Fabrication of Superconducting Quantum Sensor

@KMI School 2024

Nagoya University/KMI

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University of Tokyo/ICEPP

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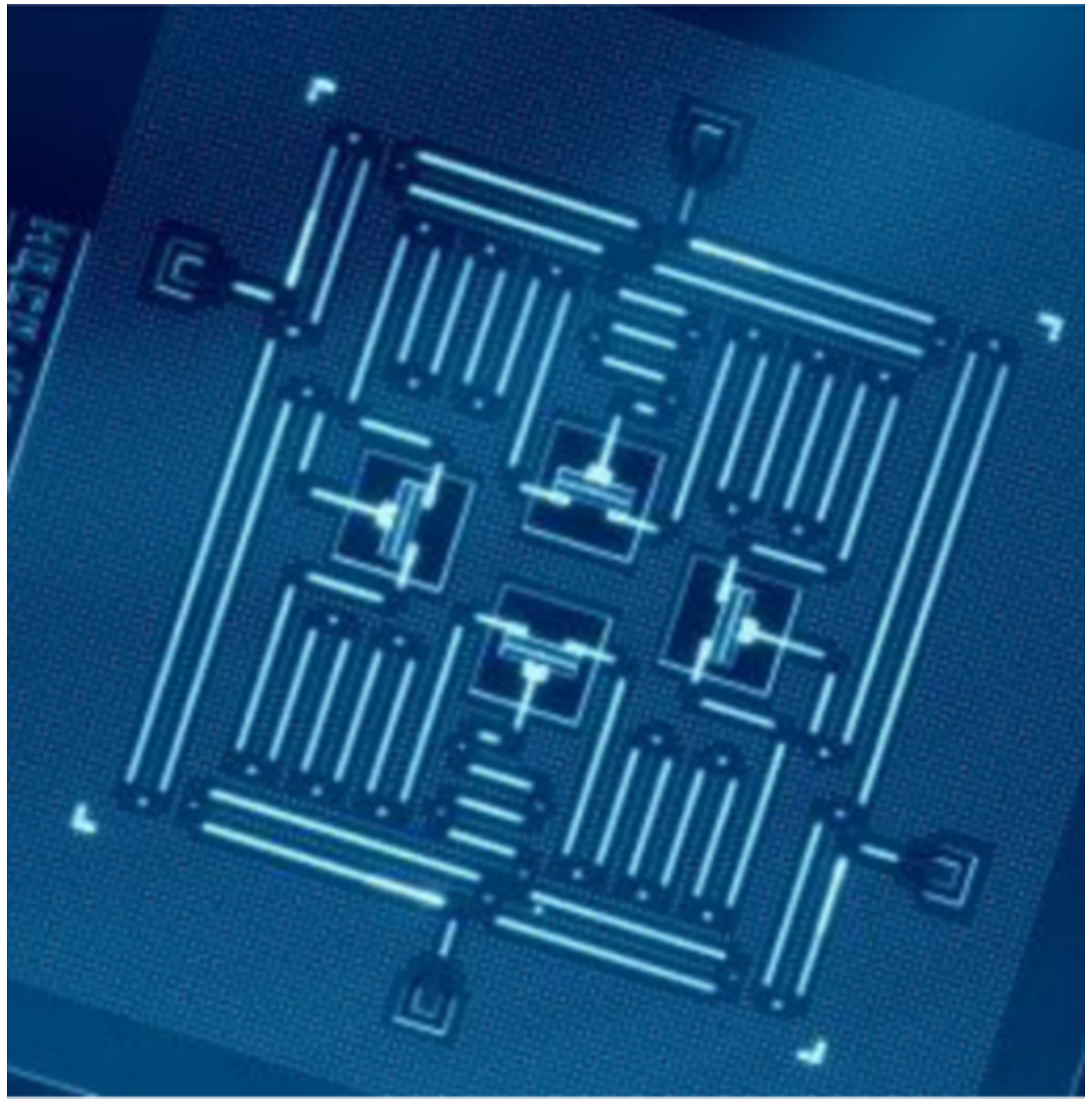
Why superconducting qubits?

Superconducting Quantum Computer



- Large electric coupling
  - $10^6 \times$ atom
- Long coherence time
  - $O(100)\ \mu s$ or more
- non-demolition readout
- Low noise environment
  - mK temperature
  - EM/Magnetic shields

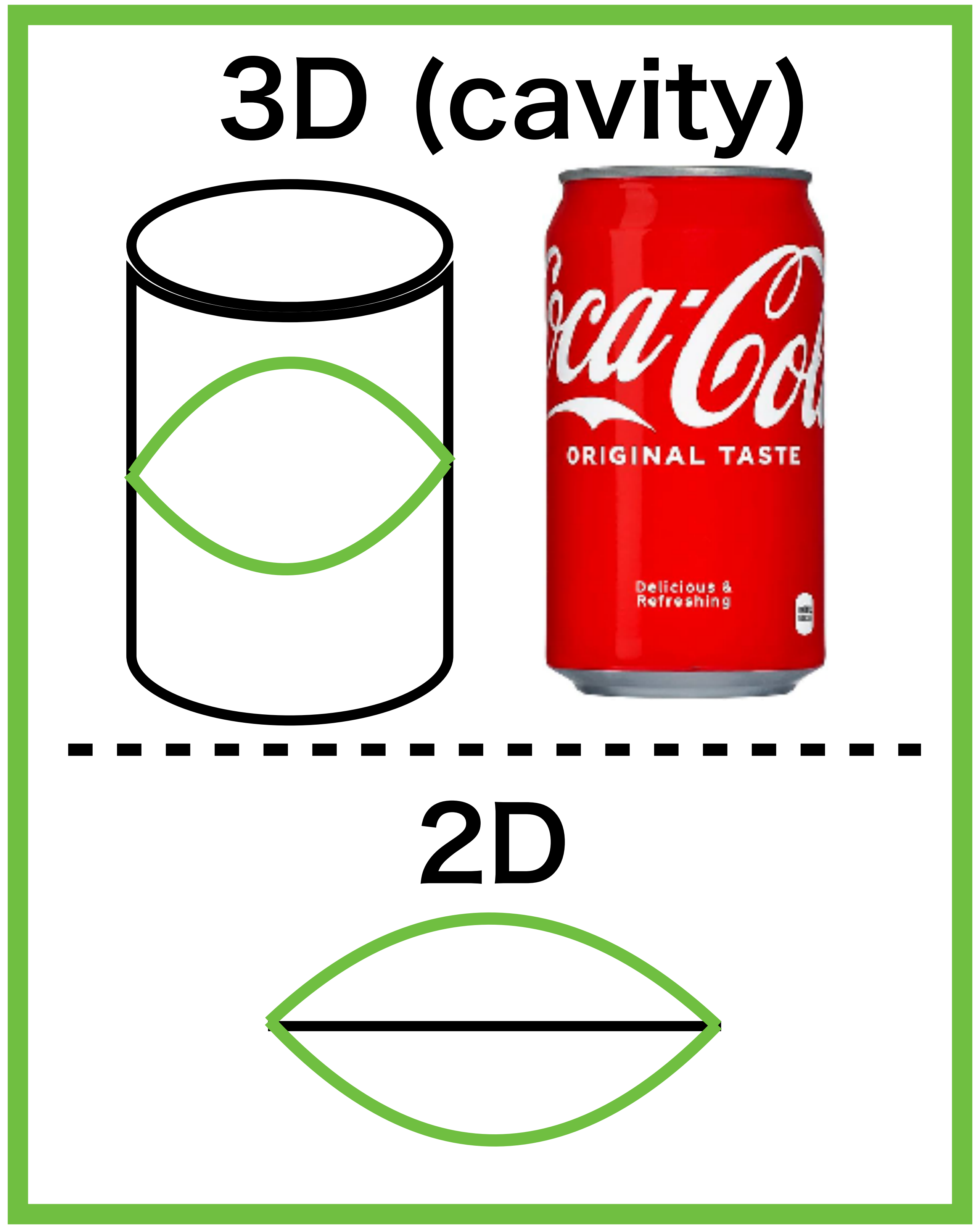
Quantum sensor

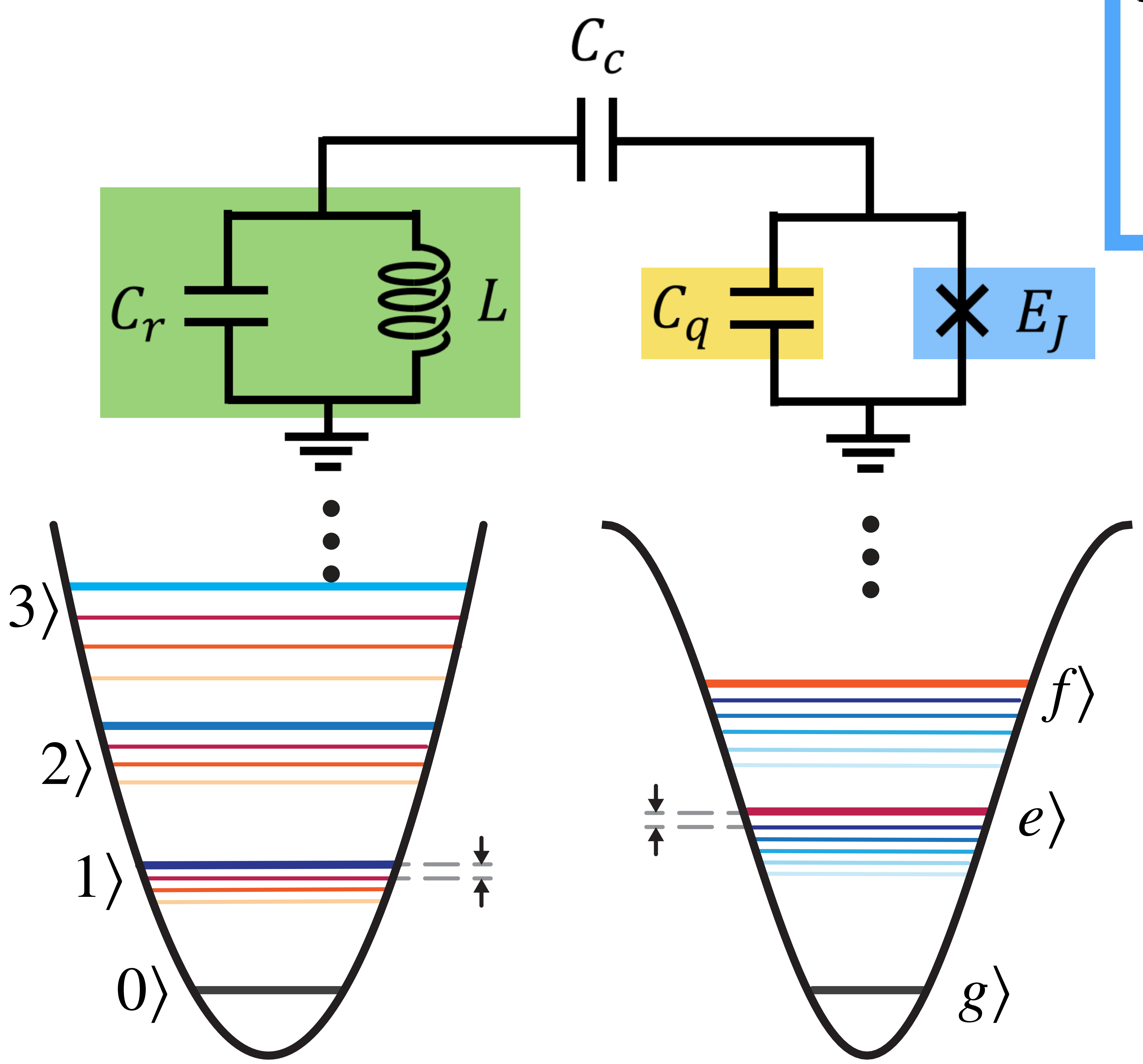
- Very sensitive to weak EM field
- Easy to do manipulate
- Drastically decrease uncertainty
- Low dark count

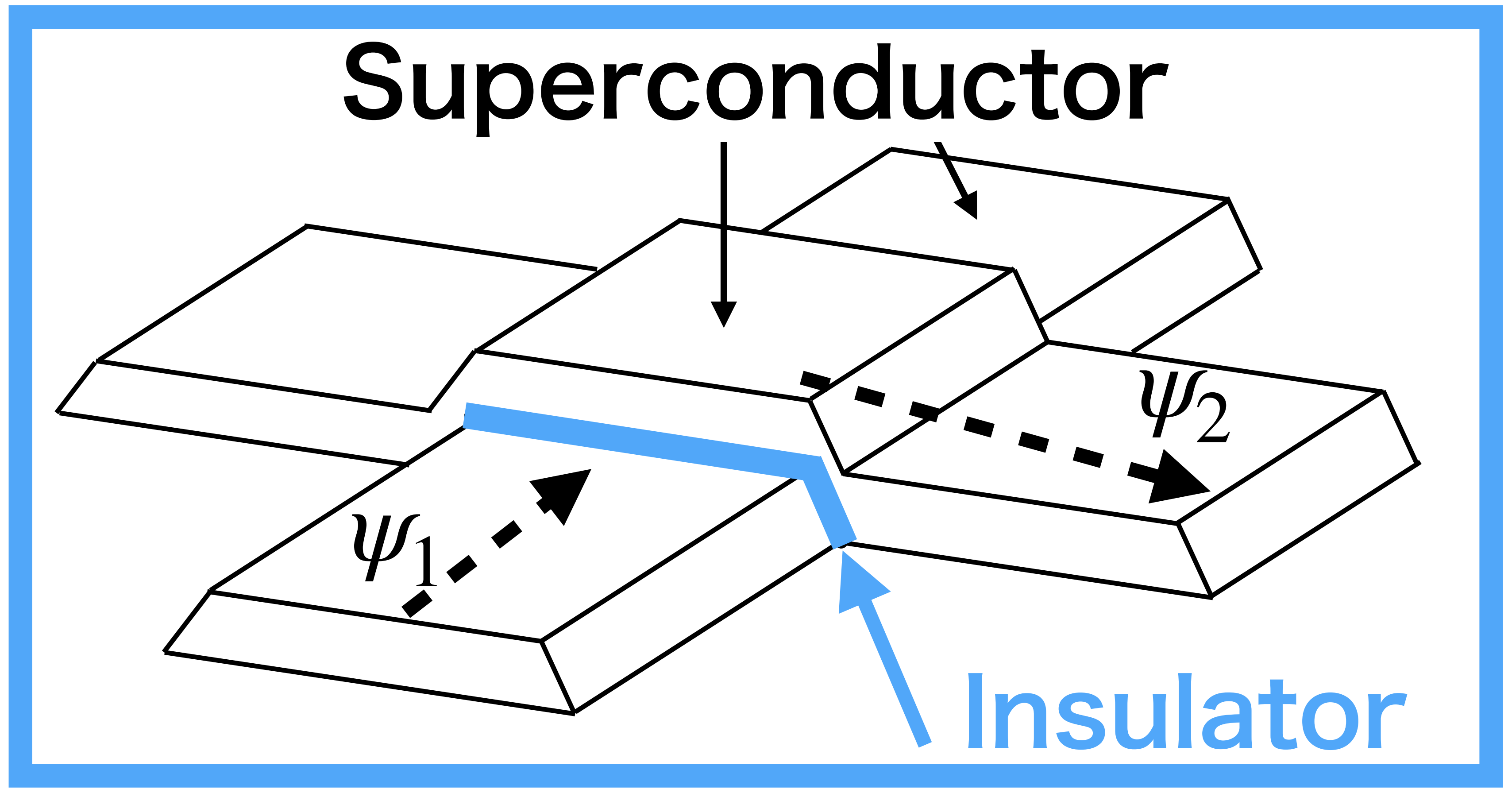
Superconducting qubit must be suitable as a sensor

A qubit in a nutshell

Resonator

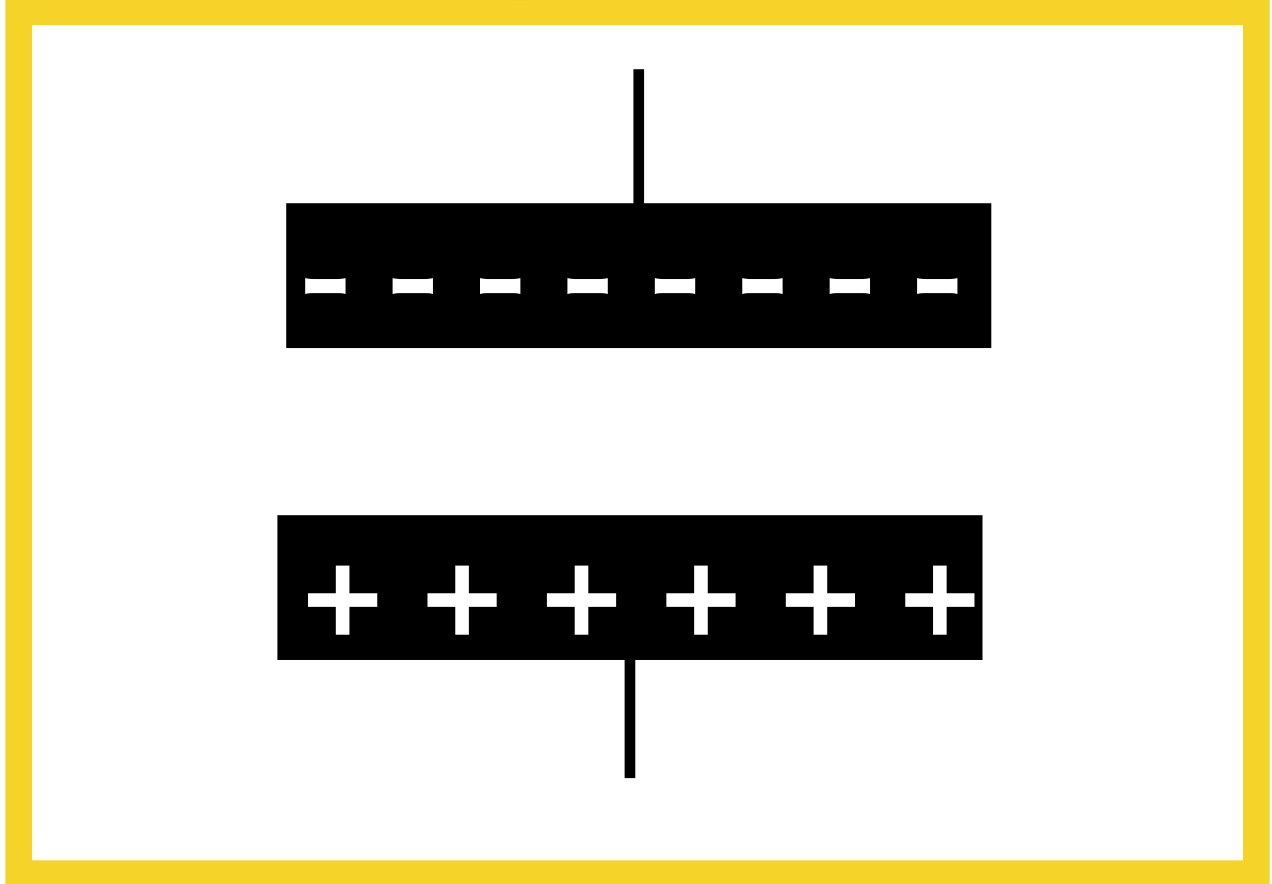






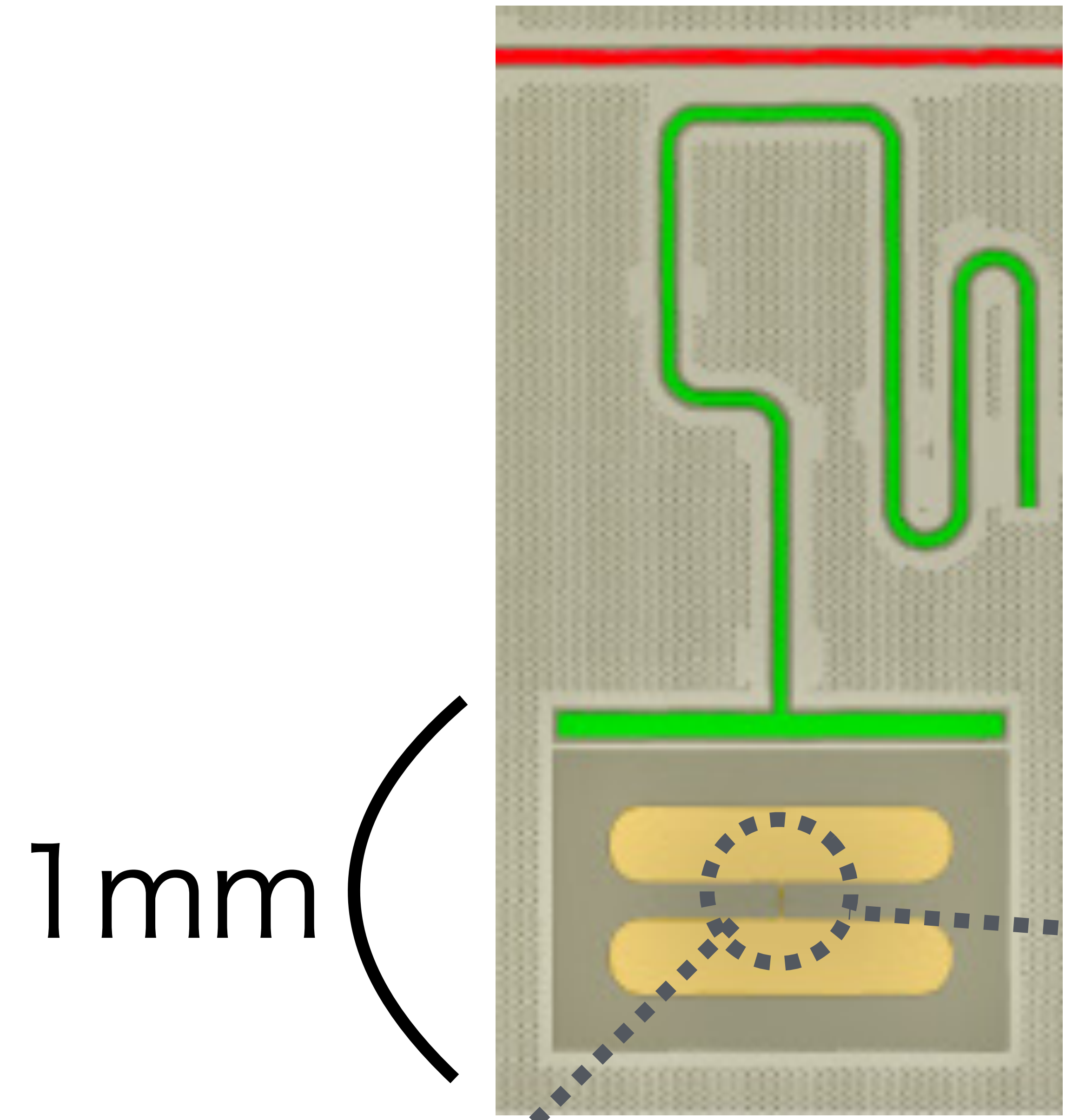
Josephson Junction (JJ)

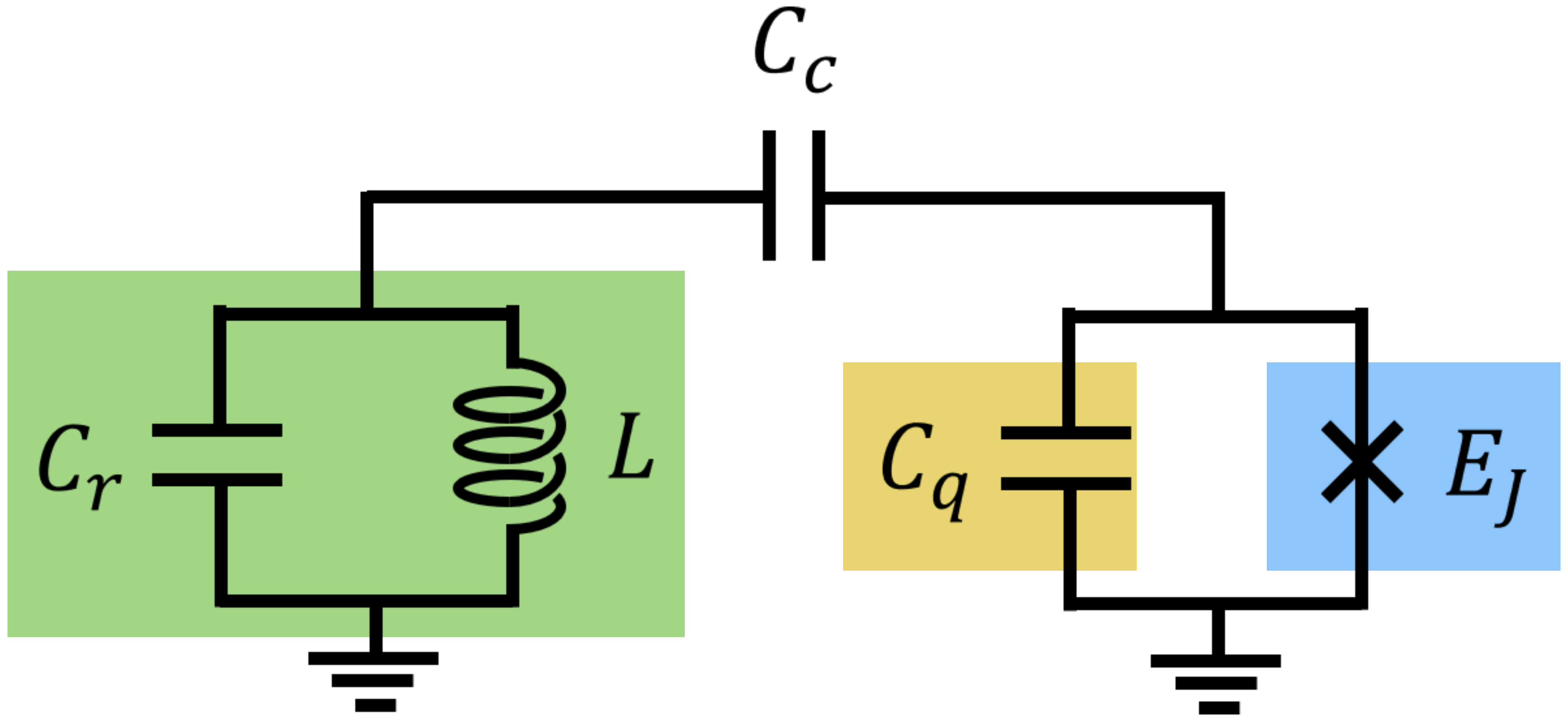
Capacitor



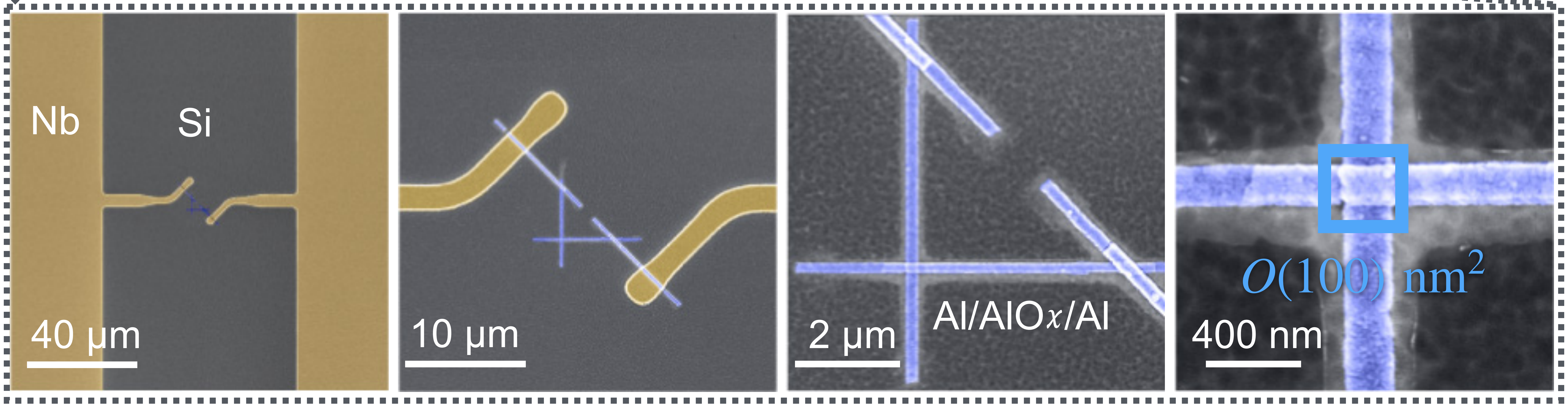
$$\mathscr{H} = \frac{\hbar}{2}\left(\omega_q + \frac{g^2}{\Delta}\right)\sigma_z + \hbar\left(\omega_c + \frac{g^2}{\Delta}\sigma_z\right)a^\dagger a$$

Physical design (2D Resonator)

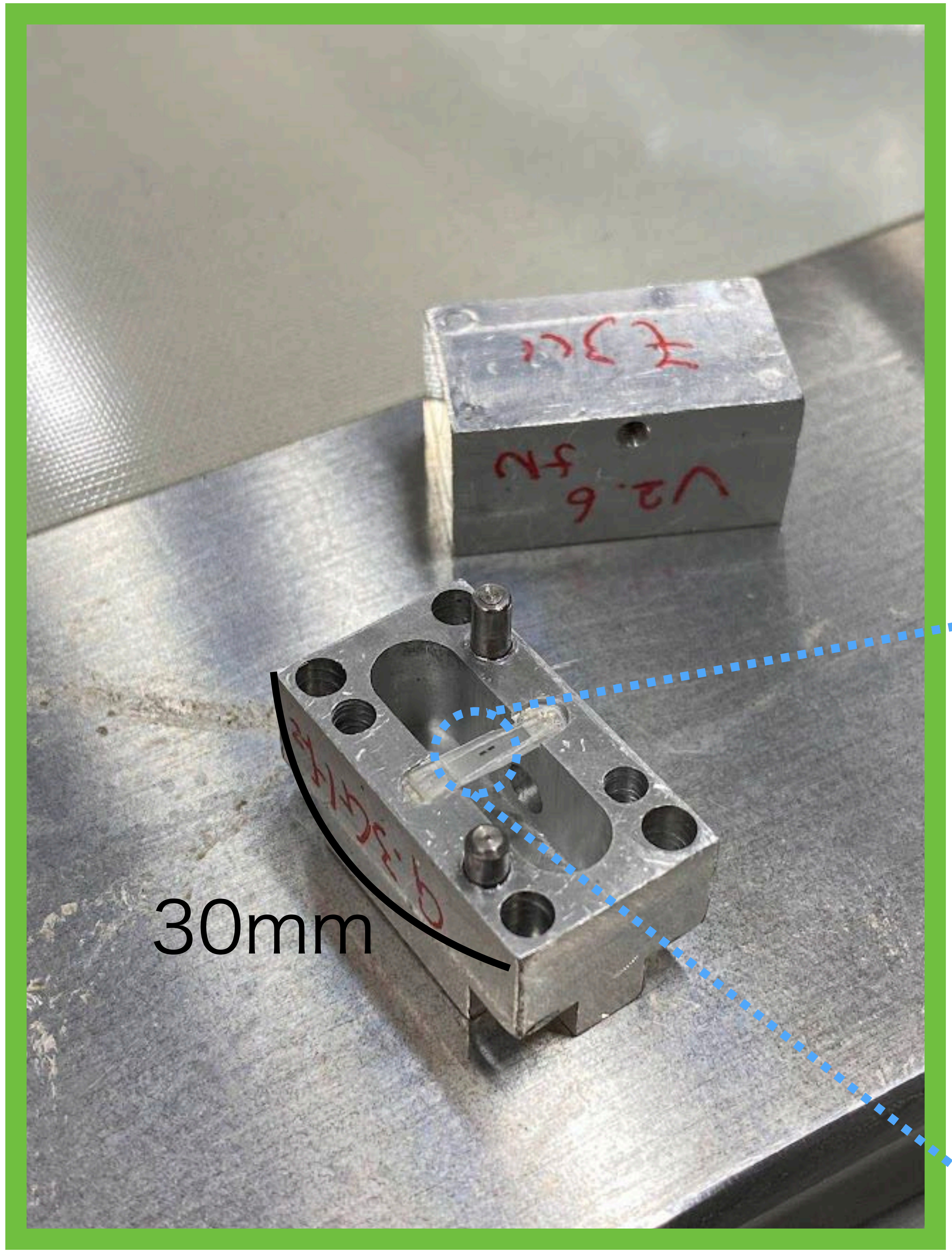


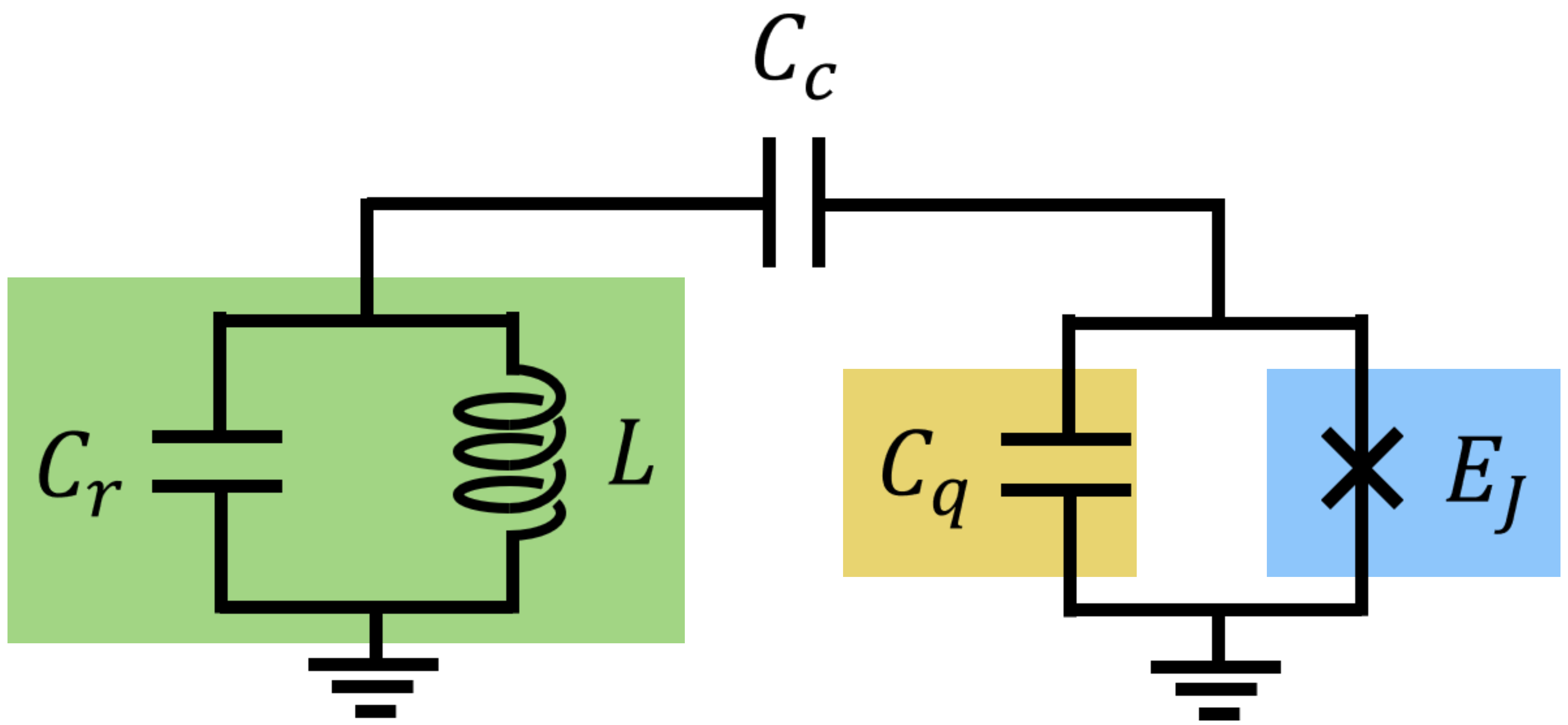


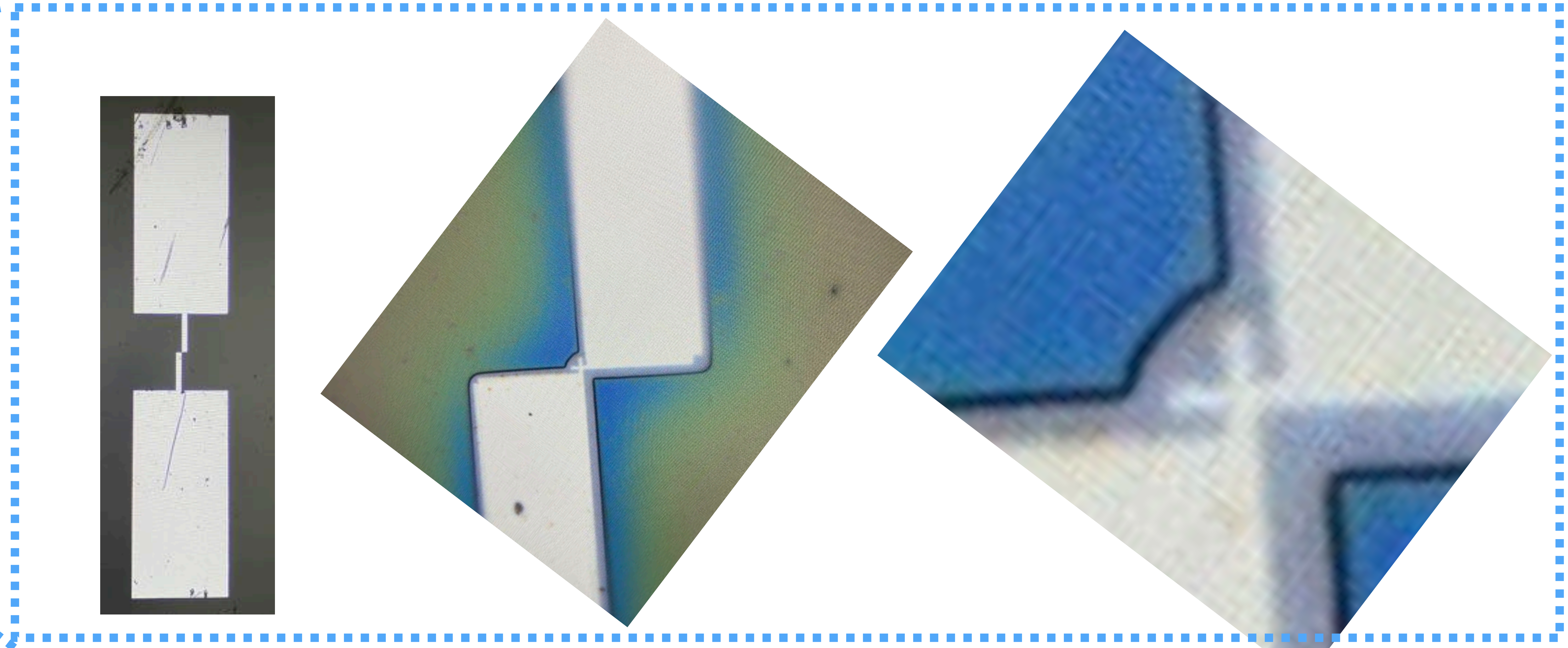
Kono et.al., 2305.02591v1



Physical design (3D Resonator)

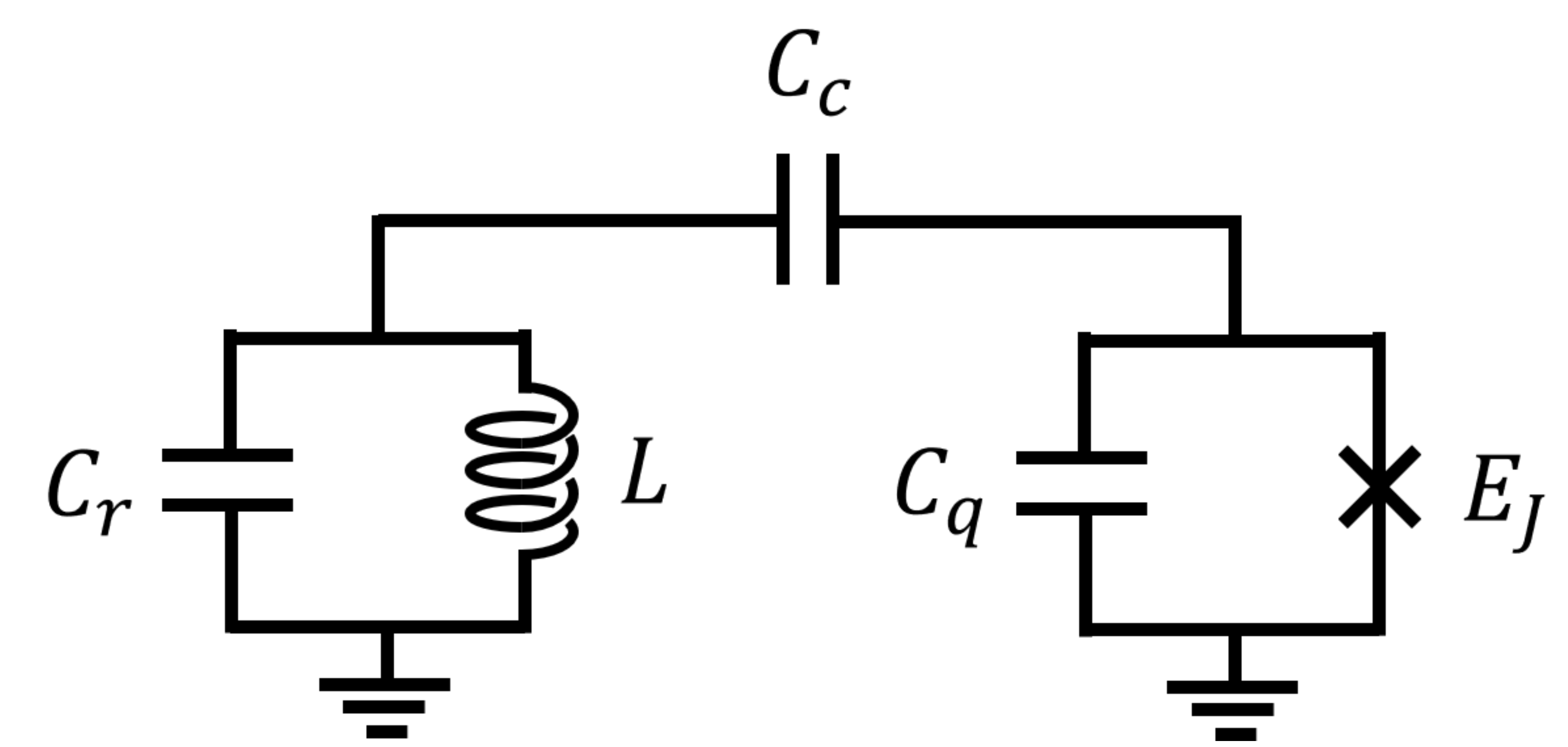


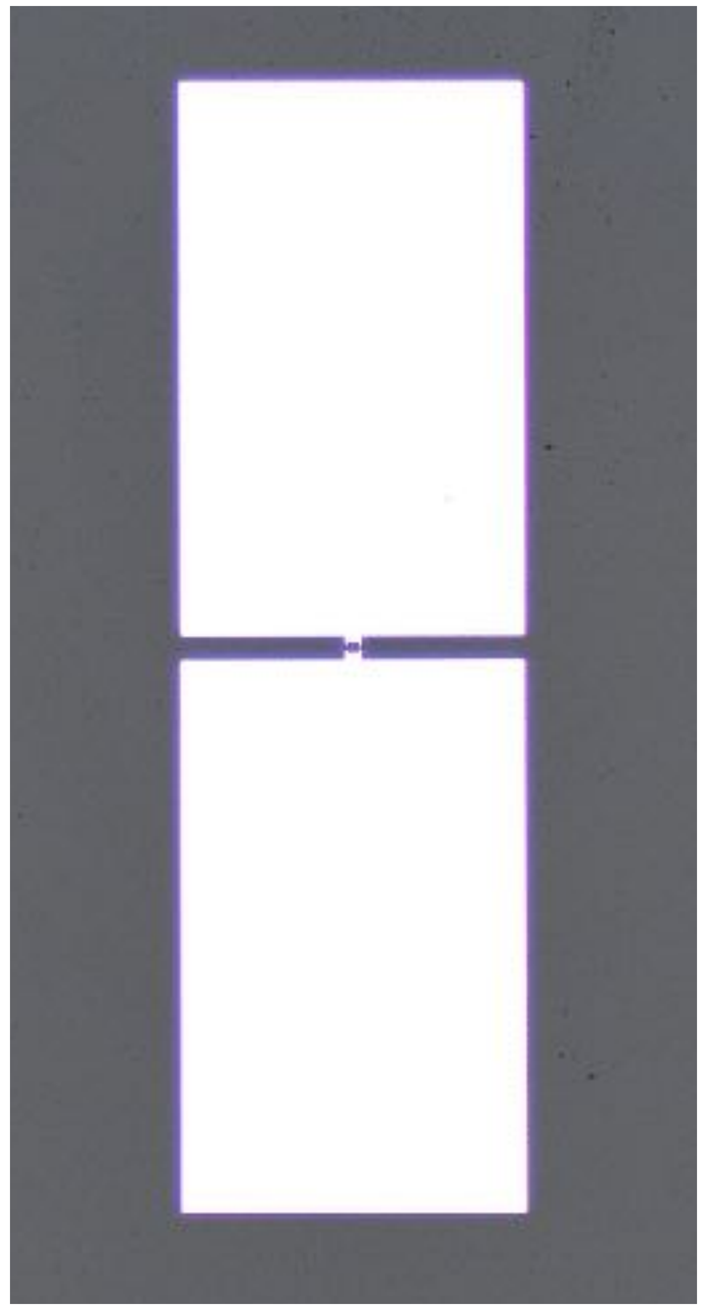




Good qubit ~ Clean qubit

Two Level System (TLS)





