Superconducting van der Waals devices for quantum technology

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www.tifr.res.in/~nano

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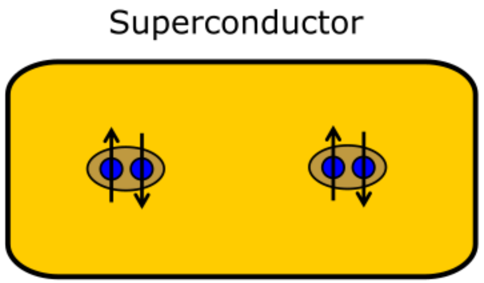
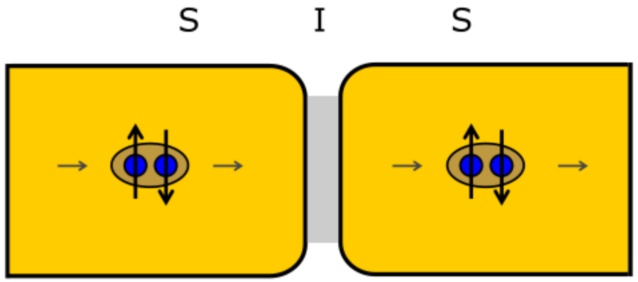
Outline

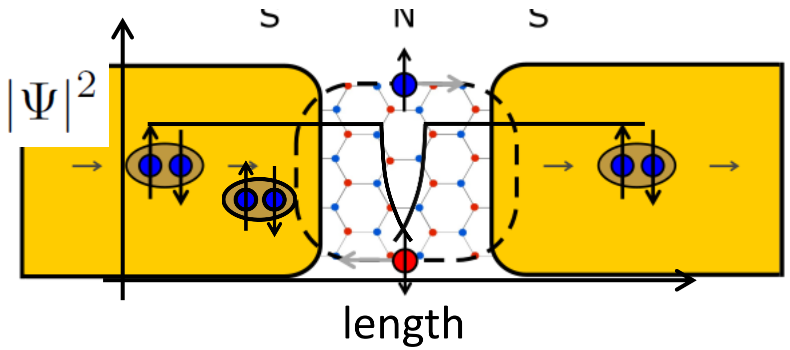
- Josephson junctions
  - Why are they interesting?
  - How are they realized?
- High temperature Josephson diode
- Quantum noise-limited RF amplifier using graphene Josephson junction
- What next?

What are Josephson junctions?





$$\Psi_{1,2} = \sqrt{n_{1,2}} e^{i\phi_{1,2}}$$



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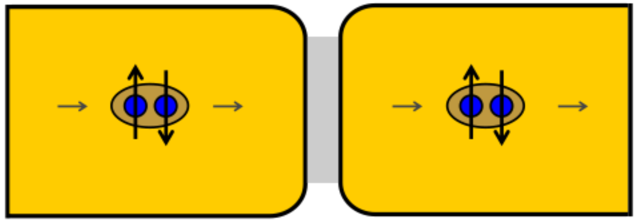


$$\Psi_{1,2} = \sqrt{n_{1,2}} e^{i\phi_{1,2}}$$

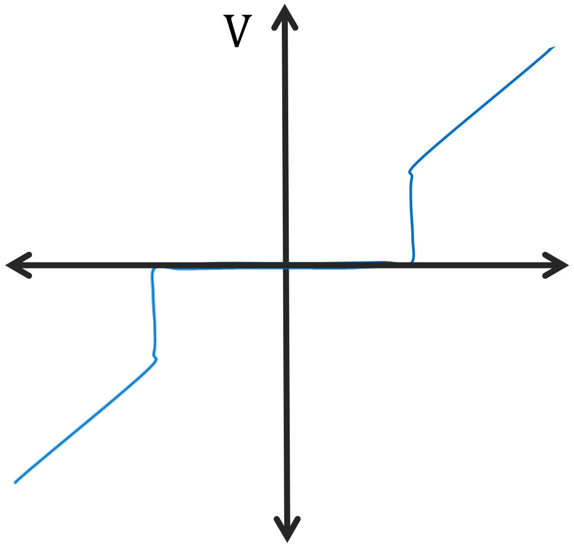
$$I = I_0 \sin(\phi)$$

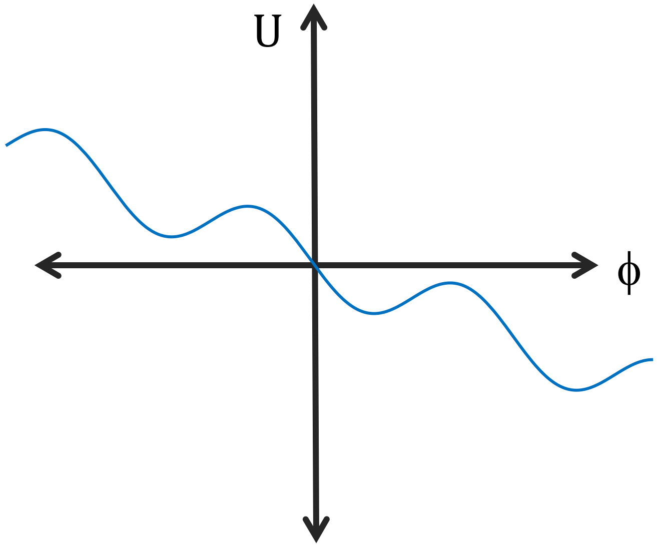
$$V = \frac{\Phi_0}{2\pi}\dot{\phi}$$

where, $\phi = \phi_2 - \phi_1$

	DC Josephson effect
δ	constant
V	zero!

	AC Josephson effect
δ	function of time
V	non-zero reactance!

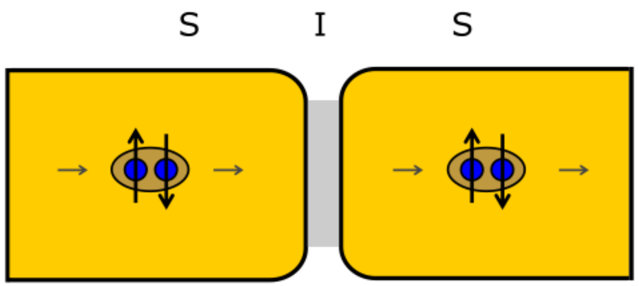


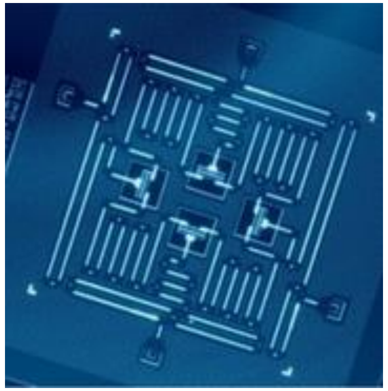


$$L = \frac{L_{J0}}{\sqrt{1-(\frac{I}{I_0})^2}}$$

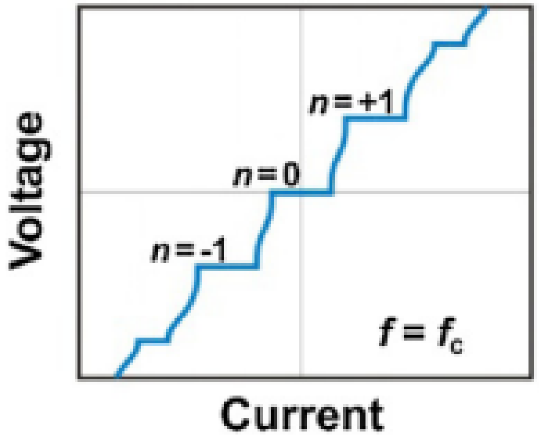
Non-linear inductor

Why Josephson junctions are interesting?

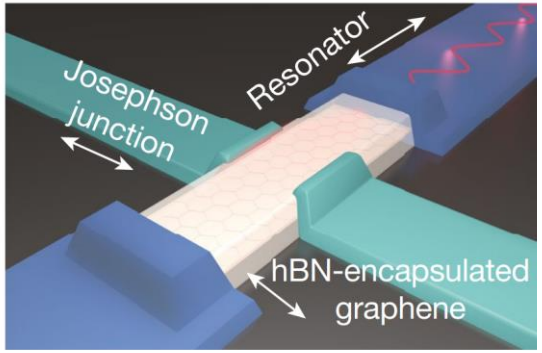




Superconducting qubits, amplifiers



Metrology – voltage standard



Quantum sensors

- Primarily fabricated using Al-AlOx-Al based tunnel barriers
- Using extensive van der Waals materials library new functionality can be added

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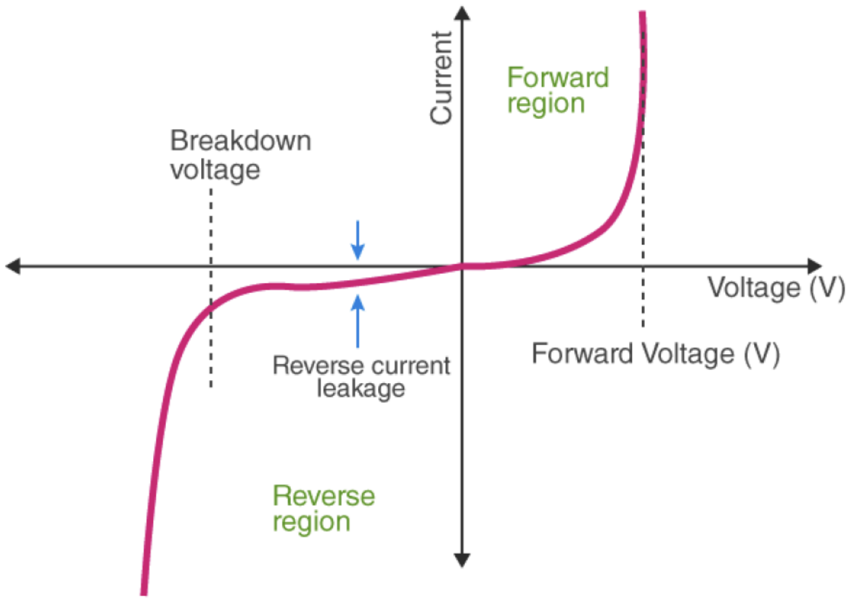
Non-reciprocal charge transport :

