Introduction to Superconductivity & Device Application with Quantum Materials

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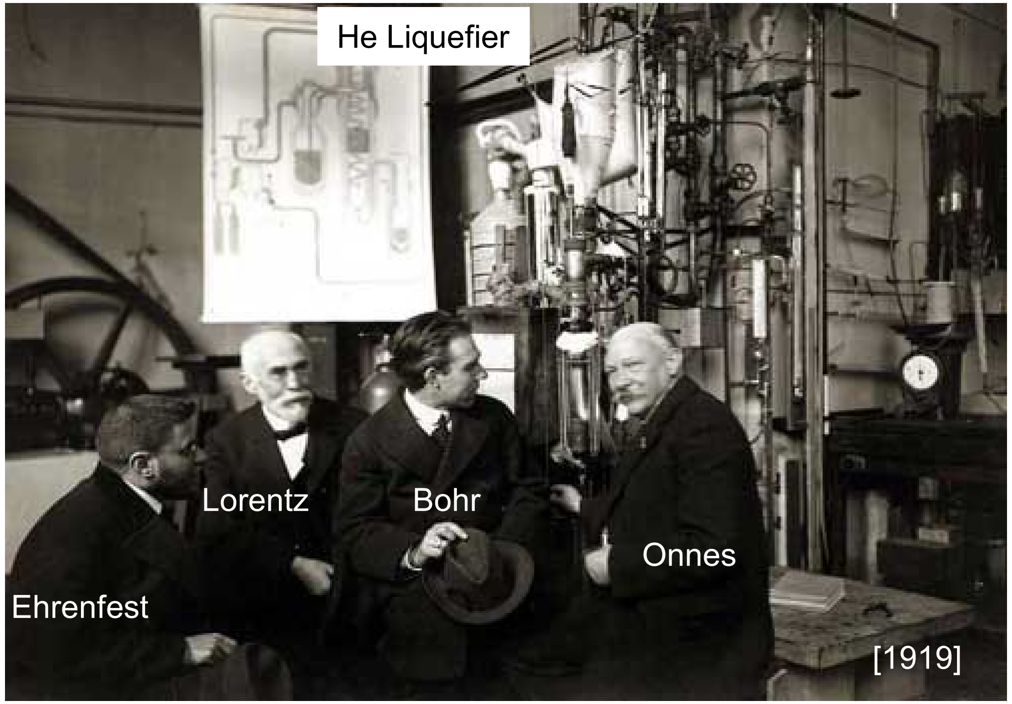
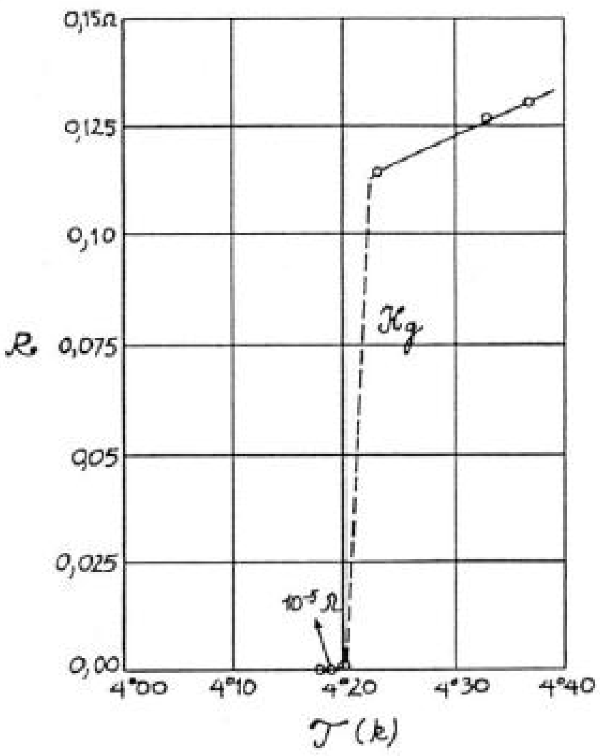
Basics of Superconductivity & Josephson Junction

Superconductivity

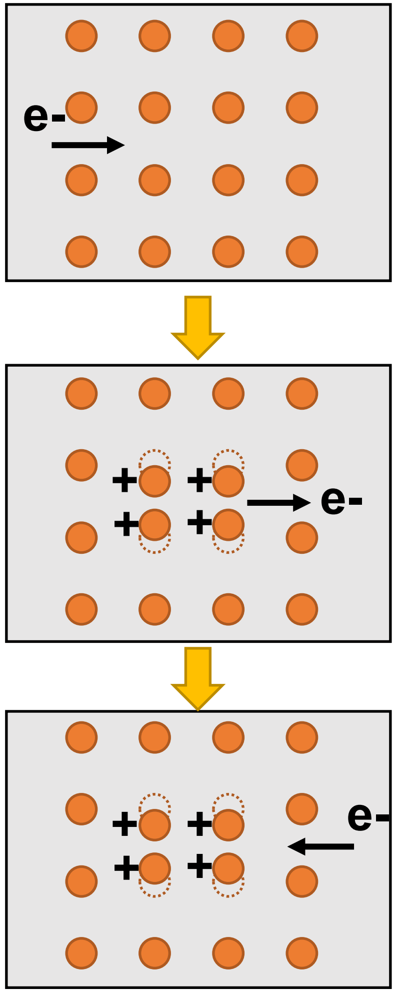


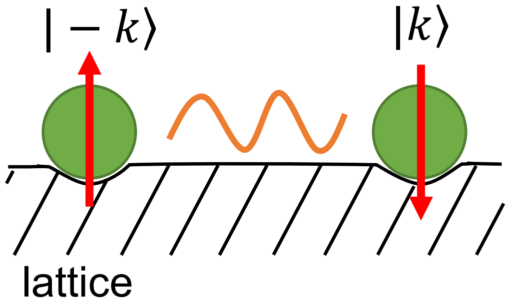
Superconductivity of Mercury (1911)



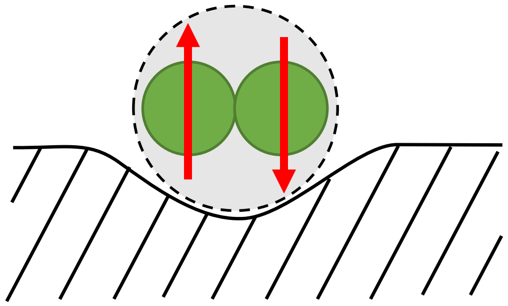
Superconductivity: Macroscopic Quantum Phenomena

Microscopic mechanism – BCS theory (1957)





Cooper pair



in BCS superconductor

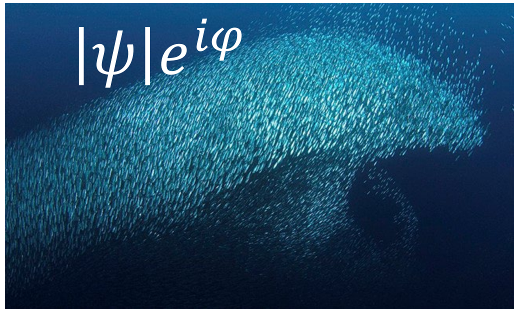
Spin-singlet (anti-sym.)

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

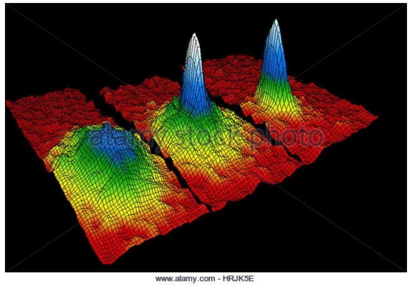
Orbital : *s*-wave (sym.)

Macroscopic quantum phenomena

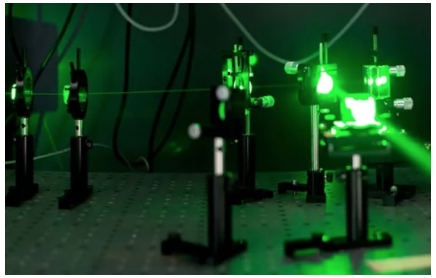
10^{23}-electroncs in superconductor behaves as a single quantum object



BEC condensate of atoms



Laser



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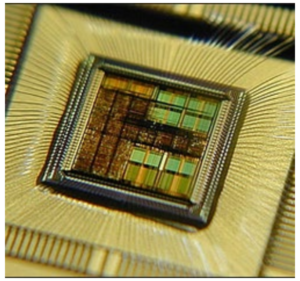
Quantum Electronics

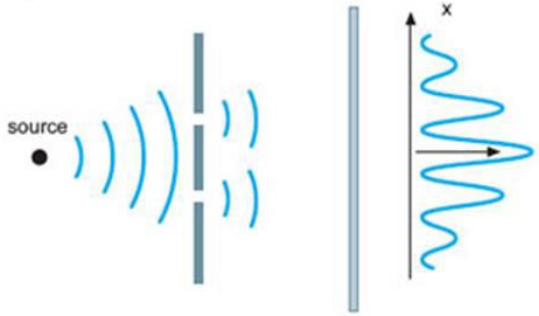
Fundamental Science		Applied Science
Classical Mechanics	→	Mechanical Engineering
Electromagnetics	→	Electrical Engineering
Quantum Mechanics	→	**Quantum Engineering**

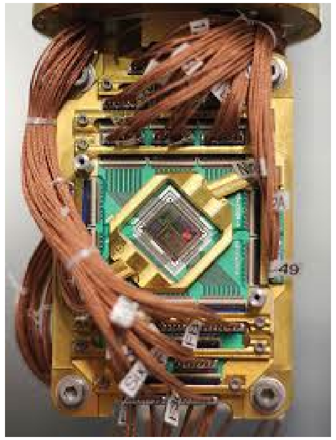
ex.) Mechanical Engine



ex.) CPU

e.g.) quantum coherence, superconductivity

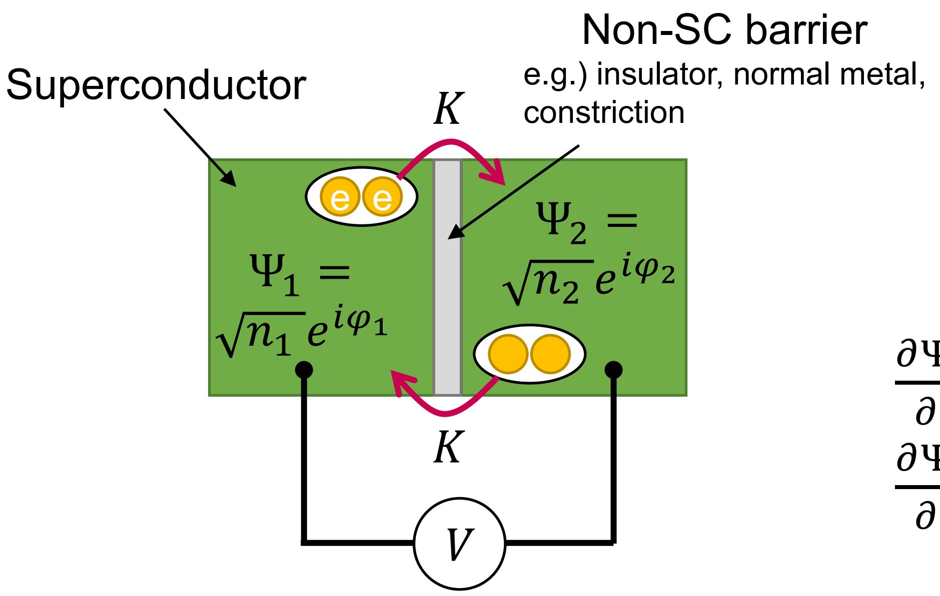




ex.) Quantum Computers

Tunneling Josephson Junction (JJ)

Predicted by B. D. Josephson in 1962



n: density of Cooper pair
φ: phase of order parameter
K: Coupling parameter

Equation of motion for JJ

$$U_1 - U_2 = qV$$
$$q = 2e$$

$$\begin{cases} i\hbar \dfrac{\partial \Psi_1}{\partial t} = U_1 \Psi_1 - K\Psi_2 \\ i\hbar \dfrac{\partial \Psi_2}{\partial t} = U_2 \Psi_2 - K\Psi_1 \end{cases}$$

We set $\frac{U_1+U_2}{2} = 0$, then $U_1 = \frac{qV}{2}, U_2 = -\frac{qV}{2}$

$$\frac{\partial \Psi_1}{\partial t} = \frac{1}{2\sqrt{n_1}} e^{i\varphi_1} \frac{dn_1}{dt} + i\sqrt{n_1} e^{i\varphi_1} \frac{d\varphi_1}{dt} = \frac{qV}{2i\hbar}\sqrt{n_1} e^{i\varphi_1} - \frac{K}{i\hbar}\sqrt{n_2} e^{i\varphi_2} \quad \text{- Eq. (1)}$$

$$\frac{\partial \Psi_2}{\partial t} = \frac{1}{2\sqrt{n_2}} e^{i\varphi_2} \frac{dn_2}{dt} + i\sqrt{n_2} e^{i\varphi_2} \frac{d\varphi_2}{dt} = -\frac{qV}{2i\hbar}\sqrt{n_2} e^{i\varphi_2} - \frac{K}{i\hbar}\sqrt{n_1} e^{i\varphi_1} \quad \text{- Eq. (2)}$$

$$(1) \times e^{-i\varphi_1},\ (2) \times e^{-i\varphi_2}$$

Phase difference: $\varphi \equiv \varphi_2 - \varphi_1$

$$\frac{1}{2\sqrt{n_1}} \frac{dn}{dt} + i\sqrt{n_1} \frac{d\varphi_1}{dt} = -i\frac{qV}{2\hbar}\sqrt{n_1} + i\frac{K}{\hbar}\sqrt{n_2} e^{i\left(\boxed{\varphi_2 - \varphi_1}\right)} \quad \text{- Eq. (1)'}$$

$$\frac{1}{2\sqrt{n_2}} \frac{dn}{dt} + i\sqrt{n_2} \frac{d\varphi_2}{dt} = +i\frac{qV}{2\hbar}\sqrt{n_2} + i\frac{K}{\hbar}\sqrt{n_1} e^{-i\left(\boxed{\varphi_2 - \varphi_1}\right)} \quad \text{- Eq. (2)'}$$

DC & AC Josephson Relationship

by using $e^{i\varphi} = \cos\varphi + i\sin\varphi$,

$$\frac{1}{2\sqrt{n_1}}\frac{dn_1}{dt} + i\sqrt{n_1}\frac{d\varphi_1}{dt} = -i\frac{qV}{2\hbar}\sqrt{n_1} + i\frac{K}{\hbar}\sqrt{n_2}(\cos\varphi + i\sin\varphi) \quad \text{- Eq. (1)''}$$

$$\frac{1}{2\sqrt{n_2}}\frac{dn_2}{dt} + i\sqrt{n_2}\frac{d\varphi_2}{dt} = +i\frac{qV}{2\hbar}\sqrt{n_2} + i\frac{K}{\hbar}\sqrt{n_1}(\cos\varphi - i\sin\varphi) \quad \text{- Eq. (2)''}$$

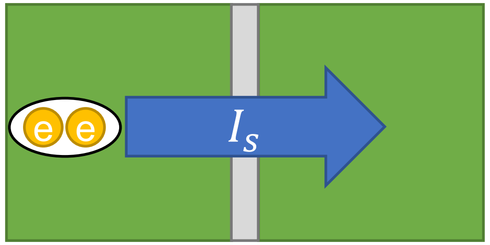
- Real part of Eqs. (1)'' and (2)''

$$\frac{dn_1}{dt} = -2\frac{K}{\hbar}\sqrt{n_1 n_2}\sin\varphi$$

$$\frac{dn_2}{dt} = +2\frac{K}{\hbar}\sqrt{n_1 n_2}\sin\varphi$$

Supercurrent:

$$I_s \propto -\frac{dn_1}{dt} = \frac{dn_2}{dt}$$



DC Josephson relationship

$$I_s = I_c \sin\varphi$$

- Imaginary part of Eqs. (1)'' and (2)''

$$\frac{d\varphi_1}{dt} = -\frac{qV}{2\hbar} + \frac{K}{\hbar}\sqrt{\frac{n_2}{n_1}}\cos\varphi$$

$$\frac{d\varphi_2}{dt} = \frac{qV}{2\hbar} + \frac{K}{\hbar}\sqrt{\frac{n_1}{n_2}}\cos\varphi$$

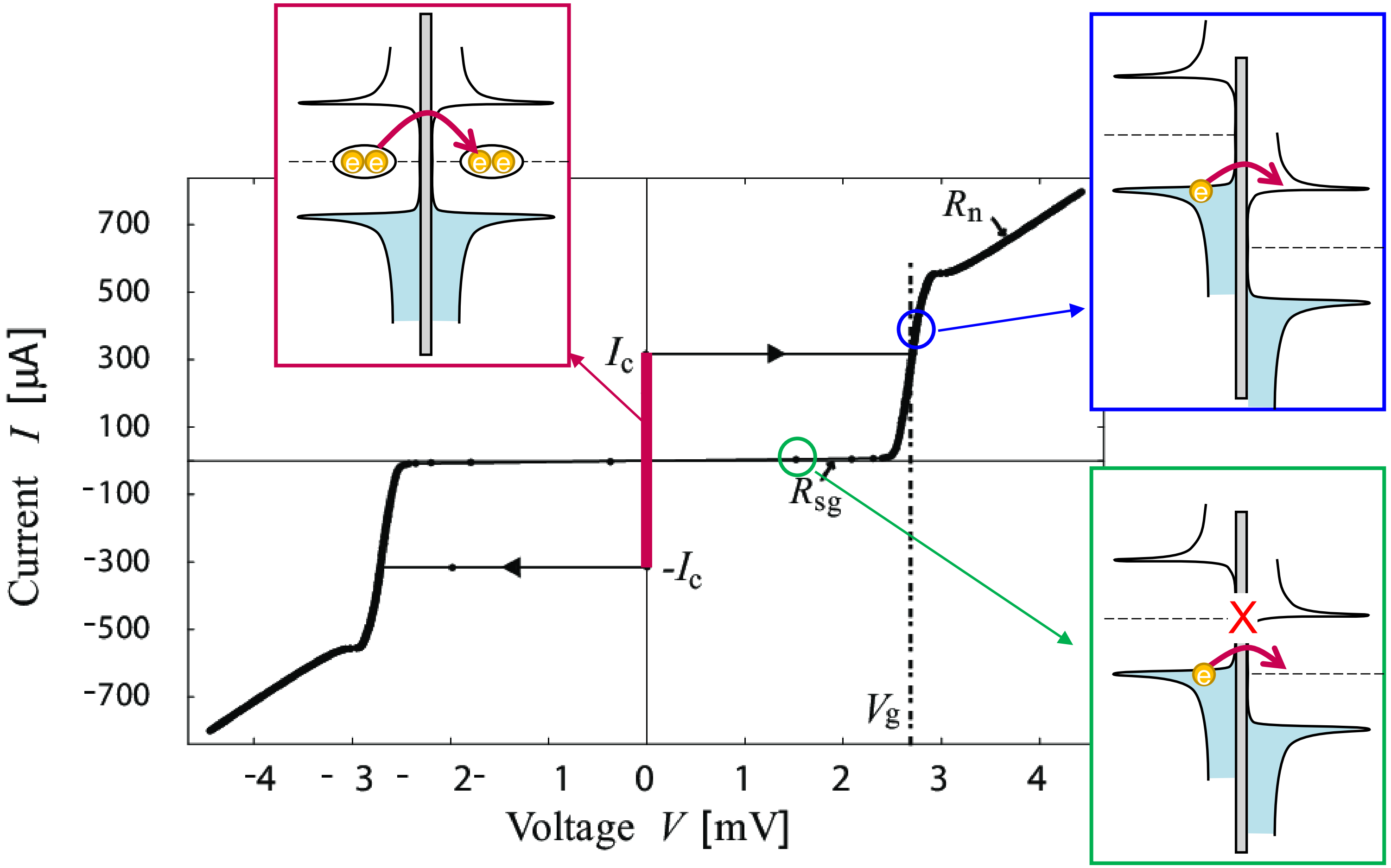
If $n_1 \approx n_2$,

$$\frac{d\varphi}{dt} = \frac{d\varphi_2}{dt} - \frac{d\varphi_1}{dt} = \frac{qV}{\hbar} = \frac{2eV}{\hbar}$$

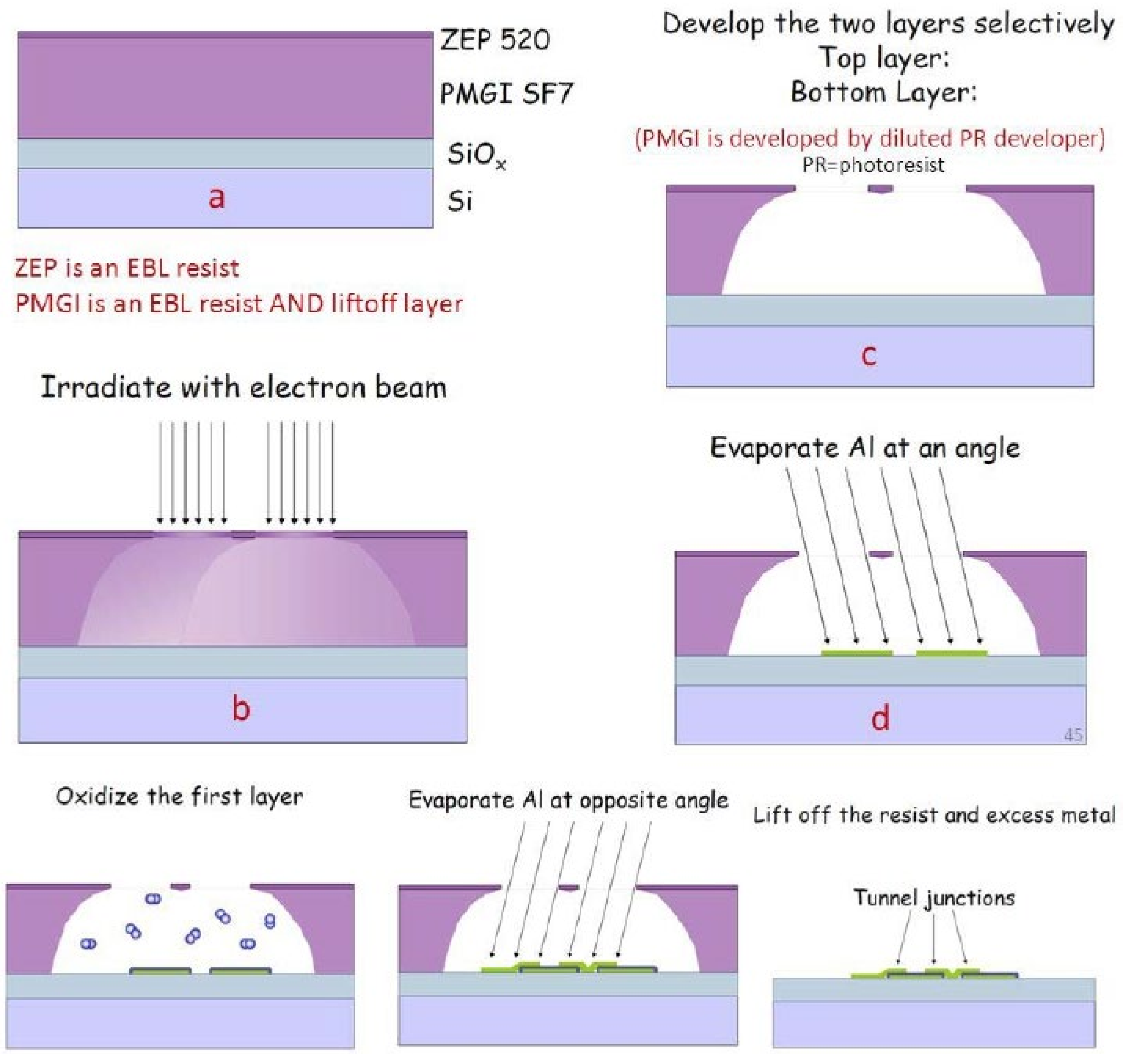
AC Josephson relationship

$$\frac{d\varphi}{dt} = \frac{2e}{\hbar}V$$

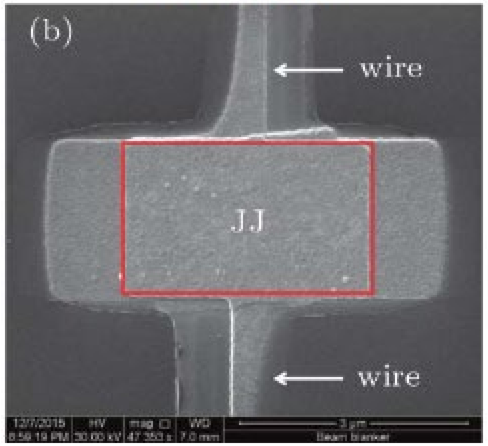
Typical Current-Voltage Characteristics of JJ