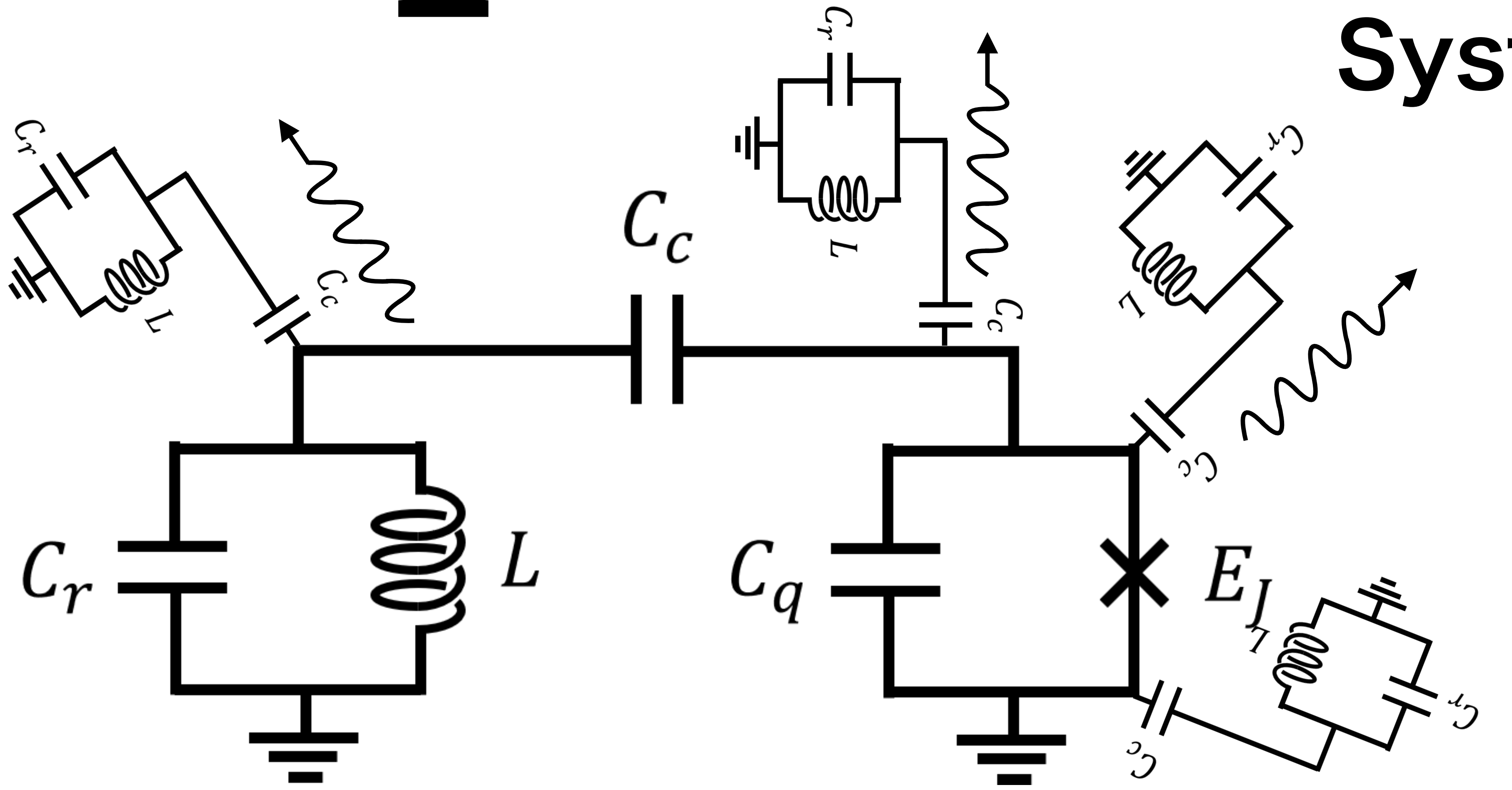
Cross-section of JJ

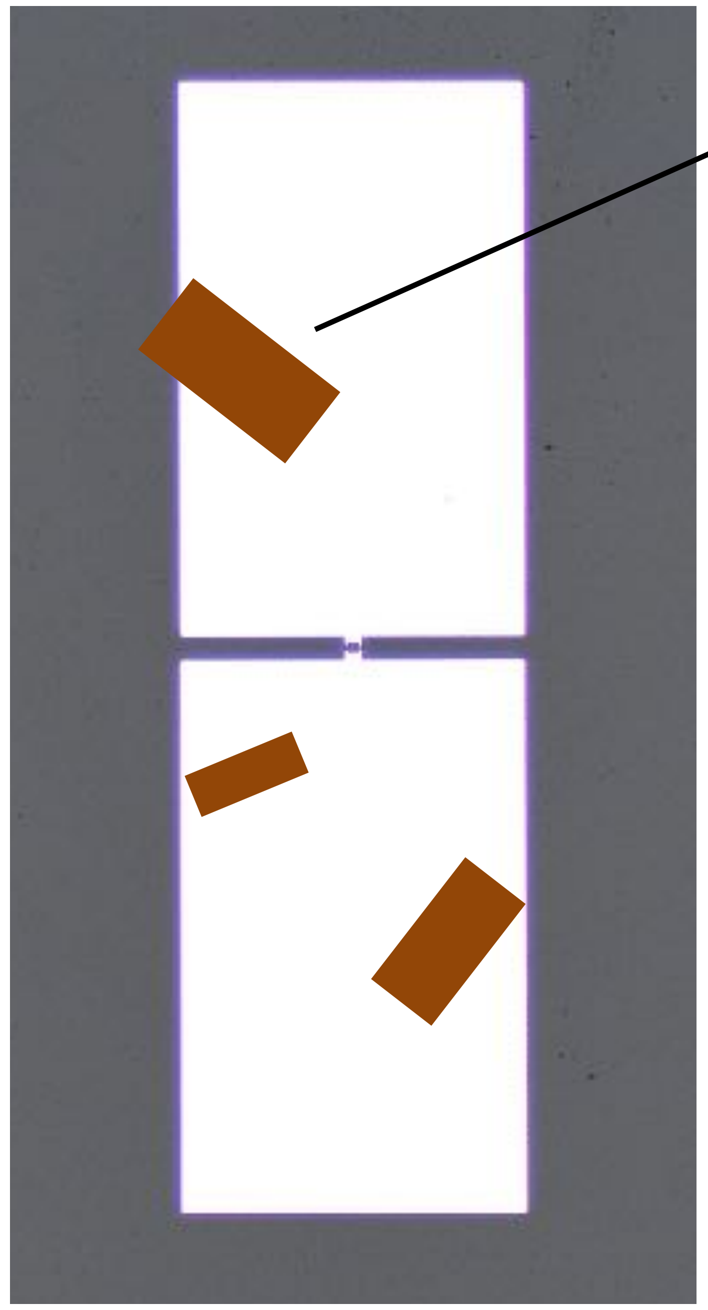
Dust

O (10) um

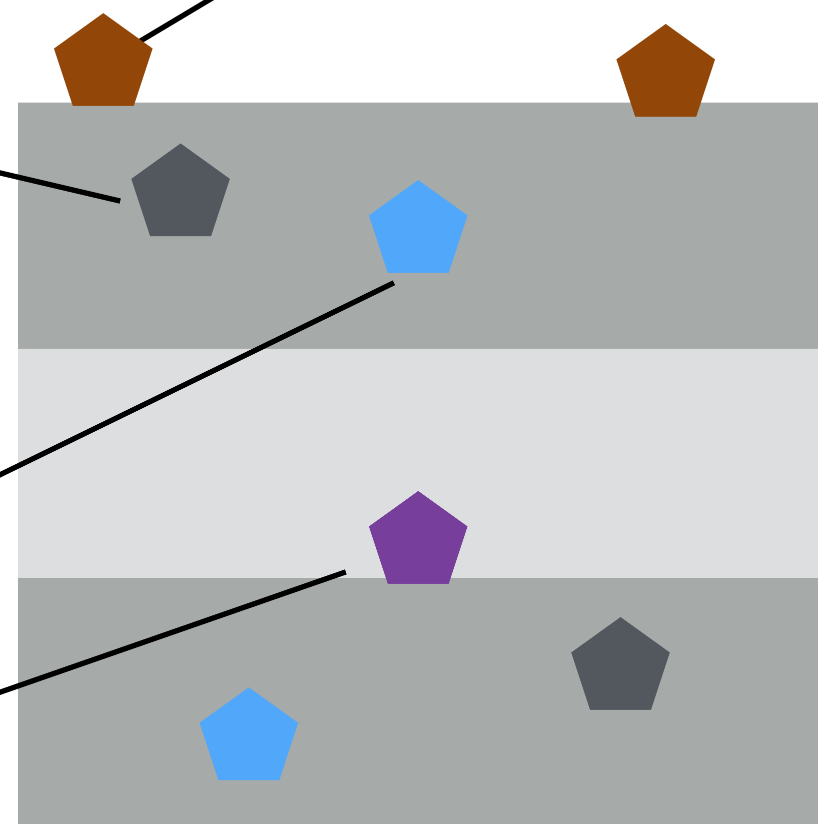
JJ

O (100) nm





Dust/Scratch



What environment you need?

Clean room

ISO Class 5 is fine

(<30 x 5 um dusts/m^3)

Equipments

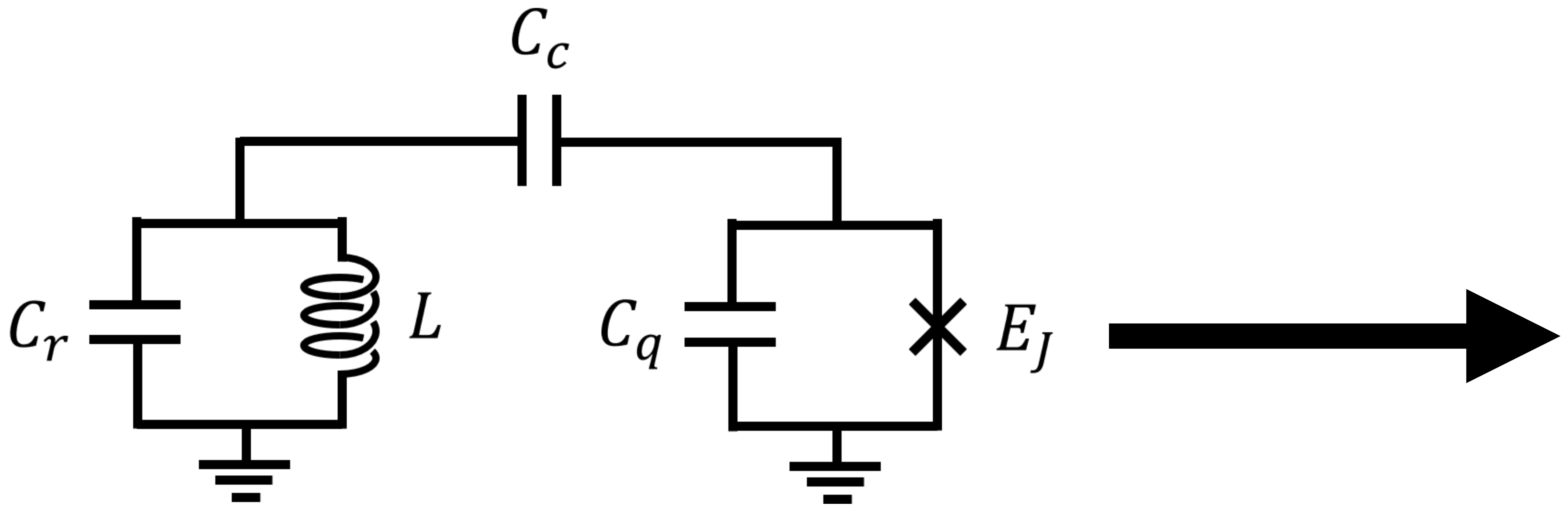
- Sputter
- EB evaporator
- Chemical draft
- Photolithography
- EB lithography
- Plasma etcher etc…

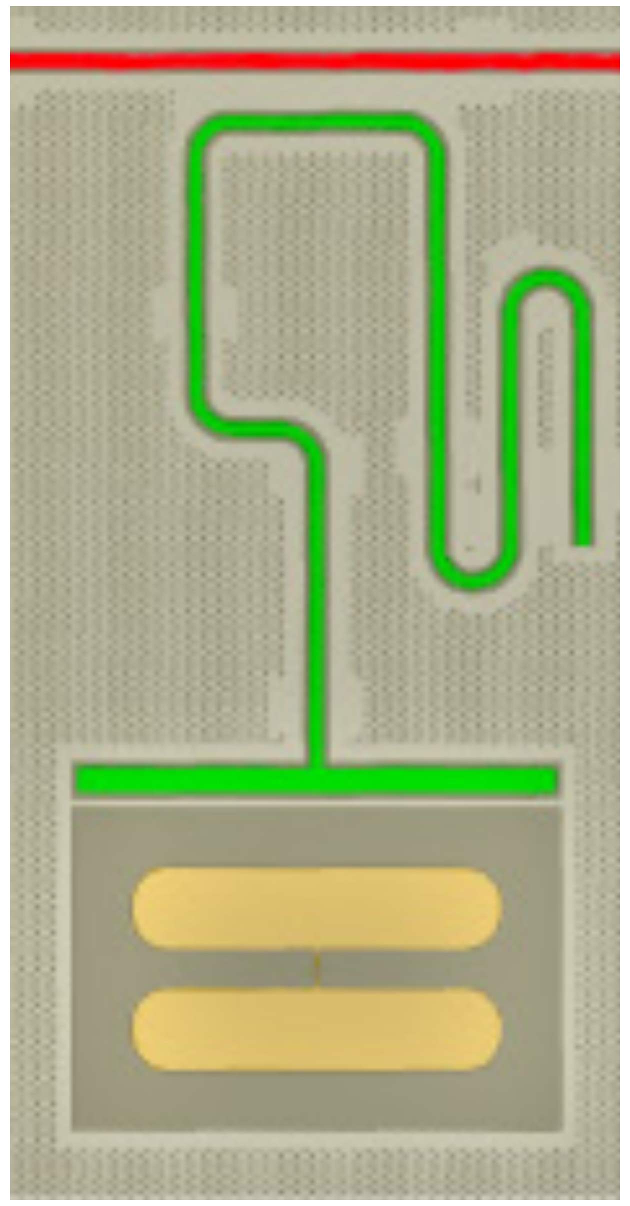
Deposition in high vacuum

$< 10^{-8}$ Pa seems very important

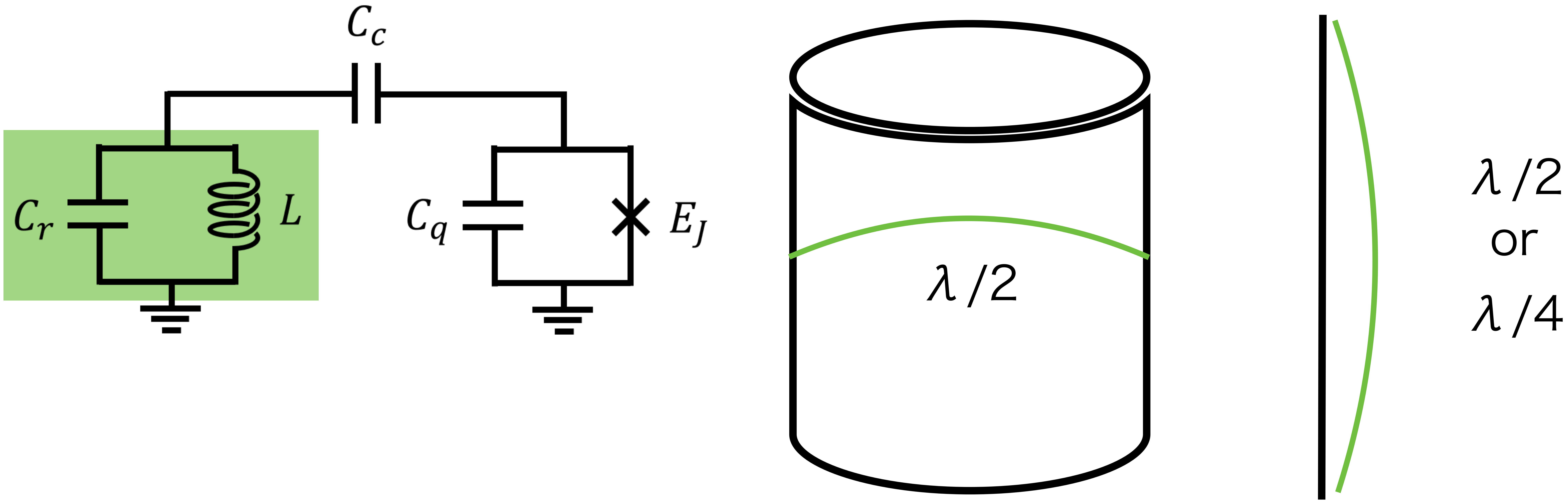
Standard Fabrication Process

1. Design





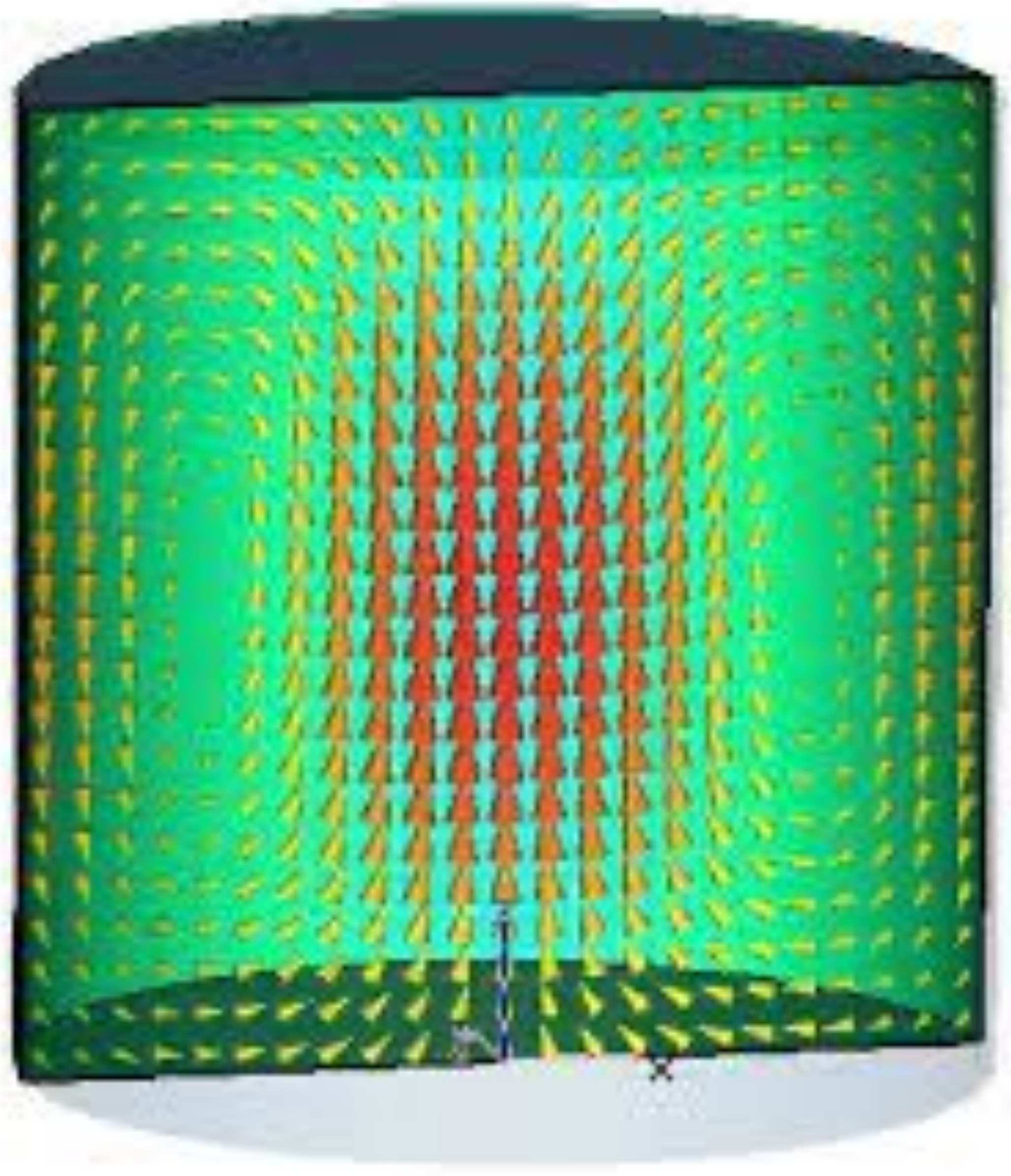
1. Design: Resonator



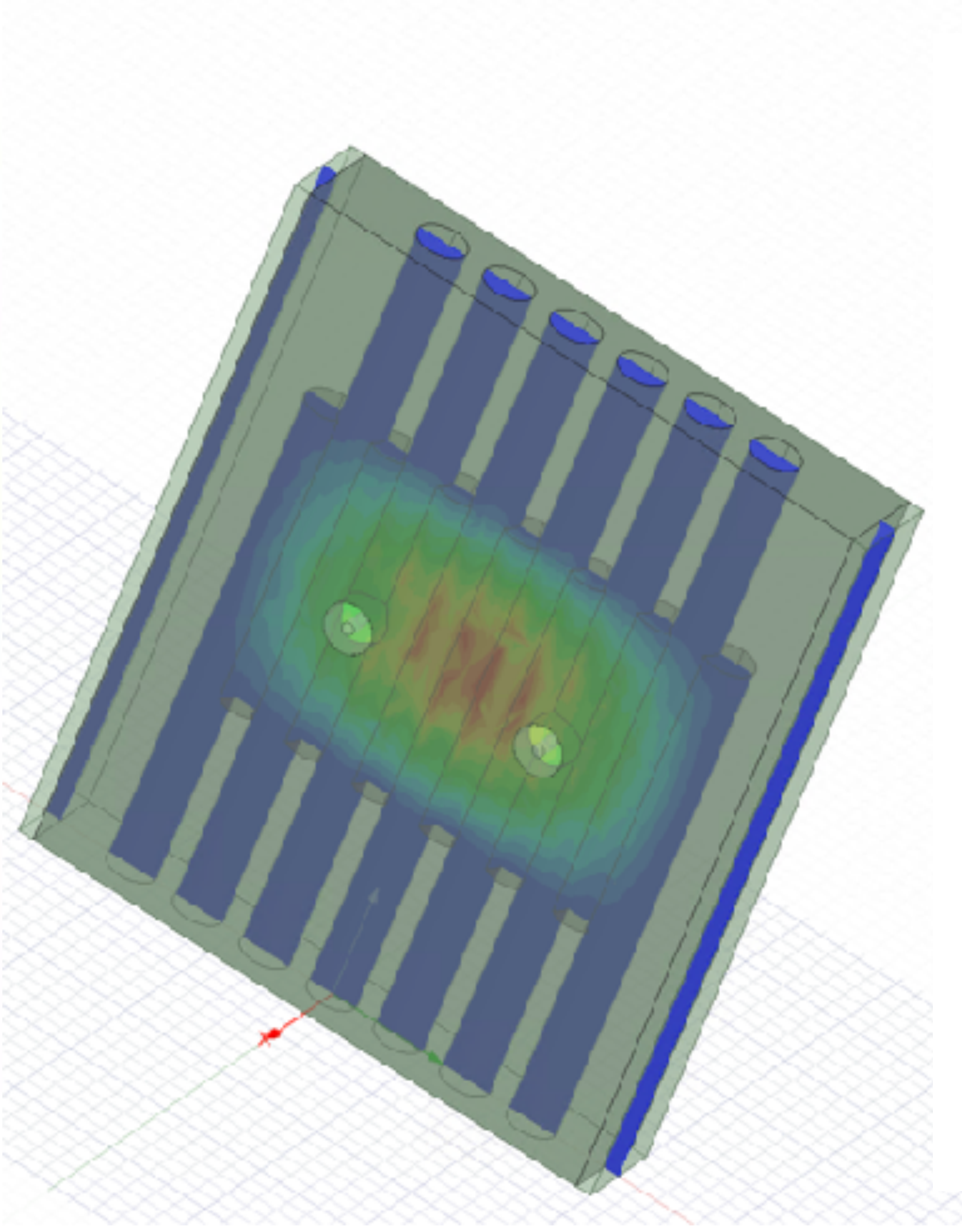
1. Design: Resonator

Detailed design is needed dedicated simulation.

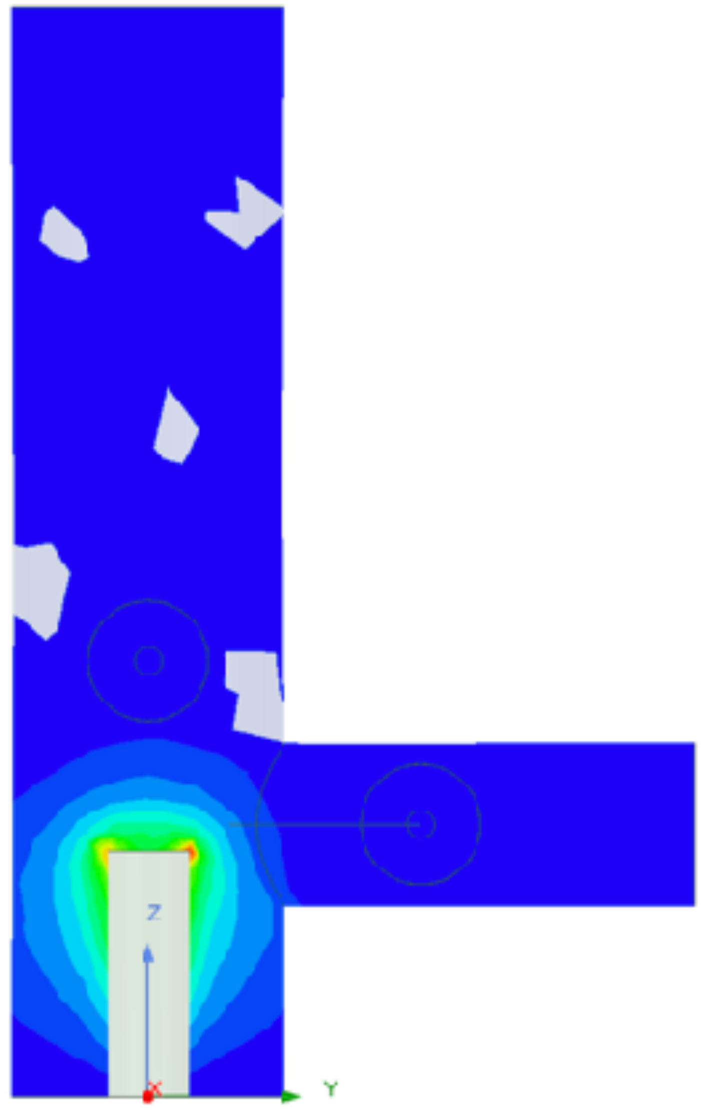
Cylinder



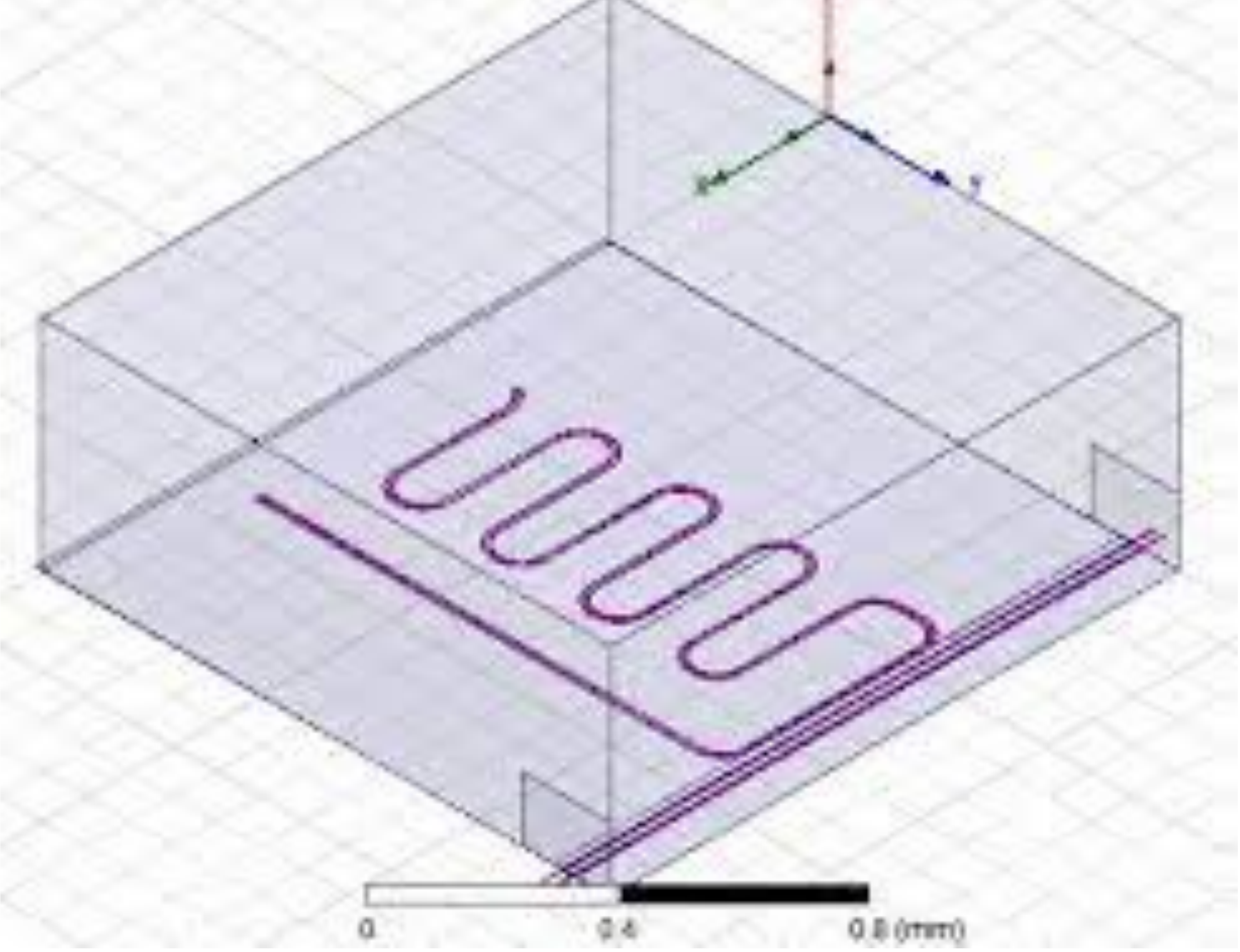
Flute



Coaxial



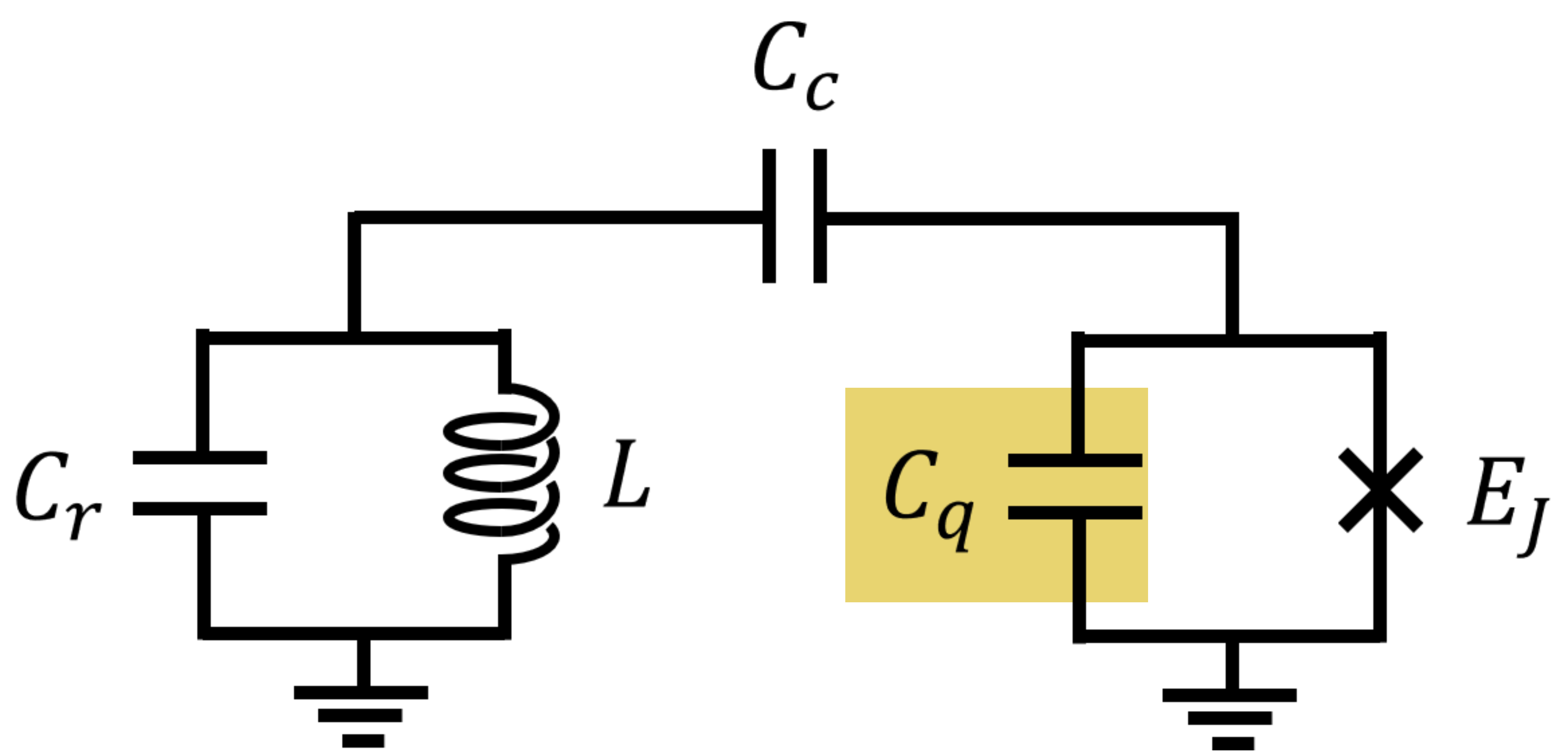
2D CPW



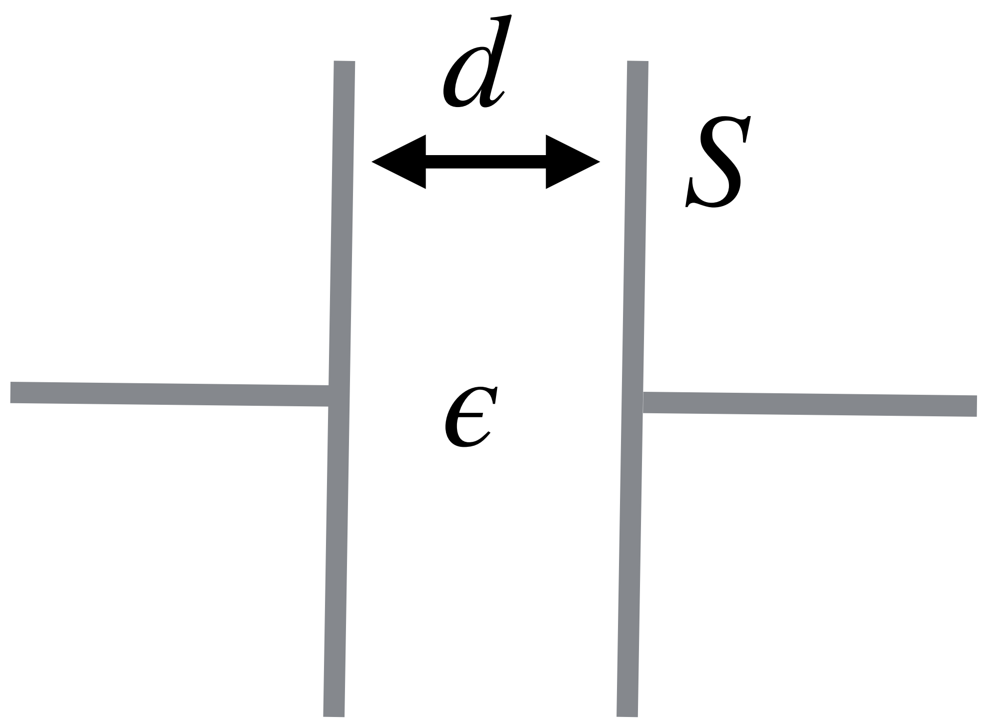
Simulation on finite element method are generally used.

ex: Ansys HFSS, Comsol multiphysics

1. Design: Capacitor

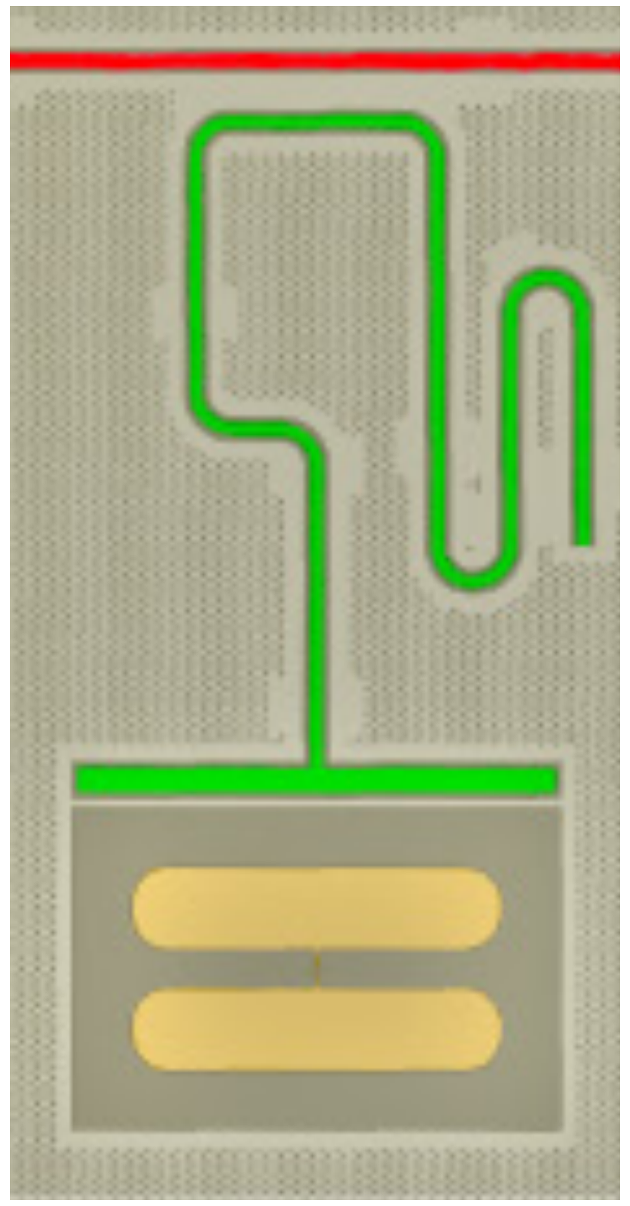


Simplest case



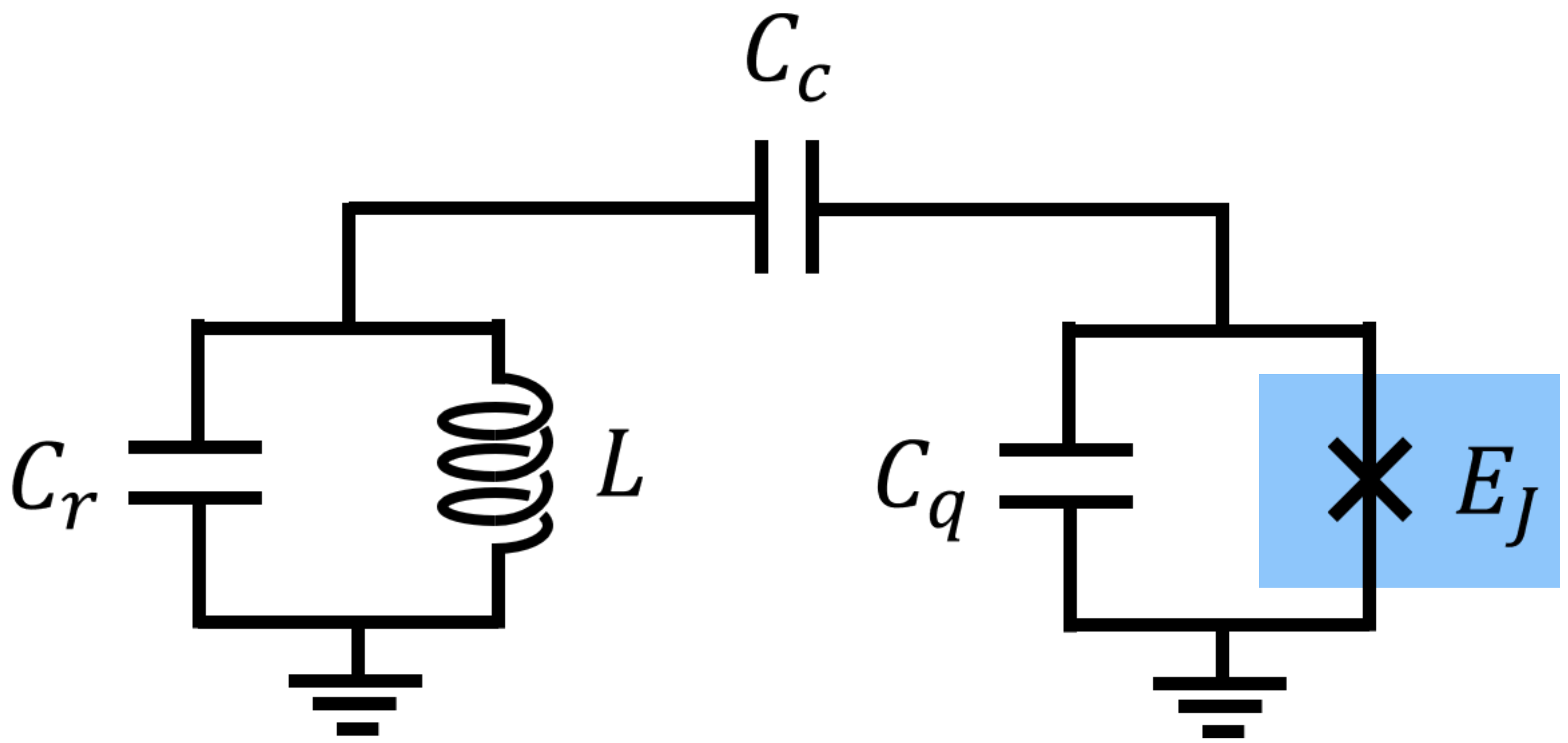
$$C = \epsilon \frac{S}{d}$$

Reality

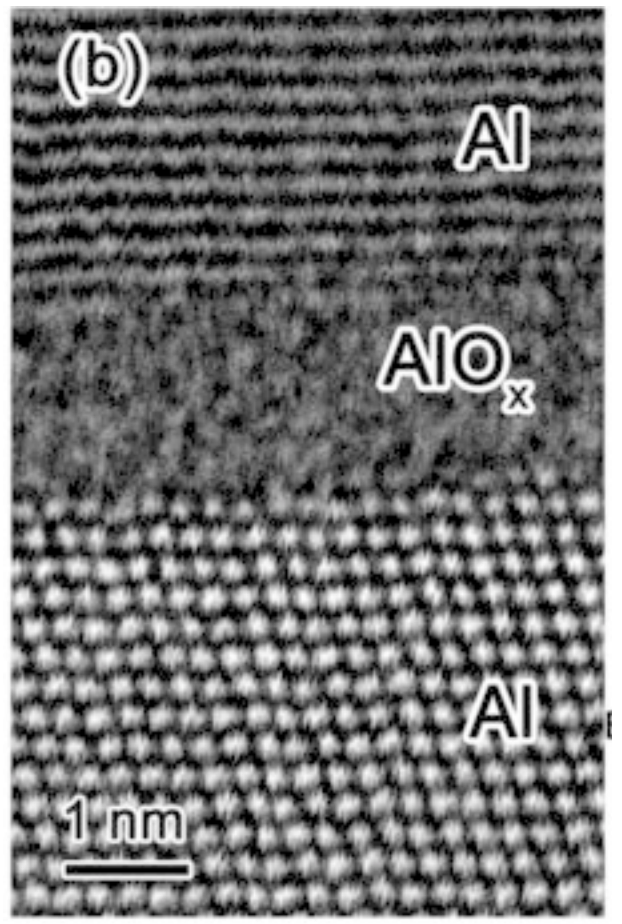


To know actual capacitance of the circuit, dedicated FEM simulation is necessary.

