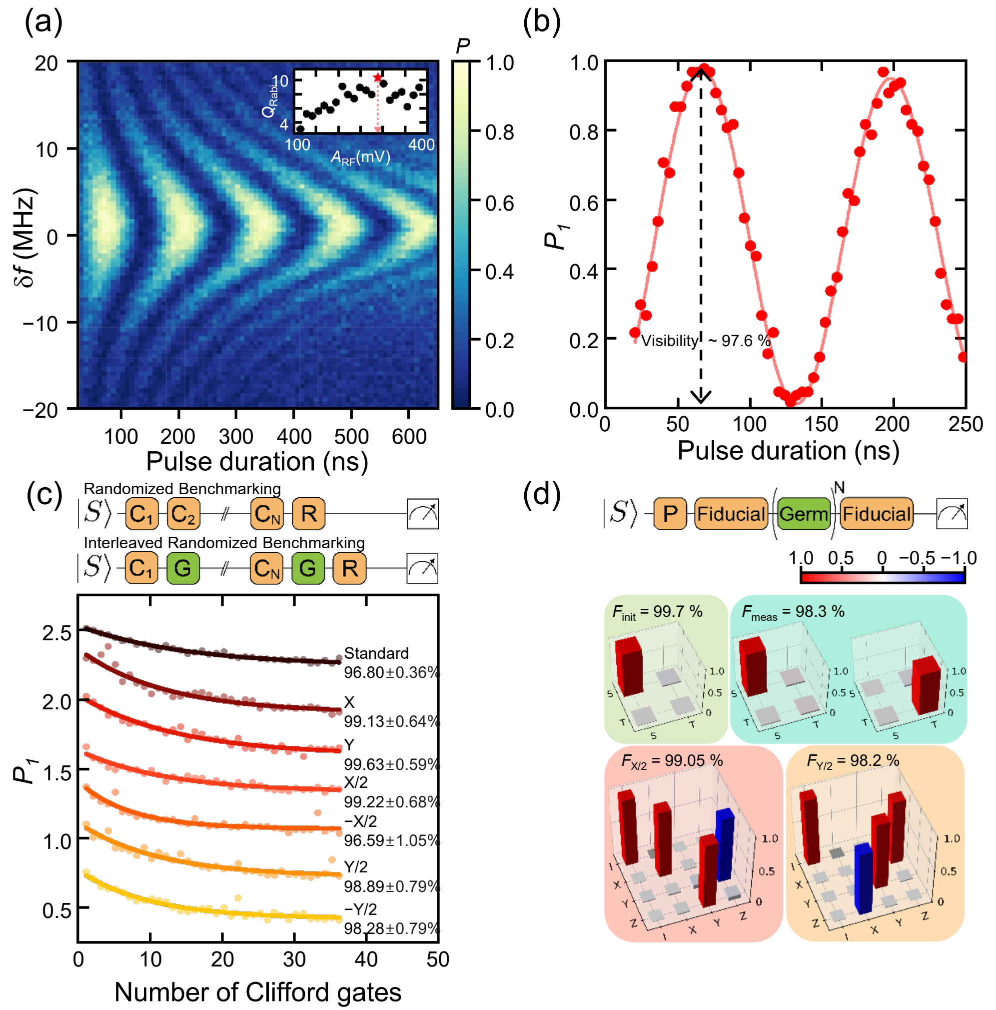


- *f probe ~ 1.3 ms (70 shots) << fluctuation time scale*
- *Heralded mode, ac-feedback mode, etc.*

Results: Bayesian Hamiltonian estimation

Active feedback mode operation - GaAs



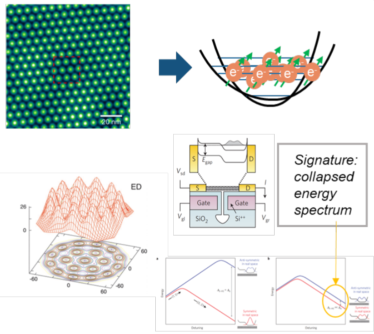


J. Kim et al, *Phys. Rev. Lett.*, **129** 040501 (2022)

97.7 % visibility, 99 % 1Q gate (Bayesian) 99.9 % I, 99 % M

Aside: GaAs 전자-핵스핀 제어, nuclear polarization

Small size counterpart of Wigner crystal: *Wigner molecule* in a confined system



Ground state electron density in a parabolic QD, N=19, $R_W = 5$ (Unrestricted Hartree-Fock)

C. Yannouleas and U. Landman., *PNAS.* **103** 10600 (2006)

S. Pecker et al., *Nature Phys.* **9** 576 (2013)

- Wigner parameter : dominance of e-e correlation

$$R_W = (e^2/\kappa l_0)/\hbar\omega_0$$

e-e Coulomb repulsion | *Kinetic energy (confinement potential)*

$$l_0 = (\hbar / m^* \omega_0)^{1/2}$$

Spatial extent of 1s Single-particle state

κ : Dielectric const. **(12.9)**

m^* : Effective mass **(0.067 m_e)**

$\hbar\omega_0$: few meV

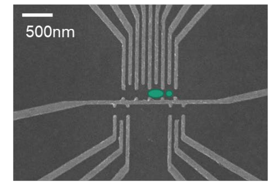
Conventional semiconductor quantum dot

$R_W \sim 1$

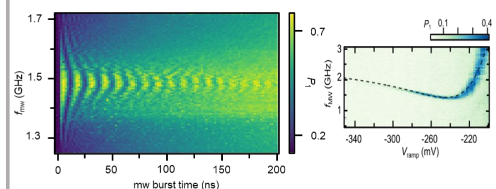
confinement potential design – R_W tunability

We were also lucky : FCI theory already confirmed WM in our previous device

Our experimental report

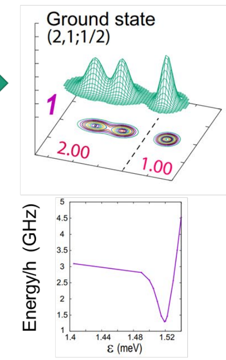


Confinement potential information, experimental parameters

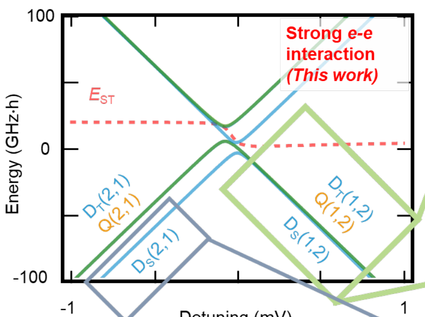


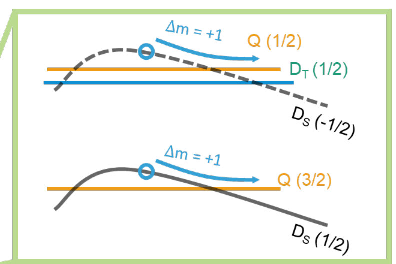
W. Jang et al., Nano Letters, **21** 4999 (2021)

FCI calculation

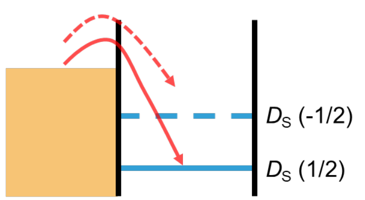


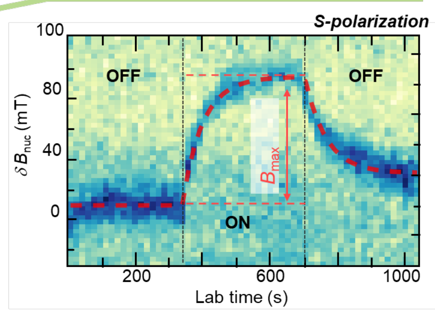
C. Yannouleas and U. Landman., *Phys. Rev. B* **105** 205302 (2022)

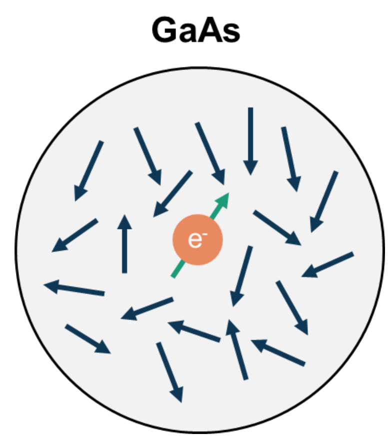




Initialize to either $D_S(1/2)$ or $D_S(-1/2)$

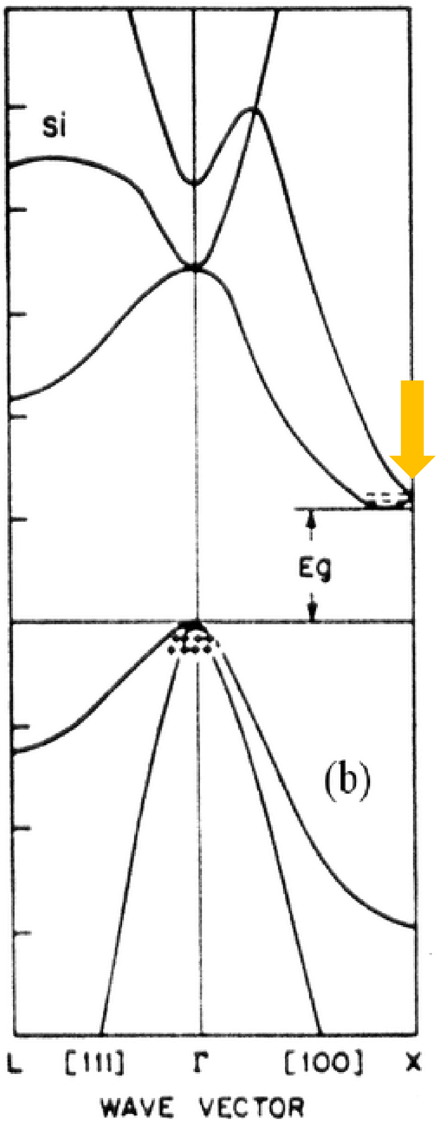






- Confinement 조절로 다양한 강상관분자 형성 가능
- 터널링을 이용한 핵스핀 분극 제어
- 다전자 스핀 큐비트
- 그러나 Quantum Engineering 측면에서는 역시 **실리콘**이…

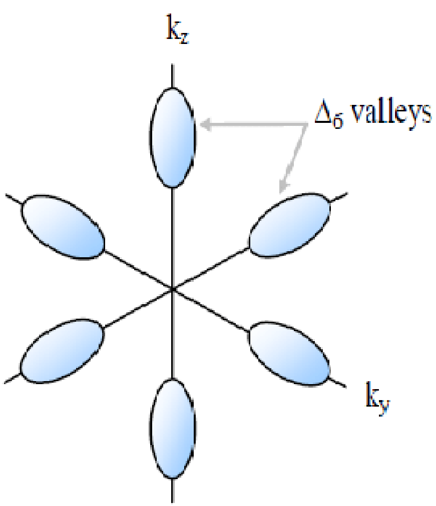
Material issue in Si : Valley degeneracy