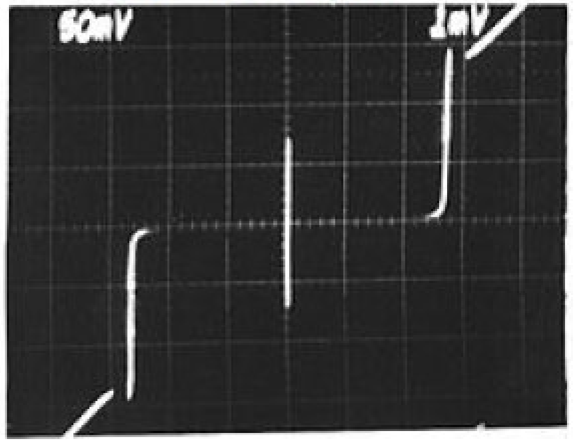
Angle Evaporation for Tunneling JJ



Device image



I-V Characteristics



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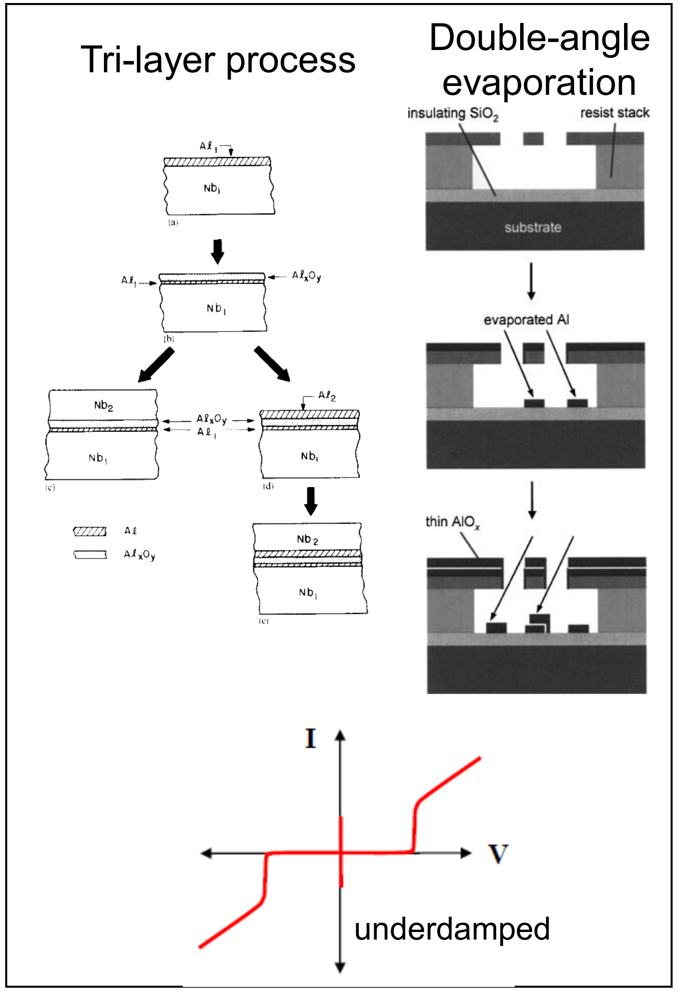
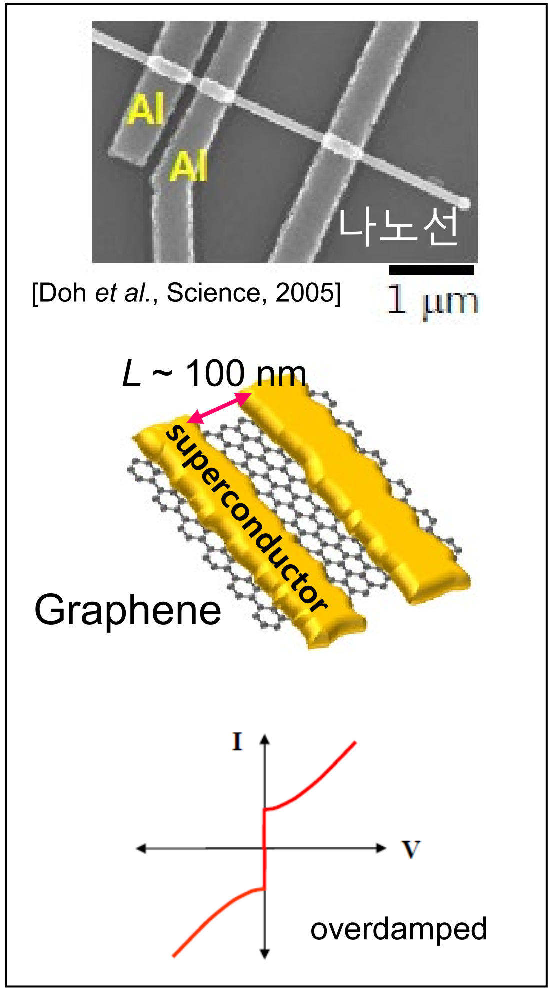
Various types of Josephson Junctions

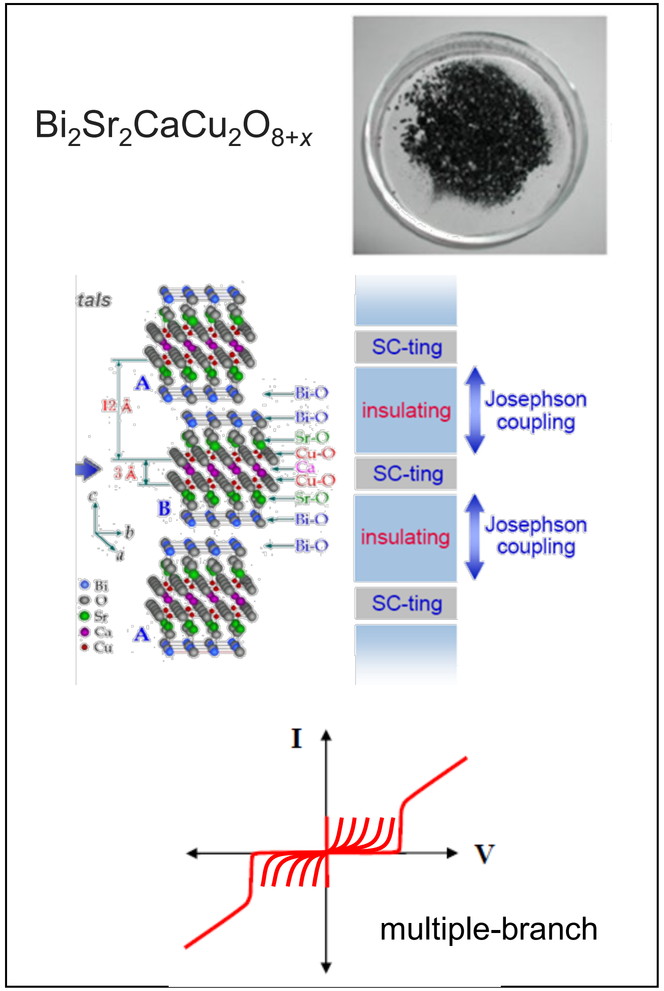
투과형 조셉슨 접합 (tunneling Josephson junction)



근접형 조셉슨 접합 (proximity Josephson junction)



선천성 조셉슨 접합 (intrinsic Josephson junction)



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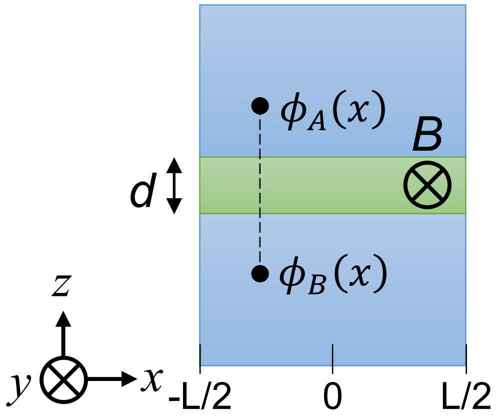
Fraunhofer Pattern

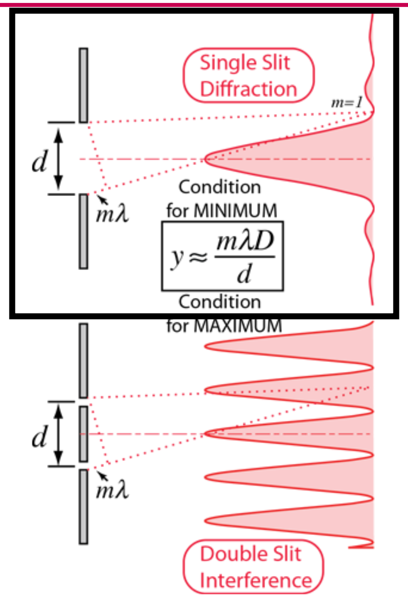
- With external magnetic field $B\hat{y}$,



- Phase difference: $\phi(x) \equiv \phi_B(x) - \phi_A(x)$
- $\phi(x) = \phi(0) + 2\pi(Bd/\Phi_0)x$
- Overall Josephson current:

$$I_J(\Phi) = \int_{-L/2}^{L/2} dx\, J(x)\, \sin[\phi(x)].$$

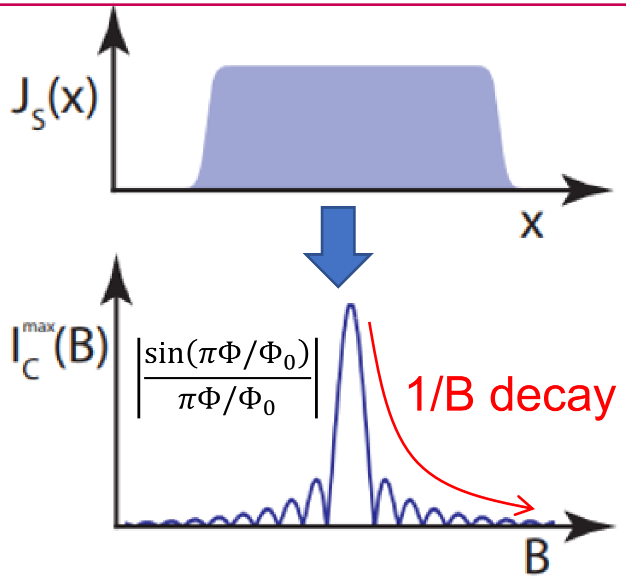
Josephson current density



- For **uniform** Josephson coupling [$J(x)$ = 'constant'],

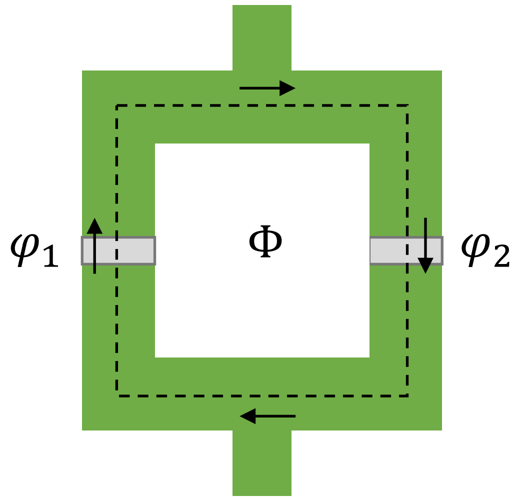
Critical current: $\boxed{I_c(\Phi) = \max_{\phi(0)}\{I_J(\Phi)\} = I_c\left|\frac{\sin\alpha}{\alpha}\right|},$

with reduced external flux $\alpha = \pi\Phi/\Phi_0$, $\Phi = BdL$



SQUID (Superconducting Interference Device)

Two JJs connected in parallel



$$\varphi_{\text{total}} = \varphi_2 - \varphi_1 + 2\pi \frac{\Phi}{\Phi_s} = 2\pi n$$

$$\varphi_1 - \varphi_2 = 2\pi \frac{\Phi}{\Phi_s} \pmod{2\pi}$$

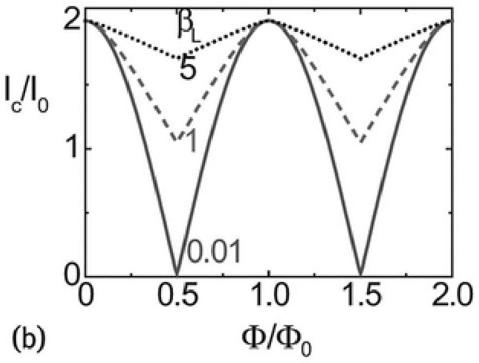
Φ: external magnetic flux threading SQUID loop
$\Phi_s = h/2e$: flux quantum for Cooper pairs
n: integer number

- Supercurrent through SQUID:

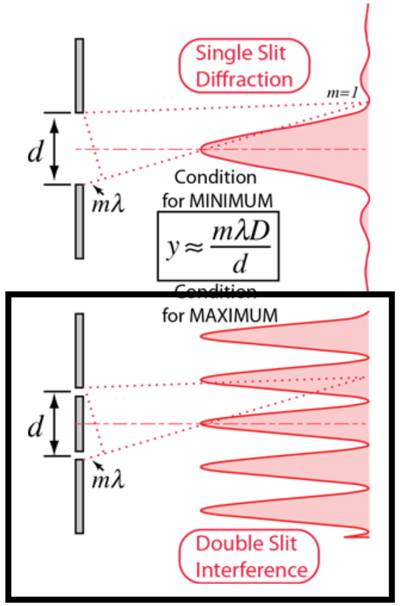
$$I_{s,\text{SQ}} = I_c \sin\varphi_1 + I_c \sin\left(\varphi_1 - 2\pi\frac{\Phi}{\Phi_s}\right)$$
$$= 2I_c \cos\left(\frac{\pi\Phi}{\Phi_s}\right)\sin\left(\varphi_1 - \pi\frac{\Phi}{\Phi_s}\right)$$

- Critical current for SQUID:

$$I_{c,\text{SQ}} = \max_{\varphi_1} I_{s,\text{SQ}}(\varphi_1) = 2I_c\left|\cos\left(\frac{\pi\Phi}{\Phi_s}\right)\right|$$



For 1 mm x 1 mm SQUID,
Φ_s corresponds to $20\ \mu G$.
↓
SQUID can be used as
a very sensitive magnetometer



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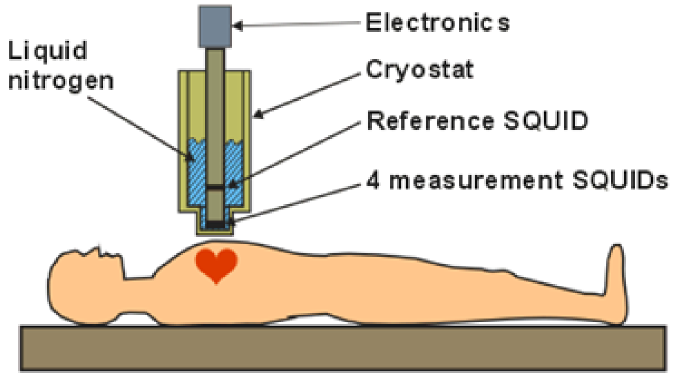
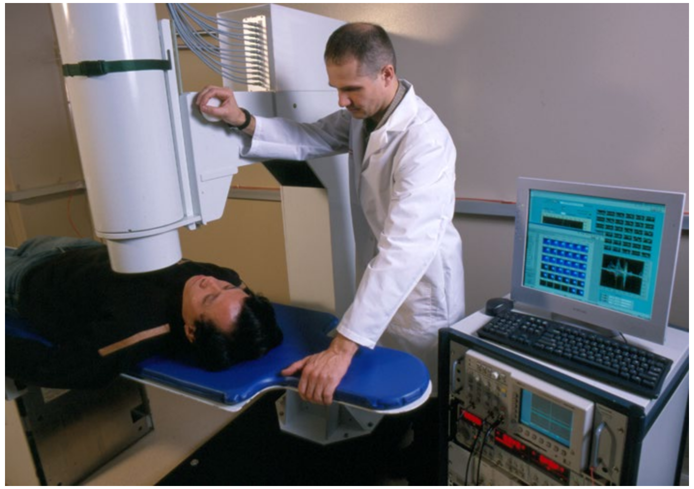
MCG (심자도) & MEG (뇌자도)

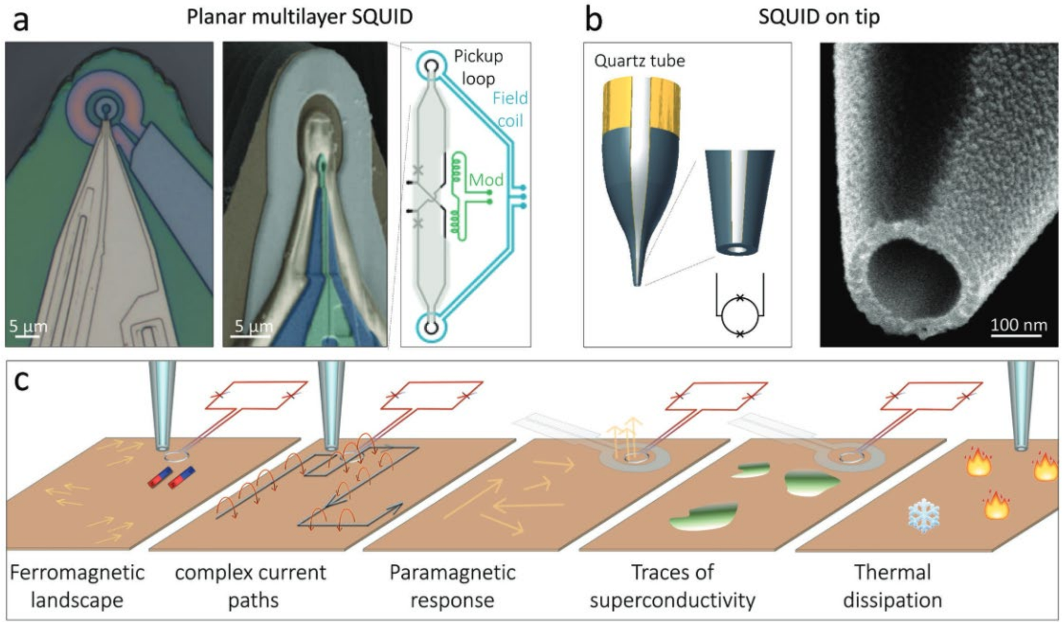
Magneto-Cardio-Graphy (MCG)



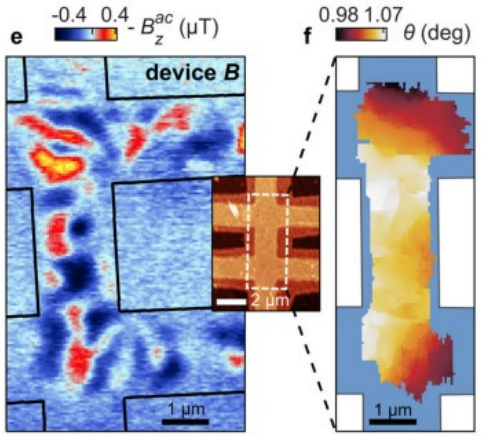


Magneto-Encephalo-Graphy (MEG)

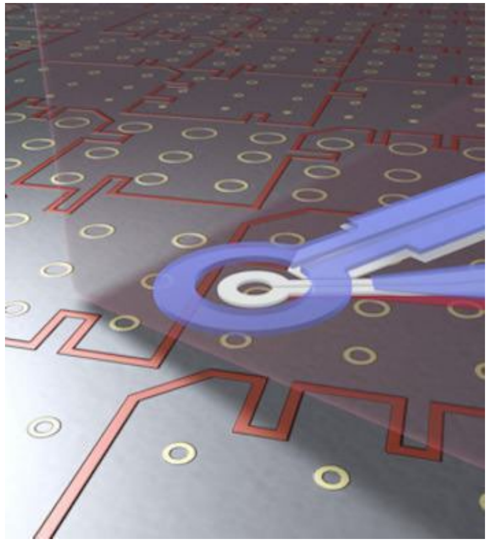
Scanning SQUID Microscope



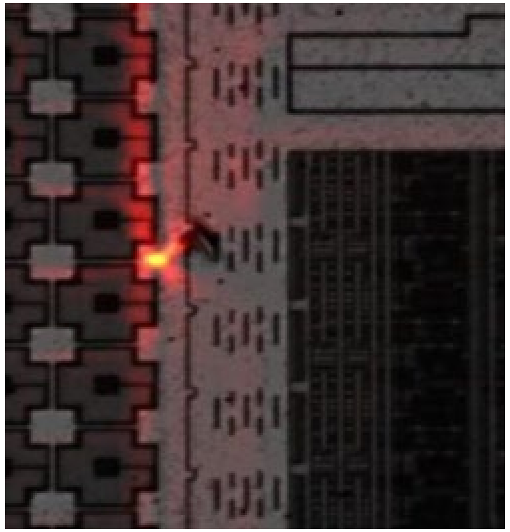
e.x.) mapping twist angle of magic angle twisted bilayer graphene



[Nature 581, 47–52 (2020)]



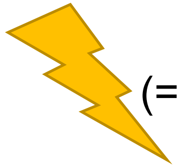
Commercial product by Nocera



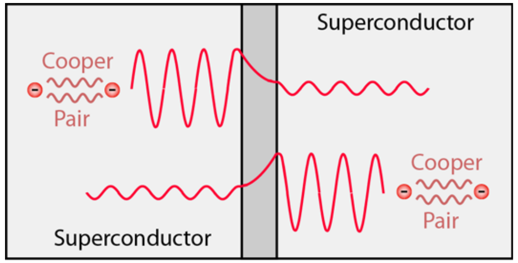
Non-invasive
Circuit Failure Analysis

Shapiro step (1963)

$V(t) = V_{ac}\cos\omega t$



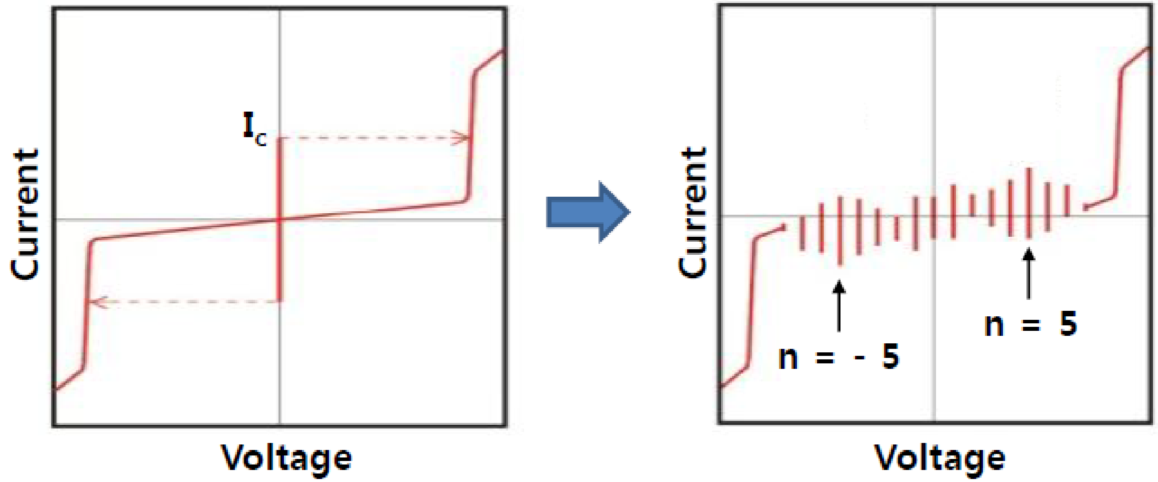
Microwave
(= AC voltage biasing)



$$\frac{d\varphi(t)}{dt} = \frac{2eV(t)}{\hbar}$$
$$\varphi(t) \propto \sin\omega t$$
$$I_J = I_c\sin(\varphi(t)) \propto \sin(\sin\omega t)$$

Resonance of Josephson junction with microwave

$$V_n = n\frac{\hbar\omega}{2e} \quad (n\text{=integer})$$



“AC→DC converter”

Voltage standard “AC→DC”

$$V_n = n\frac{\hbar\omega}{2e}$$

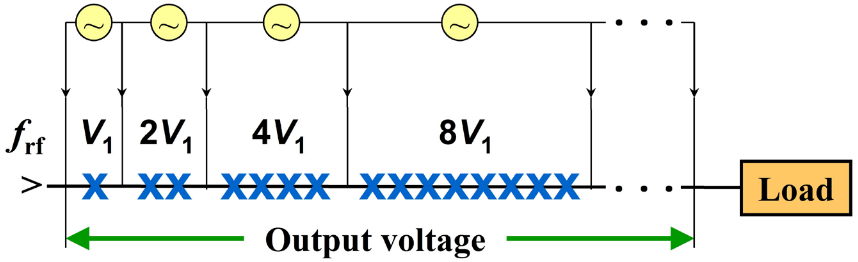
Fundamental constant

(n=integer)

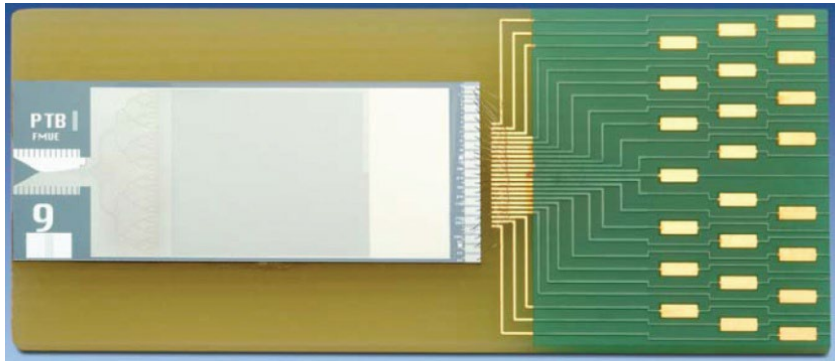
~2.06783385… μV/GHz

Generation of precise voltage using Shapiro steps

Schematics of voltage standard

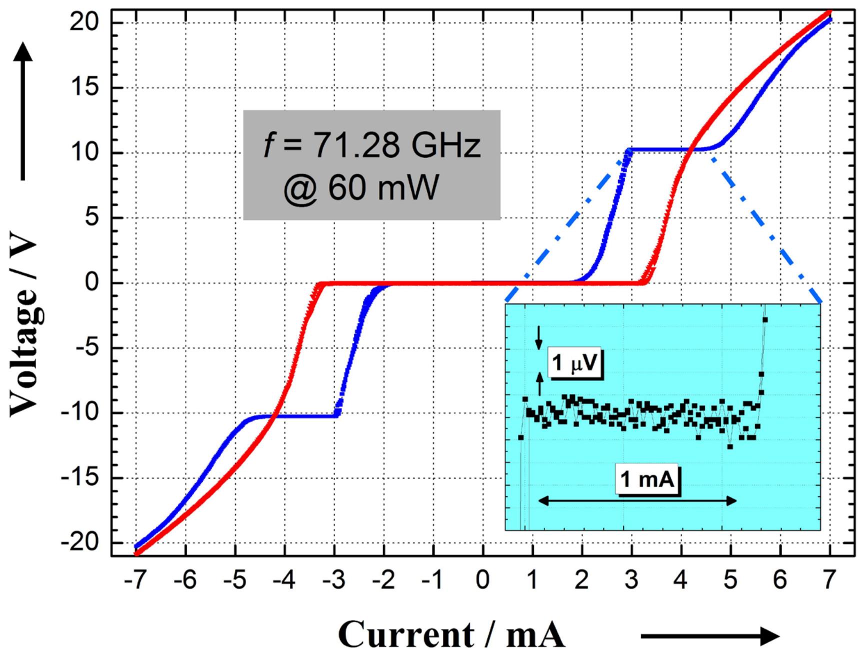


~ Array consisting of 70,000 Josephson junctions



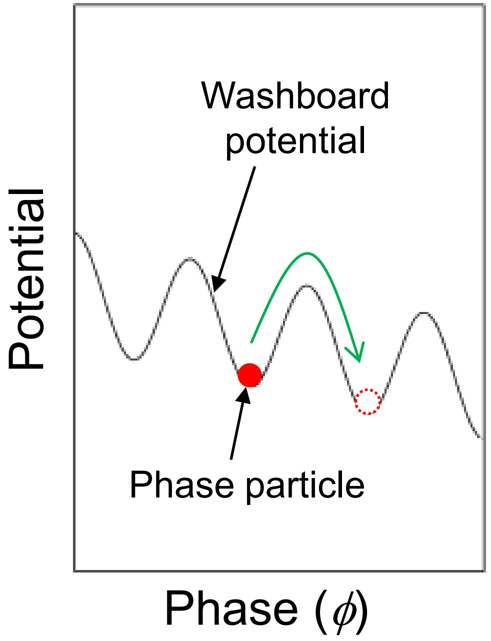
[F. Mueller et al. (2009)]