Semiconducting p-n junction diode

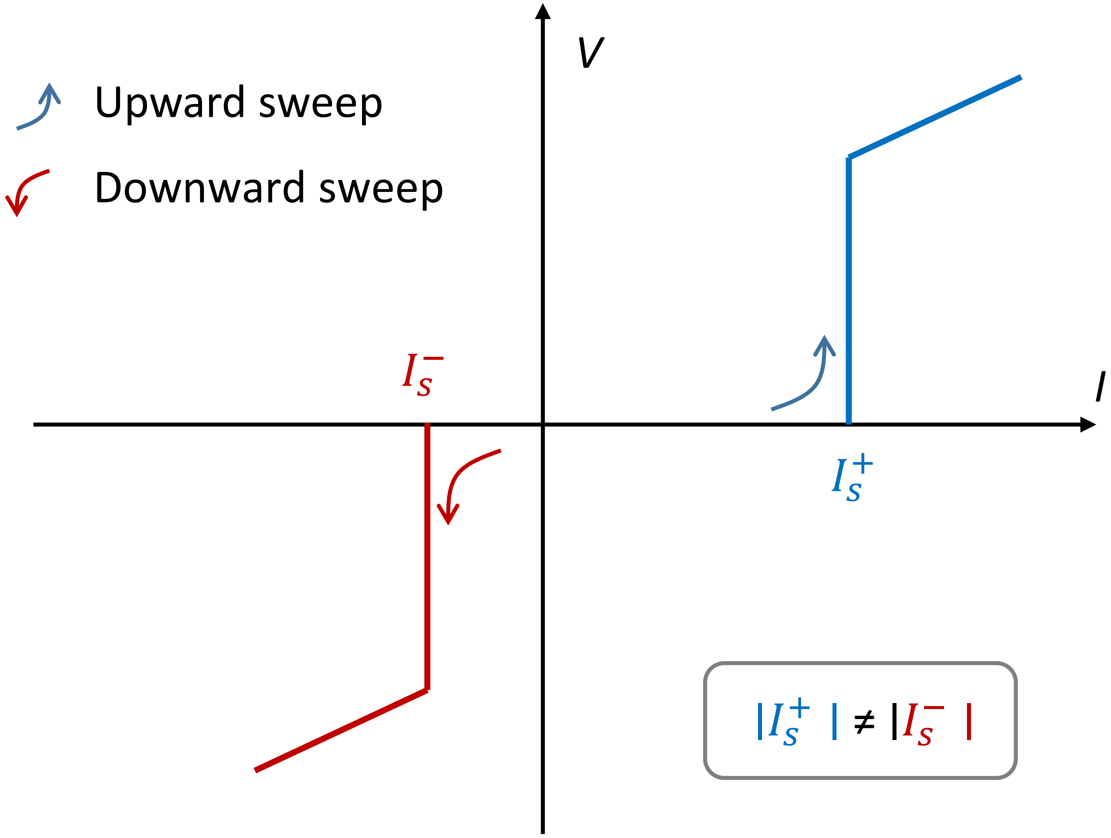


Non-reciprocal response $I\ (+V) \neq I\ (-V)$

Broken inversion symmetry due to doping

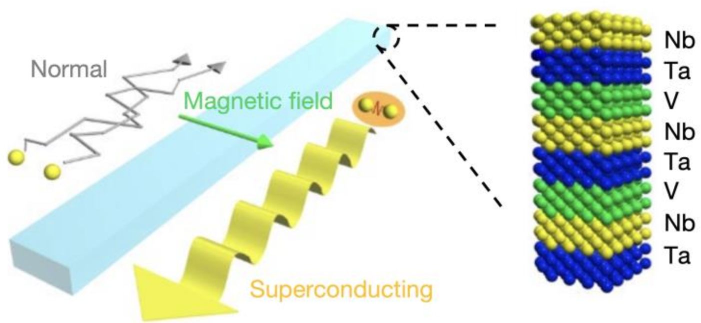
Superconducting diode

Broken inversion symmetry + Broken time-reversal



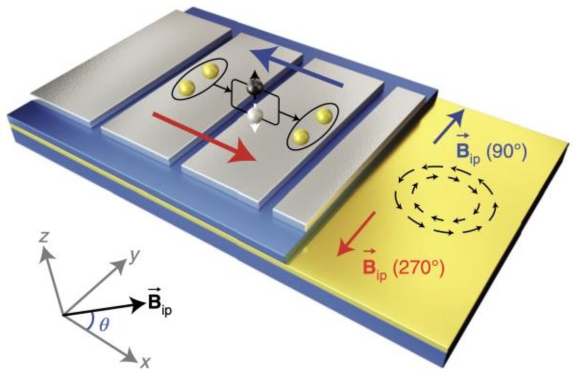
Superconducting diode effect in different systems :

Artificial superlattice



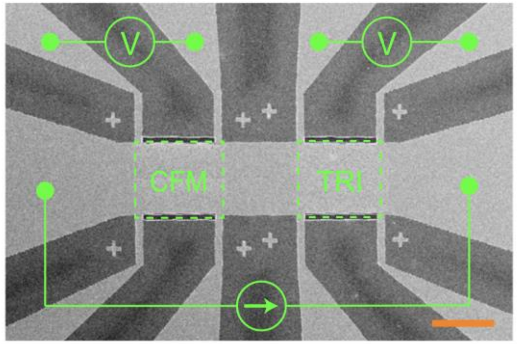
Nature 584, 373–376 (2020)

Josephson junction



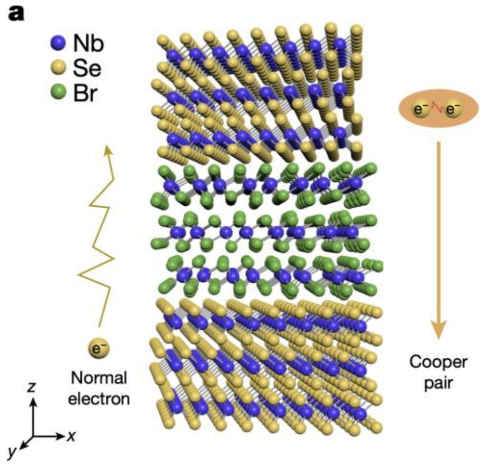
Nature Nanotechnology 17, 39–44 (2022)

Nano hole patterned superconductor



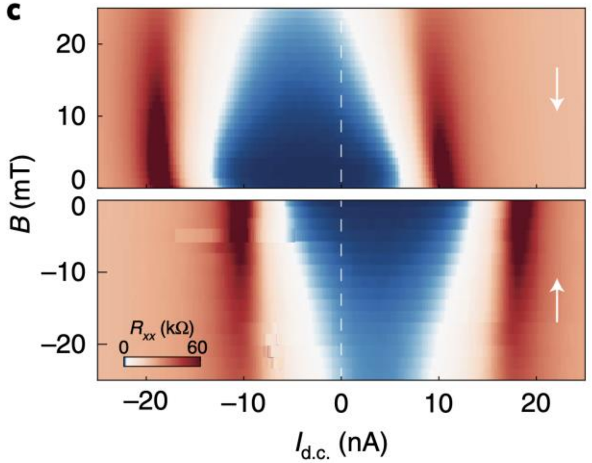
Nature Communications 12, 2703 (2021)

Magnetic tunnel junction



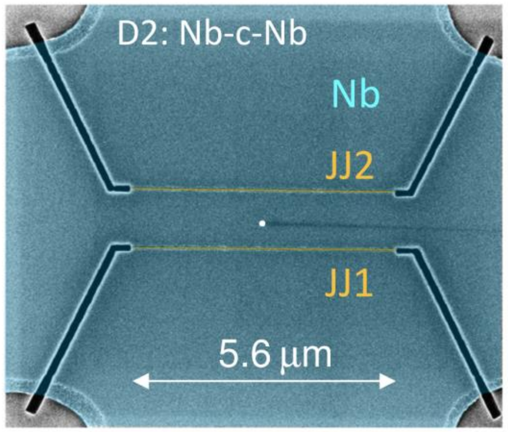
Nature 604, 653–656 (2022)

Twisted trilayer graphene



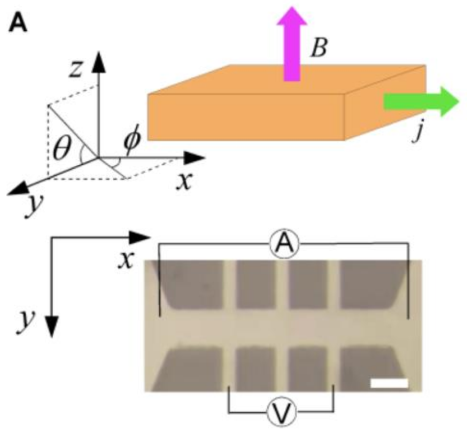
Nature Physics 1–7 (2022)

JJ with non-uniform bias



Nature Communications 13, 3658 (2022)

