A tale of two JJs – graphene parametric amplifier and high temperature Josephson diode

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

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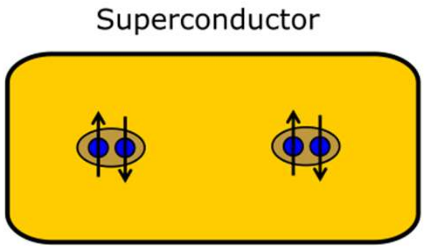
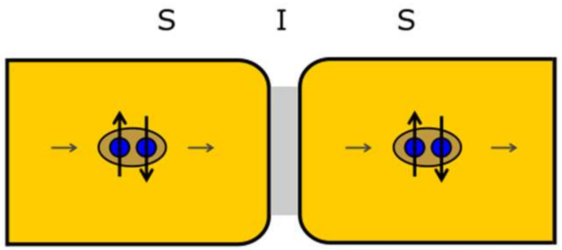
Outline

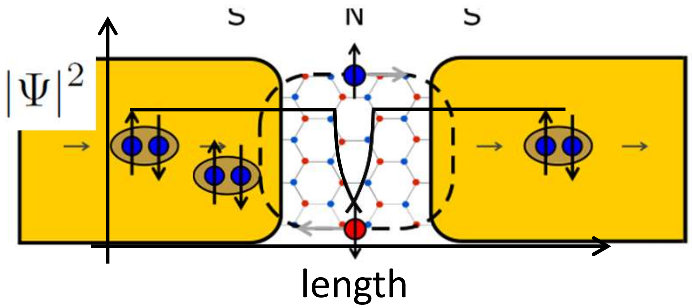
- Josephson junctions
  - Why are they interesting?
  - How are they realized?
- Quantum noise-limited RF amplifier using graphene Josephson junction
- High temperature Josephson diode
- What next?

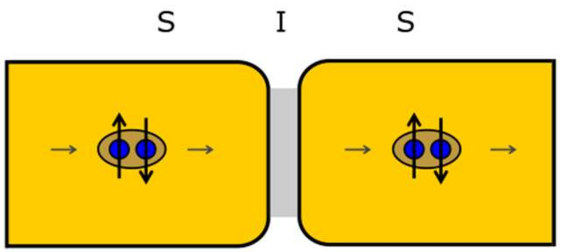
Josephson junction basics





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





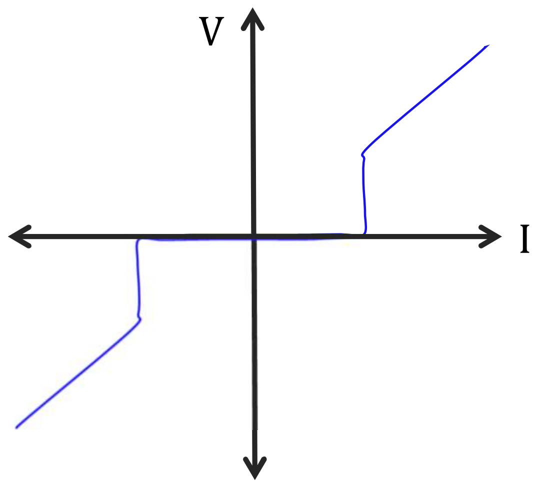
$$\Psi_{1,2} = \sqrt{n_{1,2}}e^{i\phi_{1,2}}$$

	DC Josephson effect
δ	constant
V	zero!

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

$$I = I_0 \sin(\phi)$$
$$V = \frac{\Phi_0}{2\pi}\dot{\phi}$$

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



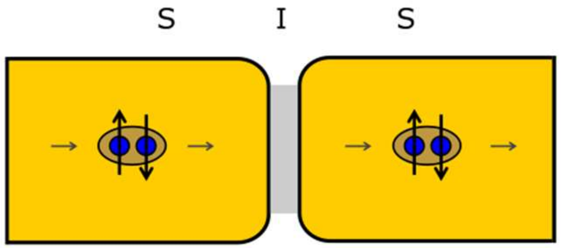
Rev. Mod. Phys. **76**, 411 (2004)

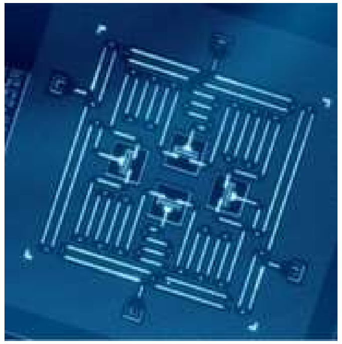
$$V = L\frac{dI}{dt} \rightarrow \frac{\Phi_0}{2\pi}\dot{\phi} = LI_0\dot{\phi}\cos(\phi) \rightarrow L = \frac{\Phi_0}{2\pi I_0 \cos\phi} \rightarrow L = \frac{L_{J0}}{\cos\phi}$$

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

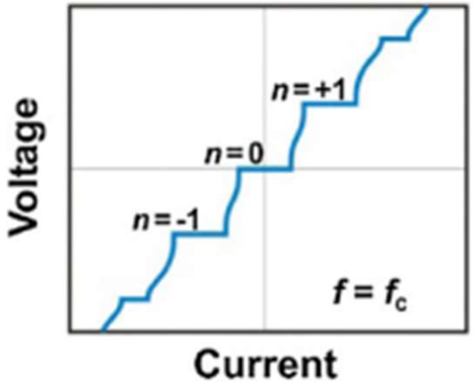
Non-linear inductor

Why are Josephson junctions interesting?

