# Towards Quantum Computing Devices based on High-$T_c$ Superconductor and Topological Insulator

Jonghyun Song

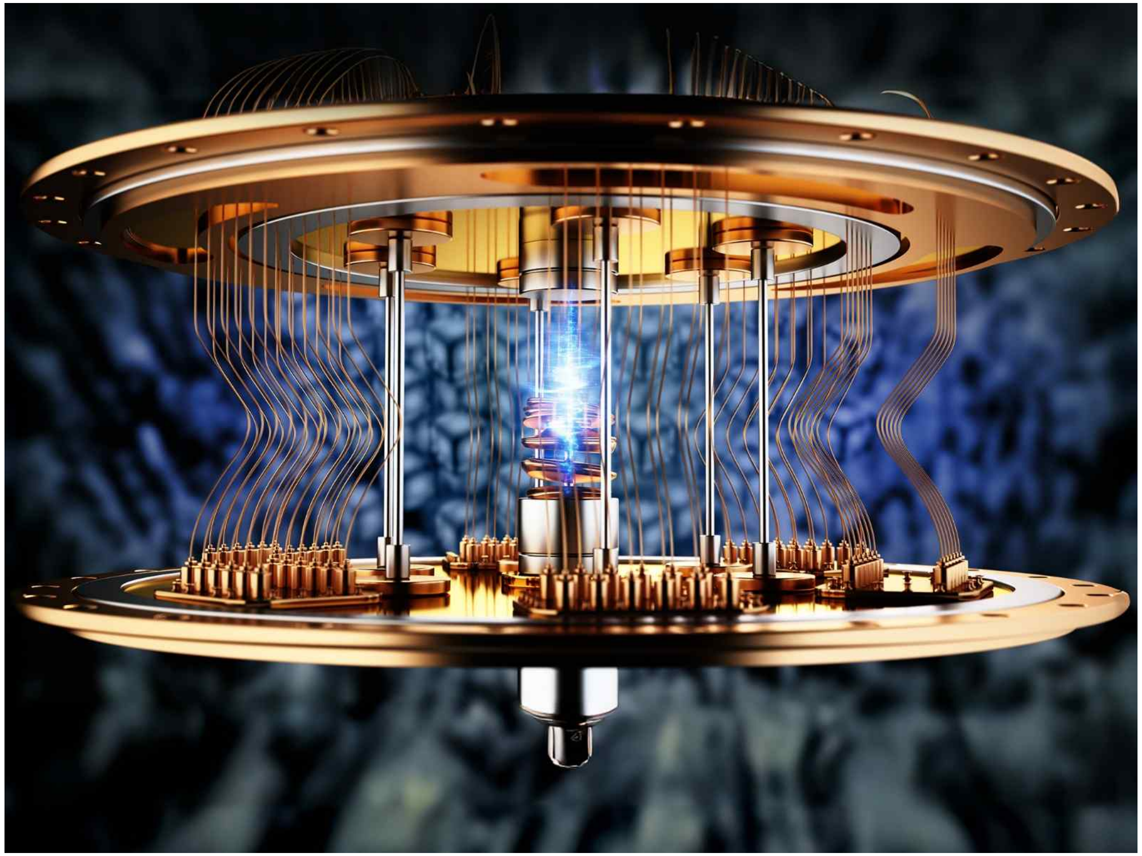
Department of Physics, Chungnam National University, Daejeon 34134, Republic of Korea

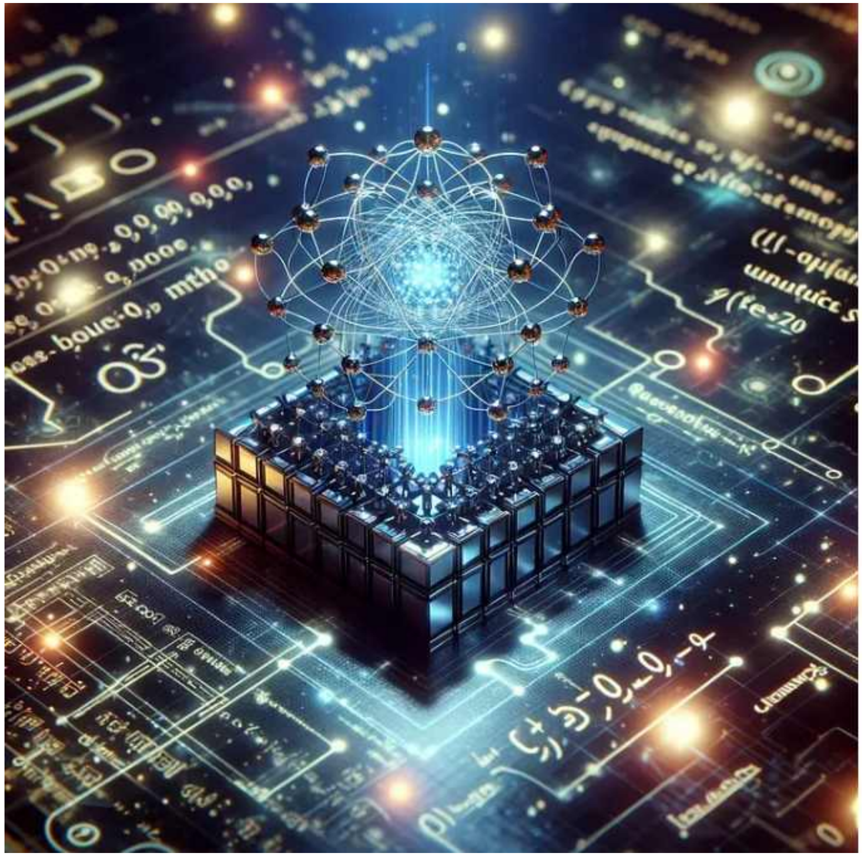
SOLID
Spintronics & Oxide lab. for Interface Device

# Outline

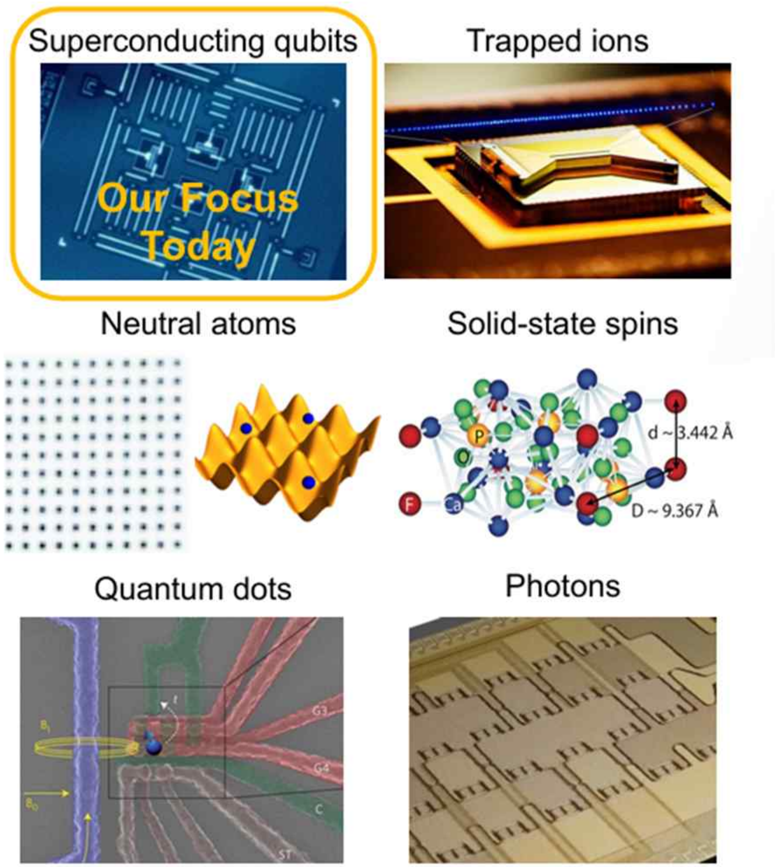
- Quantum Computing
- Superconducting Qubits
  - ✓Josephson Junction
  - ✓Transmon Qubits
- Toward to the High-Temperature Superconductor(HTS) Qubits
  - ✓s-wave and d-wave Superconductors
  - ✓HTS and Topological Insulator
- YBCO Epitaxial Thin Film Growth
- YBCO Josephson Junction
- YBCO 5 GHz Resonator Fabrication
- Summary

# Quantum Computing





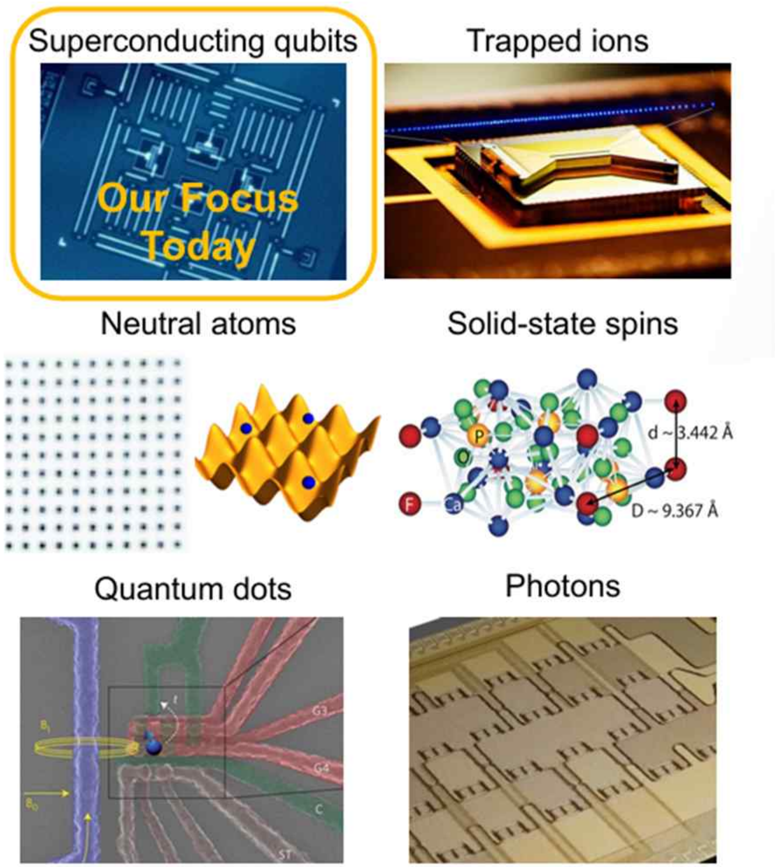
# Quantum Computing



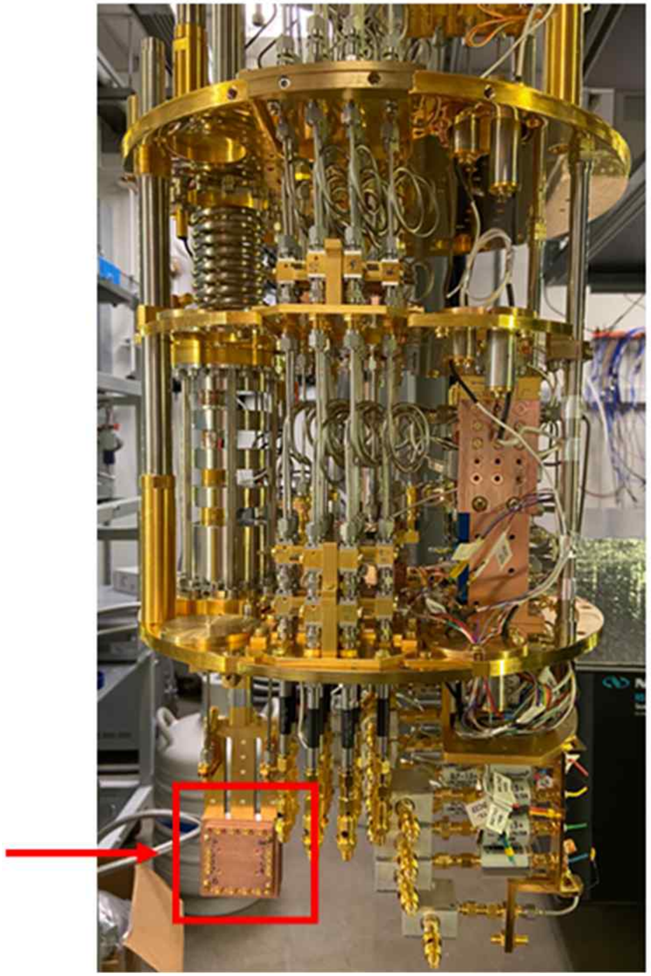

**Superconducting Qubits**

- Fast Gate Speeds
- Scalability Based on Direct Fabrication (using standard semiconductor lithography processes)
- High-Precision Control

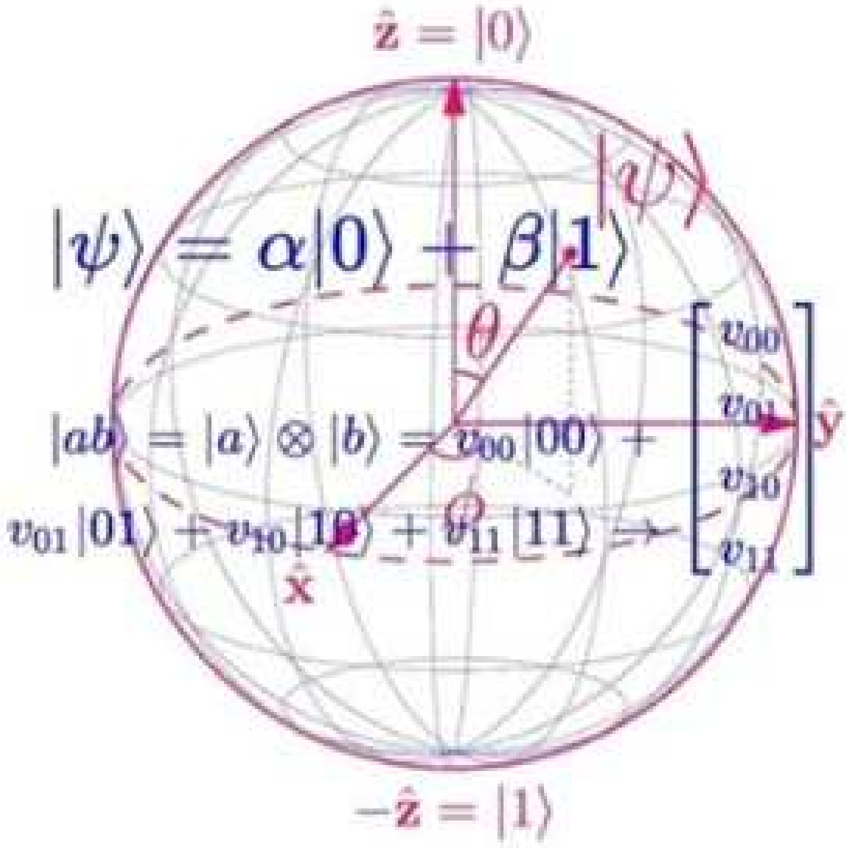
# Quantum Computing



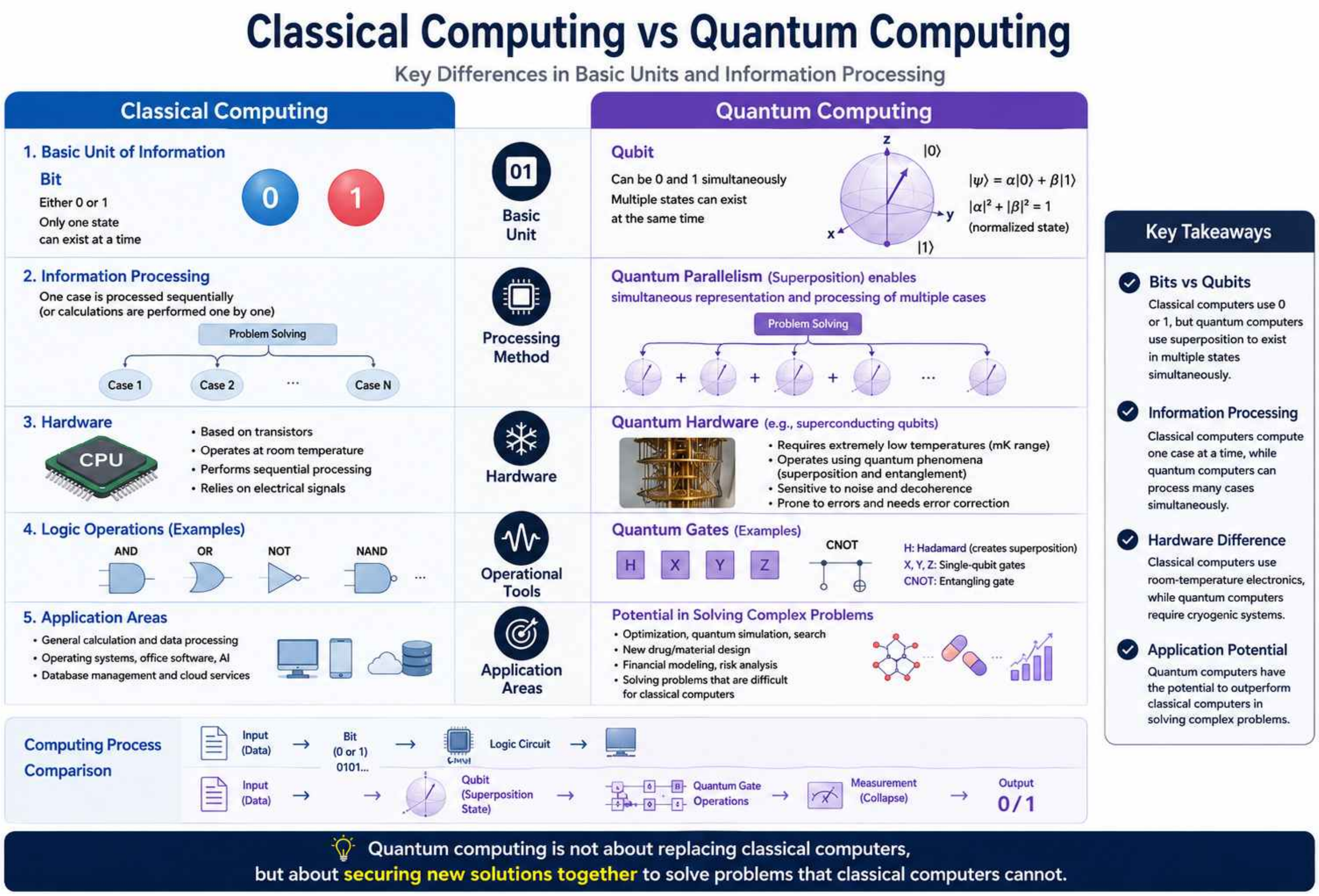

Supercondcutor qubit ≈ 10 mK



# What is the Quantum Computing & Qubits?

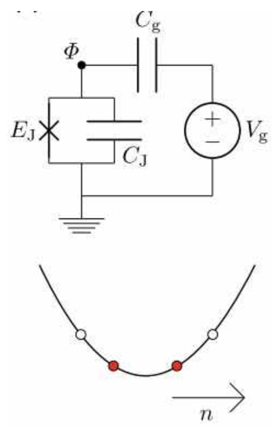
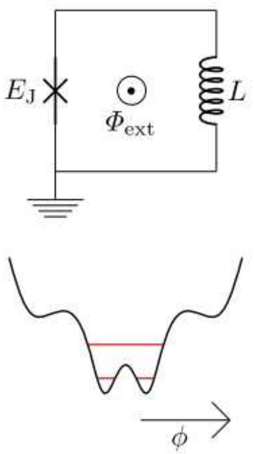
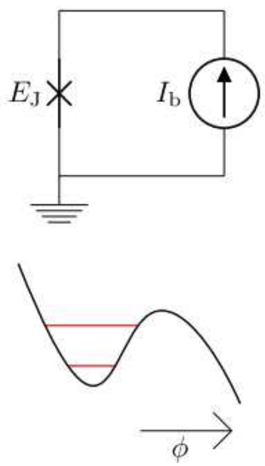