Superconducting thin film



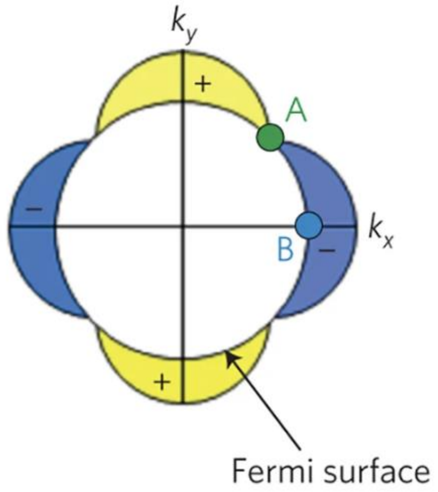
Phys. Rev. Lett. 131, 027001 (2023)

All are at temperatures ∽ 4 K or less

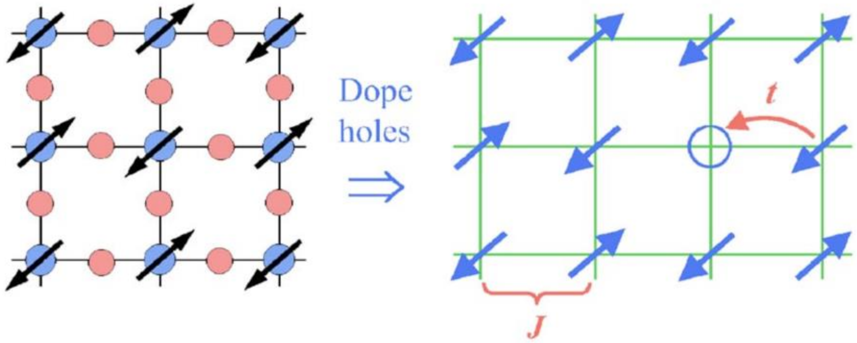
We demonstrate the Josephson diode effect in twisted BSCCO above 77 K and record asymmetry

Superconductivity in cuprates $Bi_2Sr_2CaCu_2O_{8+\delta}$ (BSCCO) :

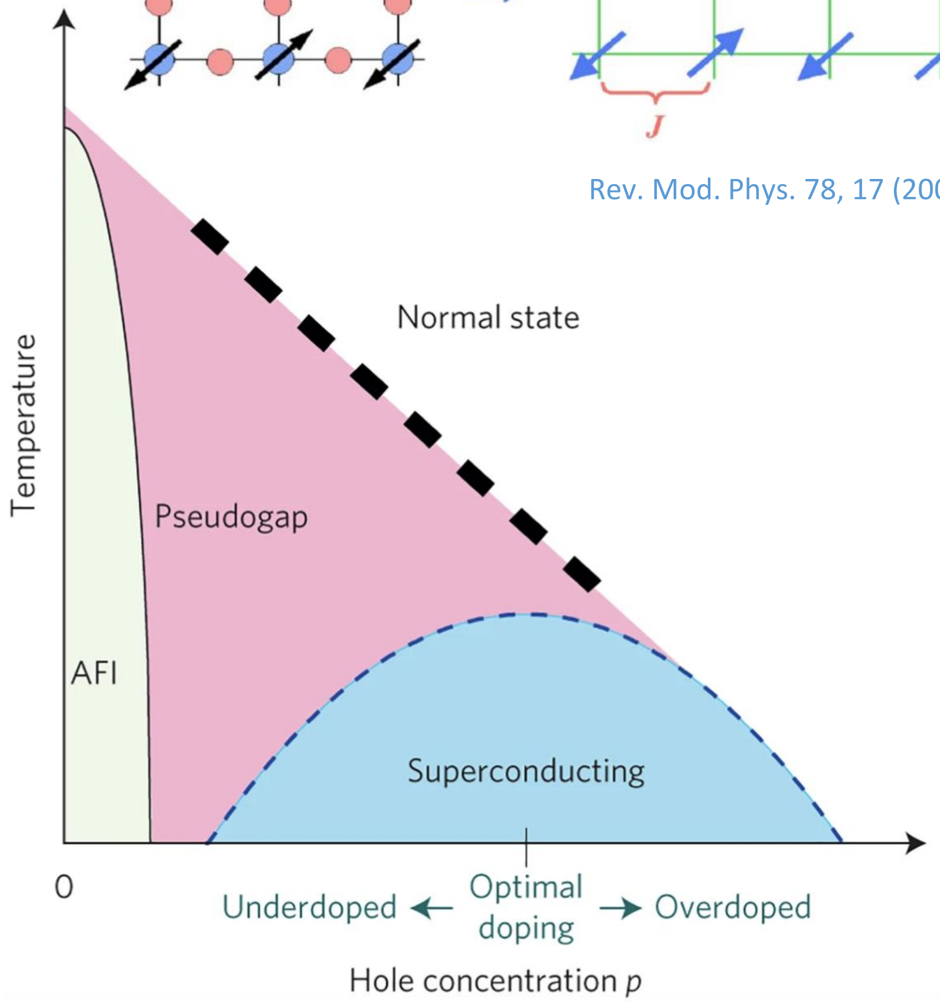
- Layered van der Waals material
- General formula $Bi_2Sr_2Ca_{n-1}Cu_nO_{2n+4+\delta}$
- Superconducting gap ~ 40 meV, ξ ~ 2 nm
- Δ has d-wave symmetry



$$\Delta = \Delta(\mathrm{k})\, e^{i\varphi(k)}$$

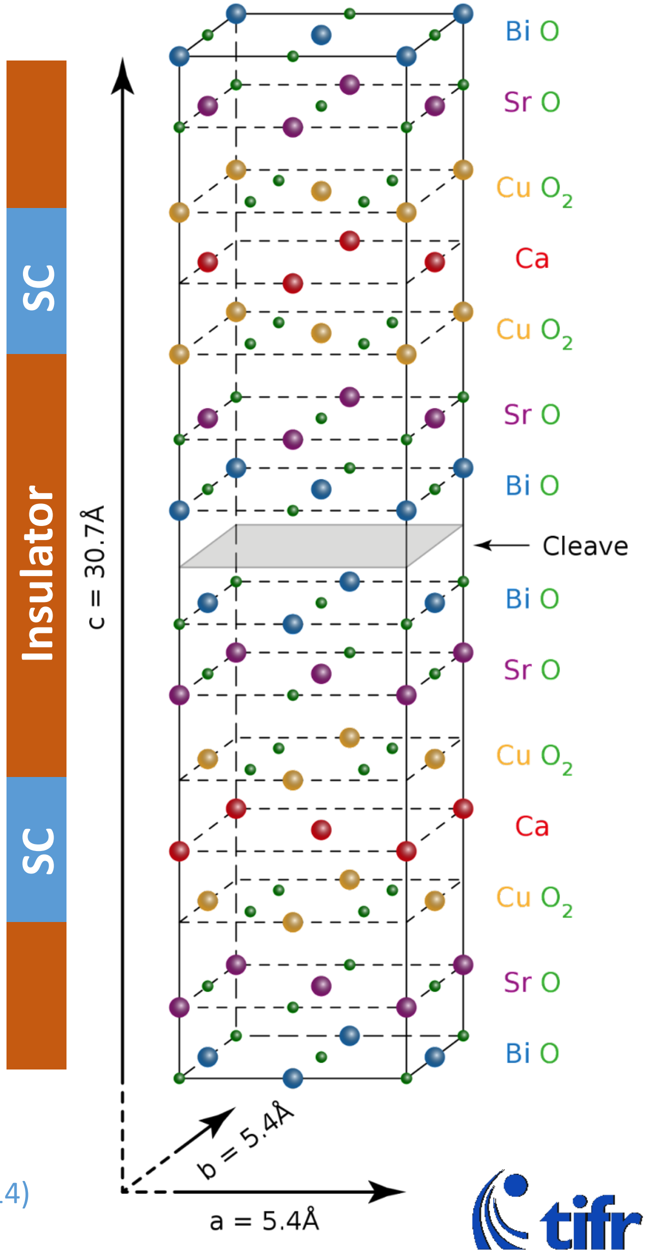


Rev. Mod. Phys. 78, 17 (2006)

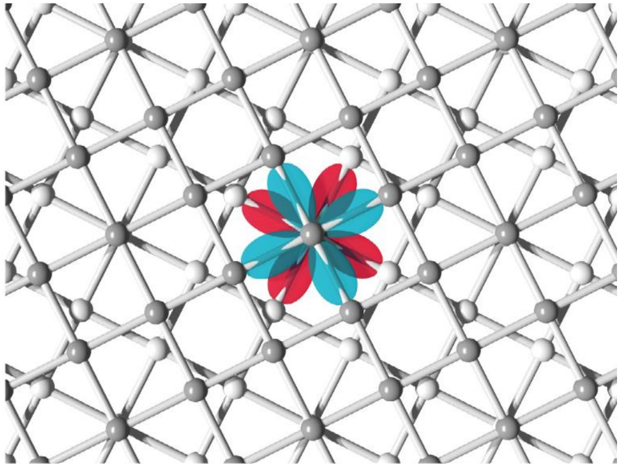


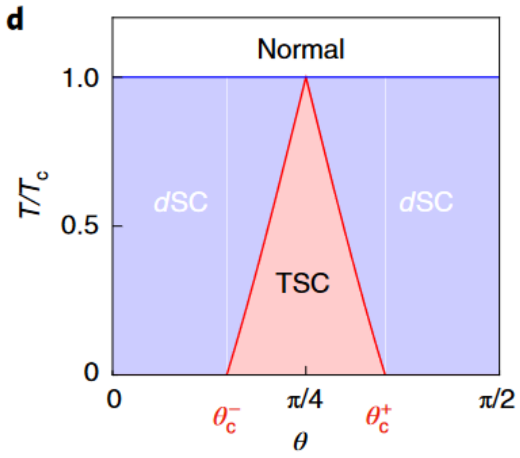
Nat. Phys. 10, 483-495 (2014)