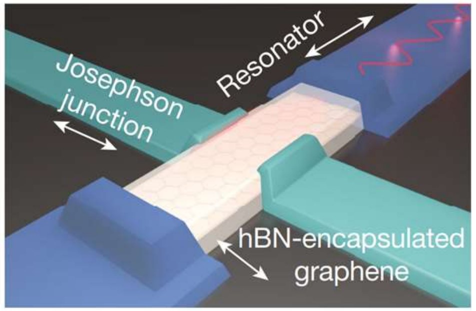




Superconducting qubits, amplifiers



Metrology – voltage standard



Quantum sensors

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

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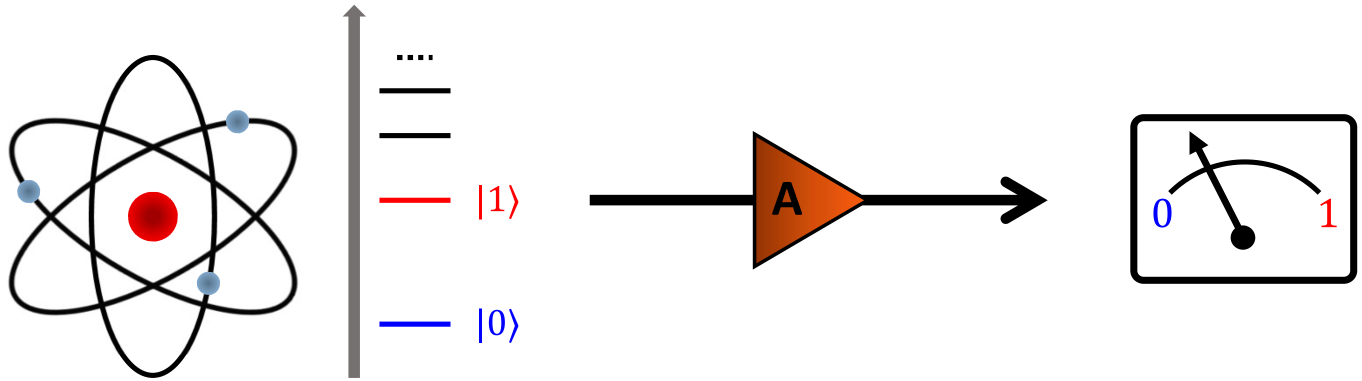
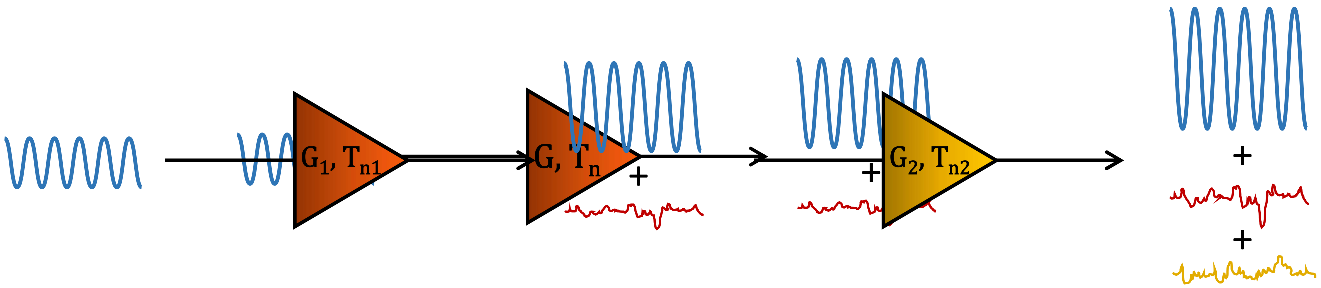
Quantum information processing: requirement of low-noise amplification



P ≈ -130 dBm ≈ 10^{-16} W
T ≈ 10 mK

P ≈ 10^{-3} W
T ≈ 300 K



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

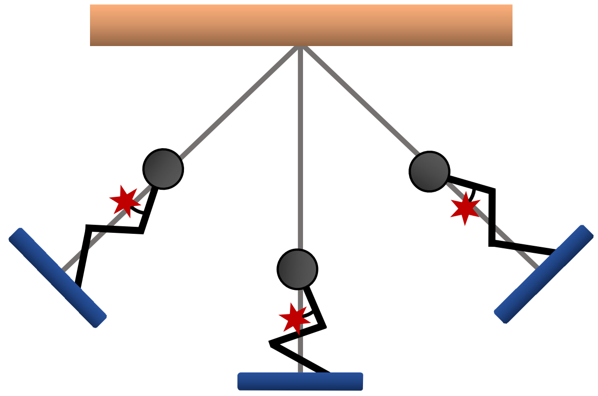
$$T_{sys} = T_{n1} \quad G_1 \quad G_1 G_2 \quad \frac{T_{nN}}{G_1 G_2 \cdots G_{N-1}}$$

A quick intro to parametric resonance and amplification

Driven damped harmonic oscillator:

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

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

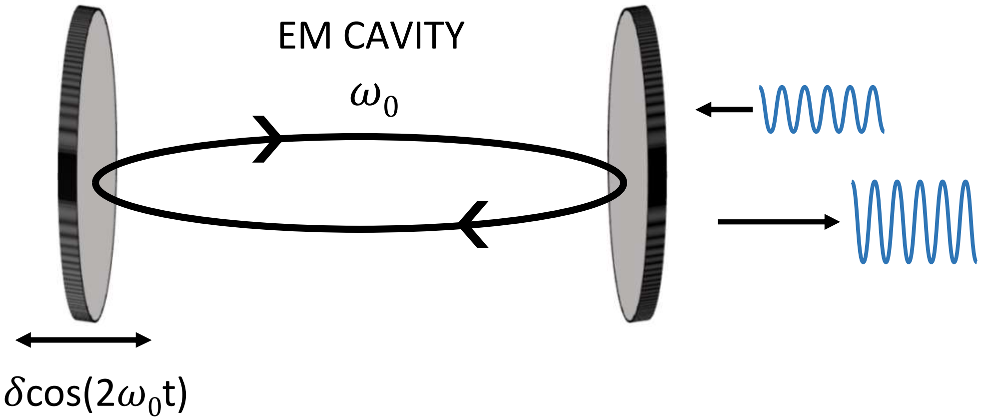


Parametrically driven damped harmonic oscillator:

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

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

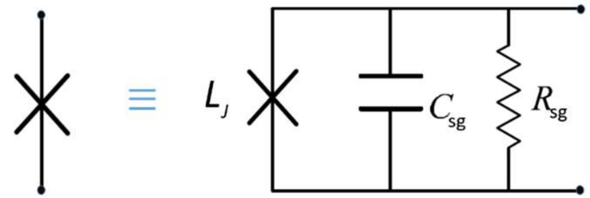
reduction in damping

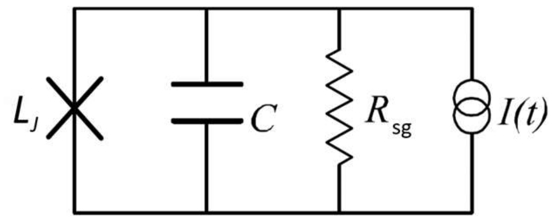


Resistively capacitively shunted junction (RCSJ) model of a JJ: inherent non-linearity

The **RCSJ** model of Josephson junctions:

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





Equation of motion of a driven non-linear oscillator

Inherent non-linearity $\sim \phi^3/6$

Josephson parametric amplifier: a nonlinear resonator

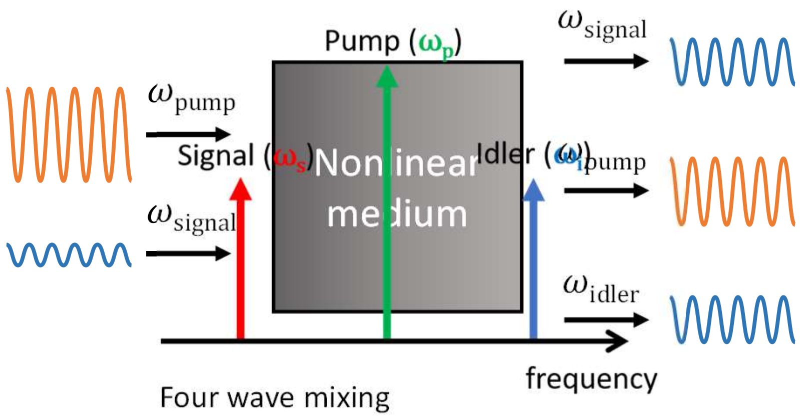
Non-linear driven damped oscillator:

$$\ddot{x} + 2\Gamma\dot{x} + \omega_0^2(x - \alpha x^3) = F_p \cos\omega_p t$$

$$\ddot{x} + 2\Gamma\dot{x} + \omega_0^2(x - \alpha x^3) = F_p \cos\omega_p t + F_s \cos\omega_s t$$

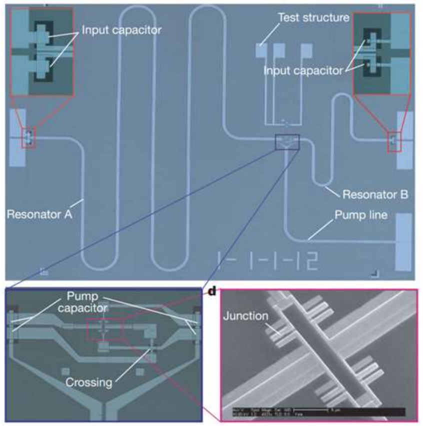
$$x_{sol}(t) = x_p \cos(\omega_p t + \phi) + y(t) \qquad F_s \ll F_p, \; |y(t)| \ll x_p$$