# 일반 컴퓨팅 vs 양자 컴퓨팅

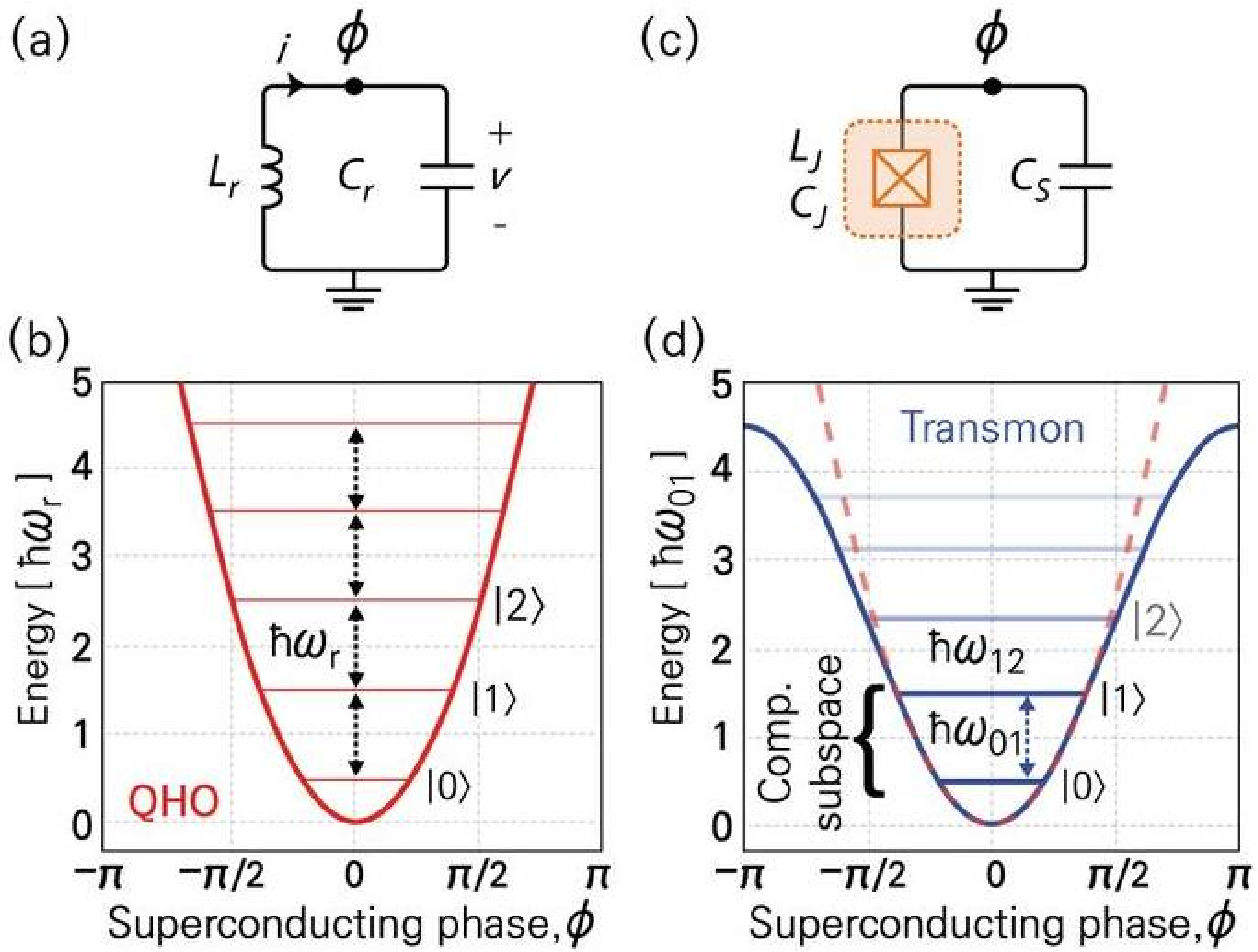


# Superconducting Qubit?

Josephson Junction + Capacitor + Inductor + Superconducting loop

| charge qubit | flux qubit | phase qubit |
| --- | --- | --- |
|   Josephson junction + capacitor |   Josephson junction + superconducting loop |   Josephson Junction + bias current |

# Superconducting Qubit?

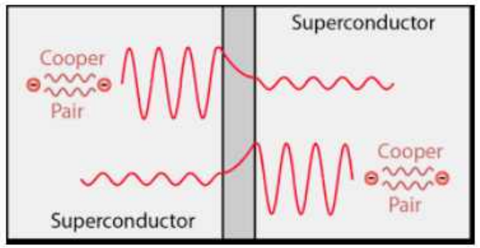



Josephson Junction

# Josephson Junction

- Theorized by Brian Josephson in 1962,experimen tally realized the following year.
- Josephson junctions consist of two or more super conductors coupled by a weak link .
- Characterized by the quantum tunneling of super conductive Cooper pairs , which are pairs of elec trons with total spin zero.
- Employed in a several cutting-edge applications s uch as
  - Superconducting quantum computers
  - (Qubits)
  - High-sensitivity devices (SQUIDs)
  - Quantum simulations

Nobel Prize (1973).
"For his theoretical predictions of the properties of a supercurrent through a tunnel barrier, in particular those phenomena which are generally known as the Josephson effect“




Scheme of a superconductive Josephson junction

# Josephson Junction

The gas of **Cooper pairs** can be described by a macroscopic wavefunction

$$\Psi(\vec{r},t) = \underbrace{\sqrt{N_L(t)}e^{i\varphi_L(t)}}_{\psi_L(t)}\phi_L(\vec{r}) + \underbrace{\sqrt{N_R(t)}e^{i\varphi_R(t)}}_{\psi_R(t)}\phi_R(\vec{r}) \quad (1)$$

whose time-dependent parts obey the following coupled equations

$$\begin{cases} i\hbar\partial_t\psi_L(t) = U_L\psi_L(t) + K\psi_R(t) \\ i\hbar\partial_t\psi_R(t) = U_R\psi_R(t) + K\psi_L(t) \end{cases} \quad (2)$$

where $U_L = -U_R = eV$ depends on the electrical charge $e$ and the external potential $V$, while $K$ is the coupling energy (tunneling energy).

# Josephson Junction

Subtracting the first equation the second one in Eq.(2) and separeting the real part from the imaginary part, one can obtain the **Josephson equations**[2]. These equations are given by

$$\begin{cases} I(t) & = I_c \sin\varphi(t) \\ \frac{d\varphi}{dt} & = \frac{2e}{\hbar} V \end{cases} \tag{3}$$

where $\varphi(t) = \varphi_L(t) - \varphi_R(t)$ is the phase difference, which is called **Josephson phase**, $I_C$ is the critical current, defined as

$$I_c \equiv \frac{4}{\hbar} Ke\sqrt{N_L(t)N_R(t)} \simeq \frac{2}{\hbar} KeN \tag{4}$$

since in superconductors $N_L(t) \simeq N_R(t) \simeq N/2$ and the electric current is given by

$$I = e[\dot{N}_L(t) - \dot{N}_R(t)]. \tag{5}$$

# Josephson Junction

Josephson predicted two main effects from the Josephson equations, namely:

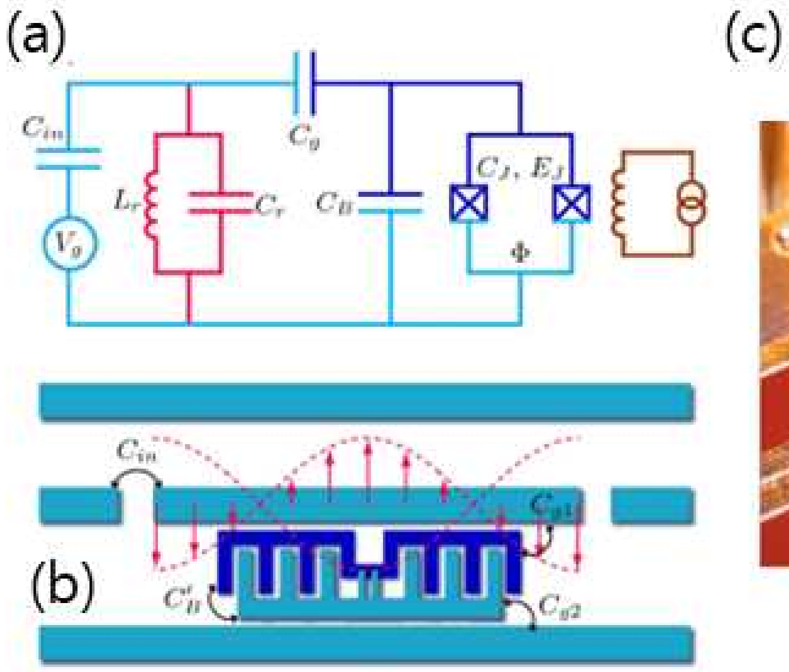
- **DC Josephson effect**: In the absence of an external potential $V$, there is still a direct current $I$ proportional to the sine of the Josephson phase $\varphi(0)$:

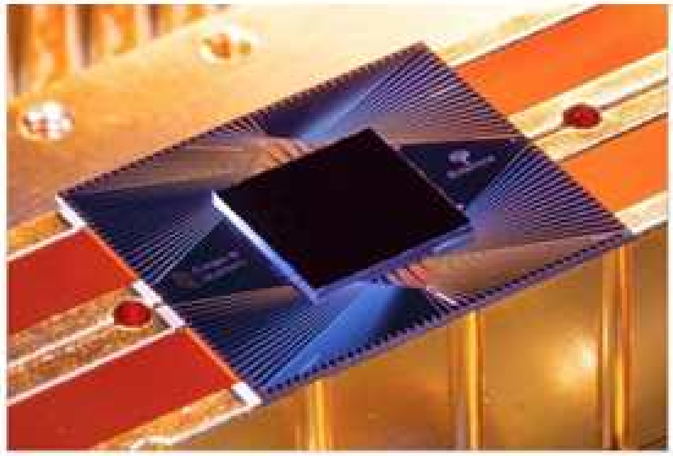
$$V = 0 \implies I = I_c \sin \varphi(0) \tag{6}$$

- **AC Josephson effect**: In the presence of a constant external potential $V$, there is a sinusoidal alternating current:

$$V = V_0 \implies I(t) = I_c \sin\left(\frac{2eV_0 t}{\hbar} + \varphi(0)\right) \tag{7}$$

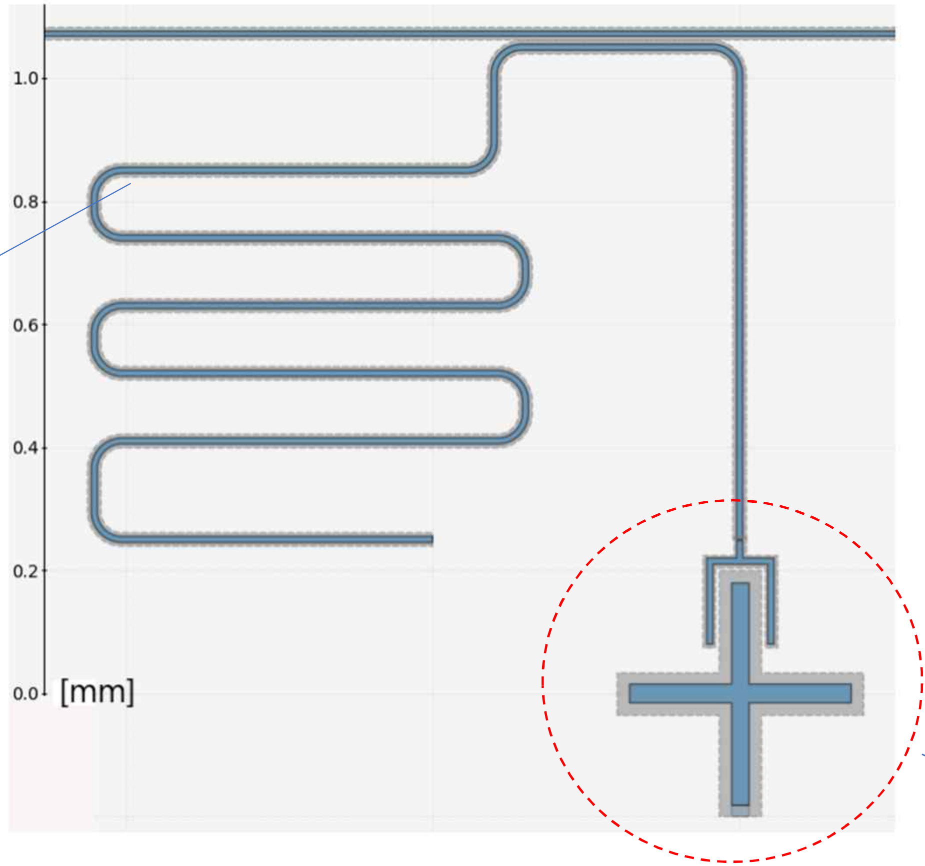
# Transmon Qubit: Superconducting Quantum Bit (IBM and Google)



Sycamore (Google)

# Transmon Qubit: superconducting quantum bit (IBM and Google)




CPW(Coplanar Waveguide) Resonator

Transmon  Qubit

**Transmon Qubit**

- 기존 Charge qubit에 Shunt capacitor를 병렬연결하여 $E_J/E_C$을 높임으로서 Charge noise를 극복하여 Coherence time을 증가시킴.