Highly anisotropic



Exciting possibilities with twistronics and BSCCO

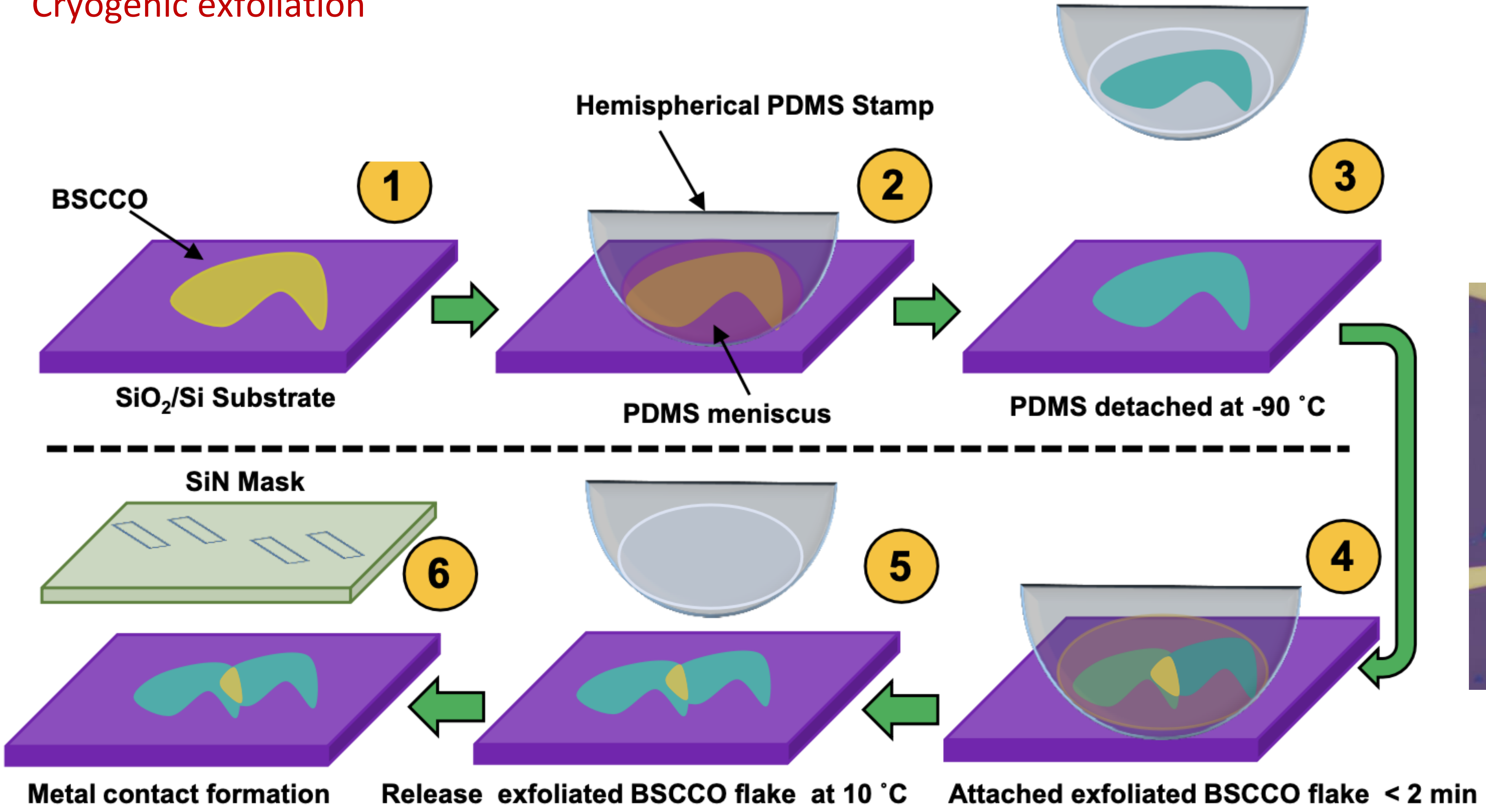


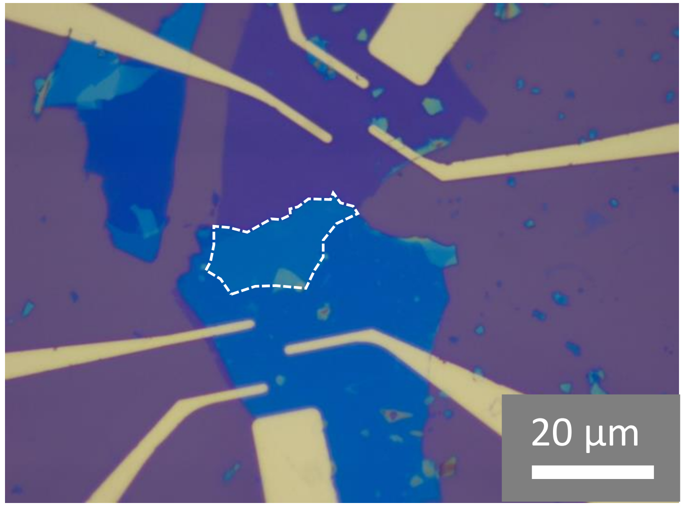


Can and Franz et al. Nature Physics 17, 519 (2021).

Fabrication of twisted BSCCO JJ :

Cryogenic exfoliation





Following Zhao et al. Science (2023) (Kim group @Harvard) with some modification

Details for building cryogenic exfoliation setup Patil et al. Scientific Reports 14, 11097 (2024).

Non-reciprocal transport in 45 degree twisted BSCCO JJ :

Similar results from Kim group @ Harvard -- S. Y. F. Zhao et al., Science (2023)

Magnetic field tunable non-reciprocal transport in 45 degree twisted BSCCO JJ

Asymmetry = $\left(\frac{I_c^+ - |I_c^-|}{I_c^+ + |I_c^-|}\right) \times 100\ \%$

- Asymmetry tunable by a small magnetic field
- Field corresponds to few flux quanta in the AJJ

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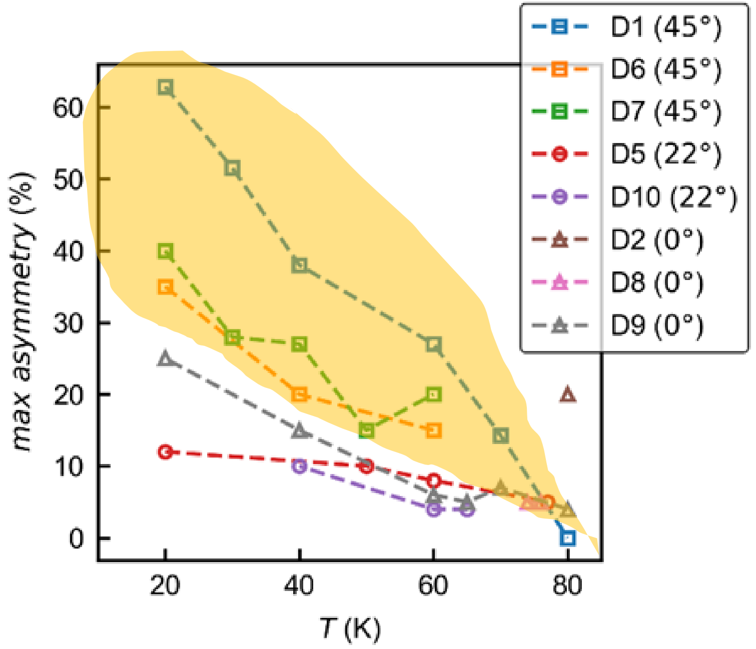
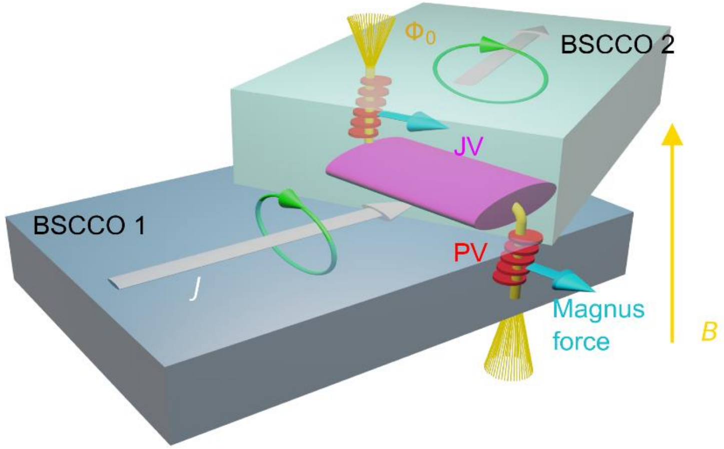
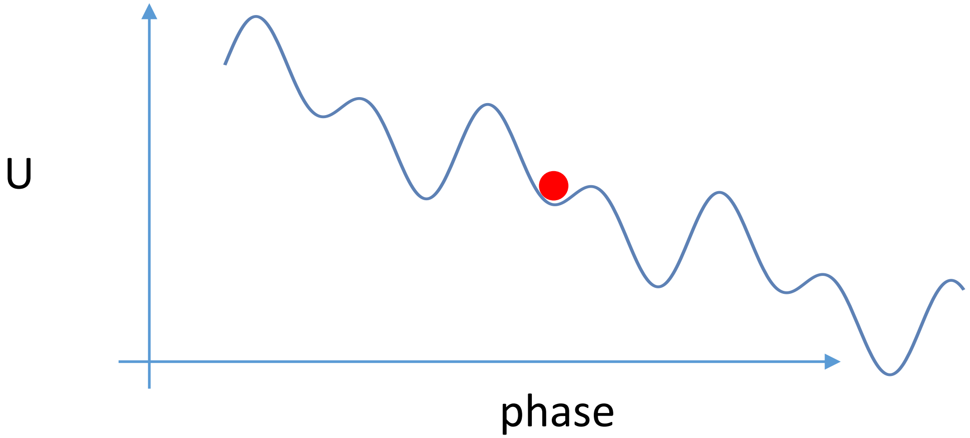
JJ Diode – asymmetry a strong function of the twist angle