Indirect band gap : the conduction band minima are not k = 0. They are at $k/2\pi = 0.85/a$

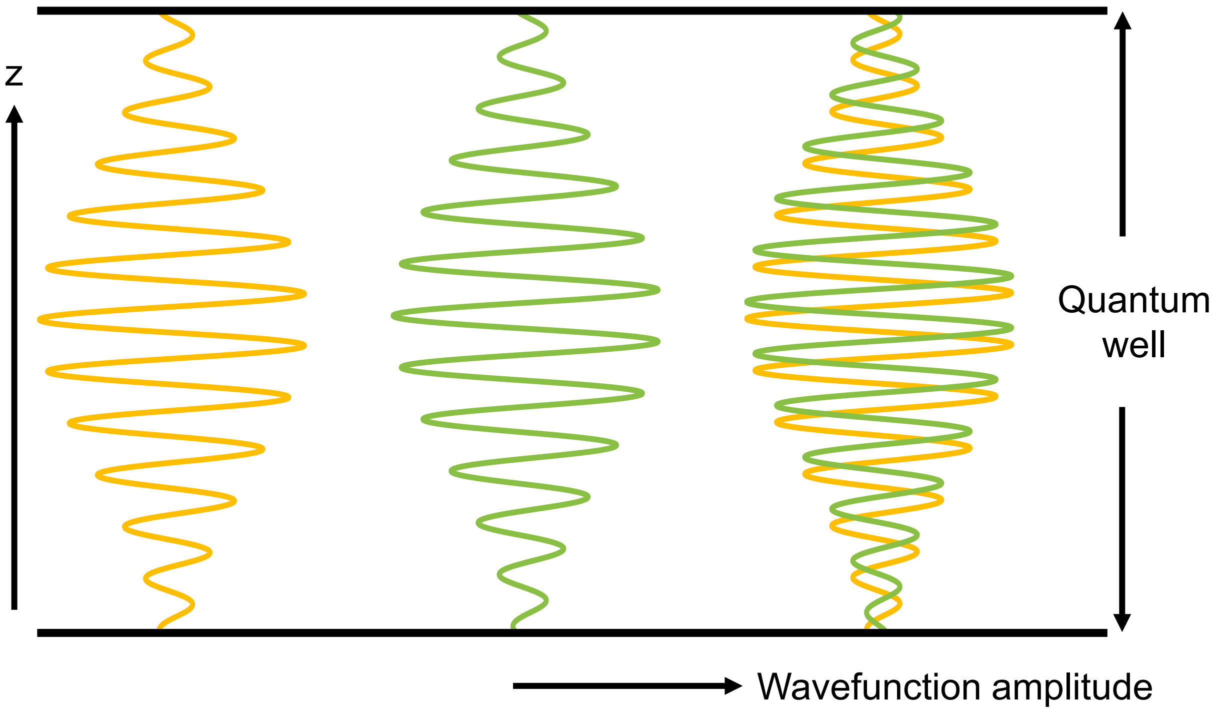
E_g = 1.12 eV

6 degenerate conduction band minima along
±x, ±y, ±z
→ **"valleys"**



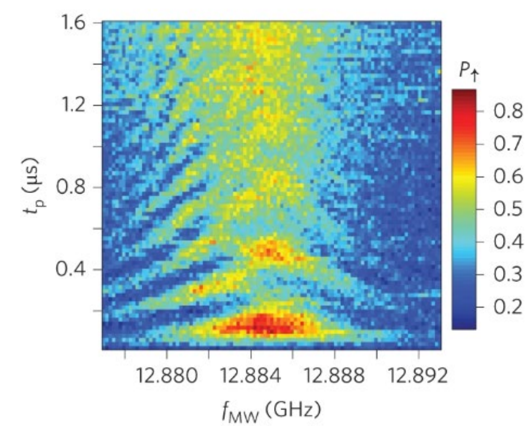
Valley splitting should be large

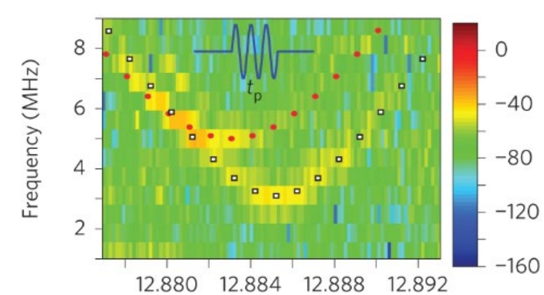
The eigenstates are symmetric / antisymmetric combinations of the relevant valleys
→ the shape of the confinement determines whether they have the same energy or not



Lowest energy symmetric eigenstate	Lowest energy antisymmetric eigenstate	Envelopes of two eigenstates are the same : phases of fast oscillations are different

Valley splitting 작으면 이렇게...

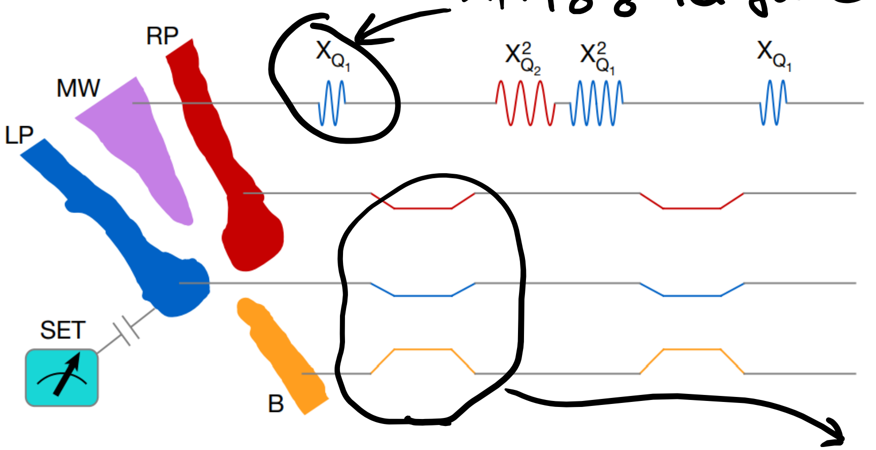




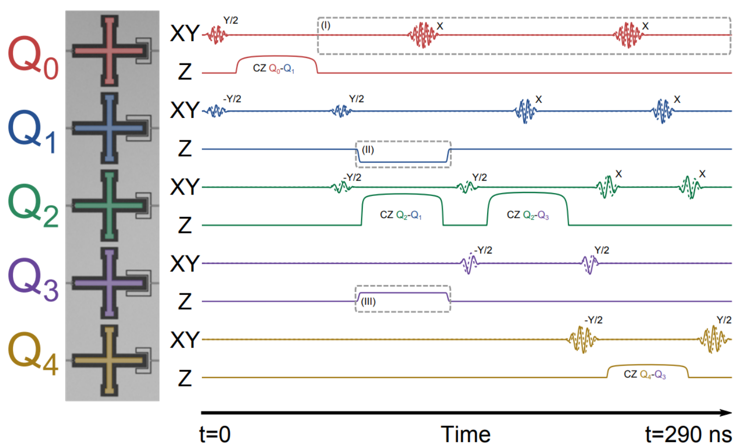
E. Kawakami et al, *Nature Nanitech.*, **9** 666 (2014)

Research status

Current state of the art

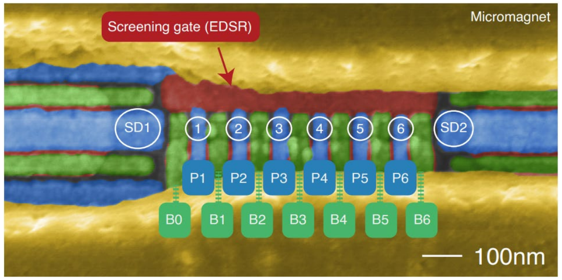


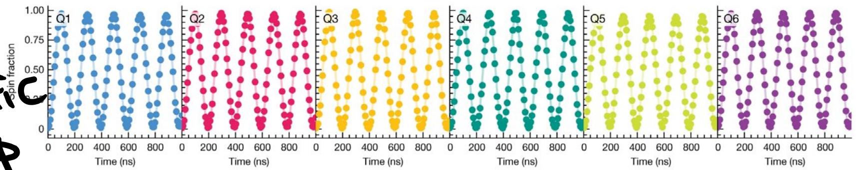
Cf. 5- SC qubit experiment (UCSB 2014, Nature)

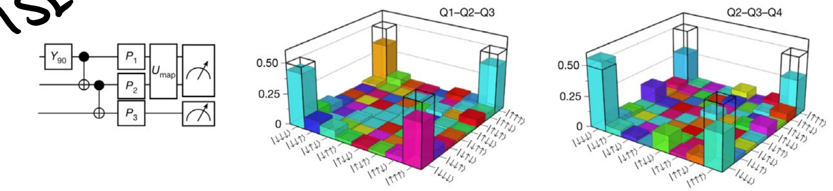


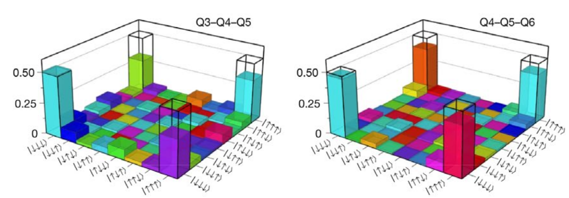
Lieven Vandersypen (2001, NMR 로 15=3x5)

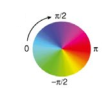
quTech, Nature **609**, 919 (2022)