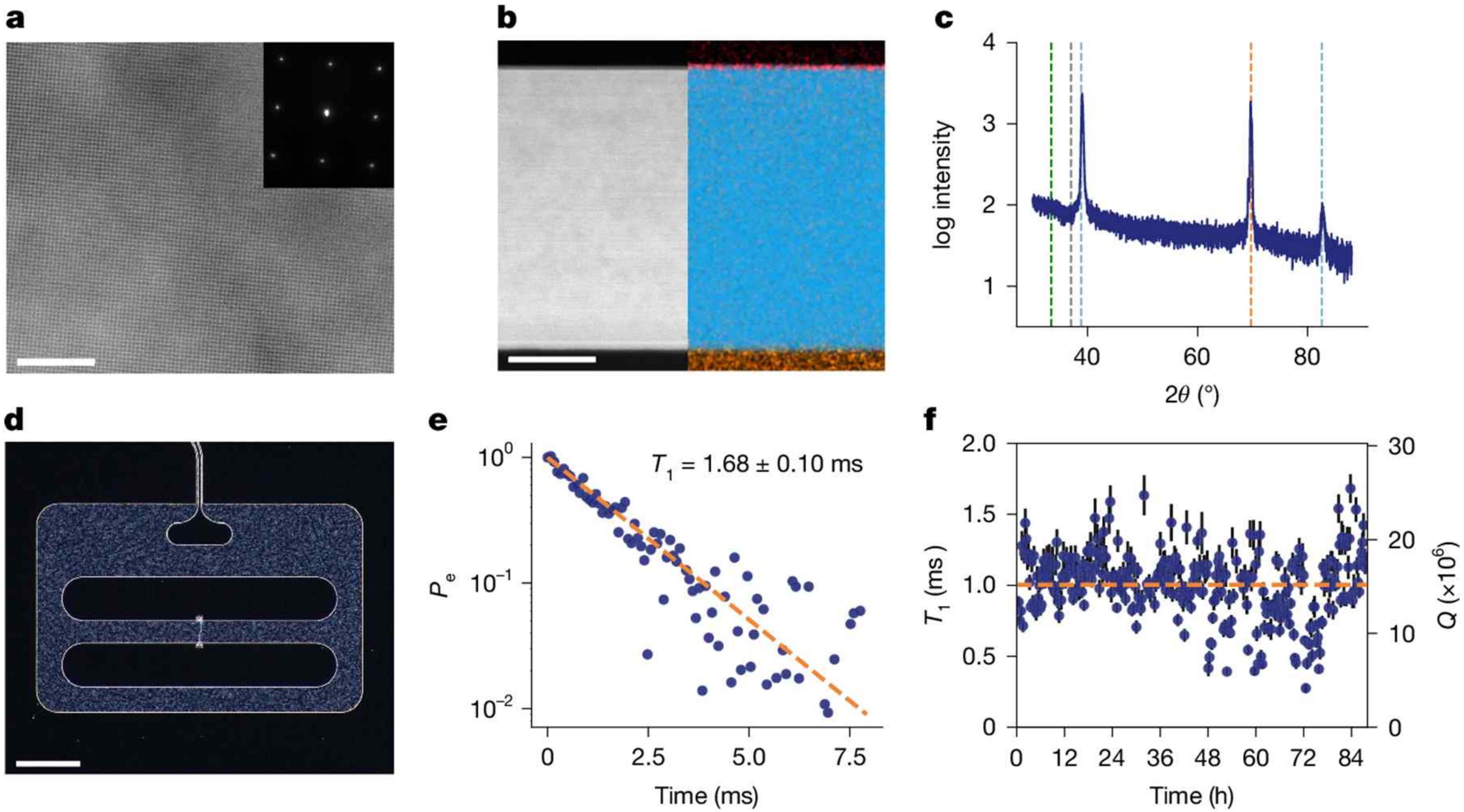
- Ec를 낮춤으로서 Anharmonicity가 줄어들어 오류가 발생하기 쉬움.
- 알루미늄 기반 초전도체 특성상, Thermal excitation를 막기 위해서 10 mK 수준의 극저온 환경필요.
- Charge noise는 극복했으나, 유전체 손실 및 quasiparticle로 인한 decoherence는 여전히 존재

# Transmon Qubit

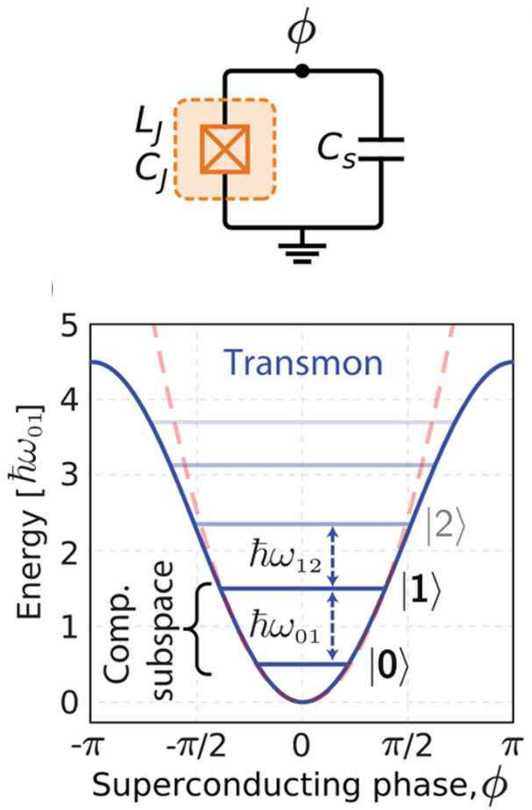
| 목표구분 | 단위 | 세계최고수준 (보유국/기관) 성능수준 | 국내기술수준 (보유기관) 성능수준 | 기술개발 목표치 | 목표달성 검증방법 |
|---|---|---|---|---|---|
| 조셉슨 접합 임계전류 | uA | 6.4 μA @ 4.2 K (미국/IBM) | 0.8 μA @ 70 mK (POSTECH) | **> 5 μA @ 20 K** | 목표 온도에서 임계전류 측정 |
| 조셉슨 접합 동작온도 | K | ~ 70 K (이스라엘 Technion) | < 1 K (POSTECH) | **< 20 K** | 온도별 임계전류 측정 |

# Materials Improvement (Ta-Si)

Bland, Matthew P., et al. "Millisecond lifetimes and coherence times in 2D transmon qubits." *Nature* (2025): 1-6.



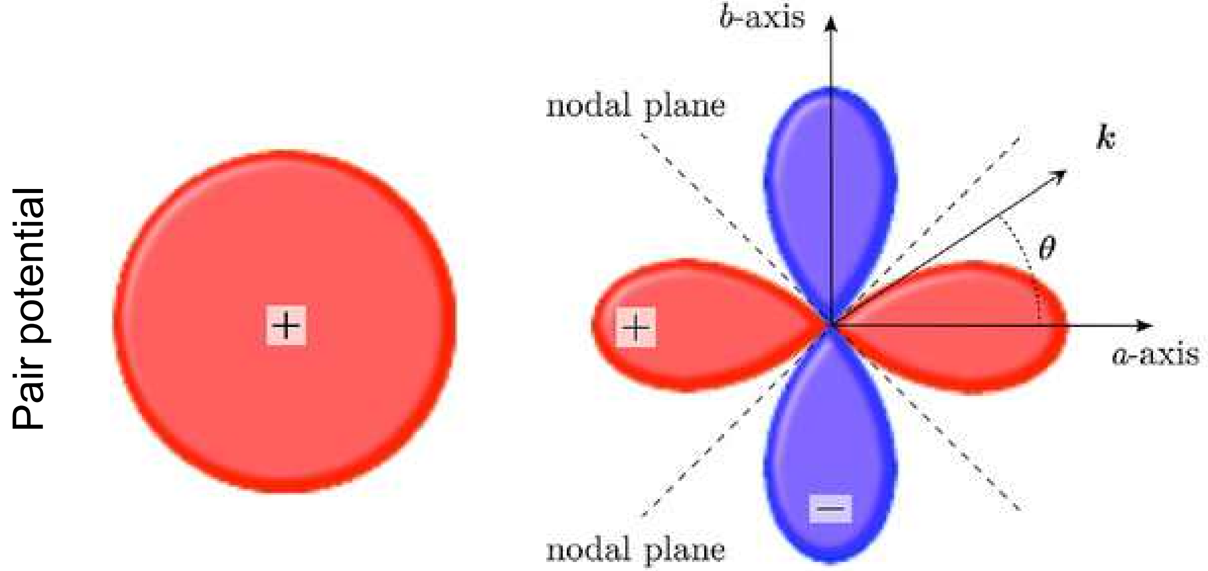
# High-Temperature Superconductor Qubit




$$\hbar w_{01} = E_1 - E_0 \approx \sqrt{8E_J E_c} - E_c$$

$$\left(E_J = \frac{\Phi_0 I_c}{2\pi}, \Phi_0 = \frac{h}{2e}, E_c = \frac{e^2}{2C}\right)$$

# Toward to the High-Temperature Superconductor Qubits



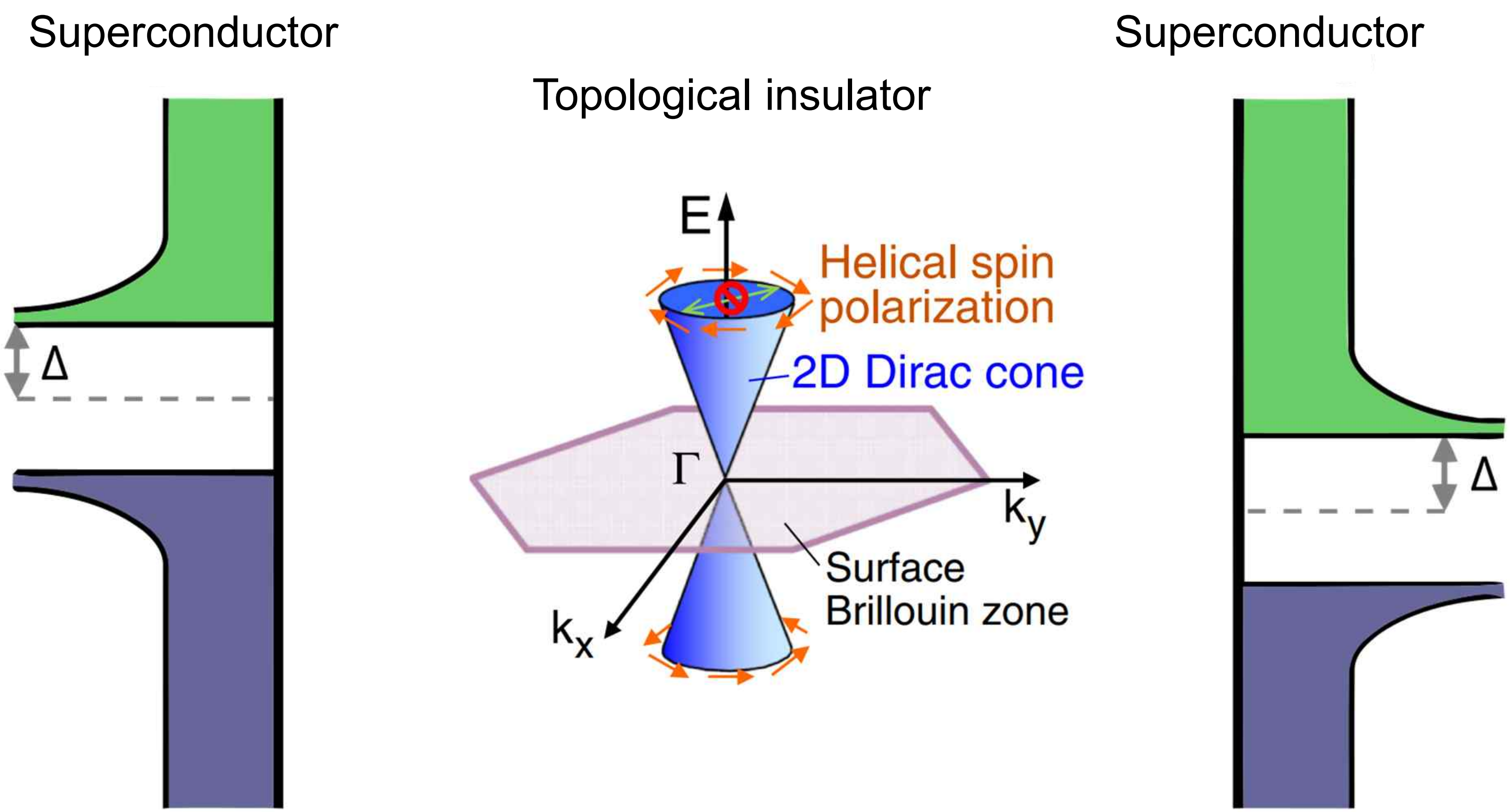

s-wave
superconductor

d-wave
superconductor

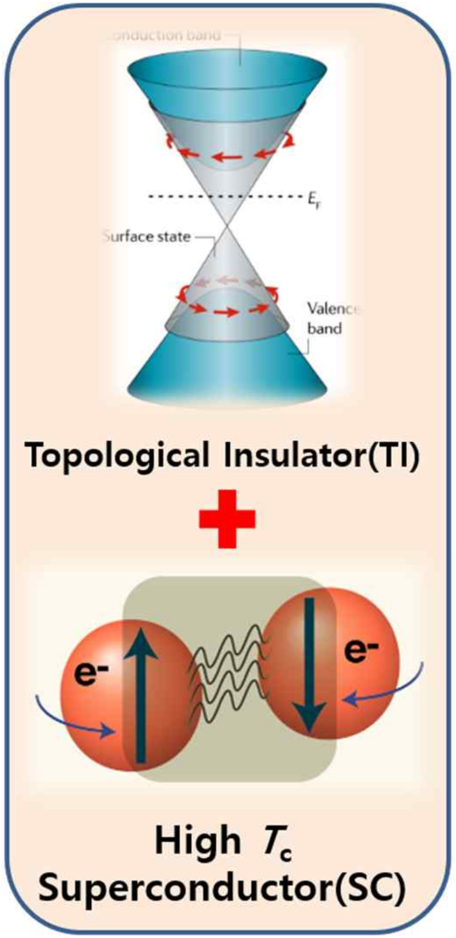
# *s*-wave and *d*-wave Superconductors

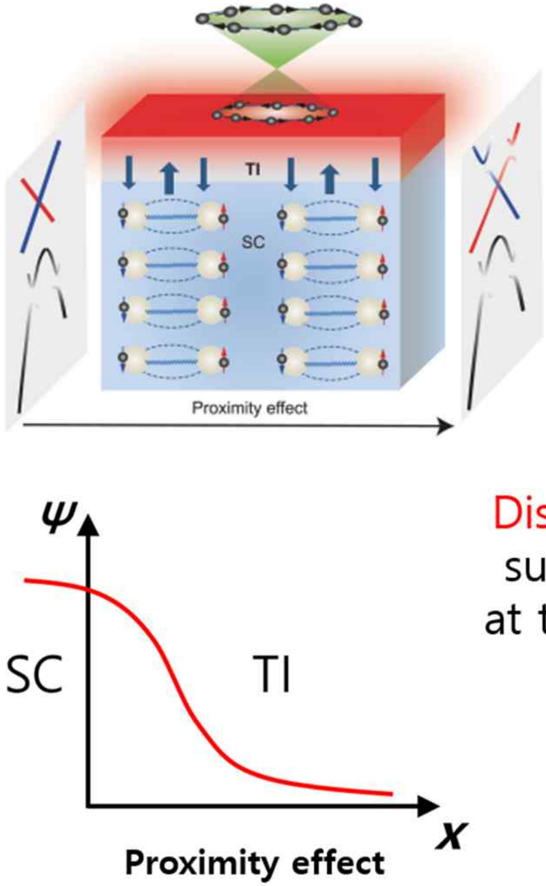
| Characteristics | *s*-wave S.C. | *d*-wave S.C. |
|---|---|---|
| Gap symmetry | Isotropic | $d_{x2-y2}$ (anisotropic) |
| Gap nodes | No | Yes |
| Energy gap | 1–3 meV | 20–40 meV (YBCO 기준) |
| Typical coherence length | 30–1000 nm | 1–3 nm (*ab*-plane) |
| Cooper pair size | Very large | Very small |
| Josephson junction Fab. | Easy | Difficult |
| Materials | Al, Pb, Nb | YBCO, BSCCO, LSCO |

# HTS Superconductor + Topological Insulator



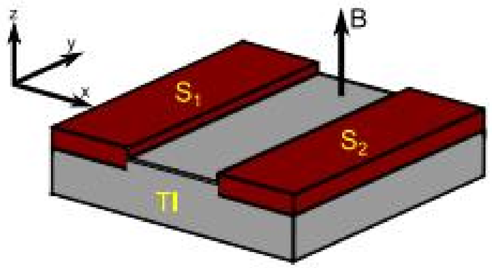
# HTS Superconductor + Topological Insulator