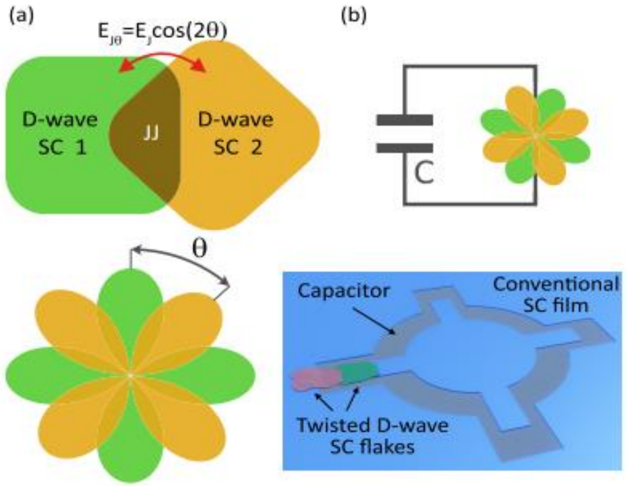
- coupling between Josephson and Abrikosov vortices



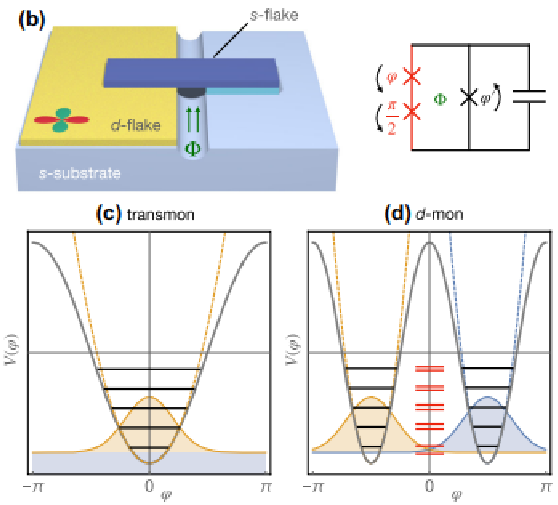
Ghosh and MMD et al. Nature Materials 23, 612 (2024)

What next?

- Twisted BSCCO SQUIDs that work at 80 K
- Engineering non-linearities in the current phase relationship to realize protected qubits



Brosco et al. Phys. Rev. Lett. 132, 017003 (2024)



Patel et al. Phys. Rev. Lett. 132, 017002 (2024)

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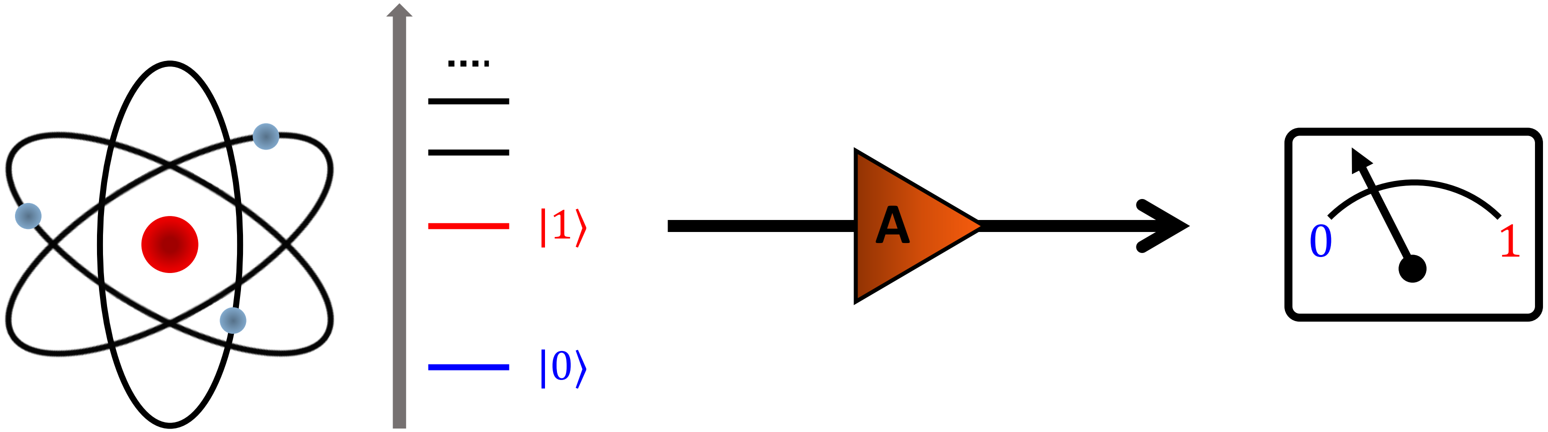
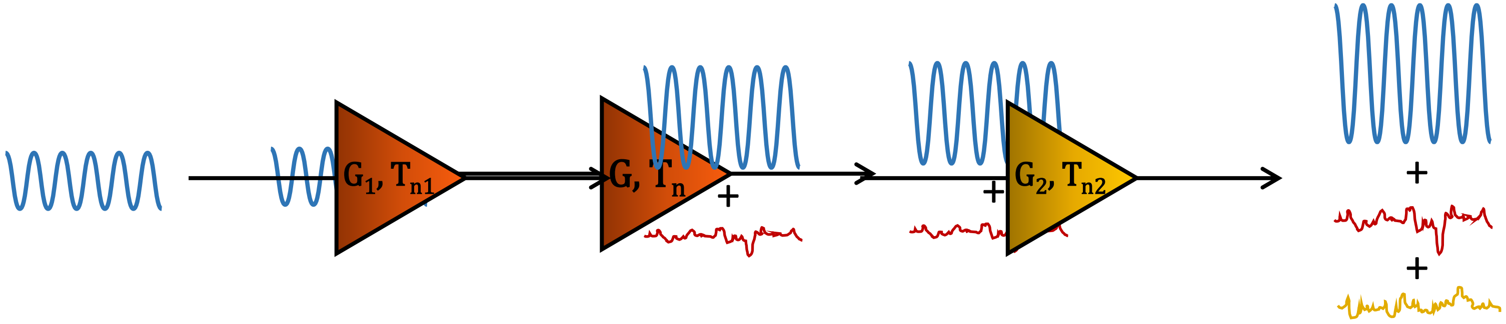
Quantum information processing: requirement of low-noise amplification



P ≈ -130 dBm ≈ 10^{-16} W
T ≈ 10 mK

P ≈ 10^{-3} W
T ≈ 300 K

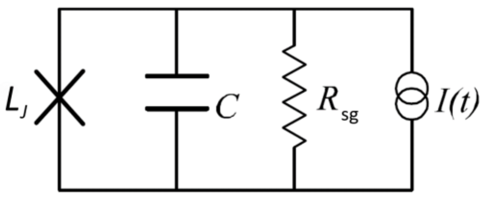


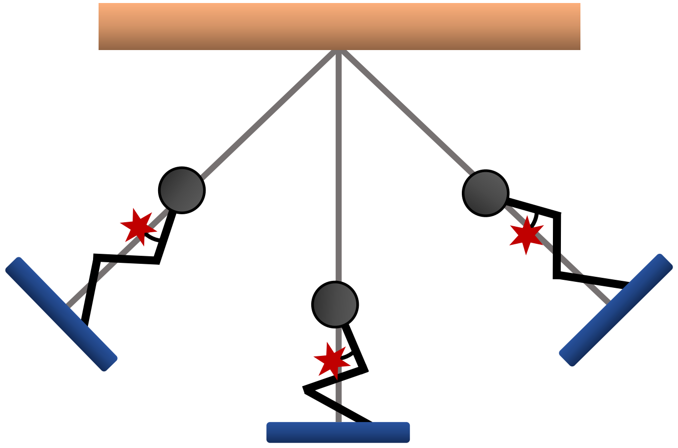
$$V_{out}(t) = \sqrt{G}V_{in}(t) + \epsilon(t)$$

$$T_{\text{sys}} = T_{n1} + \frac{T_{n2}}{G_1} + \frac{T_{n3}}{G_1 G_2} + \cdots + \frac{T_{nN}}{G_1 G_2 \cdots G_{N-1}}$$

A quick intro to parametric resonance and amplification

$$I = I_c \sin\phi + \frac{\Phi_o}{R_{sg}}\frac{d\phi}{dt} + C_{sg}\frac{dV}{dt}$$





Equation of motion of a driven non-linear oscillator

Driven damped harmonic oscillator:

$$\ddot{x} + b\omega_0\dot{x} + \omega_0^2 x = F\sin\omega_0 t$$

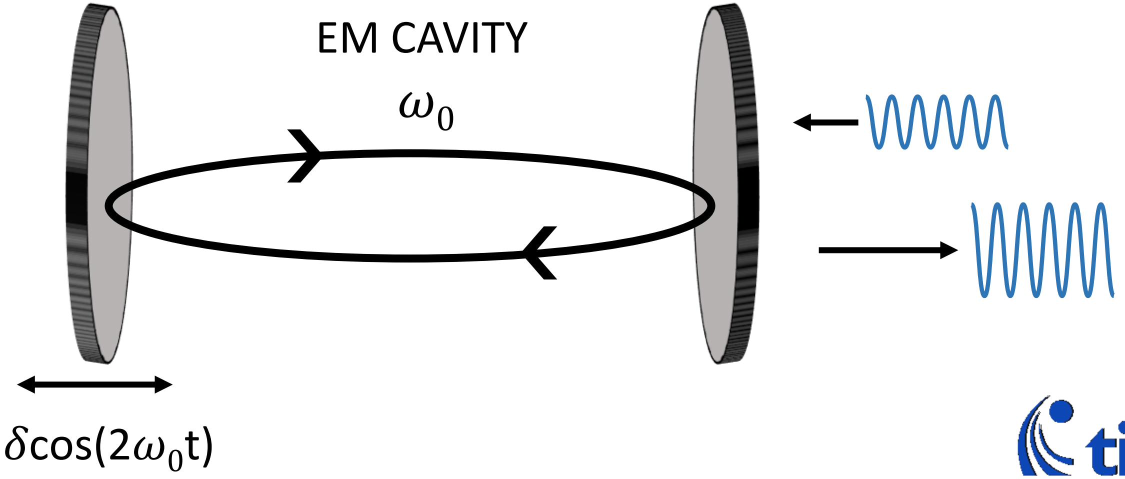
$$x_{sol} = \frac{F}{\omega_0^2 b}\sin(\omega_0 t + \phi)$$