I-V curve of 10V-voltage standard

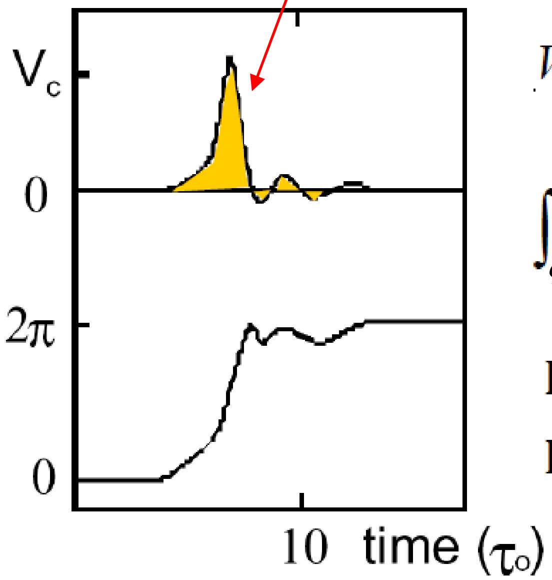


Josephson Voltage Pulse

Generation of rapid and precise voltage pulse of ~1 ps



Voltage pulse during phase particle shift to neighboring potential



$$V(t) = \frac{\hbar}{2e}\frac{d\phi}{dt}$$

Flux quantum

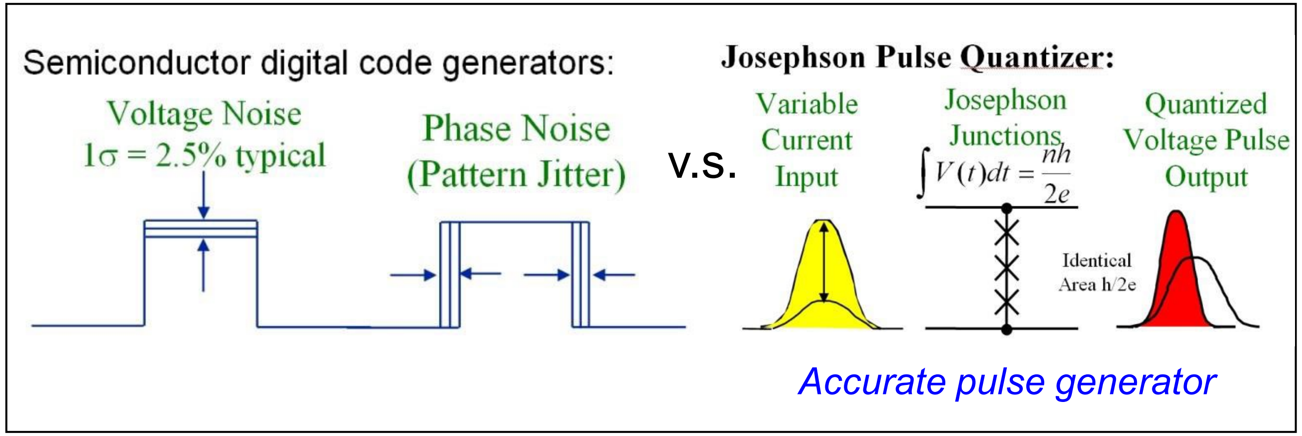
$$\int_{\phi=0}^{\phi=2\pi} V(t)dt = \frac{h}{2e} = \Phi_o = 2.07\ \mathrm{mV \cdot ps}$$

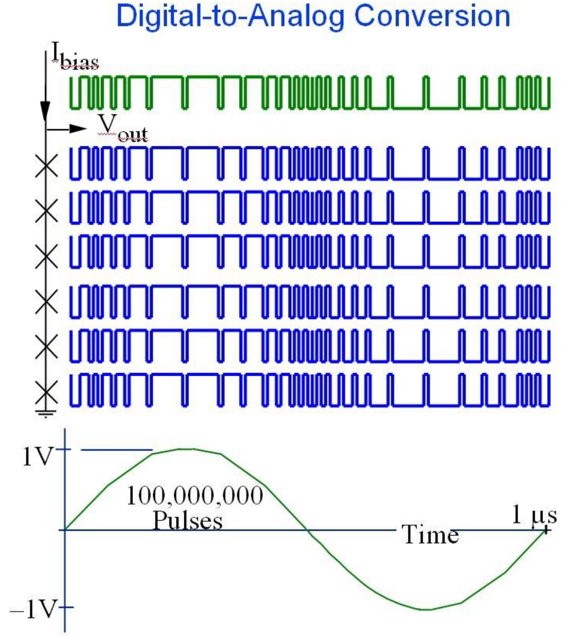
pulse height $\sim V_c = I_c R_n \sim \Delta_{sc}/e \sim k_B T_c$

pulse width $\sim \Phi_o / V_c$

JAWS & RSFQ

Josephson Arbitrary Waveform Synthesizer (JAWS)





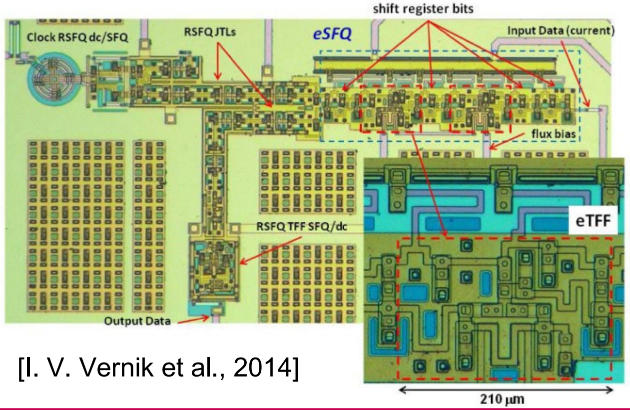
Rapid single flux quantum (RSFQ)

- Digital logic device using Josephson pulse instead of 0/5 V TTL
- Data encoding, processing, transmitting with 1ps pulse

  → Fast processing (**100 GHz** clock speed)
- Superconducting transmission line

  → Much less heating problem

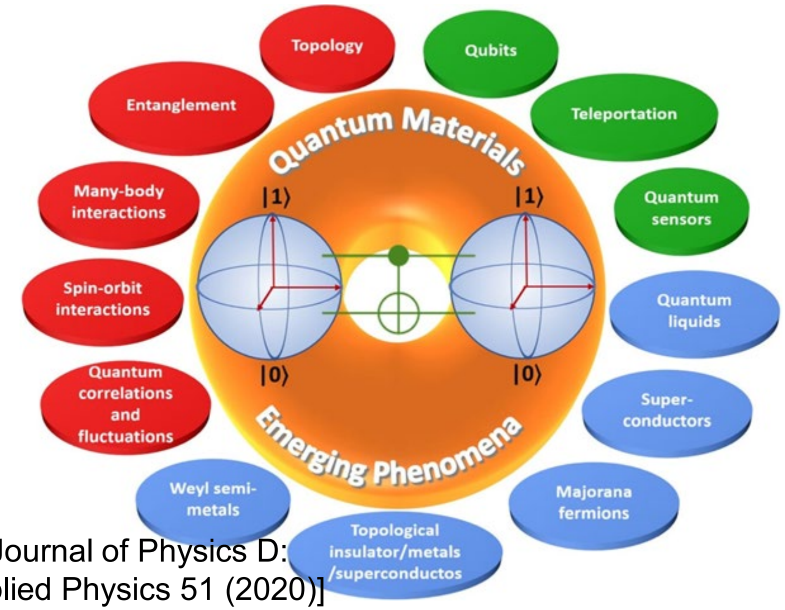
RFSQ device



[I. V. Vernik et al., 2014]

Van der Waals Material based Superconducting devices

Quantum Materials / Van der Waals Materials

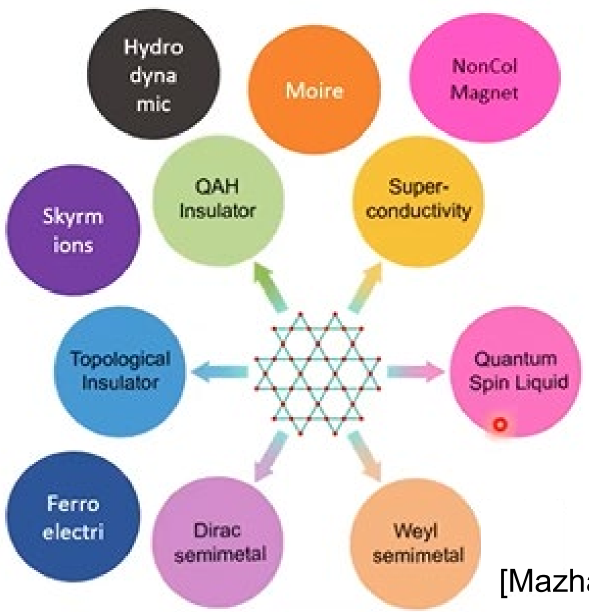


[Journal of Physics D: Applied Physics 51 (2020)]

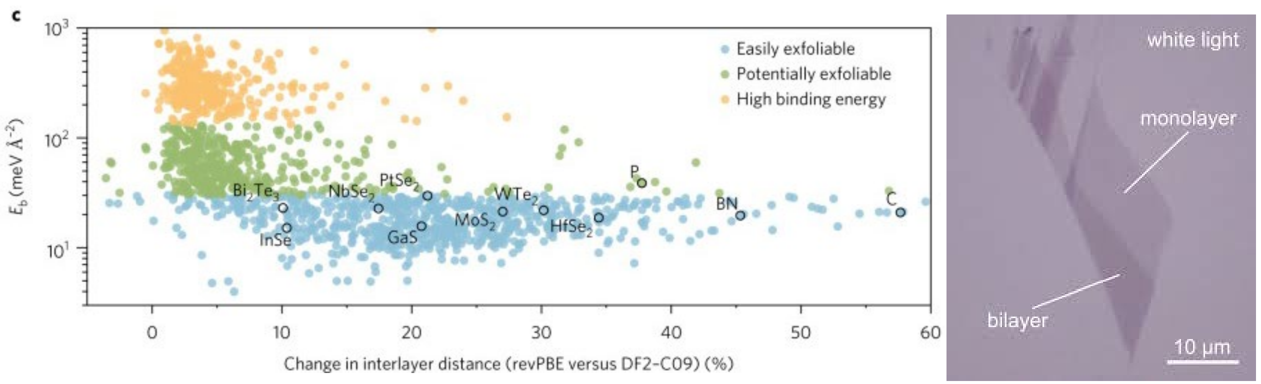
Quantum material- a material whose properties are not best described using classical particles or calculations that do not take into account the full character of the system.

- Topological materials
- Spin liquids
- Superconductors
- Non-collinear magnets
- Strongly correlated materials

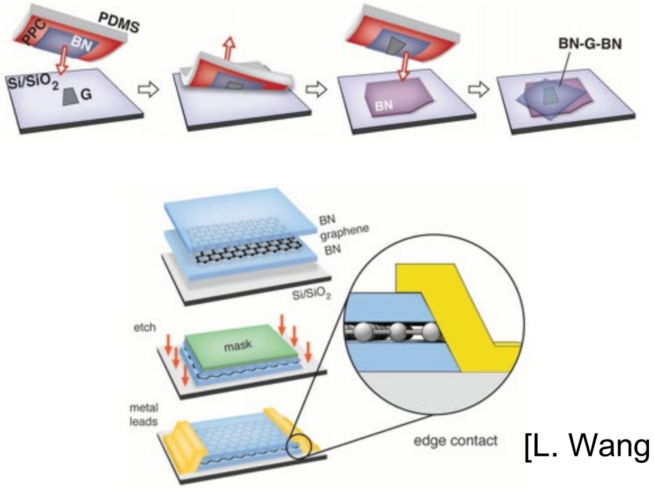
⋮



[Mazhar Ali]



[N. Mounet et al., Nat. Nanotechnol. 13, 246-252 (2018)]



vdW stacking technique

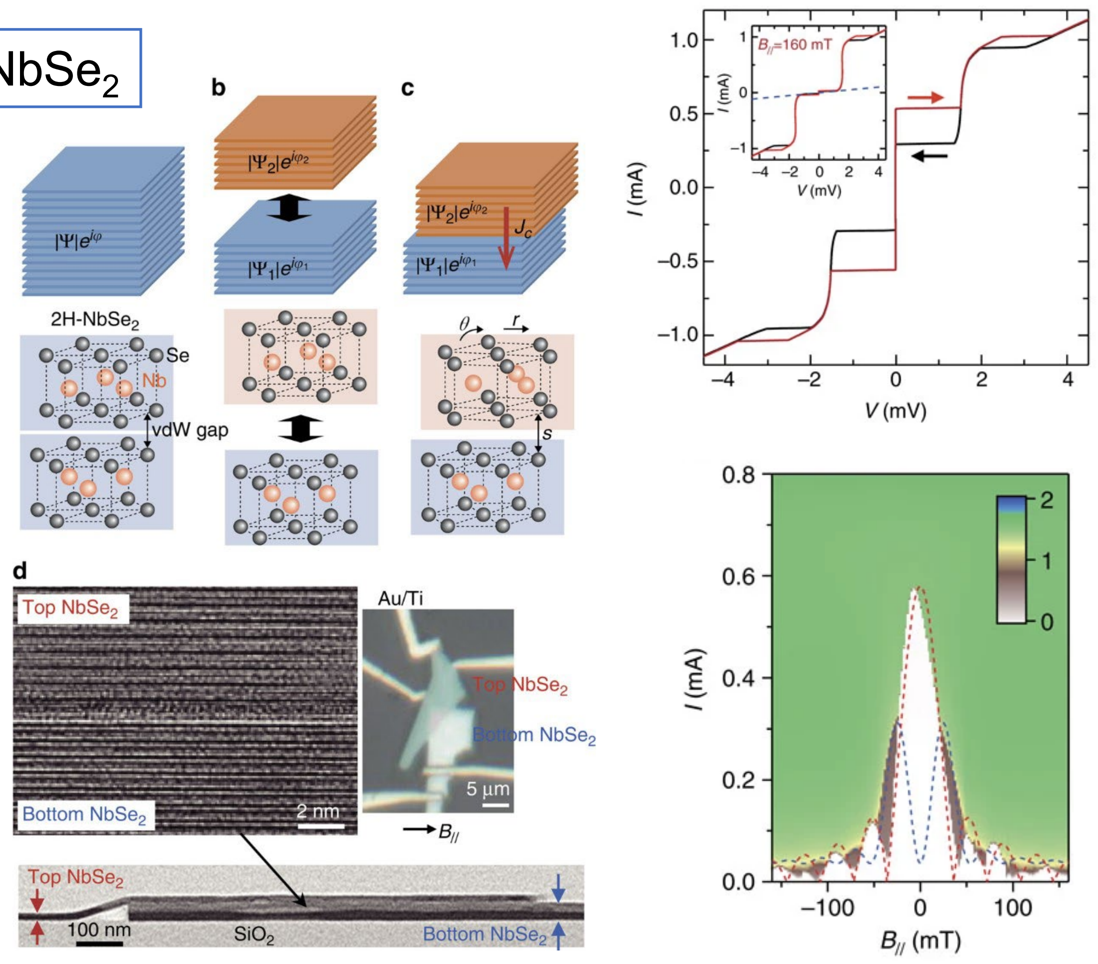
'Relatively' easy to make devices

[L. Wang et al., Science 342, 614 (2013)]

POSTECH

vdW-based Josephson Junctions (1)

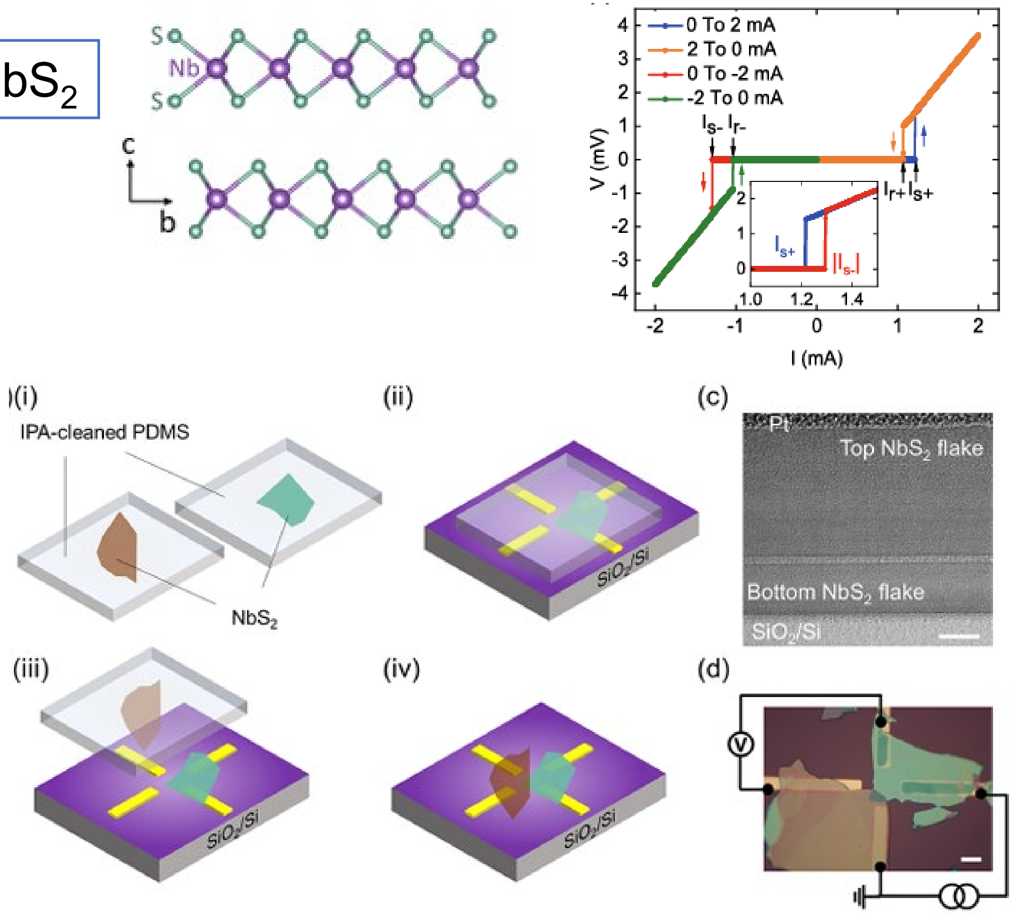
NbSe$_2$



- Exfoliated and transferred in air in < 1 hour

[N. Yabuki et al., Nat. Comm. 7, 10616 (2016)]

NbS$_2$



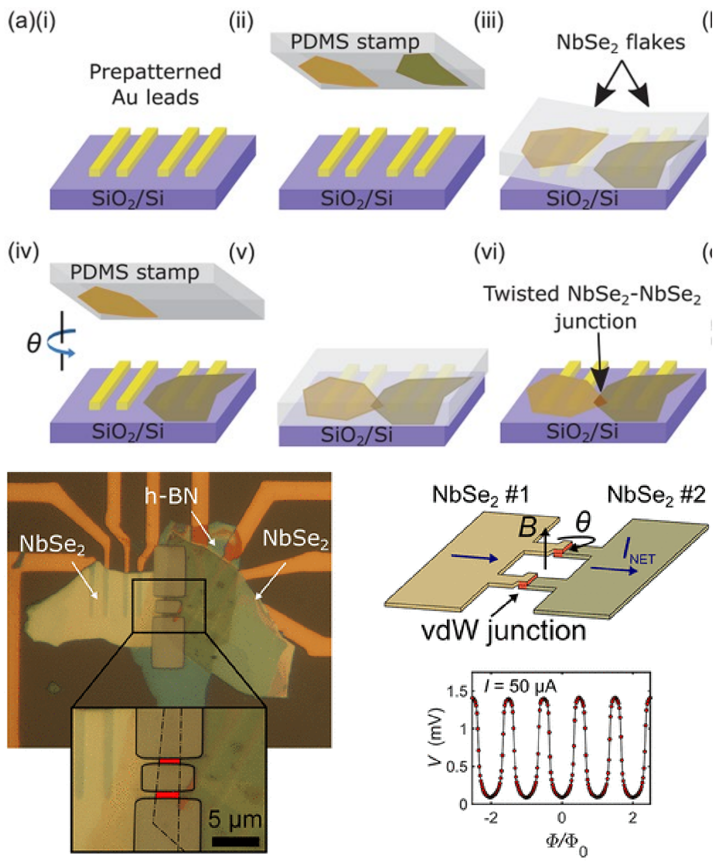
- Dry-transfer in a glovebox

[C. Zhao et al., J. Phys. Chem. Lett. 2022, 13, 46, 10811 (2022)]

POSTECH

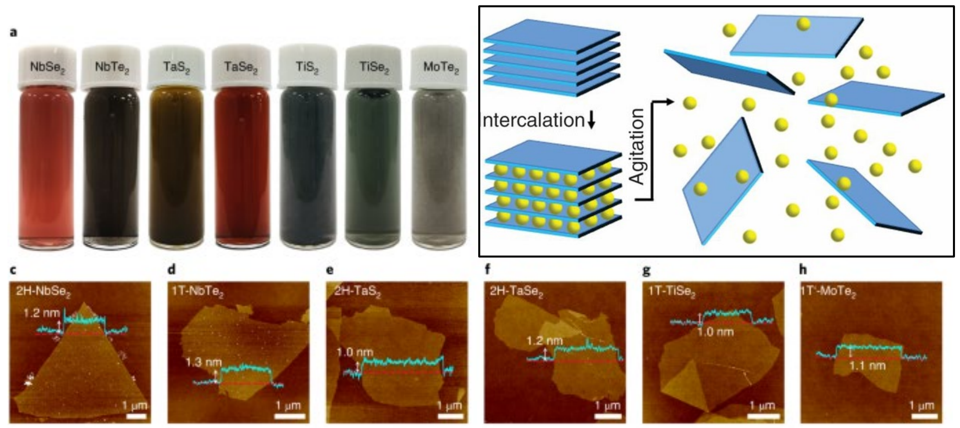
vdW-based SQUID

NbSe$_2$

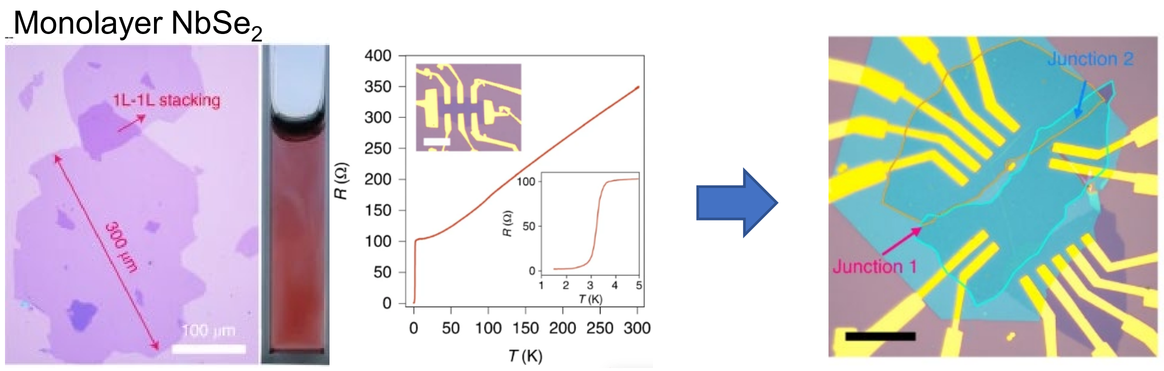


- Demonstration of vdW-based SQUID device

[L. S. Farrar et al., Nano Lett. 21, 6725 (2021)]



electrochemical exfoliation of bulk TMDs to 2D SC

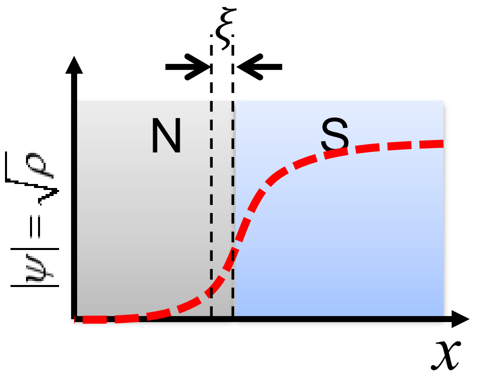


solvent protection prevents air degradation

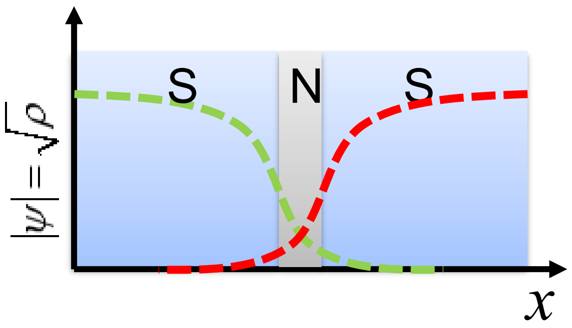
[J. Li et al., Nat. Mater. 20, 181 (2021)]

Proximity Josephson Junction

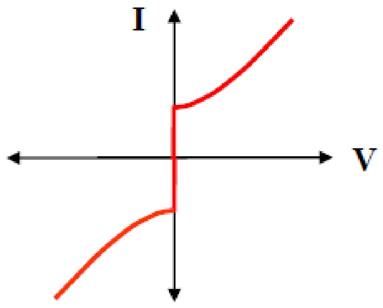
In mesoscopic point of view,



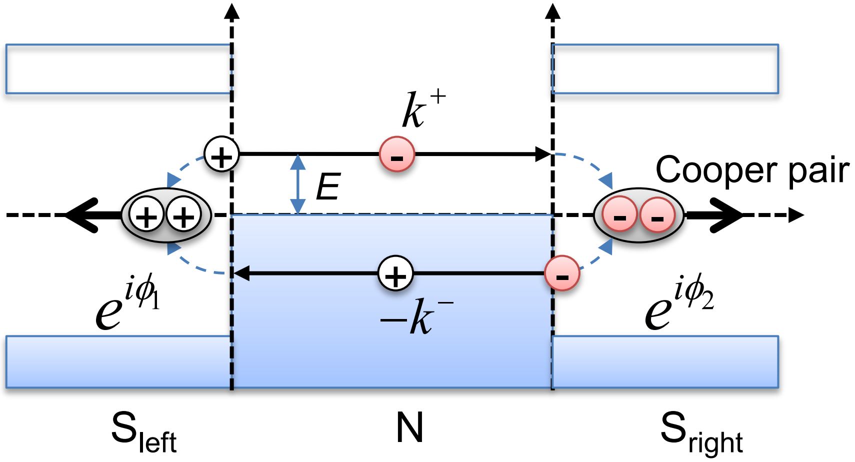
Proximity effect



Proximity Josephson coupling



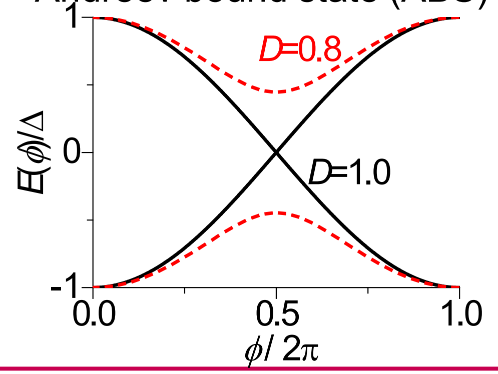
In microscopic point of view,



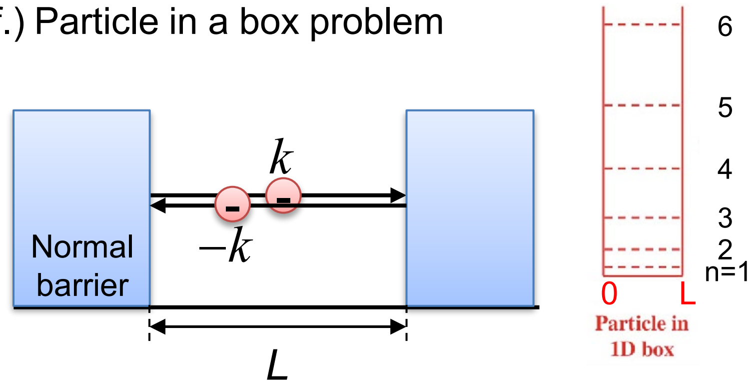
Bohr-Sommerfeld quantization:

$$2\cos^{-1}\left(\frac{E}{\Delta}\right) + k^{+}L + (-k^{-}L) \pm \phi = 2\pi n$$