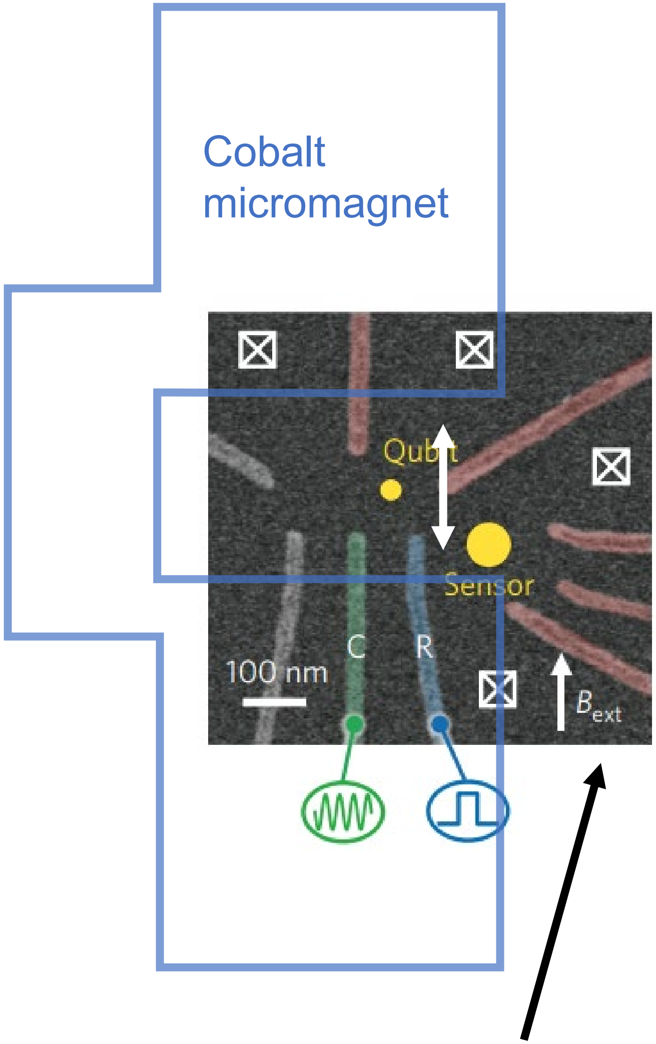




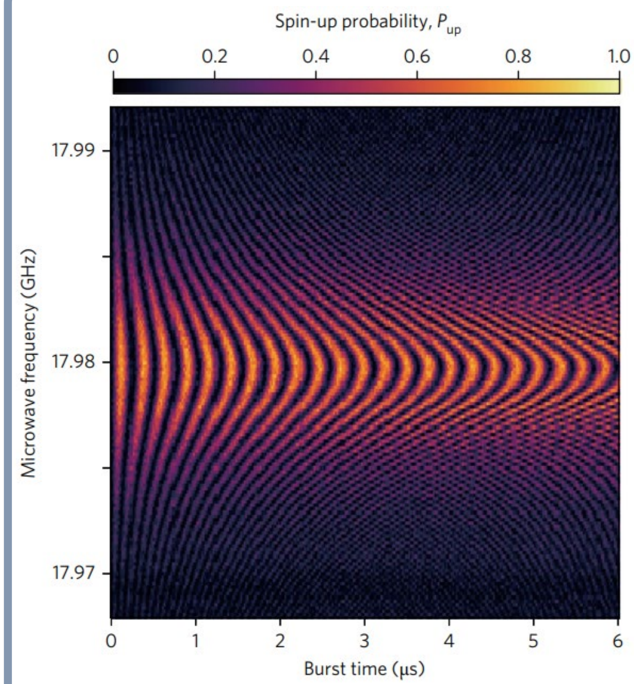
Qubits	φ (rad)	Fidelity (%)	Witness
1–2–3	2.41	76.8 ± 2.2	−0.327 ± 0.022
2–3–4	−0.32	71.4 ± 3.2	−0.297 ± 0.038
3–4–5	1.67	72.2 ± 4.0	−0.291 ± 0.036
4–5–6	2.68	83.6 ± 2.2	−0.380 ± 0.024

Both 1Q, 2Q gate fidelities exceed surface code error correction threshold.
Similarity : SC qubit (Google type) = Si spin qubit

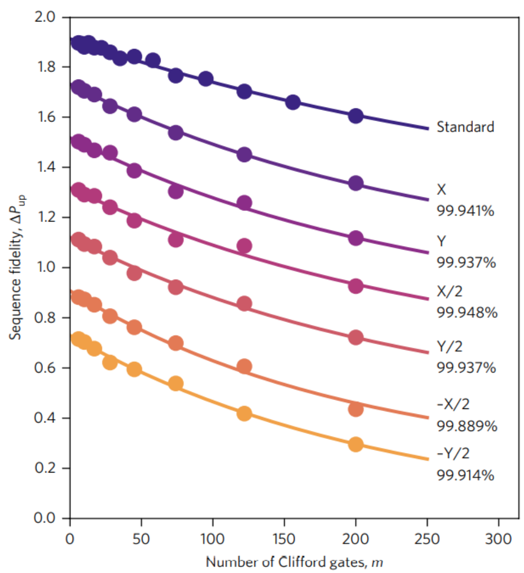
Current state of the art



Coherent Rabi Oscillation



Randomized Benchmarking

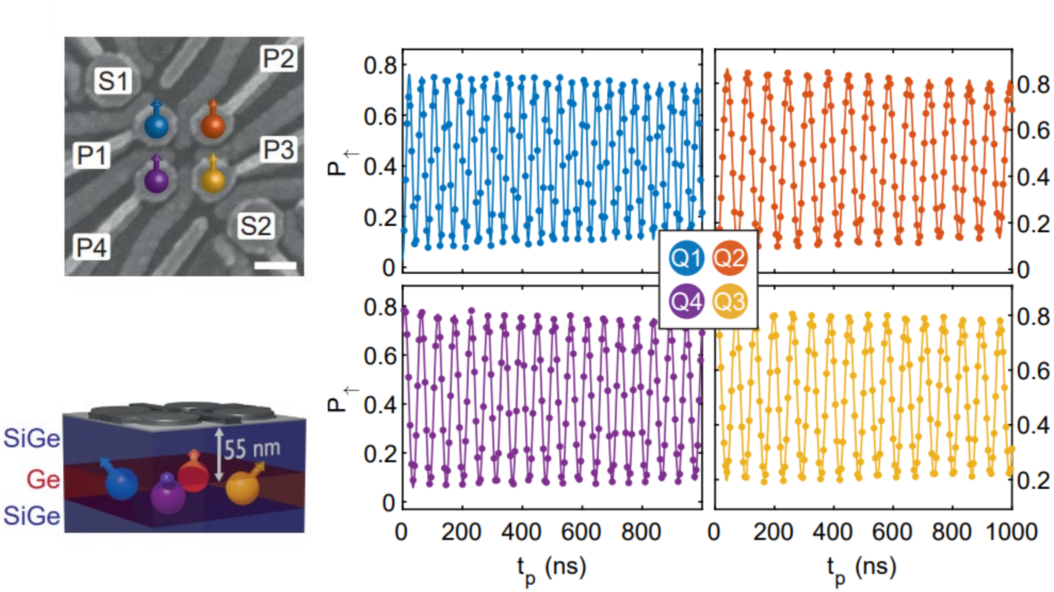


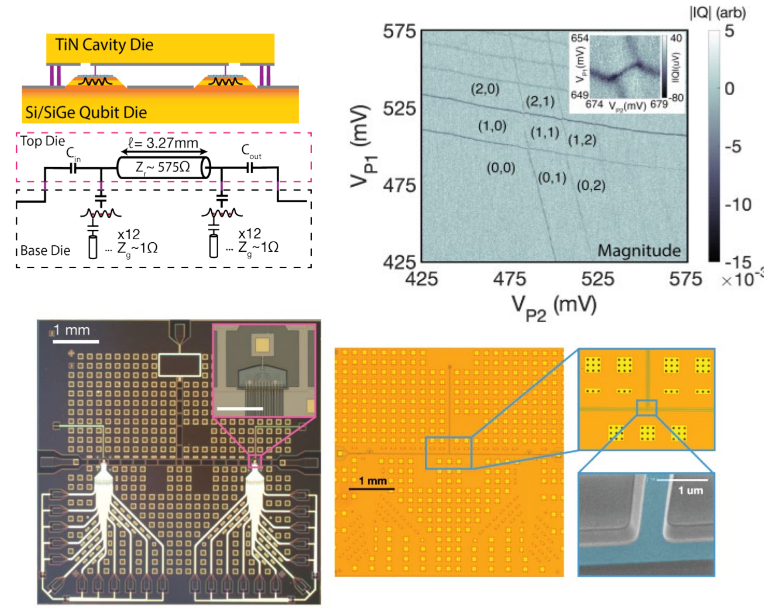
- **High fidelity single qubit control (> 99.9%,** confirmed by RB**)** in the purified ^{28}Si
- Charge noise limited coherence (CPMG, Ramsey measurement)

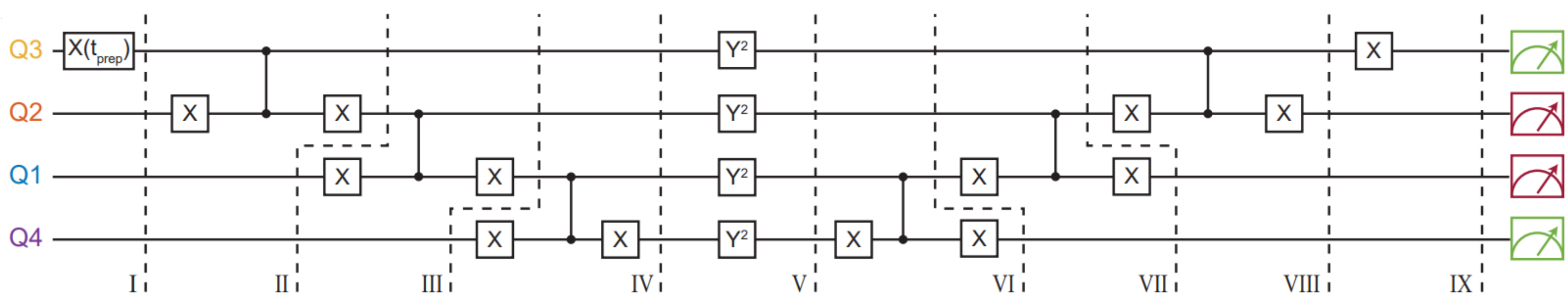
Nature Nanotech. **13**, 102 (2018)

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

4

Research status

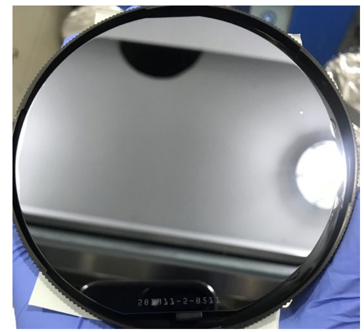
SNU team : 실리콘 스핀 큐비트 칩 개발 현황

재료 확보 – acknowledgement: Prof. Kohei Itoh, Prof. Giordano Scappucci, Prof. Mark Eriksson