1. Design: Josephson Junction

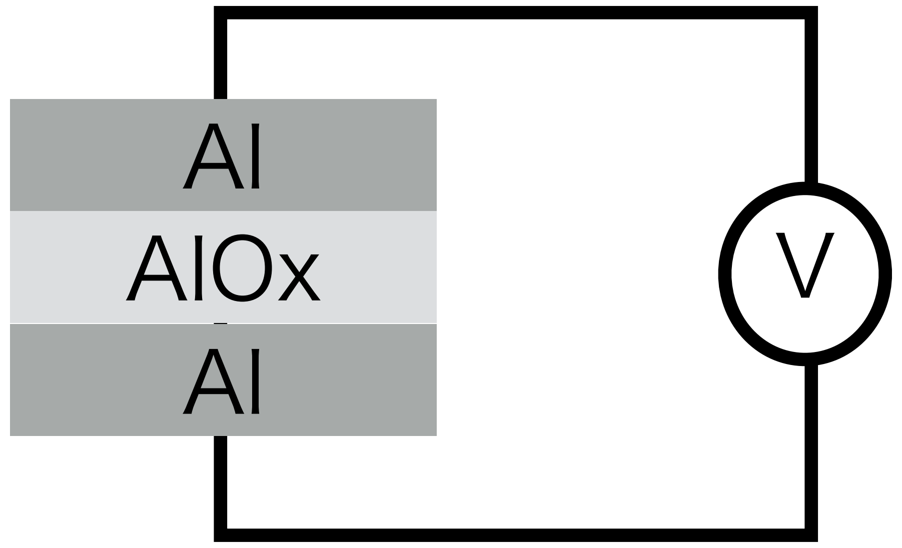


PhysRevLett.11.104



In reality, controlling R is not easy.

People do try and error at their environment



from Ambegaokar-Baratoff formula

$$E_J \sim \frac{\hbar \pi \Delta_{sc}}{4e^2 R}$$

at 0K

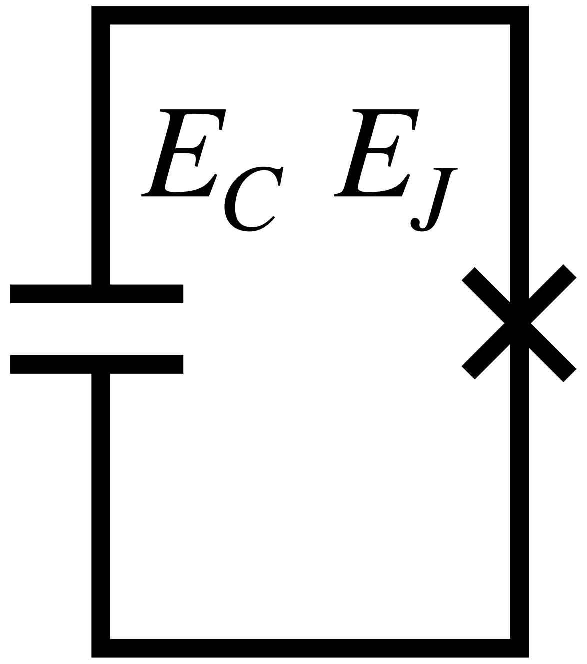
→ E_J can be designed by AlOx resistance (R)

Mostly the size is the order of <u>O(100) × O(100) × O(1) nm</u>

thickness of AlOx

1. Design: Advanced Designs

Charge qubit



<u>**Transmon**</u>

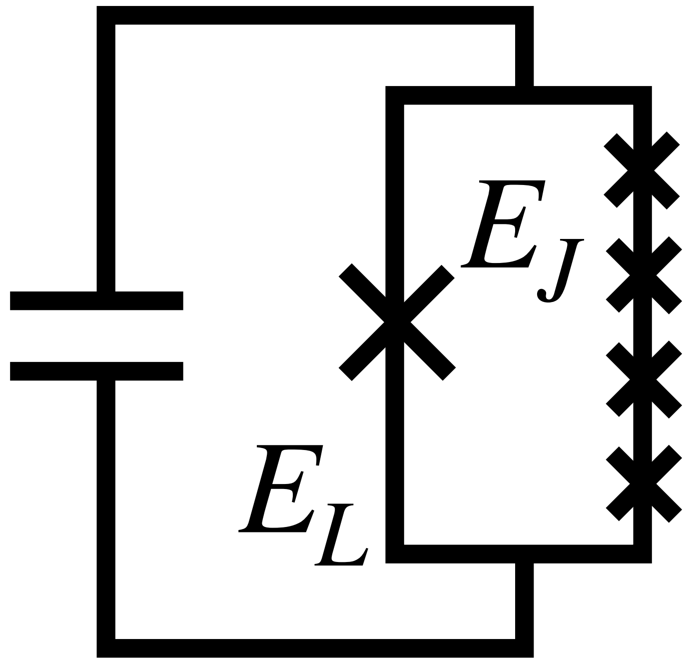
$$E_C \ll E_J$$

Cooper pair box

$$E_C \gg E_J$$

→ Fixed freq. qubit

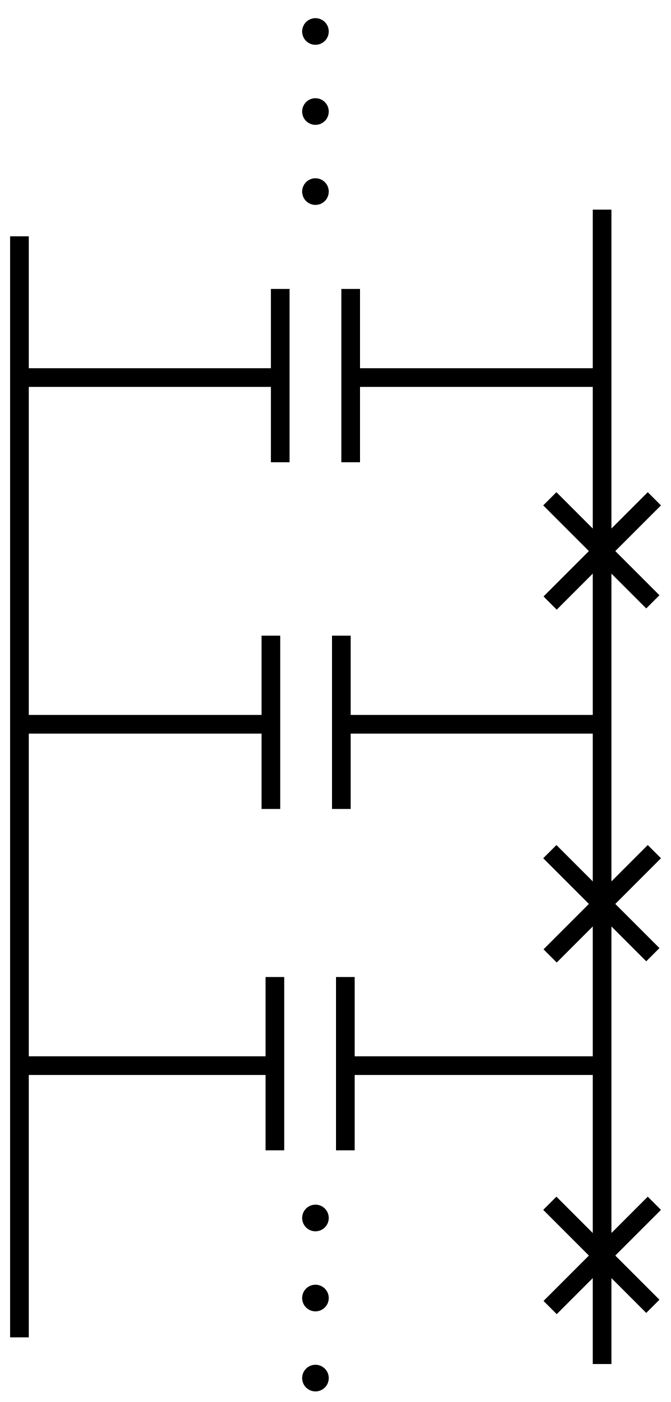
Fluxonium



$$E_C \sim E_J$$
$$E_L \ll E_J$$

→ qubit/magnetometers

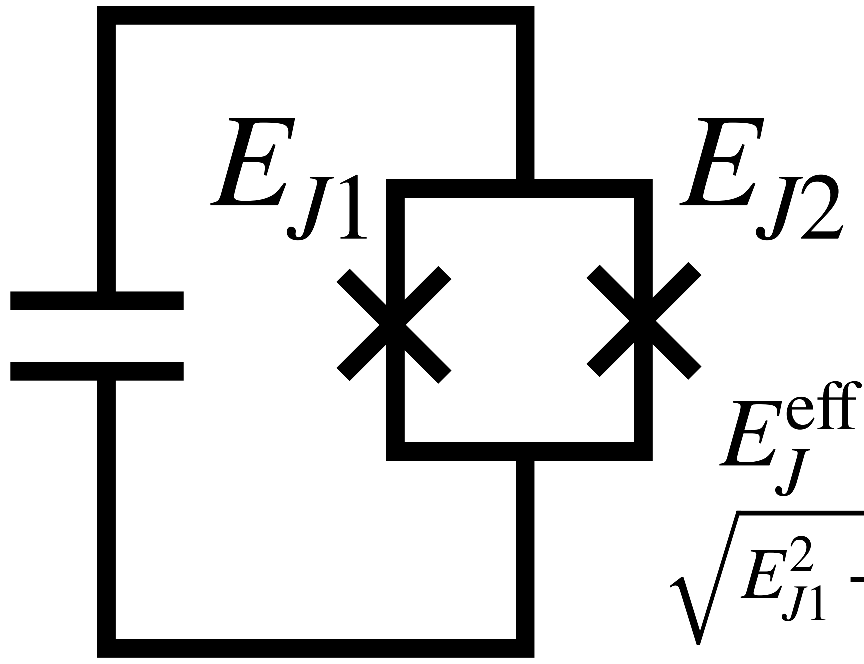
Transmission line



→ Katayama-san's study

Traveling Wave Parametric Amplifier

SQUID

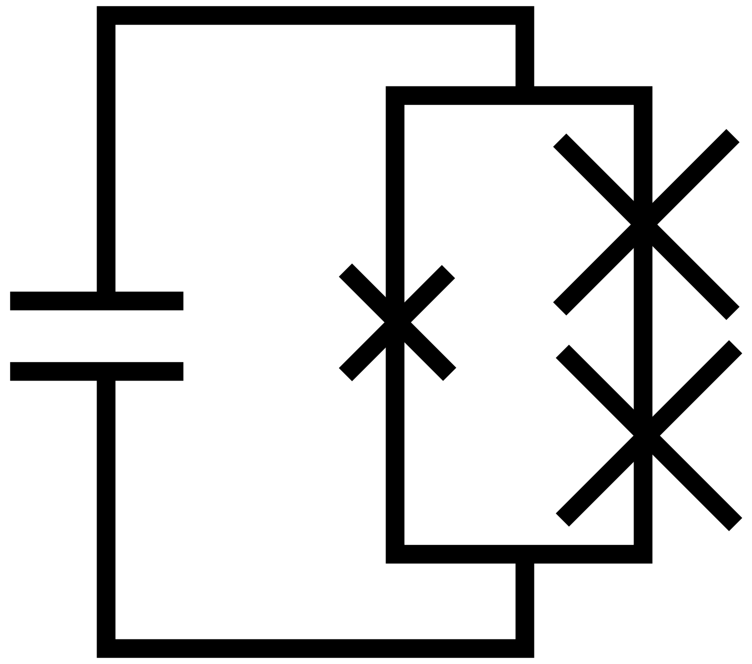


$$E_J^{\mathrm{eff}}(\phi_{\mathrm{ext}}) = \sqrt{E_{J1}^2 + E_{J2}^2 + 2E_{J1}E_{J2}\cos\phi_{\mathrm{ext}}}$$

→ Tunable freq. qubit

Josephson Parametric Amplifier

Flux qubit



$$E_C \sim E_J \sim E_L$$

→ qubits/ study amorphous⋯

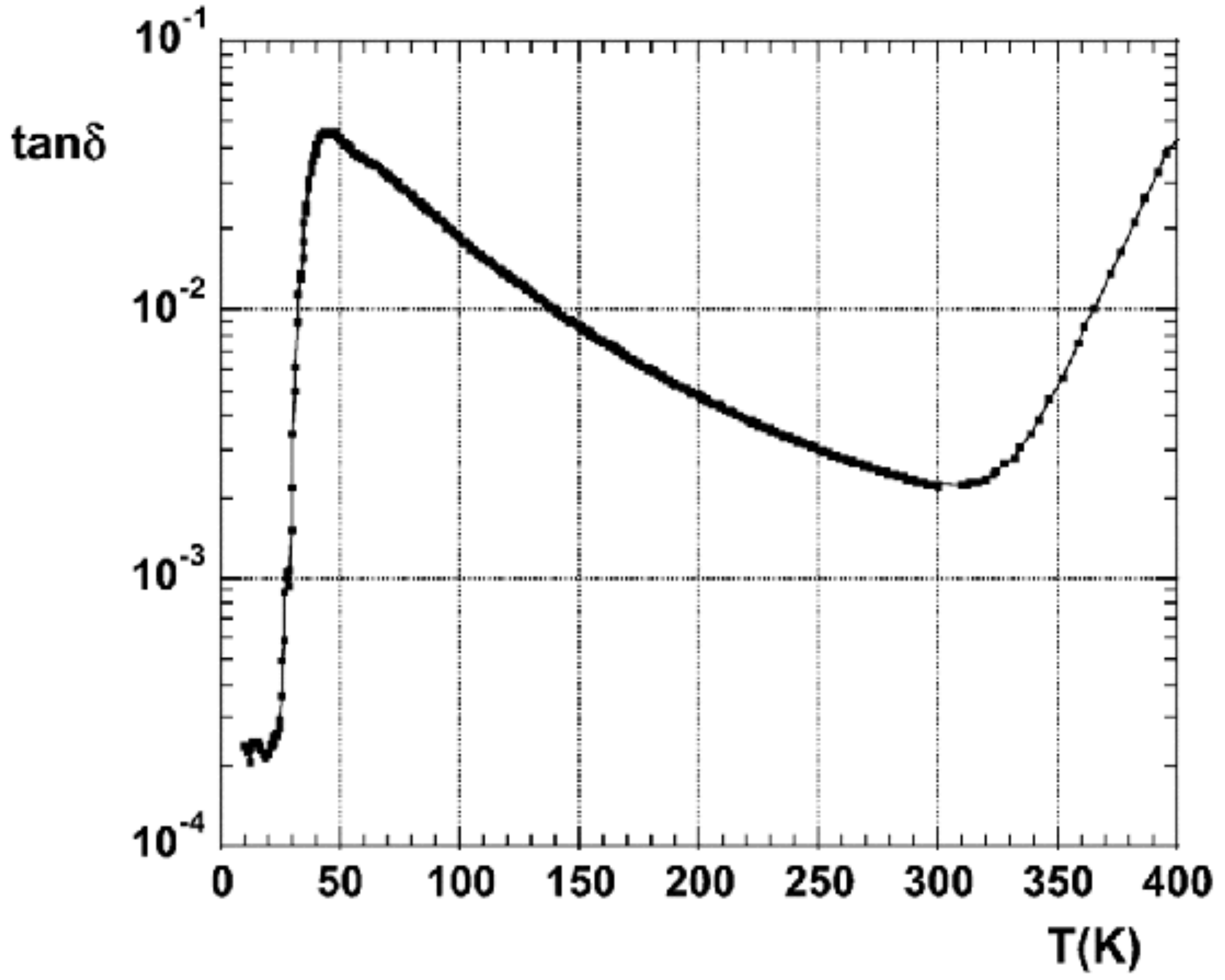
2. Select Substrate

Silicon

Resistance: >10^4 Ωcm
(Floating Zone)

Loss tangent: ~ 10^-4 @ 10 mK

Price: 1000 JPY / 100 mm wafer

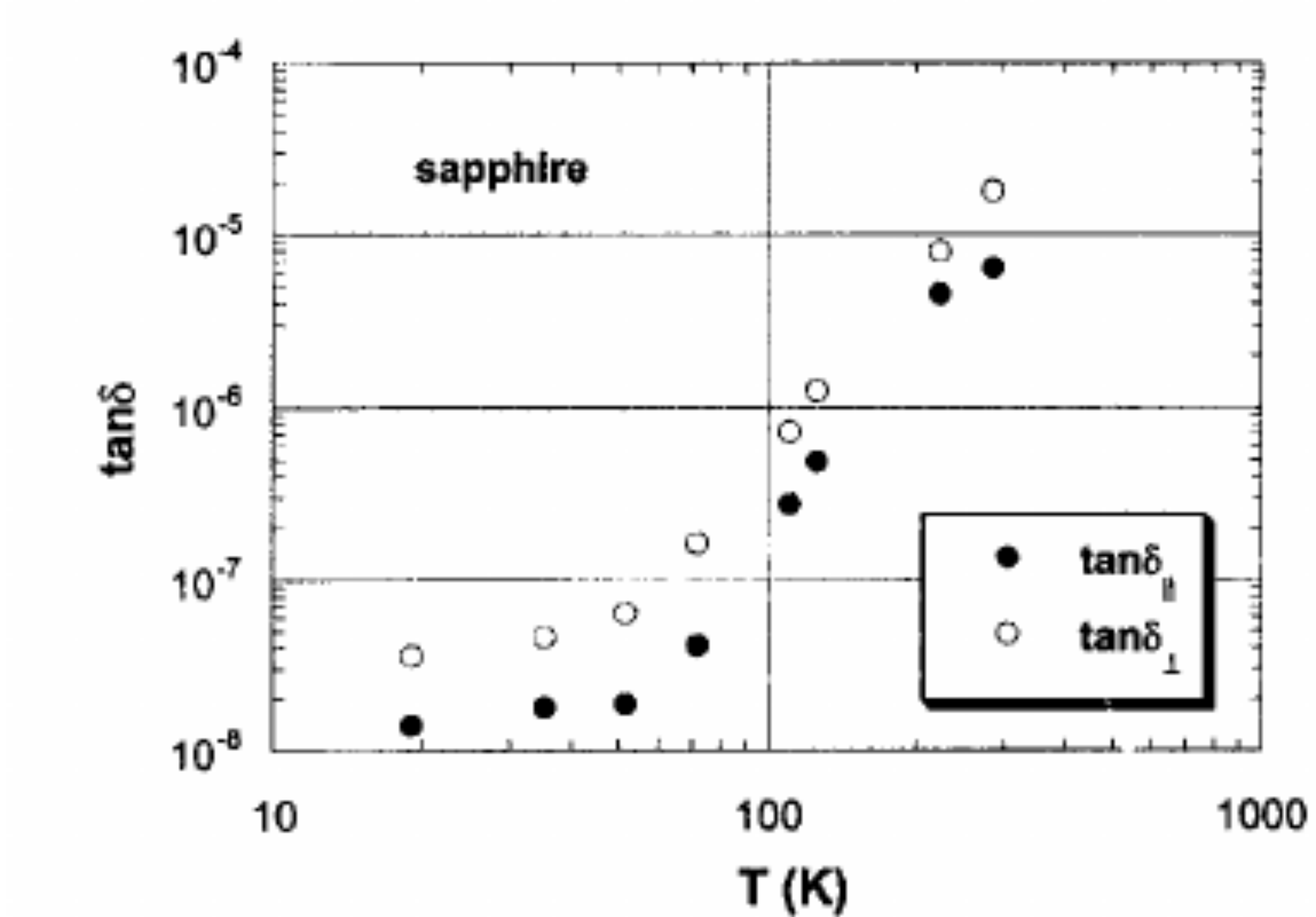


Sapphire

Resistance: 10^11Ωcm

Loss tangent: ~ 10^-8 @10 mK

Price: 4000 JPY/ 100 mm wafer



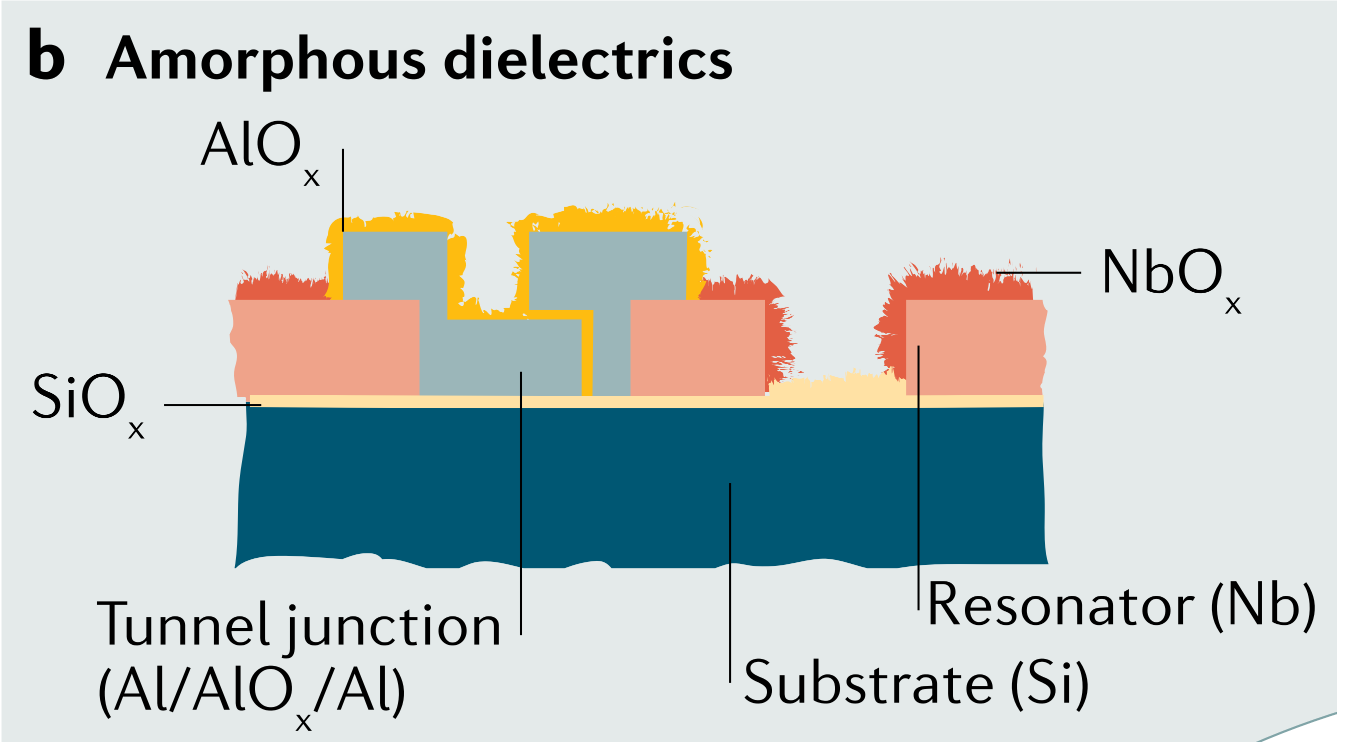
2. Substrate Cleaning

Shipped wafers

Source of impurity

- Dusts/Organic substances during fabrication
- Dusts/Organic substances during packing
- Native oxide on silicon substrate etc…

Nat Rev Mater 6, 875–891



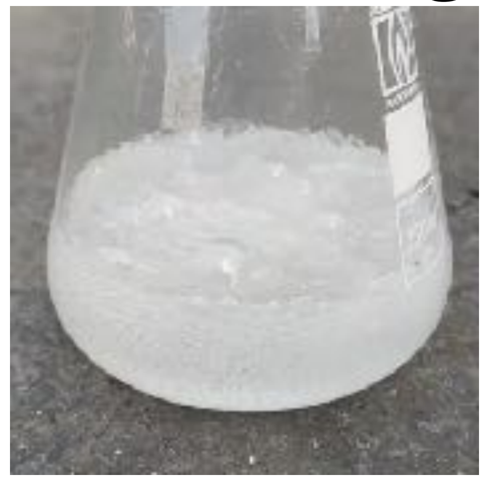
Contamination directly affects coherence of qubits

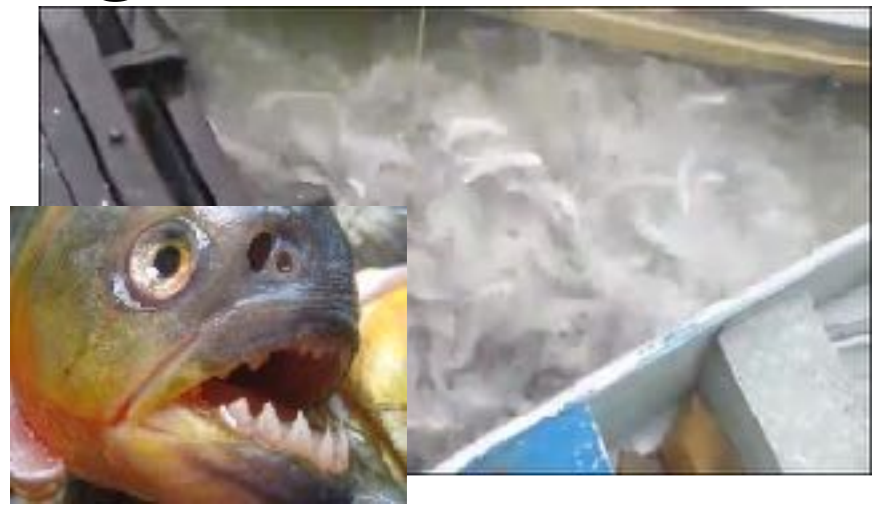
Typical Cleaning Processes

Piranha solution

$H_2SO_4 + H_2O_2$

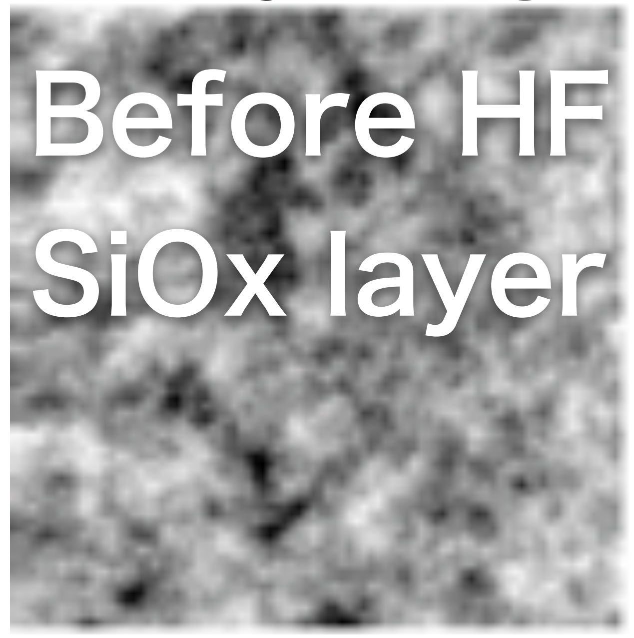
Removing organic substances

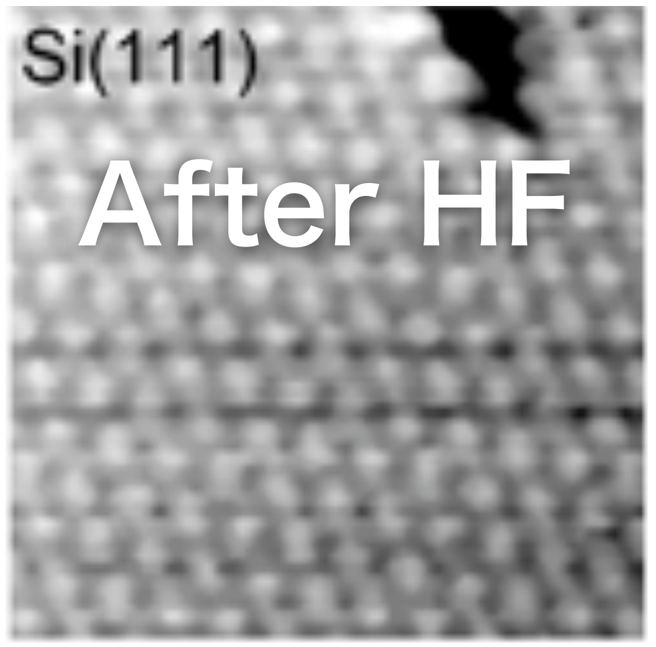




Hydrofluoric Acid (HF)

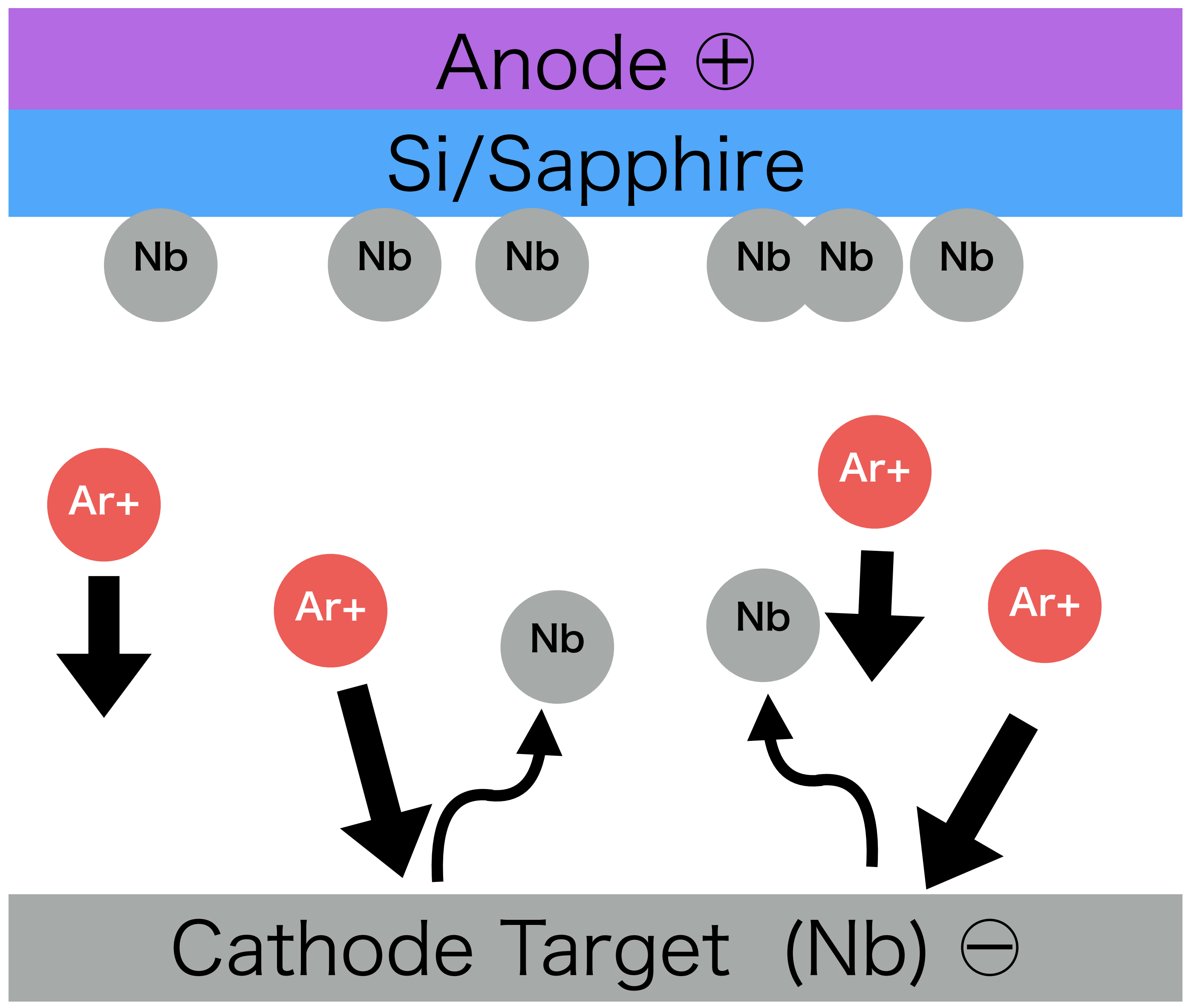
Remove oxidation layer & Hydrogen termination





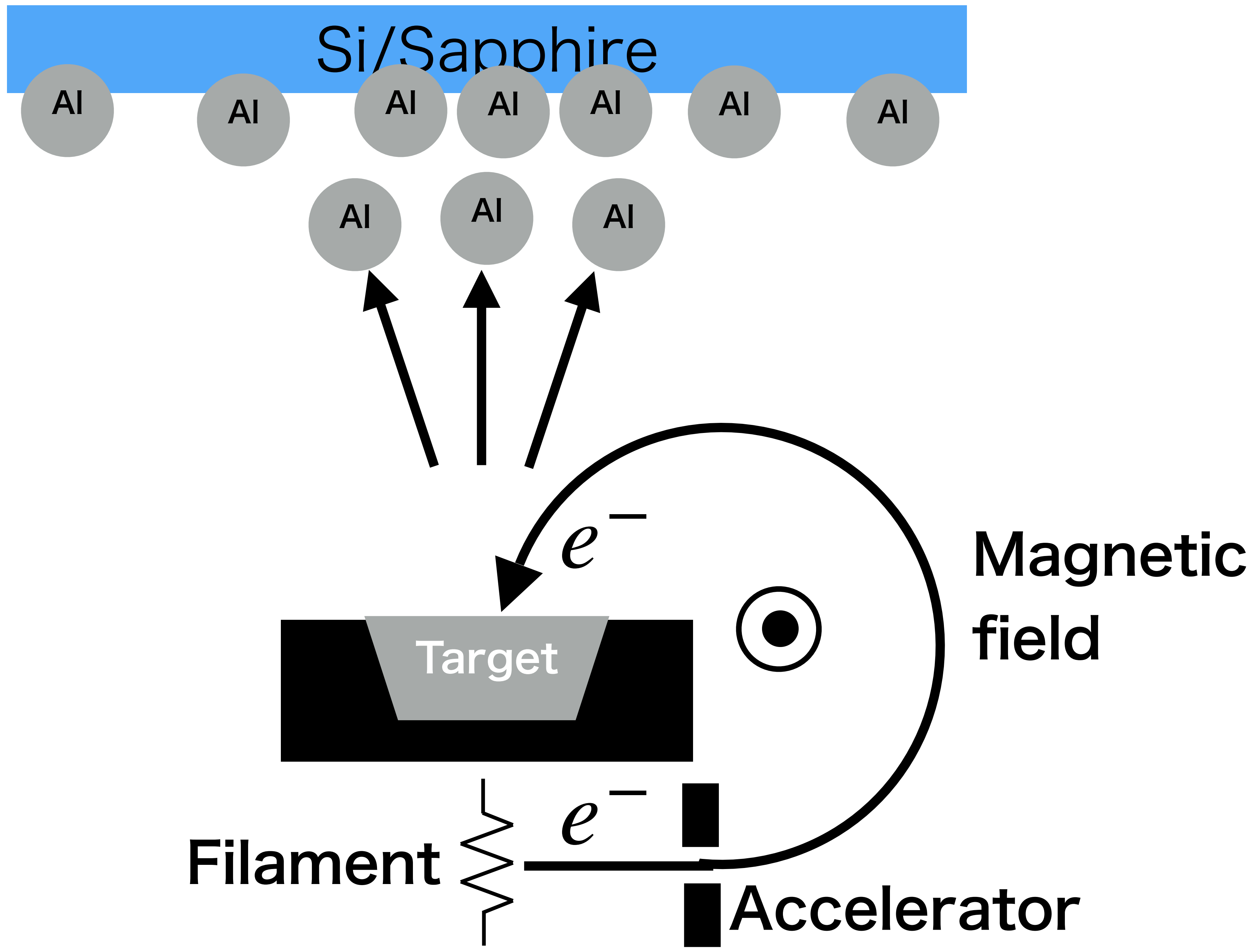
Make sure to use chemical draft and proper protections

3. Thin film deposition



←Sputter

EB vapor deposition →



Cons:

- Homogeneity film
- Larger area deposition

→ **Used to make capacitors**

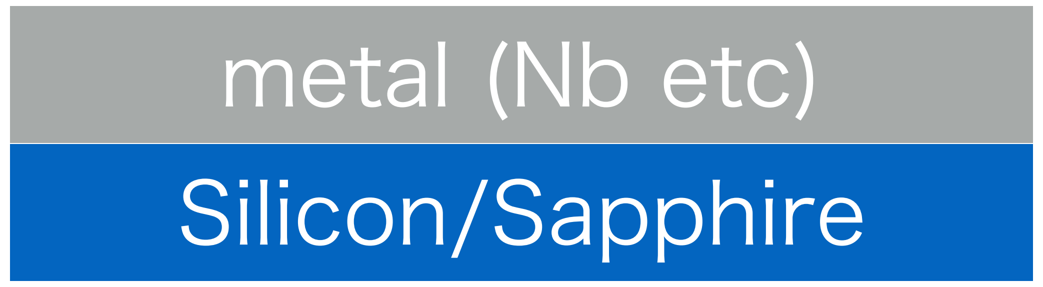
Cons:

- **Directivity**
- Faster deposition

→ **Used to make JJ**

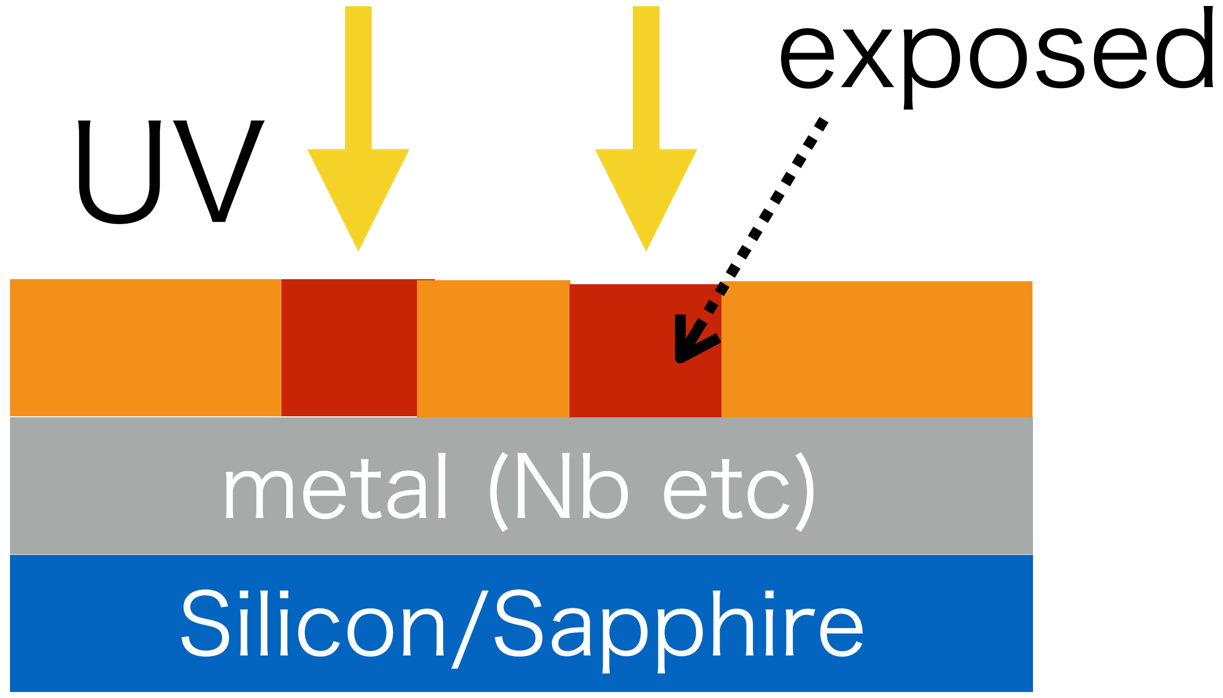
4. Photolithography

0. Prepare substrate



1. Spincoating Photoresist

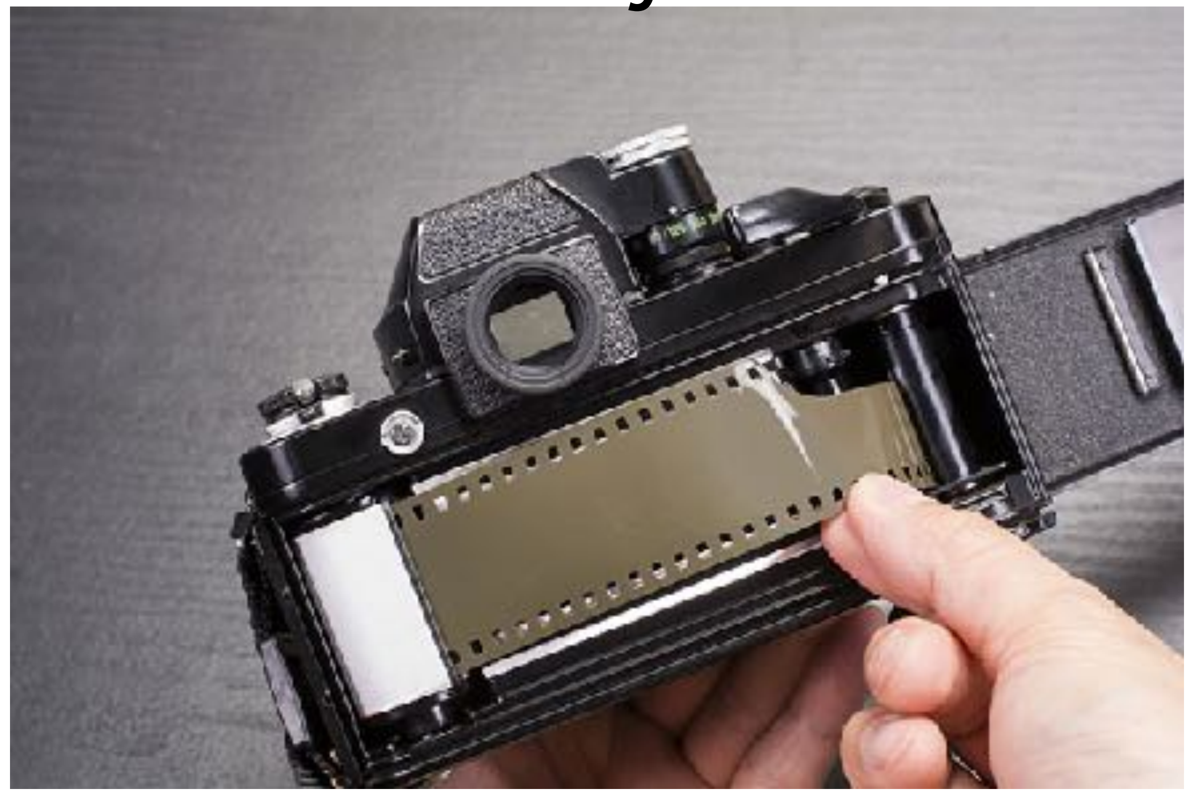
2. Exposure



3. Development

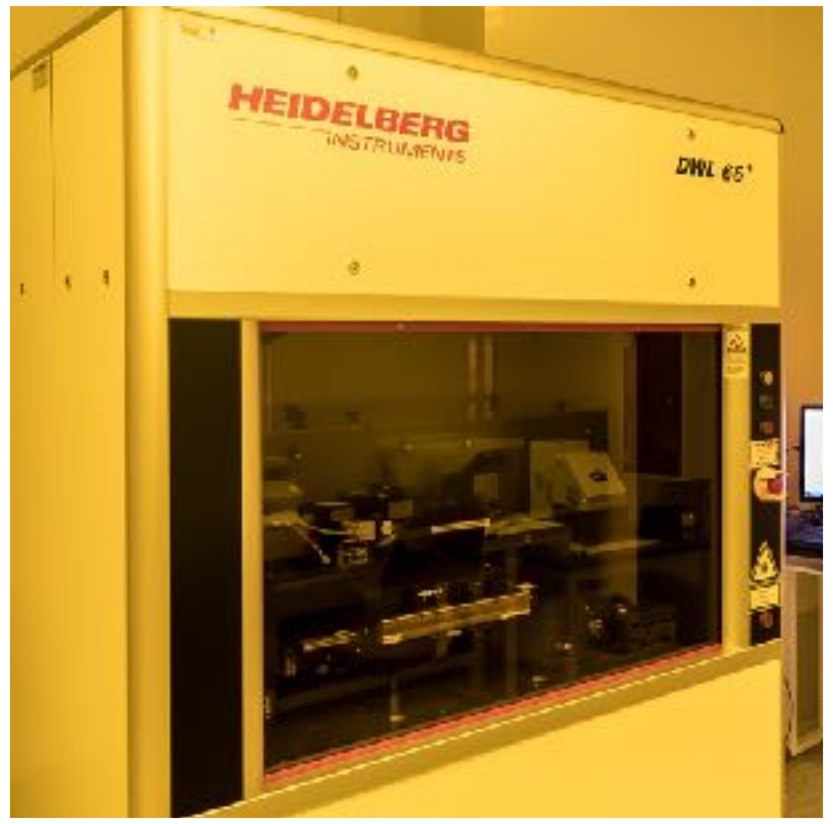
remove exposed or unexposed resist

Good example for over ~ 30 years old

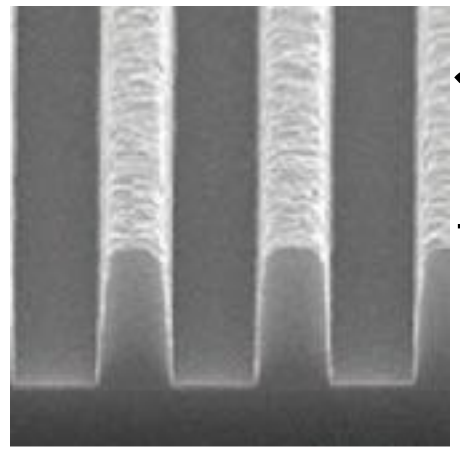


spincoater

Photolithography



Development



~ 1um resolution

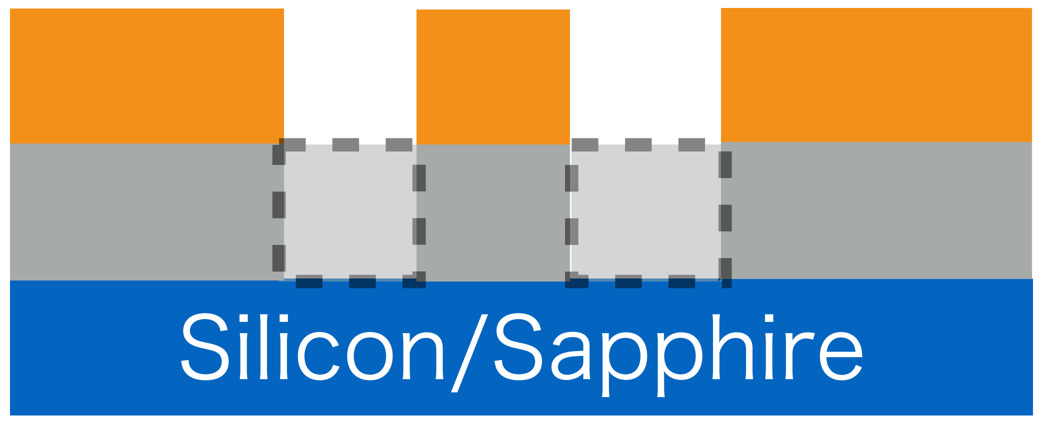
→ only for larger structures

5. Etching

0. After development

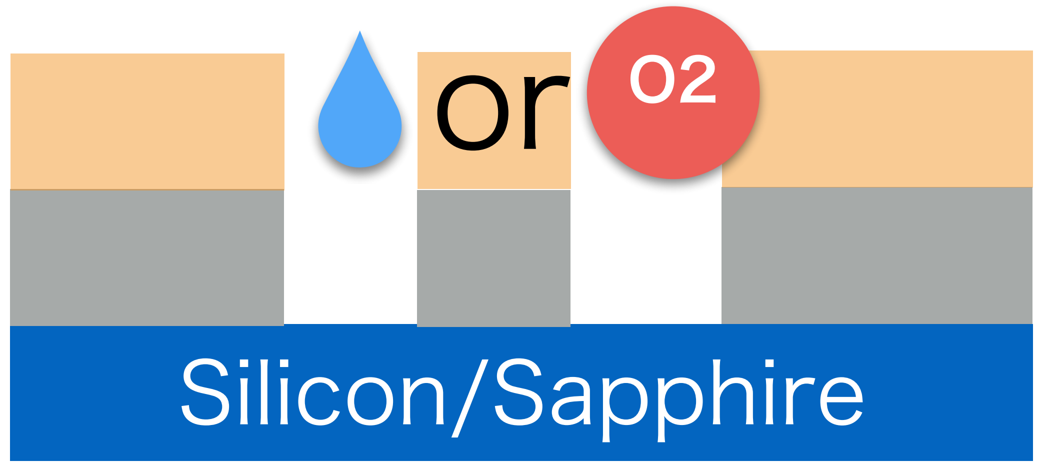
1. Etching

Removing metal
not masked by resist



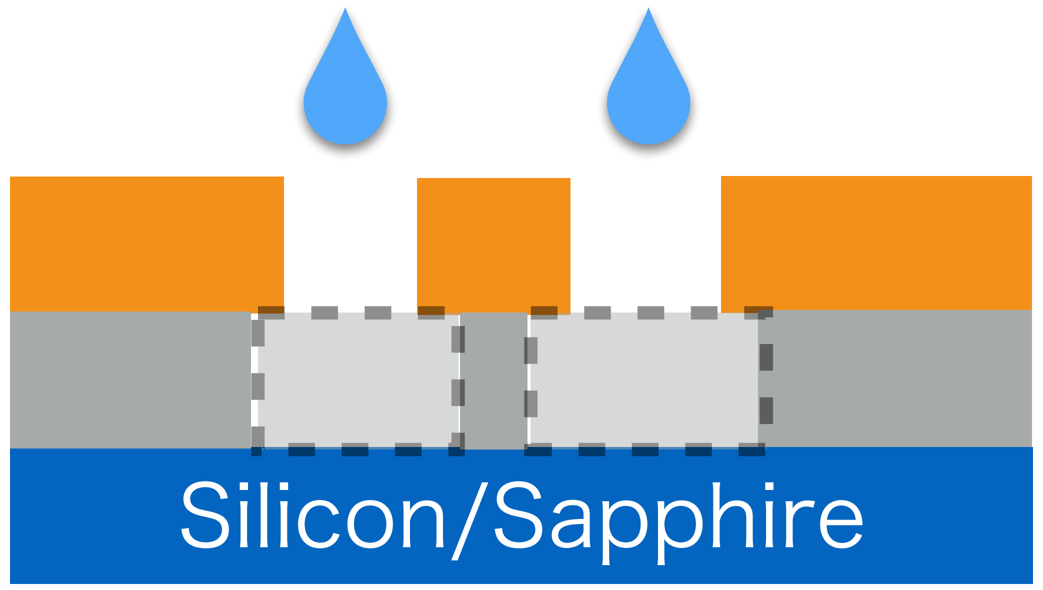
2. Ashing

Removing resist



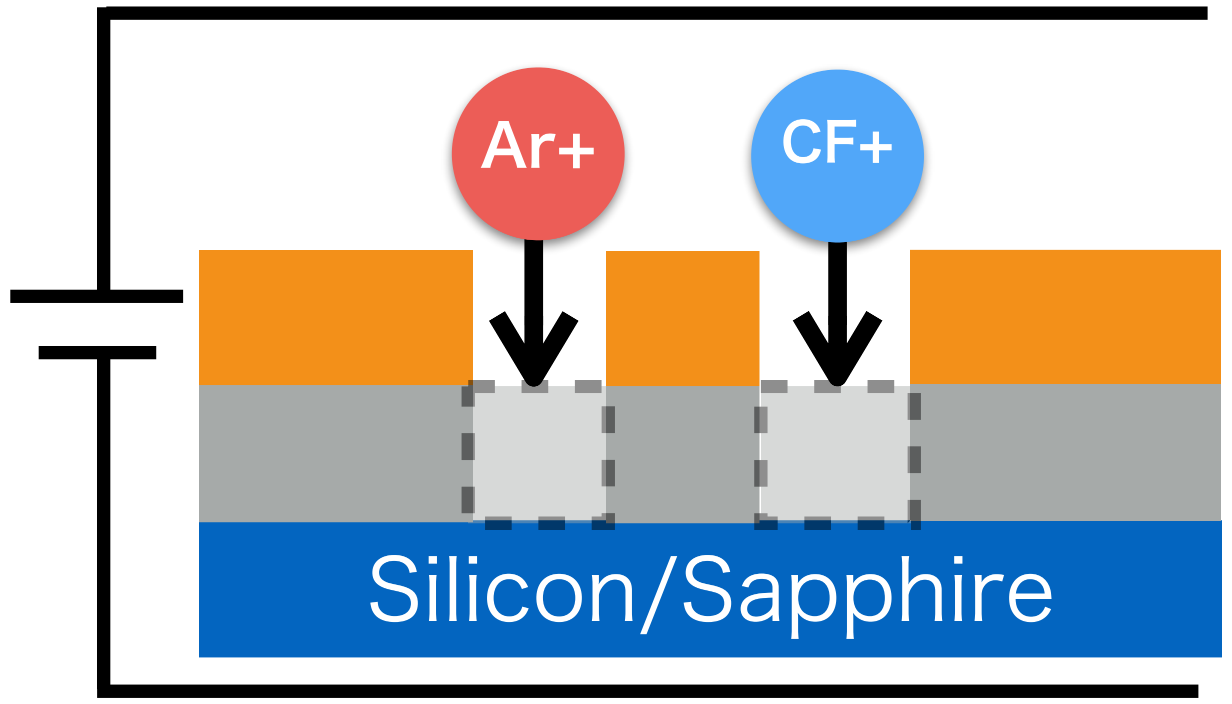
Two ways

1a. Wet etching



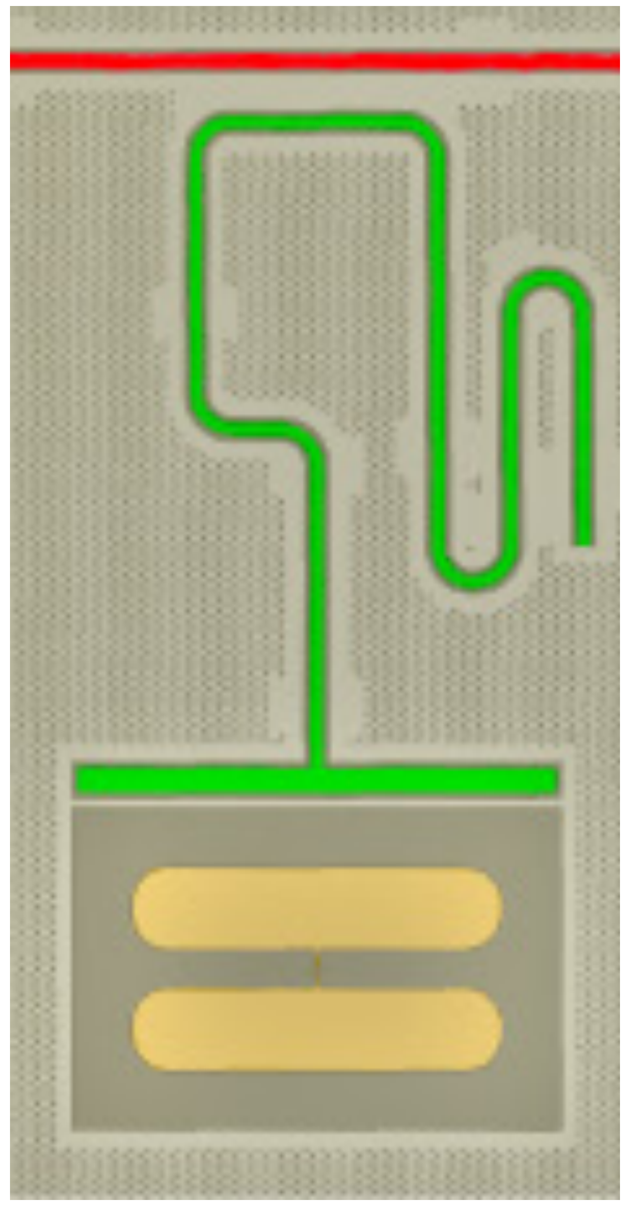
ex)
Al can be dissolved by
HNO3 + H3PO4 solution

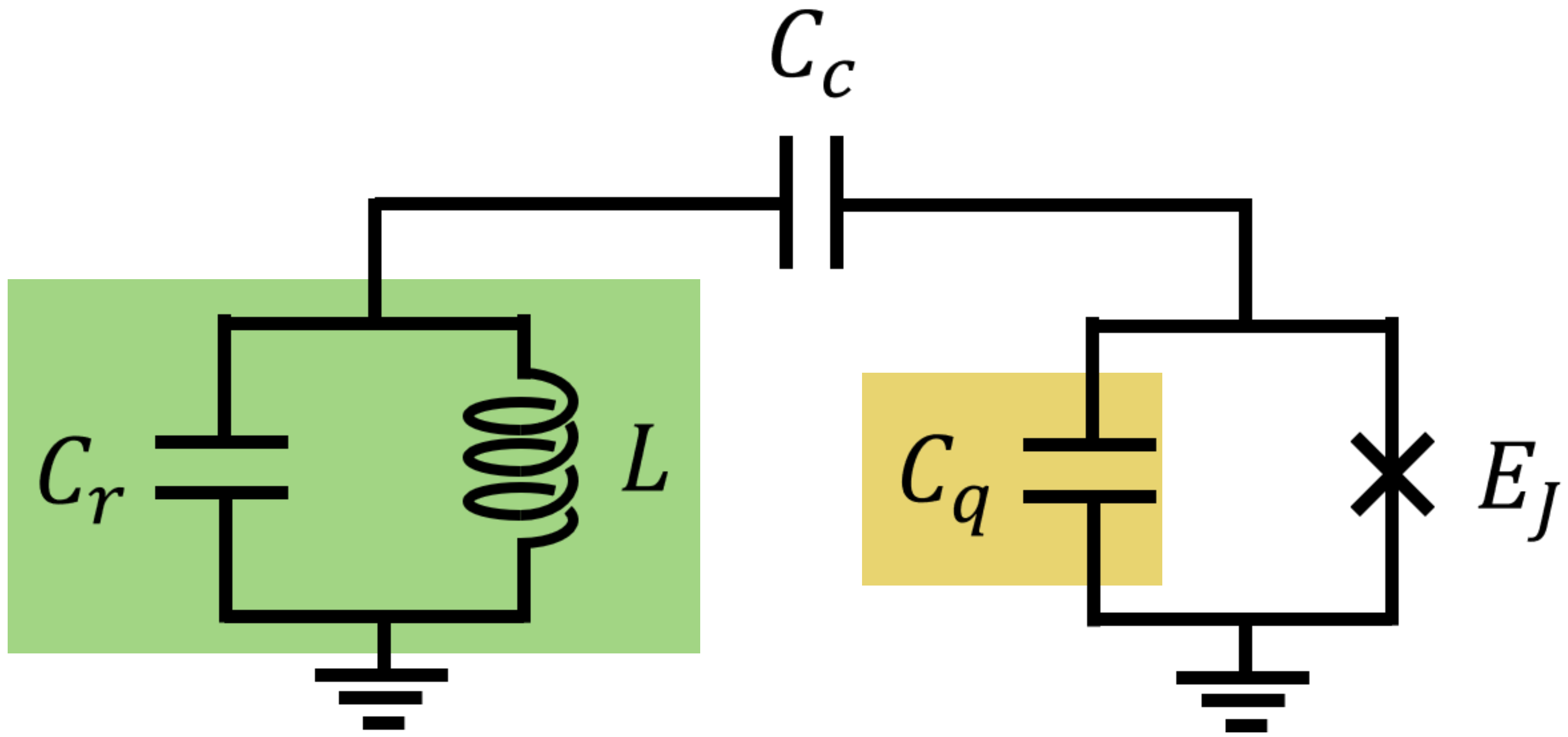
1b. dry etching



Similar to sputtering
Called RIE (reactive
ion etching)

Where we are





After Step 1-5, capacitance and resonator (in the case of 2D resonator) are fabricated.

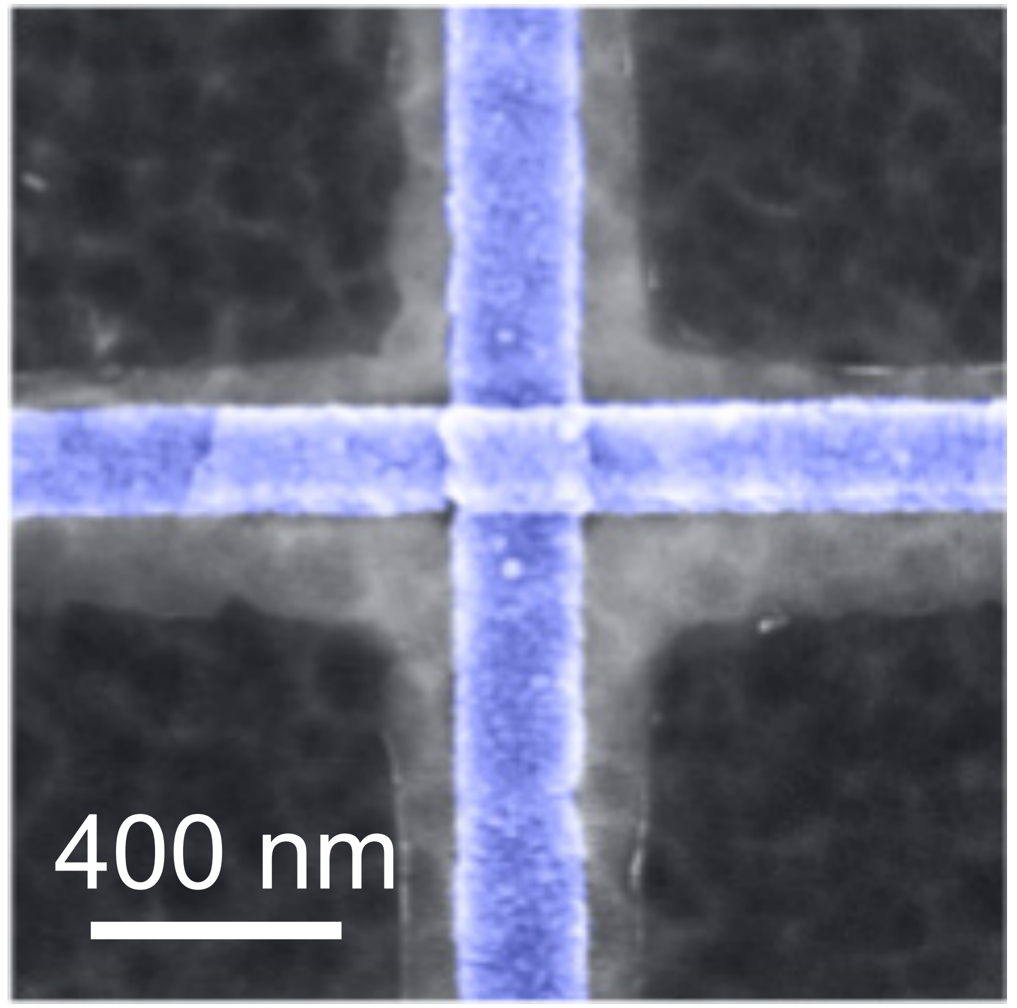
6. Electron Beam (EB) lithography

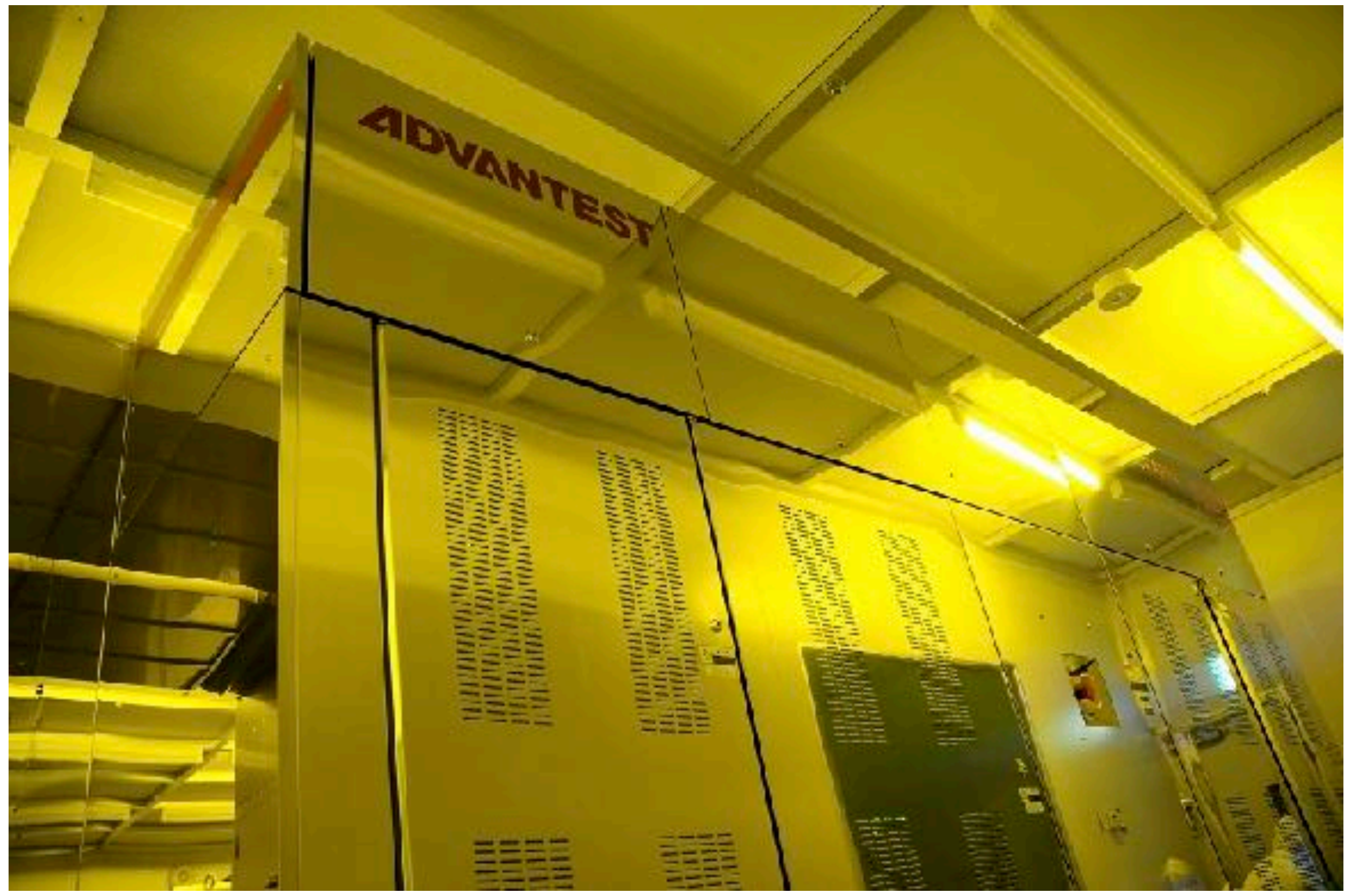
UV lights: ~10^-7 m,   electron: ~10^-10 m,   accelerator: < ~10^-17 m

Electron beam has higher energy than UV 〜 Higher resolution

ex) UV Photolithography 〜 1 μm (EUV can go better in semiconductor industry)

EB lithography 〜 10 nm

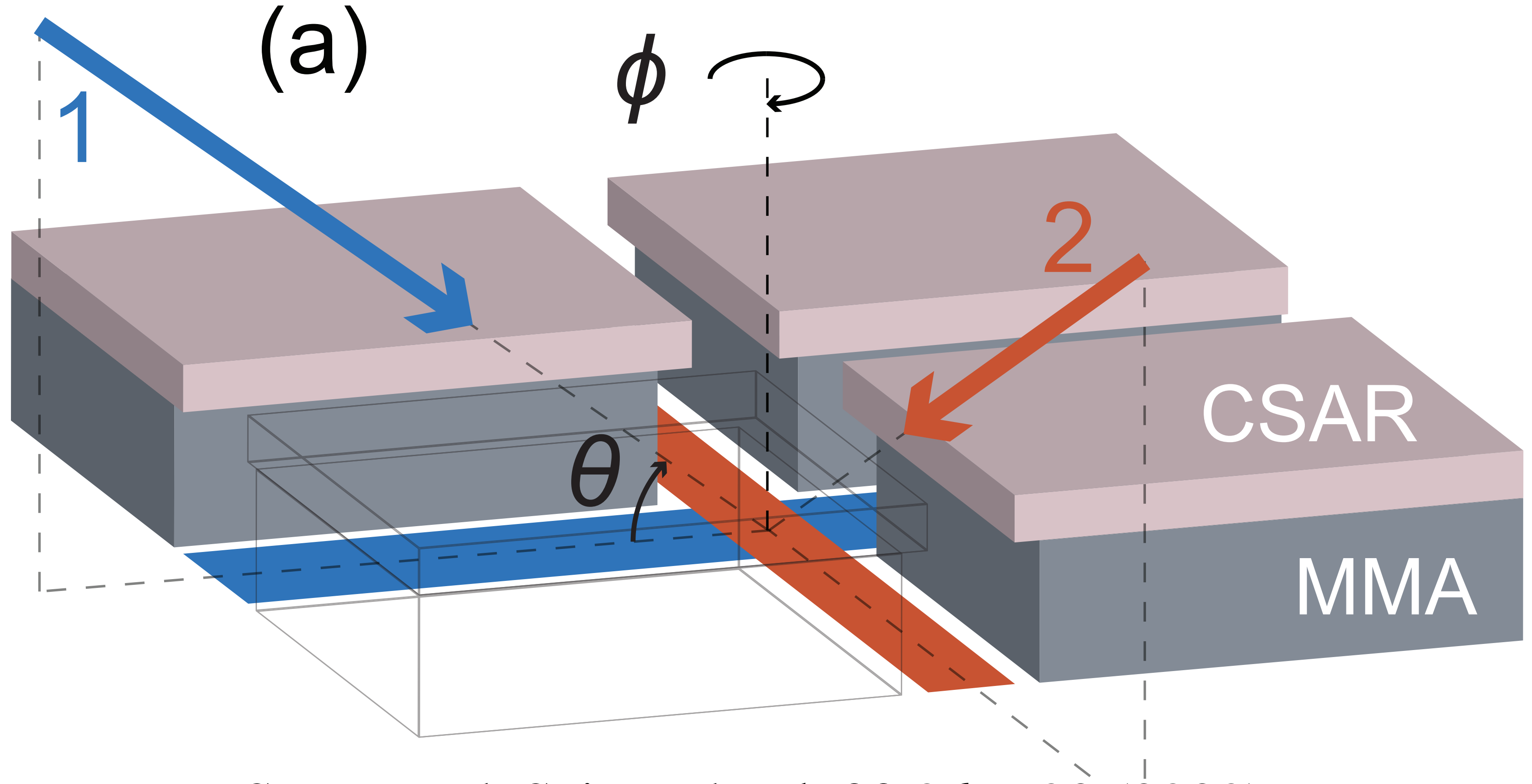




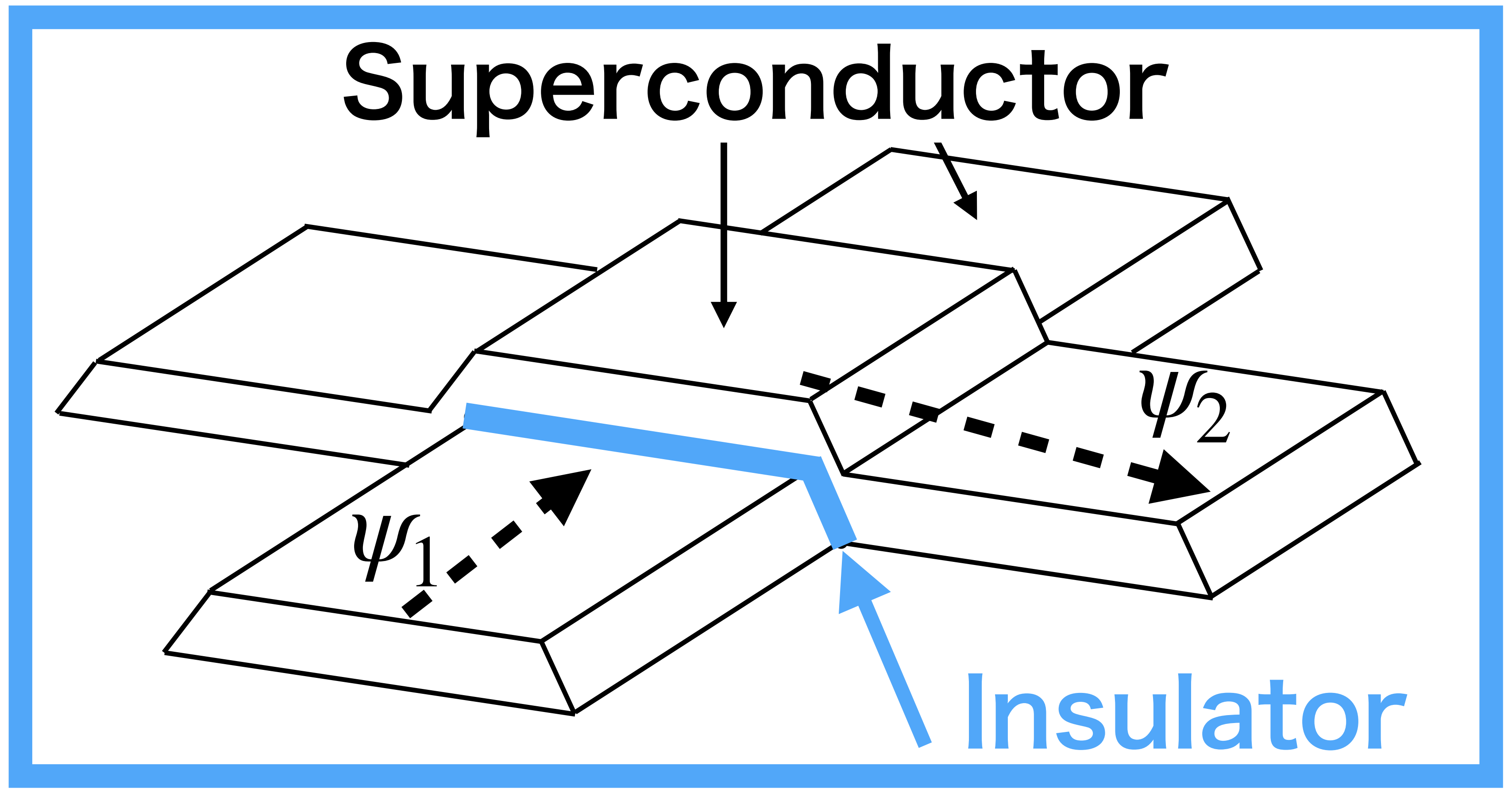
Processes are the same as photolithography

7. Shadow evaporation

"Manhattan"



Supercond. Sci. Technol. 33 06LT02 (2020)



1. First deposition
Φ=0°, θ=45°

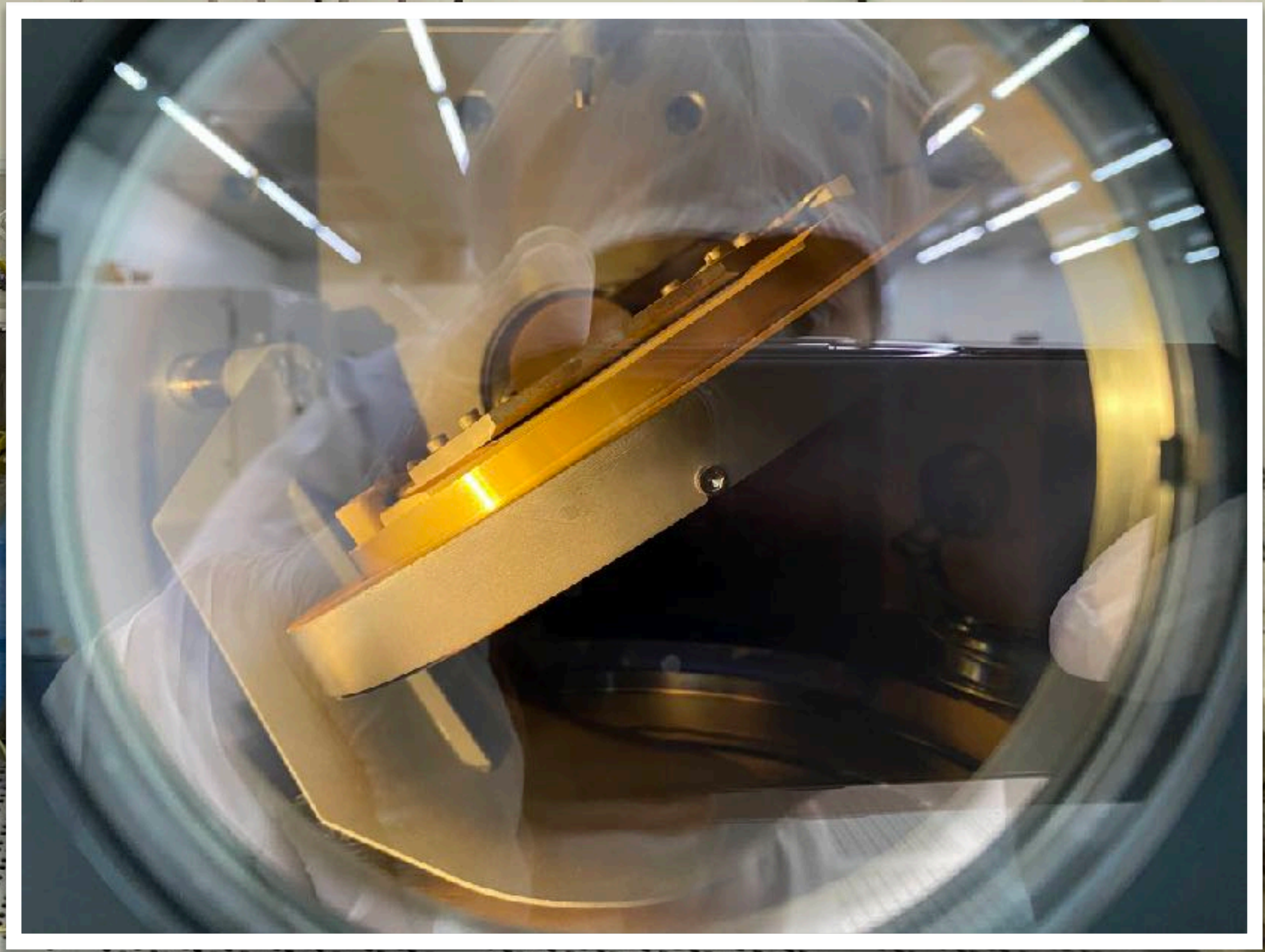
Cross-section view

2. Oxidation

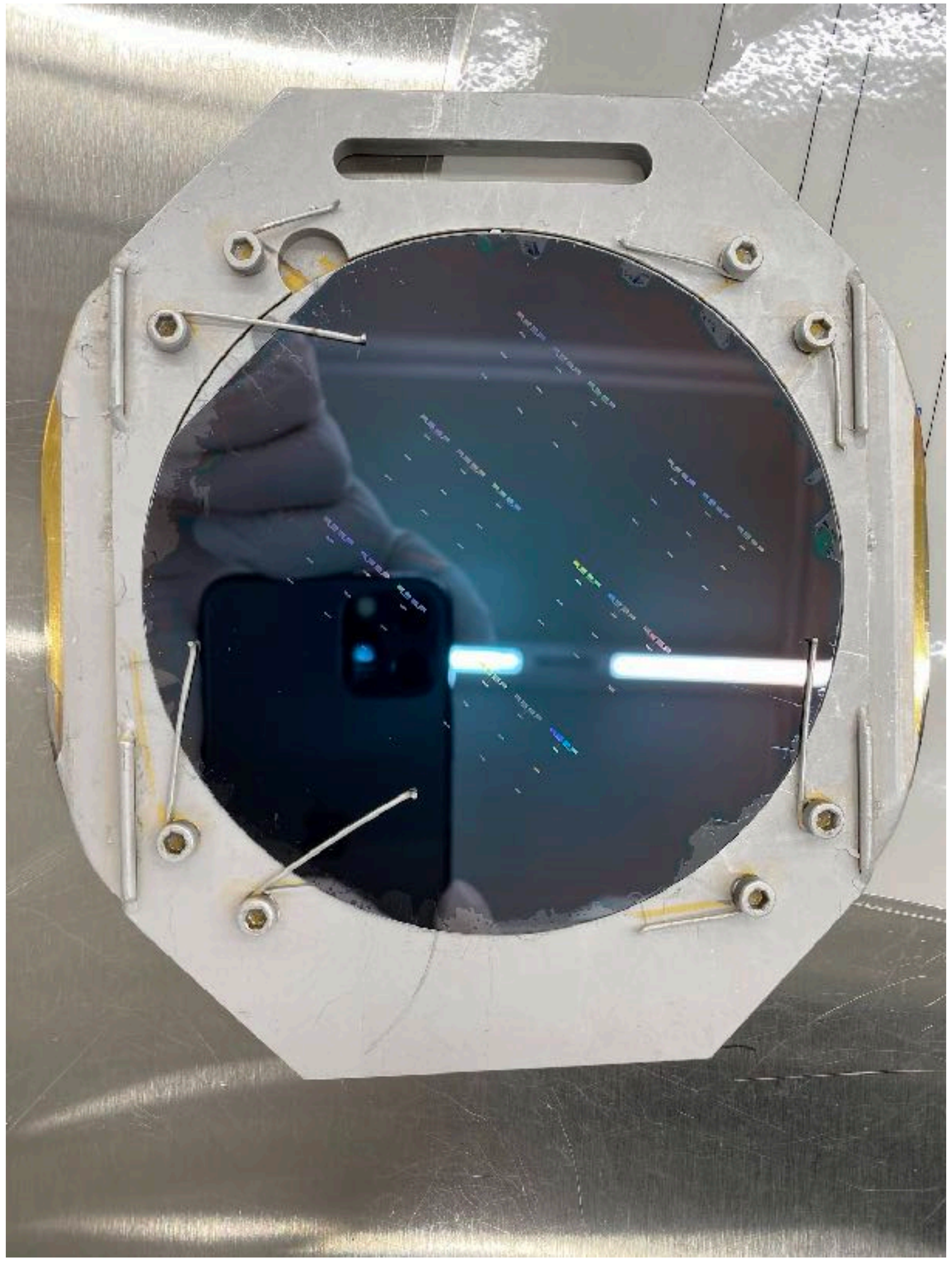
3. Second deposition
Φ=90°, θ=45°

7. Shadow evaporation

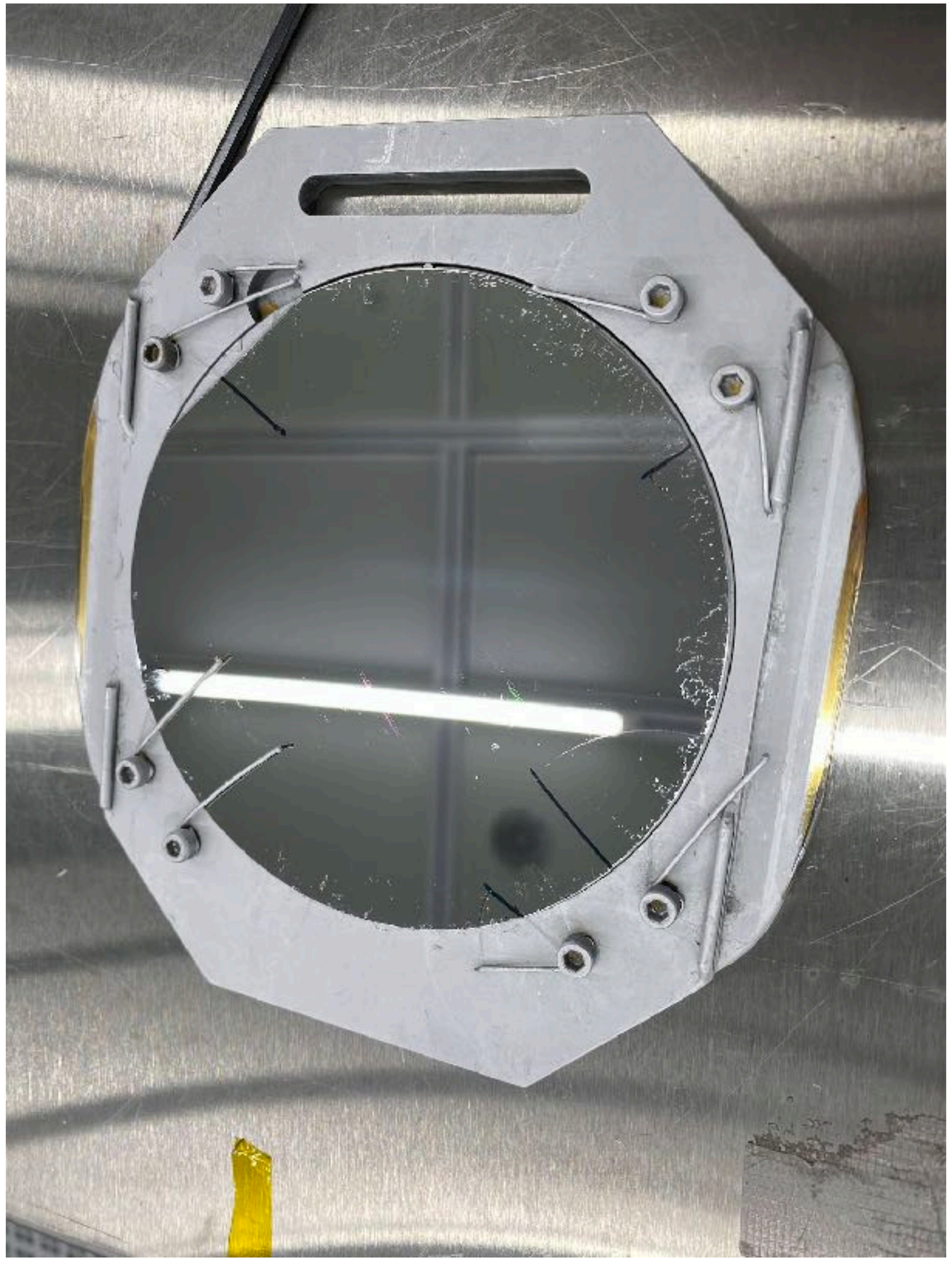
Plassys system is a standard for academic use.