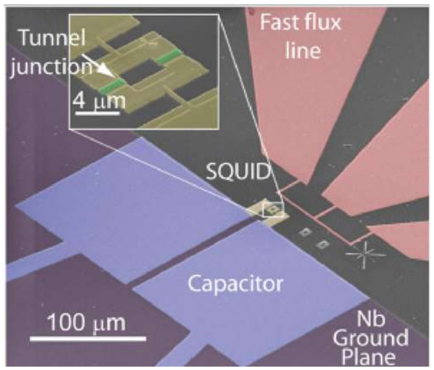
$$\ddot{y} + 2\Gamma\dot{y} + \omega_{0,eff}^2(1 + k\cos 2\omega_p t)y = F_s \cos\omega_s t$$



Four wave mixing

$2\omega_p = \omega_s + \omega_i$

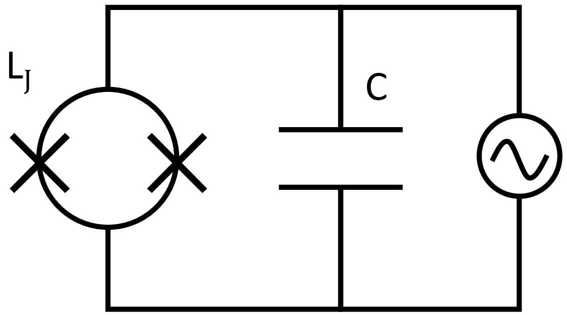




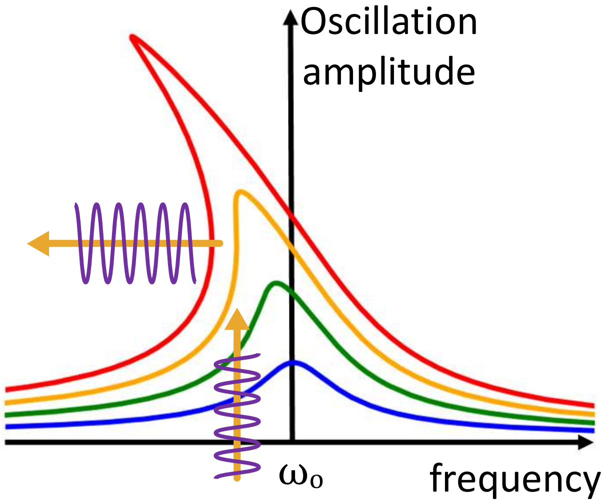
Hatridge et al., Phys. Rev. B 83, 134501 (2011)

Bergeal et al., Nature 465, 64–68 (2010)

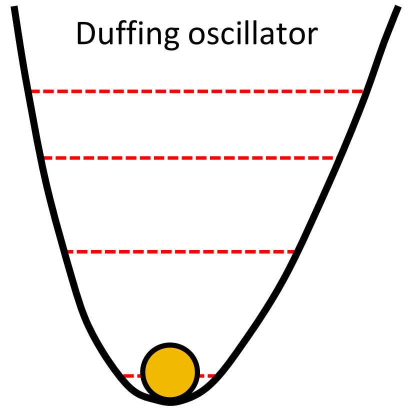
- Magnetic flux is the tuning knob



Quantum limit on the added noise



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



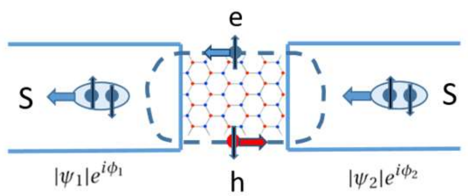
$$k_B T \ll \hbar\omega$$

~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

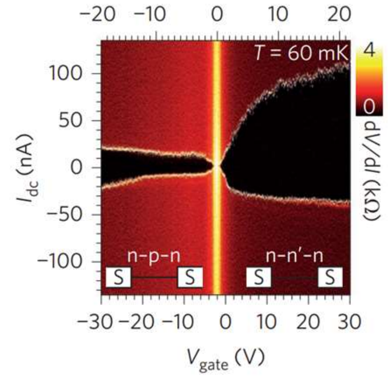
Graphene Josephson junctions (gr-JJ): a platform using electrostatic control



SNS JJ CPR

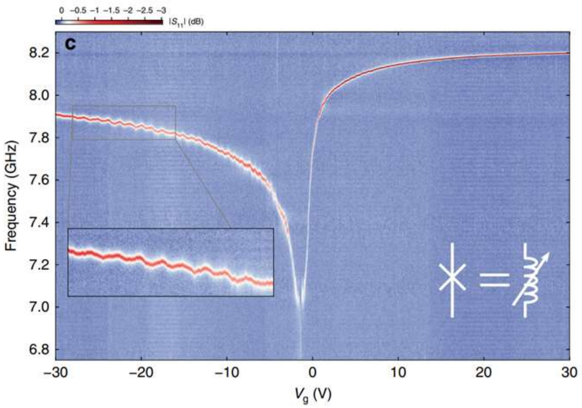
$$I_s(\phi) = \frac{\pi\Delta_o}{2eR_n}\frac{\sin\phi}{\sqrt{1-\tau\sin^2(\phi/2)}}$$

Gr-JJ



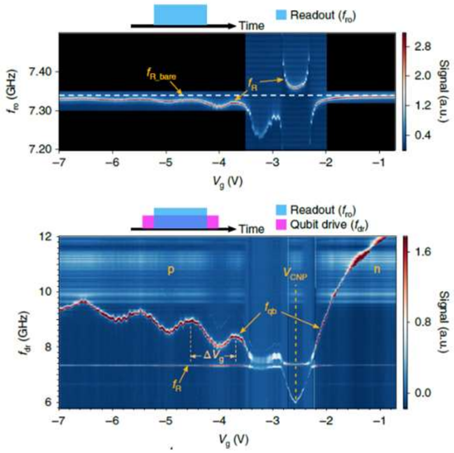
Calado et al. Nature Nanotechnology 10, 761–764 (2015)

Gr-JJ microwave resonator



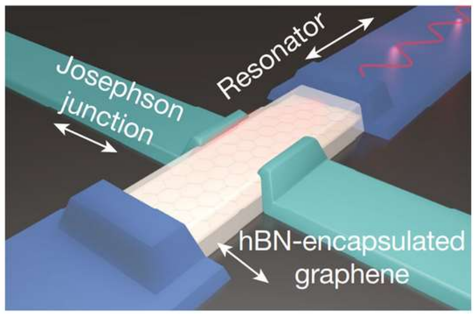
Felix et al. Nature Communications 9, 4069 (2018)

Gr-transmon qubit



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

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)