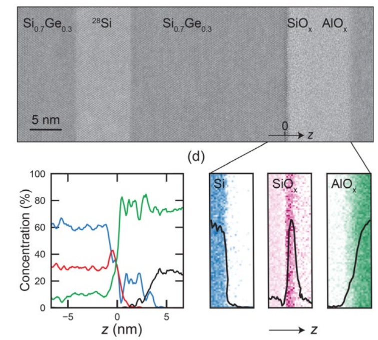
Natural Si/SiGe

동위원소 정제 ^{28}Si/SiGe - Keio

4', ^{28}Si/SiGe - quTech

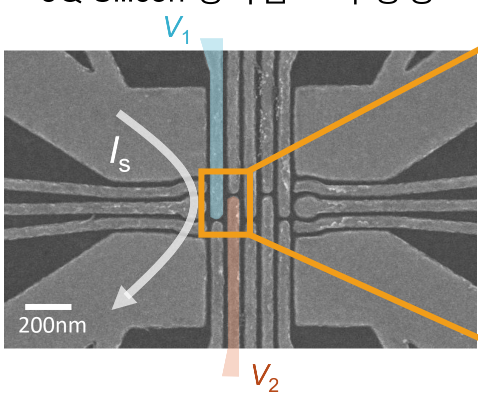


재료 단면

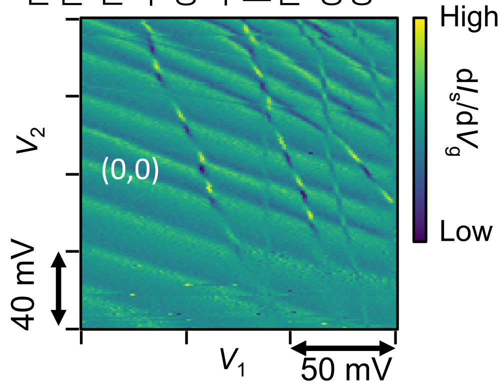


실리콘 양자점 소자 칩 초기 측정 / 마이크로 마그넷 공정 확립

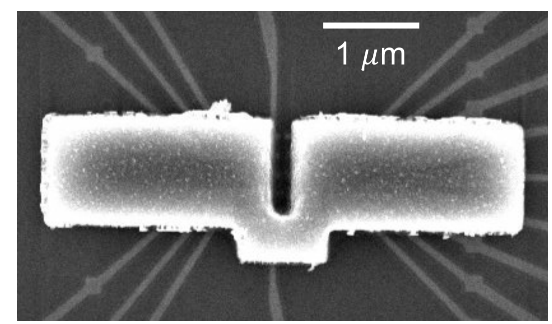
5Q Silicon 양자점 소자 공정



단일 전자 영역 도달 성공



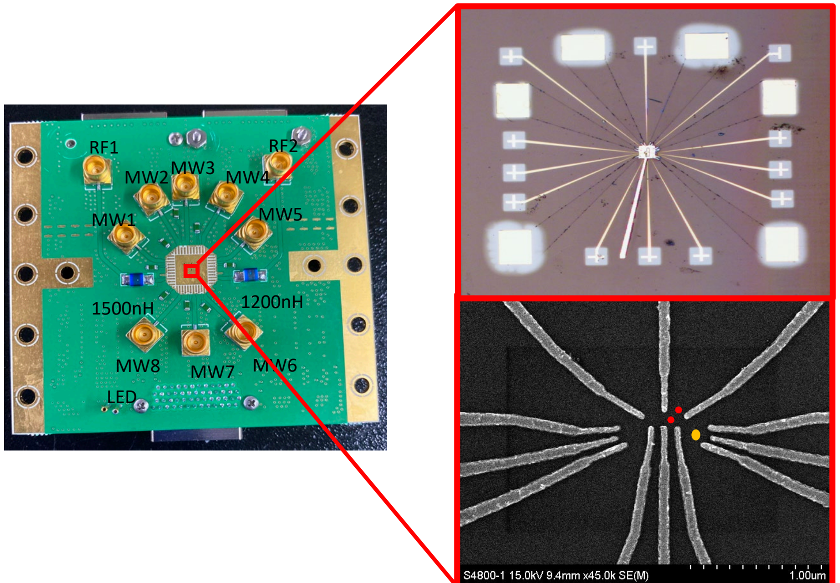
게이트 접합 마이크로 마그넷 공정 성공

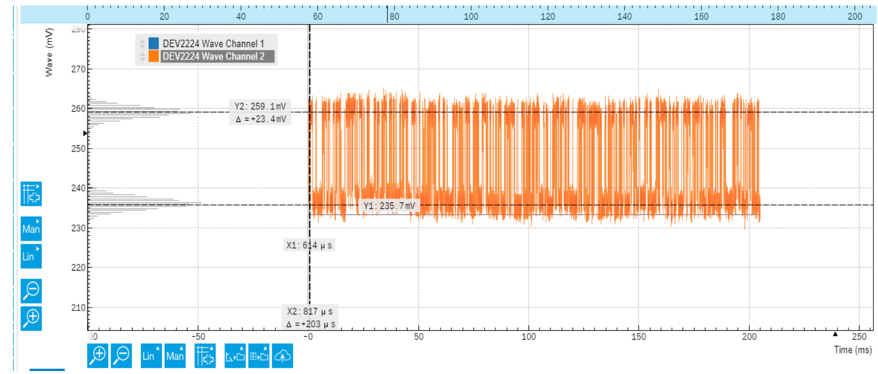


단일 전자 스핀 큐비트 구동을 위한 필수 단계

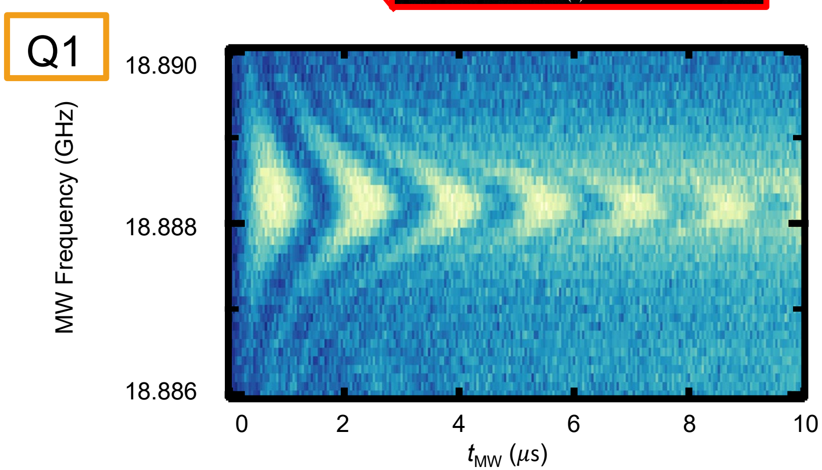
2016 ~ 2019 Si 스핀 큐비트 : 단일 layer 소자. 양자점 형성 및 단일 전자 도달 – 큐비트 동작은 실패 (소자 안정도, tunability, 극저온 셋업 성능 미달..)

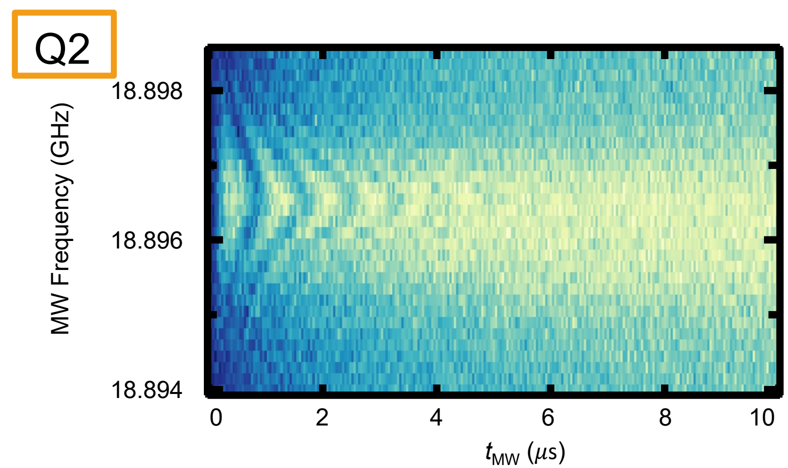
Preliminary : two single spin qubits in ^{28}Si/SiGe





SNR ~ 8.4 @ t_{int} = 1 μs



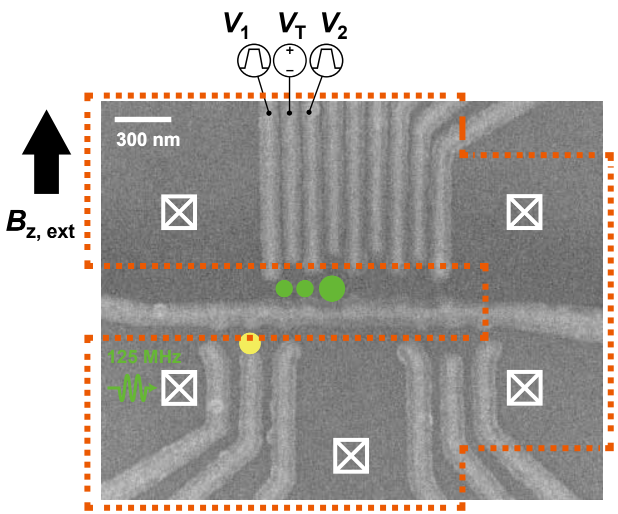


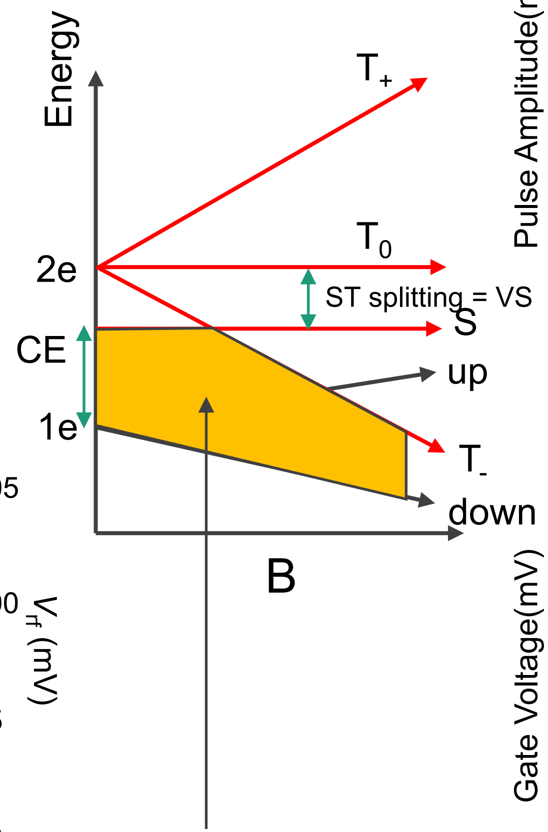
2022 status 스핀 두개의 Rabi oscillation. 작은 Field gradient: 최적화 필요. 작은 lever arm: Overlapped gate structure 필요. 낮은 visibility ~ 0.3: Single-shot fidelity 최적화 필요