7. Shadow evaporation



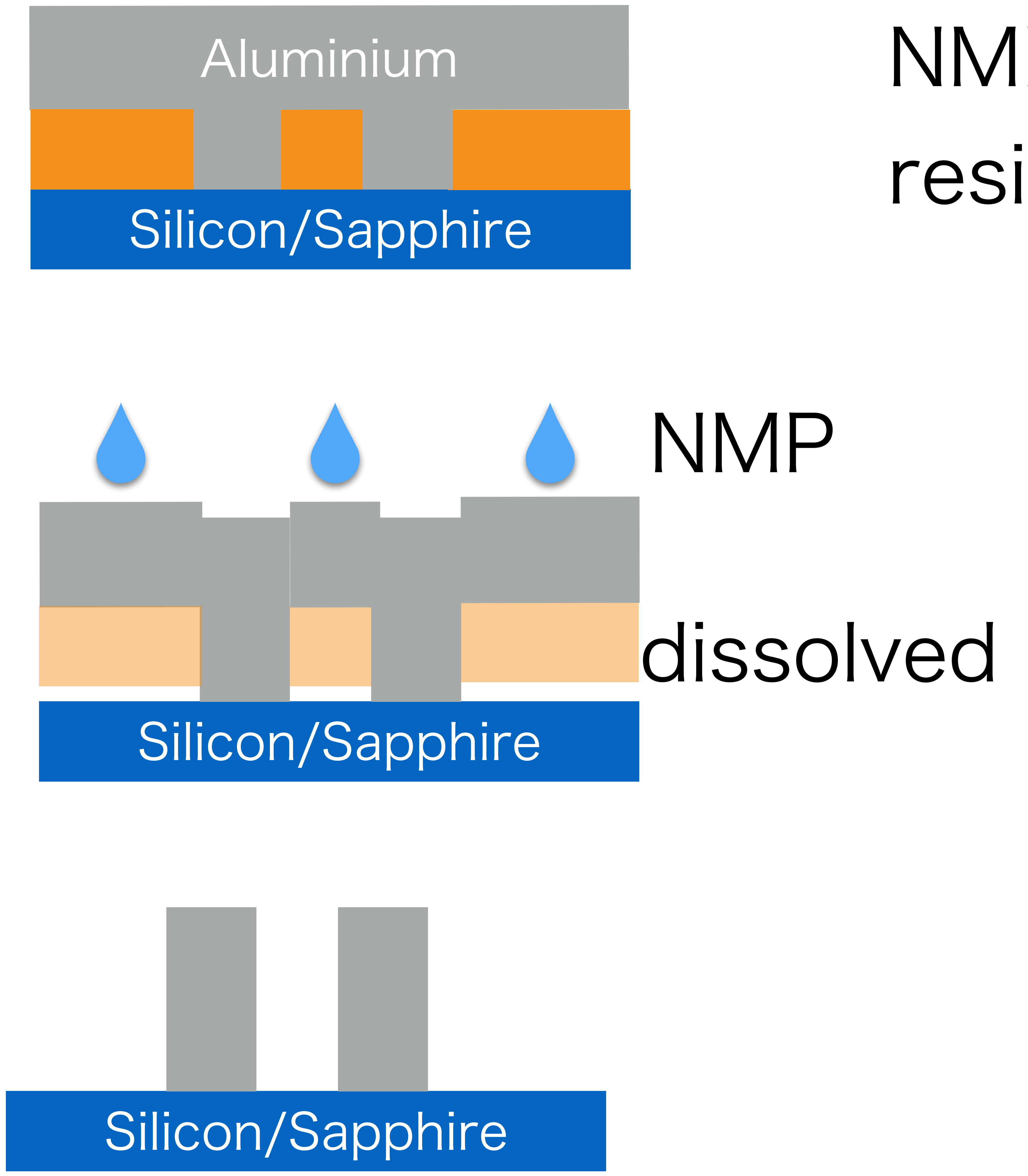
Before deposition

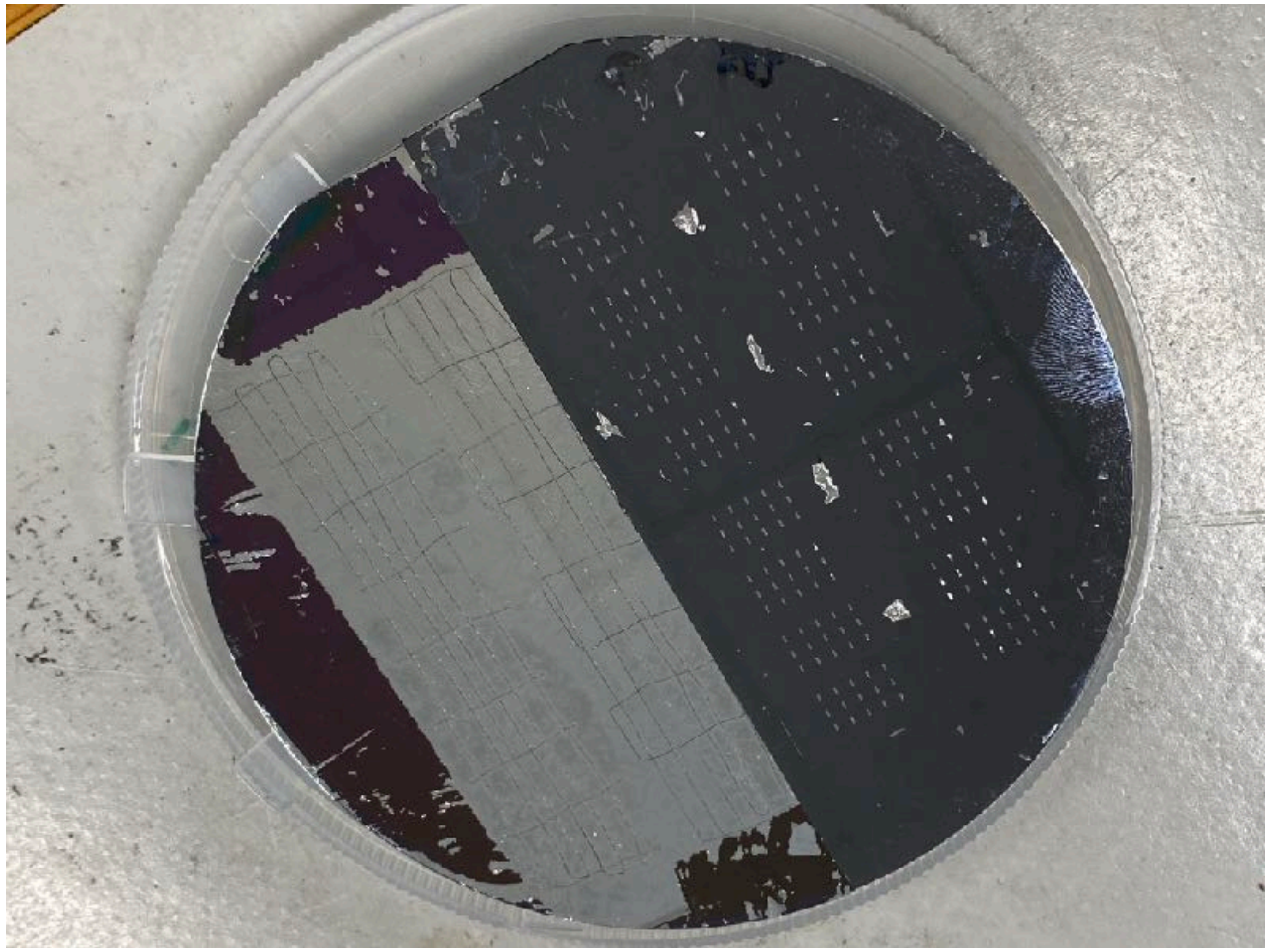


After deposition

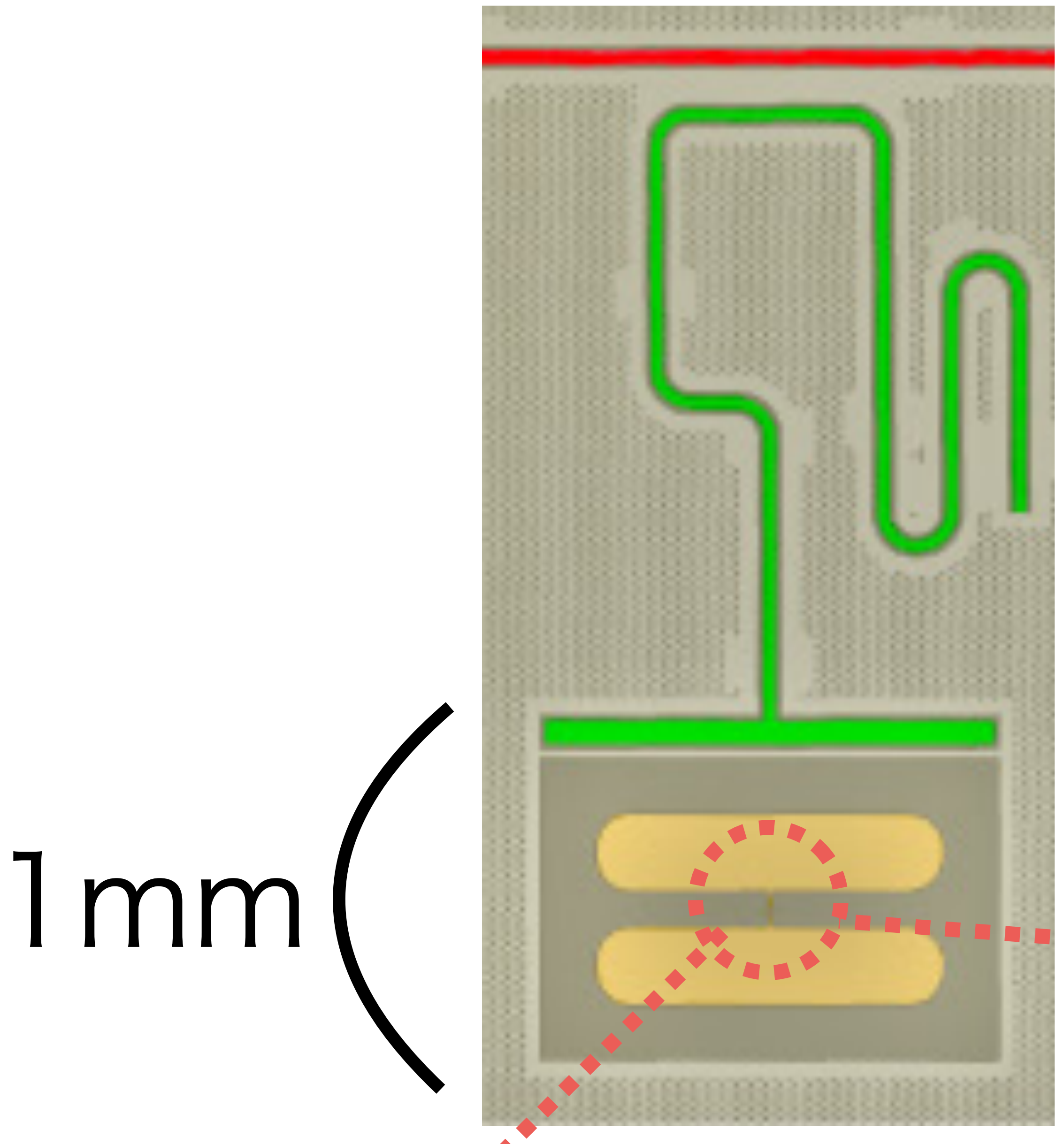
8. Lift-off

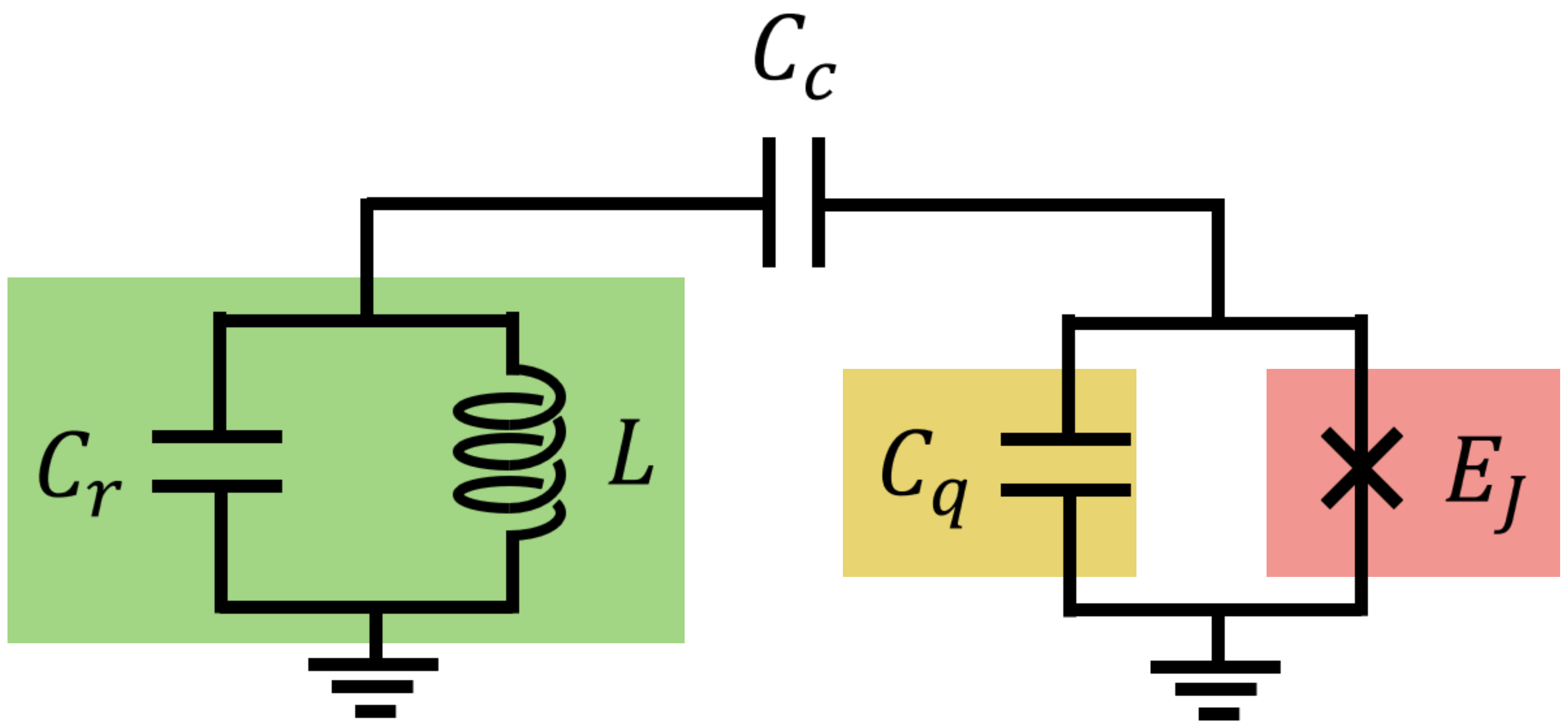
A process to remove unnecessary Aluminium film. NMP (N-methylpyrrolidone) is used to dissolve resist layer.

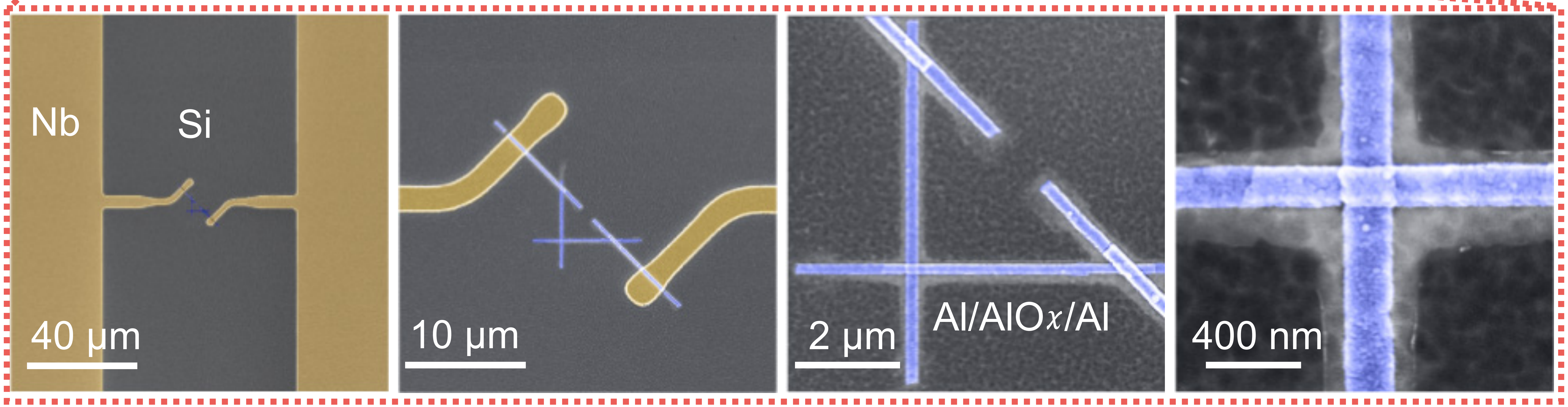




Where we are



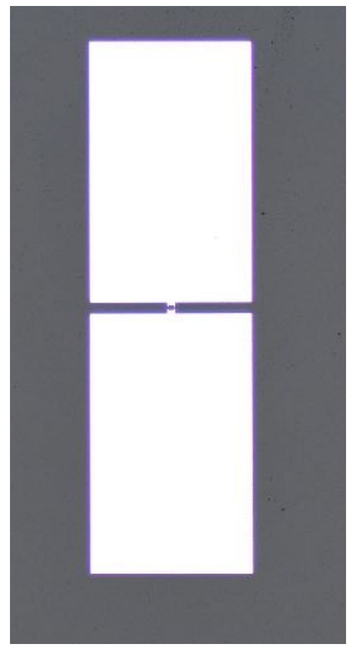




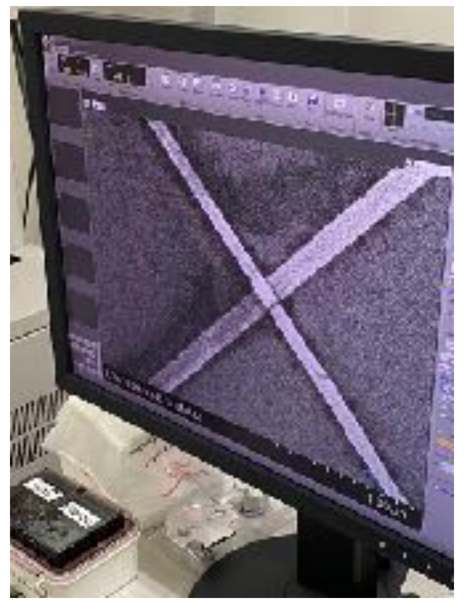
Before cryogenic test…

9. Microscope

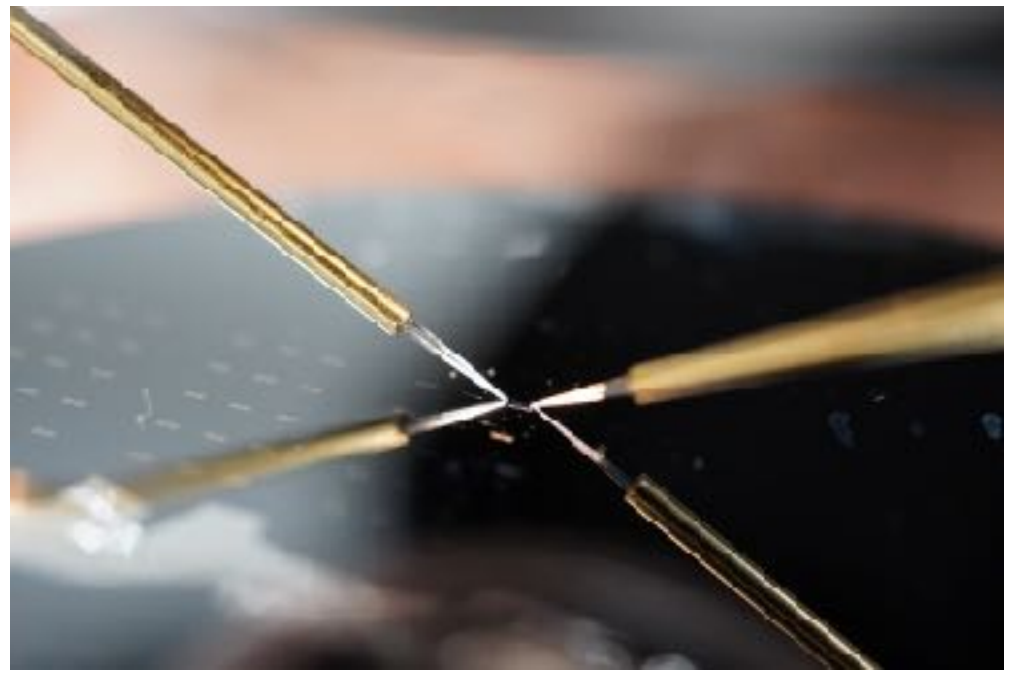
Optical



SEM

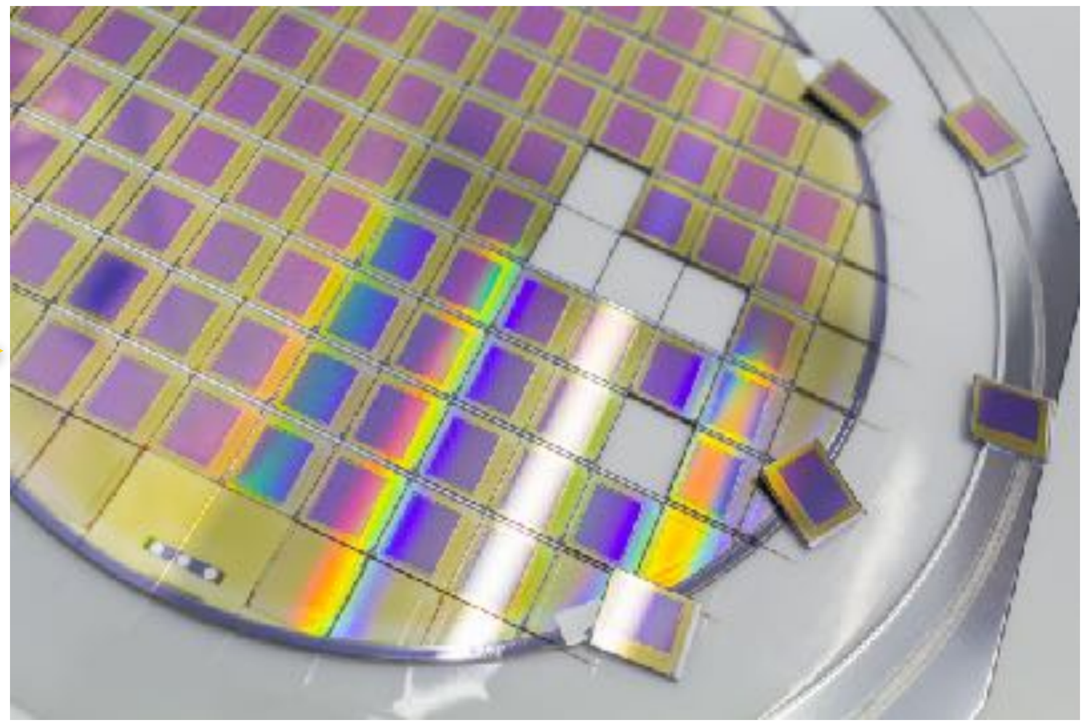


10. Resistance



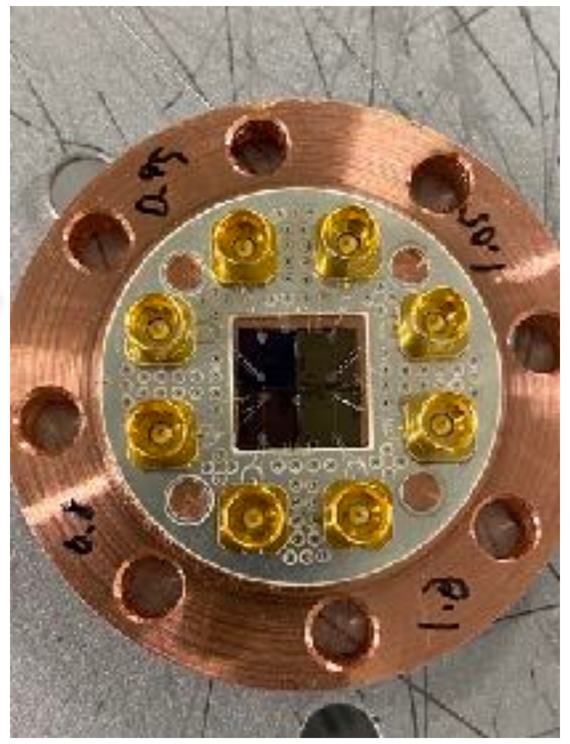
$$E_J \sim \frac{\hbar \pi \Delta_{sc}}{4e^2 R}$$

11. Dicing



12. Packaging

2D

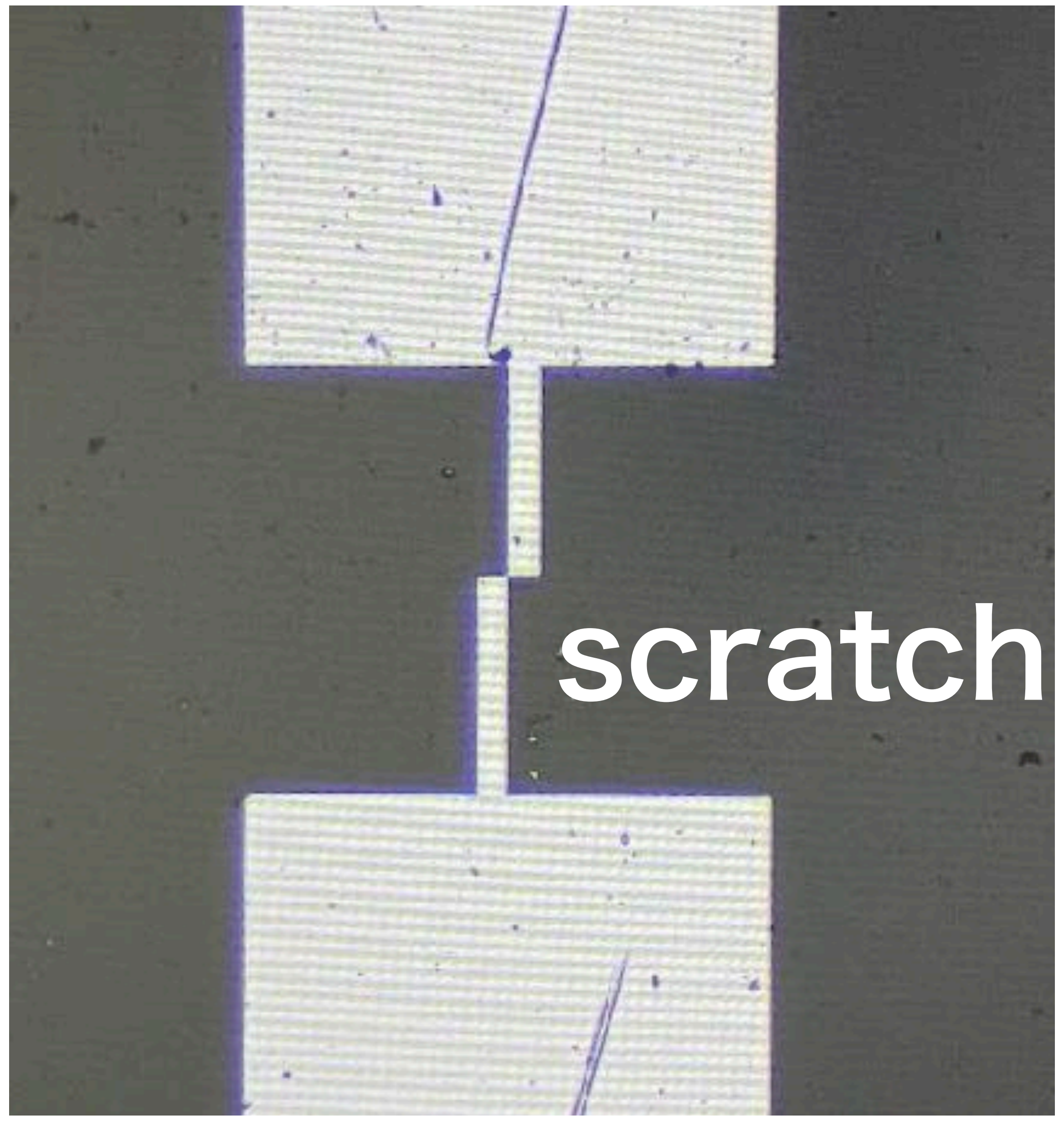


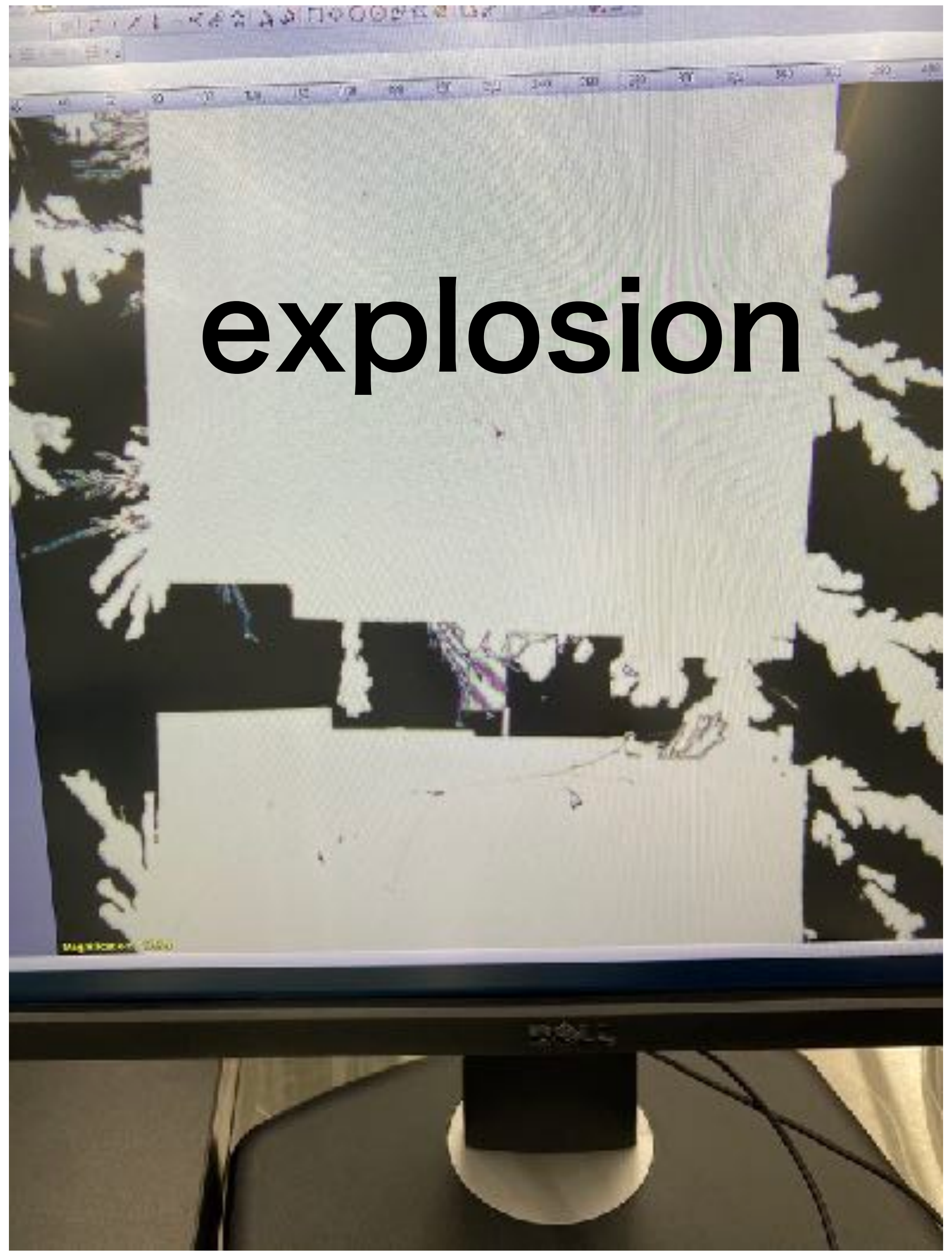
3D

9. Microscope

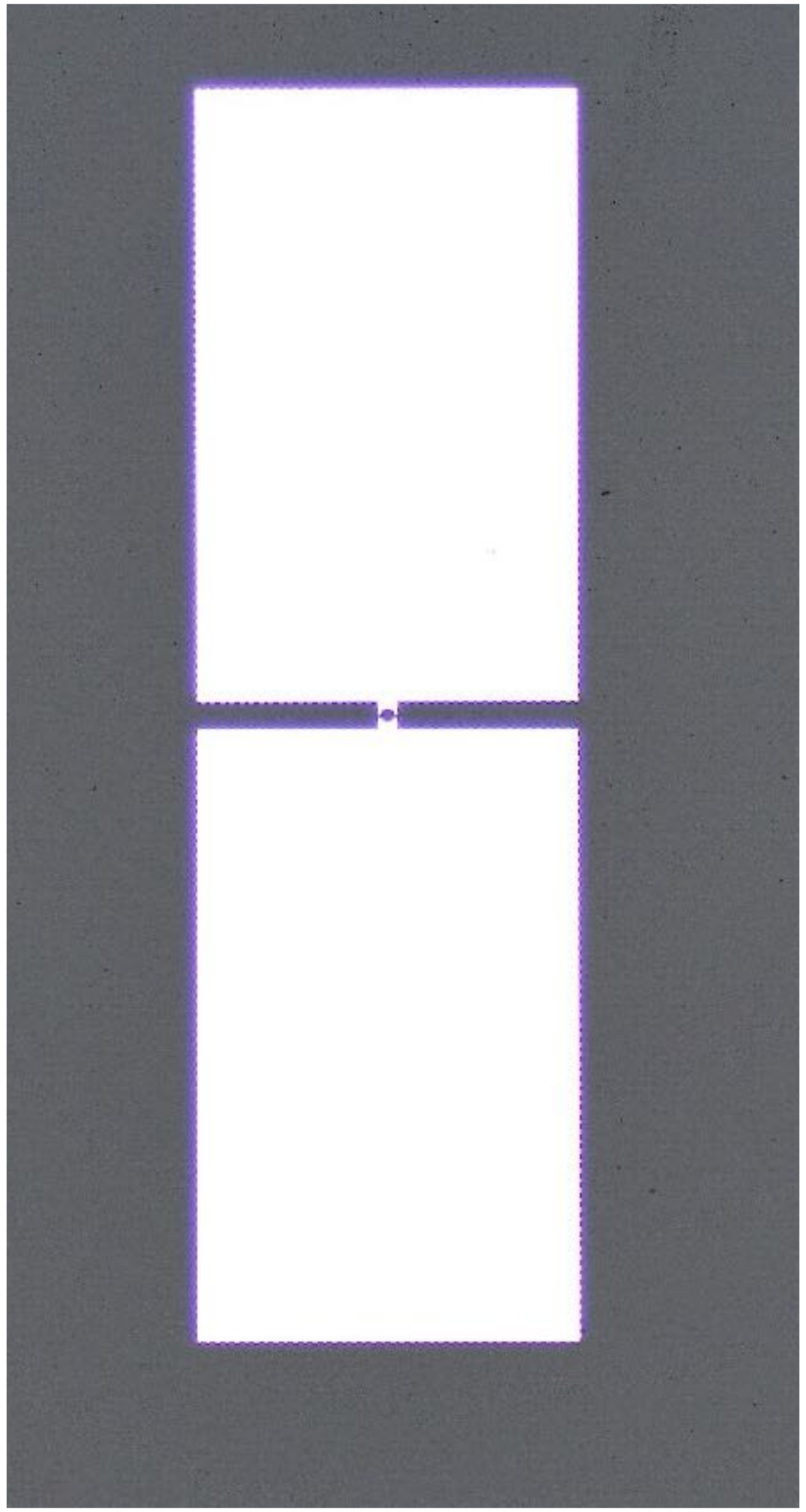
good example

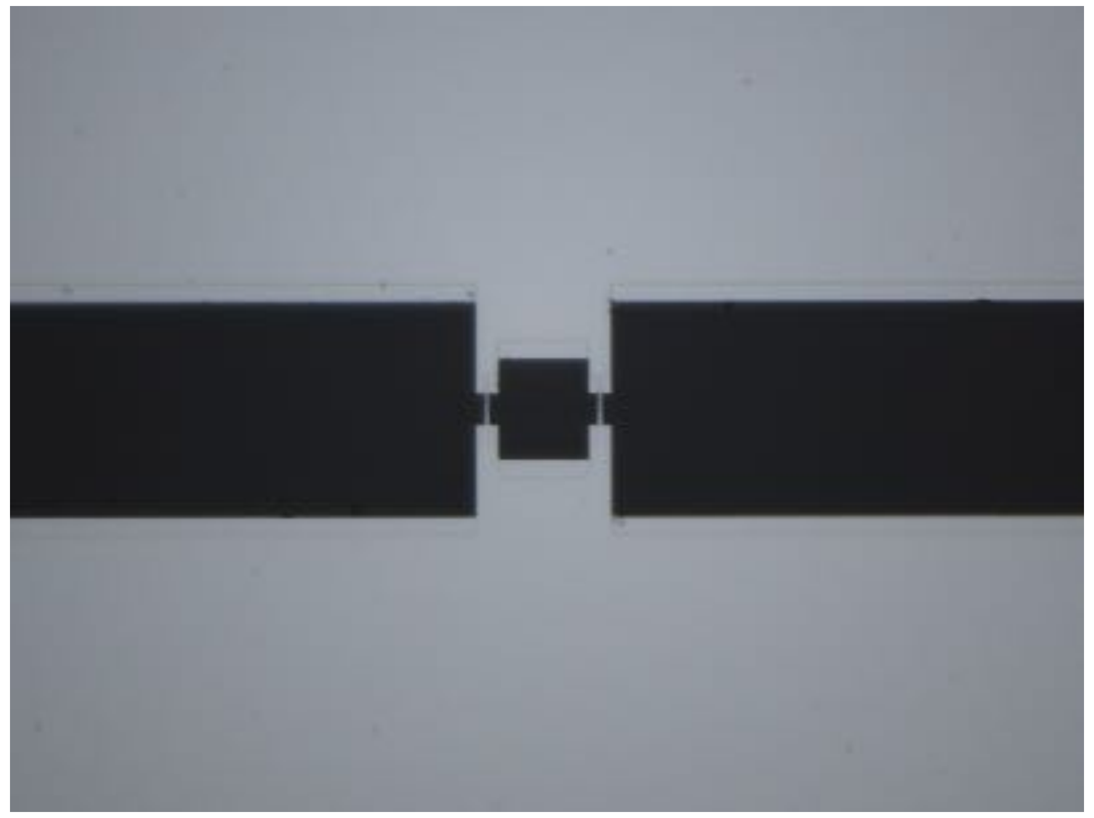
Failure example





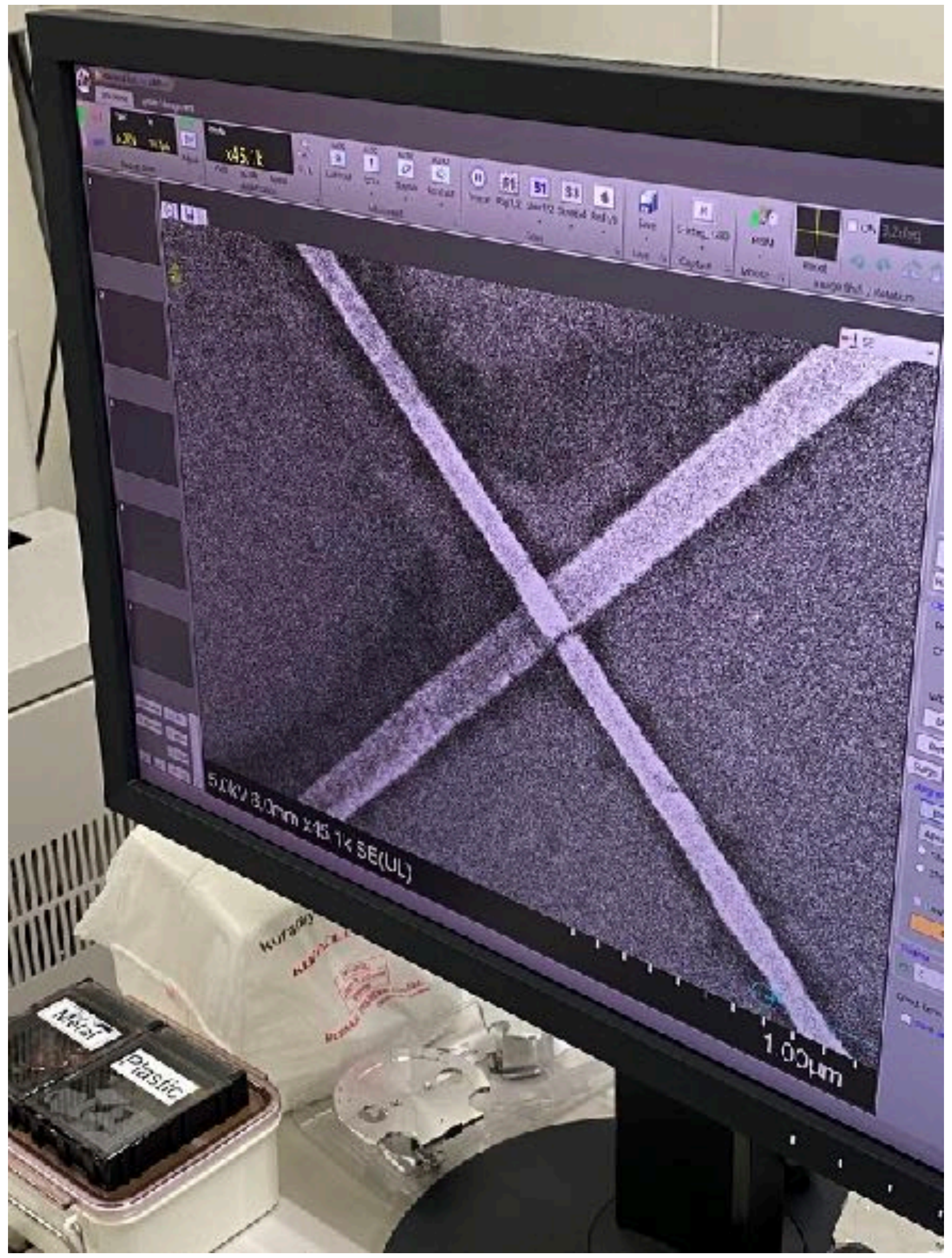
Obvious failure ones goes
to trash bin





Picked up
clean ones

9. SEM



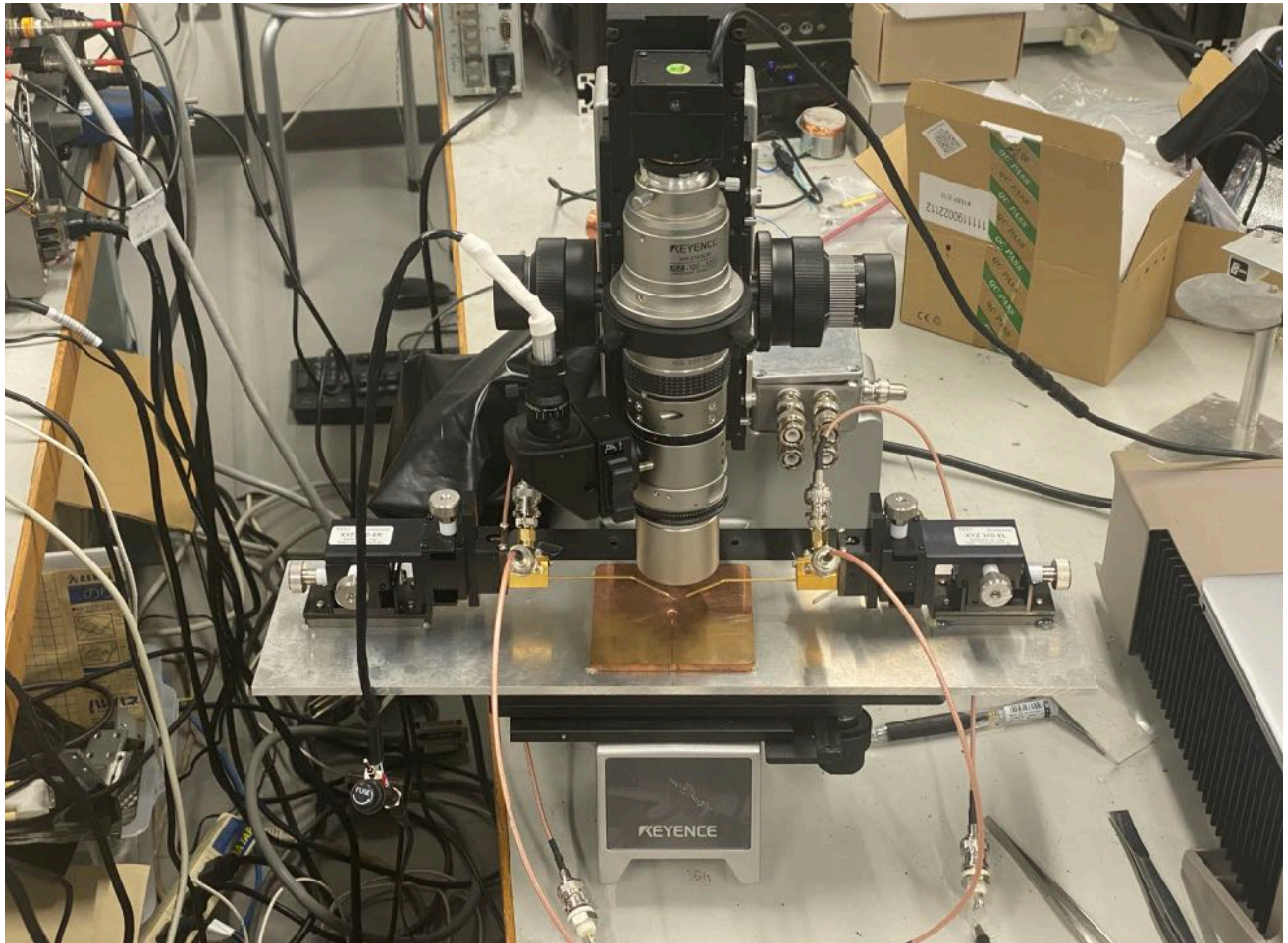
SEM(scanning electron microscope)