Parametrically driven damped harmonic oscillator:

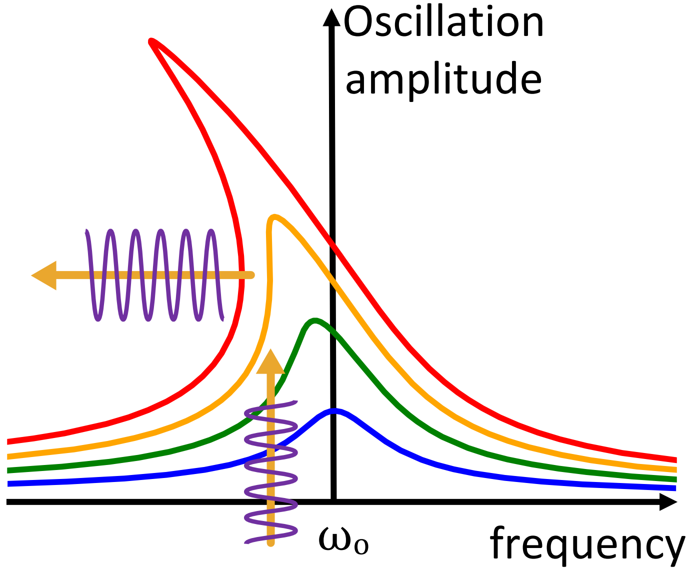
$$\ddot{x} + b\omega_0\dot{x} + \omega_0^2(1 + \delta\cos 2\omega_0 t)x = F\sin\omega_0 t$$

$$x_{sol} = \frac{F}{\omega_0^2(b - \frac{\delta}{2})}\sin(\omega_0 t + \phi)$$

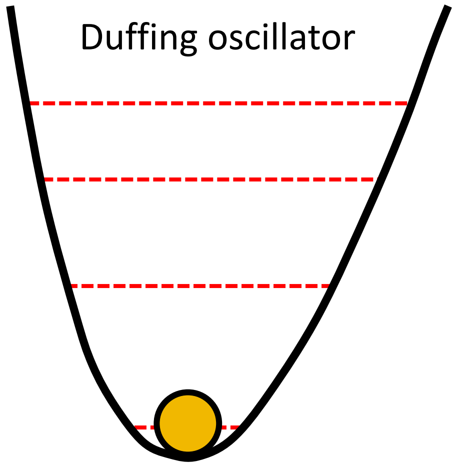
reduction in damping



Quantum noise limited amplifier



$$T_{\text{eff}} = \frac{\hbar\omega}{2k_B}$$

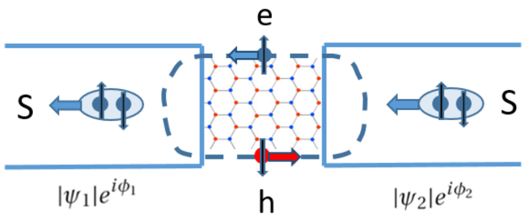


$$k_B T \ll \hbar\omega$$

~10 mK ~250 mK, @5 GHz

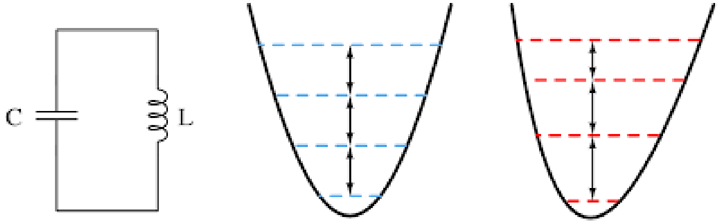
What is the need for a new kind of parametric amplifier?

- Operation in high fields
- Tunability with electrostatic gate
- Making quantum sensors exploiting 2D materials
- Candidate platform for dark matter searches



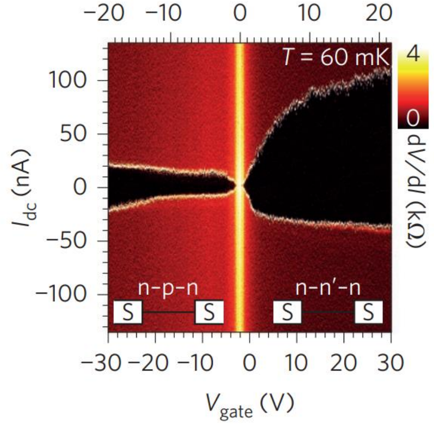
SNS JJ CPR

$$I_s(\phi) = \frac{\pi\Delta_o}{2eR_n}\frac{\sin\phi}{\sqrt{1-\tau\sin^2(\phi/2)}}$$



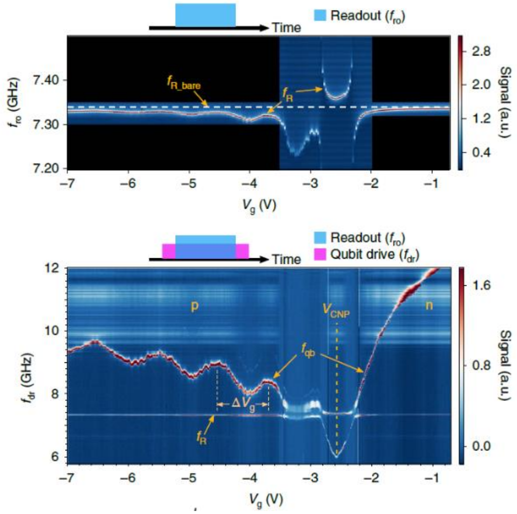
harmonic anharmonic

Gr-JJ



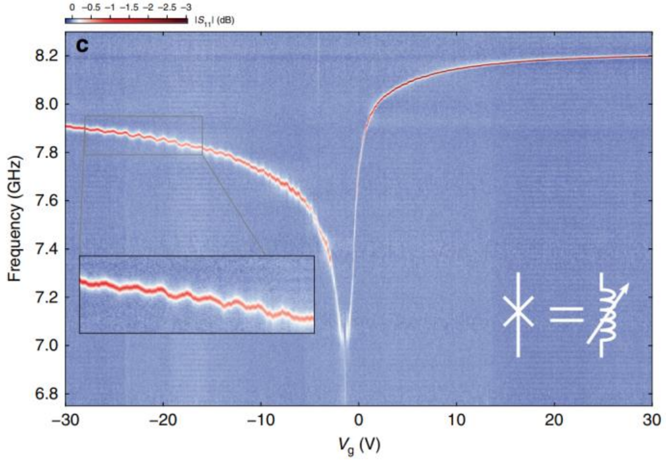
Calado et al. Nature Nanotechnology 10, 761–764 (2015)

Gr-transmon qubit



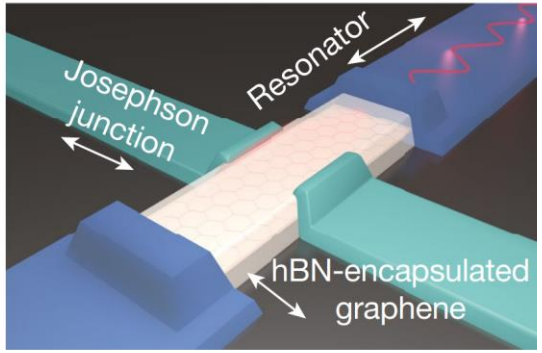
Wang et al. Nature Nanotechnology 14, 120-125 (2019)