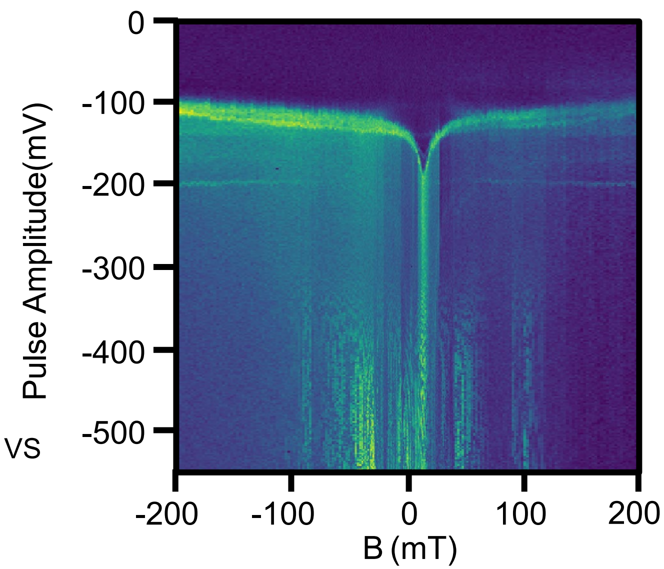
4

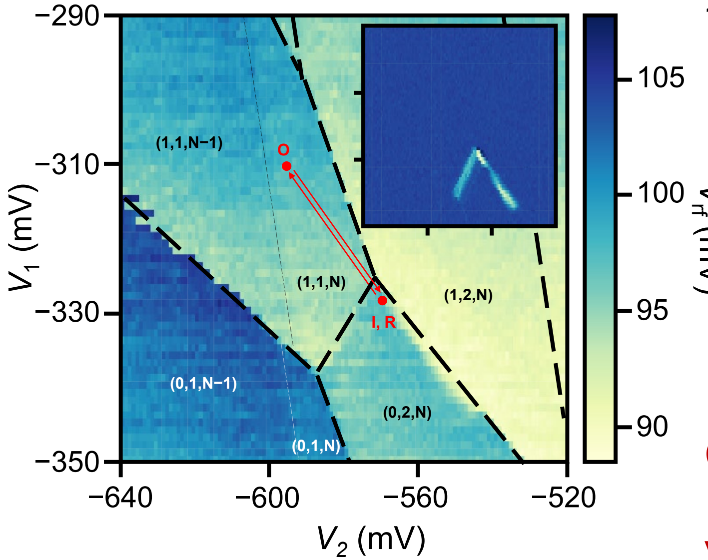
Results: Moving to silicon

First ST qubit in ^{28}Si/SiGe – two-layer device

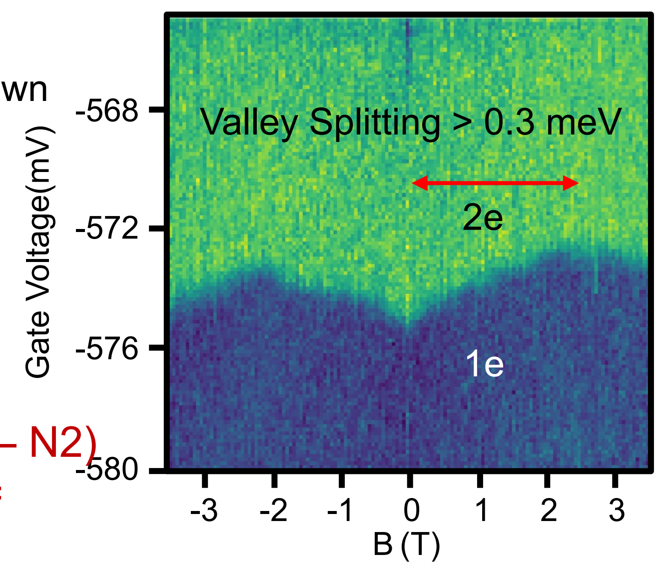




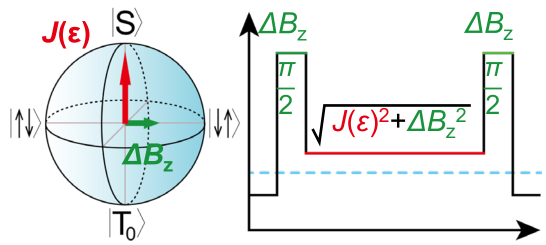




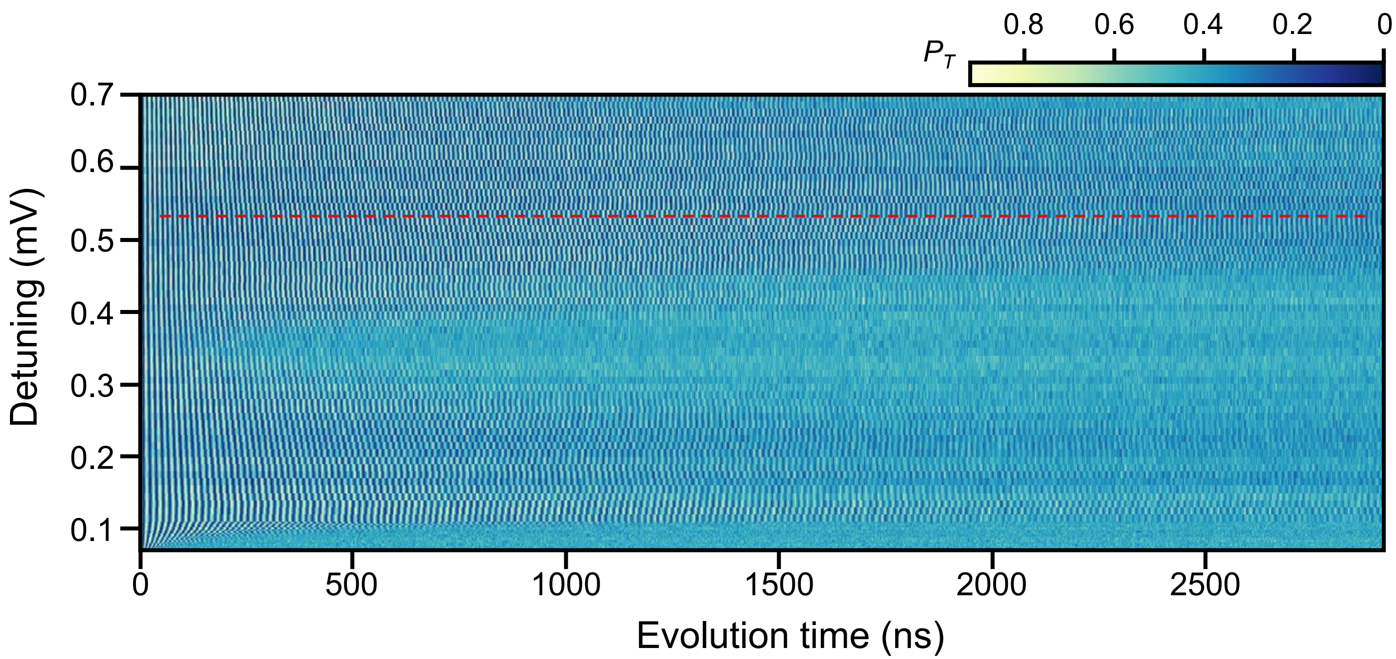
Chemical potential (N1 – N2)
: 변곡점이 ST splitting =
Valley splitting

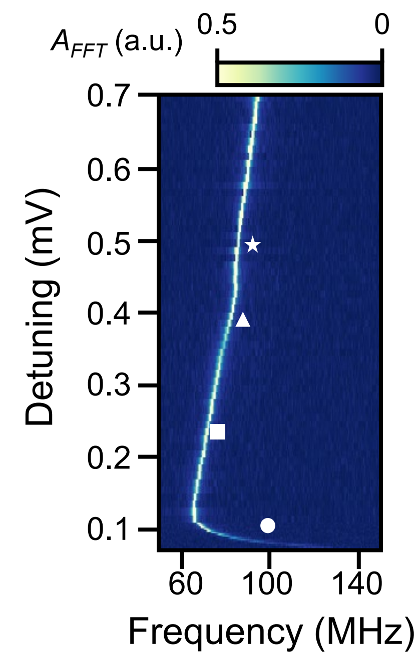


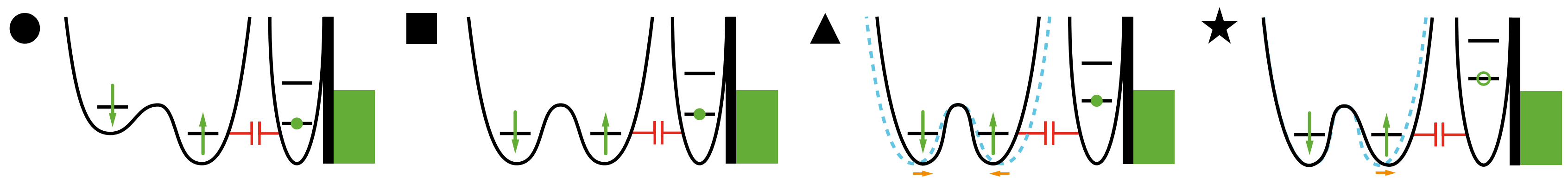
ST qubit in ^{28}Si/SiGe – coherent oscillations



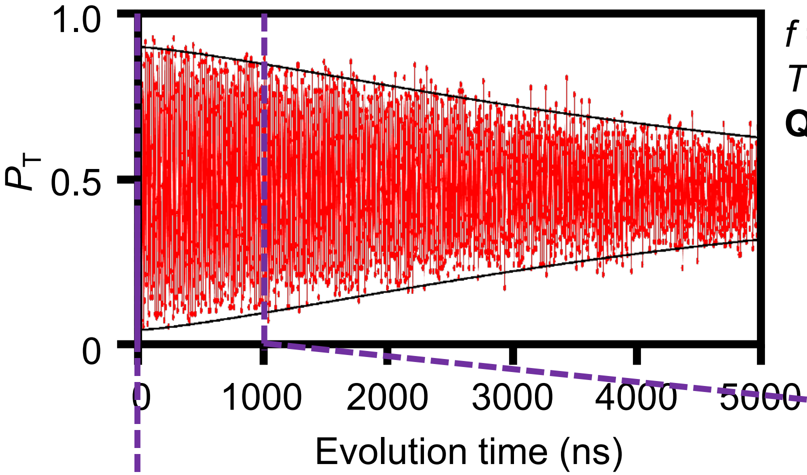
- 2022 ^{28}Si 스핀 큐비트 : two-layer 소자. 공정 + 측정 능력 향상으로 Singlet-Triplet qubit, two single spin qubit 동작성공