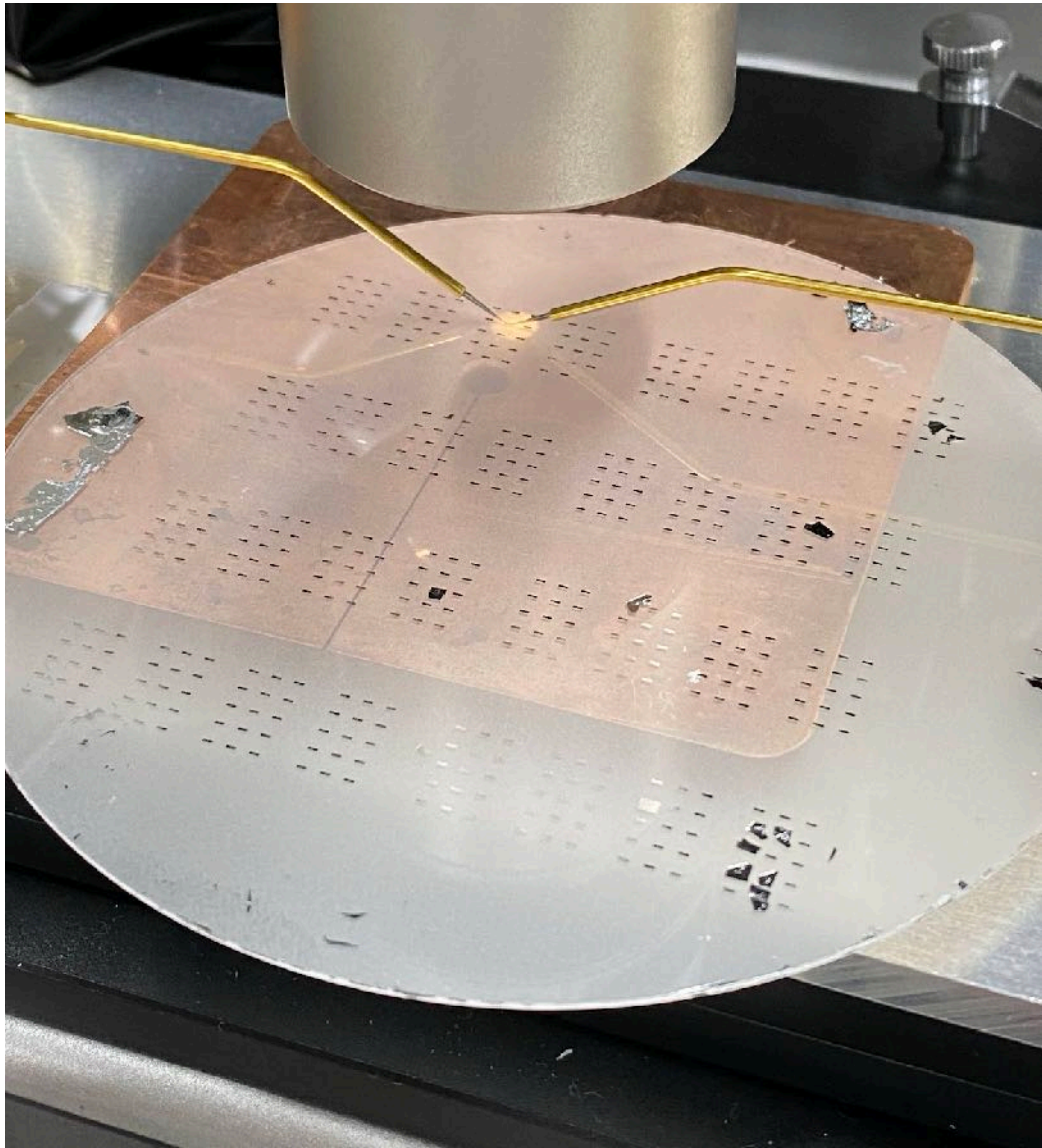
Cons: Reveal junction structure

Pros: "SEM barn" -> can't use for real sample

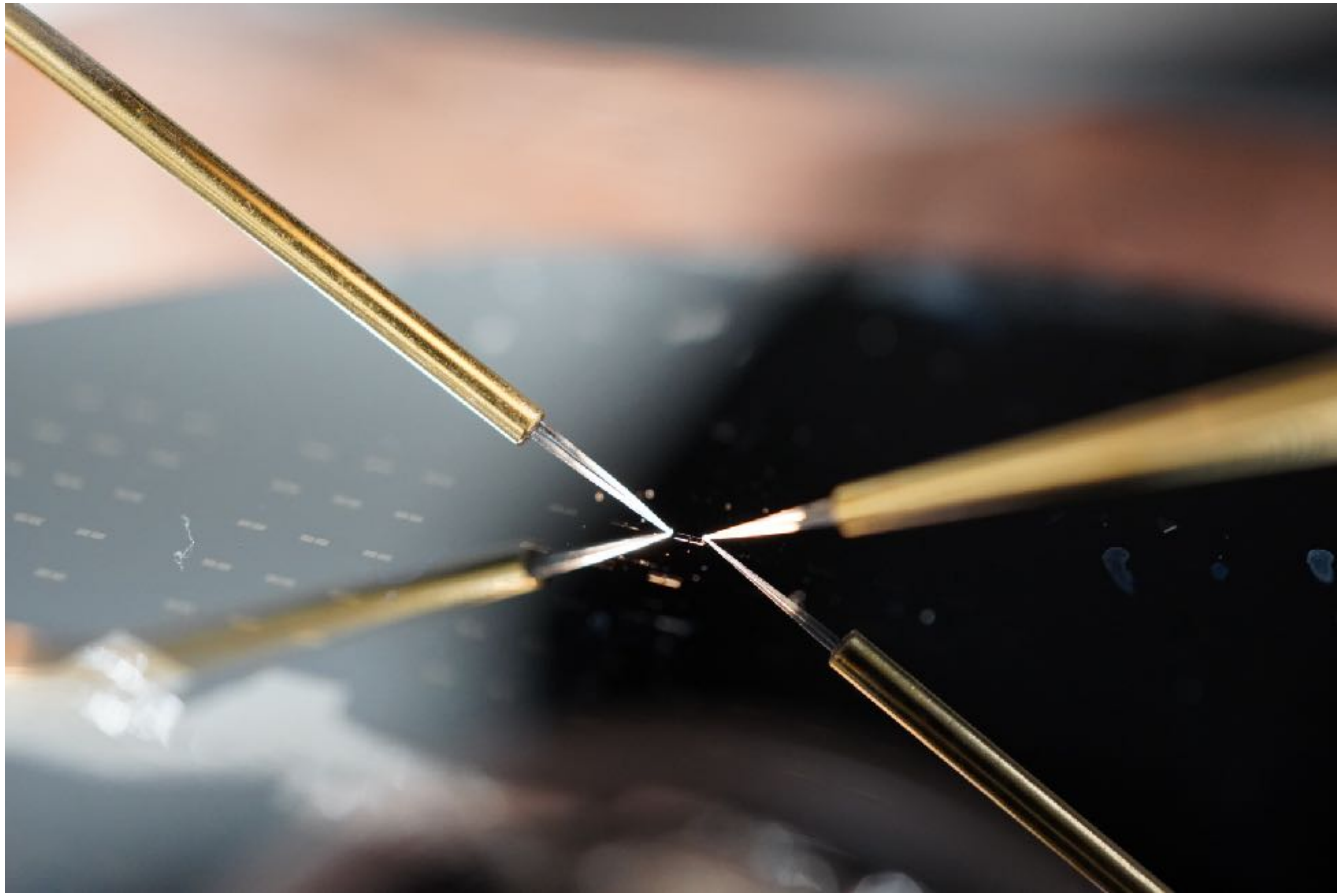
10. Resistance Measurement

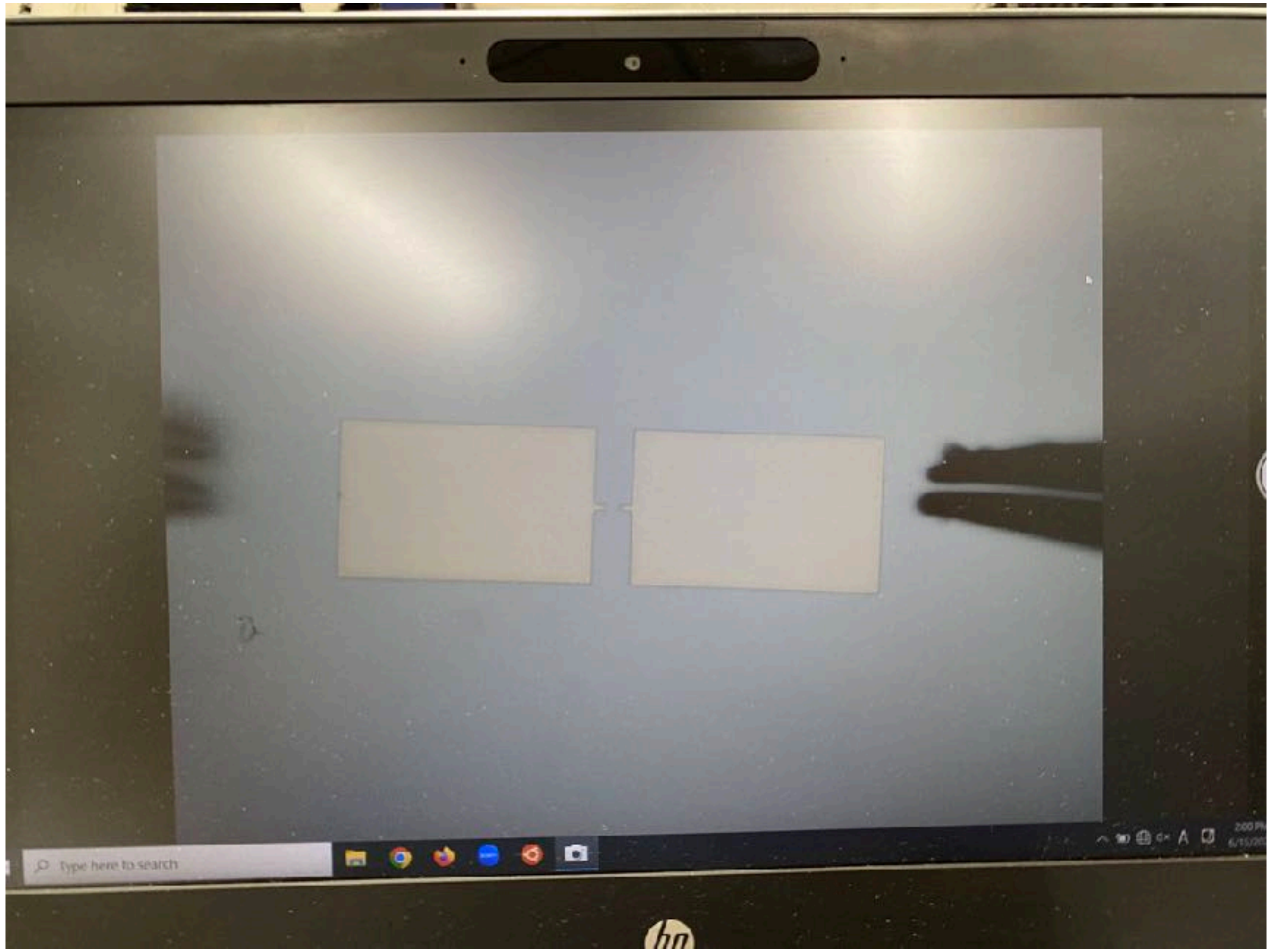
Remember $E_J \sim \frac{\hbar \pi \Delta_{sc}}{4e^2 R}$ Only effective test at room temperature





11. Resistance Measurement





- 4 wire measurement for precise reading
- current will be around uA (higher current burns JJ)
- Grounded by metal plate below wafer

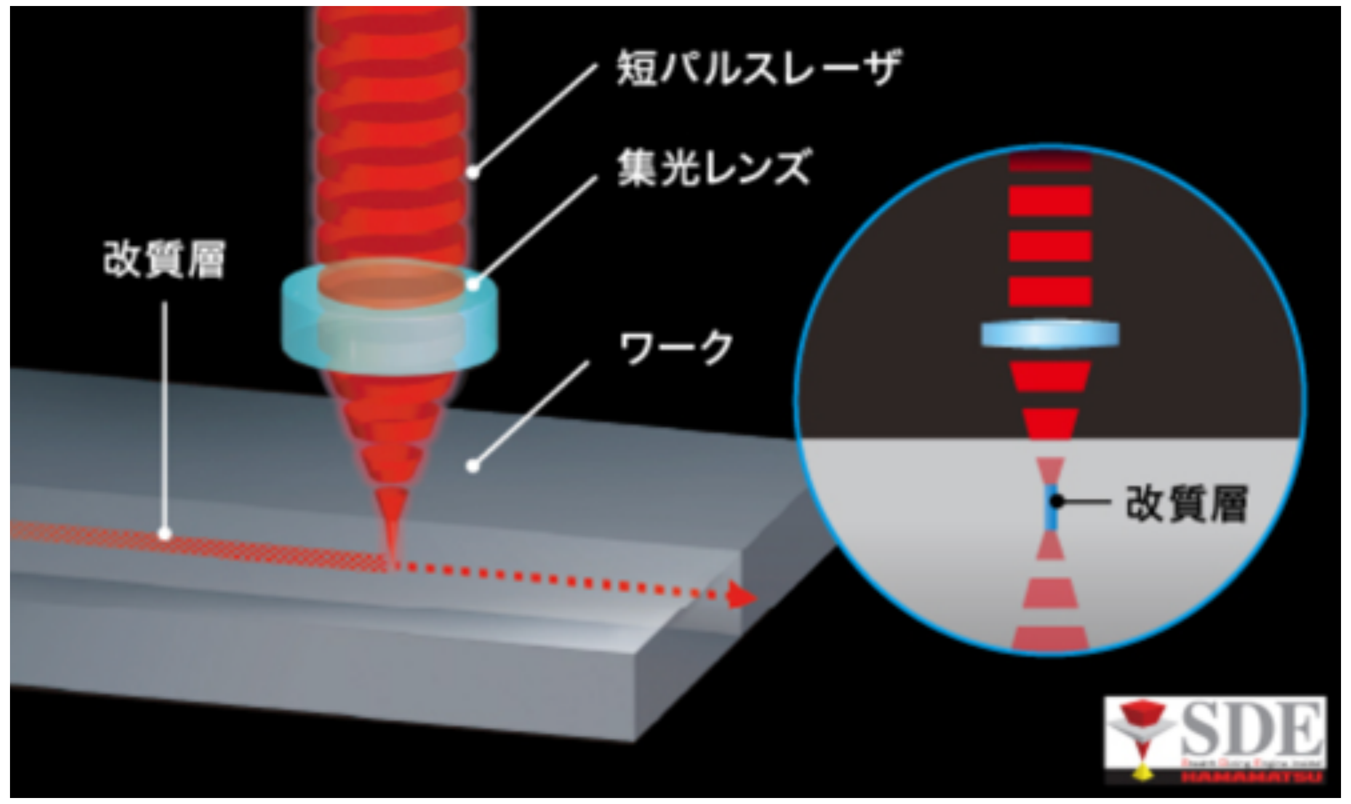
- Minimum contact to avoid making scratch

11. Dicing

Diamond cutter

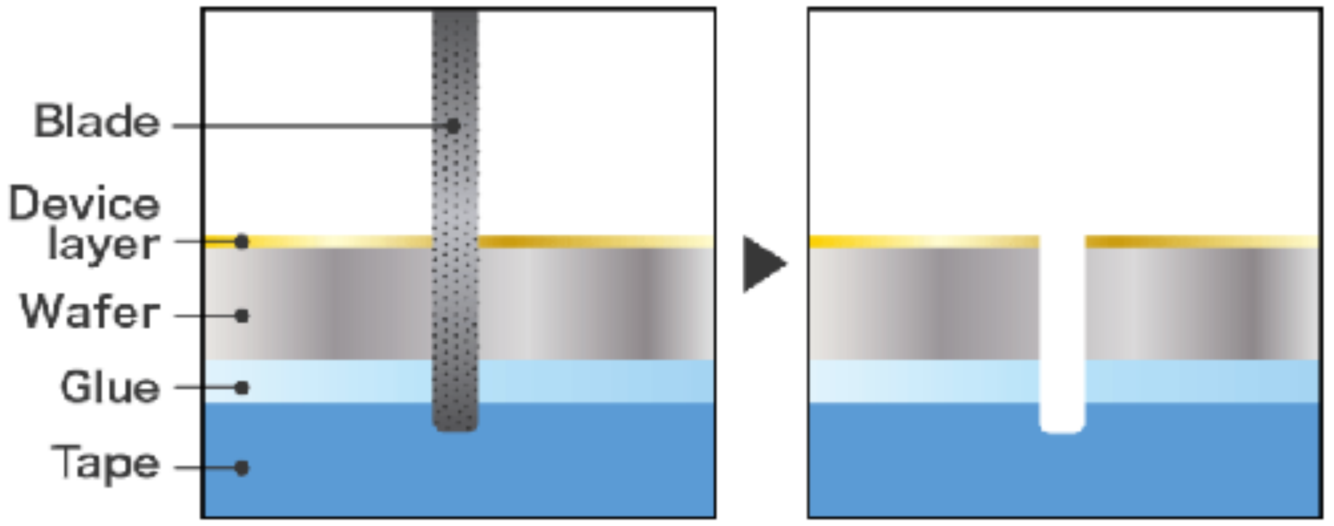
Automatic dicer

Stealth dicer



- Damage inside wafer by laser
- Expensive but clean cutting

blade dicer

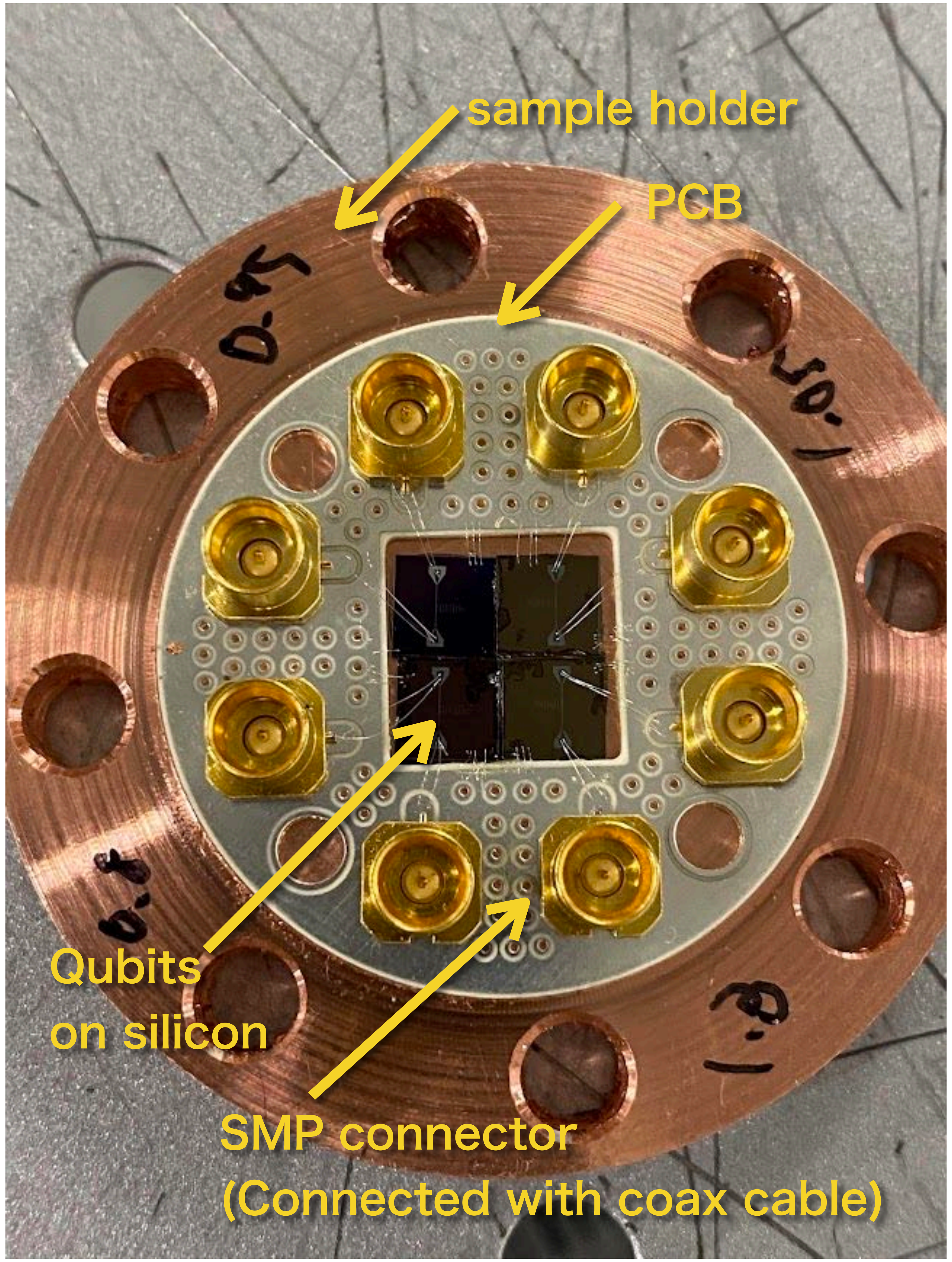


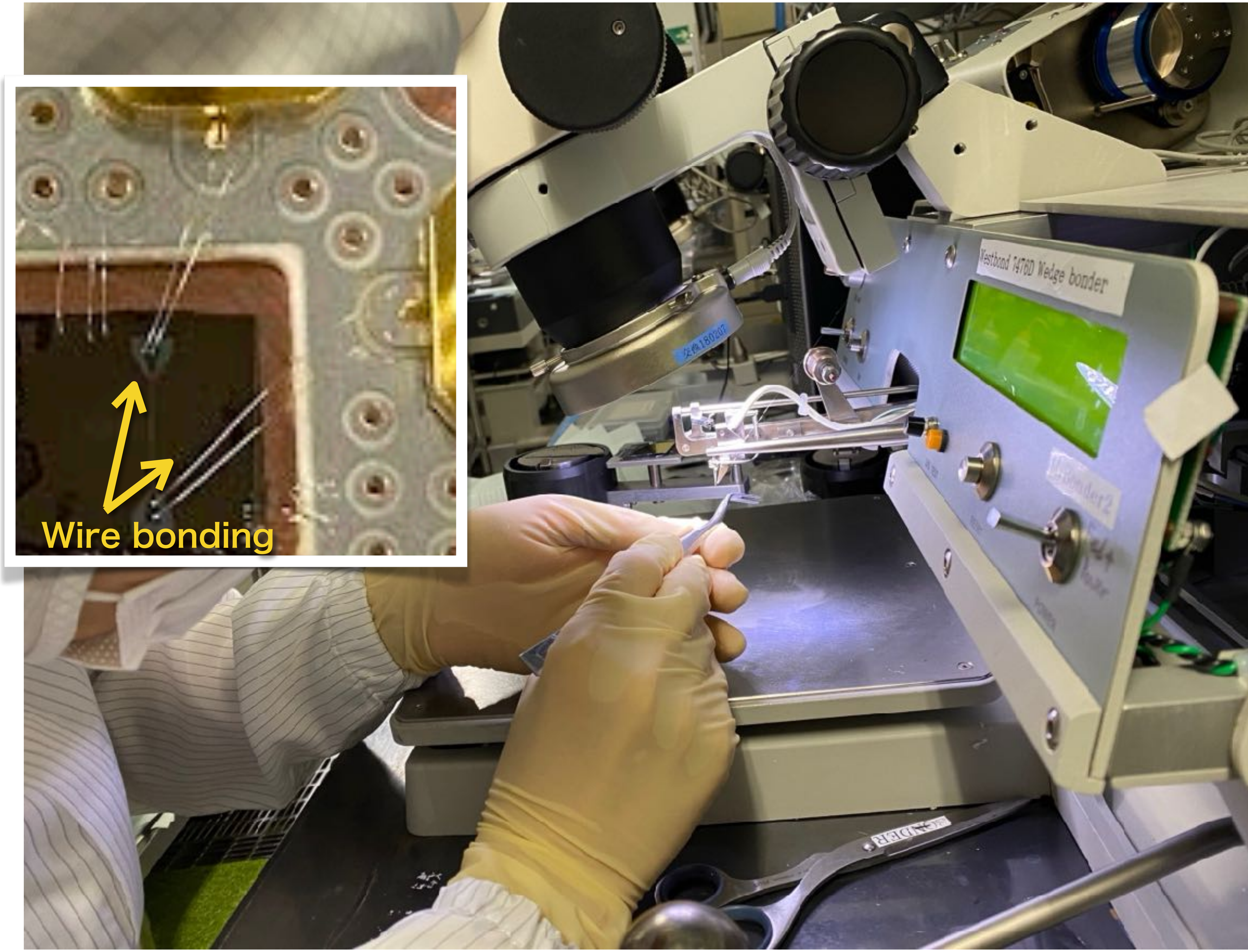
- Cutting physically by blade
- Smilier but more unclean dust and cleaning water

Looks trivial but technically difficult process

12. Wire bonding

Connecting qubit to macroscopic coax cables

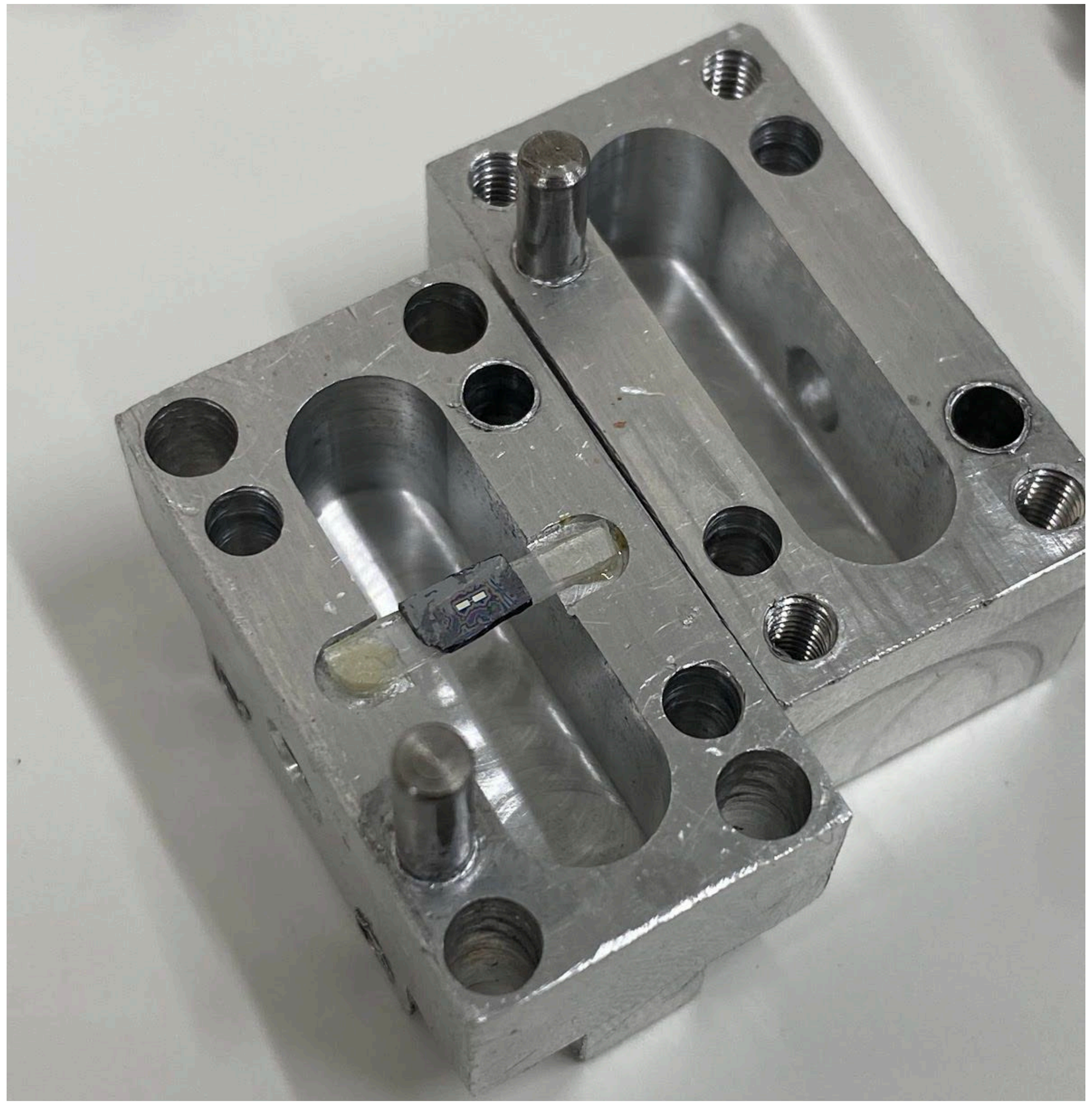




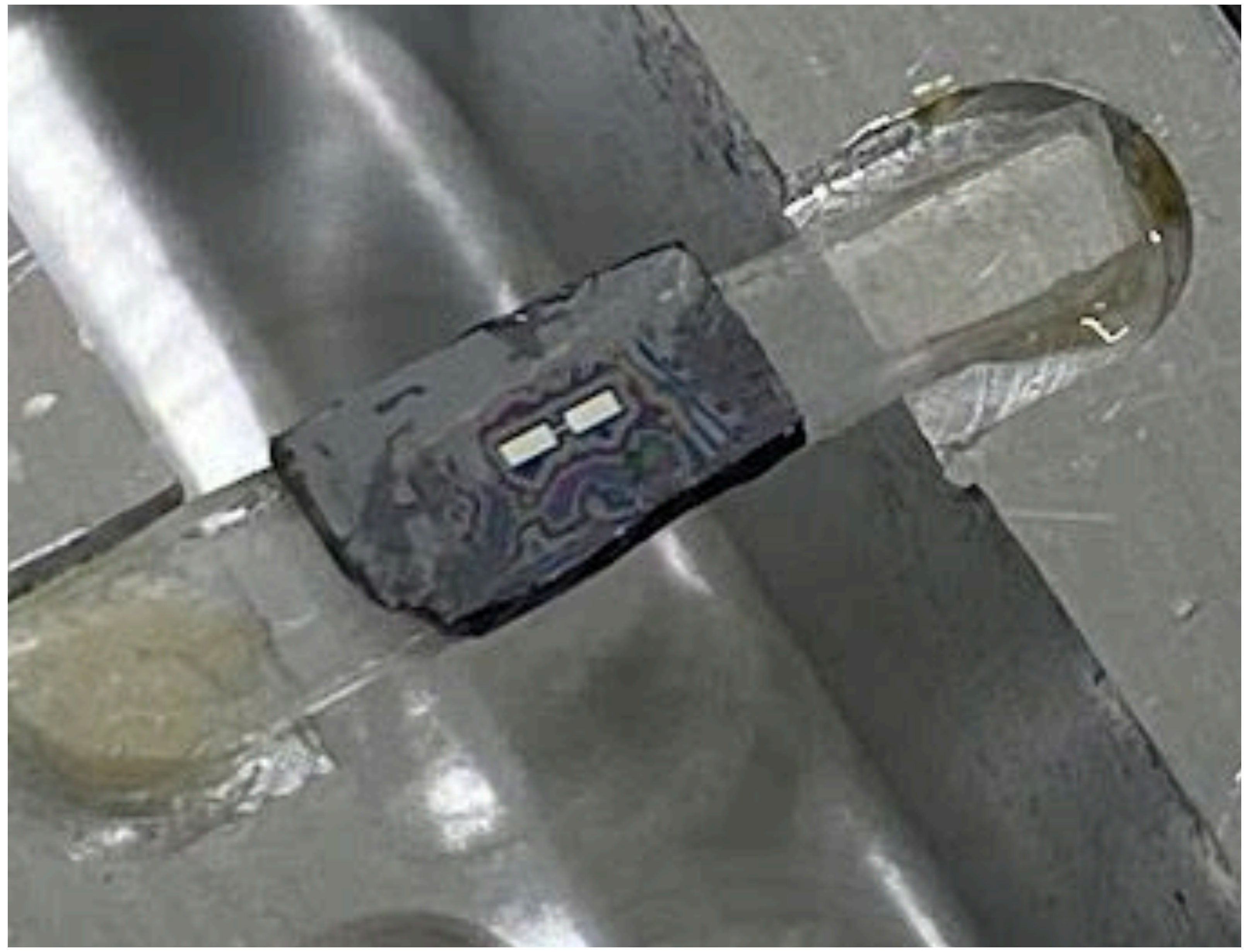
12. 3D-cavity packaging

Cavity made
by milling machine

Cu for decent cavity
Al, Nb for high quality ones



Loading qubit
on cavity

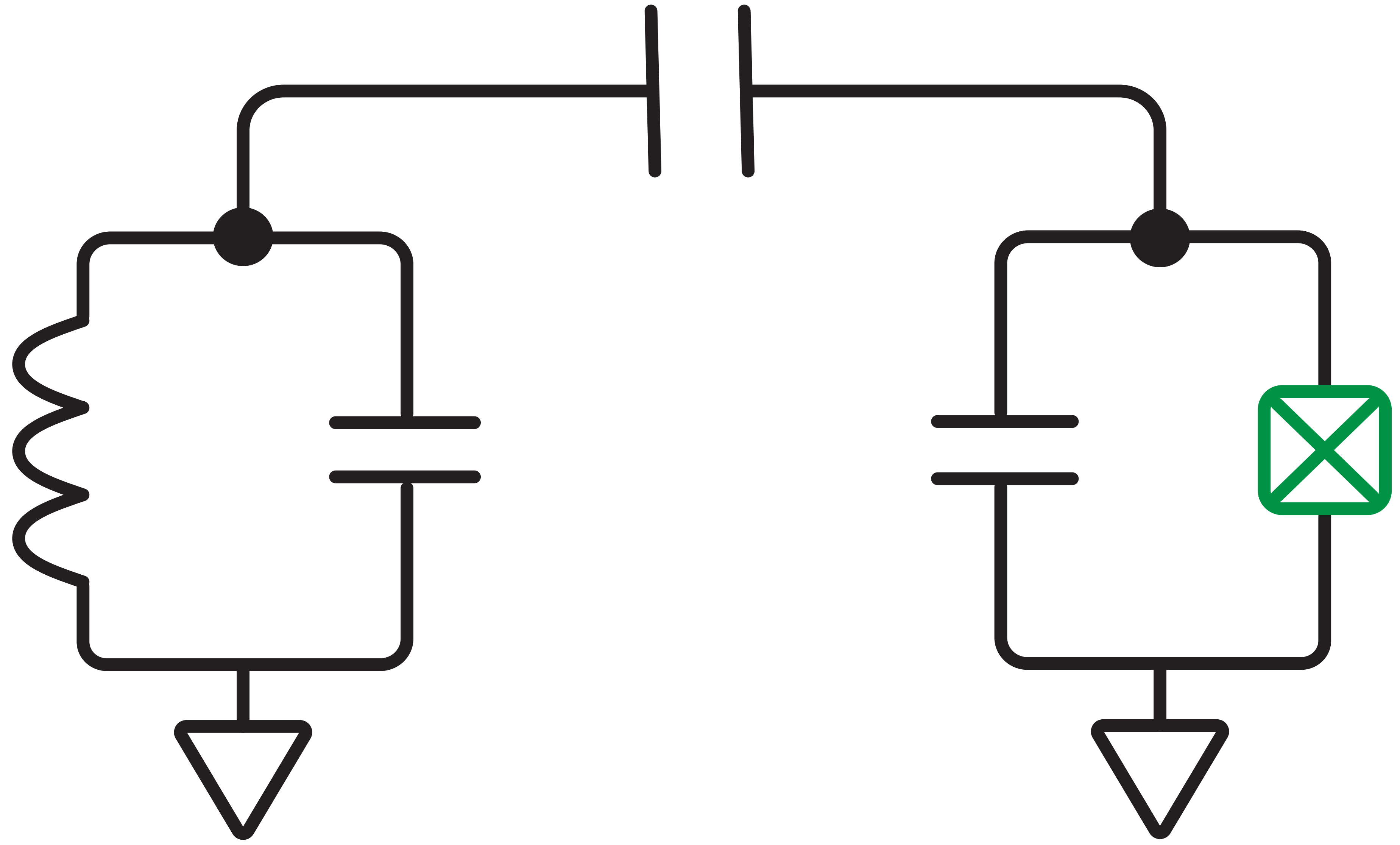


Ready to measurement!

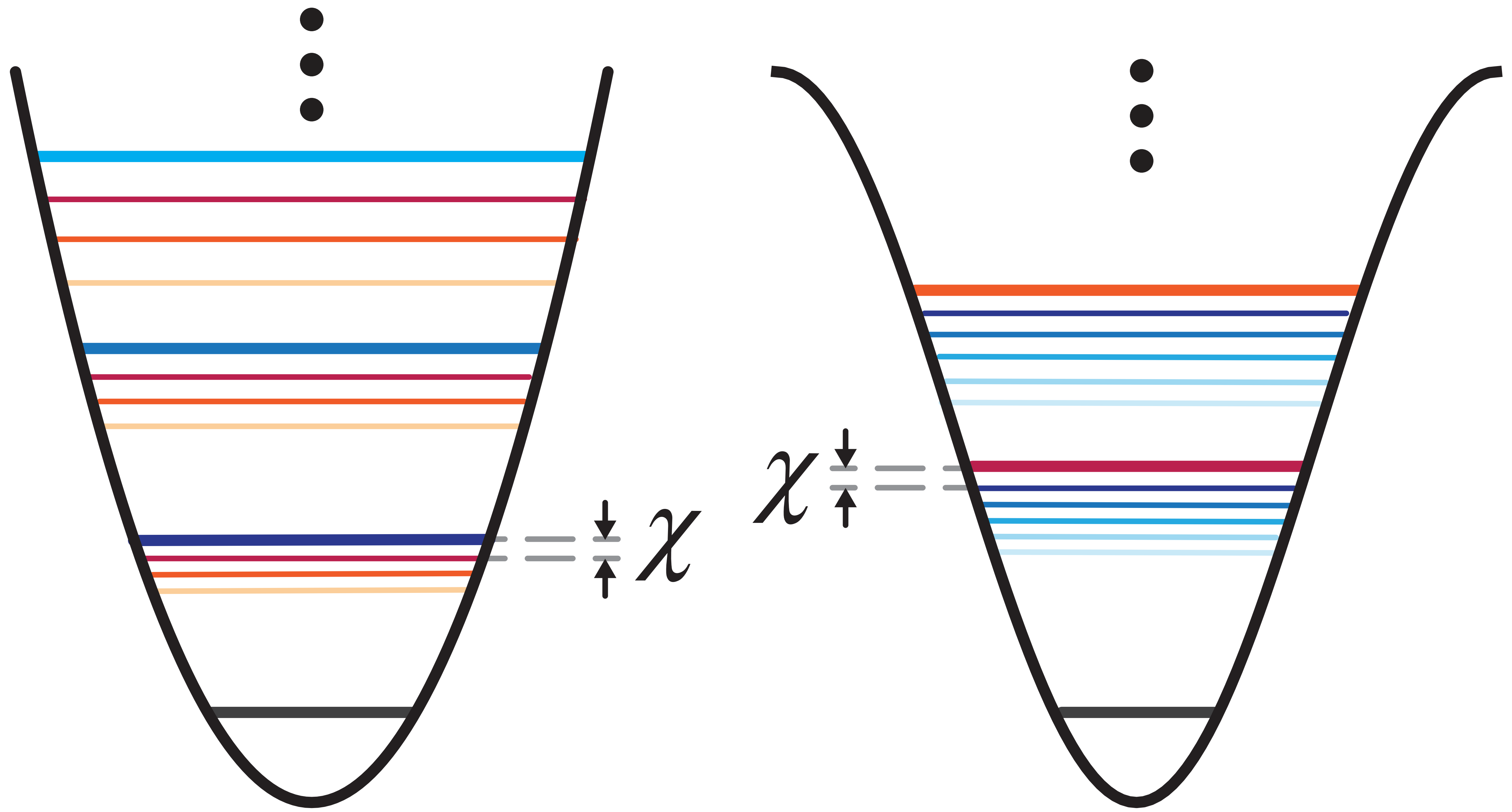
Introduced basic process to make a superconducting qubit

Next lecture shows how to measure these qubits

Backup

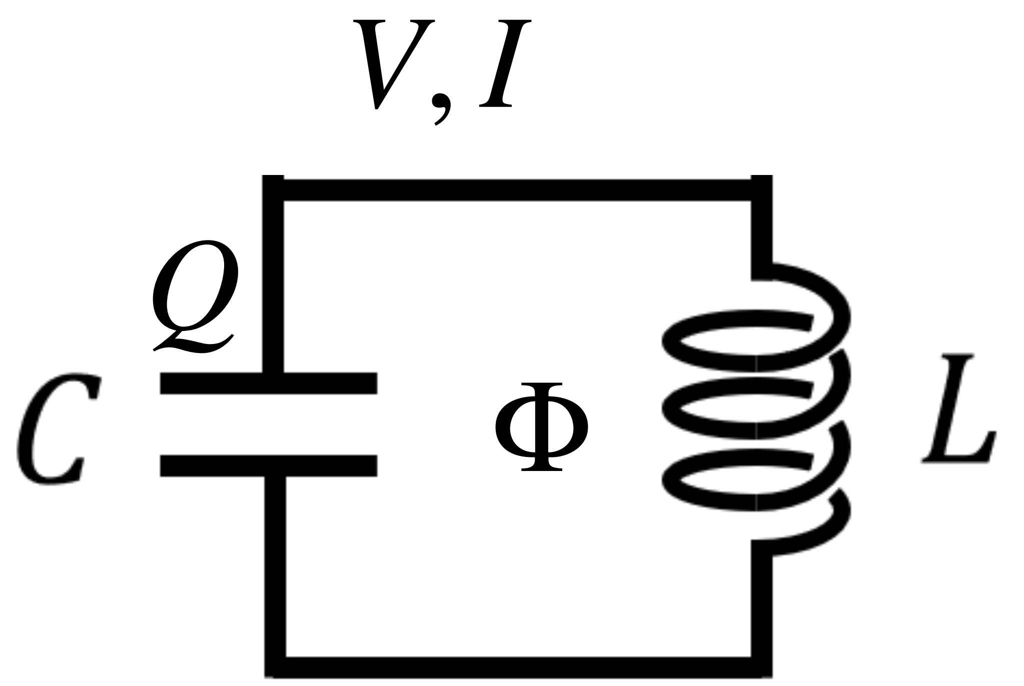


超伝導量子ビットの基礎



LC共振器の量子化

手始めに、おなじみのLC共振回路を量子化してみる。



共振周波数 $1/2\pi\sqrt{LC}$

キャパシタの電荷Qと共振回路を貫く磁束Φは

$$Q = CV, \quad \Phi = LI$$

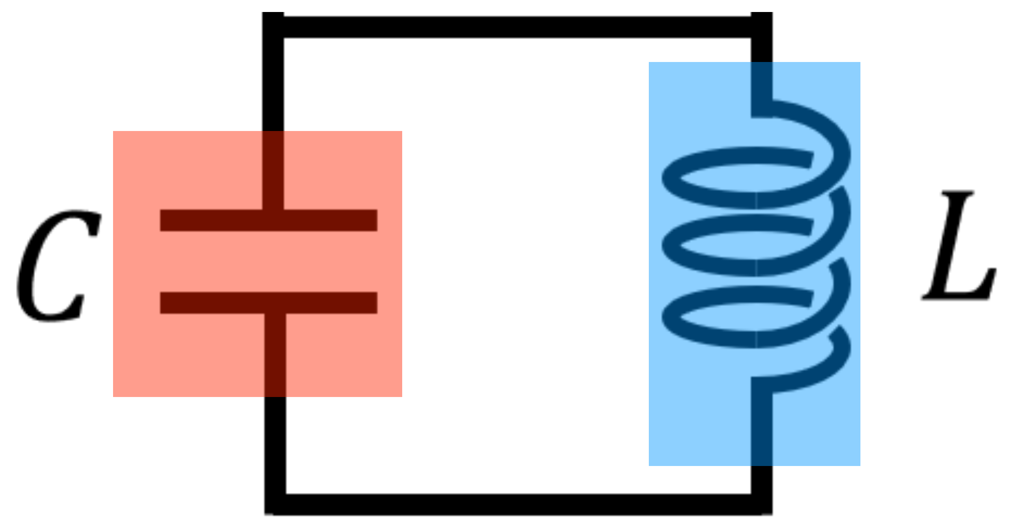
また

$$I = \frac{dQ}{dt}, V = \frac{d\Phi}{dt}$$

なので

$$\frac{d^2Q}{dt} = -\frac{Q}{LC}, \frac{d^2\Phi}{dt} = -\frac{\Phi}{LC}$$

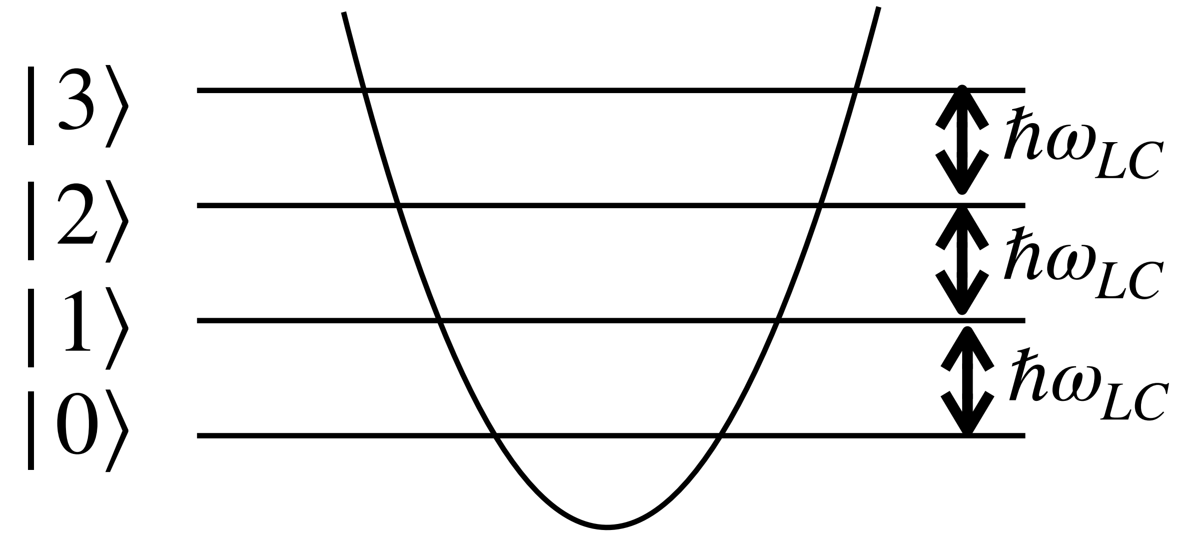
LC共振器の量子化



ラグランジアンとハミルトニアンはそれぞれ

$$\mathscr{L} = \frac{Q^2}{2C} - \frac{L}{2}\left(\frac{dQ}{dt}\right)^2, \quad \mathscr{H}_{LC} = \frac{Q^2}{2C} + \frac{\Phi^2}{2L}$$

基底状態付近のエネルギー



共振器内の光子の生成・消滅演算子を

$$a = \frac{1}{2\hbar}\sqrt{\frac{L}{C}}Q + \frac{i}{2\hbar}\sqrt{\frac{C}{L}}\Phi \qquad a^\dagger = \frac{1}{2\hbar}\sqrt{\frac{L}{C}}Q - \frac{i}{2\hbar}\sqrt{\frac{C}{L}}\Phi$$

とすると交換関係は$[a, a^\dagger] = 1$、$\mathscr{H}_{LC} = \hbar\omega_{LC}\left(a^\dagger a + \frac{1}{2}\right)$