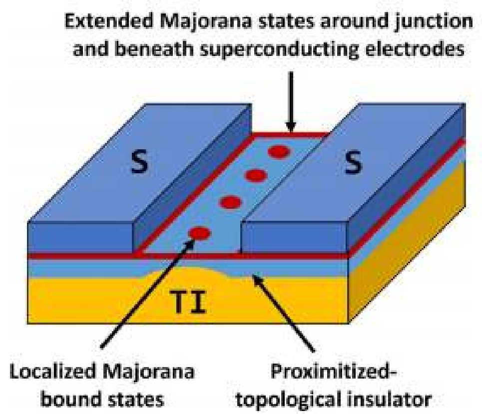


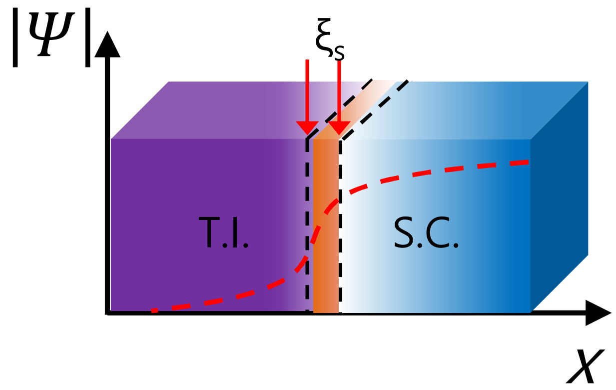



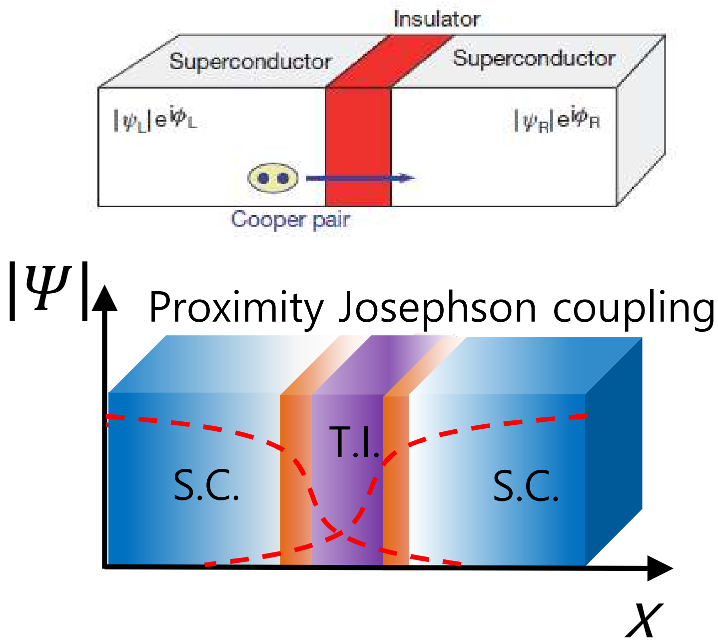

Dissipationless supercurrent at the interface

# HTS Superconductor + Topological Insulator



# *d*-wave *vs* *s*-wave in Quantum Qubits (Transmon vs Topological Platform)

## Transmon Qubit (Conventional)

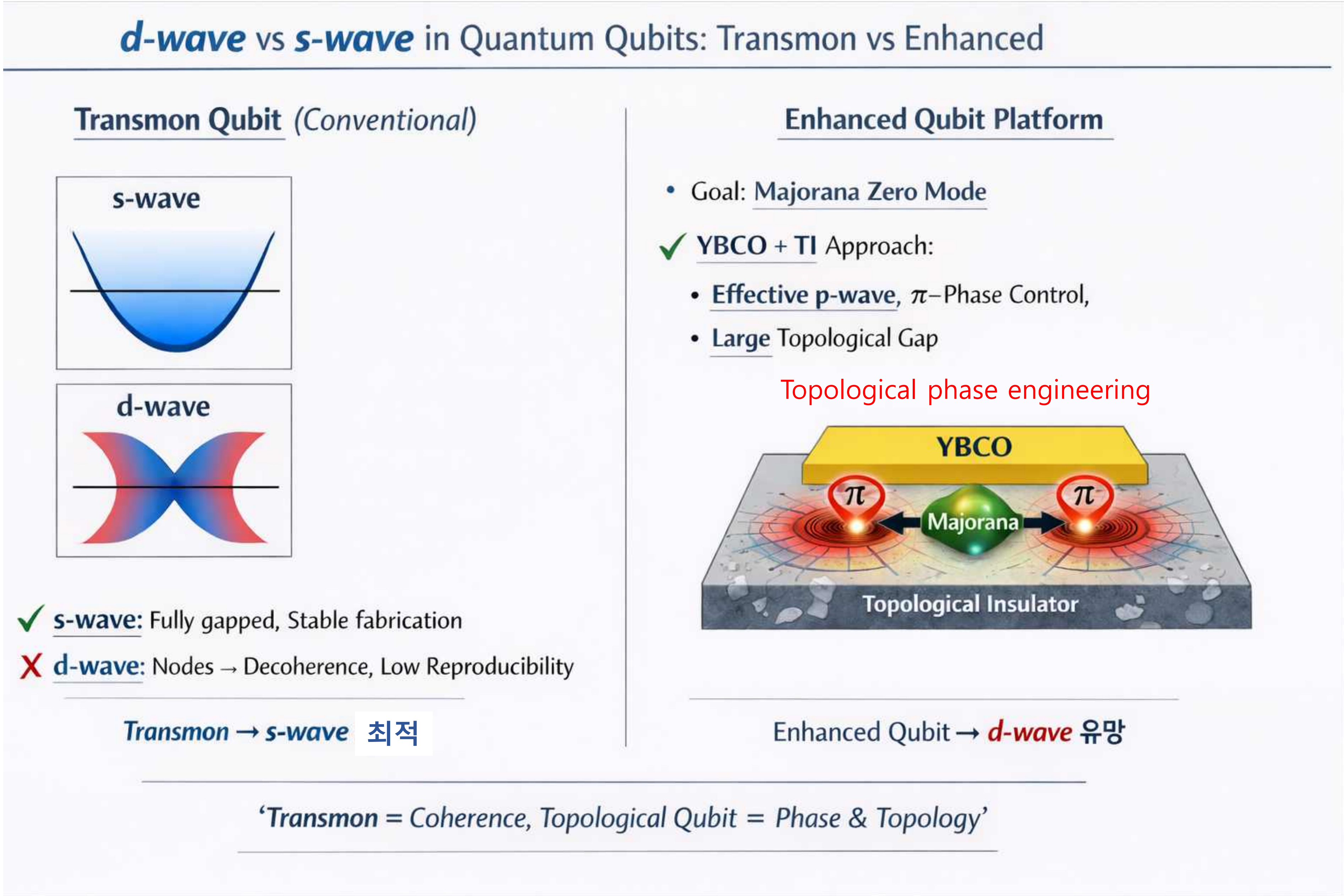
❖ s-wave superconductivity

- Fully gapped → low quasiparticles
- High coherence (T1, T2)
- Stable fabrication (Al, Nb)
- d-wave: nodes → decoherence

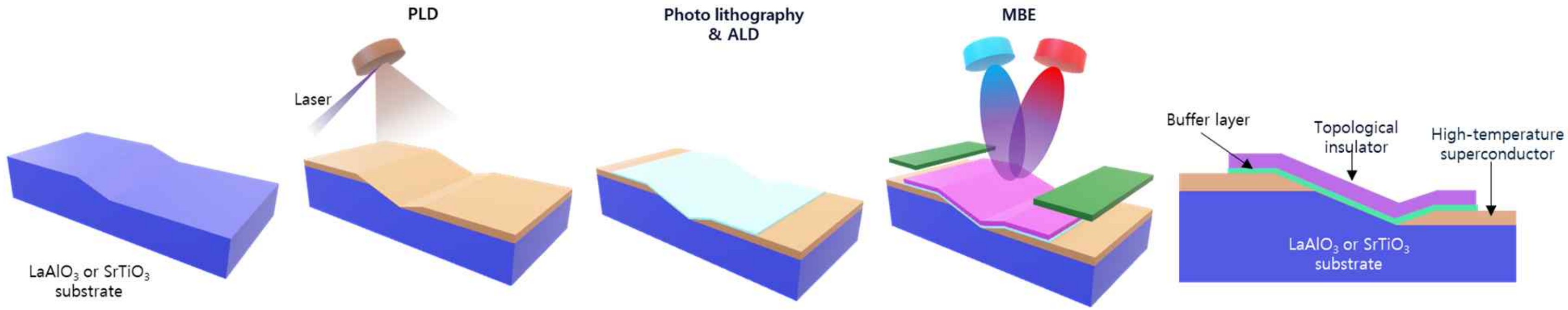
## Topological / Hybrid Platform

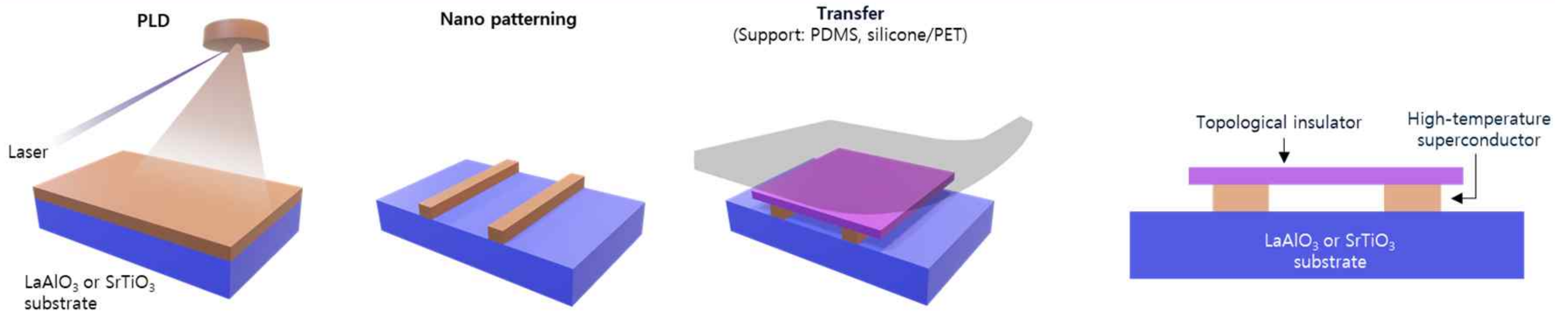
❖ Goal: Majorana Zero Modes

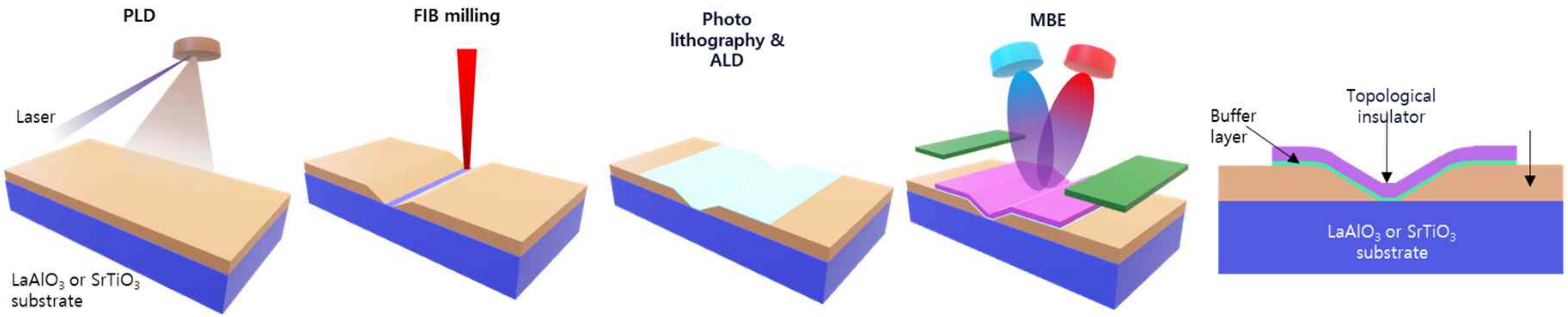
- YBCO + TI approach
- Effective *p*-wave pairing->Majorana zero mode (vortex core, $\pi$ domain boundary, edge state)
- $\pi$-phase control
- Large topological gap (potential)


d-wave vs s-wave in Quantum Qubits: Transmon vs Enhanced
Transmon Qubit (Conventional)
s-wave
d-wave
✓ s-wave: Fully gapped, Stable fabrication
X d-wave: Nodes → Decoherence, Low Reproducibility
Transmon → s-wave 최적
Enhanced Qubit Platform
• Goal: Majorana Zero Mode
✓ YBCO + TI Approach:
• Effective p-wave, π−Phase Control,
• Large Topological Gap
Topological phase engineering
YBCO
π
π
Majorana
Topological Insulator
Enhanced Qubit → d-wave 유망
'Transmon = Coherence, Topological Qubit = Phase & Topology'

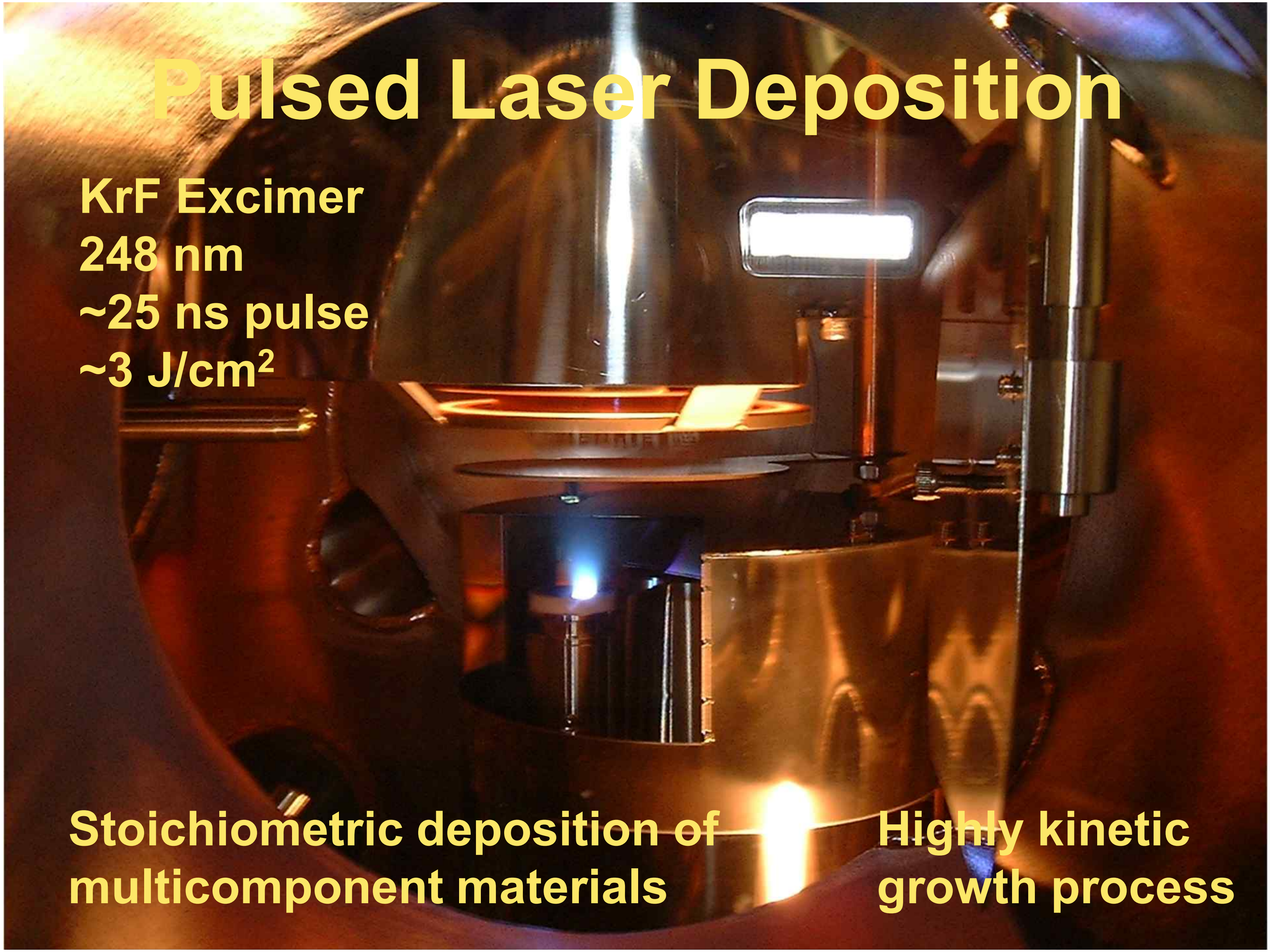
# Our strategies



# YBCO Epitaxial Thin Film Growth


Pulsed Laser Deposition
KrF Excimer
248 nm
~25 ns pulse
~3 J/cm2
Stoichiometric deposition of
multicomponent materials
Highly kinetic
growth process

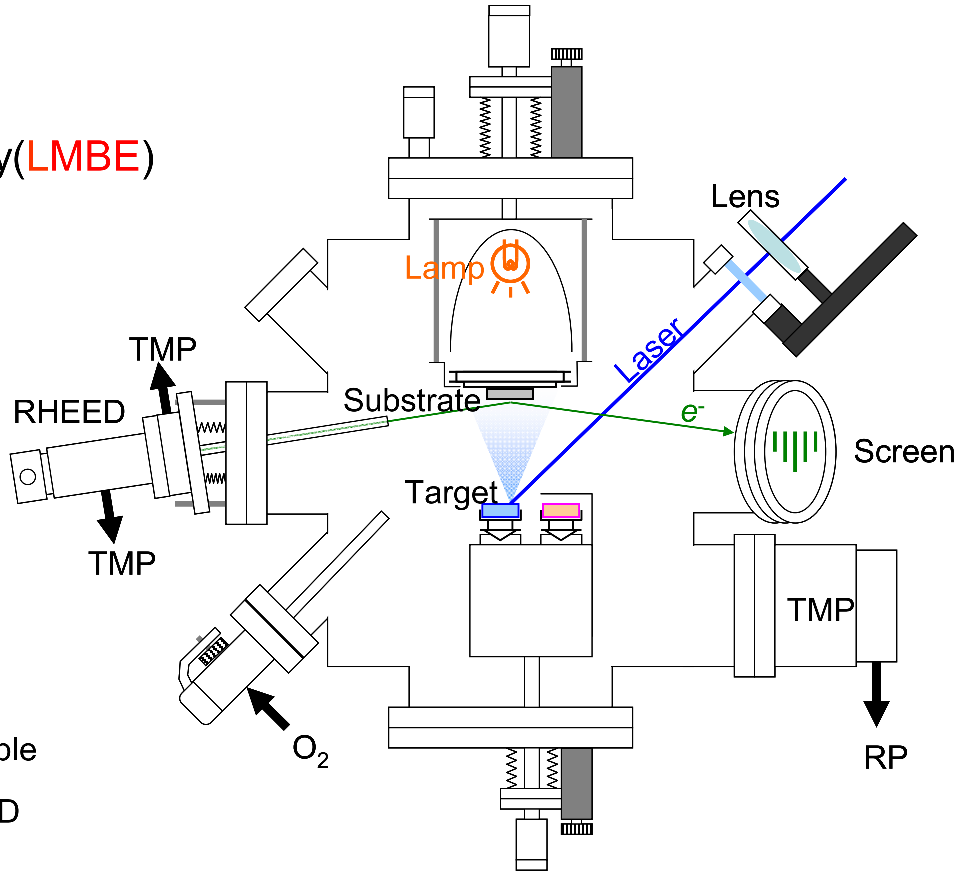
# Pulsed Laser Deposition

# Fabrication and characterization of film

- Fabrication technique
  - Pulsed Laser Deposition (PLD)
  or Laser Molecular Beam Epitaxiy(LMBE)