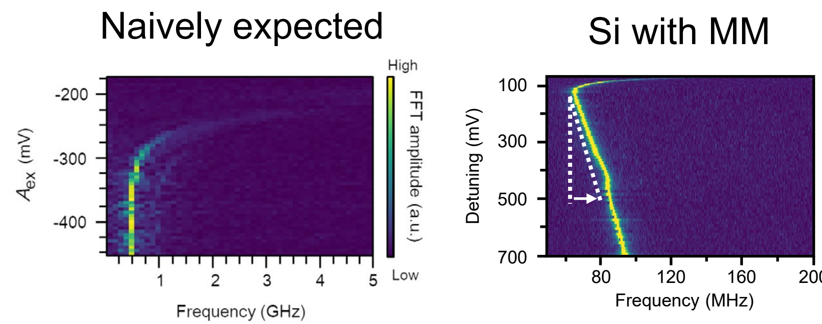




ST qubit in ^{28}Si/SiGe – without feedback

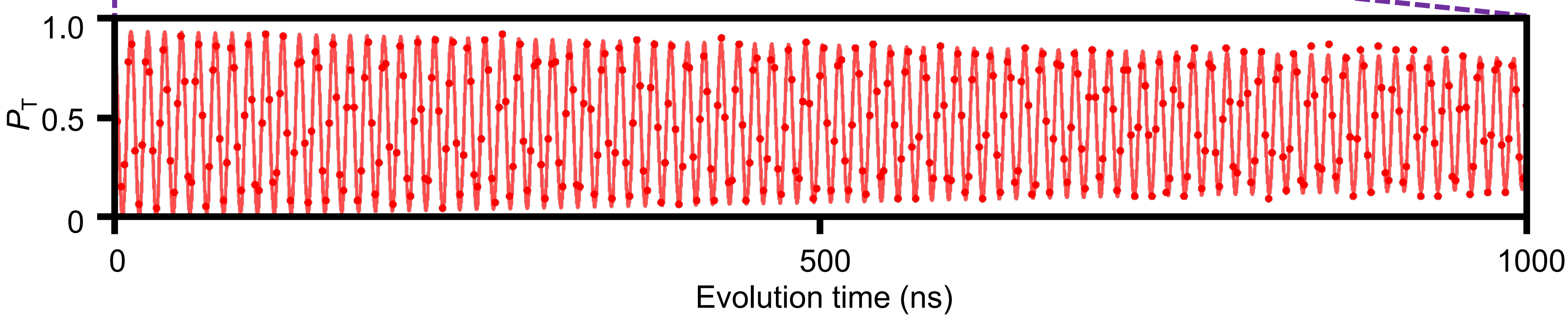


f = 122.6 MHz
T_2^* = 4.8 μs
Q = 589



npj. Quantum Inf. **6**, 64 (2020)

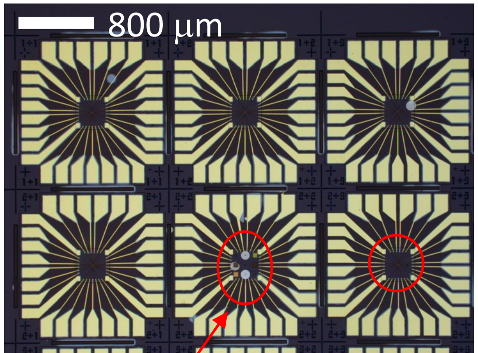
Spin-electric coupling



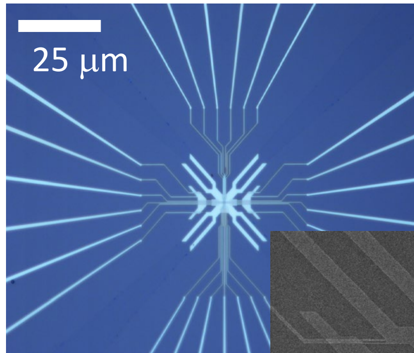
δV → QD position Shift → δ(ΔdB) : Charge noise couples to spin qubit frequency – 마그넷 design, field gradient 최적화 필요

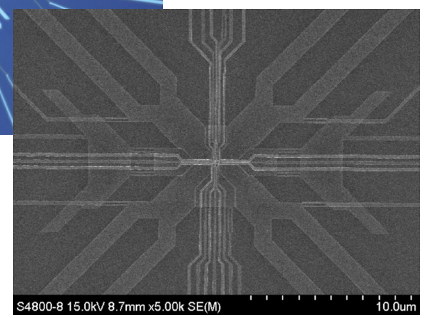
SNU team : New design 5년 과제의 마지막 버젼

Overlapped gate structure: Decent fab. yield (> 70%), 2023 년: Si 스핀 큐비트 5개 얽힘 상태 구현 목표