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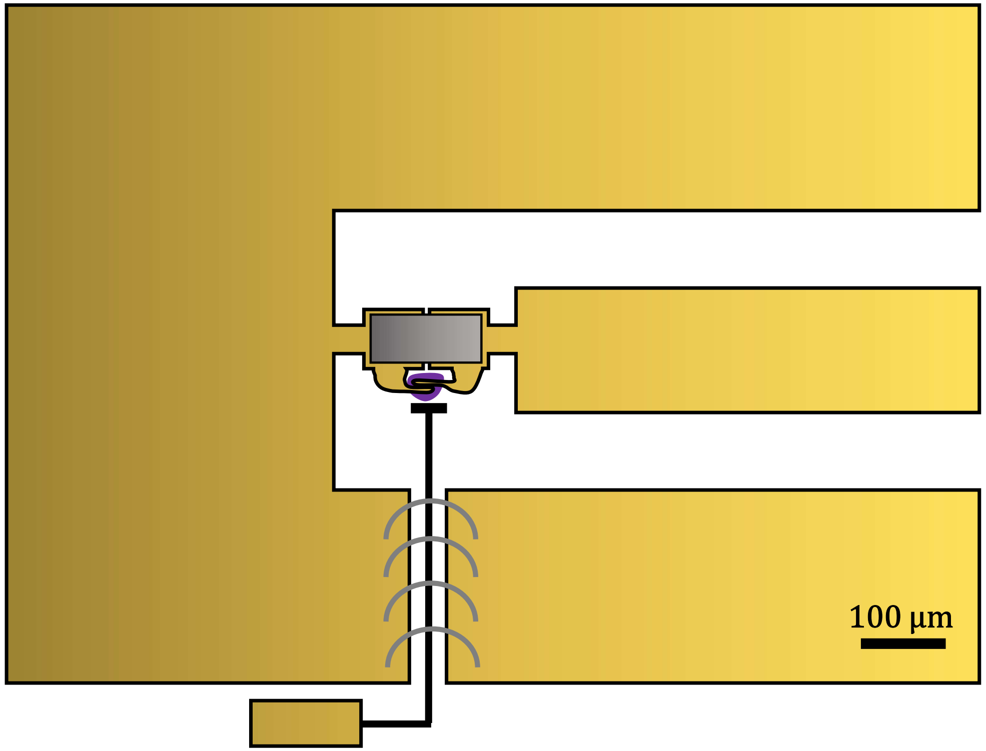
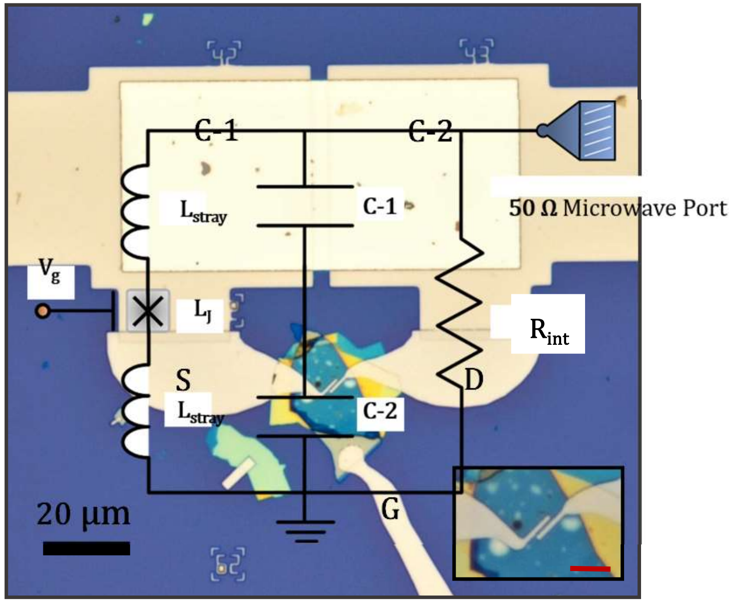
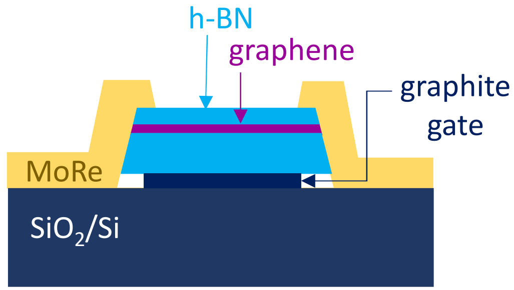
Our implementation: graphene based Josephson parametric amplifier (Gr-JPA)