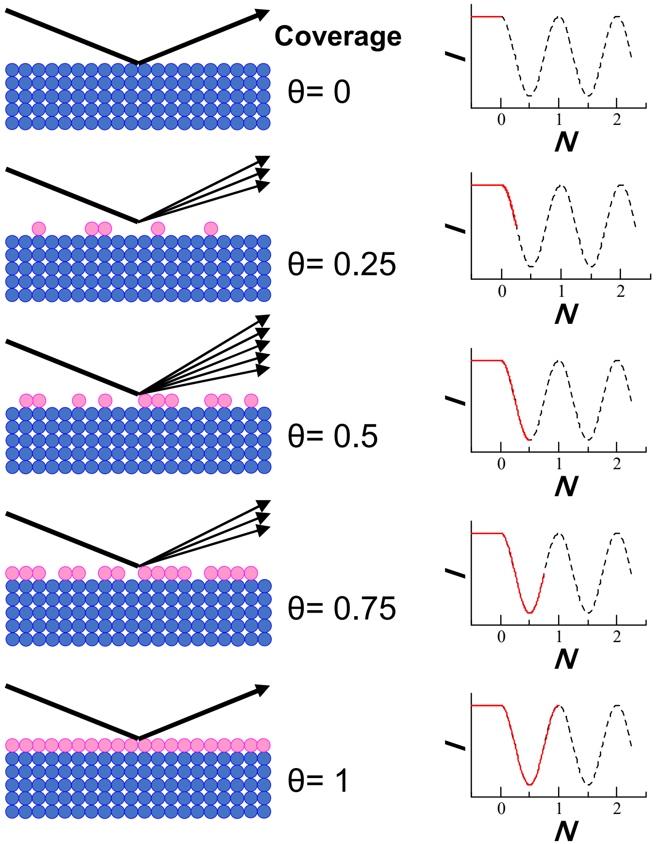
- Growth condition
  - $T_g$ : 500～900℃
  - $P_{O2}$ : 5.0 x $10^{-8}$ ～1.0 Torr
  - Fluence : ～2.5 J/$cm^2$ (4 Hz)

- Advantages
  - Many growth parameter to change
  - Kinetics of ablated species is controllable
  - Atomic layer is controllable with RHEED



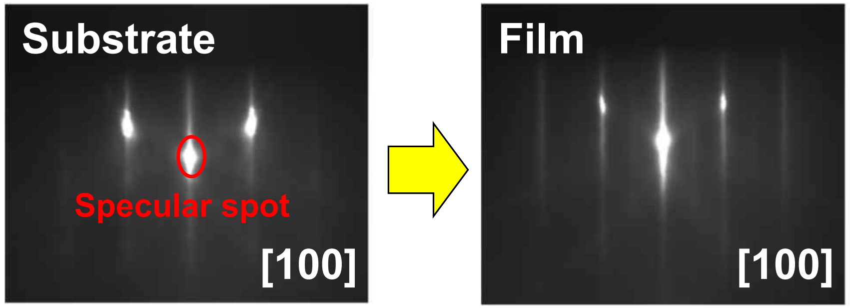
# *in-situ* Reflection High Energy Electron Diffraction (RHEED) monitoring

## Unit cell RHEED oscillations

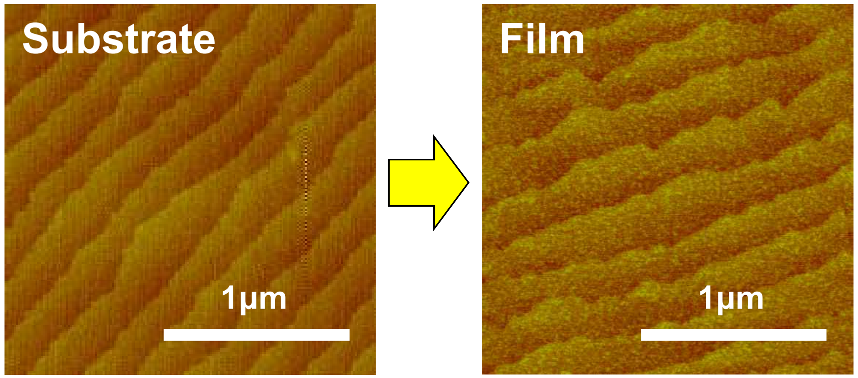



Specular spot intensity : *I*,
Number of unit cells : *N*

## RHEED pattern

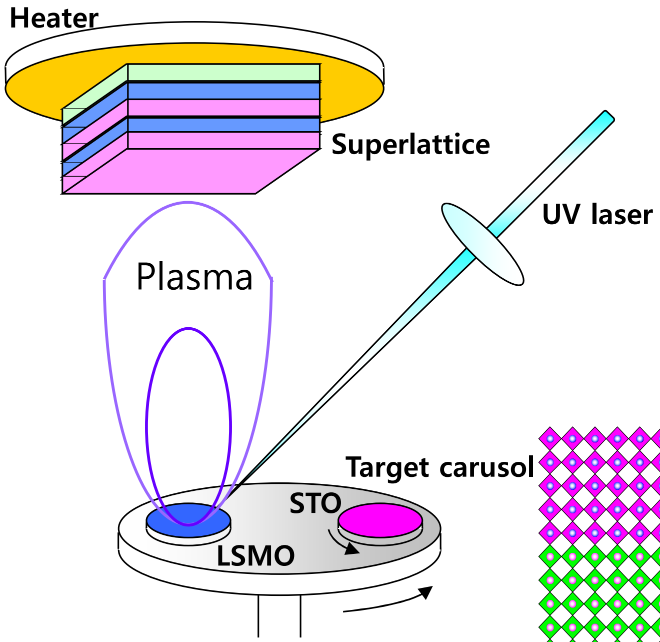


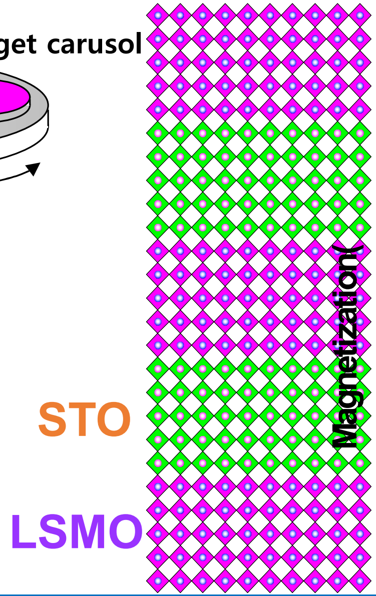

## AFM image

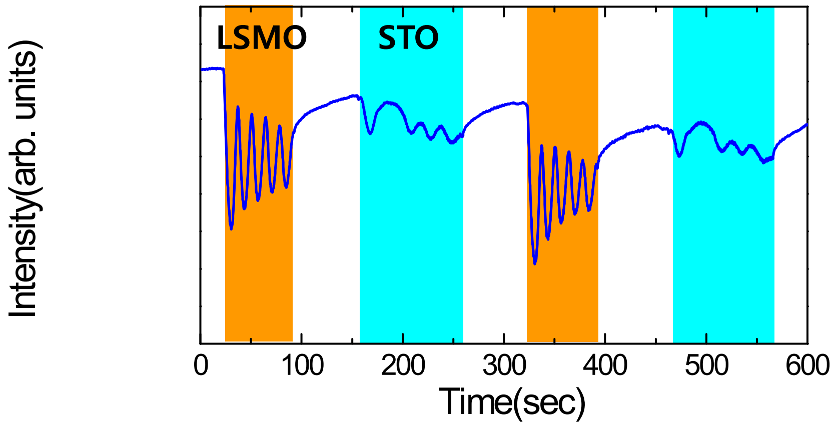



Atomically flat surface is maintained!

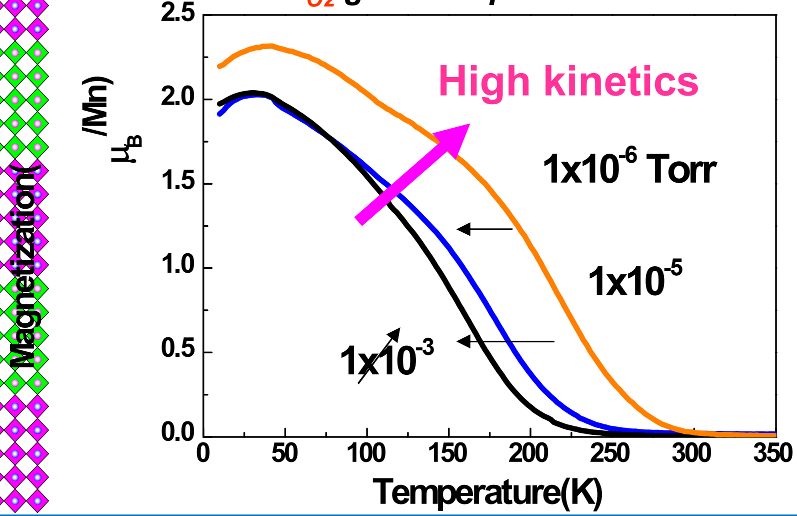
## $La_{0.7}Sr_{0.3}MnO_3$/$SrTiO_3$ nano-scale controlled superlattice




***Physical properties is better for low $P_{O2}$ grown superlattice***

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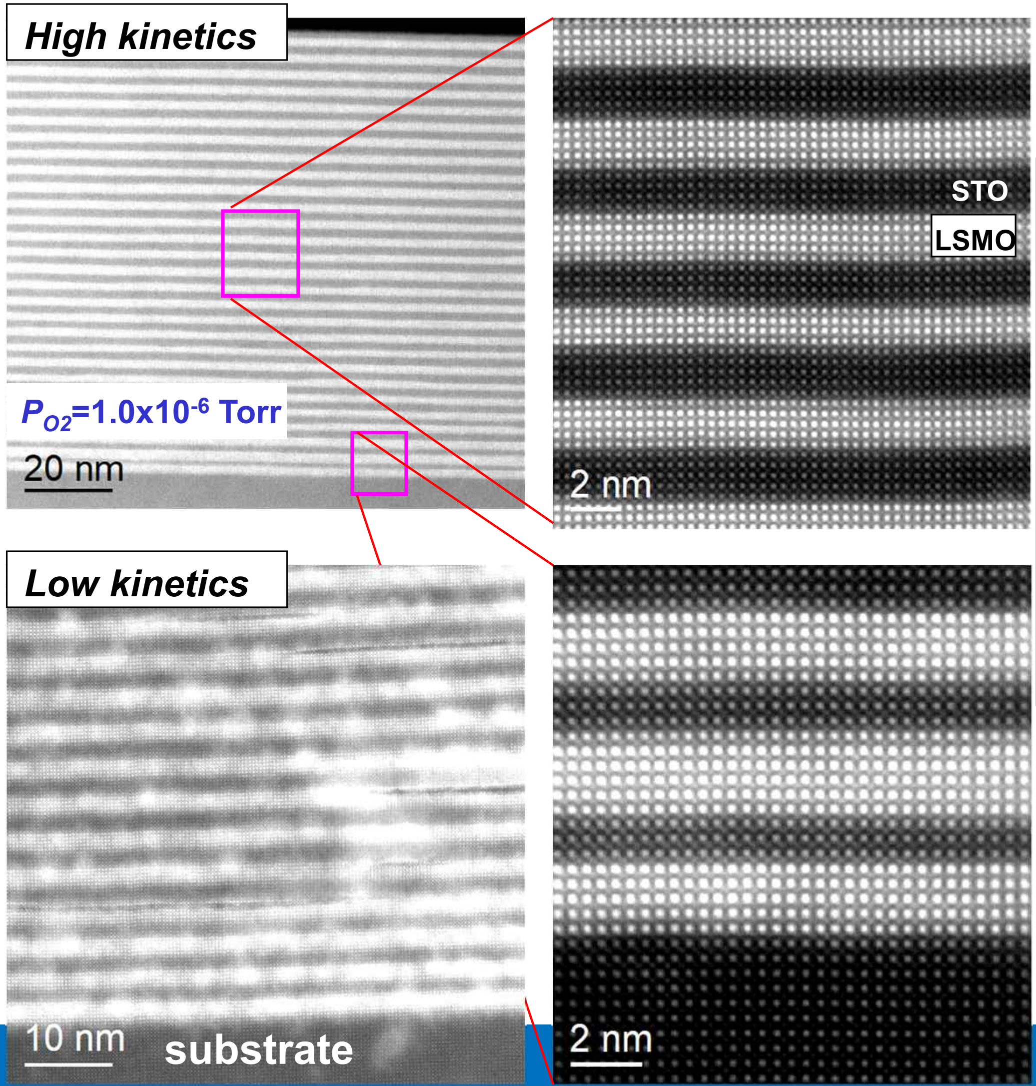
# Scanning Transmission Electron Microscopy (STEM)




$P_{O2}$=1.0x10$^{-6}$ Torr

*Sharp interface*

***High kinetics derives sharp interface!!!***

***The interface is the device***

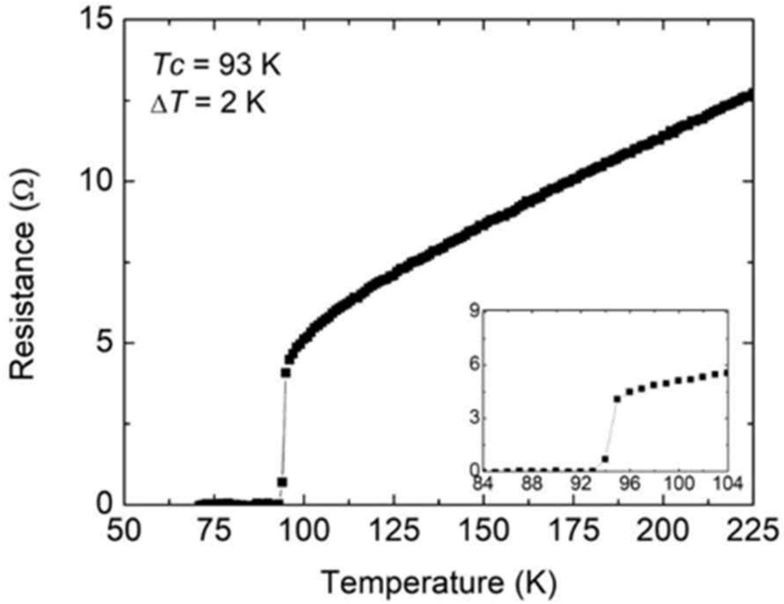
**-Herbert Kroemer (Nobel Lecture,2000)**