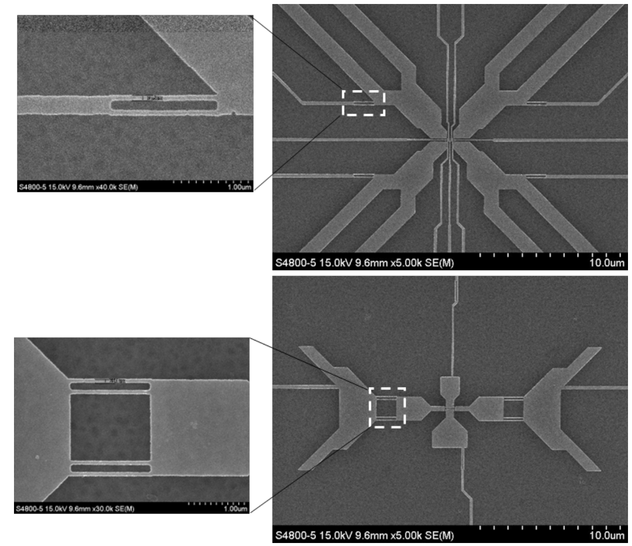


Chip 6개당 하나는 e-beam focus 용 희생양

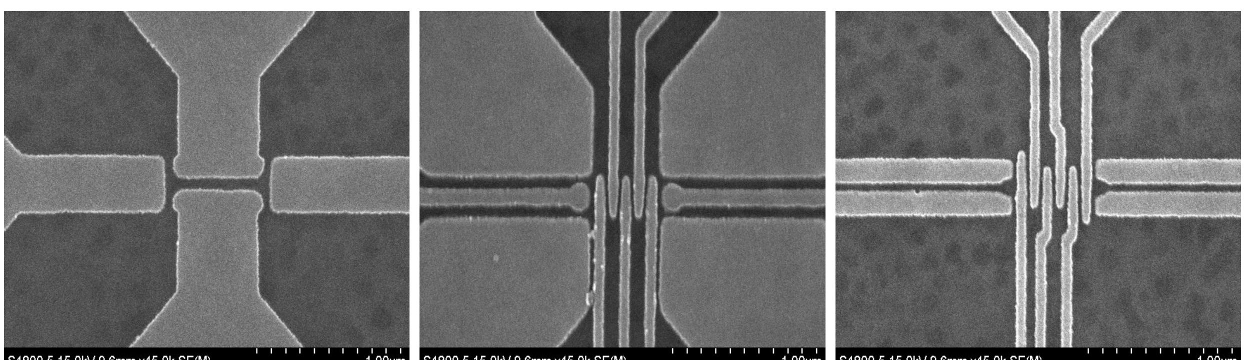


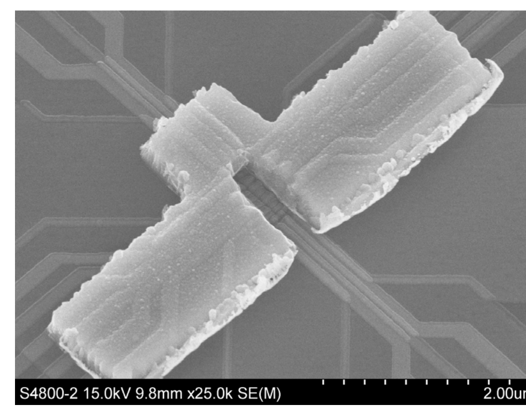


기생 cap 최소화 용 screening gate



1st 2nd 3rd



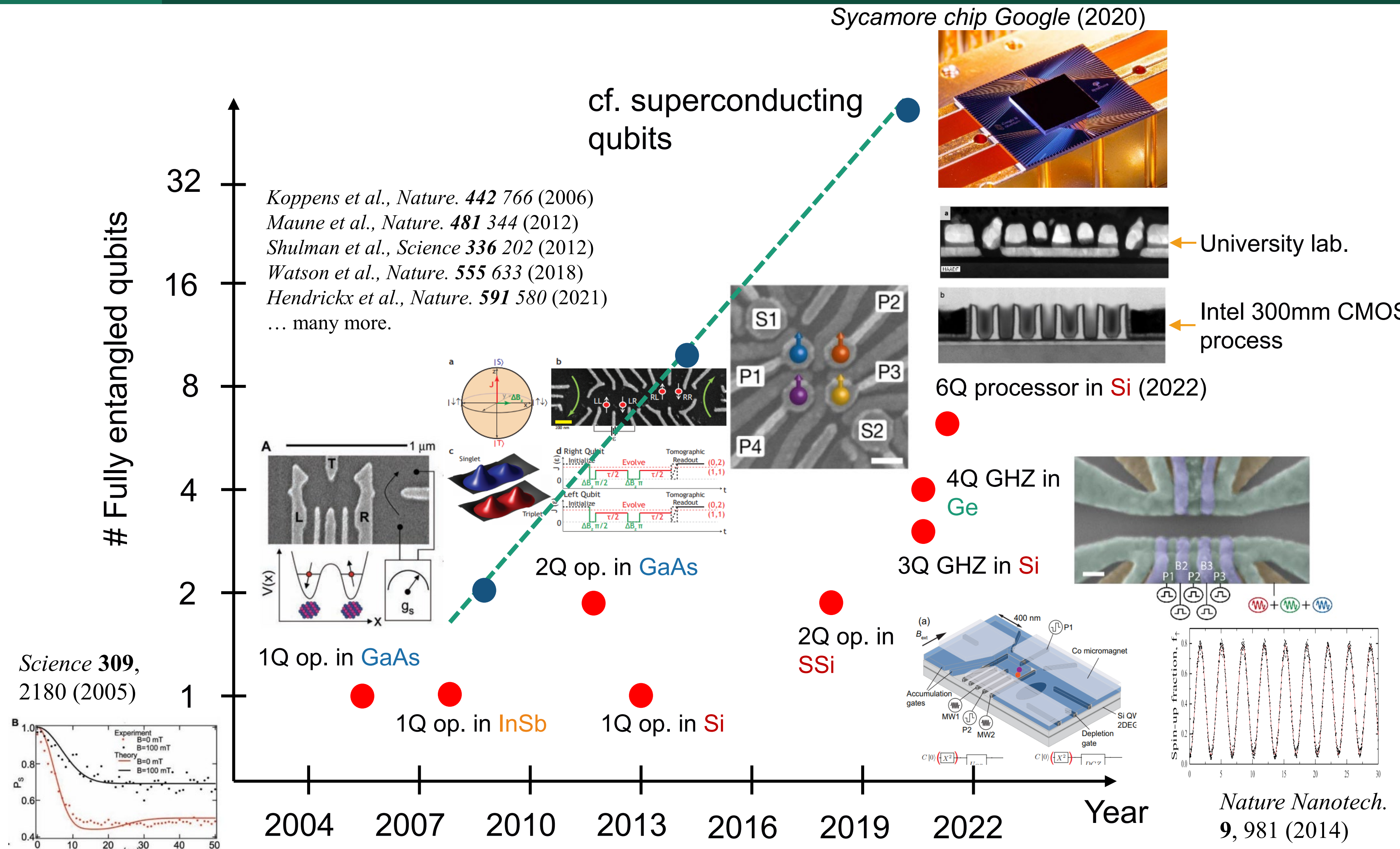


D. Esposti et al. *Appl. Phys. Lett.* **120**, 184003 (2022)

4

State of the art in single-spin qubits

Recent developments of QD-based QC



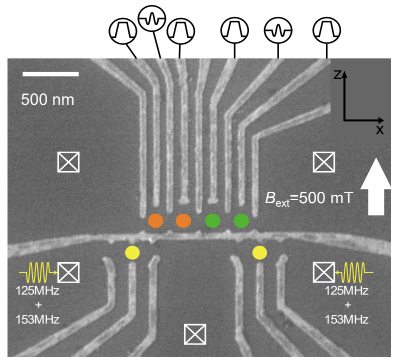
N. P. de Leon, Kohei M. Itoh, Dohun Kim, Karan K. Mehta, Tracy E. Northup, Hanhee Paik, B. S. Palmer, N. Samarth, Sorawis Sangtawesin, D. W. Steuerman "Material challenges and opportunities for quantum computing hardware" - *Science*. **372**, 253 (2021) Review paper

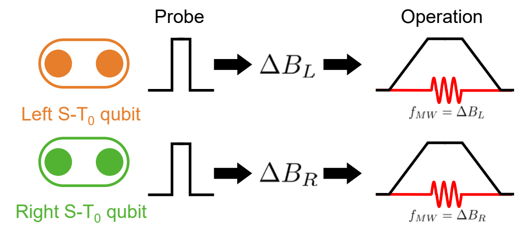
4

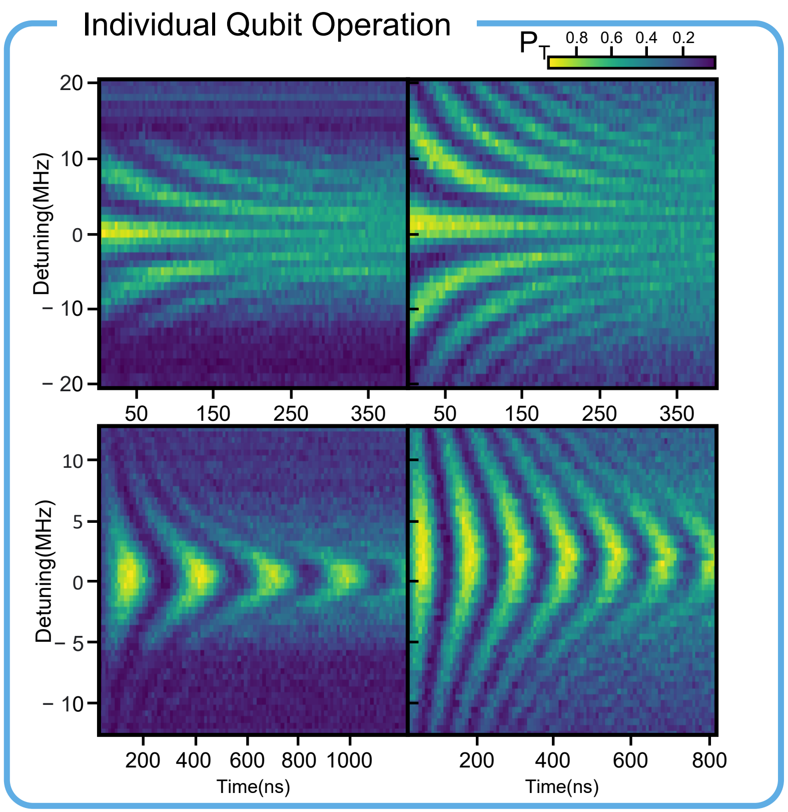
Recent contributions by SNU group

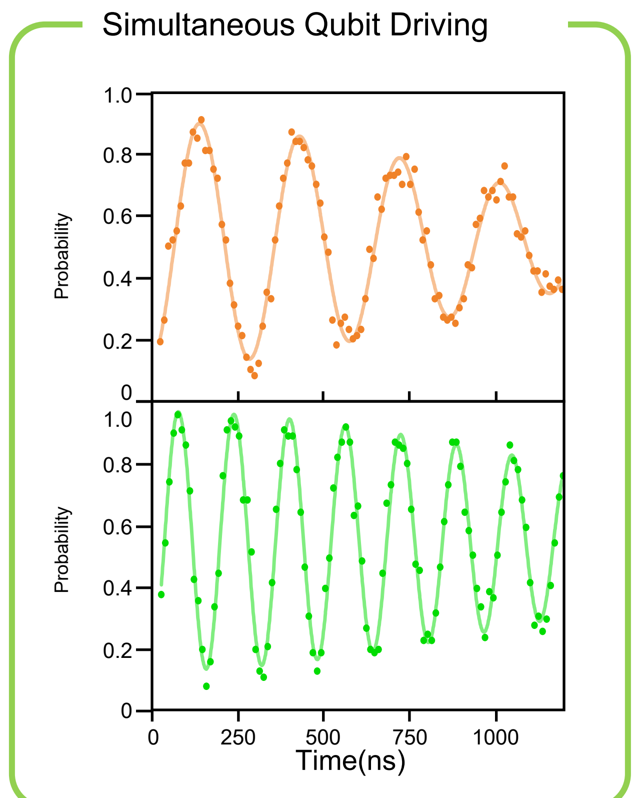
Two ST_0 qubits: Simultaneous Hamiltonian Parameter Estimation

Manuscript in preparation





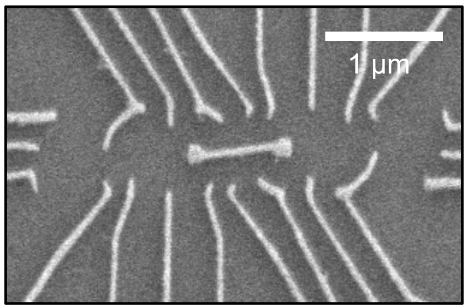




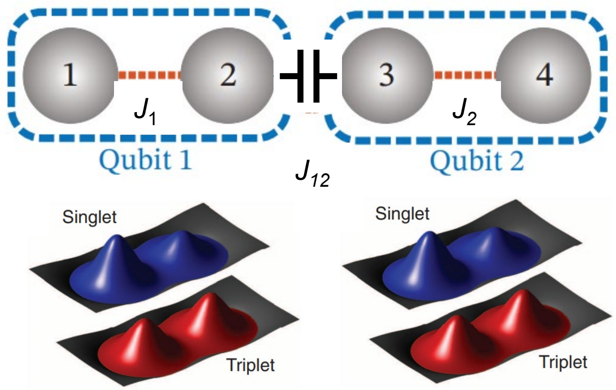
Two qubit interaction

Two qubit gate in two STQs

1. Dipolar interaction - Capacitive : possible but often slow



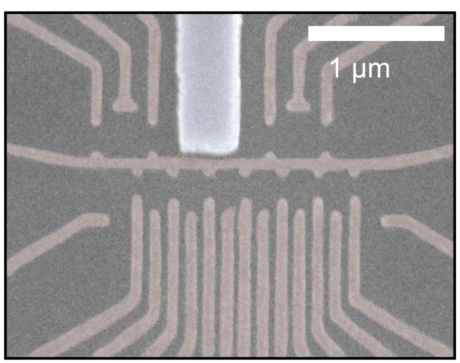
Harvard, *npj. Quant. Inf.* (2017)

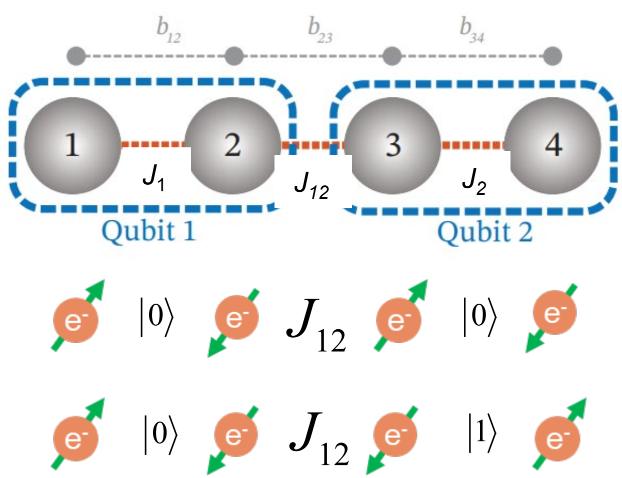


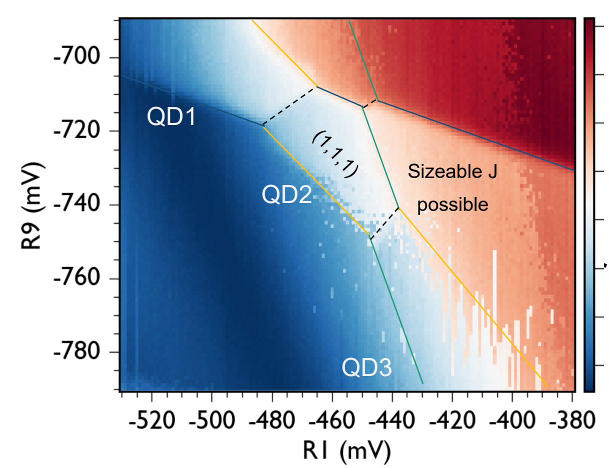
Interaction assumed to be small $\propto A(r)J_{12}J_{34}$