Andreev bound state (ABS)

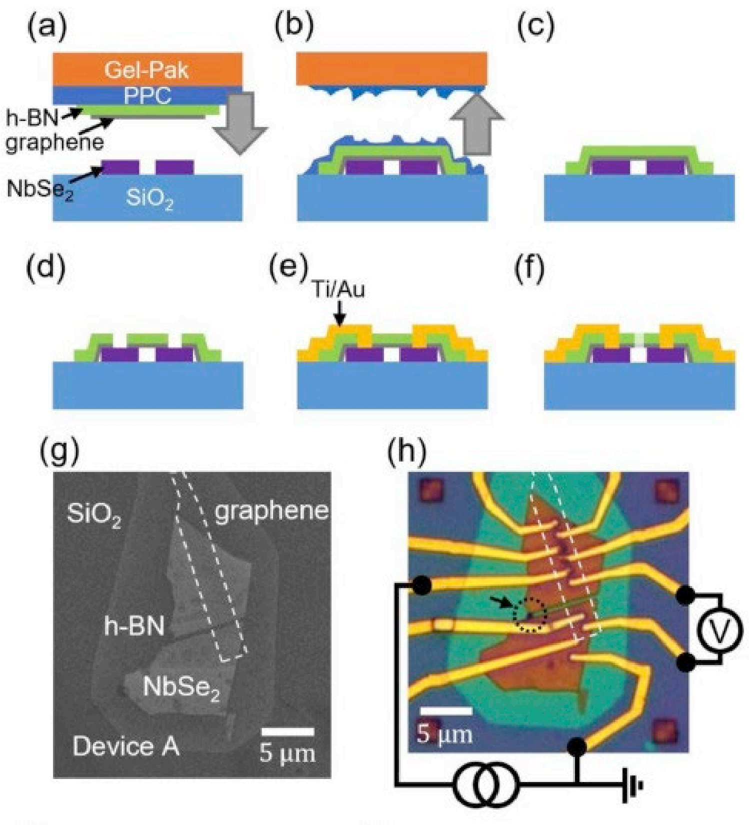


c.f.) Particle in a box problem

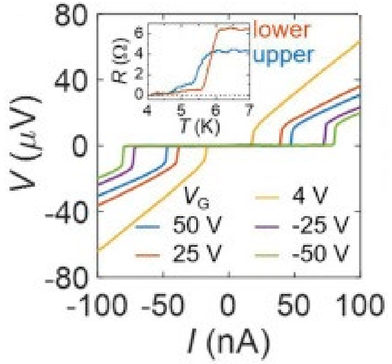


NbSe$_2$/Graphene/NbSe$_2$

Planar Josephson junction

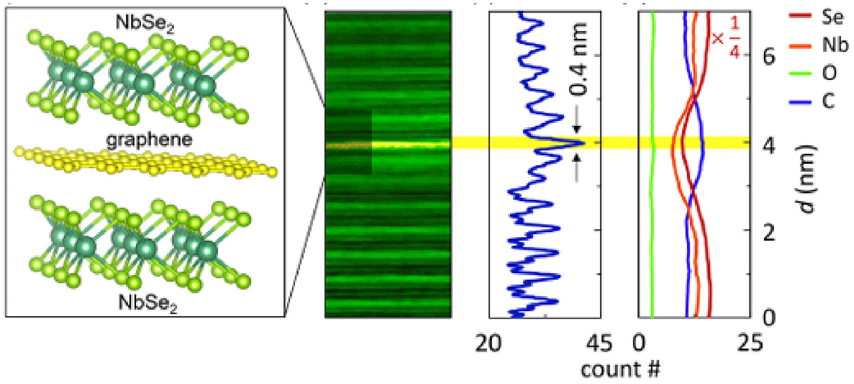


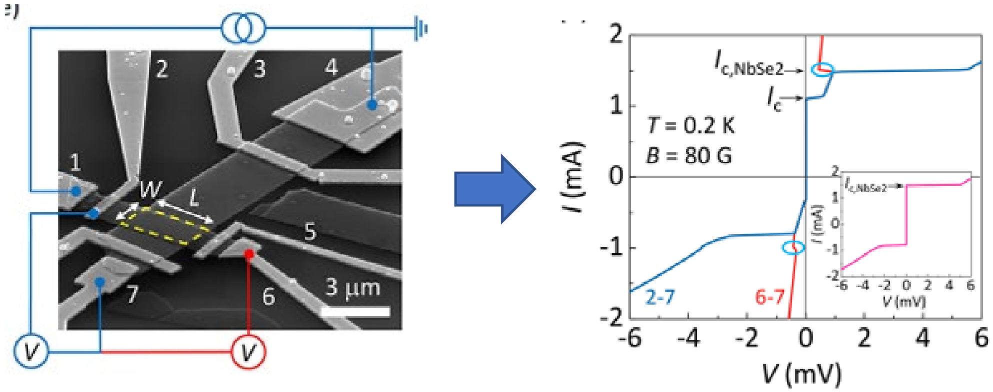
- Full vdW-based JJ
- long-diffusive junction
- $I_c R_N \sim 10\ \mu V$
- $\Delta_{NbSe2} \sim 0.8\ meV$



[Jongyun Lee et al., CAP 19, 251 (2019)]

Vertical Josephson junction

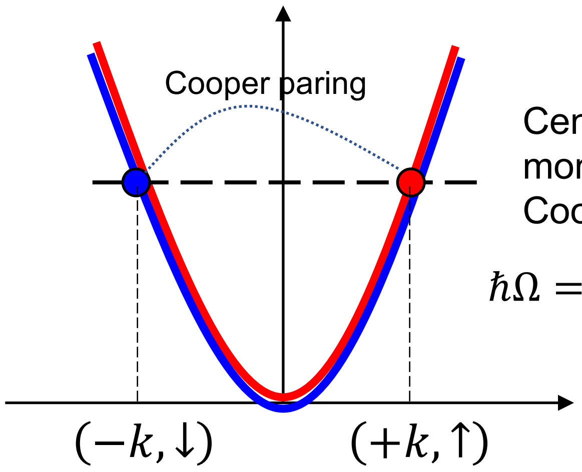




- Full vdW-based vertical JJ
- $J_c \sim 10^4\ A/m^2$

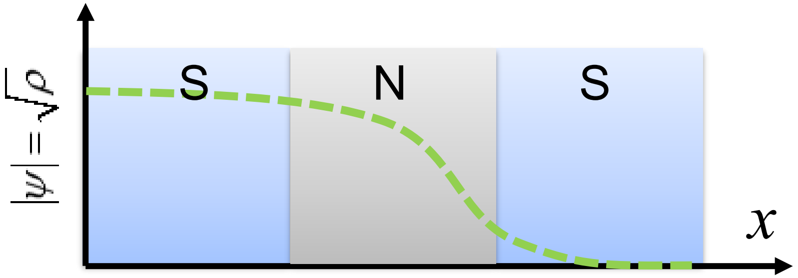
[Minsoo Kim et al., Nano Lett. 17, 6125 (2017)]

π-Josephson junction



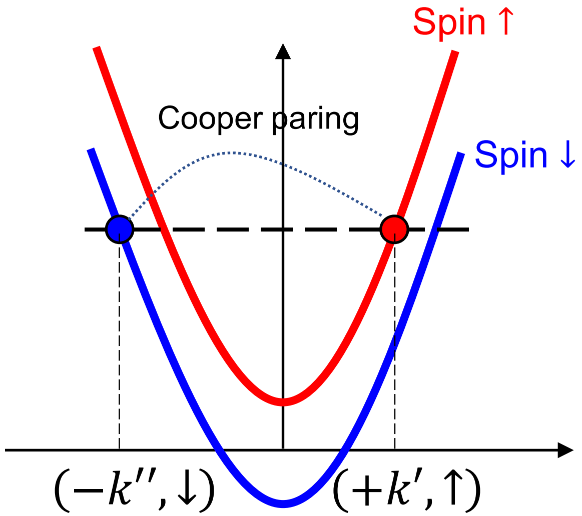
Center-of-mass momentum of Cooper pair:

$$\hbar\Omega = \hbar k + \hbar(-k) = 0$$



0-Josephson junction

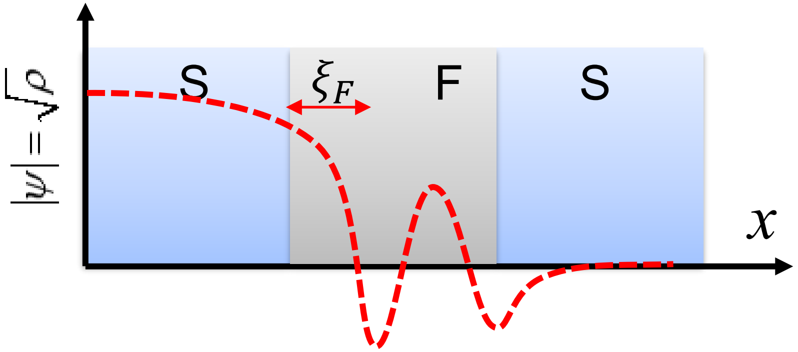
$$I_J = I_c \sin(\phi)$$



$$\hbar\Omega = \hbar k' + \hbar(-k'') \neq 0$$

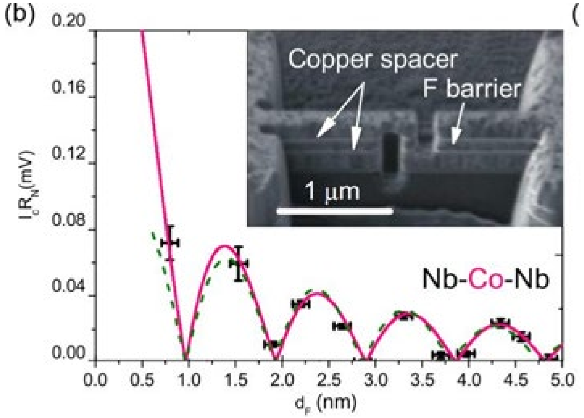
↓

Oscillating term in ψ



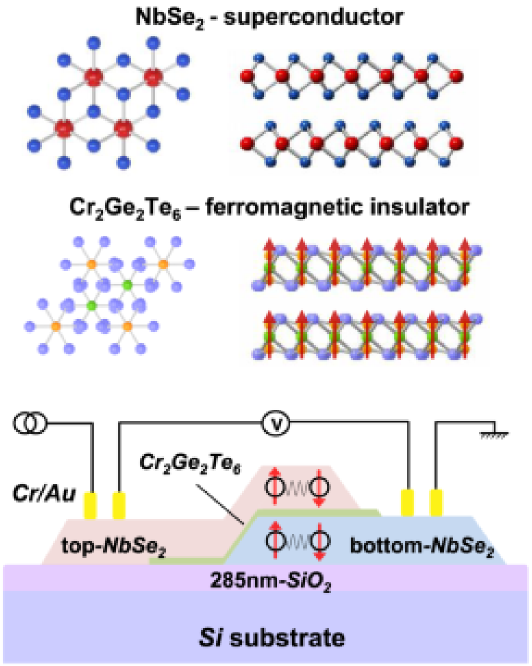
π-Josephson junction

$$I_J = I_c \sin(\phi + \pi) = -I_c \sin(\phi)$$

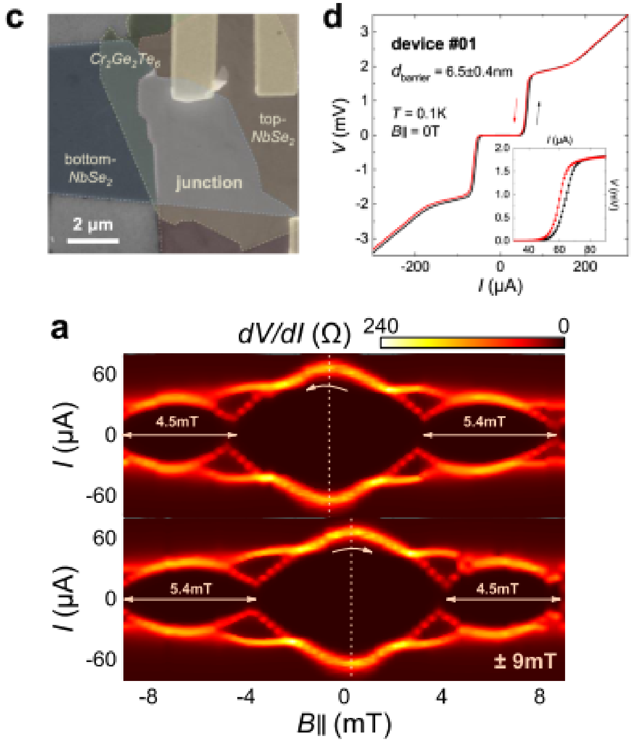


[J. W. A. Robinson et al., PRL 97, 177003 (2006)]

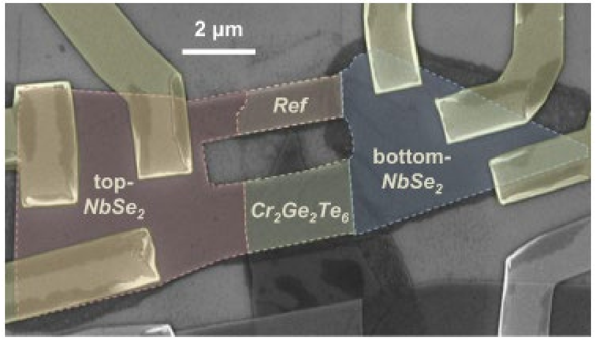
vdW-ferromagnetic Josephson junctions

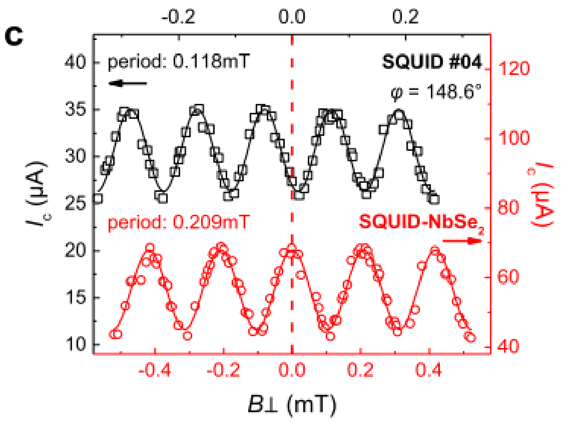


Fabricated in a glovebox

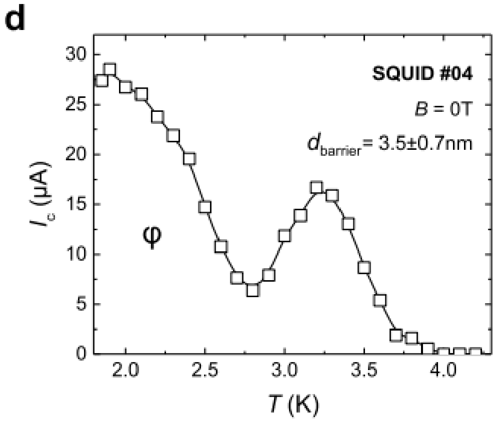


Magnetic hysteresis in Fraunhofer pattern





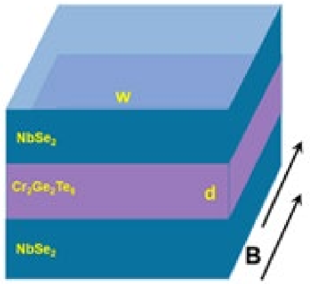
$\sim 0.8\,\pi$ phase shift in SQUID interference

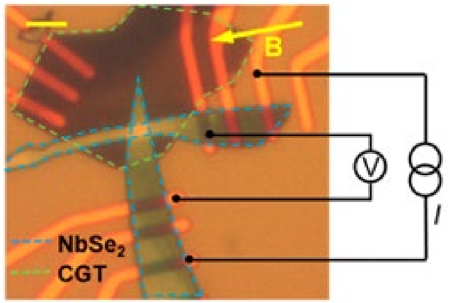


Non-monotonic $I_c(T)$

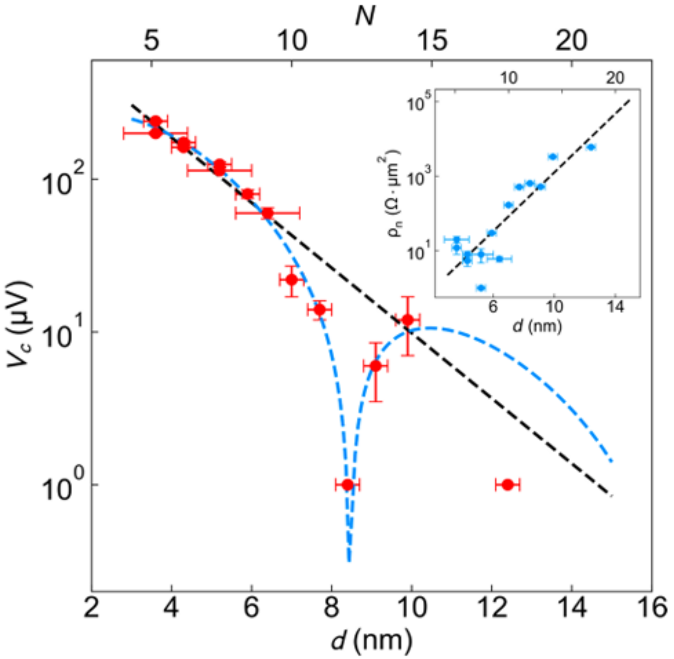
[Linfeng Ai et al., Nat. Comm. 12, 6580 (2021)]

vdW-ferromagnetic Josephson junctions

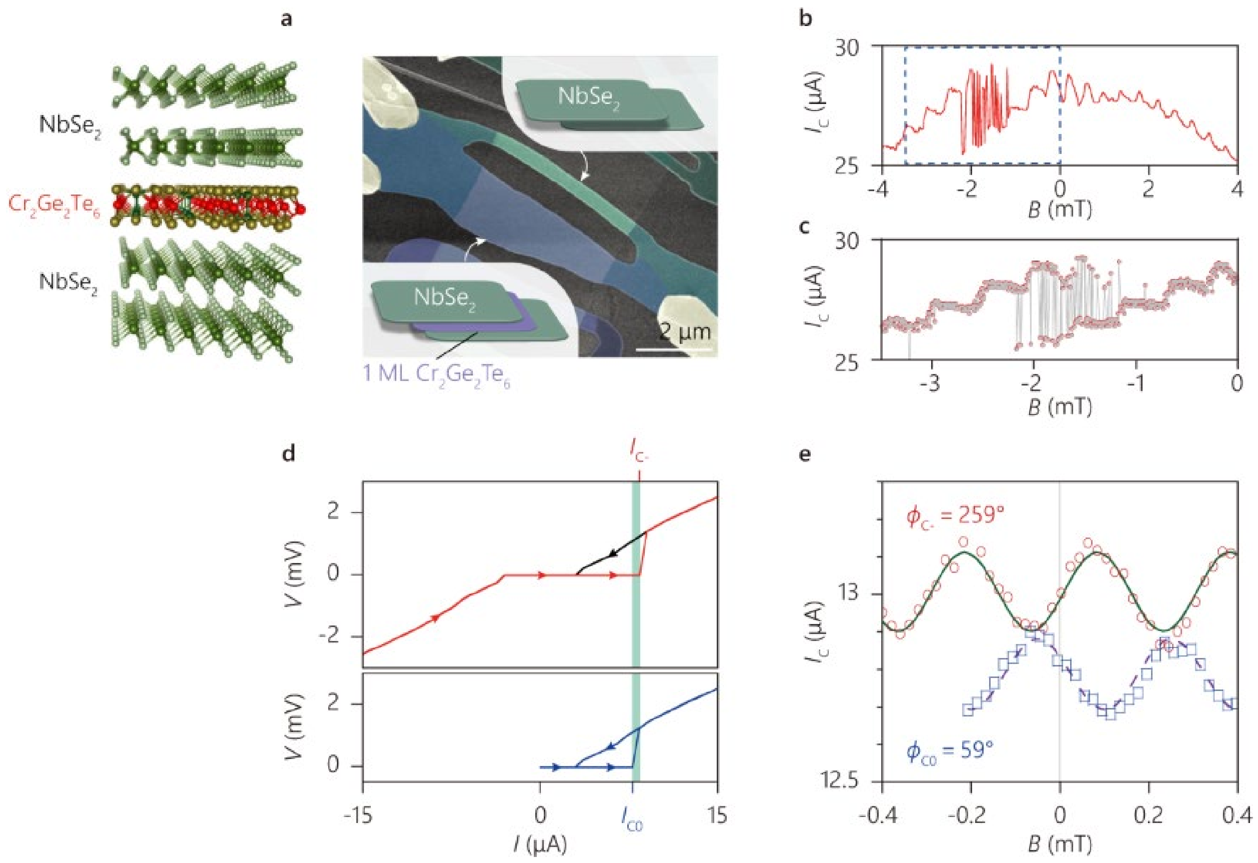




d_f dependence of $\mathrm{V}_c = I_c R_N$



[K. Kang et al., Nano Lett. 22, 5510 (2022)]

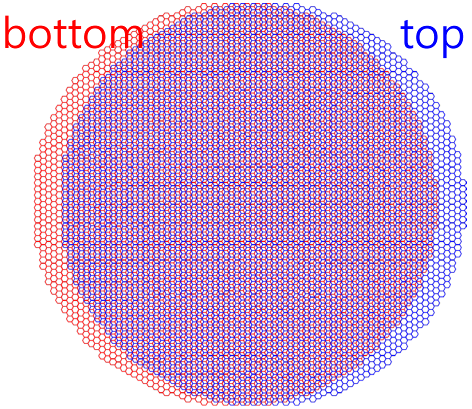


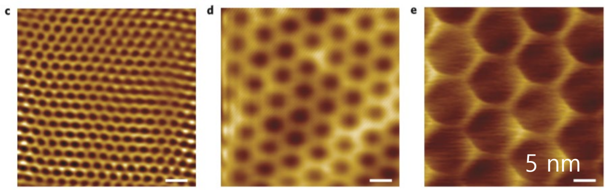
$\sim 1.4\,\pi$ and $\sim 0.3\,\pi$ phase shift in SQUID interference

[H. Idzuchi et al., Nat. Comm. 12, 5332 (2021)]

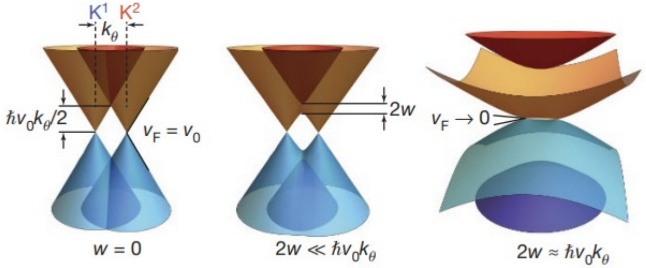
POSTECH

Twist-angle Tunable vdW Interfaces



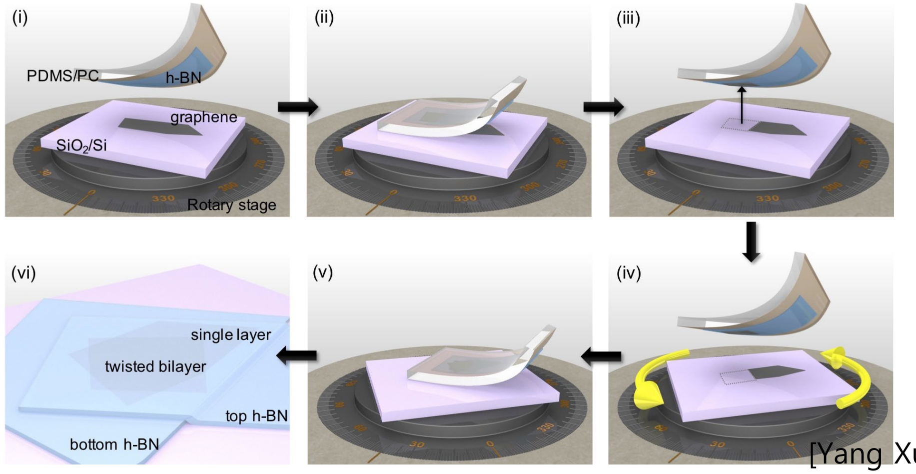


[Nat. Phys. **8**, 382 (2012)]



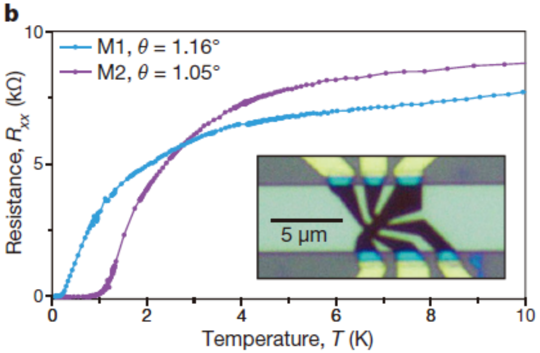
[Nature **556**, 80–84 (2018)]

Tear-and-stack method



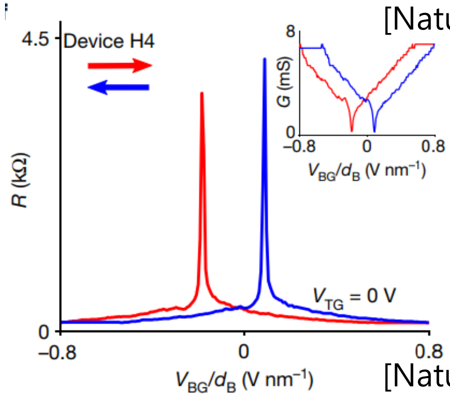
[Yang Xu]

Superconductivity



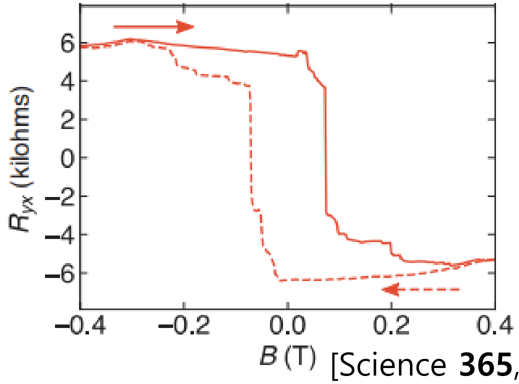
[Nature **556**, 43 (2018)]