Gr-JJ microwave resonator



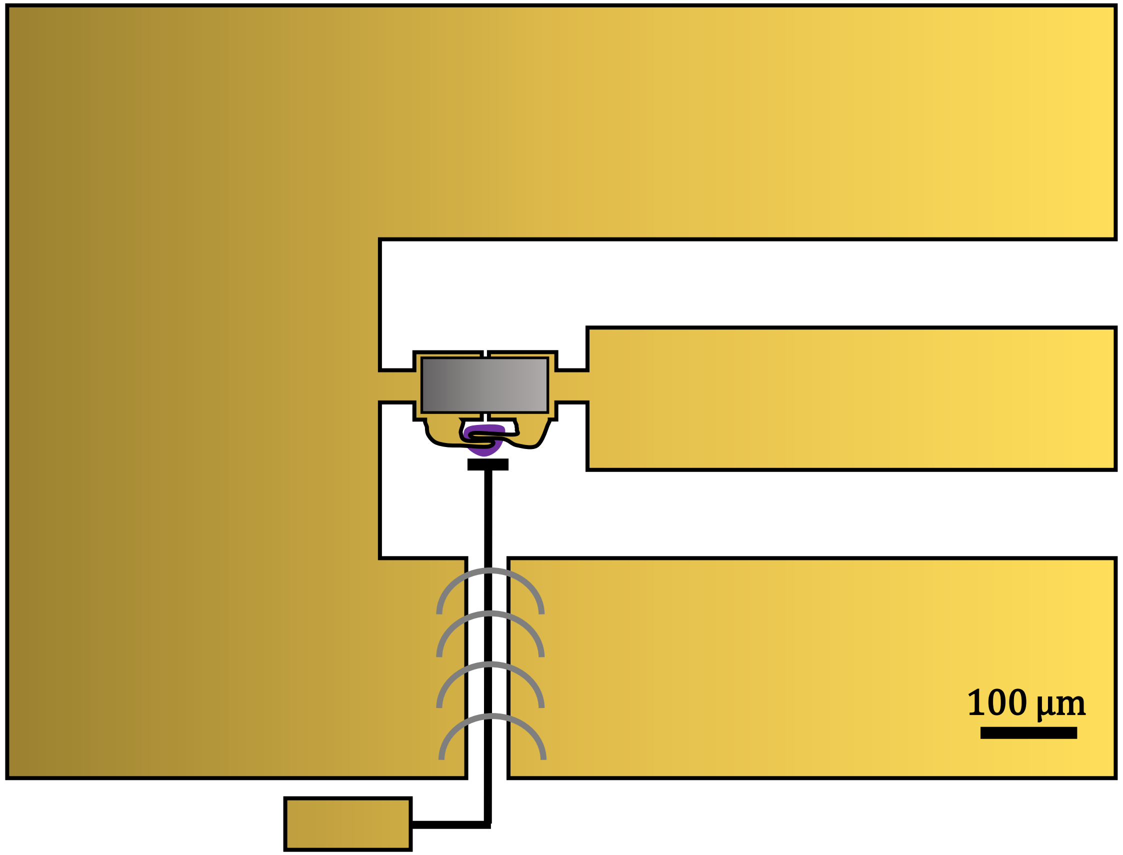
Felix et al. Nature Communications 9, 4069 (2018)

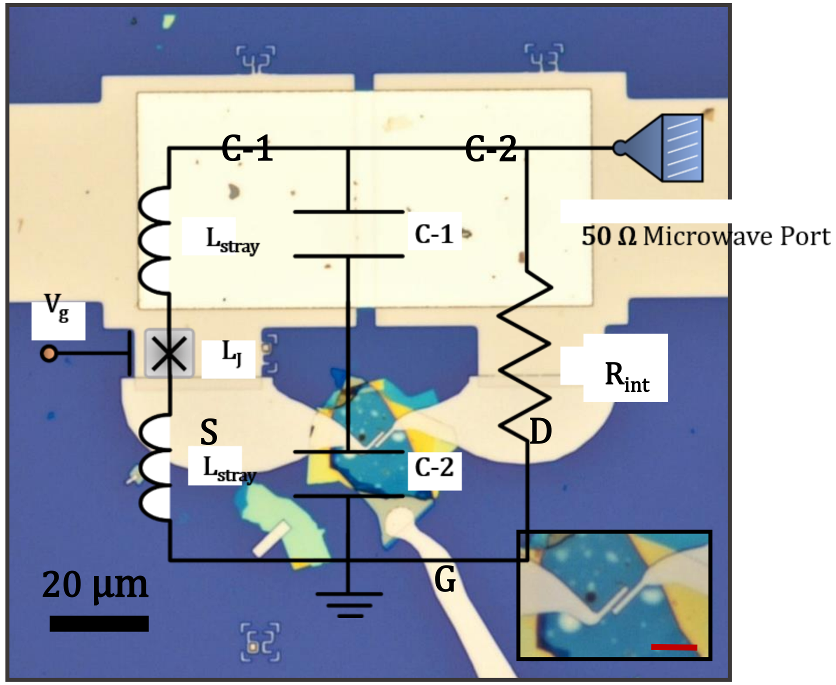
Gr-JJ bolometers

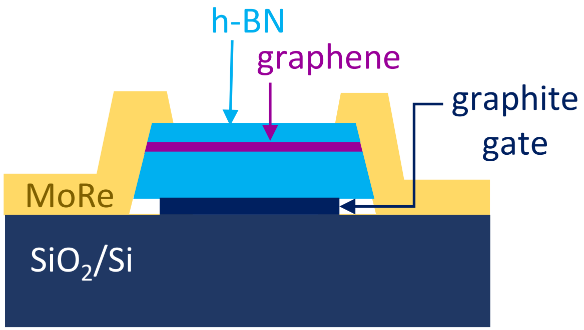


Lee et al., Nature 586, 42–46 (2020)
Kokkoniemi et al., Nature 586, 47–51 (2020)
Walsh et al., Science 372, 409–412 (2021)

Our implementation: graphene based Josephson parametric amplifier (Gr-JPA)





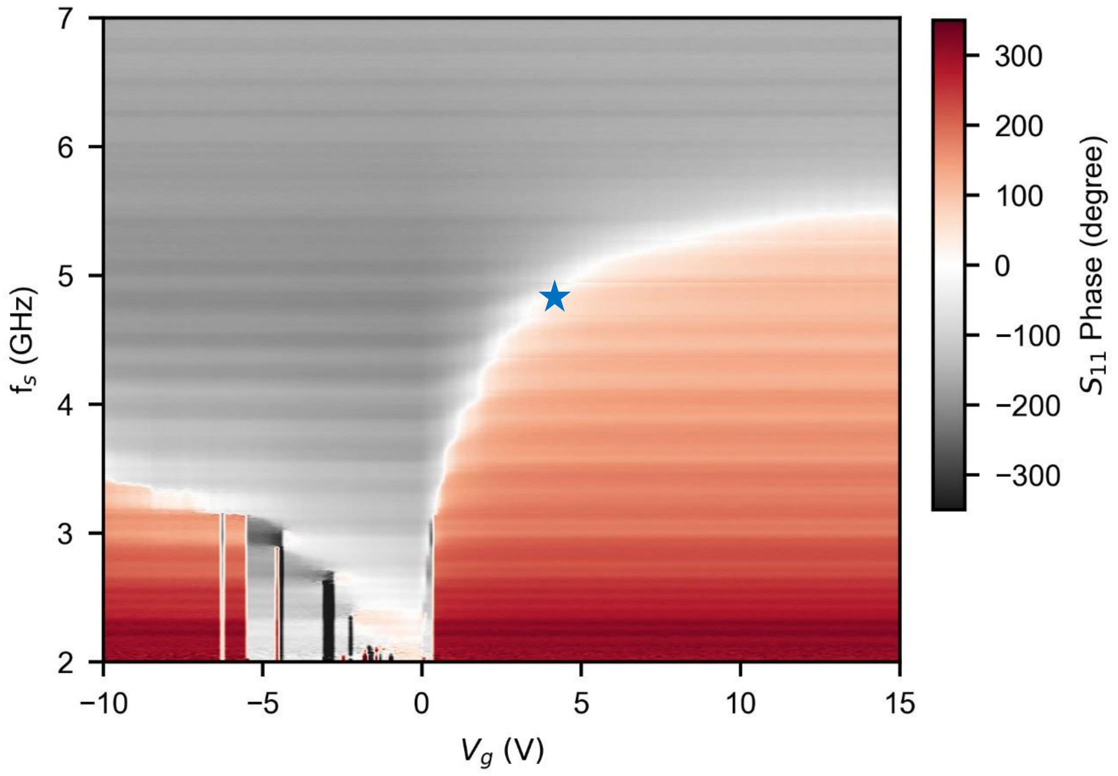


Short junctions: (L<<W)