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

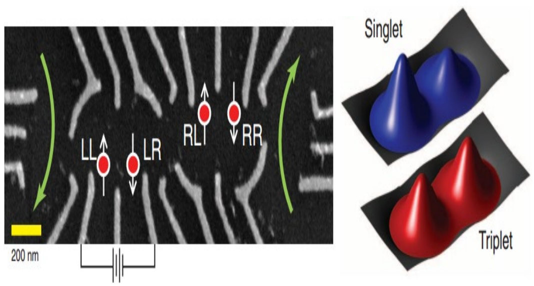
2. Inter Q exchange coupling : intrinsically fast, but leakage

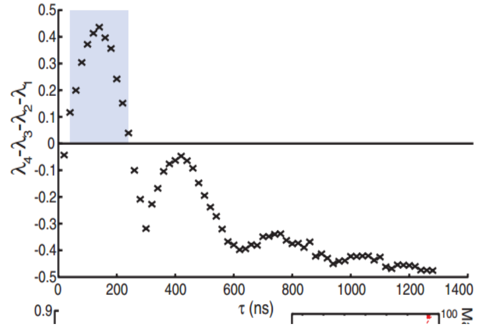


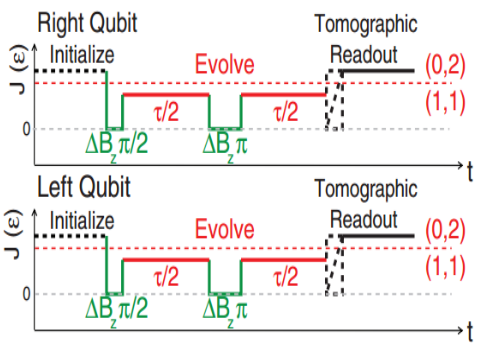


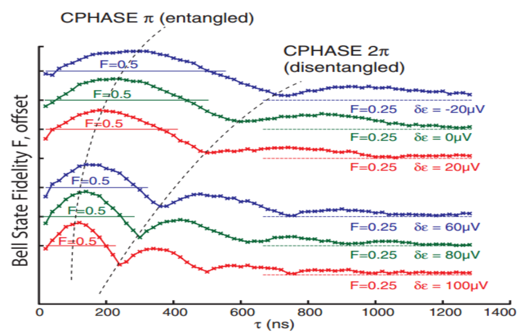


Previous entanglement demonstration

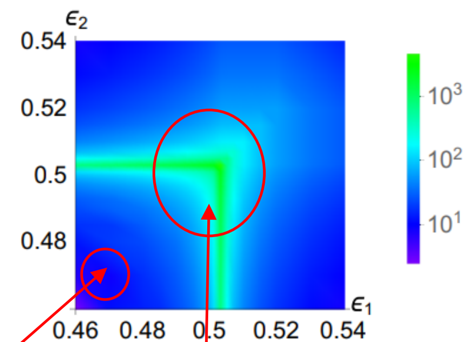








Theory of J_{12}/J_1J_2



vs.

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

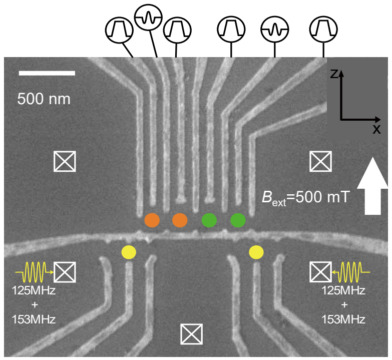
J_{12} ~ 3 MHz @ J_1, J_2 = 300 MHz ($J_{12} \sim J_1J_2$, bilinear), CZ gate fidelity ~ 70 %

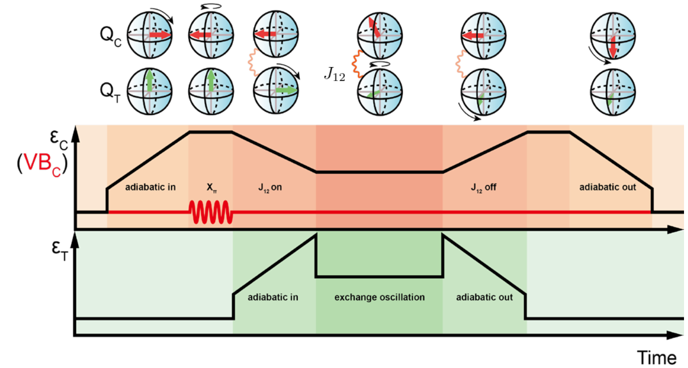
4

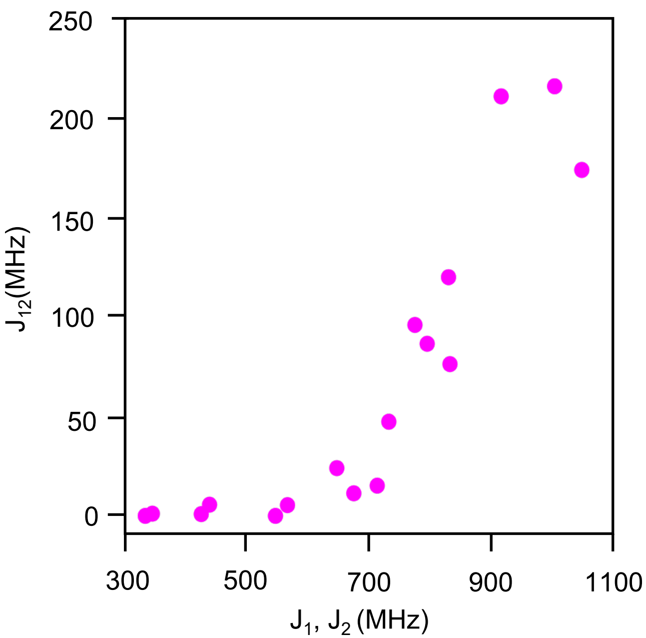
Recent contributions by SNU group

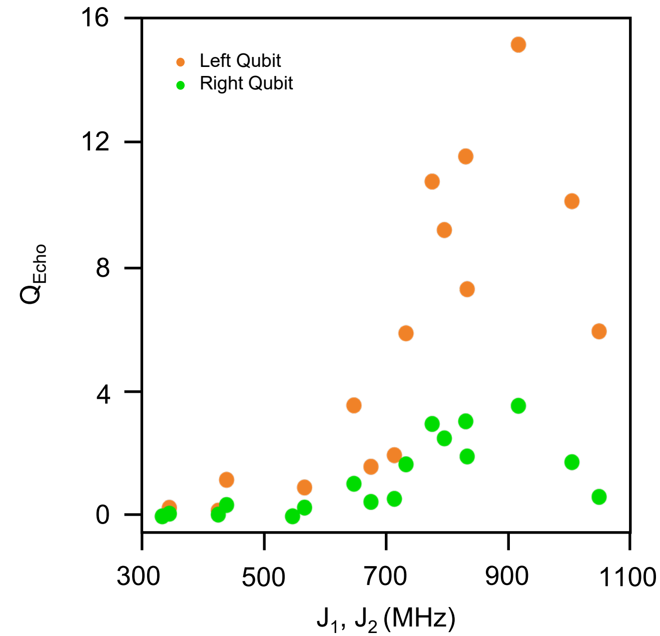
Strong capacitive coupling regime

Manuscript in preparation







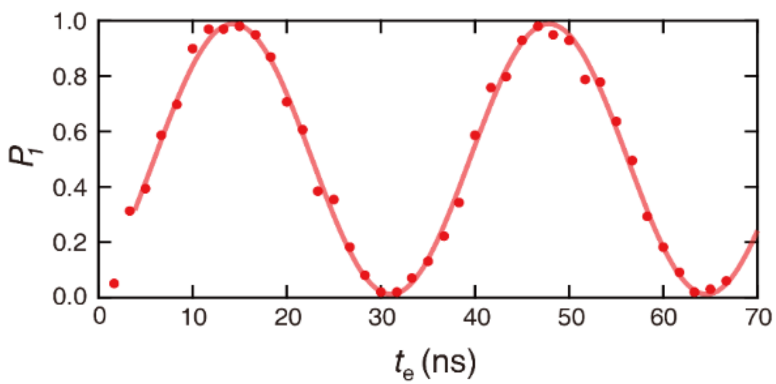


J_{12} ~ 220 MHz (> 20% of J_1, beyond bilinear regime, CZ gate fidelity > 90 %

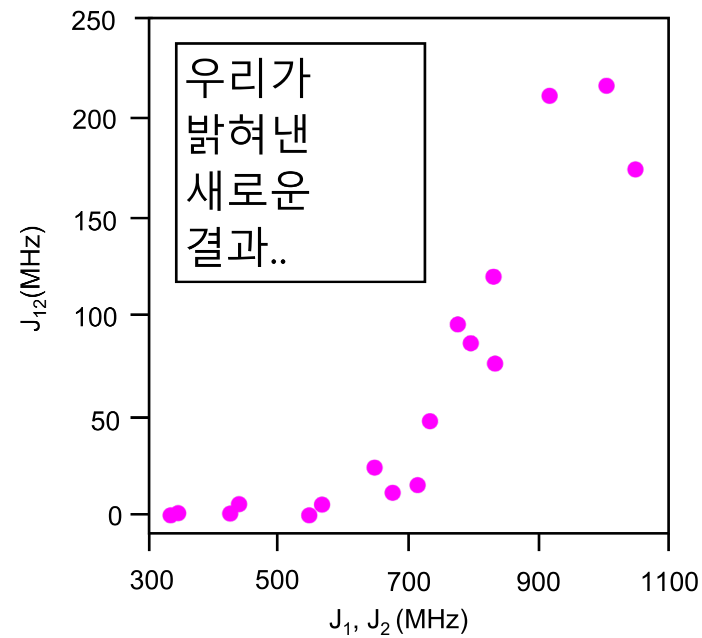
Summary of Lecture 2

Single spin qubit, Singlet-Triplet qubit

반도체 큐비트의 quality 도 이제는 다른 플랫폼에 못지 않게....



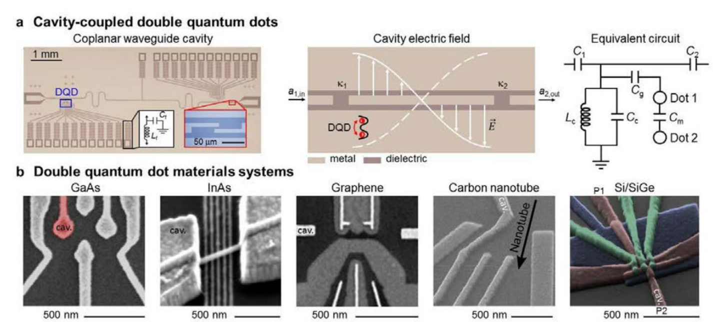
Capacitive coupling can be strong.



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)