Ferroelectricity



[Nature **588**, 71 (2020)]

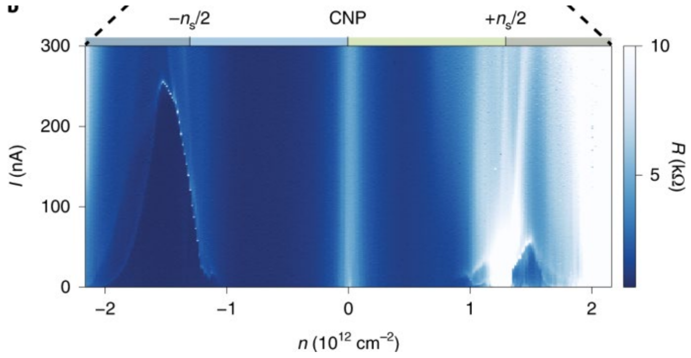
Ferromagnetism

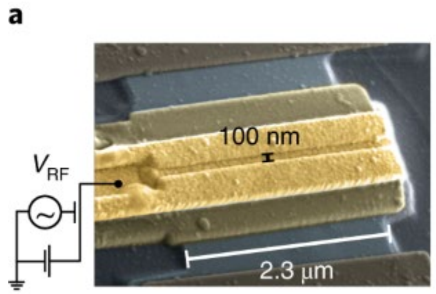


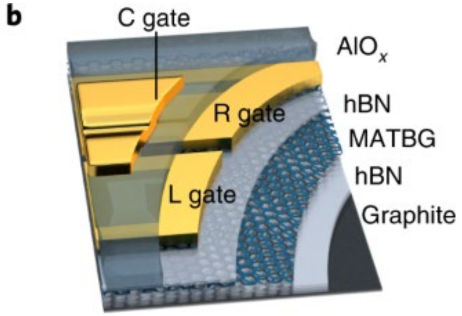
[Science **365**, 605-608 (2019)]

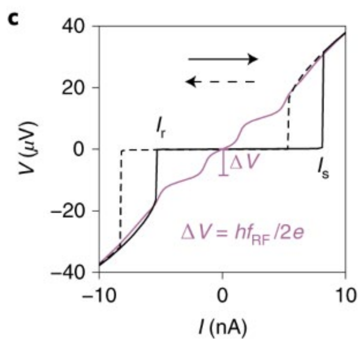
POSTECH

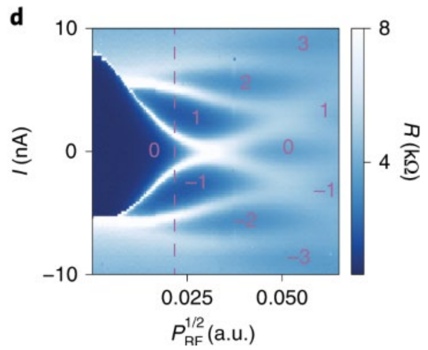
MATBG-based Josephson Junction





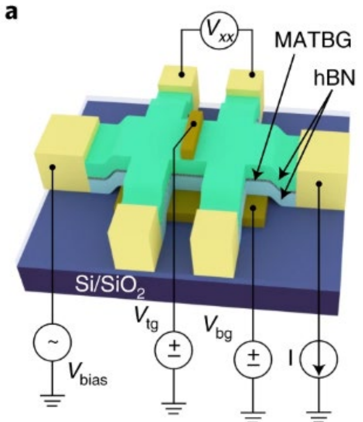




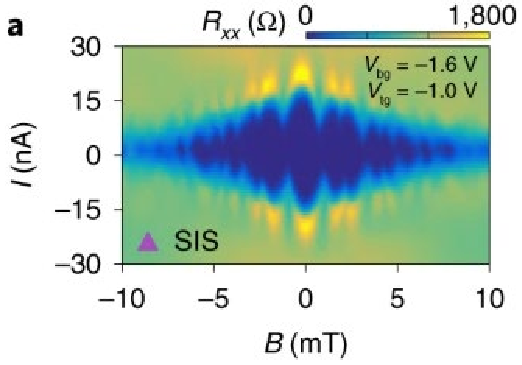


Usual Shapiro step
→ topologically trivial SC

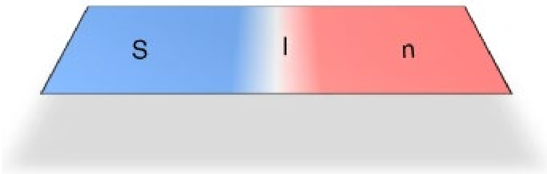
[F. K. de Vries et al., Nat. Nanotechnol. 16, 760 (2021)]

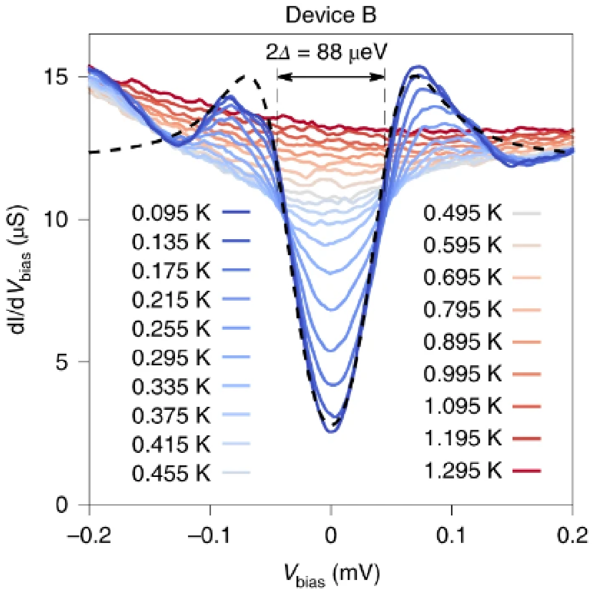


Josephson coupling



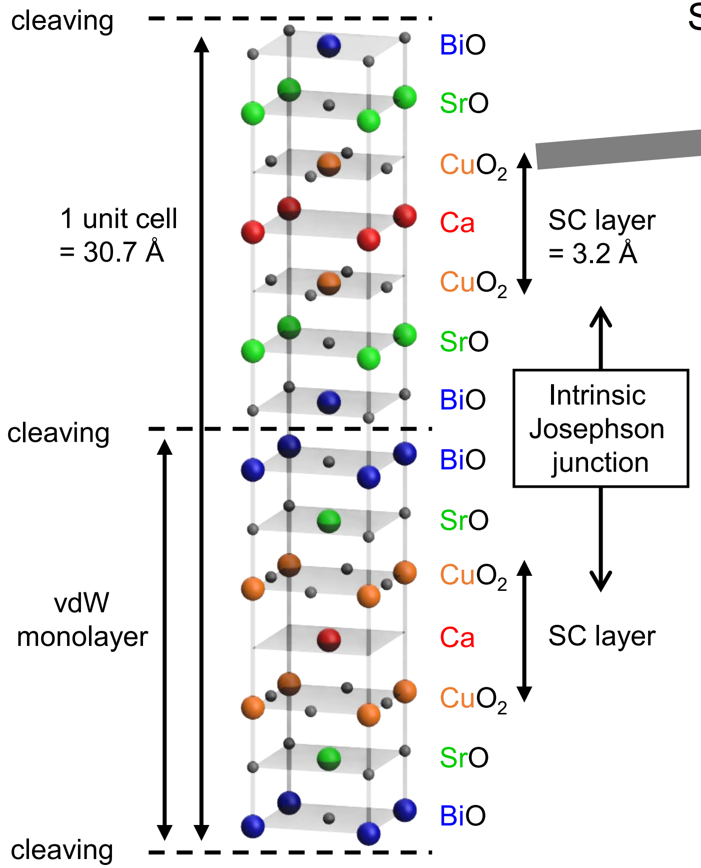
Demonstration of
tunneling spectroscopy



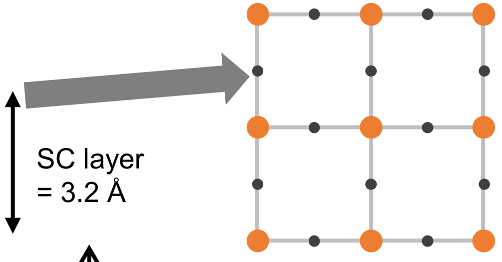


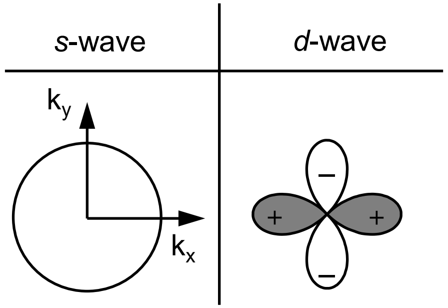
[D. Rodan-Legrain et al., Nat. Nanotechnol. 16, 769 (2021)]

Bi-2212 Twisted Josephson Junction (1/2)



CuO_2 (cuprate)
Superconducting layer

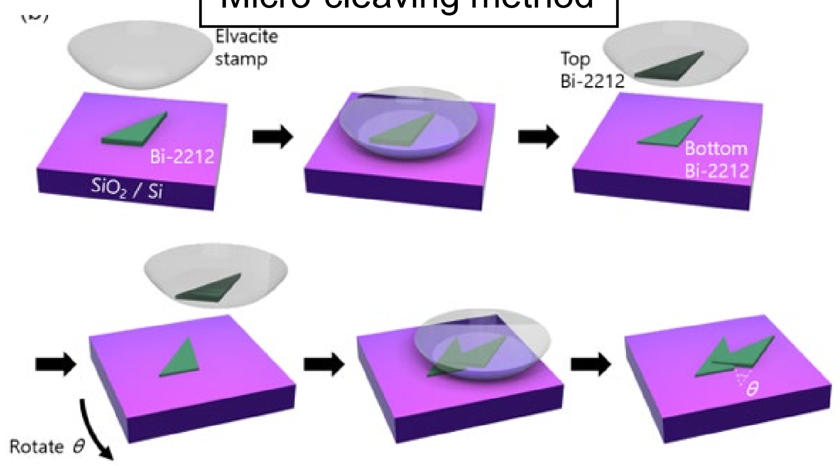


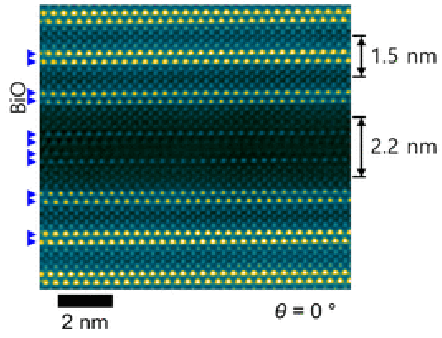


C. C. Tsuei and J. R. Kirtley,
Rev. Mod. Phys. **72**, 969 (2000)

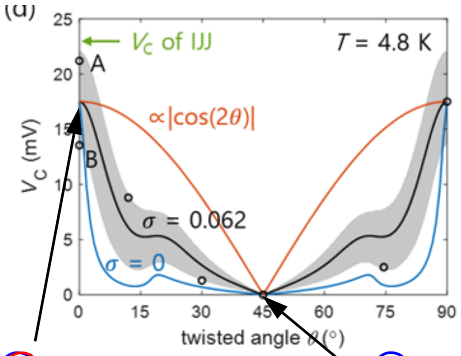
STM, ARPES experiments shows evidences of d-wave SC

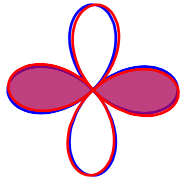
Micro-cleaving method

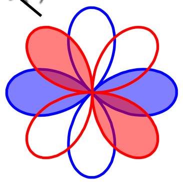




STEM image of interface







[Jongyun Lee et al.,
Nano Lett. 21, 10469 (2021)]

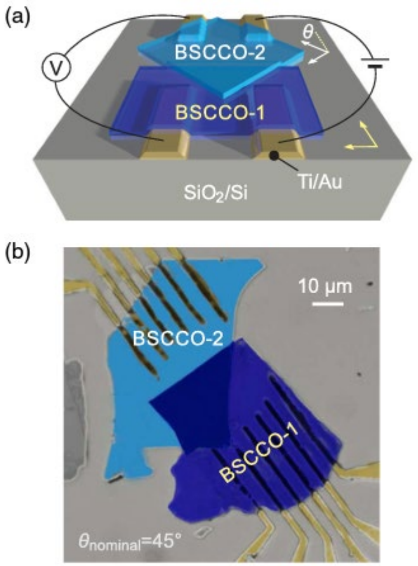
Maximum coupling

Minimum coupling

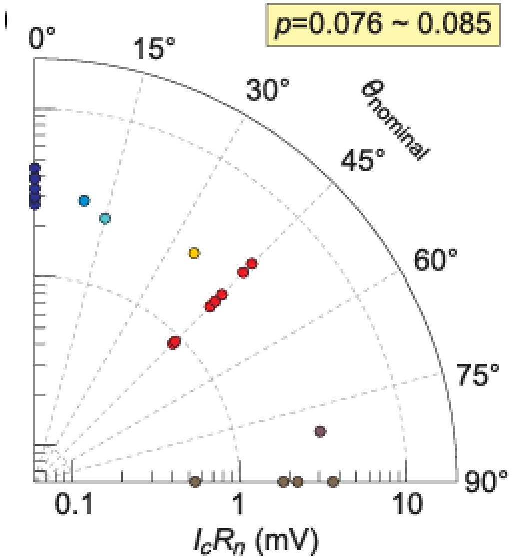
Supporting *d*-wave SC

POSTECH

Bi-2212 Twisted Josephson Junction (2/2)

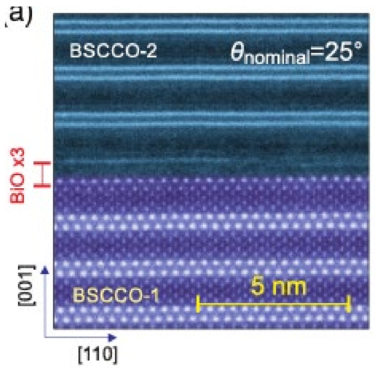


Fabricated in glovebox

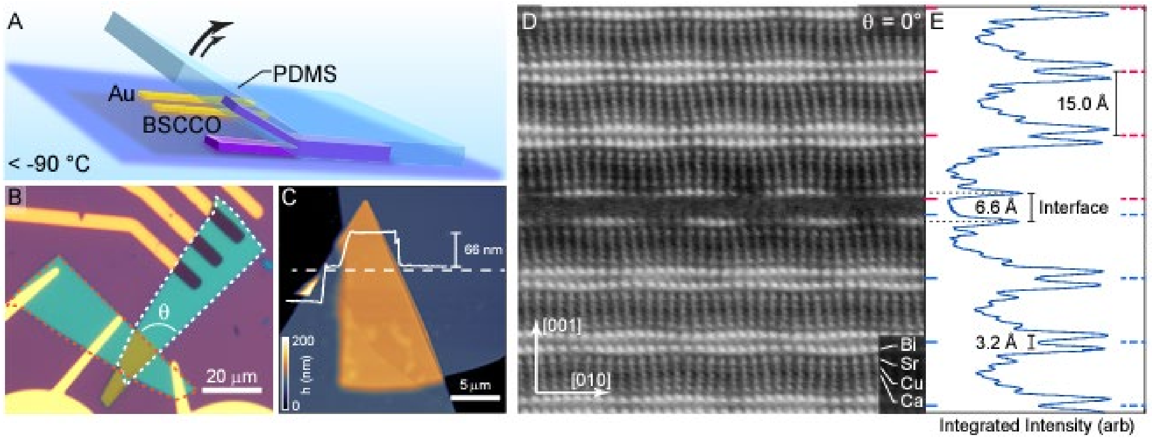


No twist-angle dependence

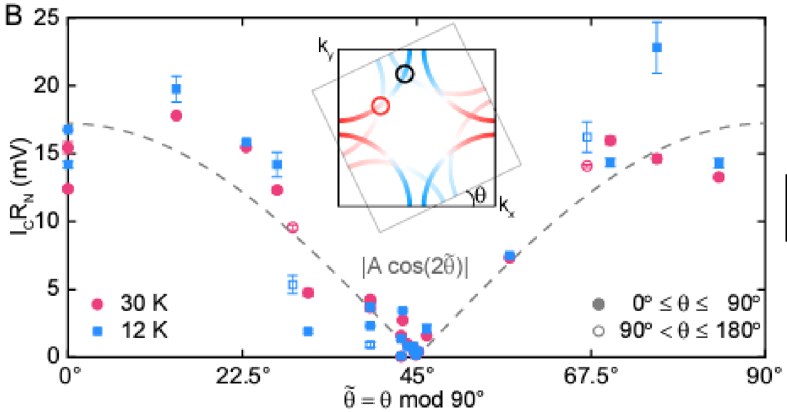
Supporting *s*-wave SC



[Y. Zhu et al., PRX 11, 031011 (2021)]



Fabricated on <u>cold stage</u>
in glovebox



Supporting *d*-wave SC

[S. Y. Frank Zhao et al., arXiv:2108.13455 (2021)]

Josephson Diode

To be updated

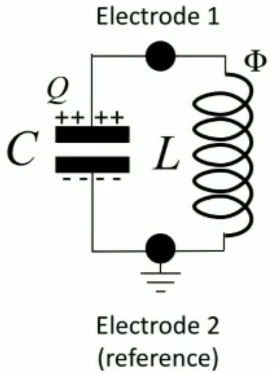
Topological Material based Josephson Junctions

To be updated

Superconducting Qubits
& possible roles of vdW materials

Quantum LC Resonator

The quantized *LC* oscillator



Hamiltonian:

$$\hat{H}_{\mathrm{LC}} = \frac{\hat{Q}^2}{2C} + \frac{\hat{\Phi}^2}{2L}$$

Capacitive term   Inductive term

Canonically conjugate variables:

$\hat{\Phi}$ = Flux through the inductor.

$\hat{Q}$ = Charge on capacitor plate.

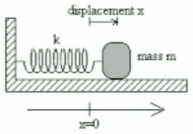
$$\left[\hat{\Phi}, \hat{Q}\right] = i\hbar$$

M. Devoret, Les Houches Session LXIII (1995)

Correspondence with simple harmonic oscillator

$$\hat{H}_{\mathrm{LC}} = \frac{\hat{\Phi}^2}{2L} + \frac{\hat{Q}^2}{2C} \qquad \left[\hat{\Phi}, \hat{Q}\right] = i\hbar$$

$$\hat{H}_{\mathrm{SHO}} = \frac{k\hat{X}^2}{2} + \frac{\hat{P}^2}{2m} \qquad \left[\hat{X}, \hat{P}\right] = i\hbar$$



Correspondence: $\hat{\Phi} \leftrightarrow \hat{X}$ $\quad L \leftrightarrow \frac{1}{k}$ $\quad \omega = \frac{1}{\sqrt{LC}} \leftrightarrow \sqrt{\frac{k}{m}}$

$\hat{Q} \leftrightarrow \hat{P}$ $\quad C \leftrightarrow m$

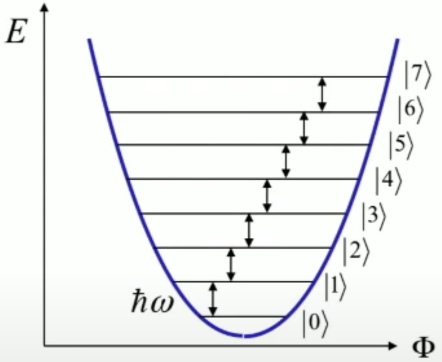
Solve using ladder operators:

$$\hat{a} = \left(\frac{\hat{Q}}{Q_{zpf}} - i\frac{\hat{\Phi}}{\Phi_{zpf}}\right) \qquad \Phi_{zpf} = \sqrt{2\hbar Z}$$

$$\hat{a}^\dagger = \left(\frac{\hat{Q}}{Q_{zpf}} + i\frac{\hat{\Phi}}{\Phi_{zpf}}\right) \qquad Q_{zpf} = \sqrt{2\hbar / Z}$$

$$Z = \omega L = \frac{1}{\omega C} = \sqrt{\frac{L}{C}}$$

$$\hat{H}_{\mathrm{LC}} = \hbar\omega\left(\hat{a}^\dagger\hat{a} + \frac{1}{2}\right) \qquad \left[\hat{a}_r, \hat{a}_r^\dagger\right] = 1$$



M. Devoret, Les Houches Session LXIII (1995)

POSTECH

Josephson Inductance

Inductance describes voltage drop, V, induced by the change of current, dI/dt,

$$V = L \times (dI/dt).$$

For Josephson junction,

I changes in time

→ φ changes in time (DC Josephson relationship)

→ V appears (AC Josephson relationship)

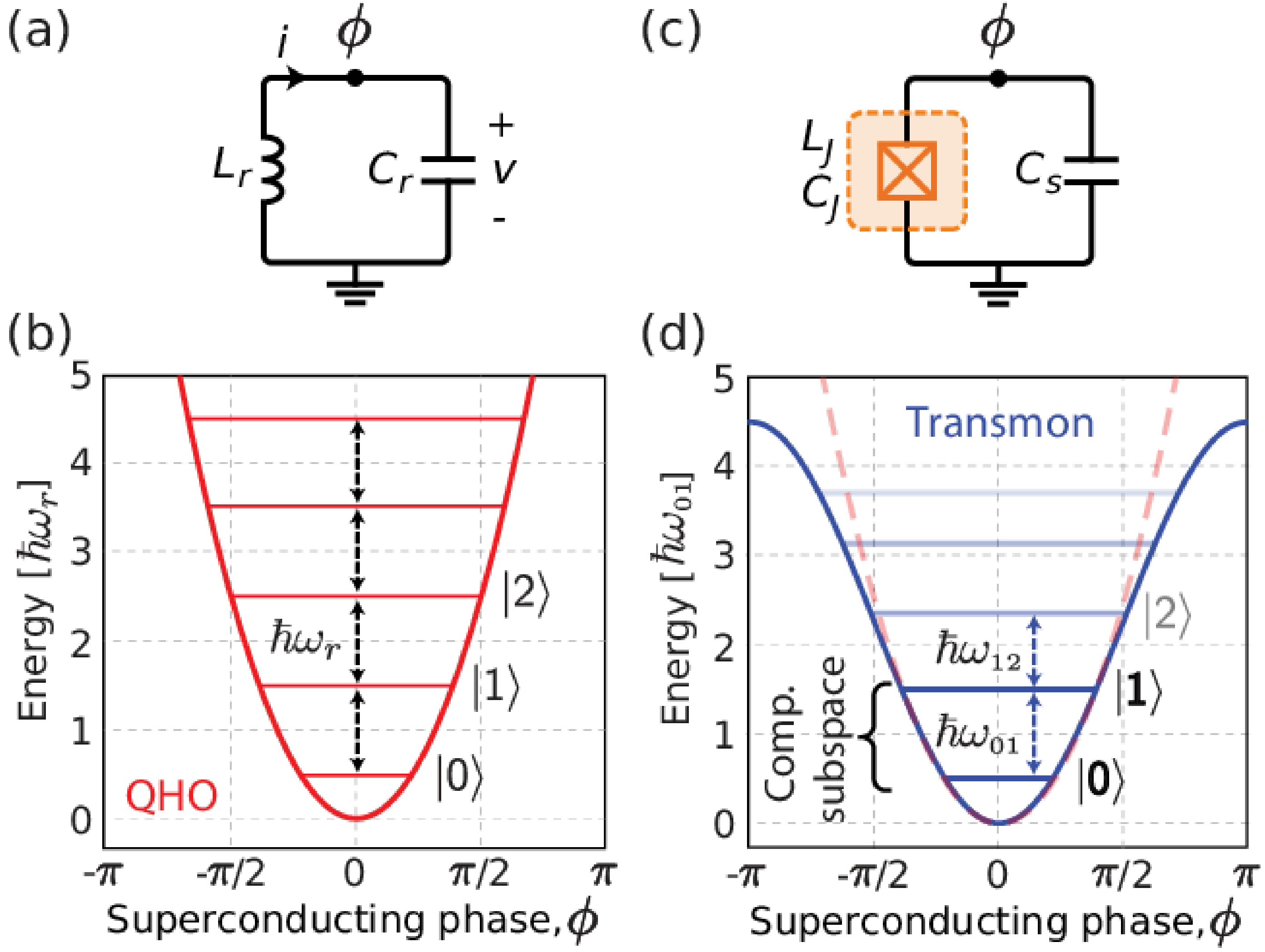
$$\frac{\partial I}{\partial \varphi} = I_c \cos\varphi, \quad \frac{\partial \varphi}{\partial t} = \frac{2\pi}{\Phi_0} V. \longrightarrow \frac{\partial I}{\partial t} = \frac{\partial I}{\partial \varphi}\frac{\partial \varphi}{\partial t} = I_c \cos\varphi \cdot \frac{2\pi}{\Phi_0} V, \longrightarrow V = \frac{\Phi_0}{2\pi I_c \cos\varphi}\frac{\partial I}{\partial t} = \boxed{L(\varphi)}\frac{\partial I}{\partial t}.$$

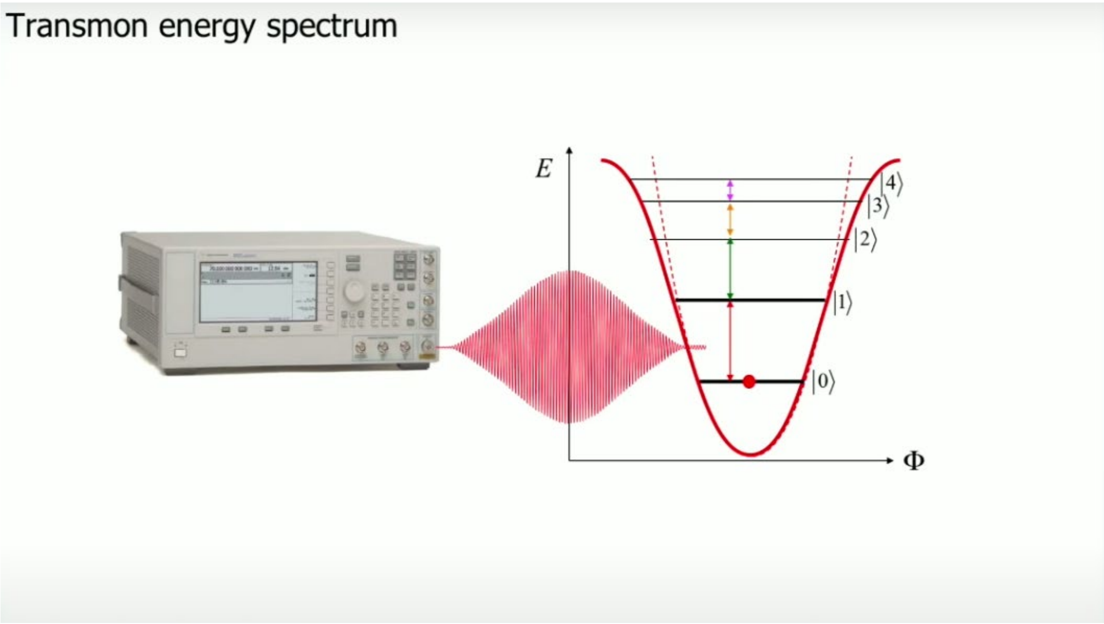
Josephson inductance $L(\varphi) = \dfrac{\Phi_0}{2\pi I_c \cos\varphi} = \dfrac{L_J}{\cos\varphi}. \qquad L_J = L(0) = \dfrac{\Phi_0}{2\pi I_c}$

Josephson junction is a 'quantum' nonlinear inductor.