注) $|0\rangle$のエネルギーは不確定性関係より0でない

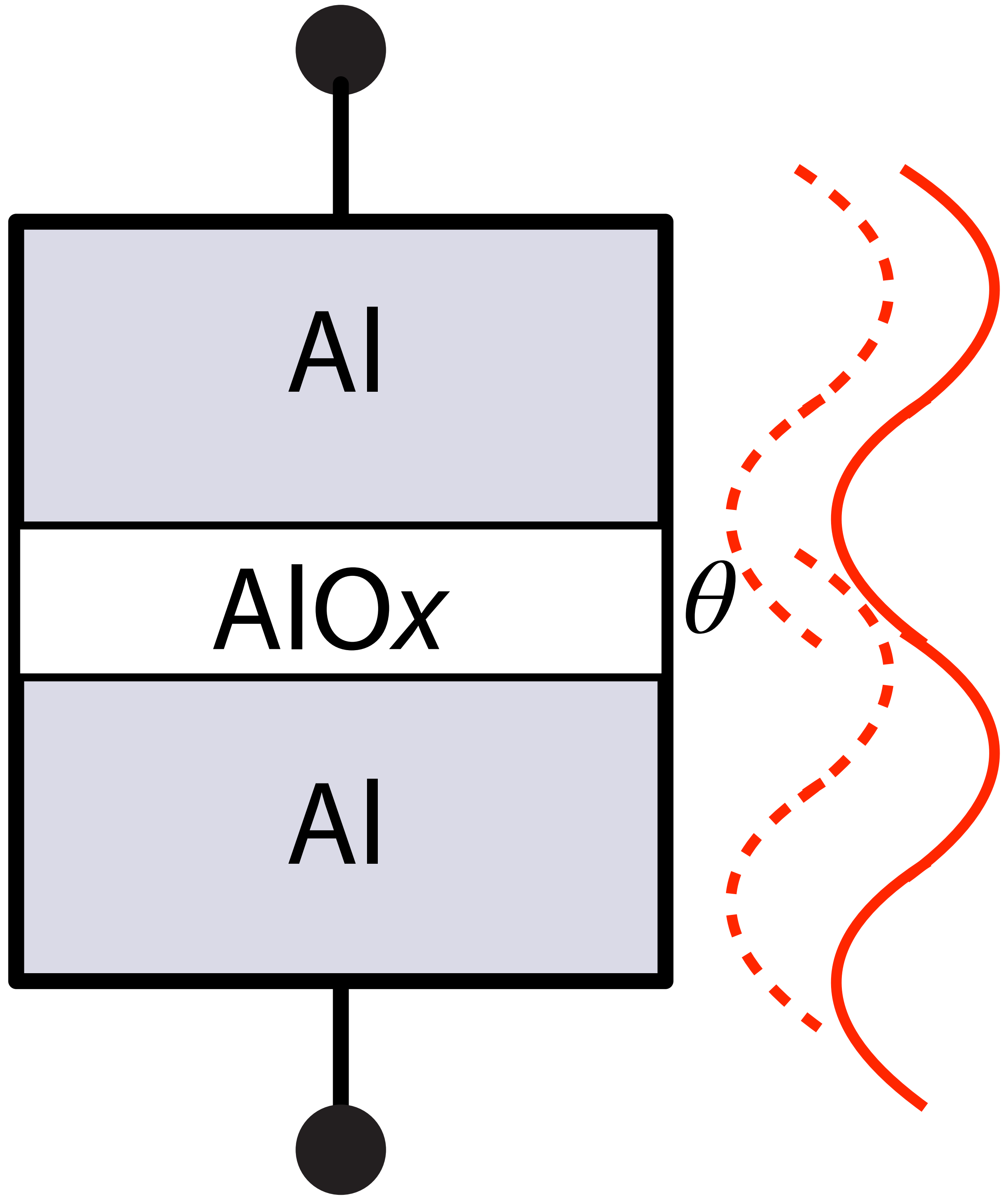
$$\Delta Q \cdot \Delta\Phi > \frac{1}{2}$$

ただしこれでは$|0\rangle$と$|1\rangle$の操作が極めて難しい

エネルギーギャップ($\hbar\omega_{LC}$)が等間隔のため

エネルギーギャップを変えるために、LかCに非線形性を導入。

ジョセフソン接合



Al: $T_C = 1.2\ \mathrm{K}$

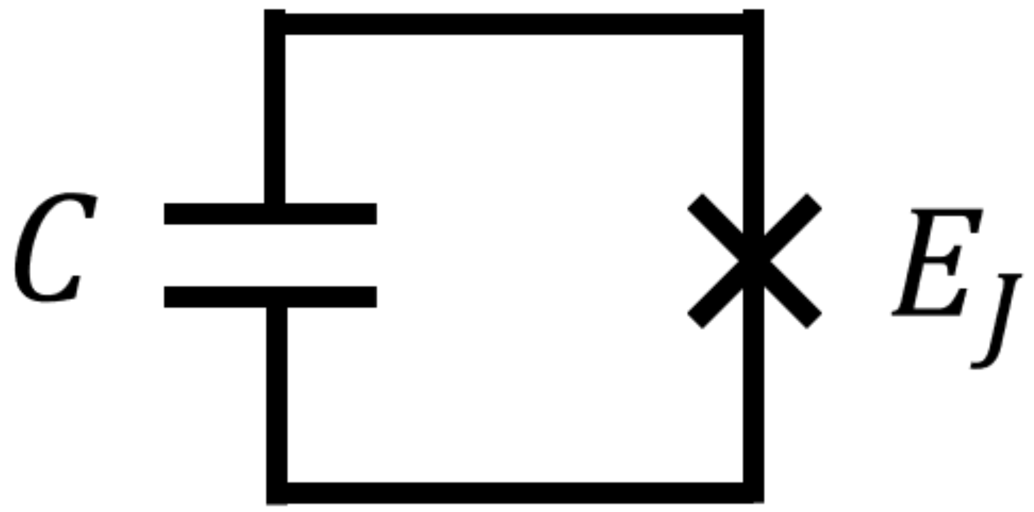
- 超伝導-絶縁体-超伝導のサンドイッチを作る
- 冷やすと超伝導体が1つの巨大な物質波を形成（ボースアインシュタイン凝縮）
- 隣接した超伝導体はそれぞれ異なった位相を持つ
  →位相差を吸収するために電流が流れる。

定量的にジョセフソン関係:

$$I = I_0 \sin\theta$$

$$V = \frac{\hbar}{2e}\frac{\partial\theta}{\partial t}$$

非線形LC共振器の量子化



$\Phi_0 = h/2e$を使って、磁束を$\Phi_J = (\theta/2\pi)\Phi_0$と定義すると

$$I = I_0 \sin\theta,\ V = \frac{\hbar}{2e}\frac{\partial\theta}{\partial t} \text{ -> } I = I_0 \sin\left(2\pi\frac{\Phi_J}{\Phi_0}\right),\ V = \frac{d\Phi_J}{dt}.$$

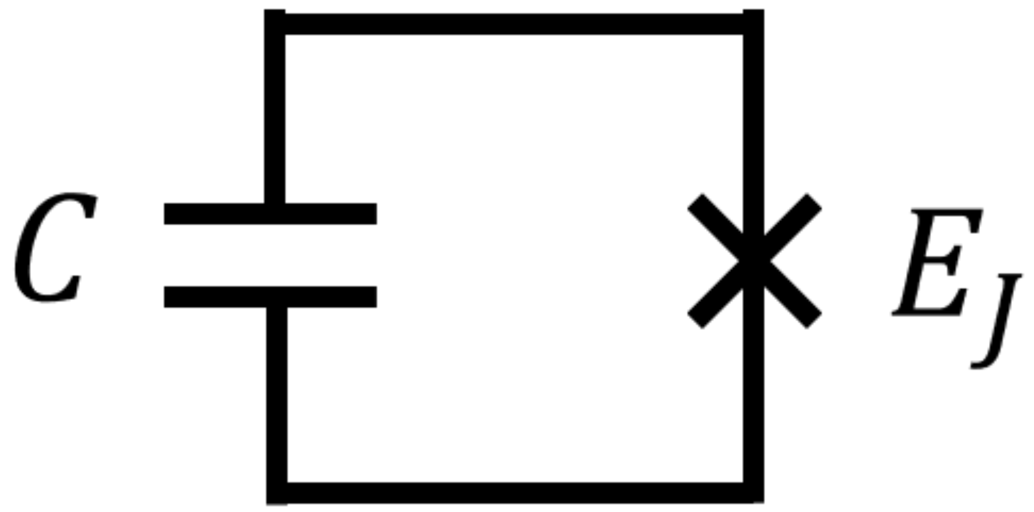
$Q = CV$より、

$$\frac{dQ}{dt} = C\frac{dV}{dt} = -I_0 \sin\left(2\pi\frac{\Phi_J}{\Phi_0}\right)$$

$$\to \quad C\frac{d^2\Phi_J}{dt^2} = -I_0 \sin\left(2\pi\frac{\Phi_J}{\Phi_0}\right)$$

Lagrange方程式

非線形LC共振器の量子化



Lagrangianは

$$\mathscr{L}_q = \frac{C}{2}\left(\frac{d\Phi_J}{dt}\right)^2 + \frac{I_0\Phi_0}{2\pi}\cos\left(2\pi\frac{\Phi_J}{\Phi_0}\right)$$

$$= \frac{Q^2}{2c} + \frac{I_0\Phi_0}{2\pi}\cos\left(2\pi\frac{\Phi_J}{\Phi_0}\right)$$

ここで$E_J = I_0\Phi_0/2\pi$ (Josephson Energy),

$E_C = e^2/2C$ (Charge Energy),

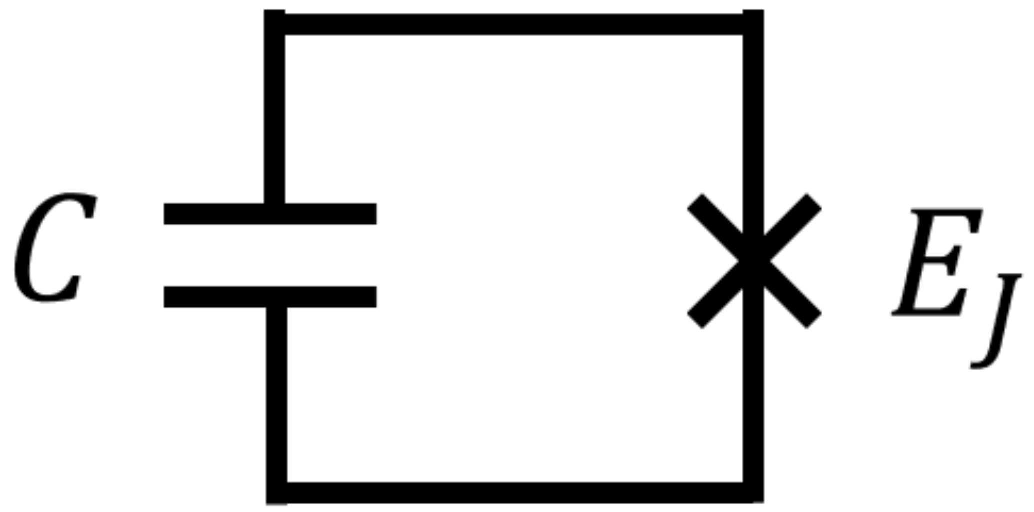
$n_C = Q/2e$ (Cooper対の個数)

を導入すると、（Legendre変換より）

ハミルトニアンがかけた

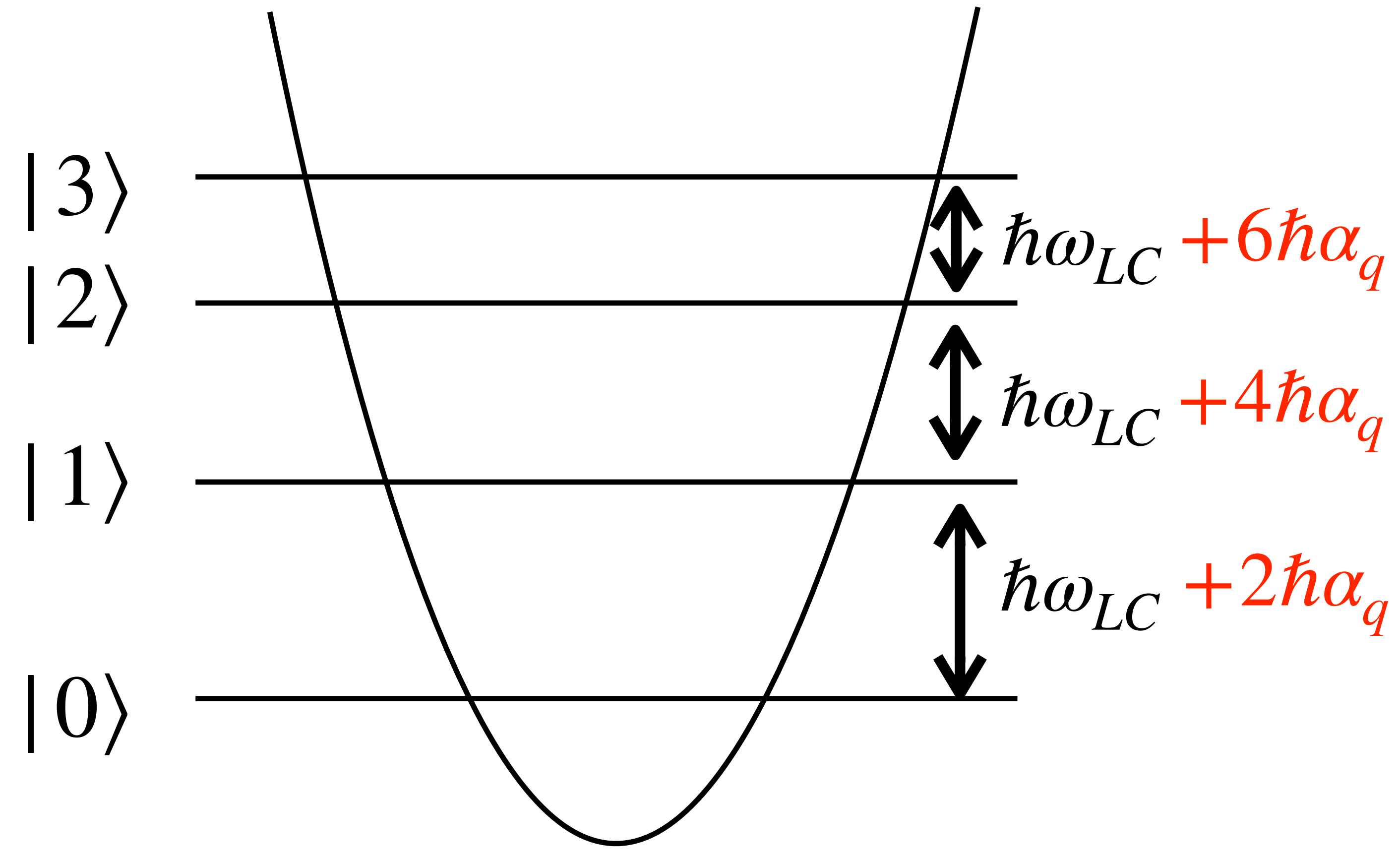
$$\mathscr{H}_q = 4E_C n_C^2 + E_J\cos\theta$$

非線形LC共振器の量子化



生成消滅演算子は

$$n_C = \left(\frac{E_J}{8E_C}\right)^{\frac{1}{4}} \frac{a + a^\dagger}{\sqrt{2}}, \qquad \theta = \left(\frac{8E_C}{E_J}\right)^{\frac{1}{4}} \frac{a - a^\dagger}{i\sqrt{2}}$$



$$\mathcal{H}_q = (\sqrt{8E_C E_J} - E_C) a^\dagger a - \frac{E_C}{2} a^\dagger a^\dagger a a$$

$$= \hbar\omega_q a^\dagger a + \frac{\hbar\alpha_q}{2} a^\dagger a^\dagger a a$$

$E_J/E_C \gg 1$として

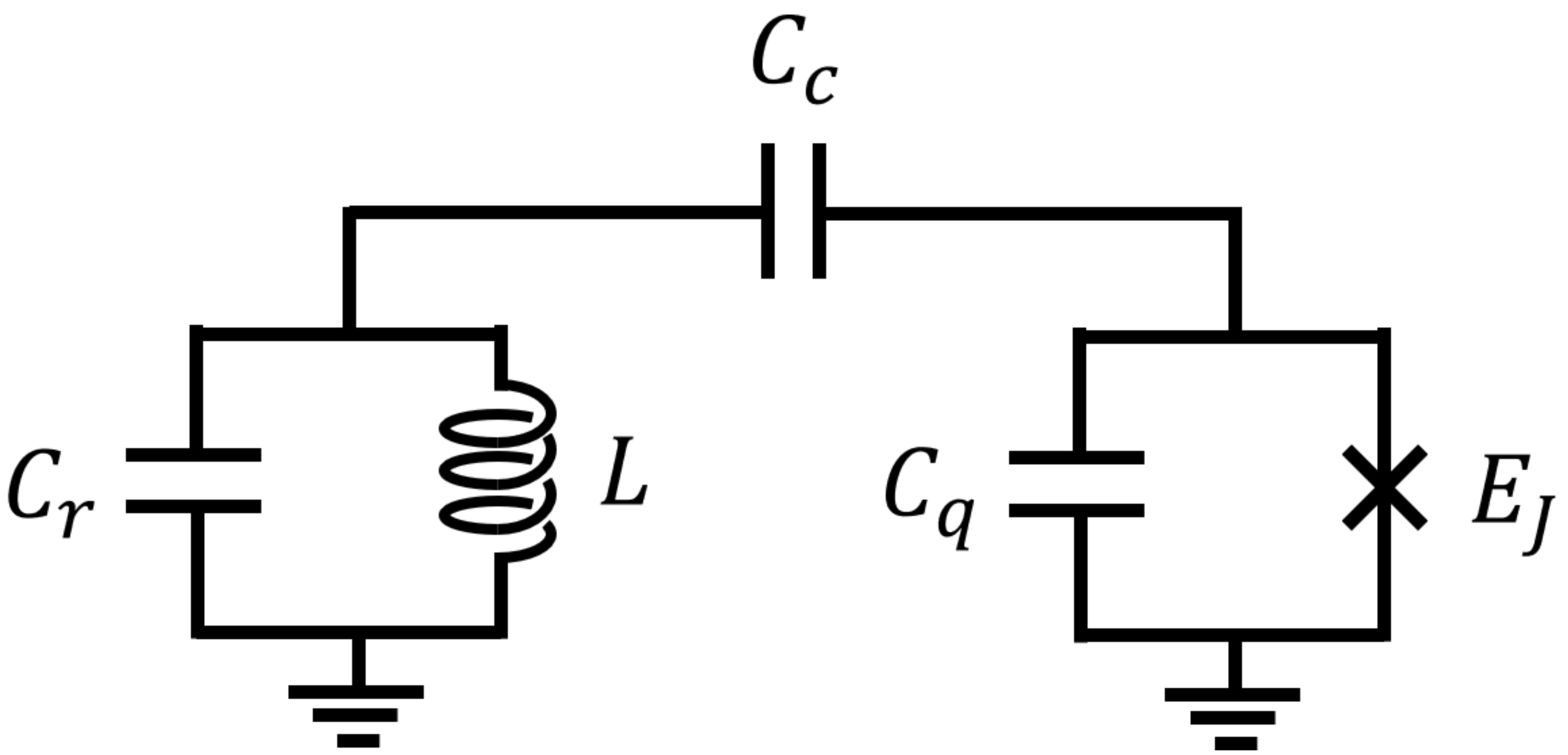
$\cos\theta \simeq 1 - \theta^2/2! + \theta^4/4!$を使っている

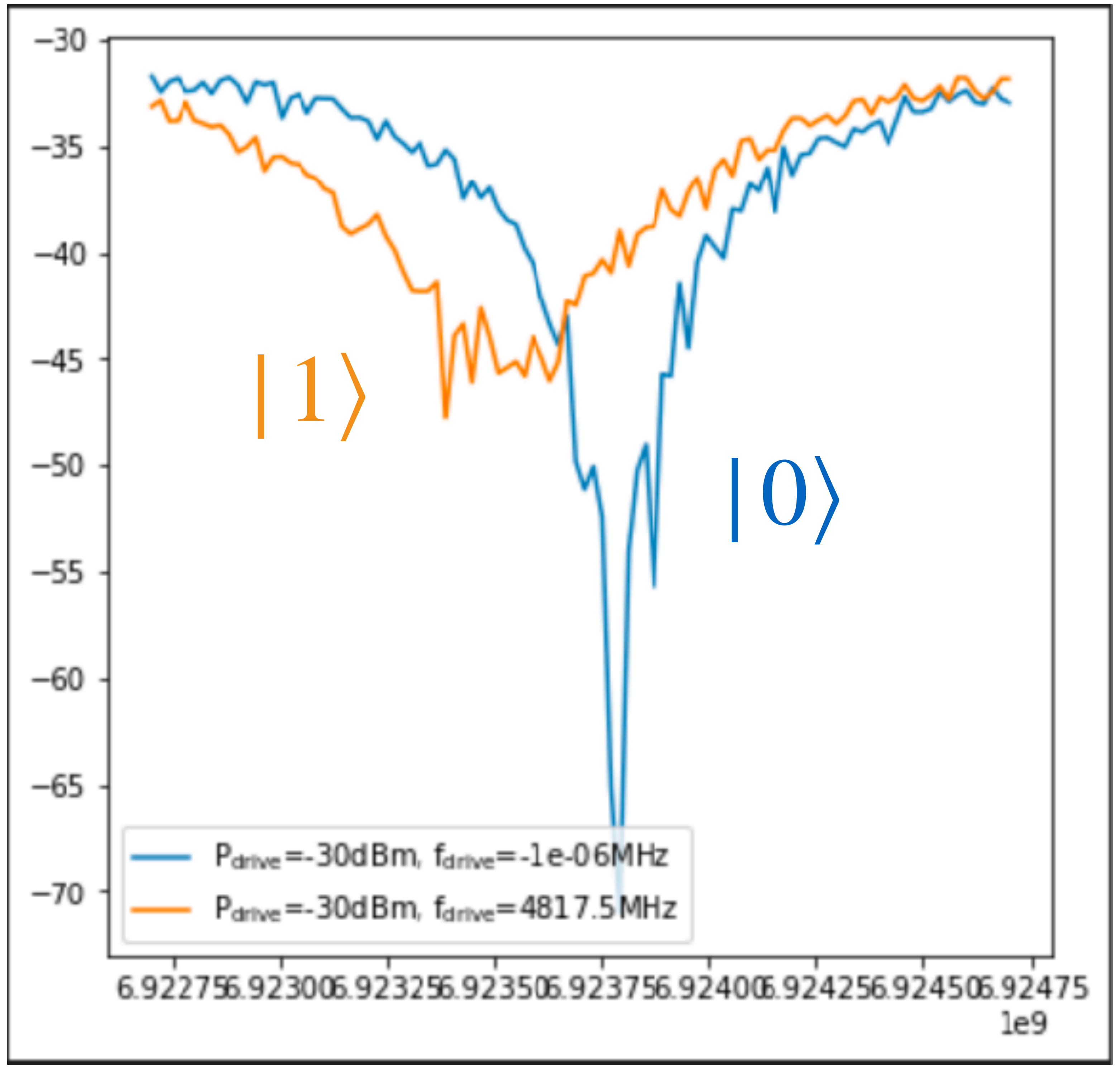
ジョセフソン接合によって、扱いやすい2準位系ができた。

これをトランズモンという。

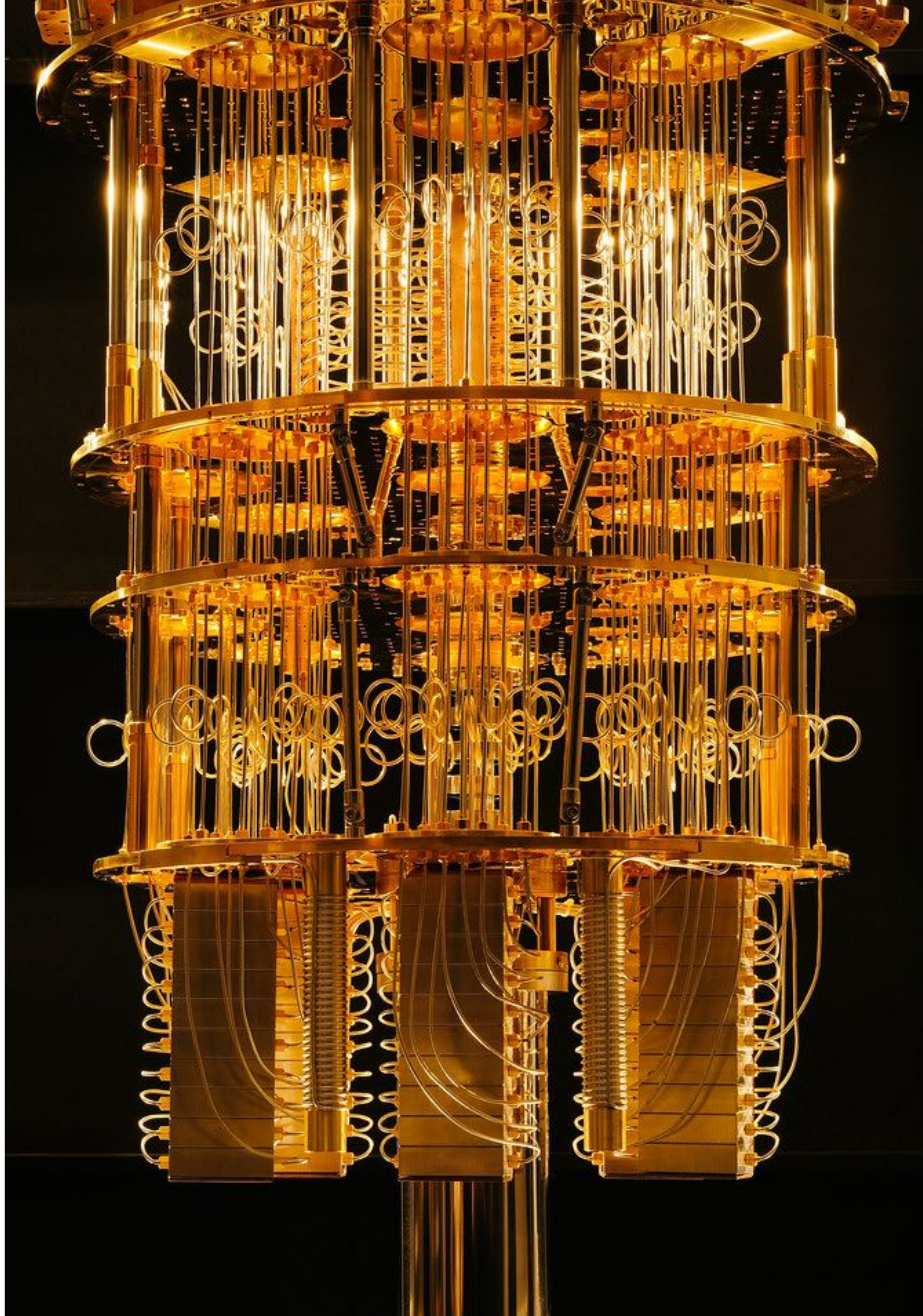
トランズモンとLC共振器の結合

トランズモンの電荷等を直接読みだそうとすると壊れやすいので、
分散シフト読み出しを通常おこなう。





測定系



極低温（mK）の必要性

1. ジョセフソン接合を超伝導温度まで下げたい
   アルミの転移温度 ~ 1.2 K

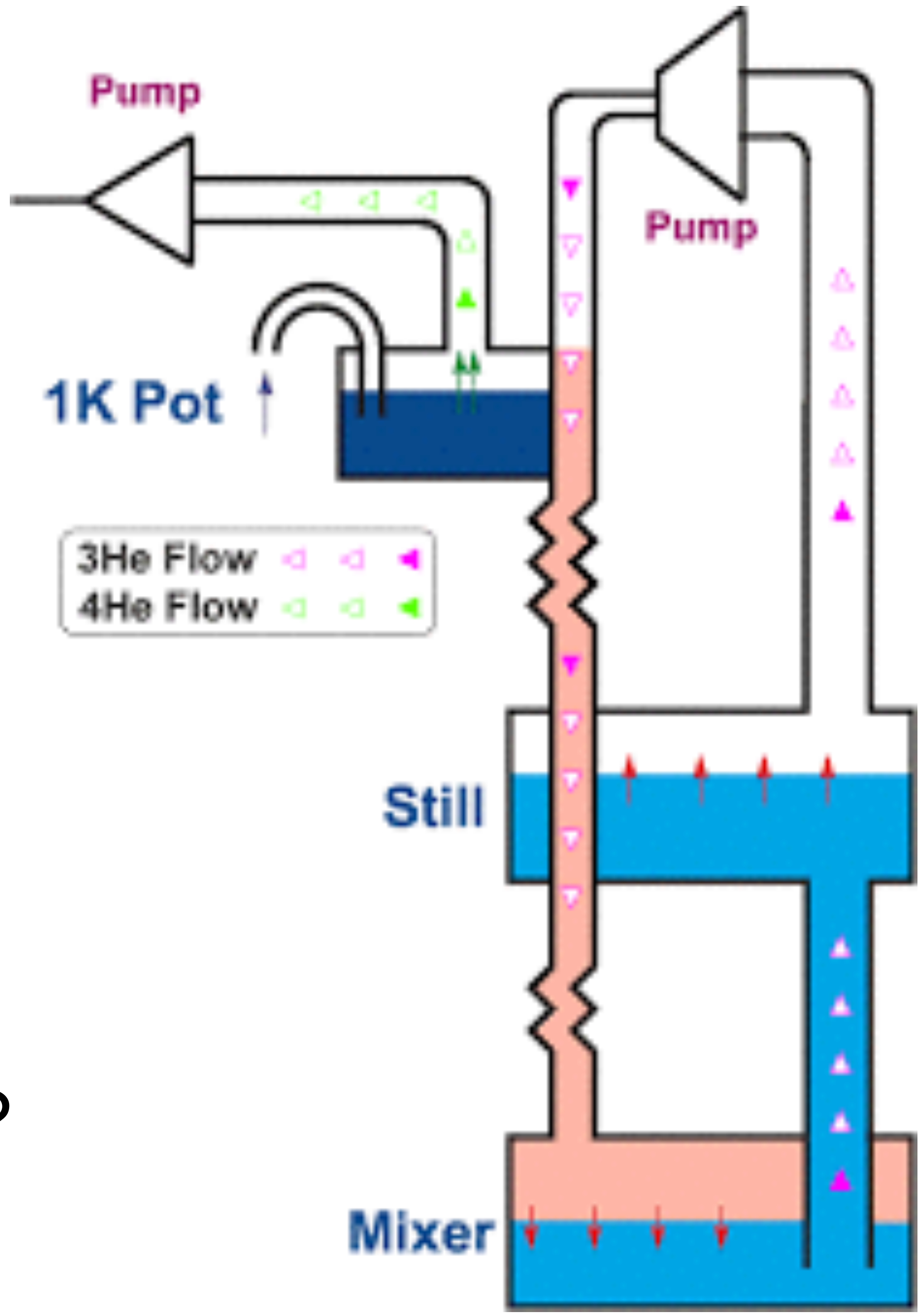
2. 分散読み出しはqubitの状態を変えないように
   低いエネルギーを当てる。
   熱ノイズが温度に比例
   $P = k_b bT$

通常の実験は~10 mKでおこなっている

冷やす方法

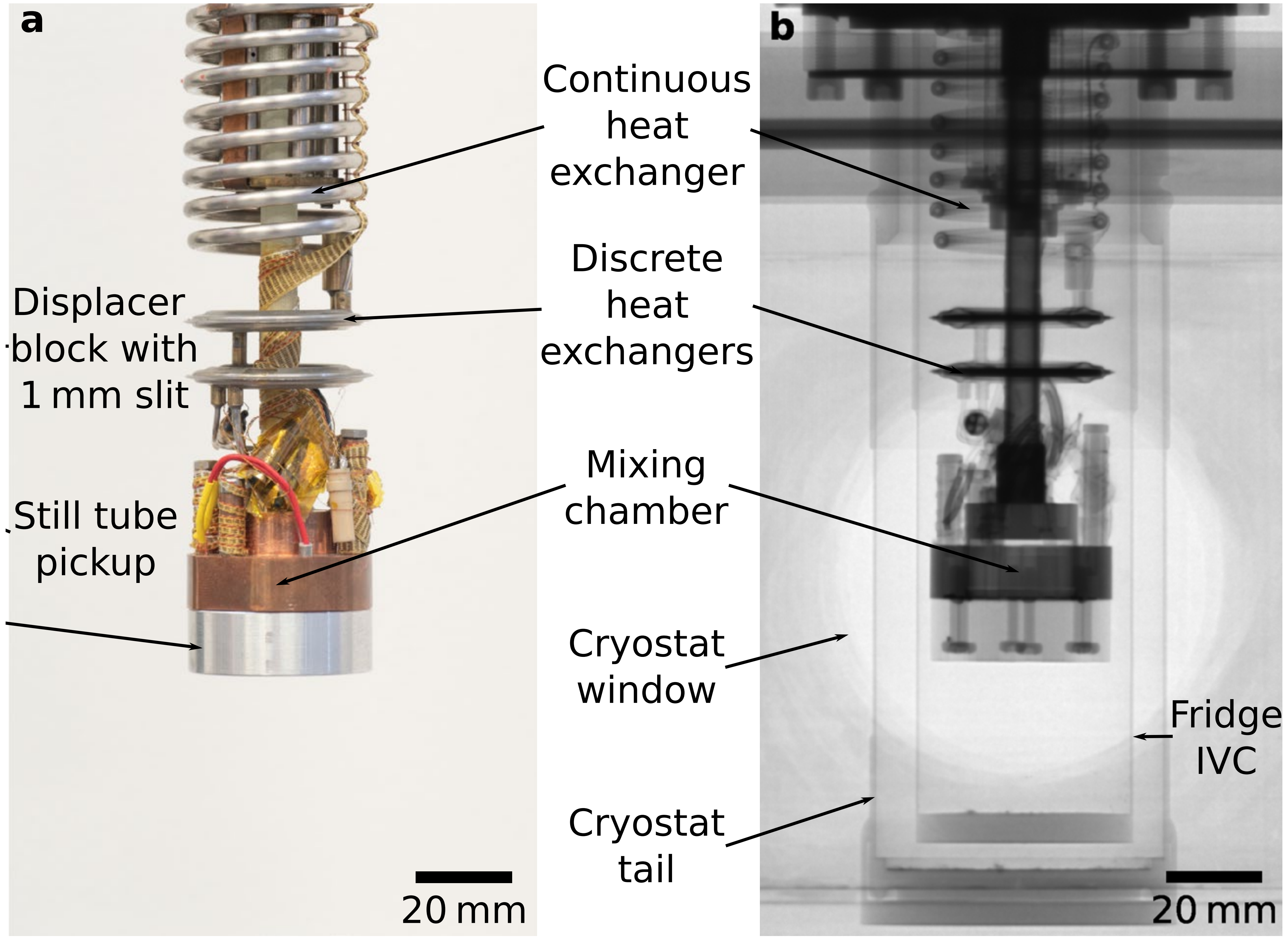
到達温度	手法	
77K	液体窒素	千円?
4.2 K	液体ヘリウム4	数十万?
1 K	液体ヘリウム4の減圧排気	100万円?
0.3 K	液体ヘリウム3の減圧排気	1000万円?
5 mK	希釈冷凍機	1億円?
1 μK	断熱消磁	1000万円?

希釈冷凍機

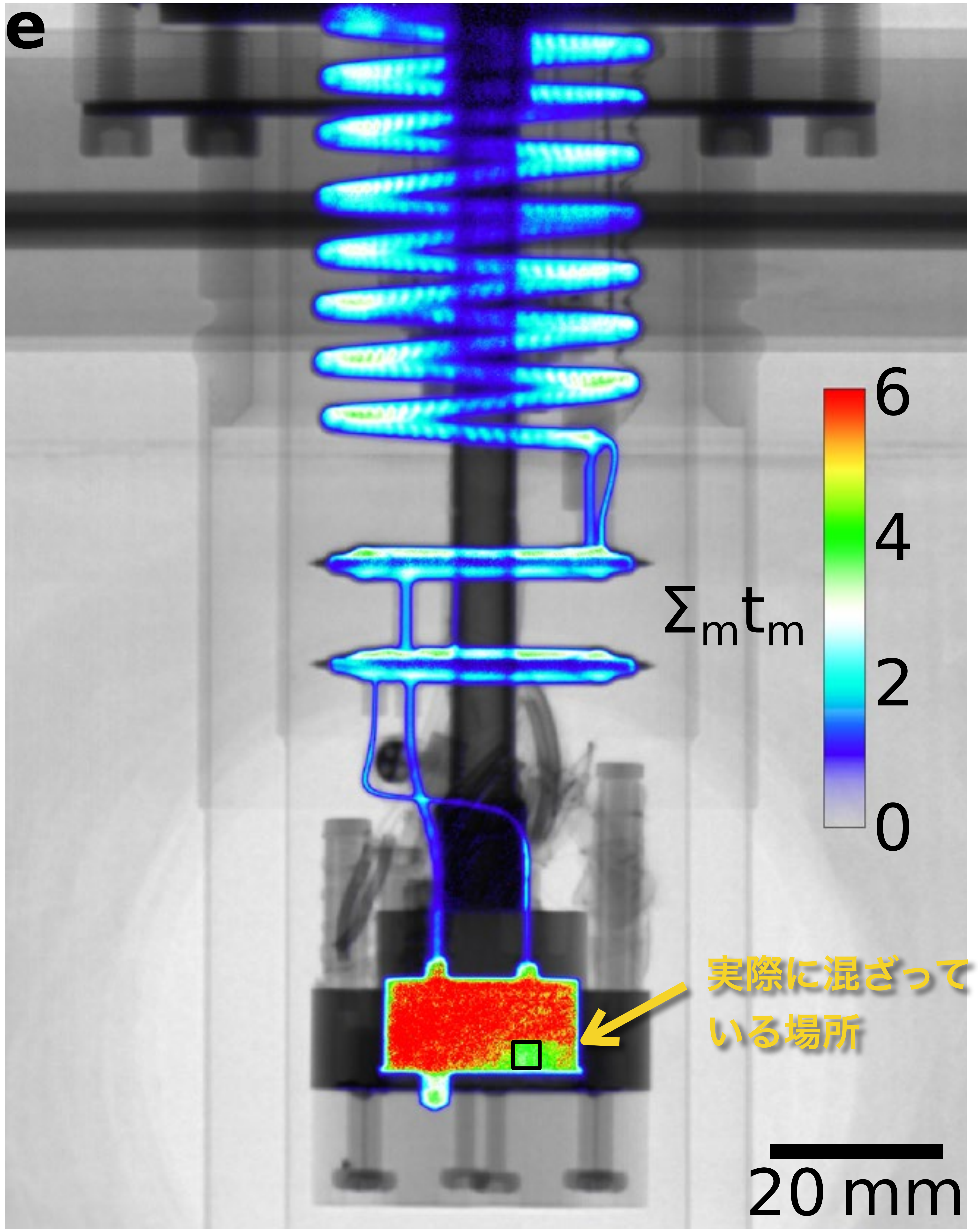


希釈冷凍機

Scientific Reports
volume
12, Article number: 1130 (2022)



中性子線写真で実写した動作途中の
希釈冷凍機



熱の制御

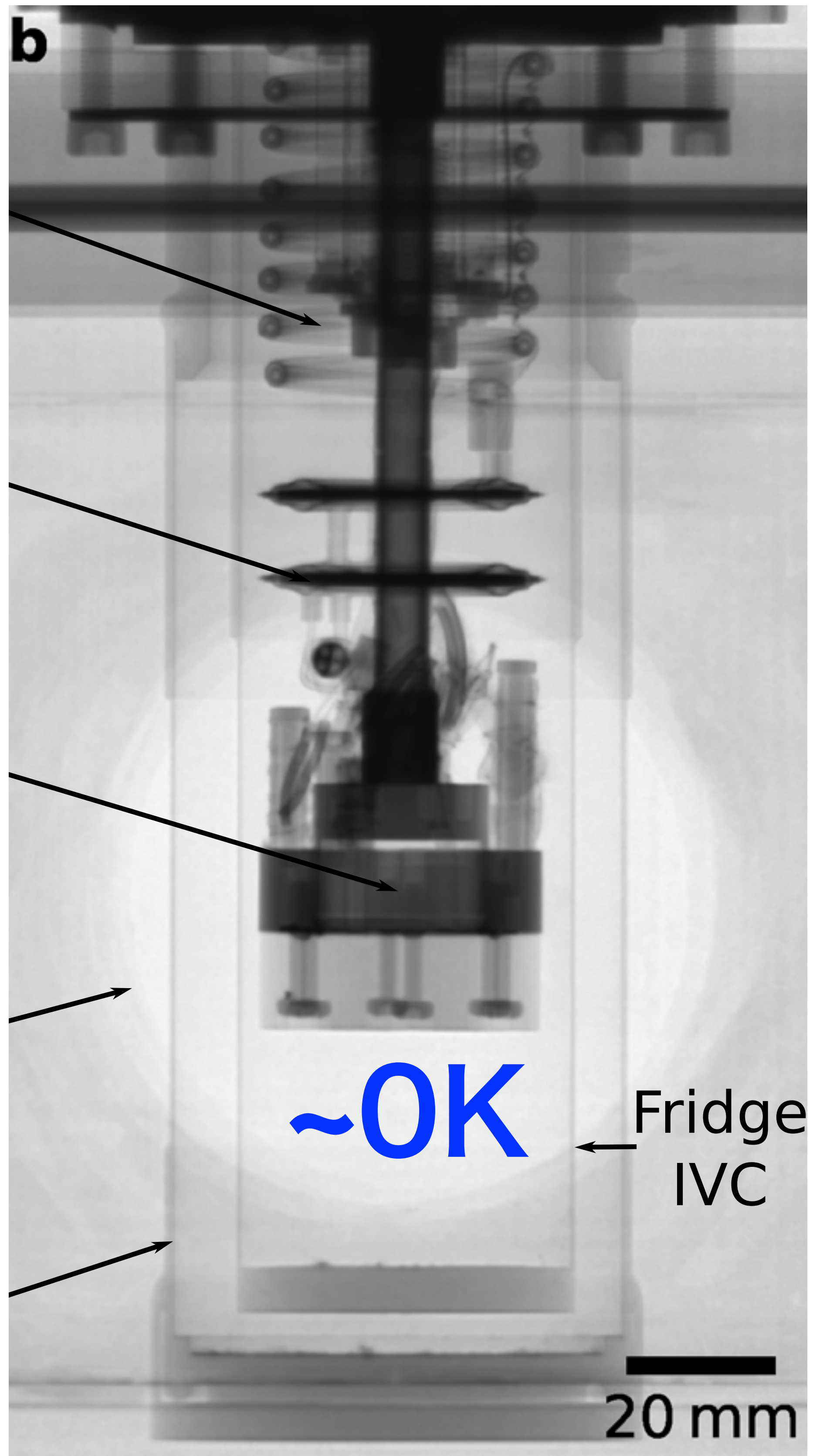
主に3つ

- conductive heat (伝導)
- convecting heat (対流)
- radiative heat (放射)

∧　この状況を作り出す

希釈冷凍機の冷凍性能

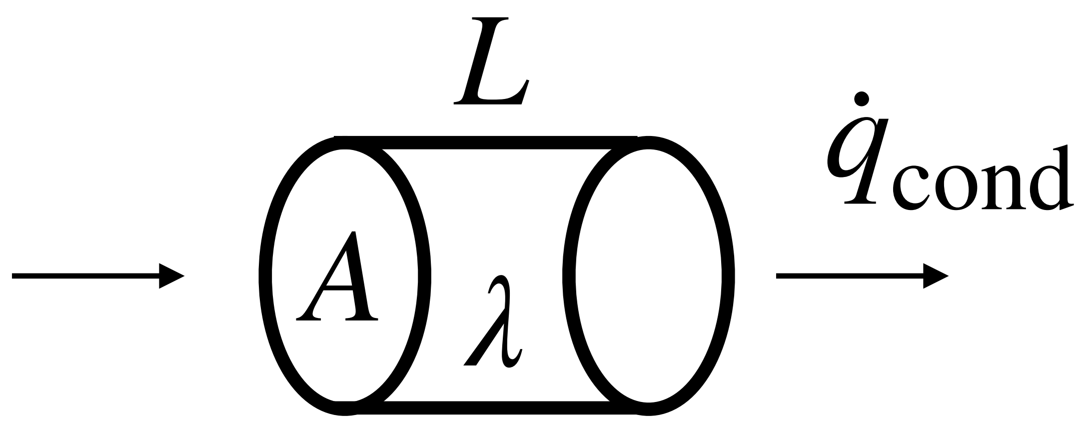
100-1000 μW



300 K

恐ろしい寒暖差

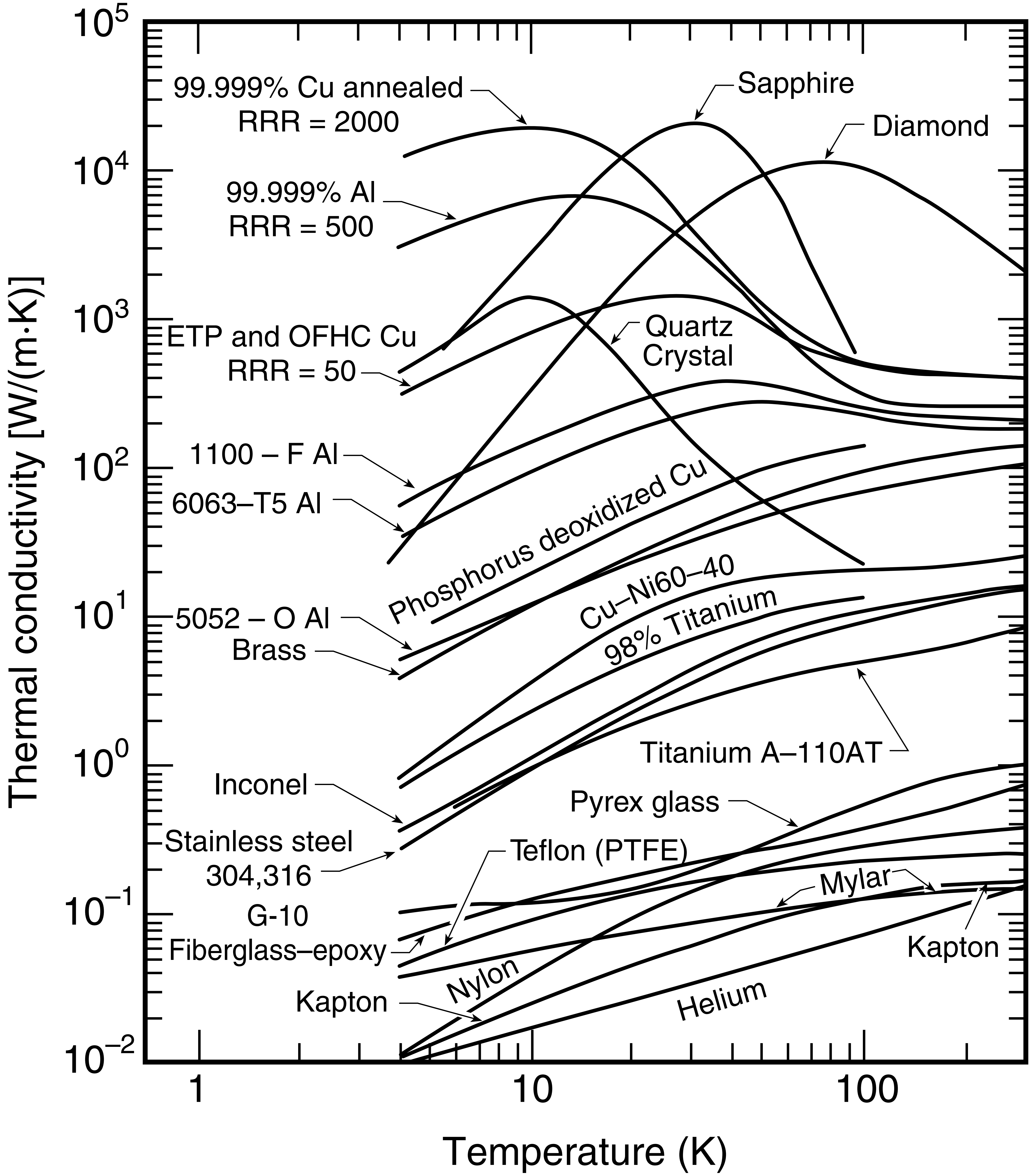
Conductive Heat



$$\dot{q}_{\text{cond}} = A/L\int_{T_1}^{T_2}\lambda(T)dT = A/L\left[\int_{4\,\text{K}}^{T2}\lambda(T)\,dT - \int_{4\,\text{K}}^{T1}\lambda(T)\,dT\right]$$