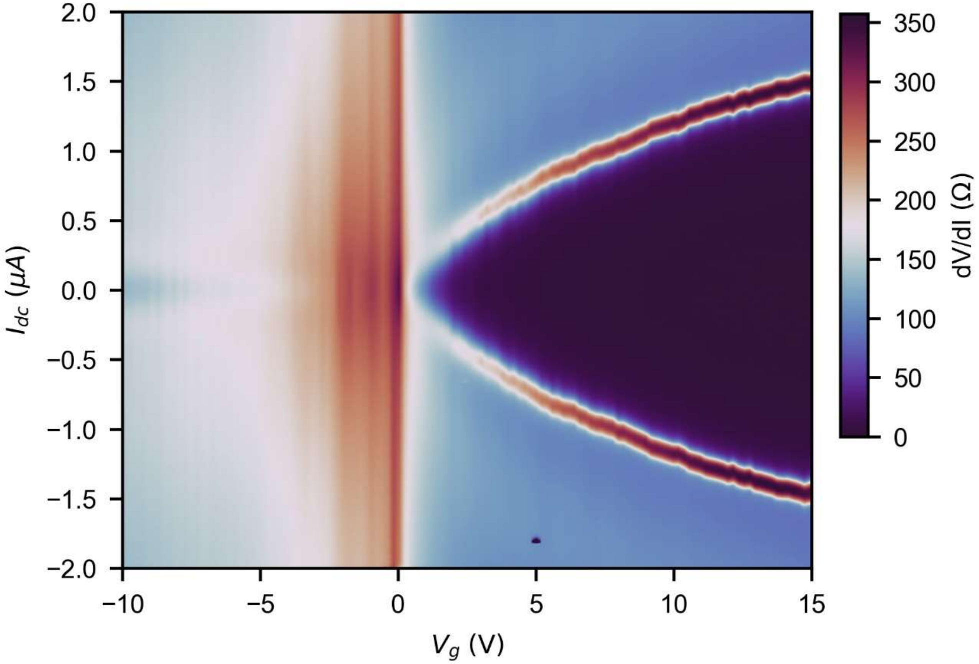


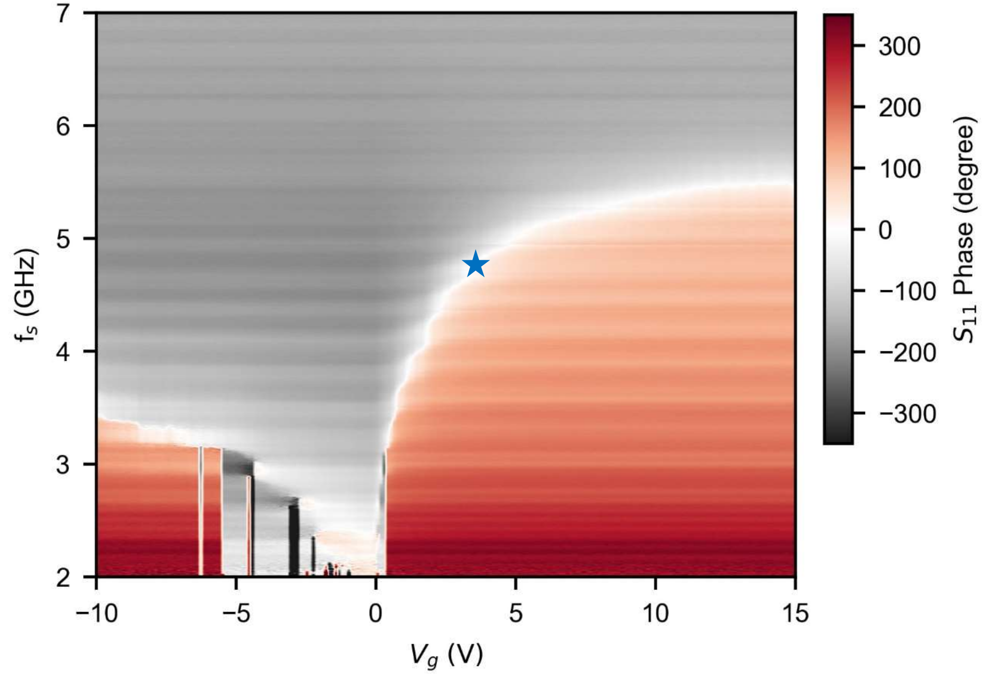




Short junctions: (L<<W)
Width(W) ~ 4 μm
Length(L) ~ 350 nm

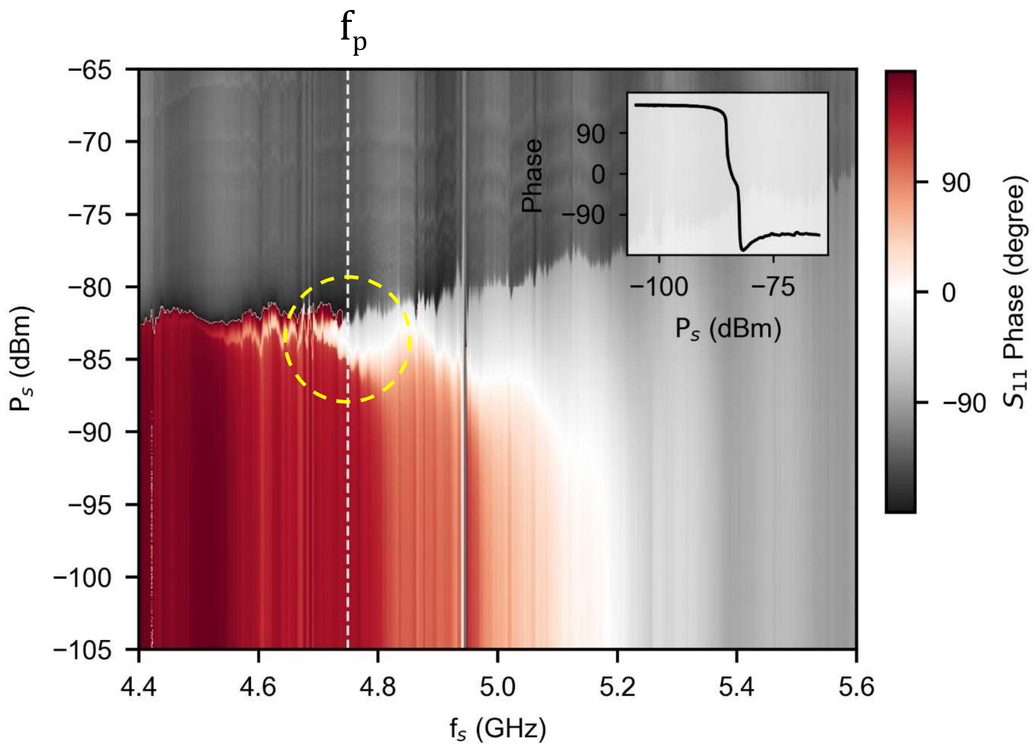
Characterization of the Gr-JPA: DC and microwave properties

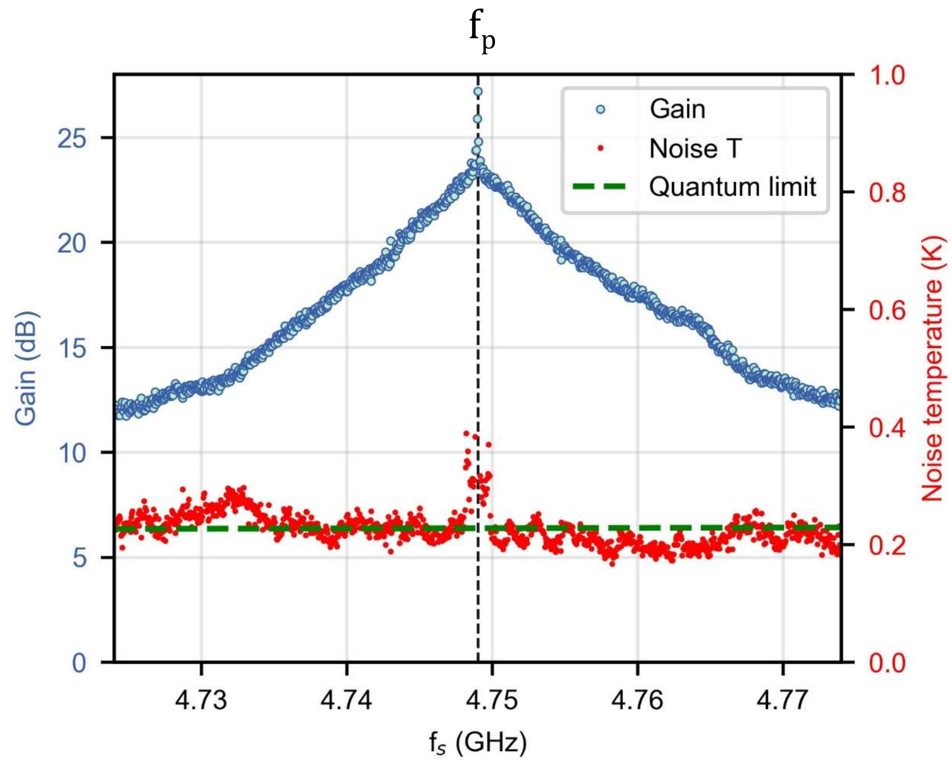




- Gr-JPA has linear resonance tunability of 3.5 GHz with gating

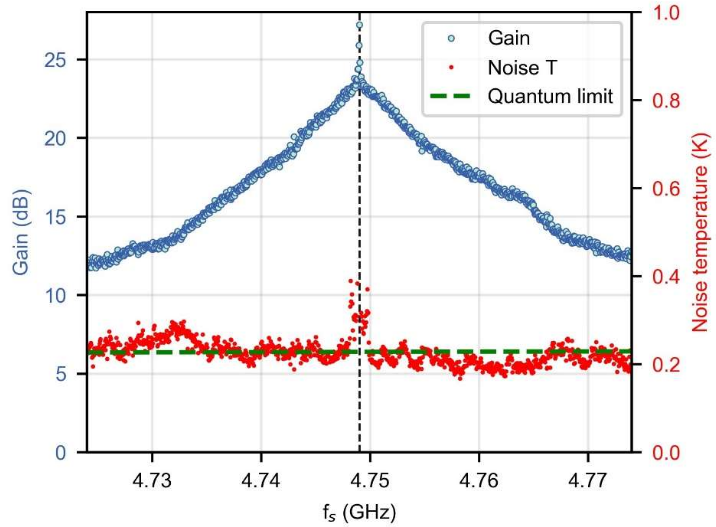
Nonlinear response and amplification of the Gr-JPA





Summary of graphene parametric amplifier

- 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



- Single photon detector integrated with the amplifier
- Scalable cQED devices based on 2D van der Waals materials

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

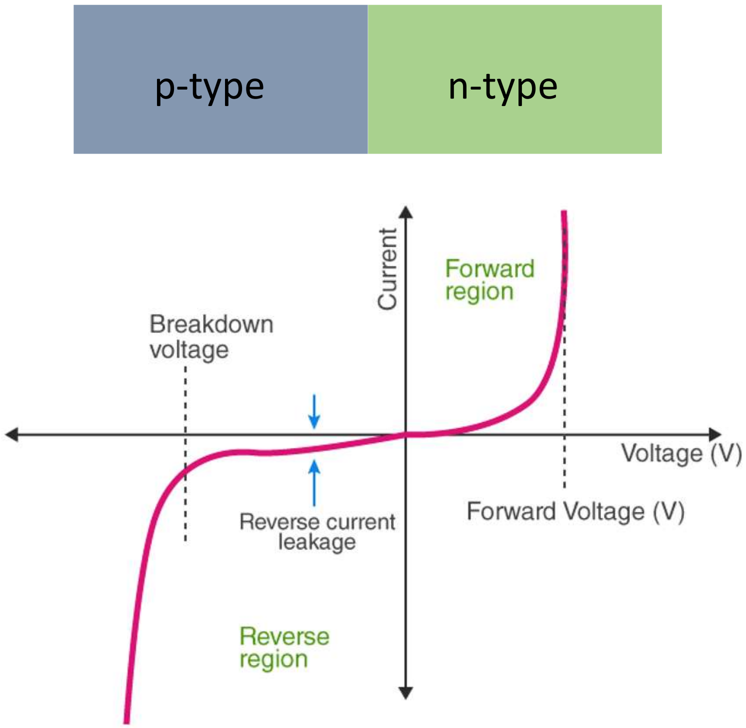
Butseraen, et al. Nature Nanotechnology 17, 1153 (2022).