POSTECH

Anharmonic LC resonator



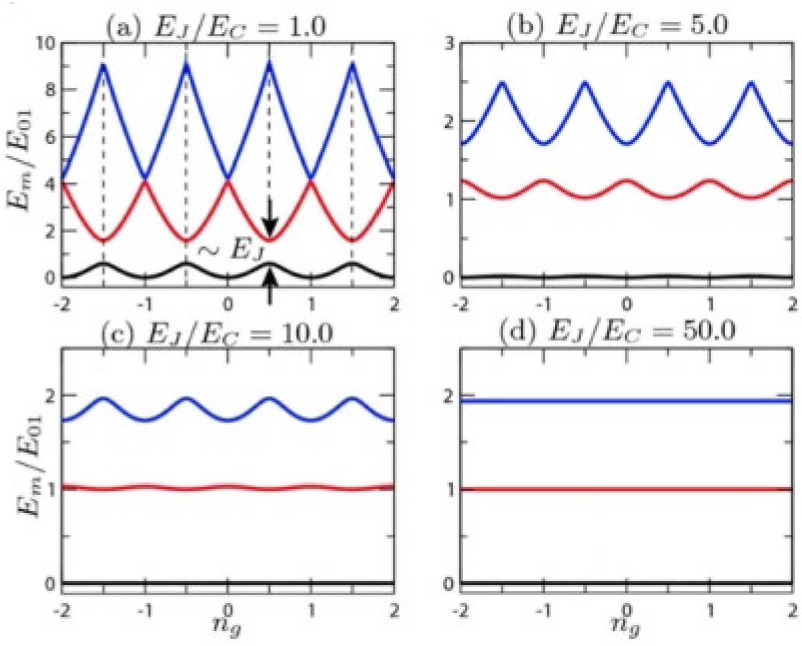


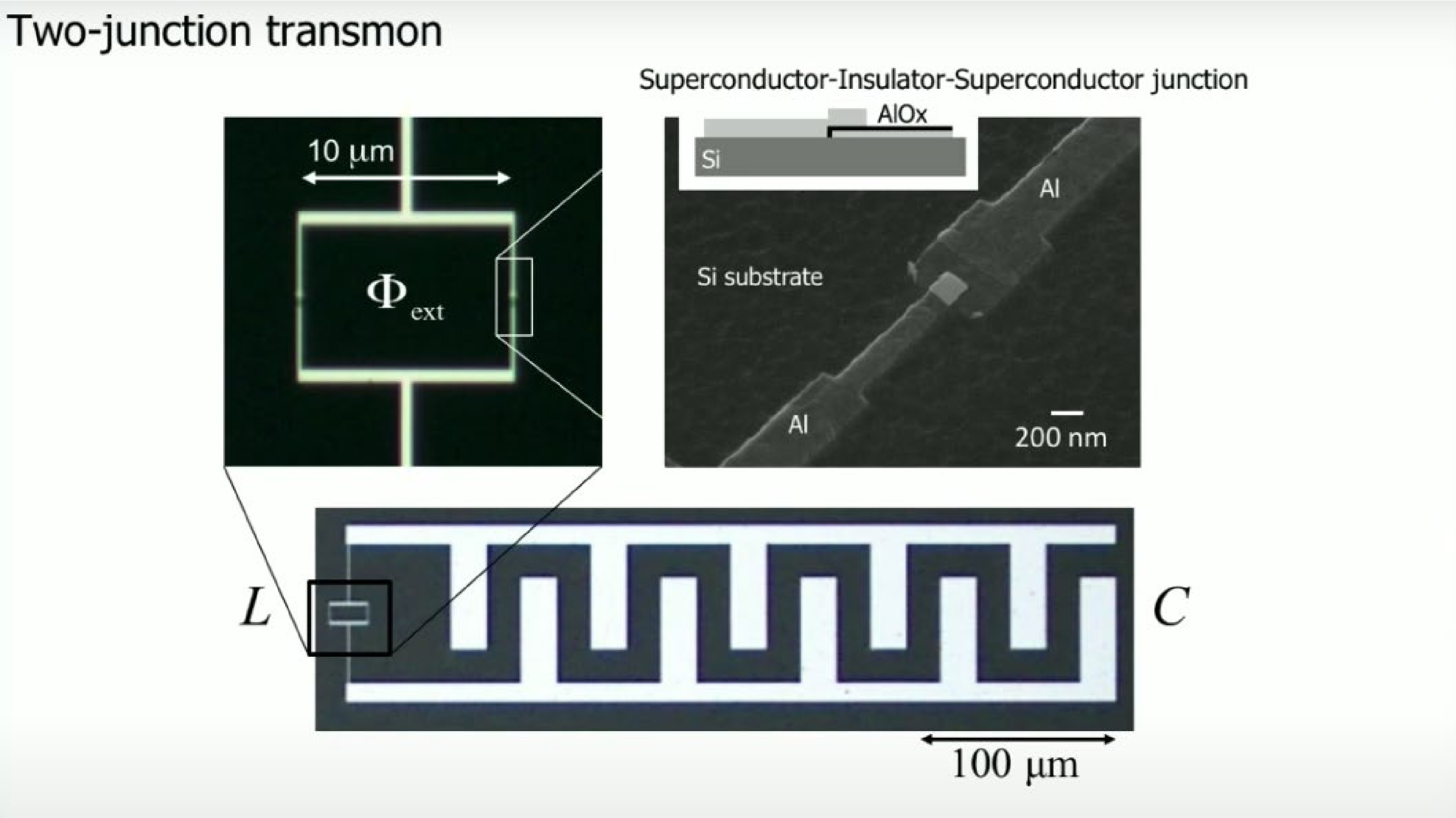
Shunting Capacitor

Energy stored in C: $E = \frac{(ne)^2}{2C} = E_C n^2$

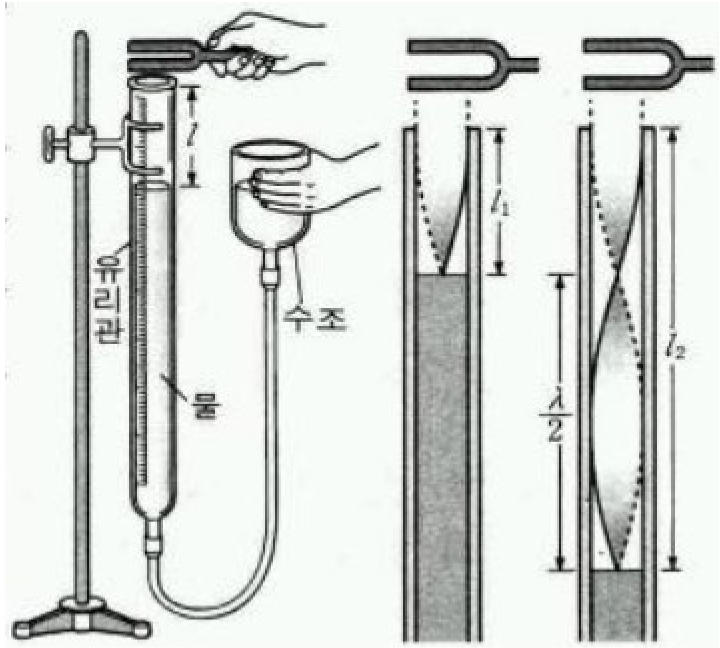
To minimize effect charge noise, E_C was decreased by adding big capacitor.

Energy diagram as a function of charging

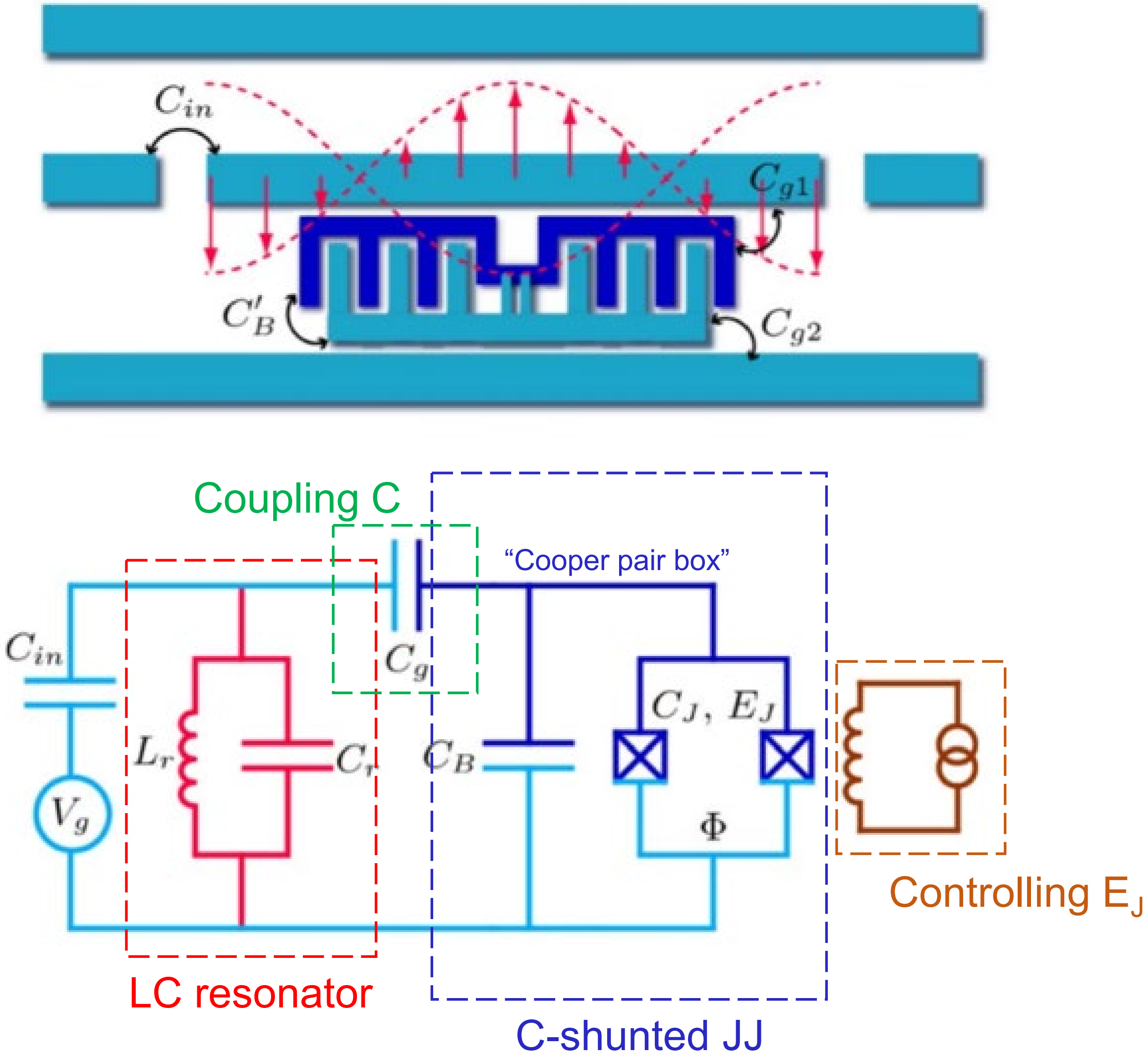




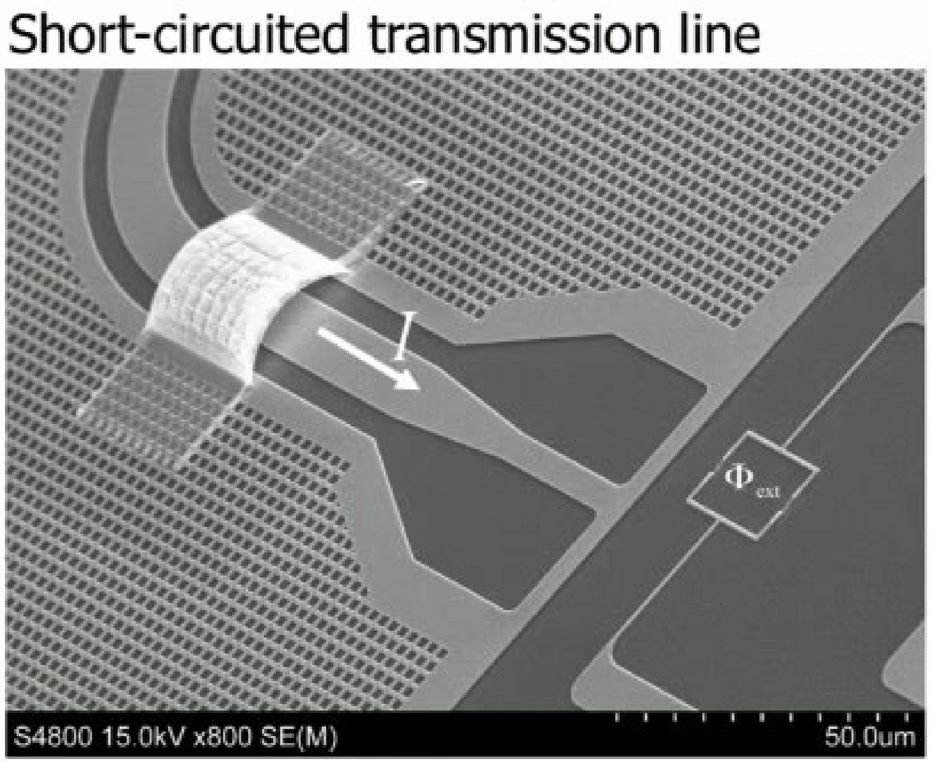
Coplanar Waveguide (CPW) coupled to Transmon

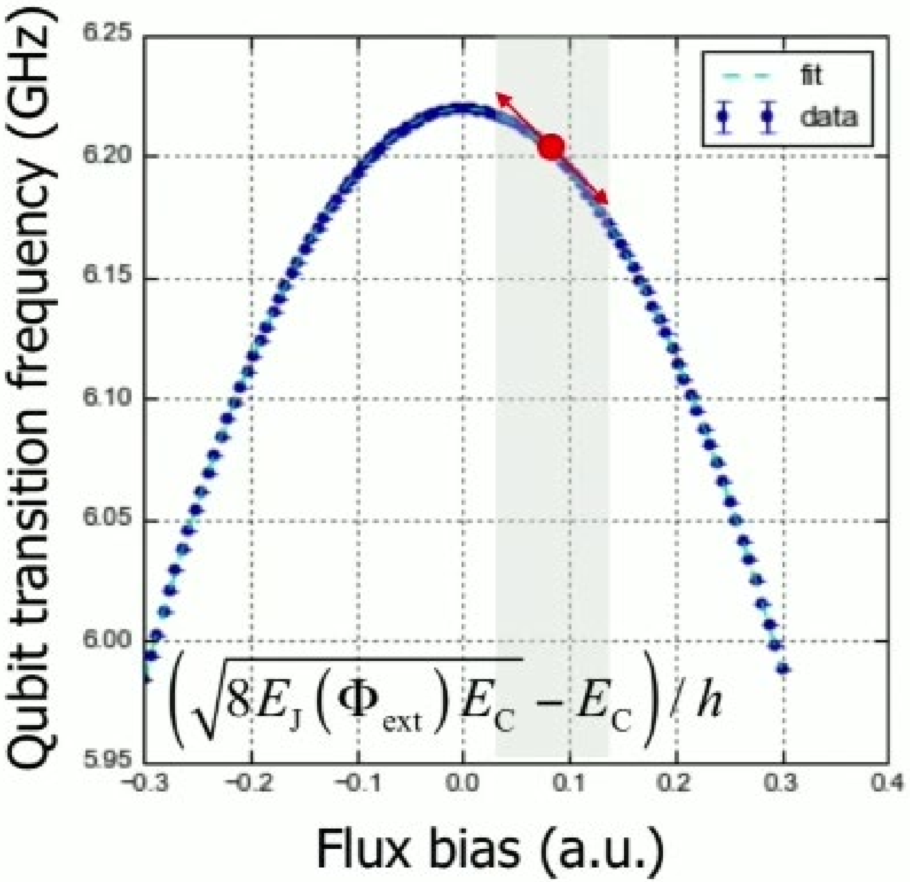


Air Column Resonance
(기주공명)



Flux control of Transmon Frequency

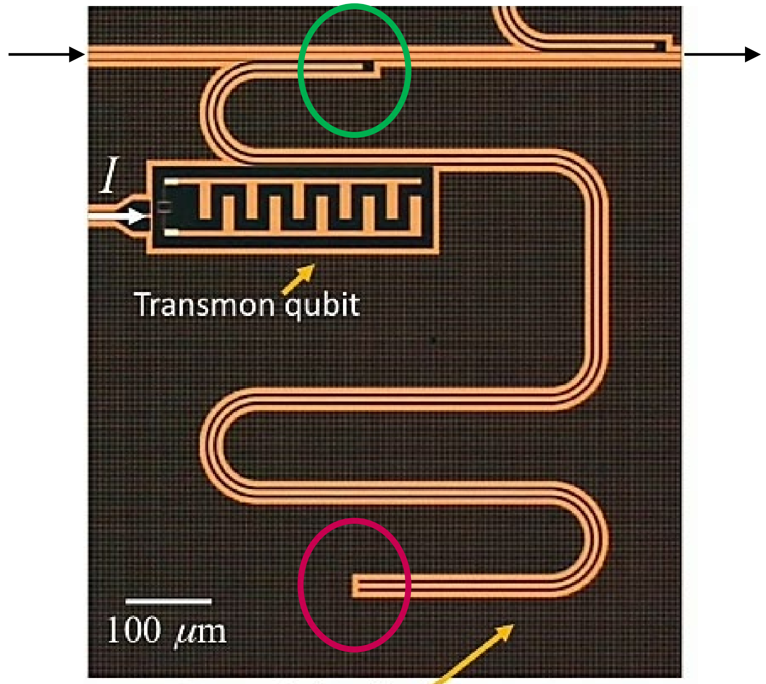




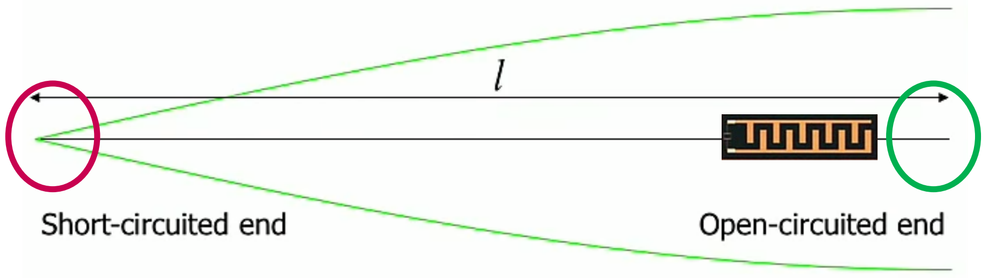
$$L_J = L(0) = \frac{\Phi_0}{2\pi \boxed{I_c}} \Rightarrow \omega = \frac{1}{\sqrt{LC}}$$

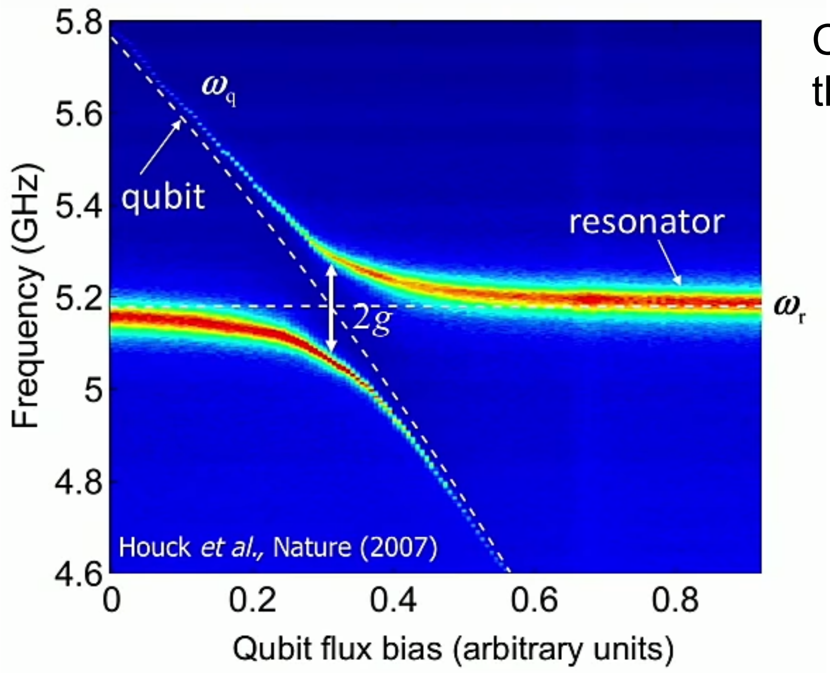
Qubit-Resonator Interaction

Qubit and resonator are capacitively coupled.



Transmission-line resonator



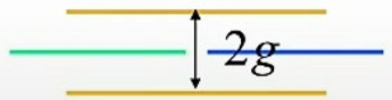


Color: absorption through readout line

Decrease qubit state

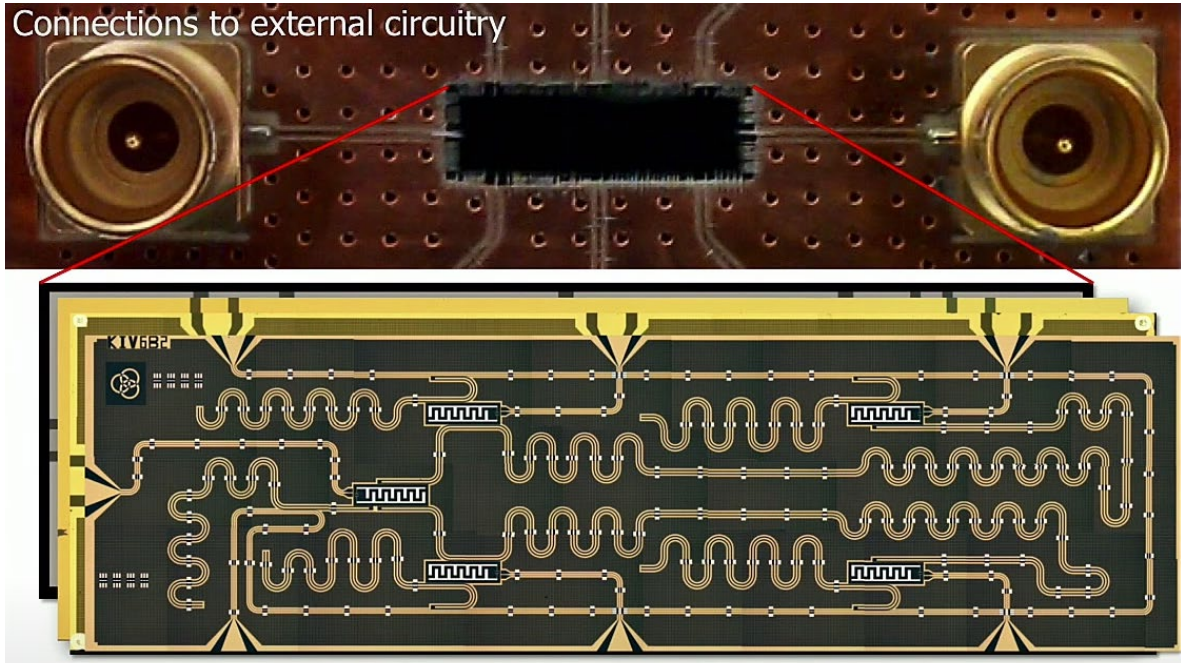
$$\hat{H}_{\text{int}} = \hbar g\left(a_r \hat{\sigma}_+ + a_r^{\dagger} \hat{\sigma}_-\right)$$ Jaynes-Cummings interaction