***Ready for device application***

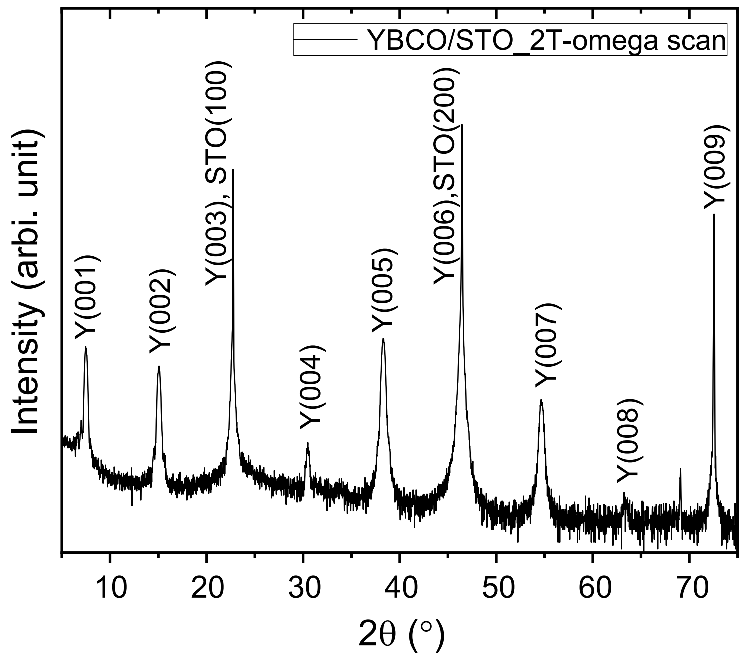
*Sharp interface*

# YBCO Epitaxial Thin Film Growth

Properties of YBCO Thin Films

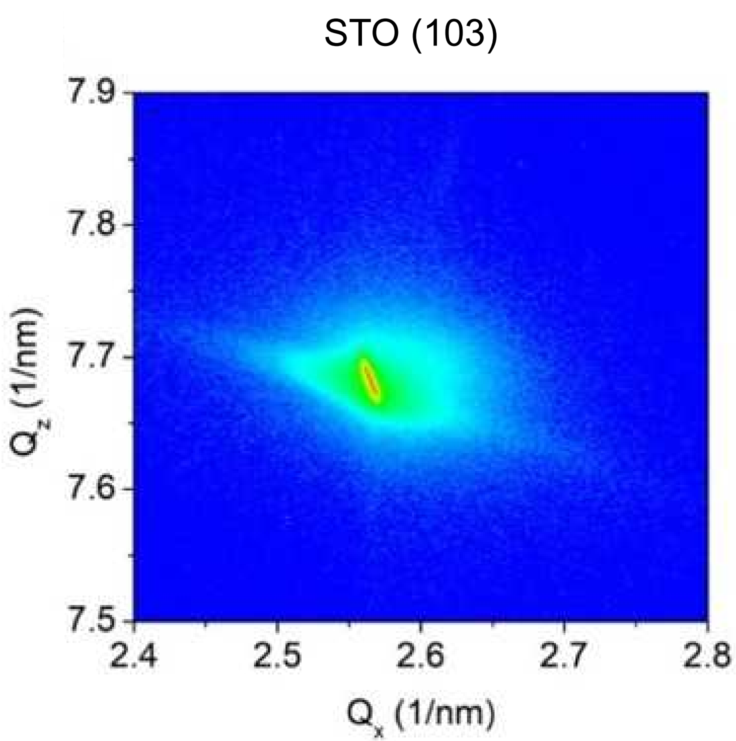


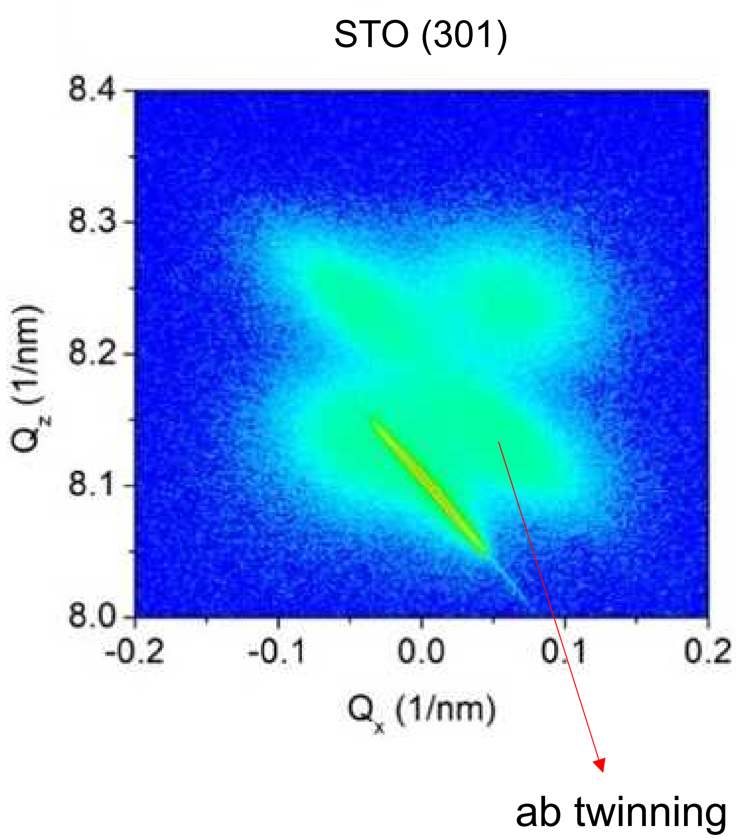

**XRD(2θ-ω scan)**



# YBCO Epitaxial Thin Film Growth

**RSM (Reciprocal Space Mapping)**

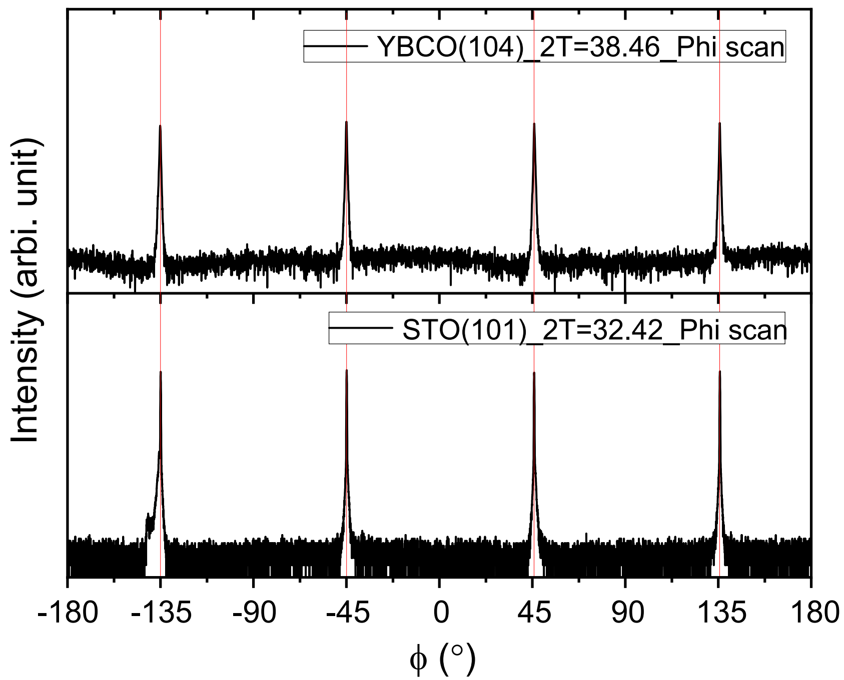


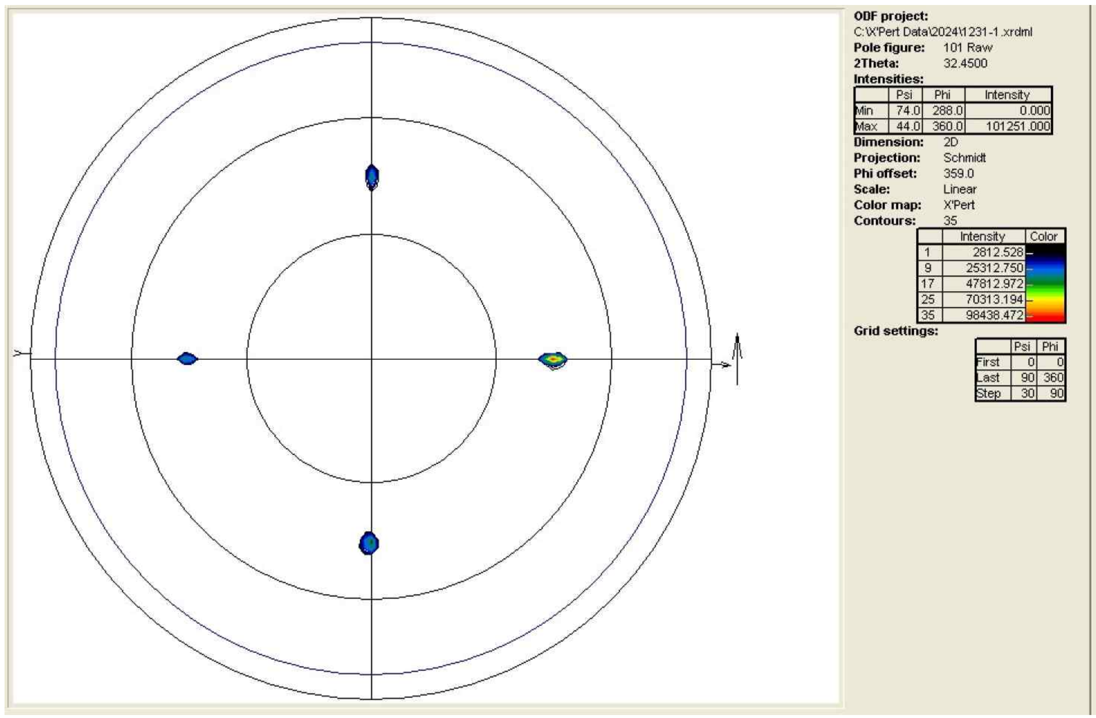
# YBCO Epitaxial Thin Film Growth

Properties of YBCO Thin Films

**φ(phi) scan**




**Pole figure**

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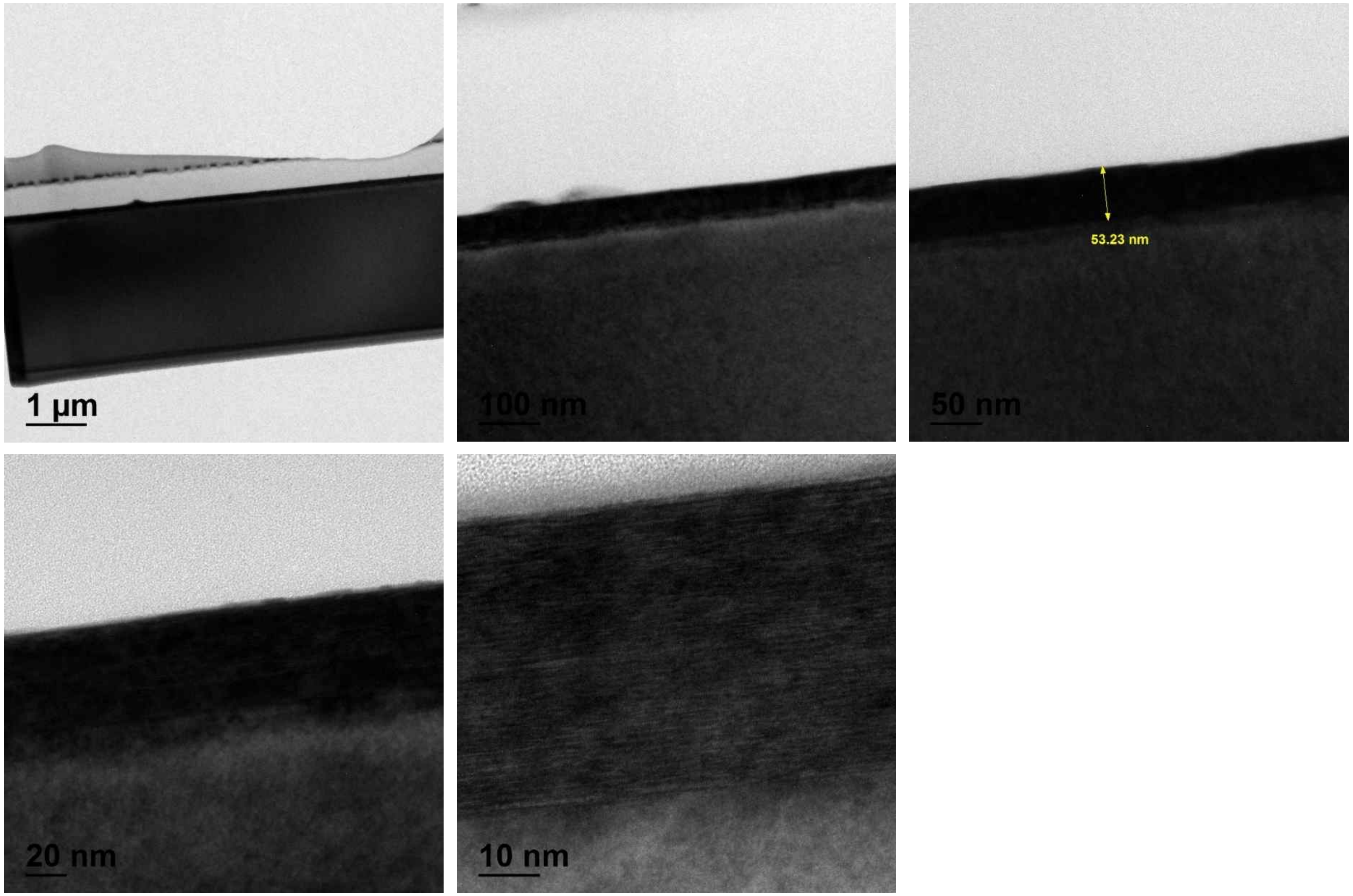
# YBCO Epitaxial Thin Film Growth

Properties of YBCO Thin Films

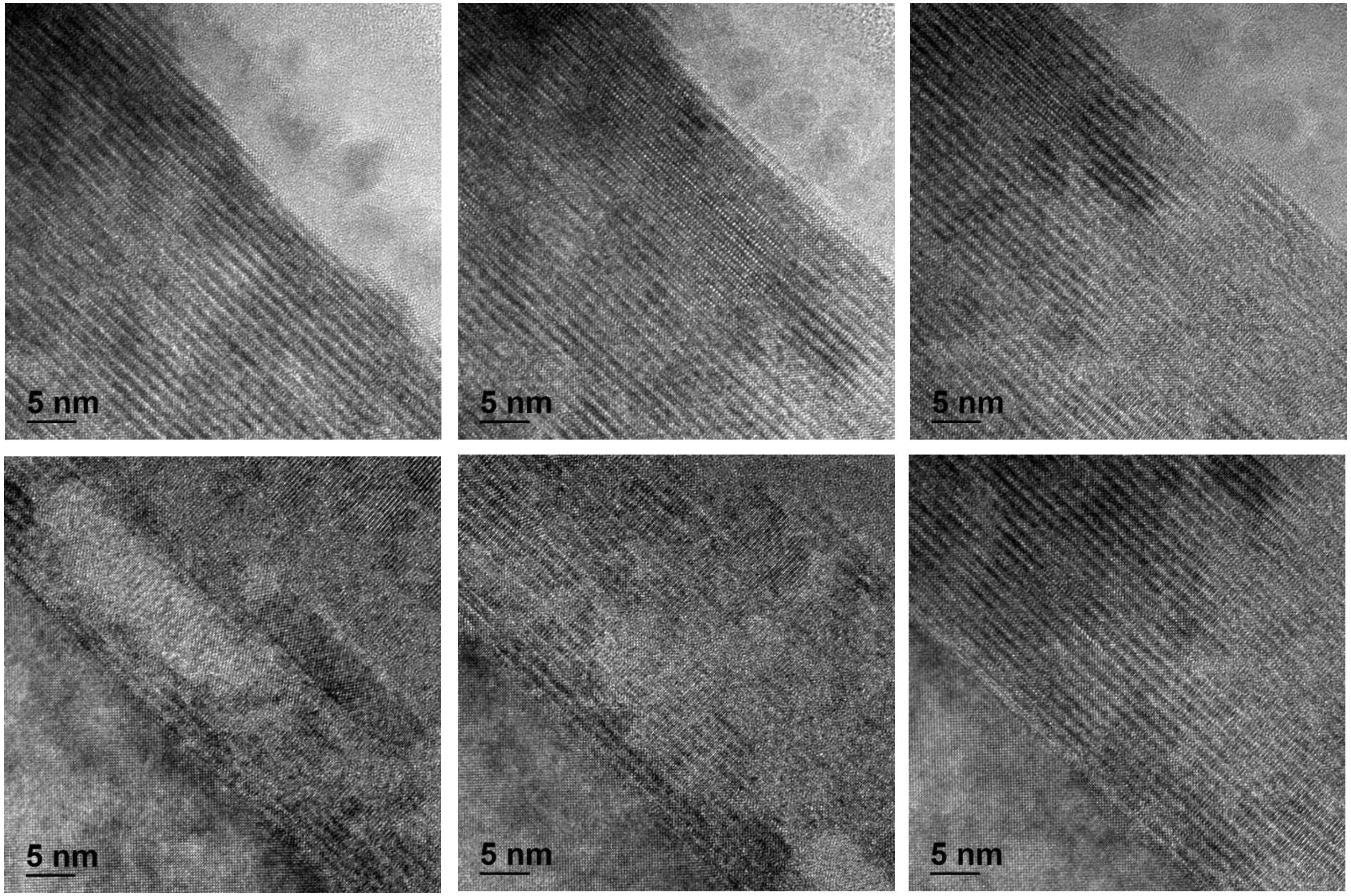
**TEM (Bright field images)**



# YBCO Epitaxial Thin Film Growth

Properties of YBCO Thin Films

**TEM (High resolution images)**

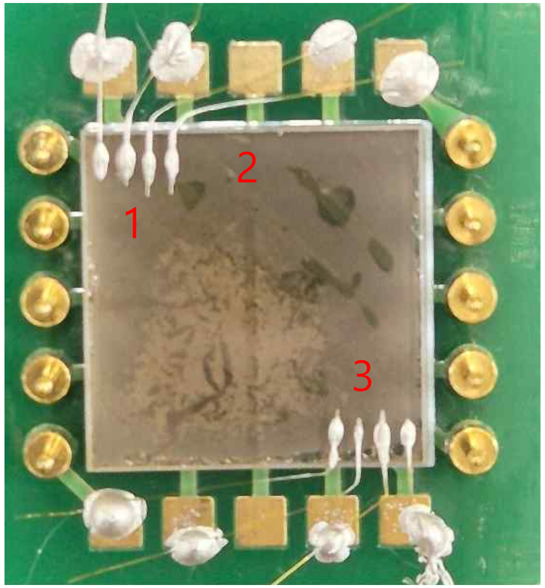


# YBCO Josephson Junction

# YBCO Josephson Junction

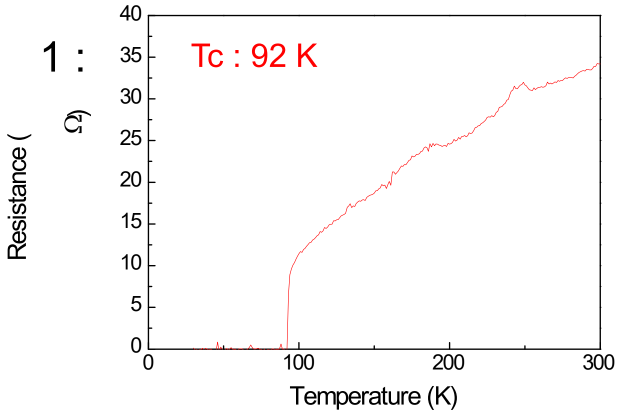
Properties of YBCO Thin Films

**Bi-Crystal YBCO #1 샘플**




**R/T data**

1 :