~10 K以上では電子が熱を伝えるので
ほぼ電気伝導度の同じ順番と考えて良い
それ以下ではフォノンによる伝導になる

異なる熱ステージの接続にはステンレスが
良く使われる。



Convecting Heat

流体的振る舞いのとき (高圧)

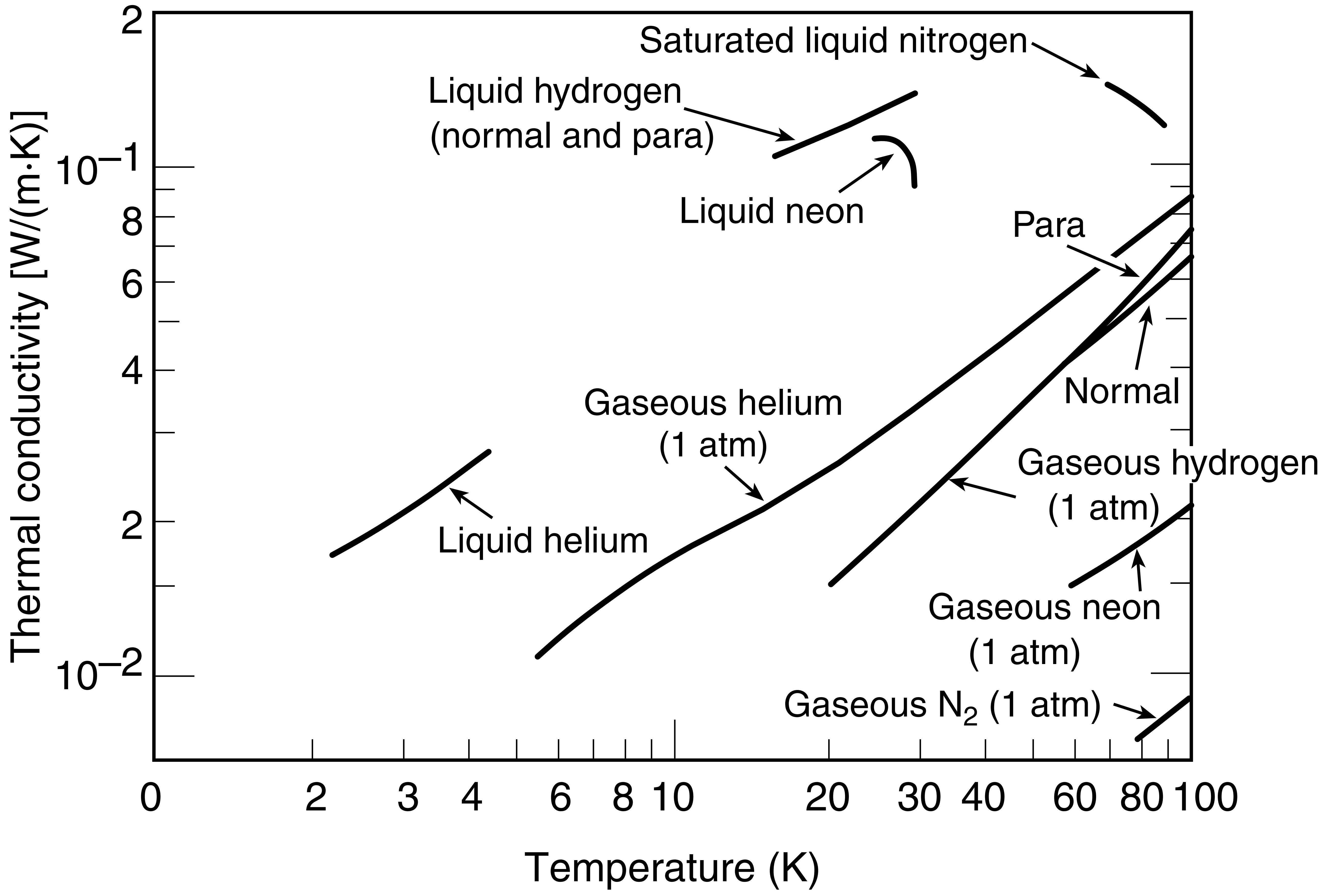
$$\dot{q}_{gas} = \bar{\lambda} A \Delta T / d$$

分子的振る舞いのとき (低圧)

$$\dot{q}_{gas} = \mathrm{k}\, a_0\, P\, A_i\, \Delta T, \text{ [watts]}$$

希釈冷凍機は高真空で動いている

ADMXは10^{-8} Paくらい



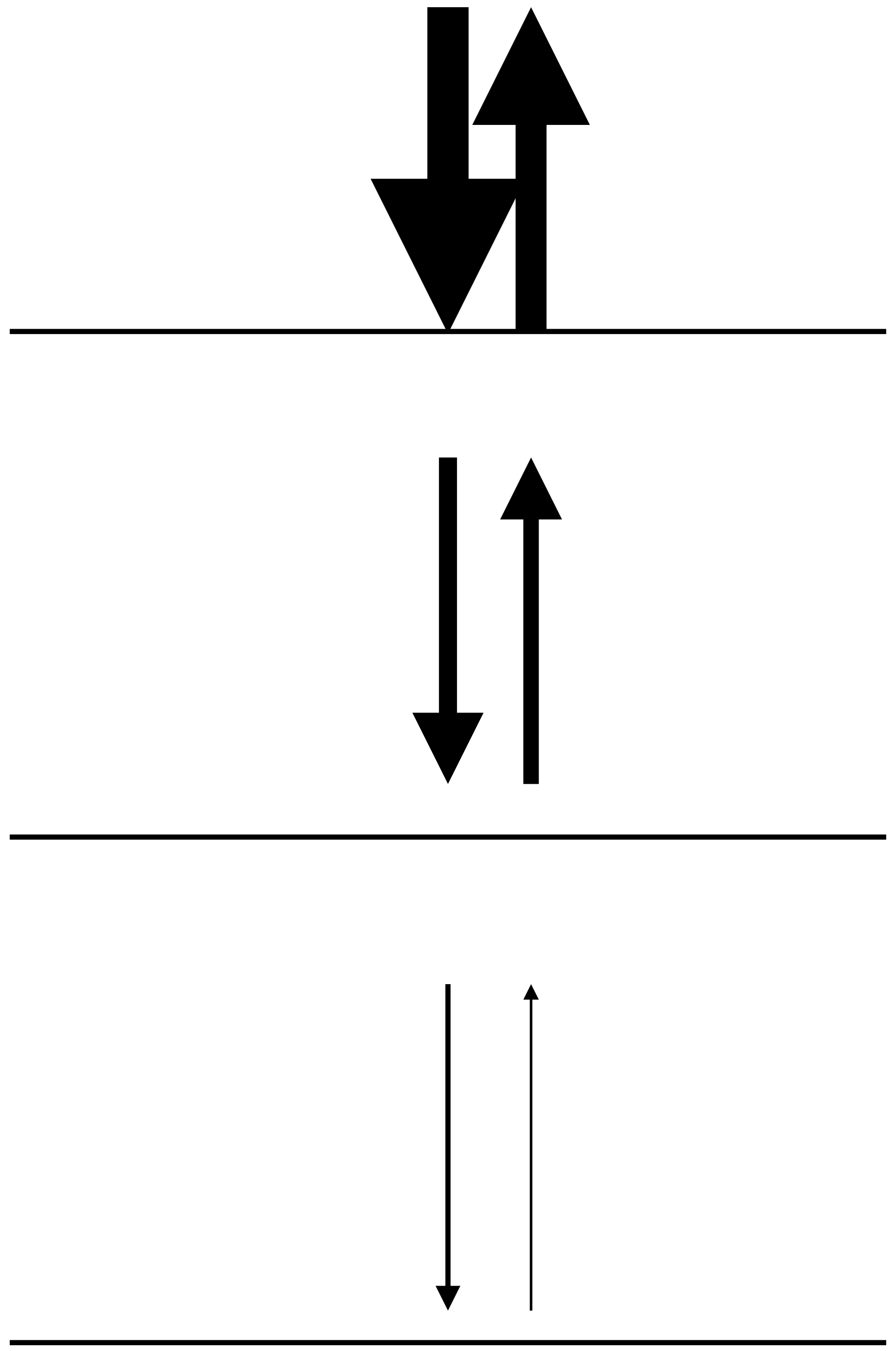
Radiative Heat

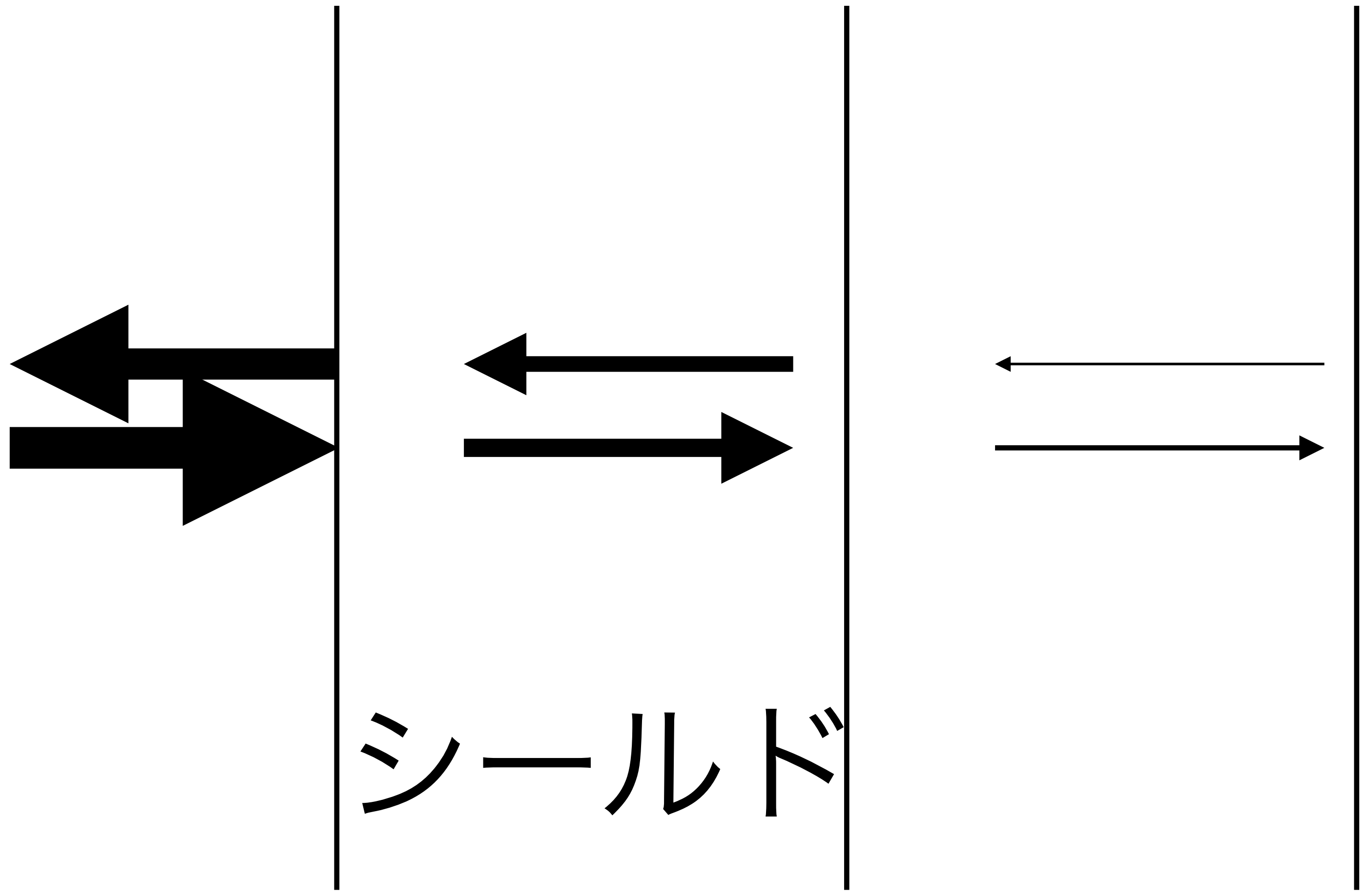
$$\dot{q}_{\mathrm{rad}} = \sigma \boldsymbol{E} A(T_2{}^4 - T_1{}^4)$$

A2.2 EMISSIVITY OF TECHNICAL MATERIALS AT A WAVELENGTH OF ABOUT 10 μm (ROOM TEMPERATURE) (SEC. 2.4)

Material	Emissivity		
	Polished	Highly oxidized	Common condition
Metallic			
Ag	0.01		
Cu	0.02	0.6	
Au	0.02		
Al	0.03	0.3	
Brass	0.03	0.6	
Soft-solder			0.03
Nb, crystalline, bulk			0.04
Lead	0.05		
Ta	0.06		
Ni	0.06		
Cr	0.07		
Stainless steel			0.07
Ti			0.09
Tin (gray), single crystal			0.6
Nonmetallic			
IMI 7031 varnish			0.9
Phenolic lacquer			0.9
Plastic tape			0.9
Glass			0.9

バッフル





冷たい

実際の様子

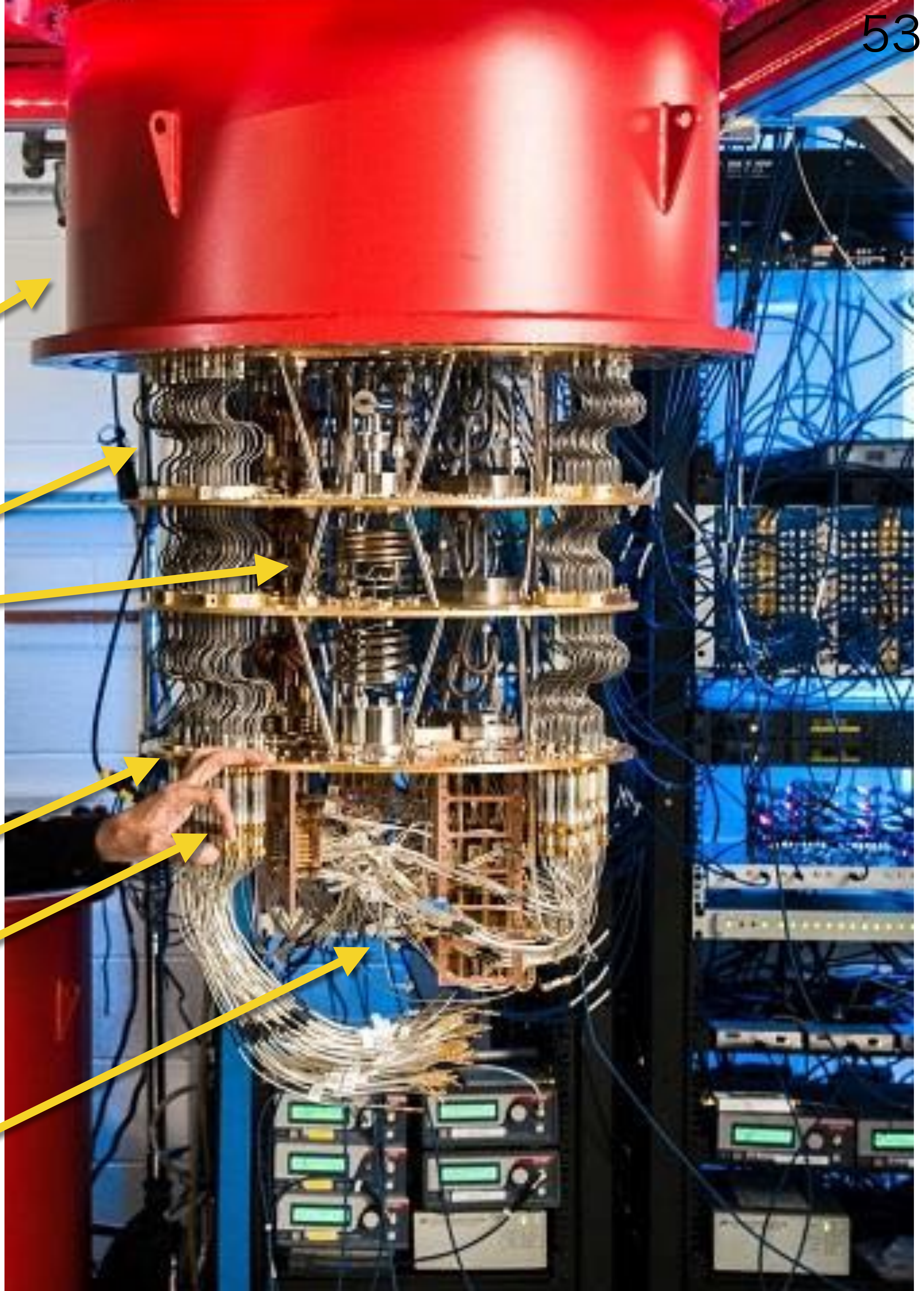
radiative shields

ステンレス
& 長い (くねくねさせる)

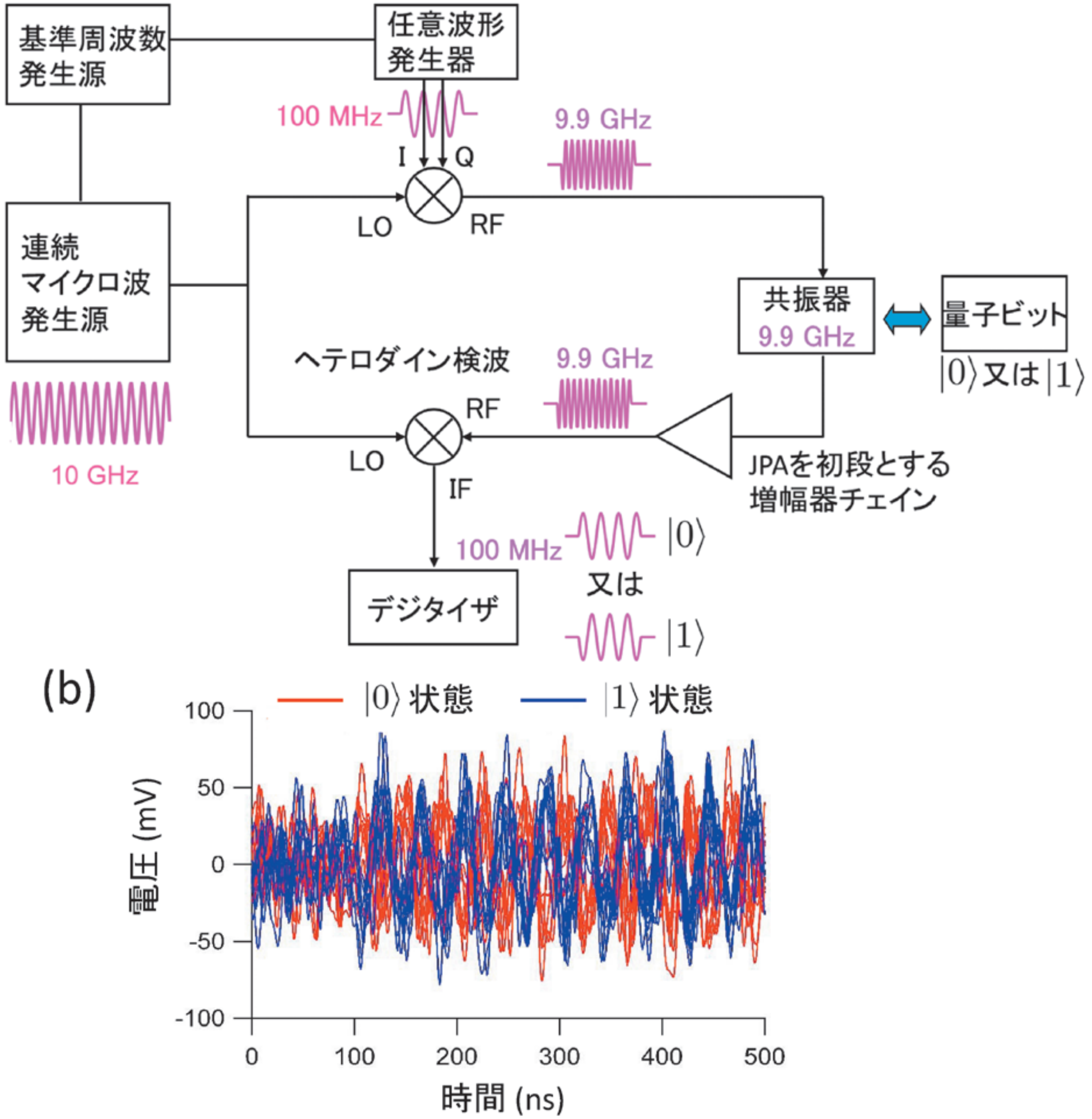
金メッキ or 銅

フィルター

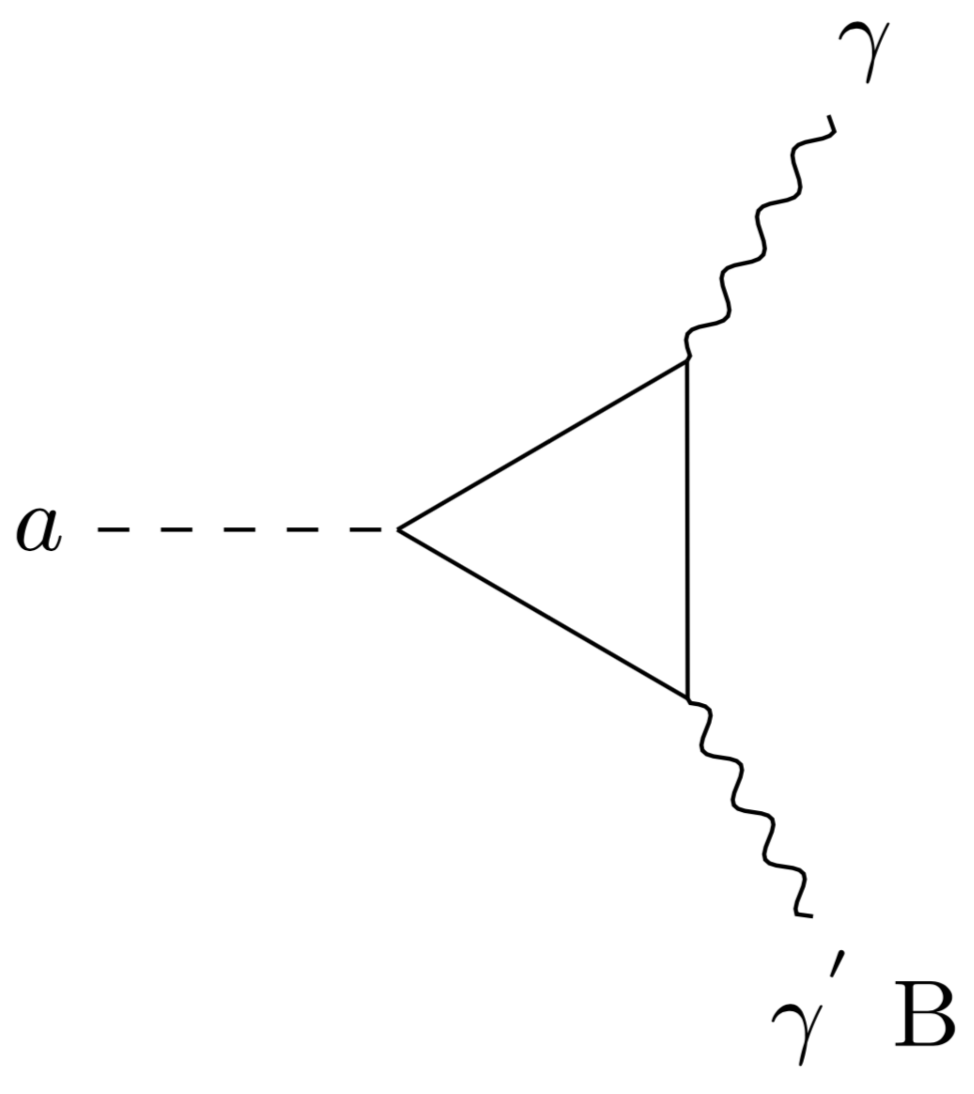
信号線は超伝導



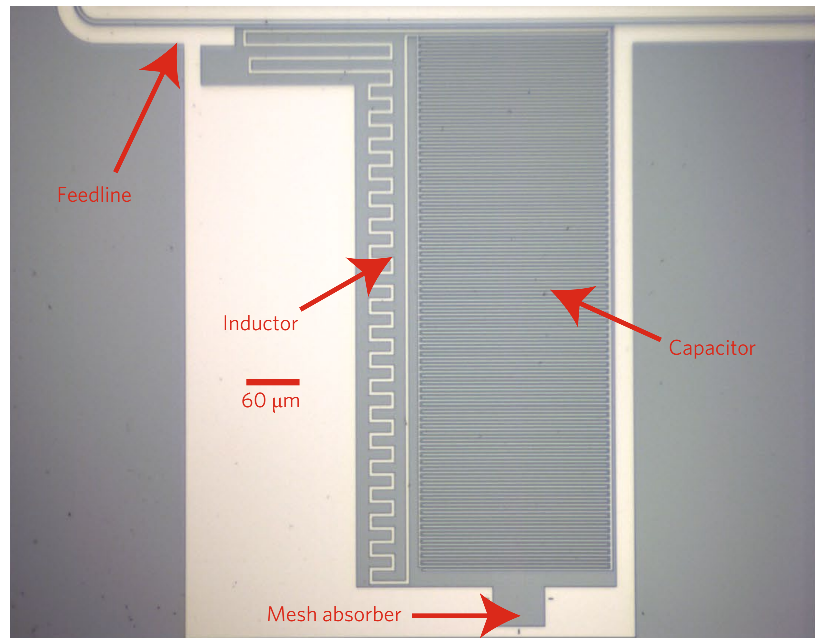
測定系

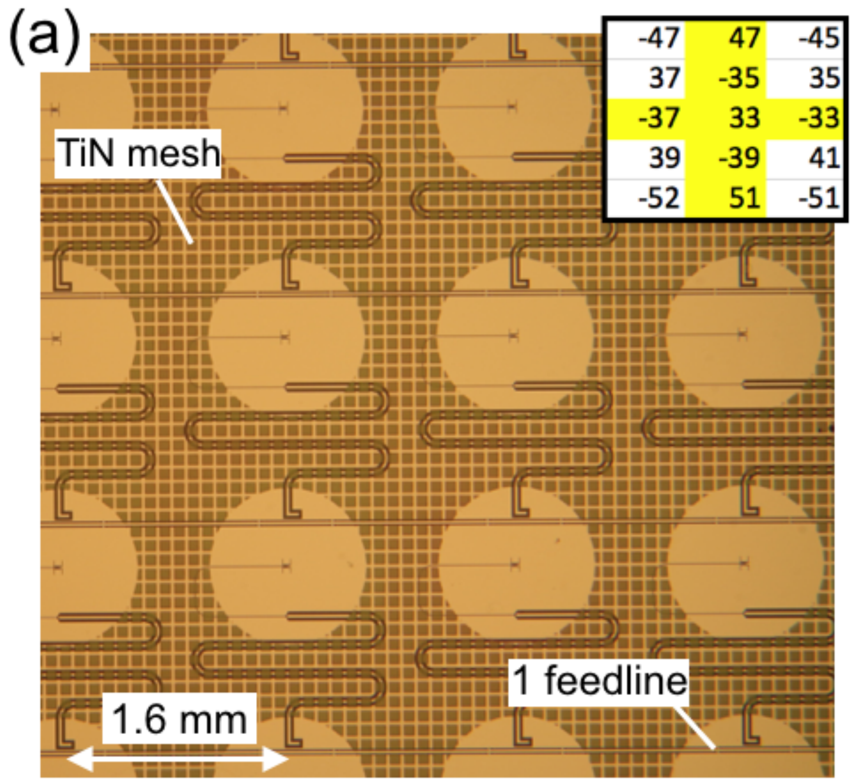

基準周波数
発生源
任意波形
発生器
100 MHz
I
Q
9.9 GHz
LO
RF
連続
マイクロ波
発生源
共振器
9.9 GHz
量子ビット
|0⟩又は|1⟩
ヘテロダイン検波
9.9 GHz
RF
10 GHz
LO
IF
JPAを初段とする
増幅器チェイン
100 MHz
|0⟩
又は
|1⟩
デジタイザ
(b)
|0⟩ 状態
|1⟩ 状態
電圧 (mV)
100
50
0
-50
-100
0
100
200
300
400
500
時間 (ns)

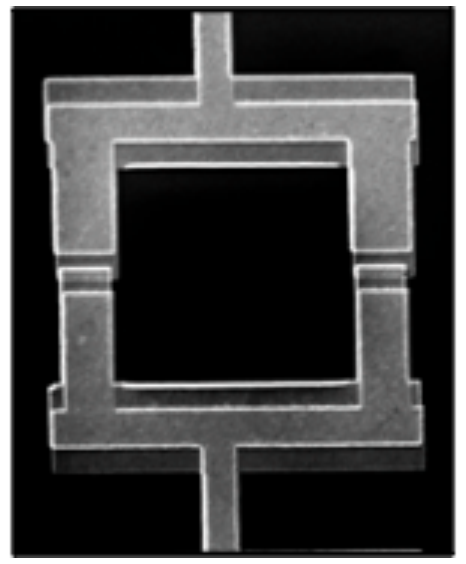
物理への応用例

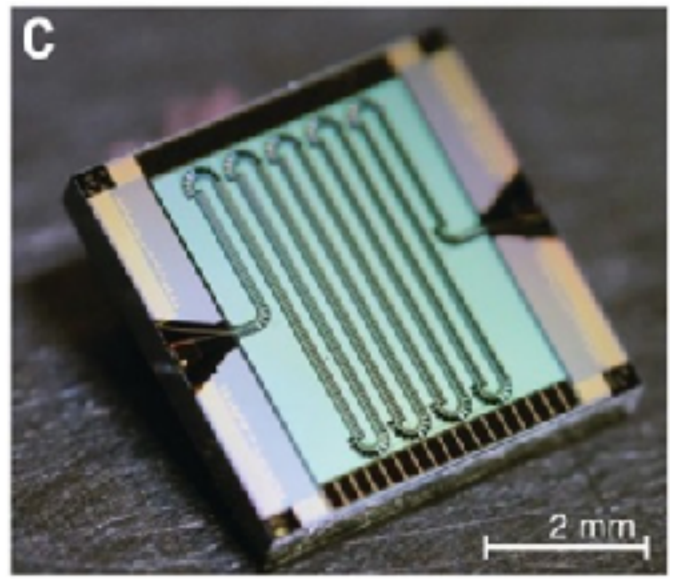


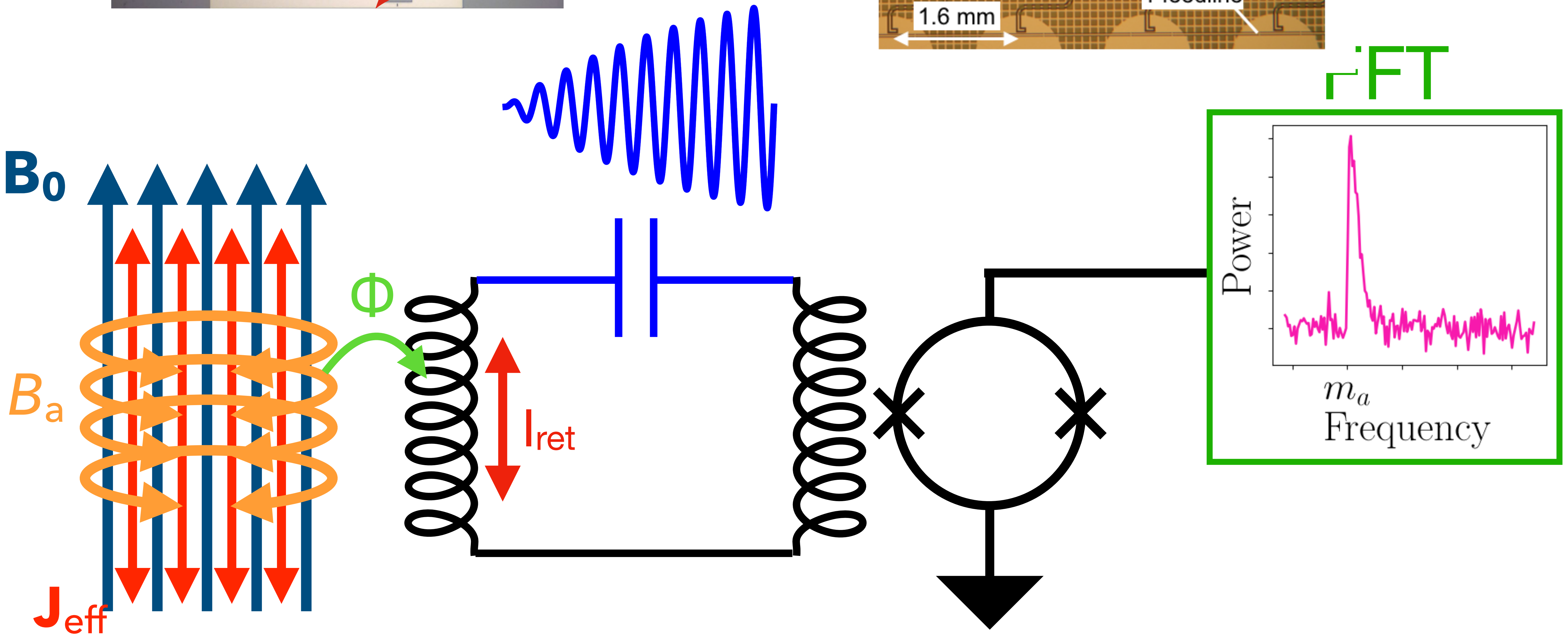
大量にある

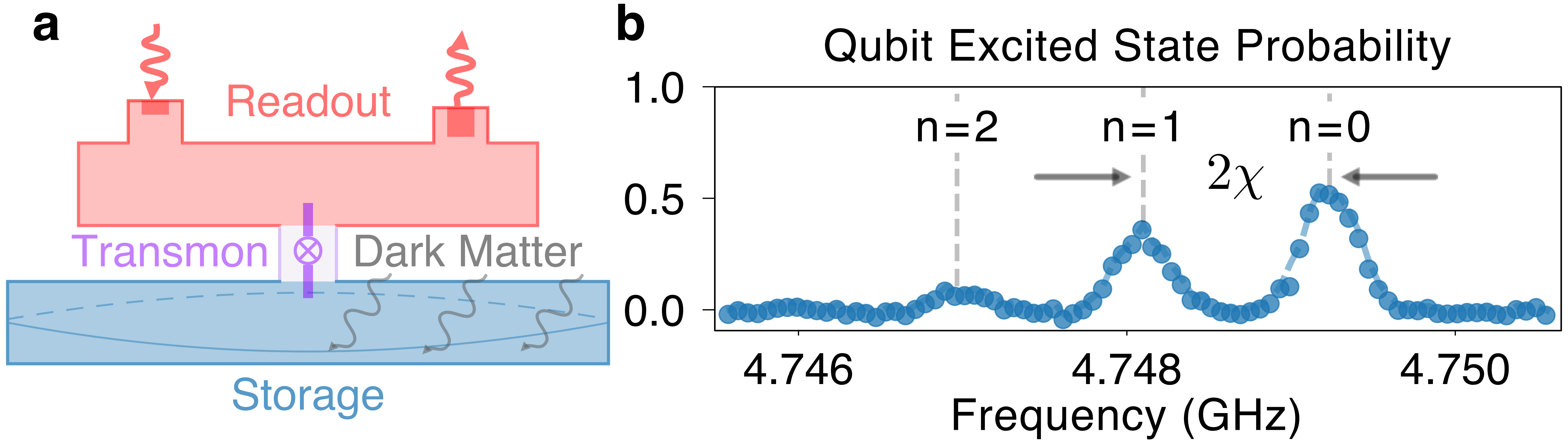

Feedline
Inductor
Capacitor
60 µm
Mesh absorber

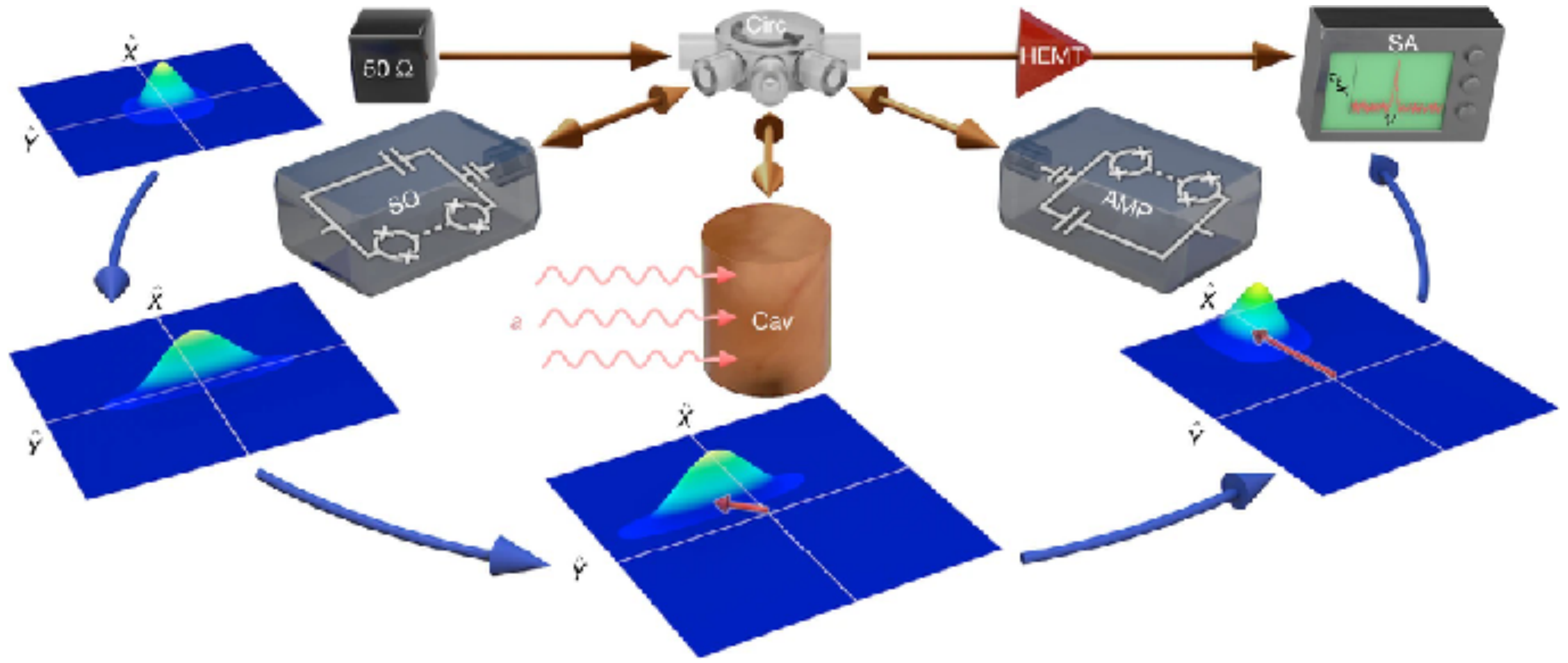

(a)
TiN mesh
1.6 mm
1 feedline
-47 47 -45
37 -35 35
-37 33 -33
39 -39 41
-52 51 -51




c
2 mm

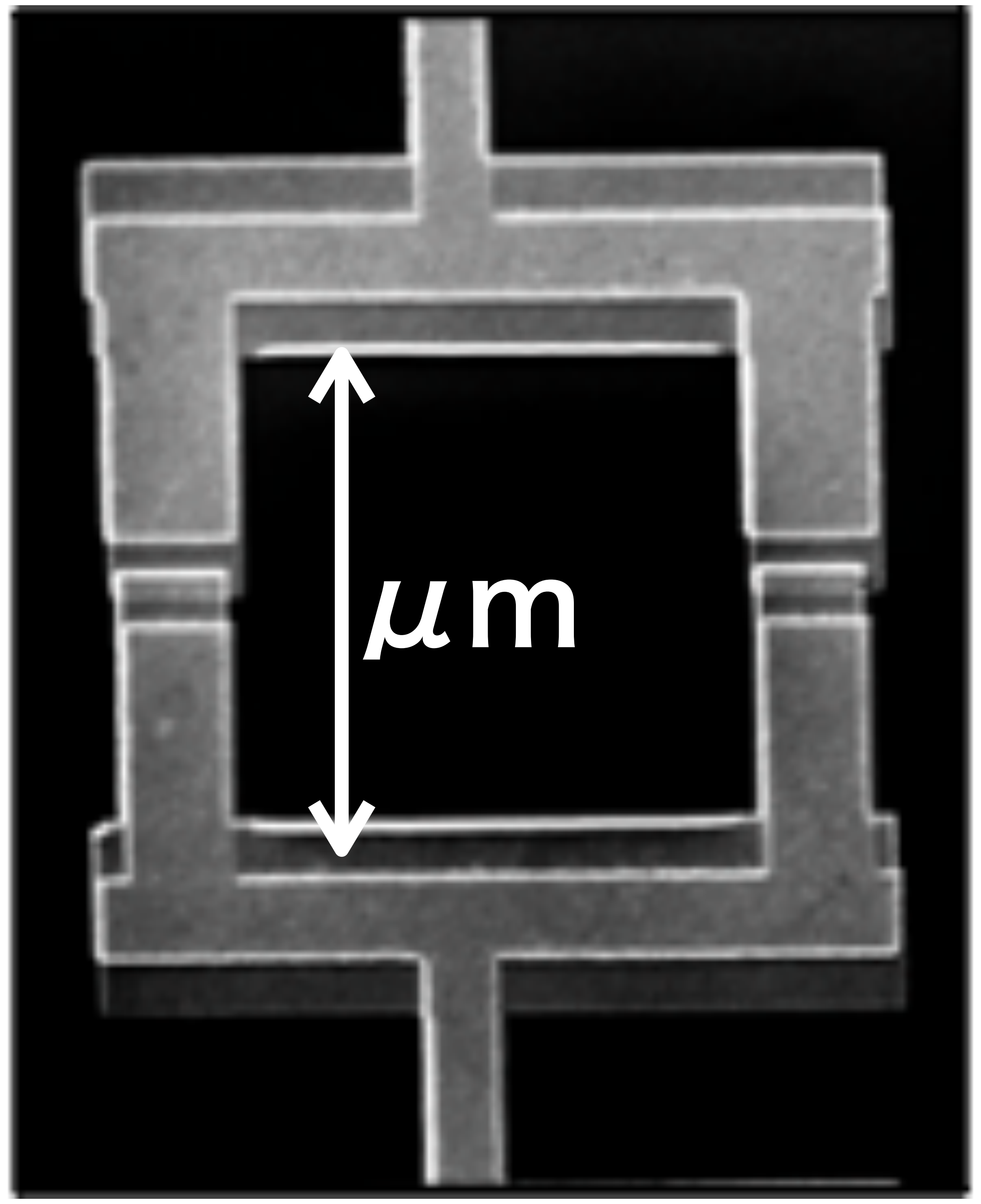

B0
Ba
Jeff
Φ
Iret
FT
Power
ma
Frequency


a
Readout
Transmon
Dark Matter
Storage
b
Qubit Excited State Probability
1.0
0.5
0.0
n=2
n=1
n=0
2χ
4.746
4.748
4.750
Frequency (GHz)


50 Ω
HEMT
SA
SQ
AMP
Cav

こつ?

重大な弱点: 量子デバイスは有効体積が小さすぎる



例: SQUIDは超高感度磁場センサーだが
そのループに入る磁束にしか感度がない。

だいたいの素粒子実験は有効体積が物を言う

→ **マクロなスケールの応答を反映させる必要がある**

(もちろん小さくても良い実験もある)

共振器はマクロな世界とミクロな世界をつなぐ

既にcmスケール

10^4倍有効体積を増やせている

ジョセフソン接合