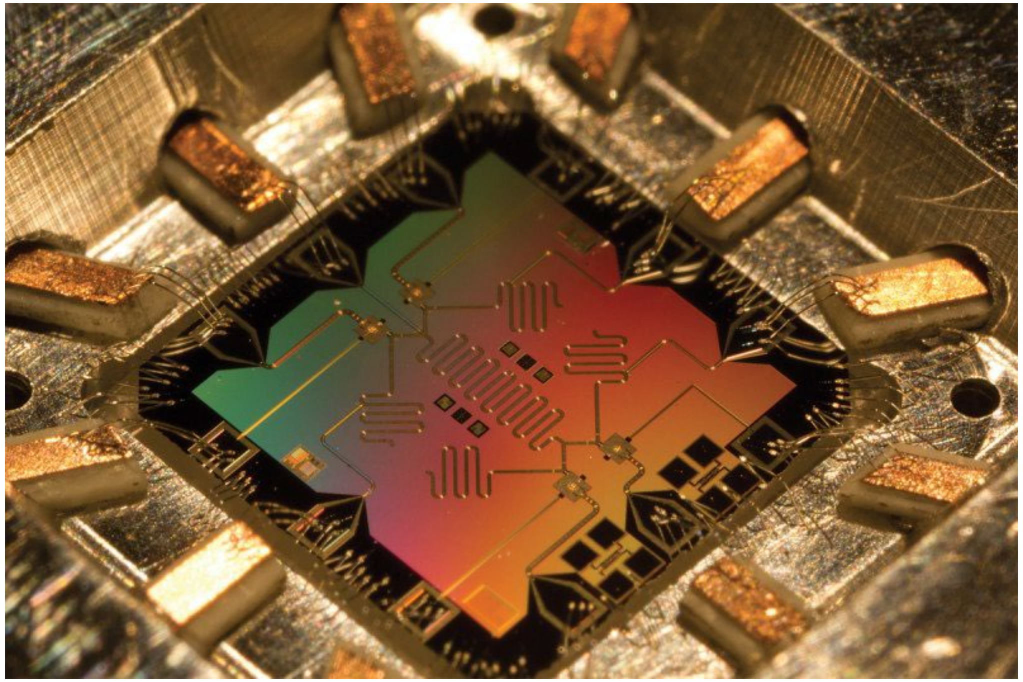
Increase resonator state



POSTECH

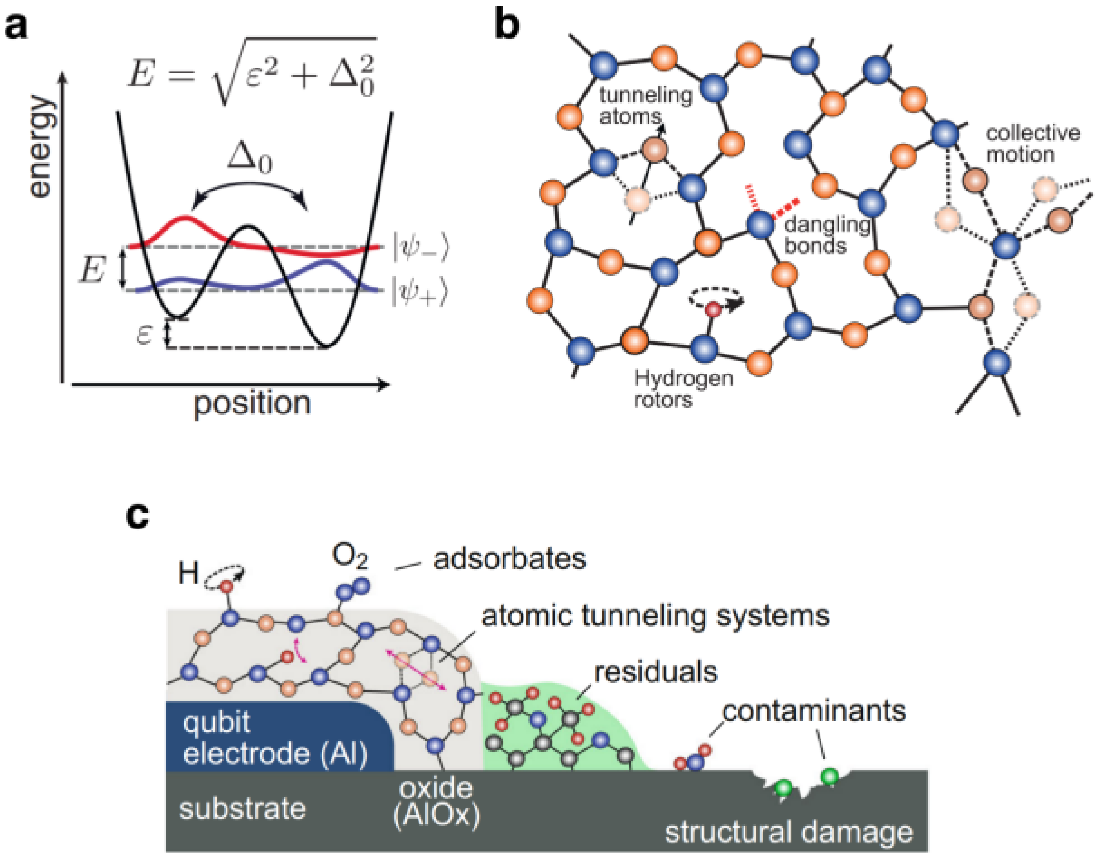
Connections to External Circuitry



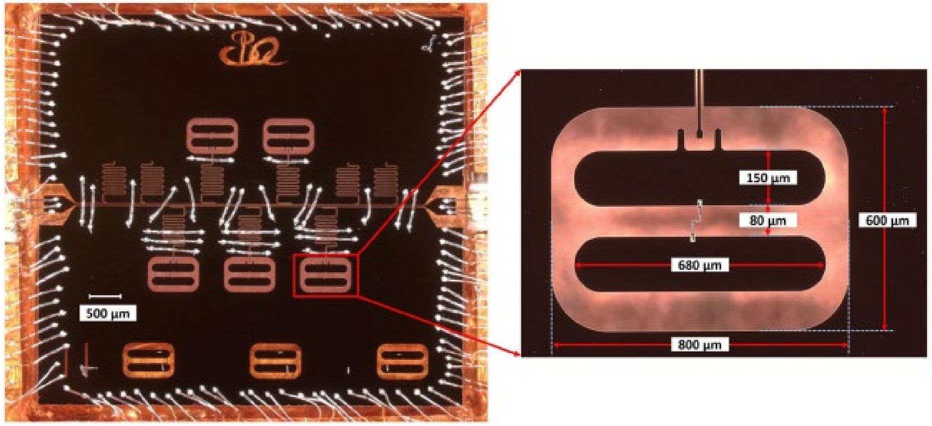


Google
version

Two Level System & State-of-art Transmon Qubit



Applications of van der Waals Materials for Superconducting Quantum Devices
[A. Antony, PhD Thesis]



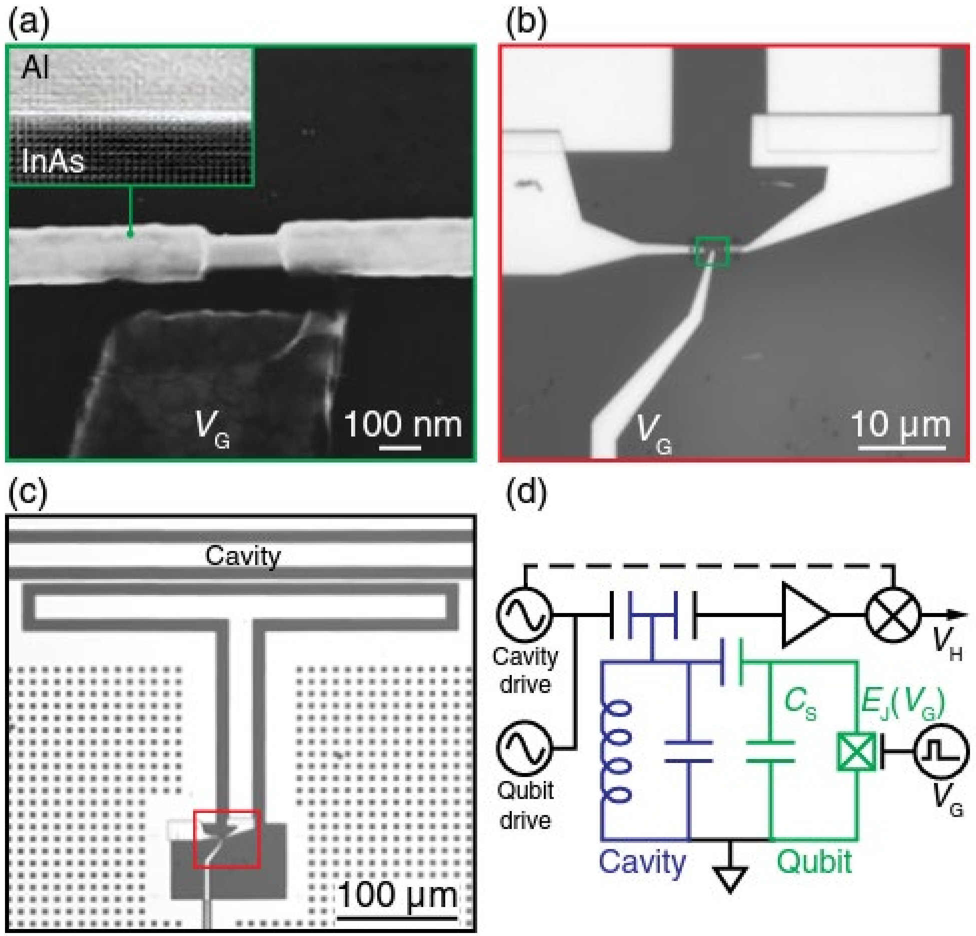
Transmon qubit made with
α-Ta film on Sapphire substrate

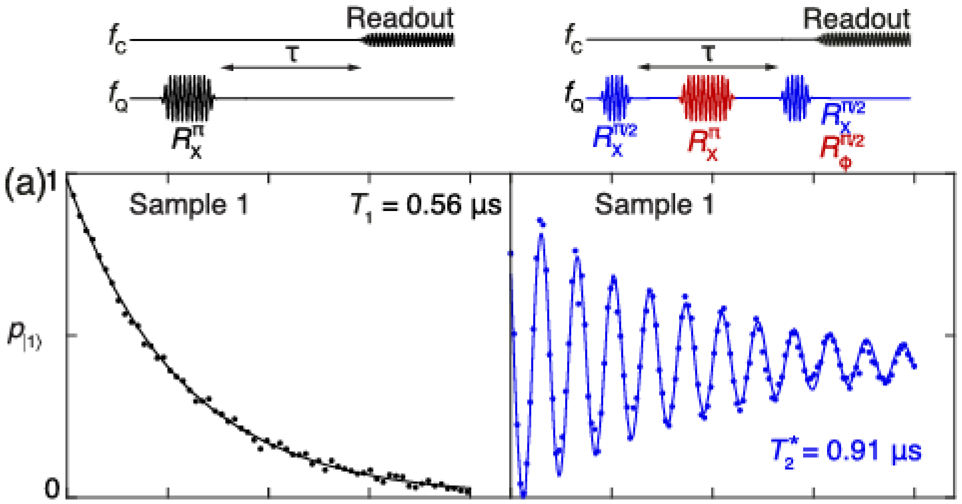
- Energy relaxation time $T_1 \sim 500\ \mu s$

[A.P. M. Place et al., Nat. Comm. 12, 1779 (2021)]
[C. Wang et al., npj Quantum Information 8, 3 (2022)]

Al/InAs/Al Gatemon Qubit

Al is epitaxially grown on InAs nanowire.

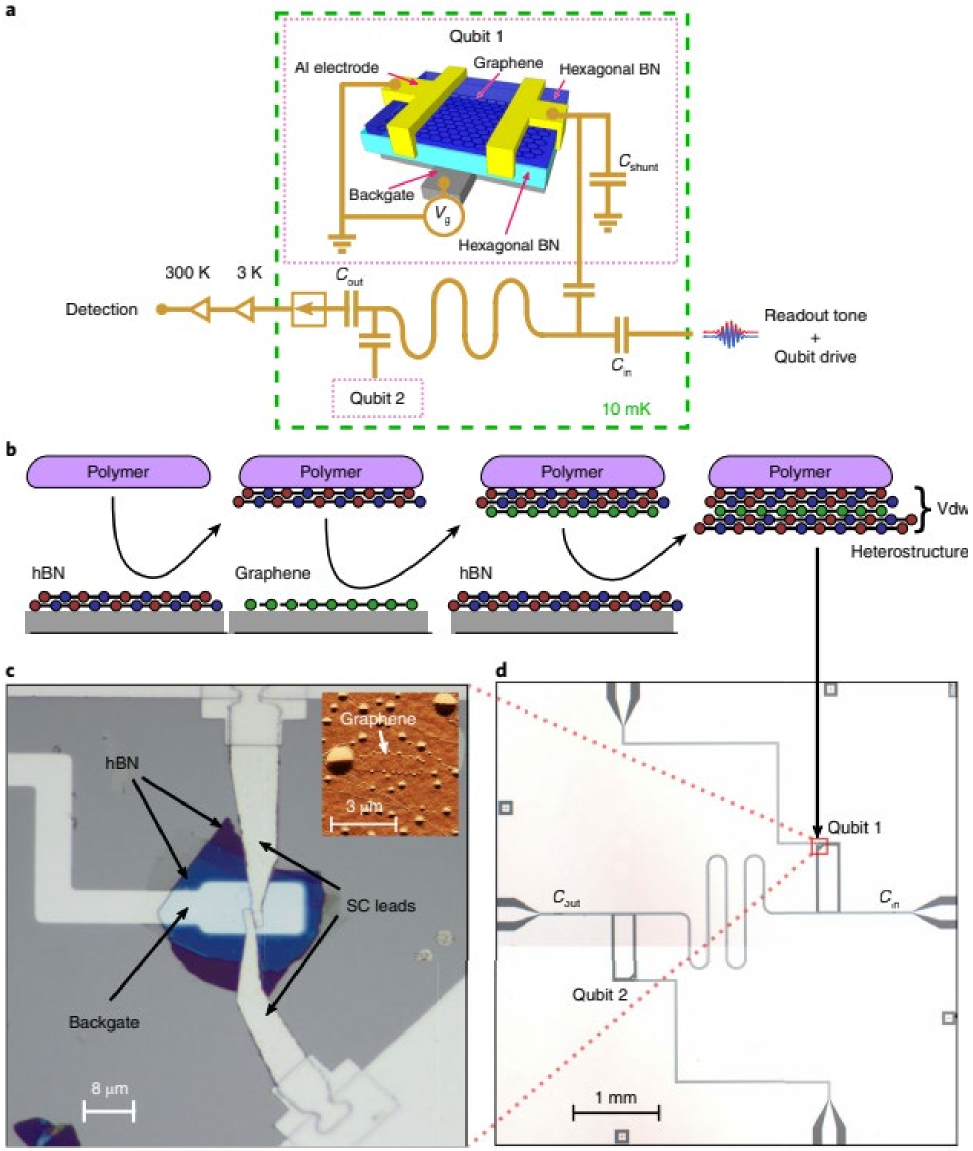


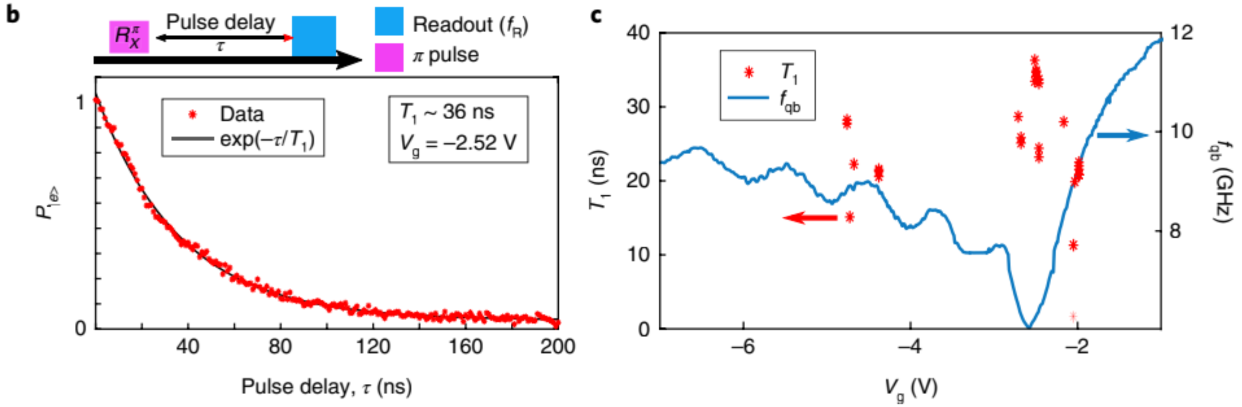


- Energy relaxation time $T_1 \sim 0.8\ \mu s$
- Dephasing time $T_2^* \sim 1\ \mu s$

Semiconductor-Nanowire-Based Superconducting Qubit
[T. W. Larsen et al., PRL 115, 127001 (2015)]

Graphene-based Gatemon Qubit

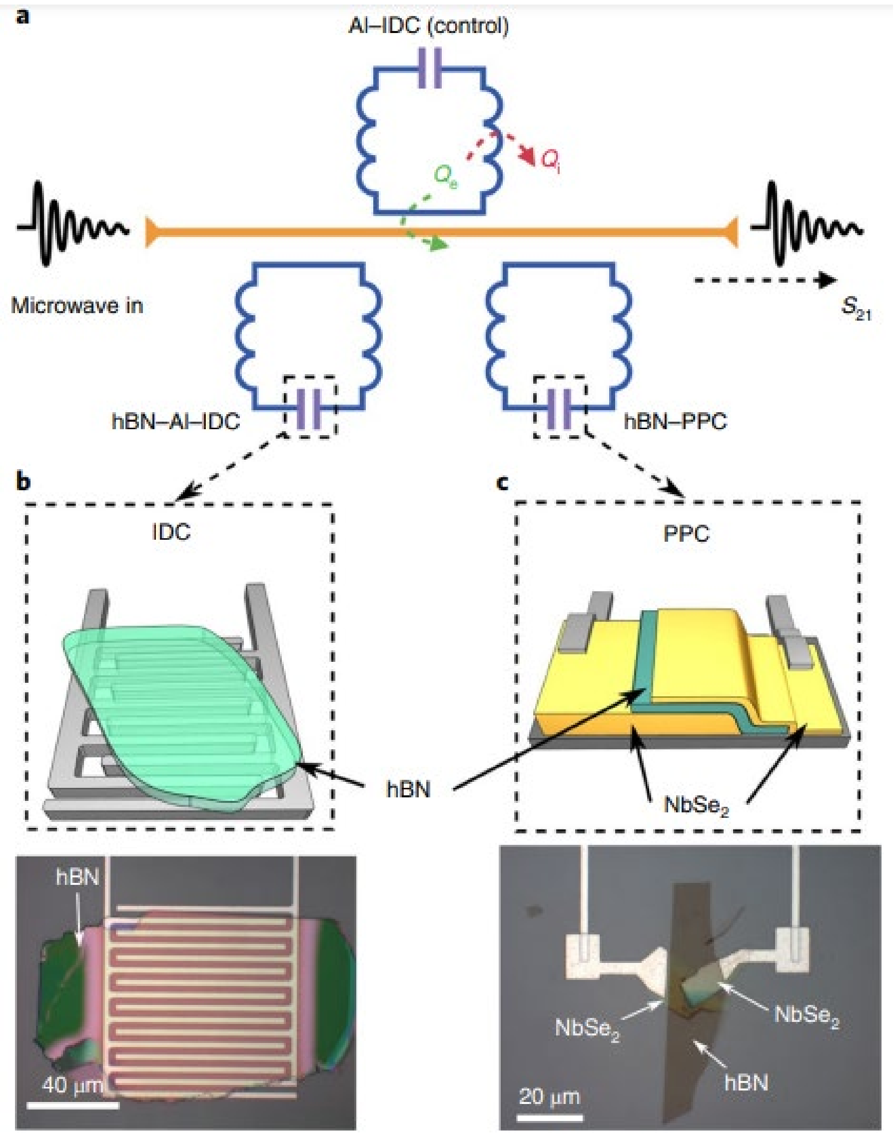


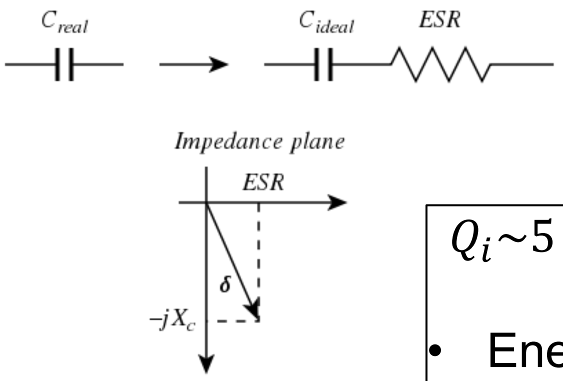


- Energy relaxation time $T_1 \sim 30\ ns$
- Dephasing time $T_2^* \sim 50\ ns$

Coherent control of a hybrid superconducting circuit made with graphene-based van der Waals heterostructures
[J. I. Wang et al., Nat. Nanotechnol. 14, 120-125 (2019)]

hBN-based Capacitor for Transmon Qubit (1/2)





Loss tangent δ describes the loss in capacitor.

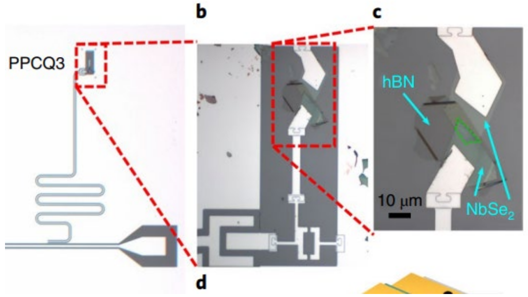
$$Q_i = 1/\tan\delta$$

$Q_i \sim 5 \times 10^6$ in a single photon limit.

↓

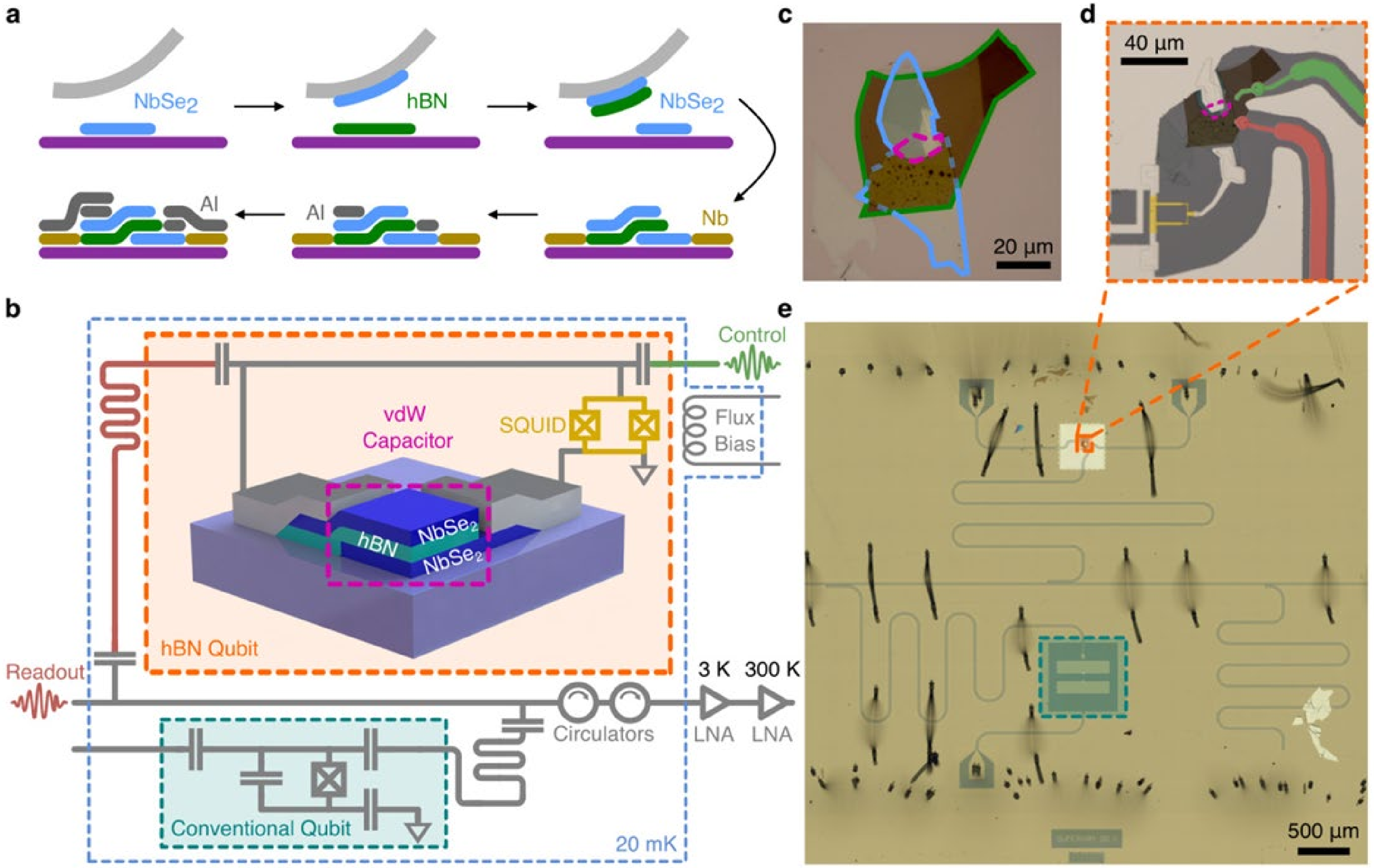
- Energy relaxation time $T_1 \sim 25\ \mu s$
- Dephasing time $T_2^* \sim 25\ \mu s$

Reducing footprint of transmon qubit



Hexagonal boron nitride as a low-loss dielectric for superconducting quantum circuits and qubits
[J. I. Wang et al., Nat. Mater. 21, 398-403 (2022)]

hBN-based Capacitor for Transmon Qubit (2/2)



- Energy relaxation time $T_1 \sim 1.1\ \mu s$
- Dephasing time $T_2^* \sim 1.7\ \mu s$

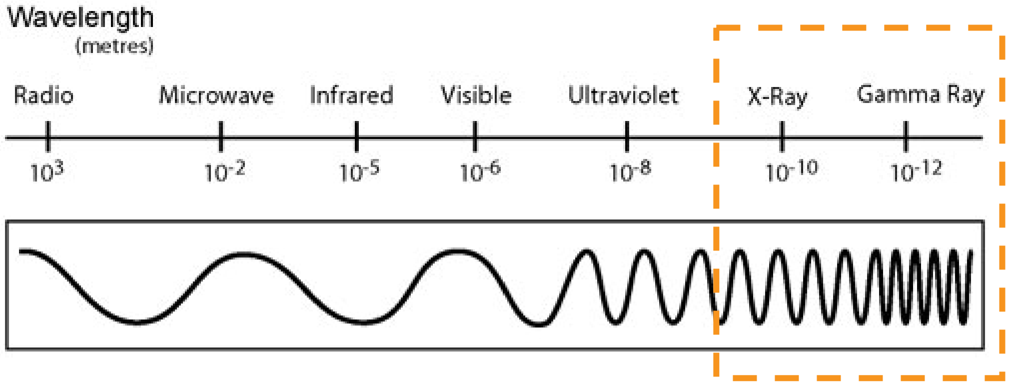
Reducing footprint of transmon qubit by 1,000 times

Miniaturizing Transmon Qubits Using van der Waals Materials
[A. Antony et al., Nano Lett. 21, 10122 (2021)]

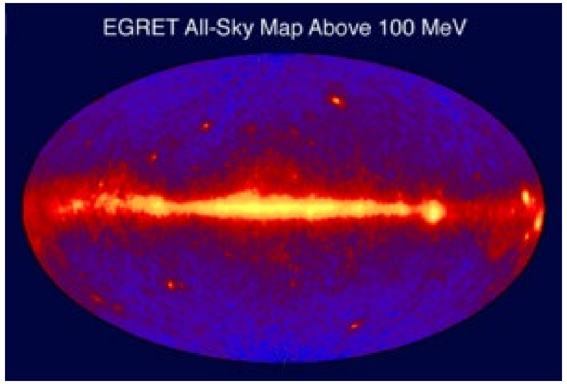
Superconducting Sensor

Ref: Superconducting photon detectors, doi.org/10.1080/00107514.2022.2043596

X/γ-Ray



Medical X-ray imaging

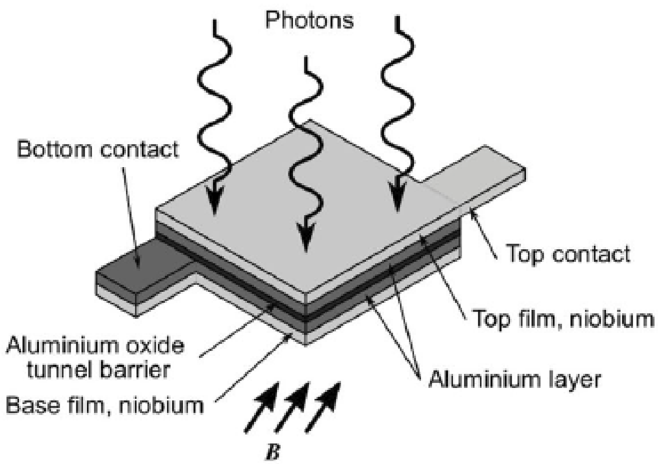


Gamma ray sky

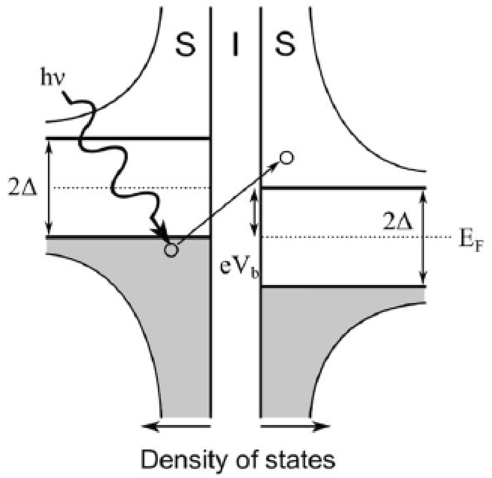
- in **X/γ-ray** range
  - Medical imaging
  - Material science
  - Astronomy science

Material Science suing synchrotrons

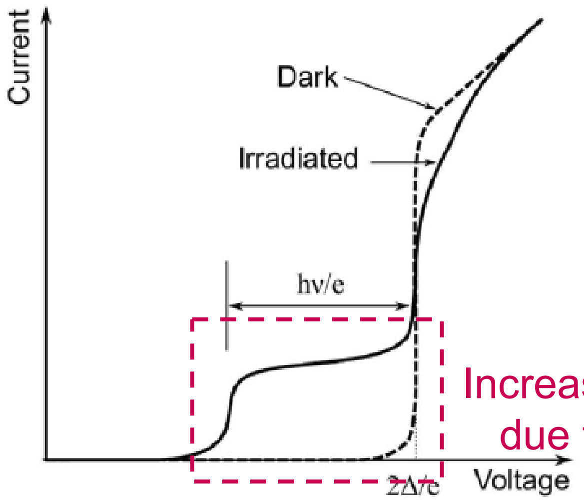
Superconducting Tunnel Junction (STJ)



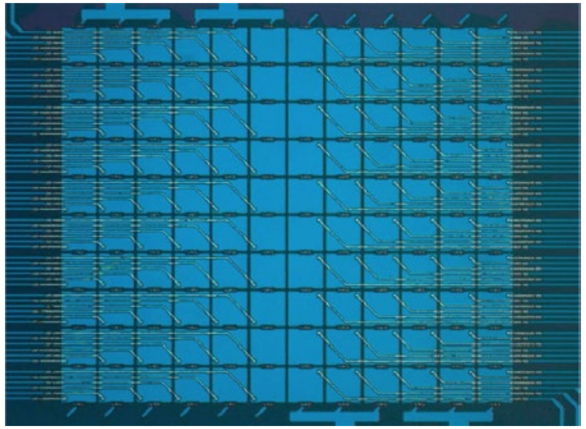
In-plane magnetic field *B* suppresses supercurrent.