Width(W) ~ 4 µm

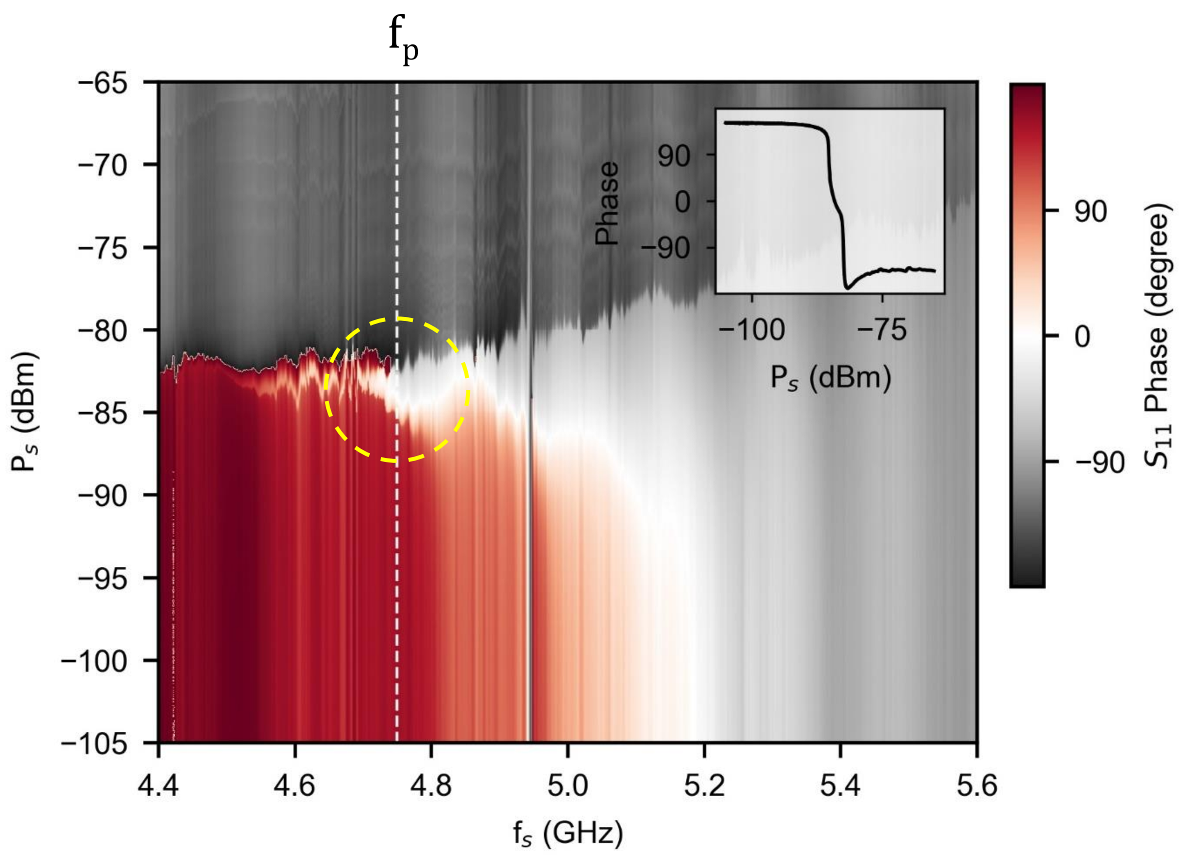
Length(L) ~ 350 nm

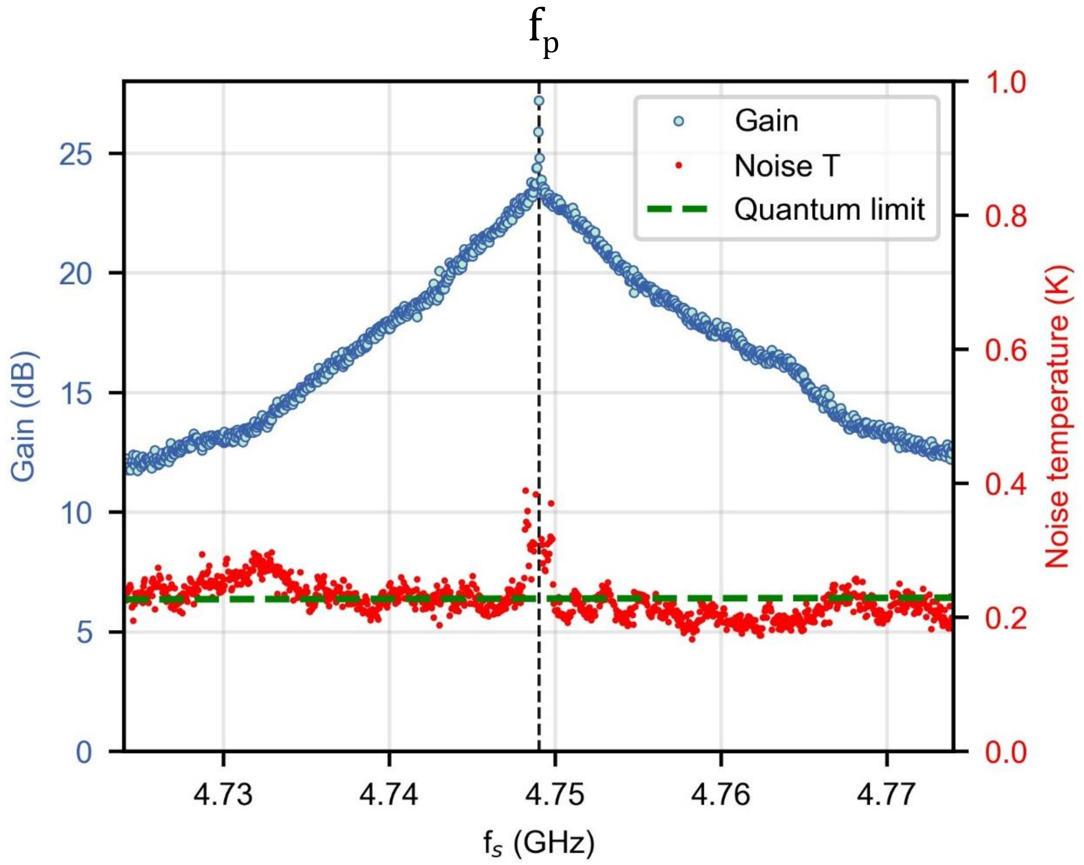
Characterization of the Gr-JPA: DC and microwave properties



- Gr-JPA has linear resonance tunability of 3.5 GHz with gating

Nonlinear response and amplification of the Gr-JPA





- First implementation of quantum noise limited amplification using graphene JJ
- 24 dB max gain, 10 MHz bandwidth, -120 dBm saturation power
- Electrostatic gating gives control on CPR and junction nonlinearity

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Our work --Sarkar et al. Nature Nanotechnology 17, 1147 (2022).
Guilliam Butseraen, et al. Nature Nanotechnology 17, 1153 (2022).

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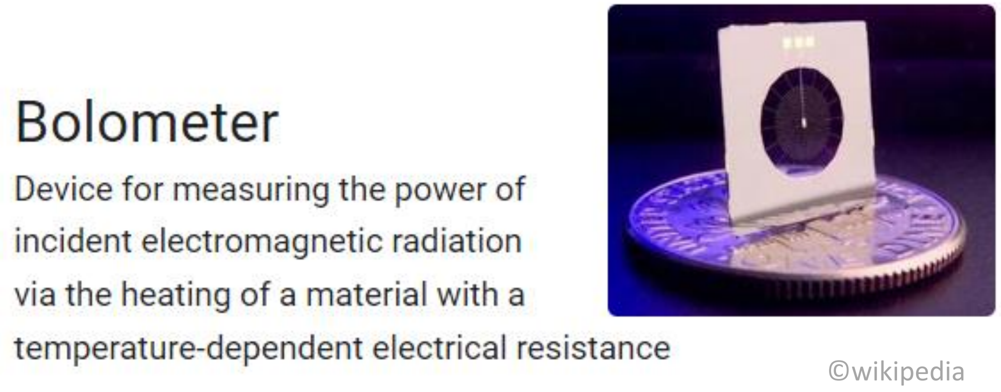
Graphene JPA as a bolometer



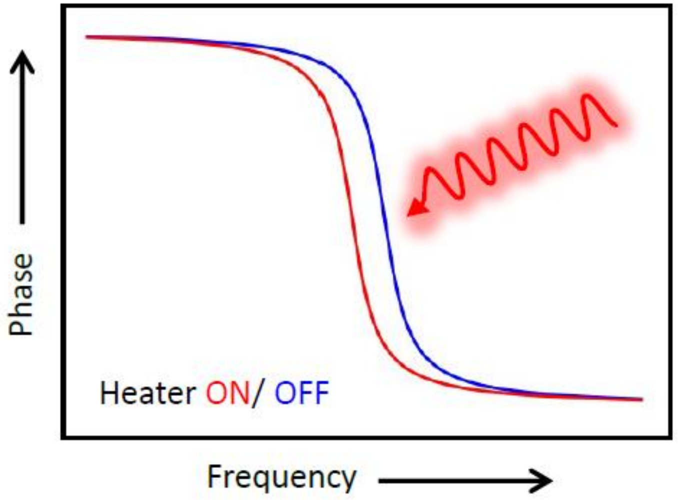
Usage:

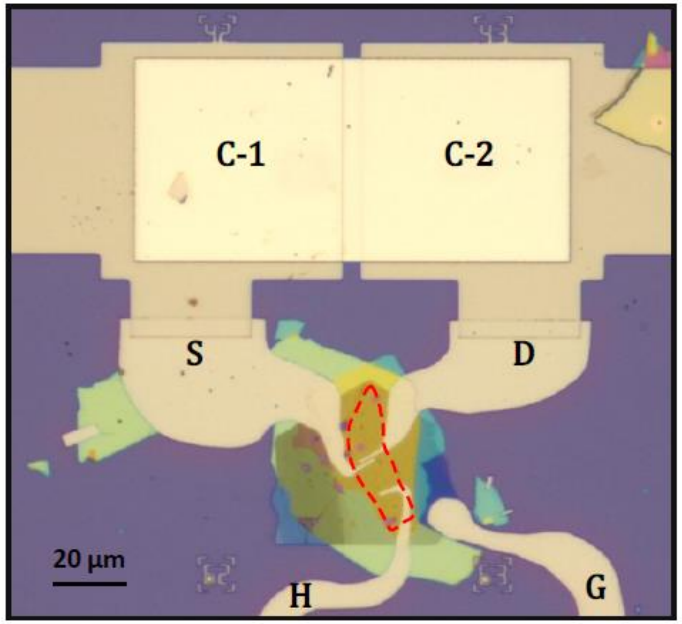
- Astronomy
- Security
- Industry

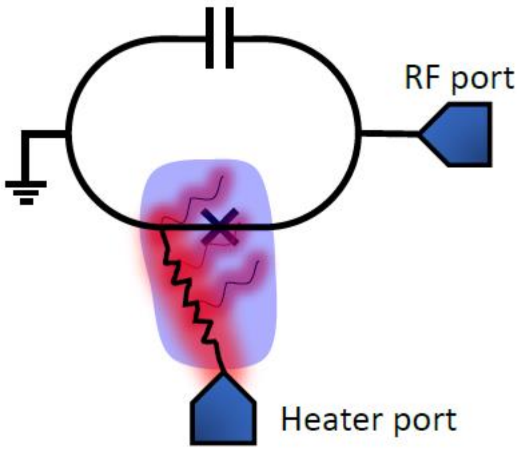
- NEP (Noise equivalent power)
- Frequency range/ Bandwidth
- Response time

Different platforms:

- TES, KID, Graphene based







Efetov et al., Nature Nano (2018)
Kokkoniemi et al., Nature (2020)
Lee et al., Nature (2020)

Walsh et al., Science (2021)
Katti at al., Nano Letters (2023)

Summary

- Josephson junction
  - Why are they interesting?
  - How are they realized?
- High temperature Josephson diode
- Quantum noise-limited RF amplifier using graphene Josephson junction

Ghosh et al. Nature Materials 23, 612 (2024)
Sarkar et al. Nature Nanotechnology 17, 1147 (2022)