Outline

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

Non-reciprocal charge transport – p-n junction diode :

Semiconducting p-n junction diode

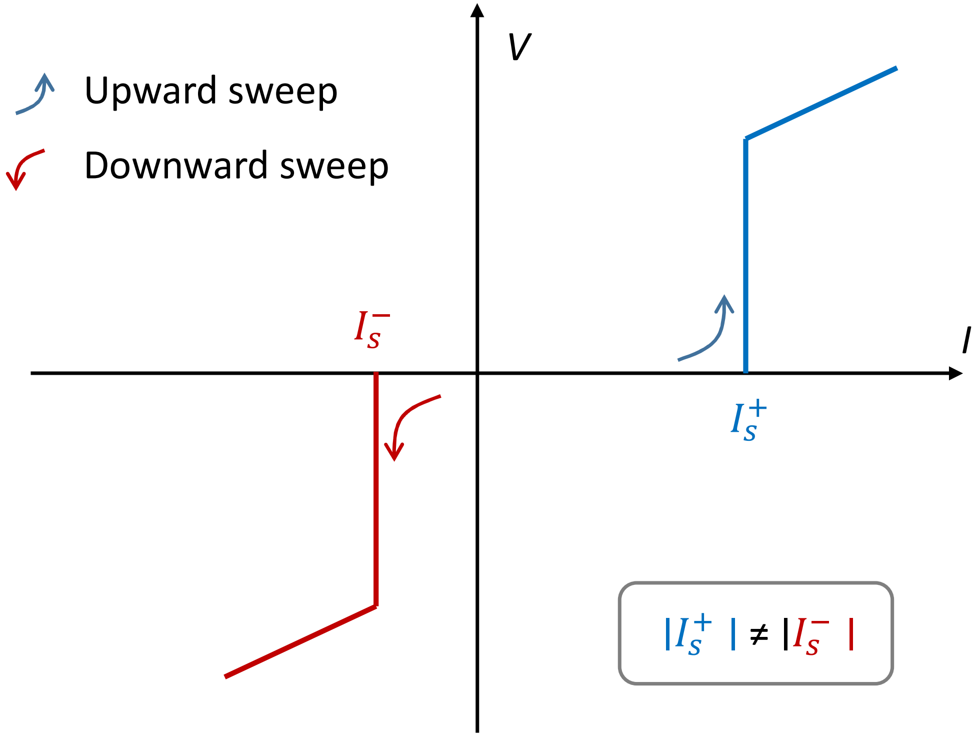


Non-reciprocal response $I\ (+V) \neq I\ (-V)$

Broken inversion symmetry due to doping

Superconducting diode

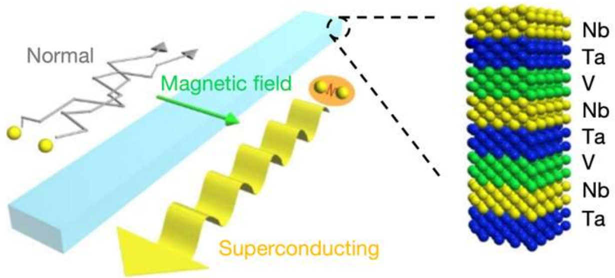
Broken inversion symmetry + Broken time-reversal



$|I_s^+| \neq |I_s^-|$

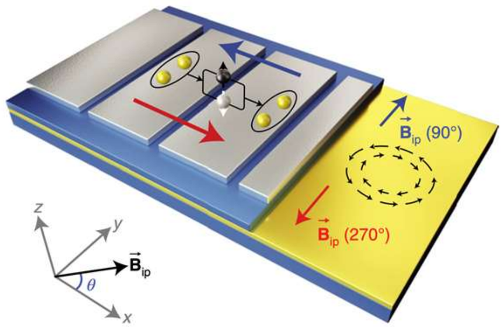
Superconducting diode effect in different systems :

Artificial superlattice



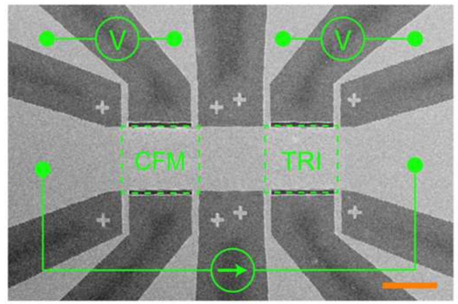
Nature 584, 373–376 (2020)

Josephson junction



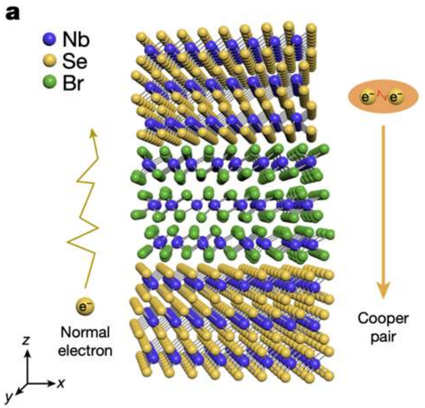
Nature Nanotechnology 17, 39–44 (2022)

Nano hole patterned superconductor



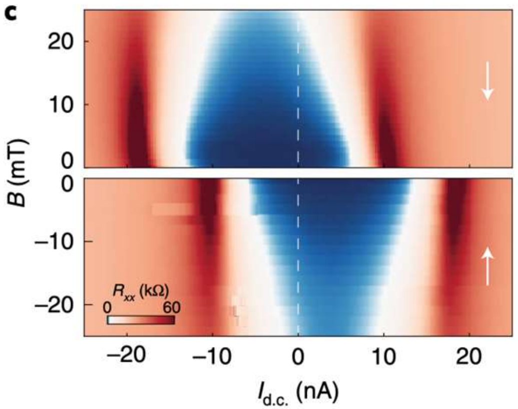
Nature Communications 12, 2703 (2021)

Magnetic tunnel junction



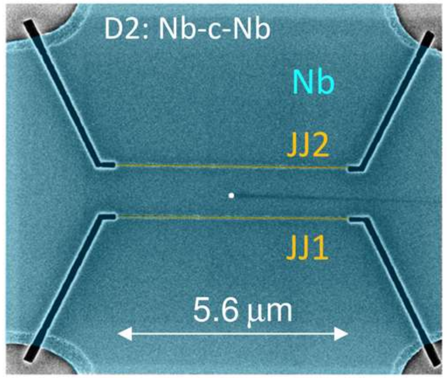
Nature 604, 653–656 (2022)