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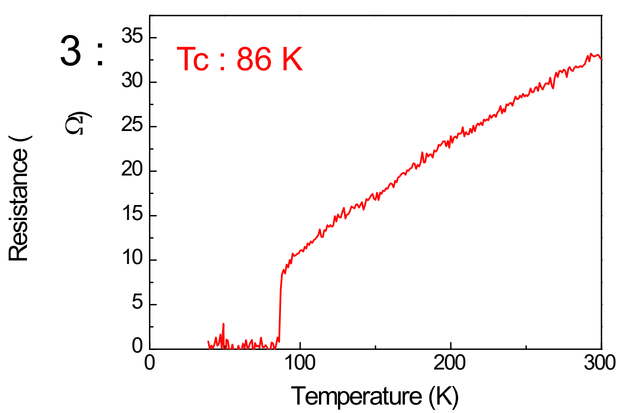
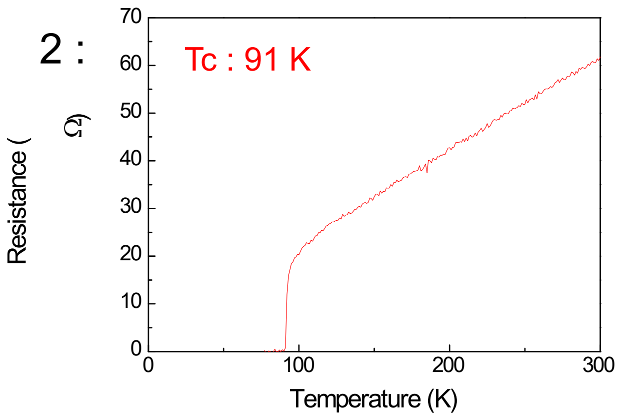


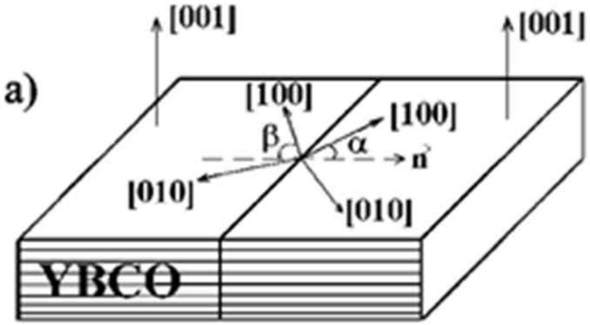

2 :

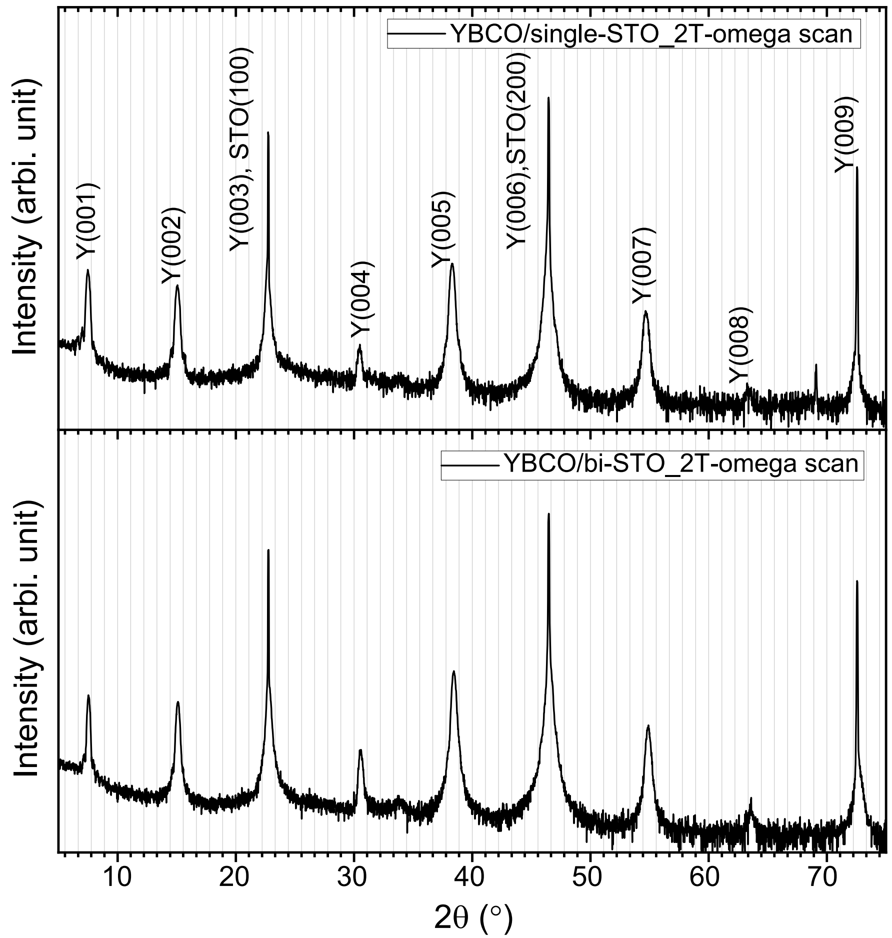


# YBCO Josephson Junction

## Properties of YBCO Thin Films

**XRD: 2θ-ω scan**

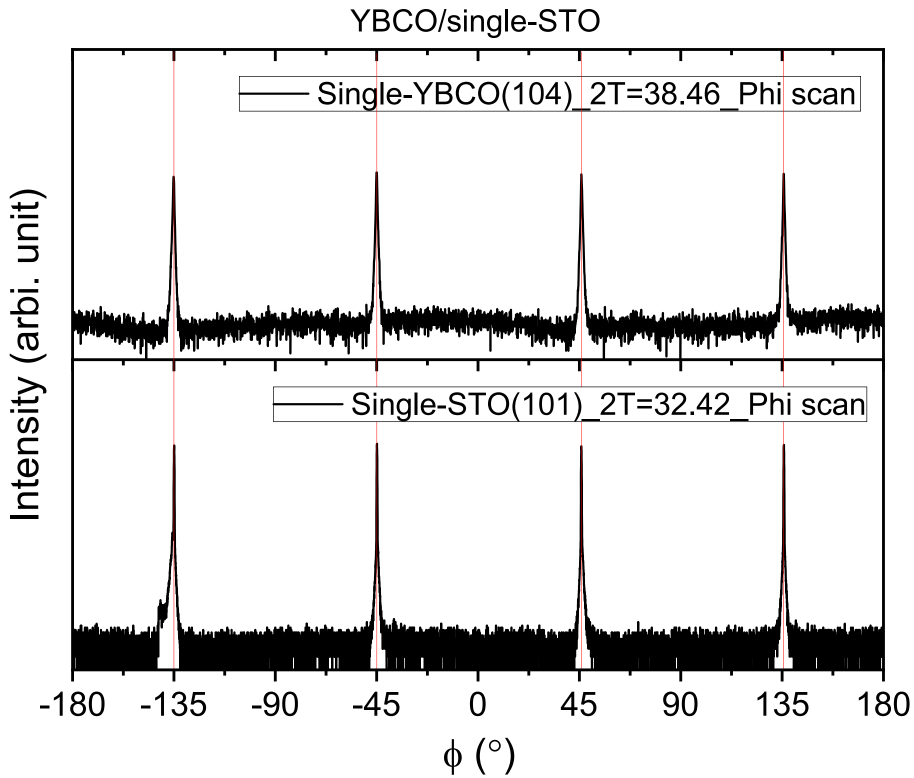


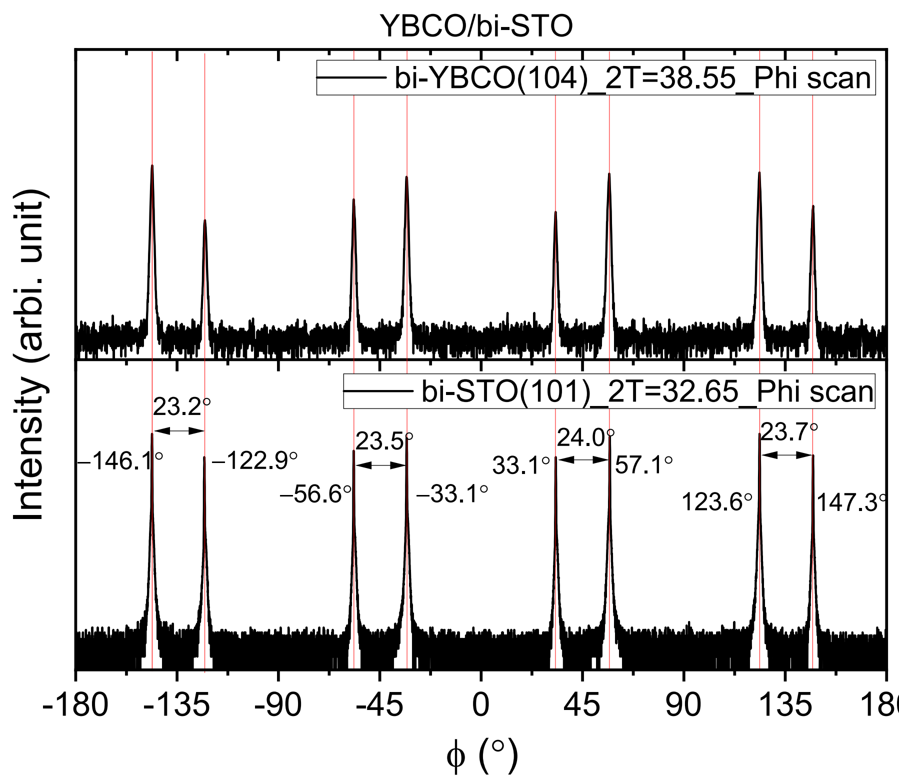



# YBCO Josephson Junction

Properties of YBCO Thin Films

**XRD: φ(phi) scan**



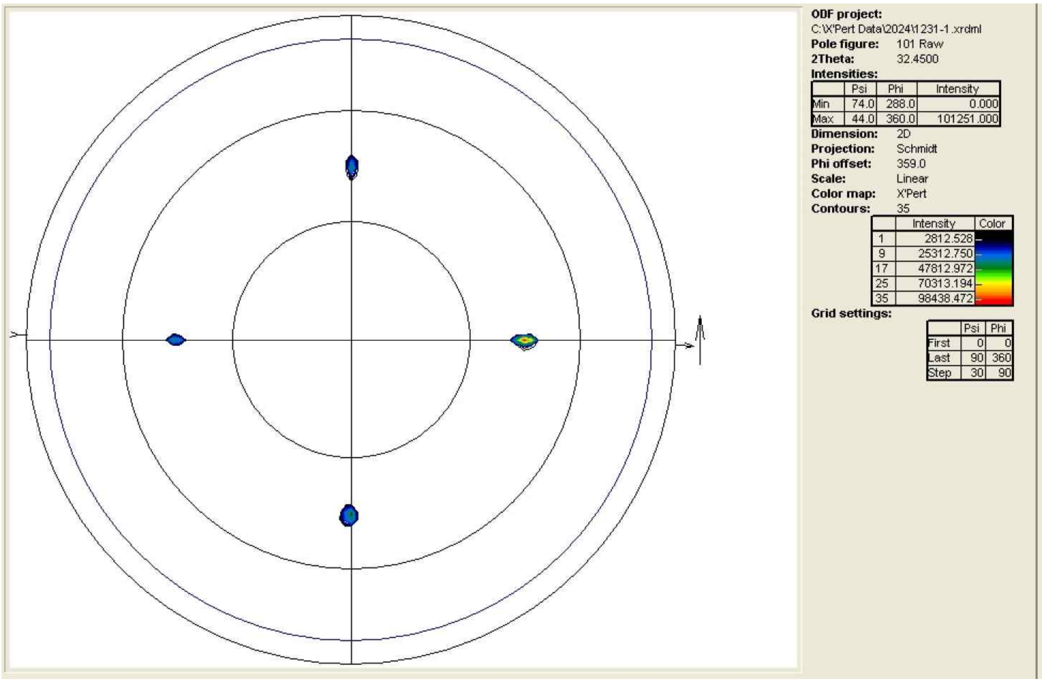

SOLID
Spintronics & Oxide lab. for Interface Device

# YBCO Josephson Junction

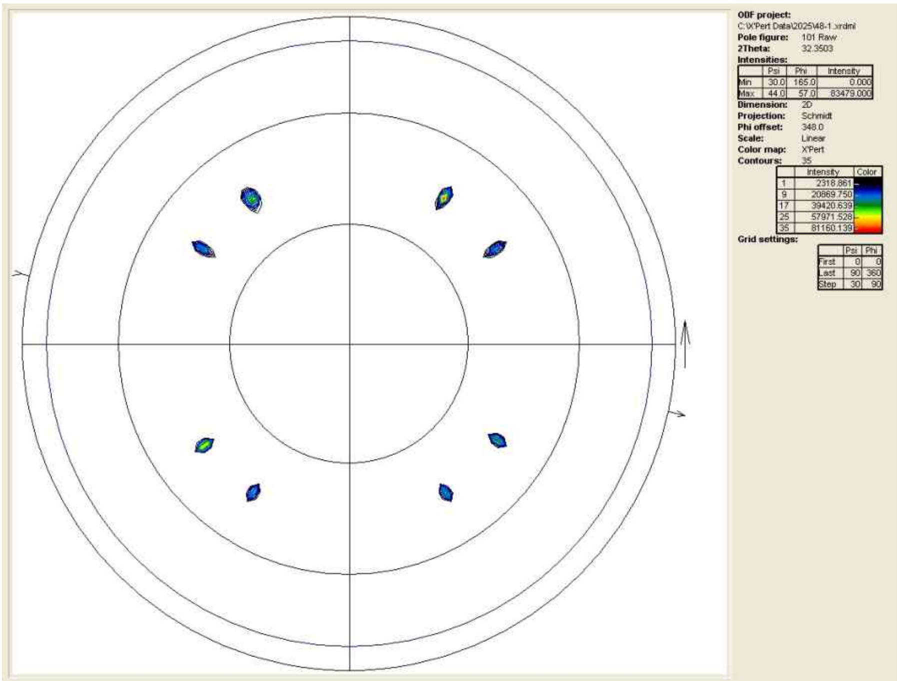
## Properties of YBCO Thin Films

**XRD: pole figure**

YBCO/single-STO




YBCO/bi-STO

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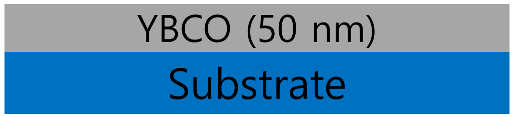
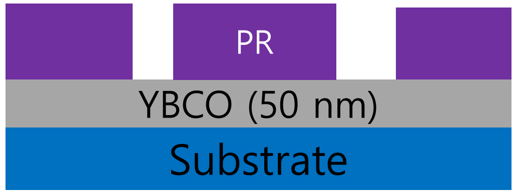
# YBCO Josephson Junction