2Δ: Cooper pair binding energy



Array of STJ

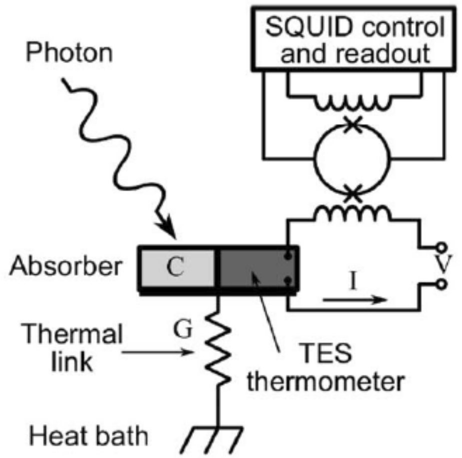


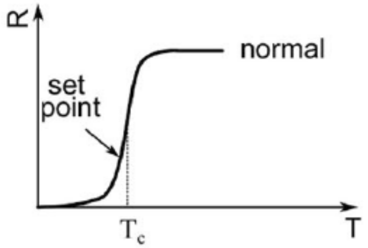
[Proc SPIE vol 6269 p. 238–248 (2006)]

[Energy resolution]
(photon energy)
$\propto$(# of created quasi-particle)
$\propto$ (resulting current pulse)

STJ covers Visible ~ UV ~ X-ray

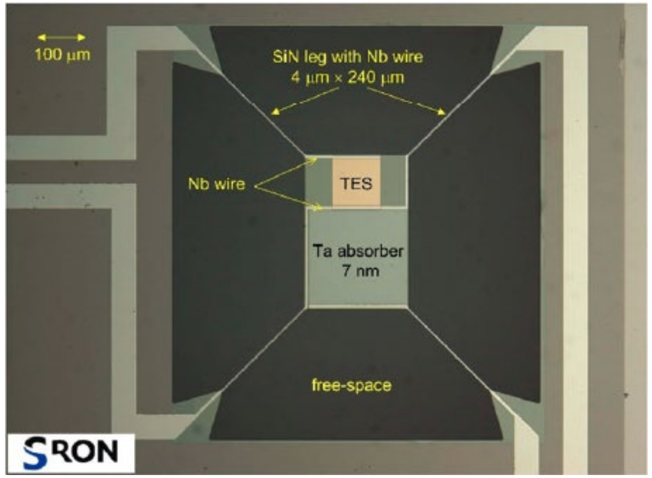
Transition Edge Sensor (TES)

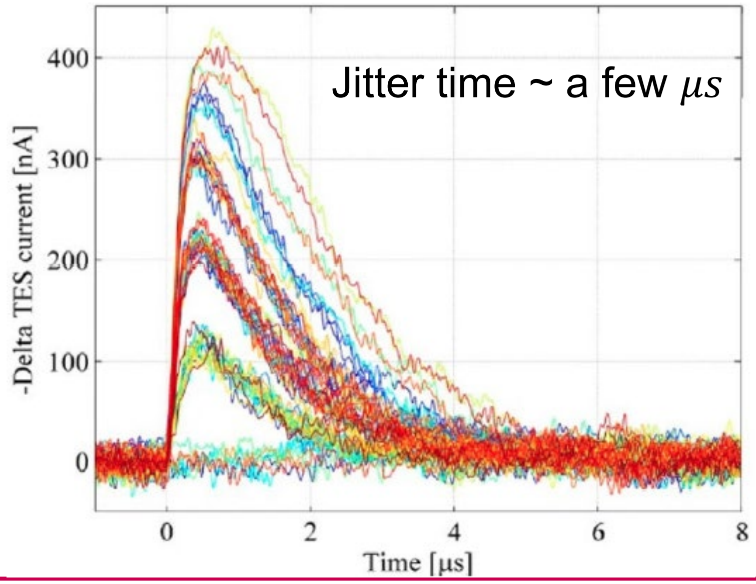


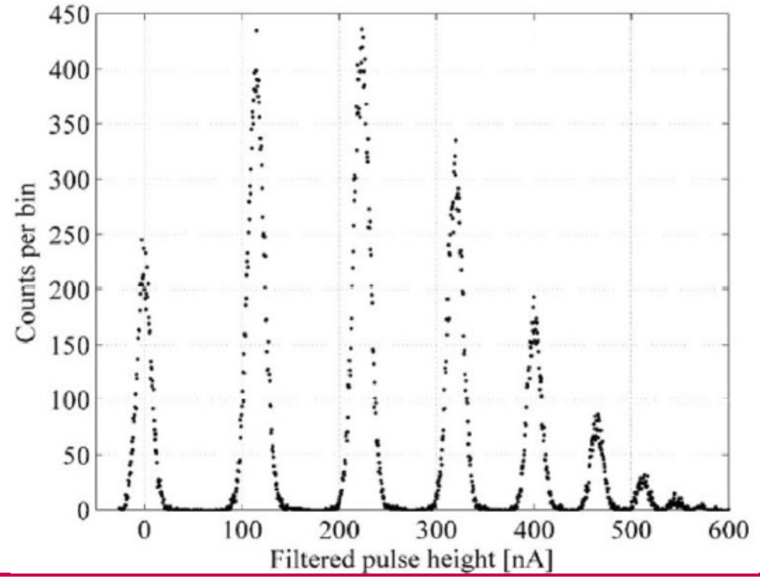


[Operation principle]

Photon is absorbed
→ Heats up SC
→ resistance changes
→ current changes
(voltage-biased)
→ Measured by SQUID





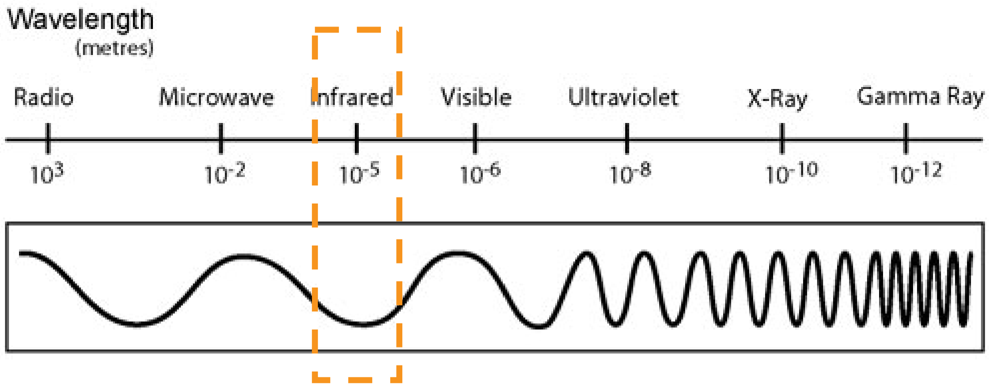


TES covers THz ~ X-ray

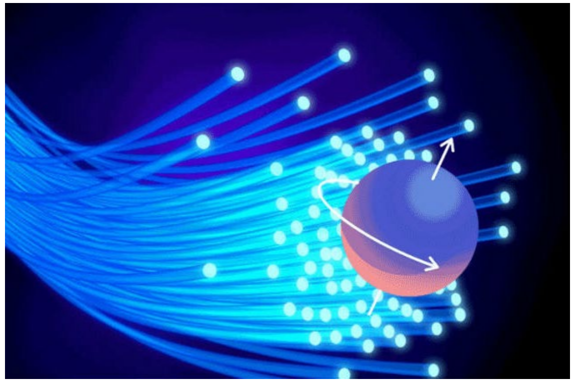
[Photon number resolving]
(Photon number)
∝ (Height of current pulse)

[Proc SPIE 7681, 71–80 (2010)]
[IEEE Trans. Appl. Supercond. 21, 188–191 (2011)]

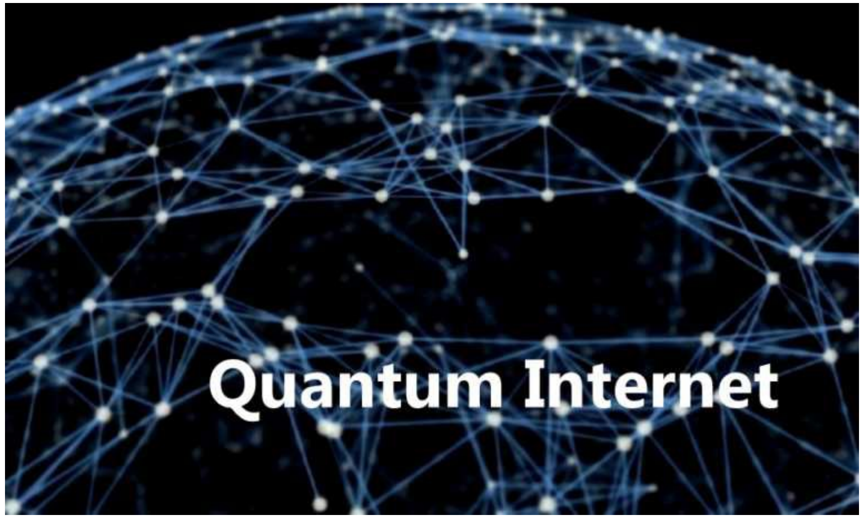
Infra-red



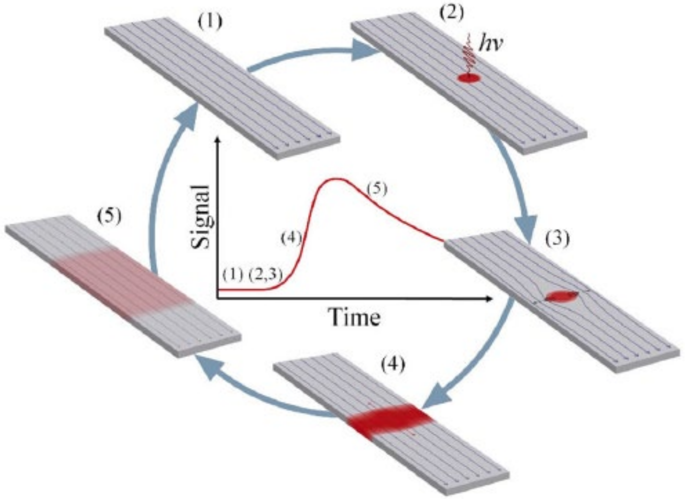

Infrared camera


Optical cable

- in **IR** range
  - optical quantum communication
  - quantum key distribution



Superconducting Nanowire Single Photon Detector (SNSPD)

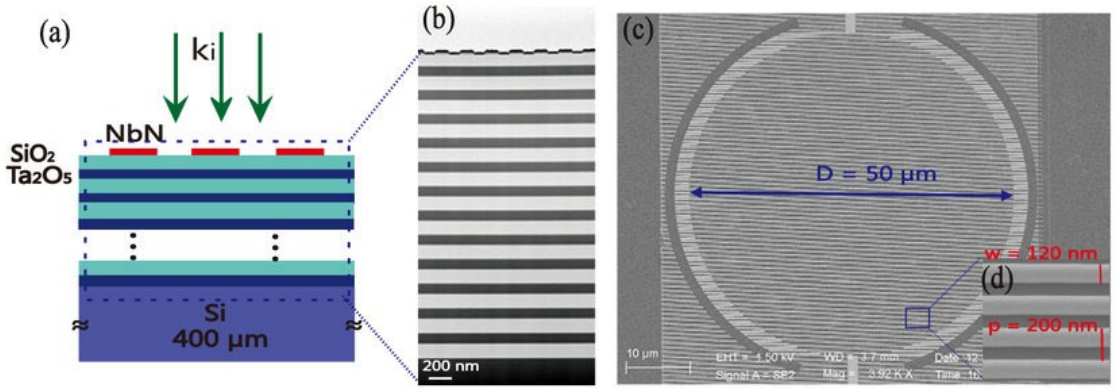


[Operation principle]

Current biased (I_b) right below I_c
→ Photon is absorbed
→ Heats up SC
→ I_b exceeds I_c
→ Generates voltage pulse

Jitter time ~ a few ps

SNSPD embedded in optical cavity



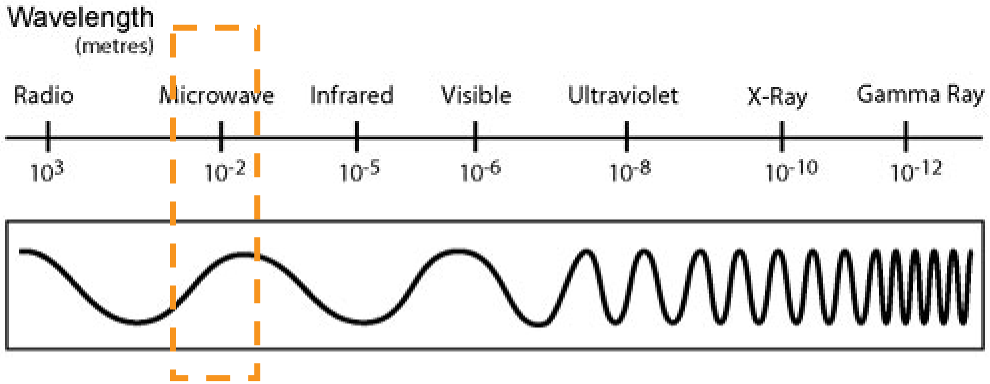
[Opt. Exp. 23, 17301-17308 (2015)]

- SNSPD is widely used for
  - long-distance quantum key distribution in optical fiber
  - quantum networks with remotely entangled qubits
  - receivers for space-to-ground classical communications
  - NASA Deep Space Optical Communications (DSOC) mission
  - scalable platform for optical quantum computing
  - optical neuromorphic computing
  - low mass/energy Dark Matter searches

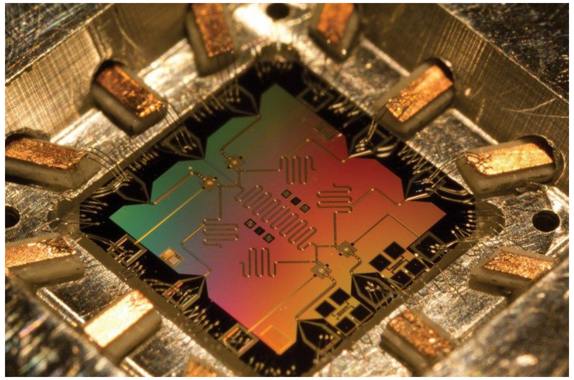
- Various SCs are used depending on purpose.
  e.g.) NbN, NbTiN, TaN, MoN, WSi, MoSi, MgB_2, YBCO, BSCCO, $NbSe_2$, etc.

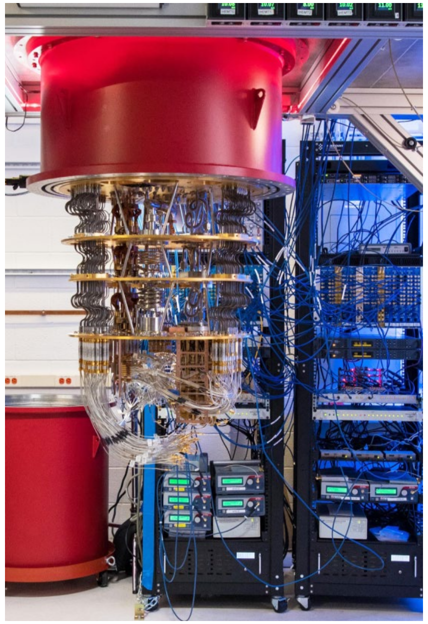
POSTECH

Microwave



- in **GHz** range
  - remote entanglement of superconducting qubits
  - high-fidelity quantum measurements
  - microwave quantum illumination

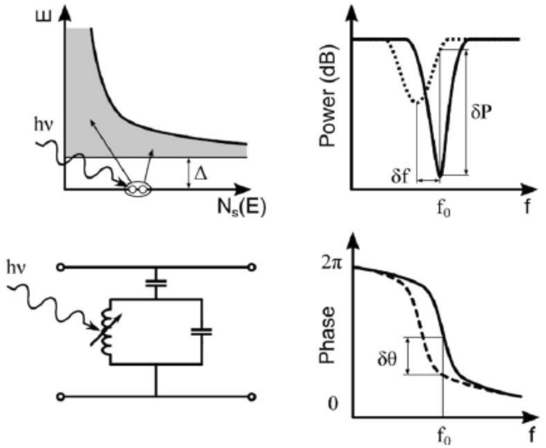




Microwave Kinetic Inductance Detector (MKID)

Kinetic inductance is due to inertial mass of charge carrier in AC electric field.

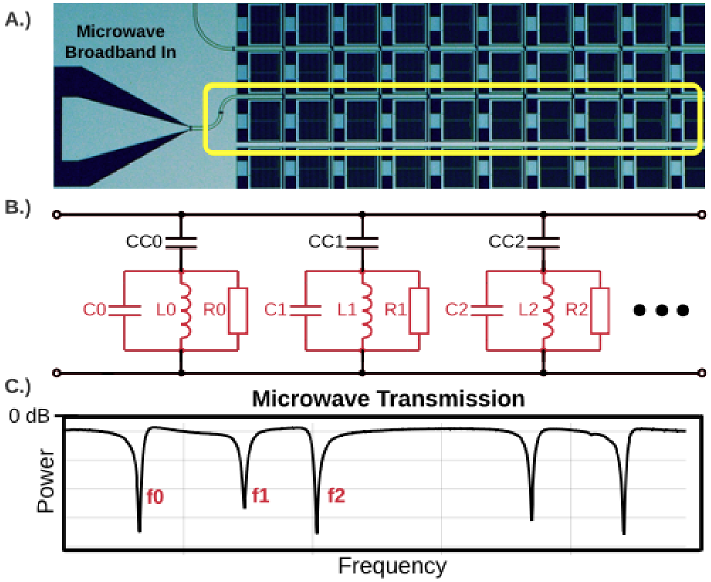
$$F = m \times (dv/dt) \quad \Leftrightarrow \quad V = L_K \times (dI/dt) \qquad L_K = \frac{m_e}{2n_s e^2}\frac{l}{A}$$



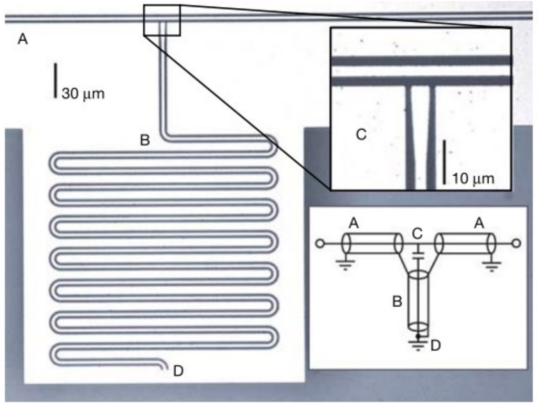
[Operation principle]

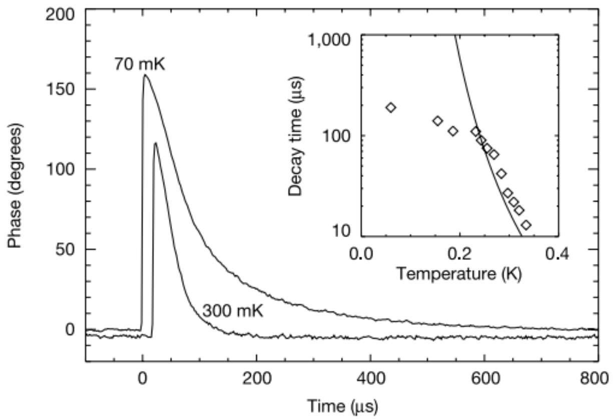
Photon is absorbed
→ L_K changes
→ Resonance frequency changes
→ Detect via transmitted microwave

Multiplexing for imaging



[arXiv:2203.16520v1 (2022)]

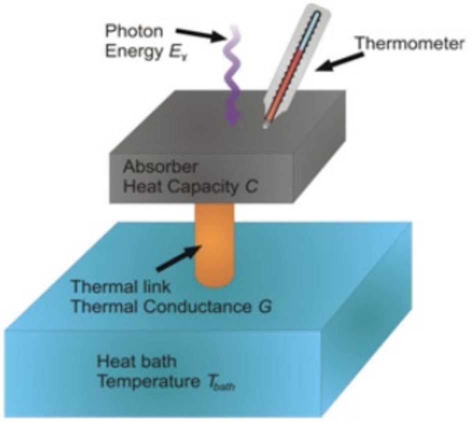


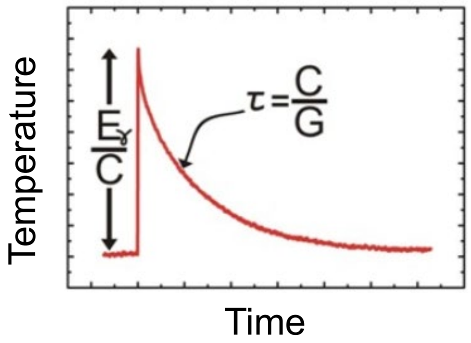


[Nature 425, 817–821 (2003)]

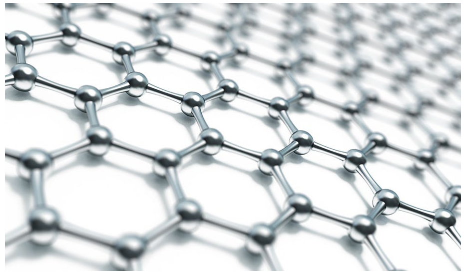
Graphene-based Josephson Junction Bolometer/SPD

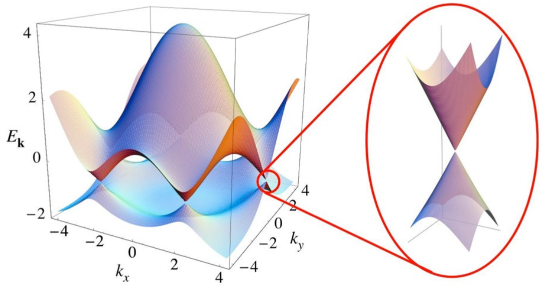
Exploit graphene's *extremely small electronic heat capacity* for detecting microwave photons

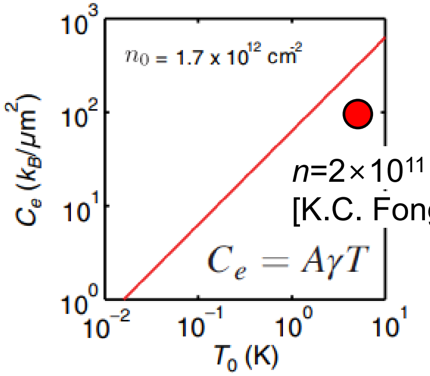




E_r: Photon energy
C : Heat capacity
G : Thermal conductance

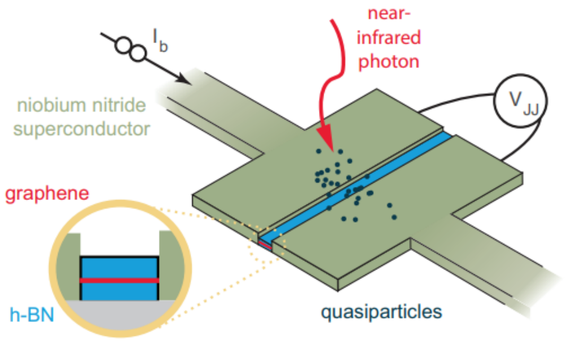






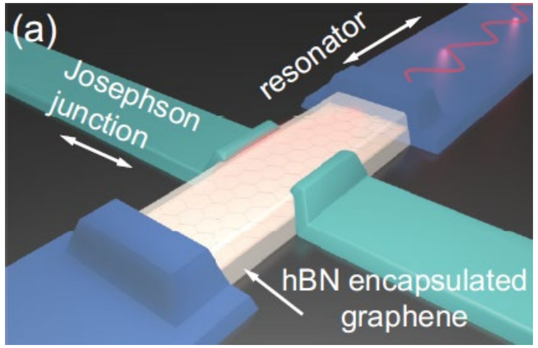
n=2×10^{11} cm^{-2}
[K.C. Fong et al., PRX (2012)]

1,550-nm IR SPD



[Science 372, 409-412 (2021)]

Fundamentally limited Microwave bolometer



[Nature 586, 42–46 (2020)]

POSTECH

Summary

To be updated