Twisted trilayer graphene



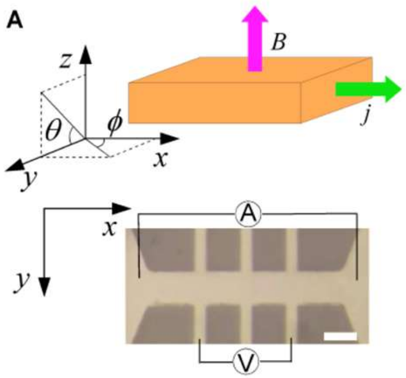
Nature Physics 1–7 (2022)

JJ with non-uniform bias



Nature Communications 13, 3658 (2022)

Superconducting thin film



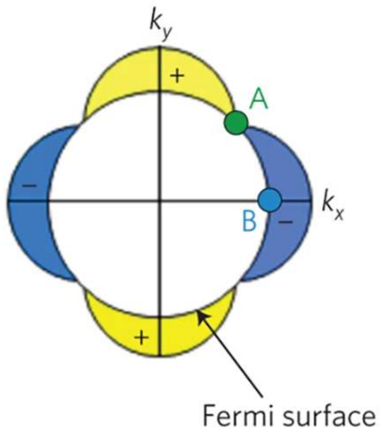
Phys. Rev. Lett. 131, 027001 (2023)

All are at temperatures ∽ 4 K or less

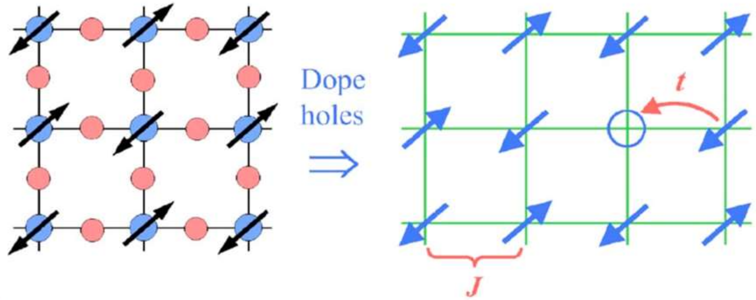
We demonstrate the diode effect in twisted BSCCO above 77 K
And record asymmetry

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

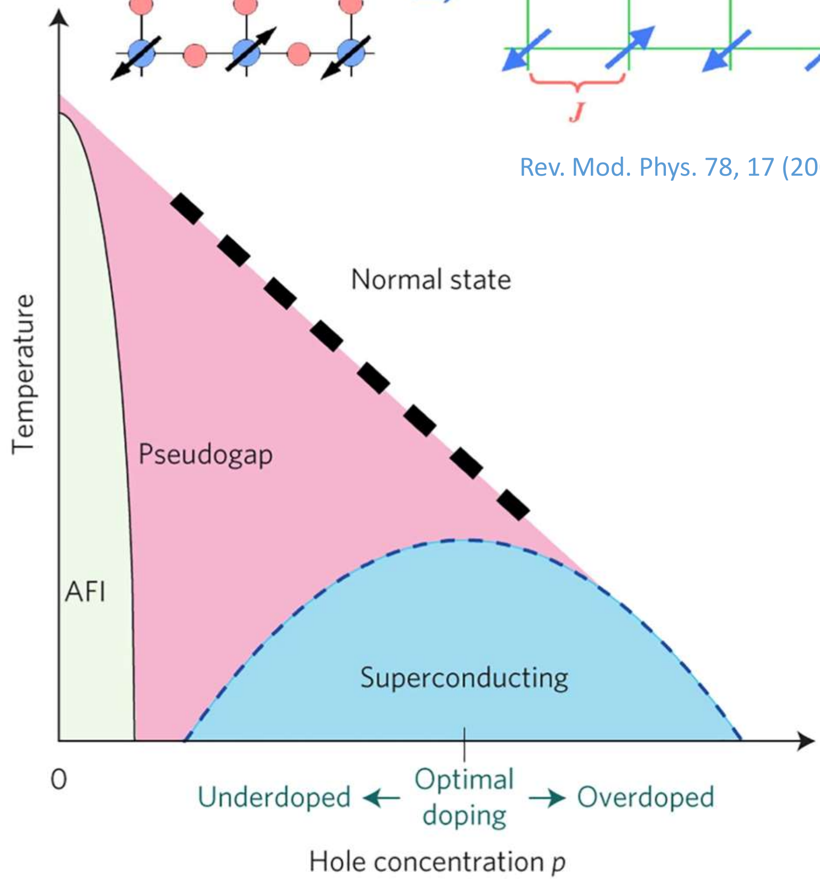
- Layered van der Waals material
- General formula $Bi_2Sr_2Ca_{n-1}Cu_nO_{2n+4+\delta}$
- Superconducting gap ~ 40 meV, ξ ~ 2 nm
- Δ has d-wave symmetry



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

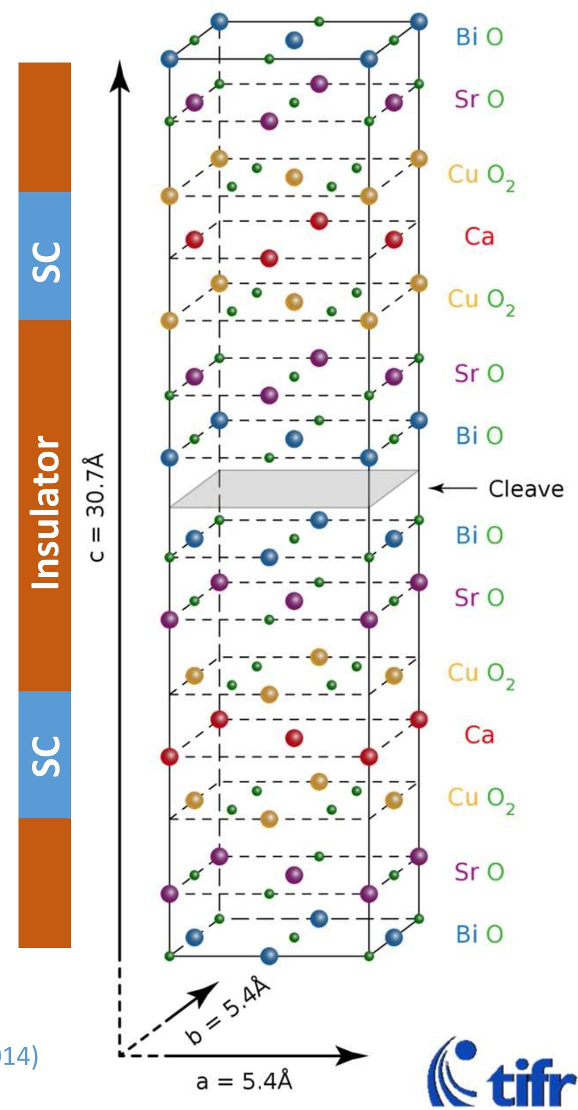


Rev. Mod. Phys. 78, 17 (2006)



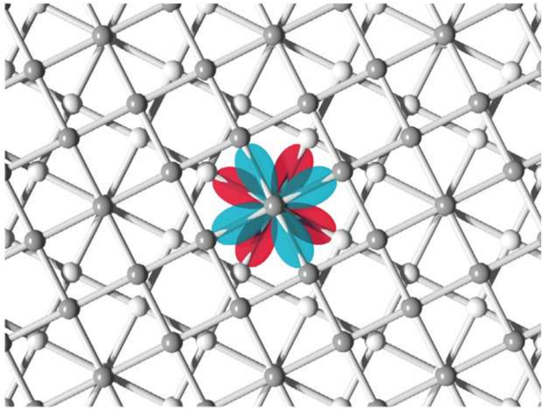
Nat. Phys. 10, 483-495 (2014)