## Device Fabrication Method

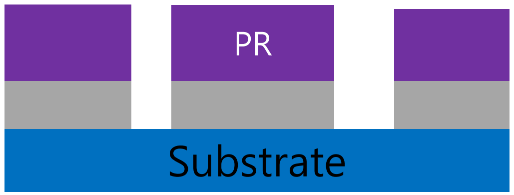
**1. Initial State**




**2. Photoresist (PR) Process**




**3. Wet etching**

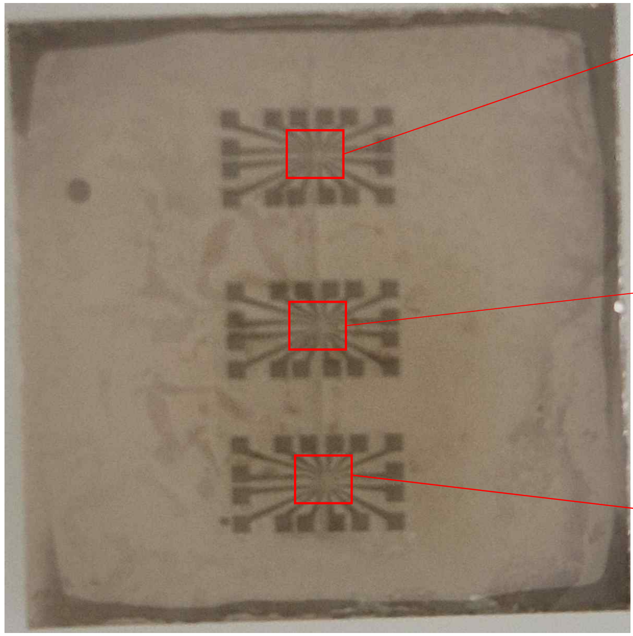


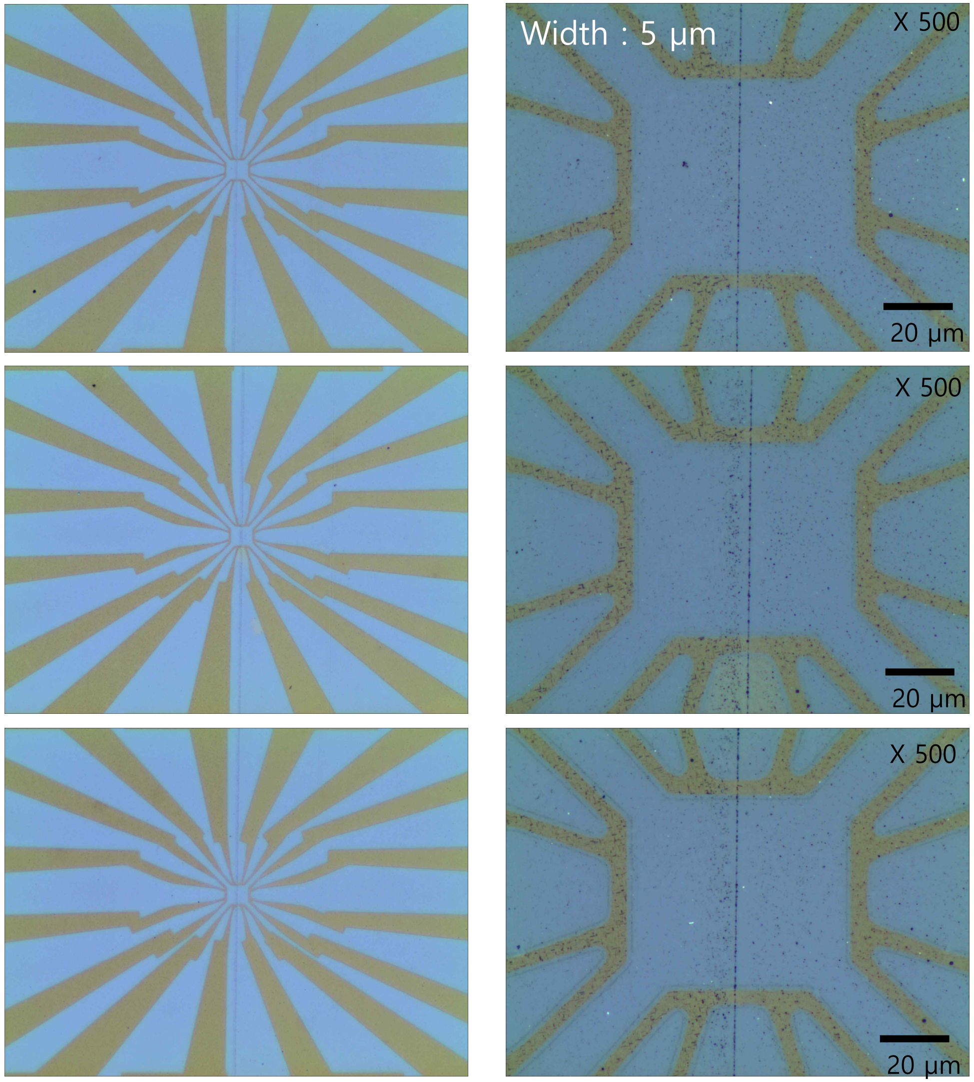

**4. Photoresist (PR) remove**

# YBCO Josephson Junction

Josephson Effect Measurement

**YBCO/STO(bi-crystal) #M7**

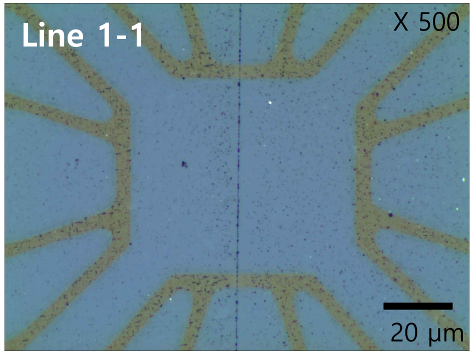




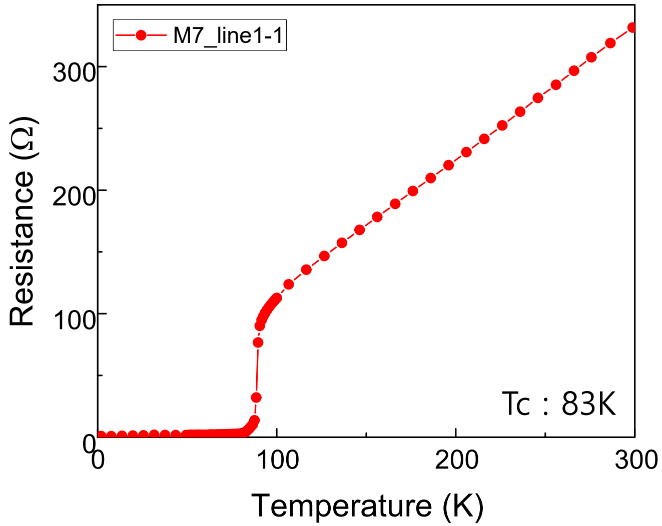
# YBCO Josephson Junction

## Josephson Effect Measurement

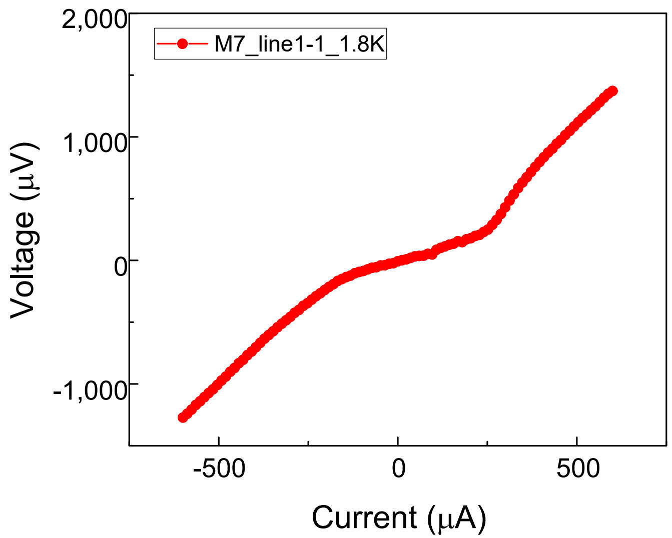
**YBCO/STO(bi-crystal) #M7**




**RT data**




**IV curve**

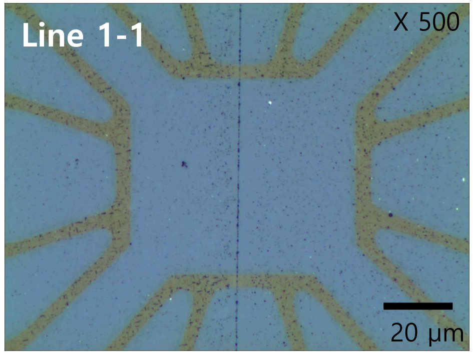



$I_c$ : 250 µA
$J_c$ : $1.0 \times 10^5$ A/cm$^2$
$I_cR_n$ : 0.69 mV

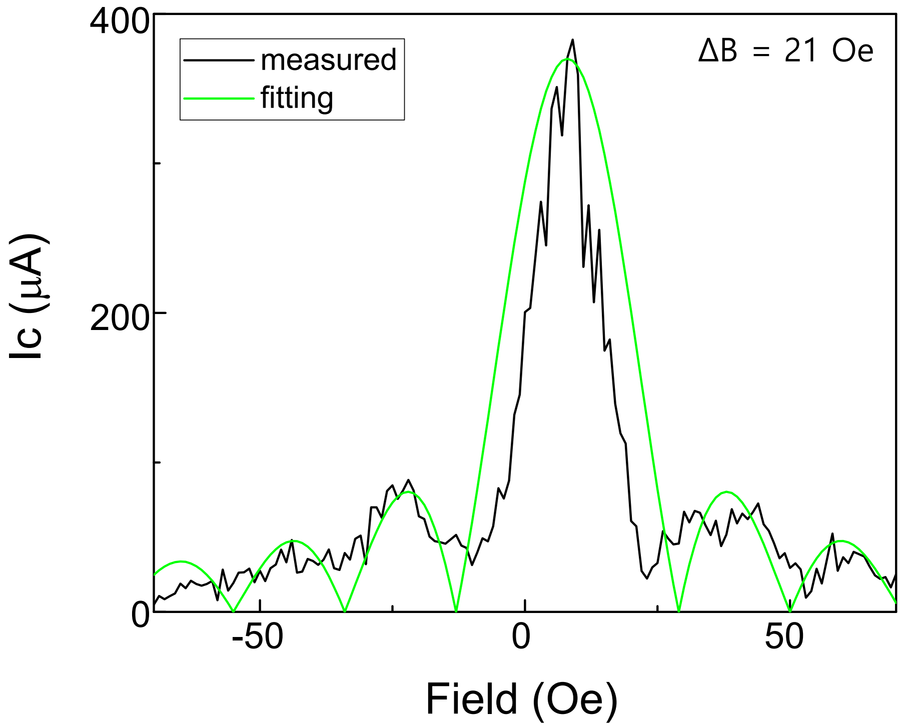
# YBCO Josephson Junction

## Josephson Effect Measurement

**YBCO/STO(bi-crystal) #M7**




**Fraunhofer pattern**




$$\Delta B = \frac{\Phi_0}{A_{eff}} = \frac{\Phi_0}{W \cdot d_{eff}}$$

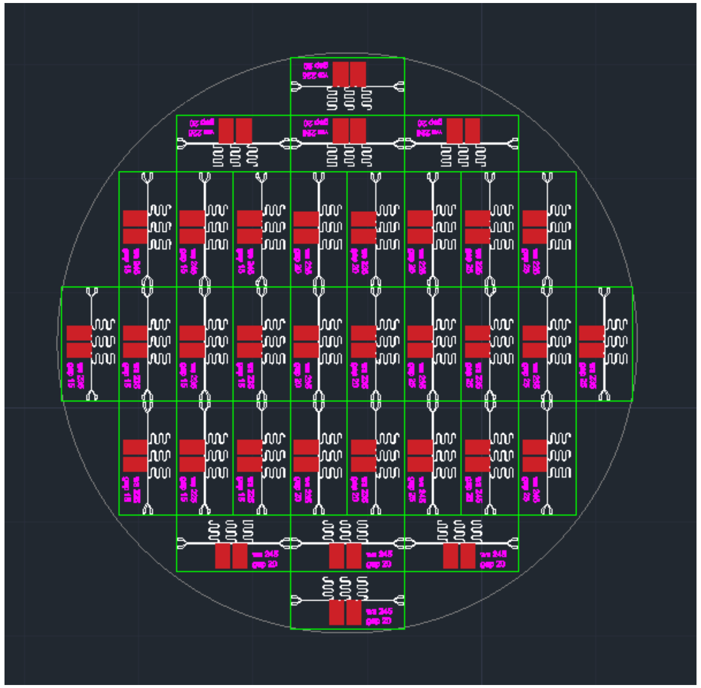
$$d_{eff} \approx t_{barrier} + \lambda_1 + \lambda_2 \approx 2\lambda_L$$
$\approx$ 197 nm
($\lambda_L \approx$ 98 nm)

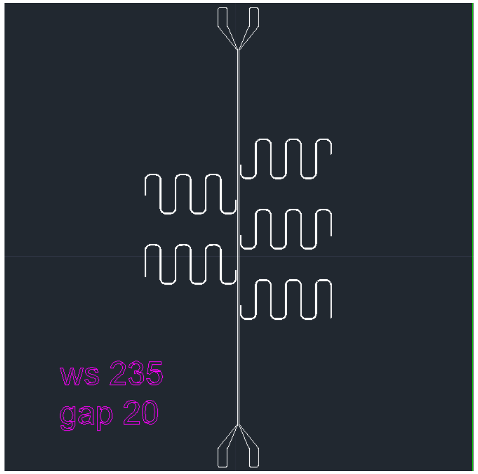
- Quasi-particle 존재
- Grain boundary에 defect 및 faceting 존재
- Trap hole 존재

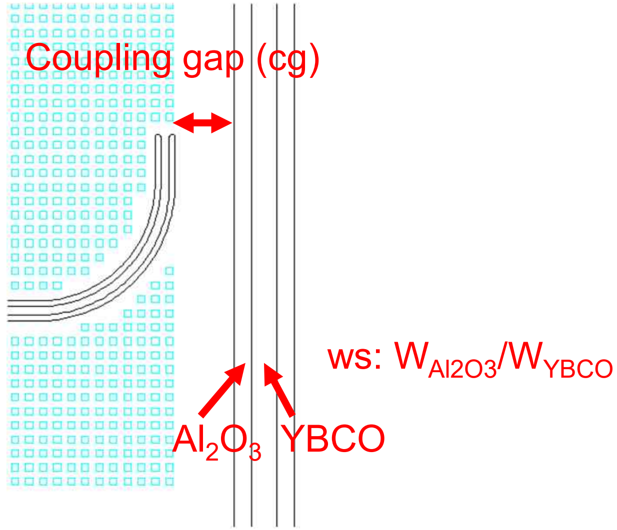
# YBCO 5 GHz Resonator Fabrication

# YBCO/Sapphire Resonator

## Device Design





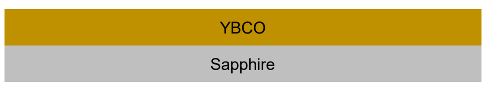




- 총 34개 셀에 각 조건으로 패턴 (조건은 오른쪽 확인)
- 각 조건은 coupling gap (gap), $Al_2O_3$ 신호선 선폭비 (ws)를 변수로 각기 달리 디자인함
- Trap hole 크기는 5 μm X 5 μm 정사각형, 간격은 5 μm.

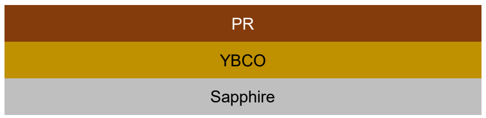
# YBCO/Sapphire Resonator

## Device fabrication stage

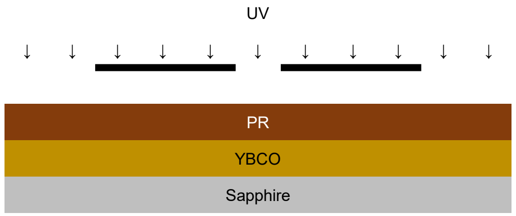
1. YBCO thin film



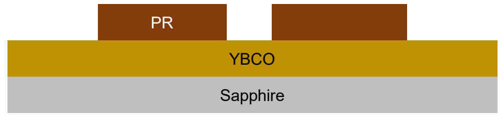

2. PR coating



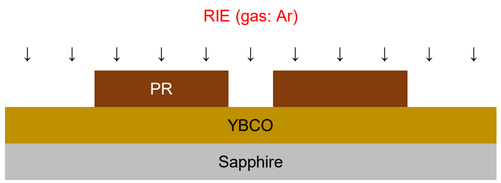

3. UV exposure



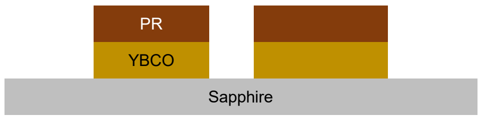

4. Develop




5-1. RIE(CCP) etch (before)



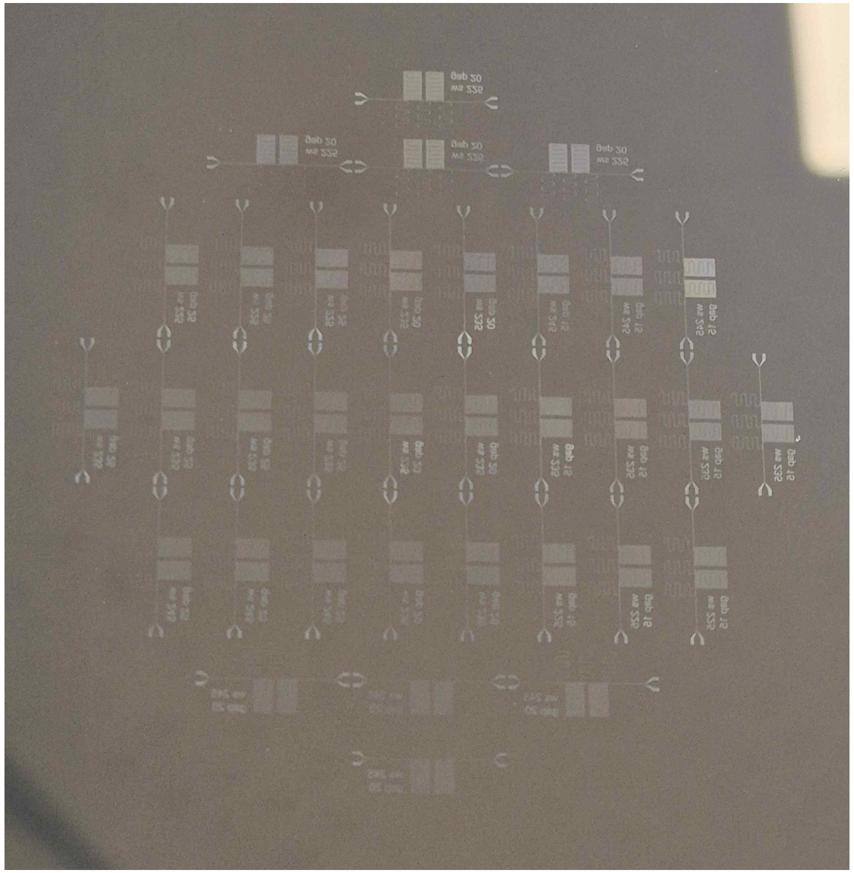

5-2. RIE etch (after)




6. PR removal

# YBCO/Sapphire Resonator

Photo mask



# Summary

**[Background & Objective]**

Conventional superconducting qubits require extreme cryogenic temperatures, and decoherence driven by quasiparticle poisoning remains a significant bottleneck. This study proposes a novel topological Josephson junction using a High-Temperature Superconductor (HTS) and Topological Insulator (TI) heterostructure to overcome these limitations.

**[Progress & Future Roadmap]**

**1.Baseline Device Verification (Completed):** We have fabricated YBCO Josephson junctions using $SrTiO_3$ (STO) bi-crystal substrates and established baseline performance through transport property measurements.

**2.HTS-TI Junction Implementation (Planned):** Building on these results, we will optimize the deposition of $Bi_2Se_3$ on YBCO films to achieve high-quality interfaces and characterize the resulting topological superconducting properties.

**3.Final Goal:** Our ultimate objective is to integrate the $Bi_2Se_3$ topological junction into a 1-qubit device and verify its enhanced coherence and quasiparticle suppression compared to conventional architectures.