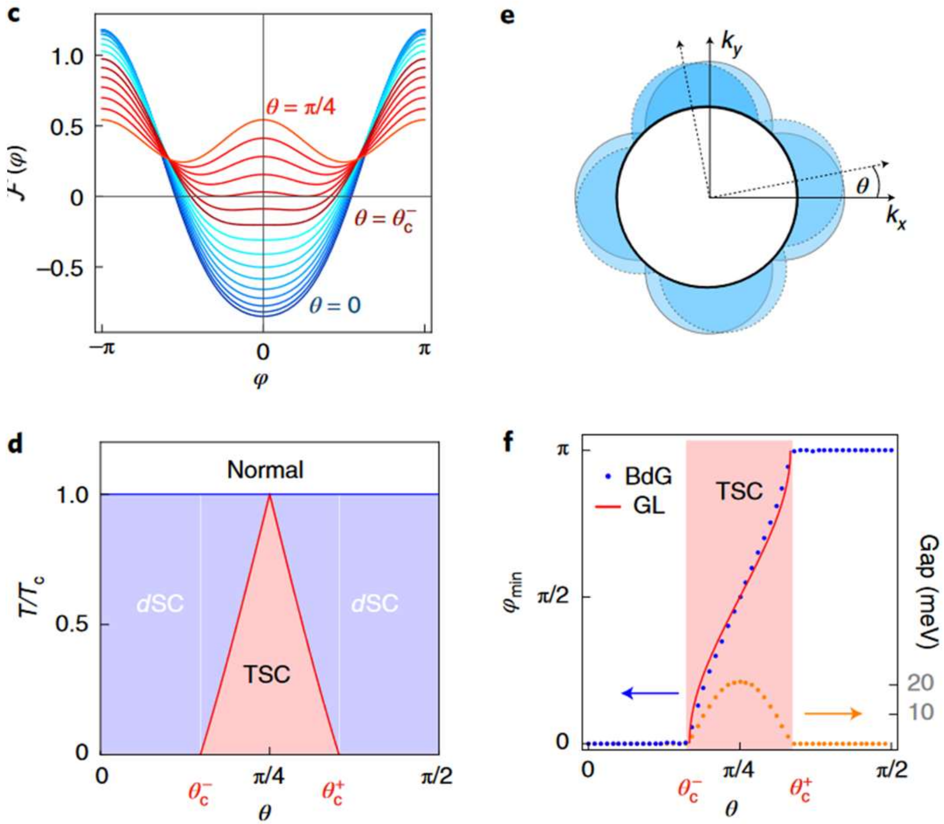
Highly anisotropic



Exciting possibilities with twistronics and BSCCO

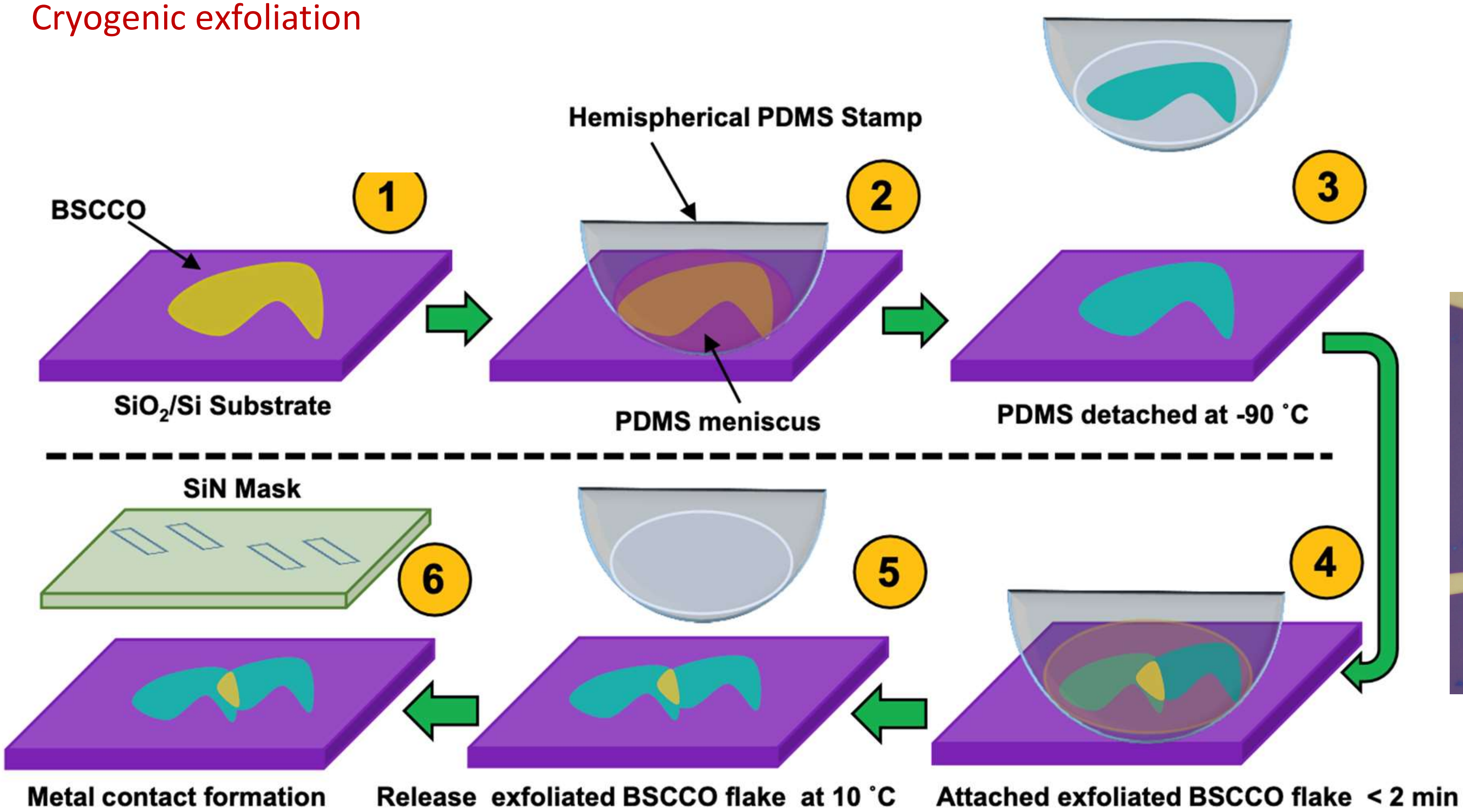
Topological superconductor at 77K

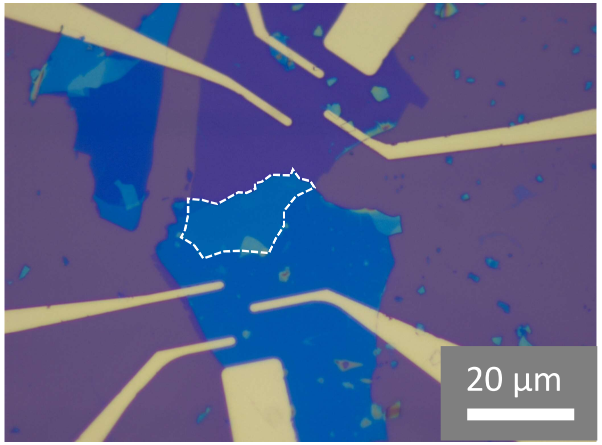




Can and Franz et al. Nature Physics 17, 519 (2021).

Cryogenic exfoliation





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

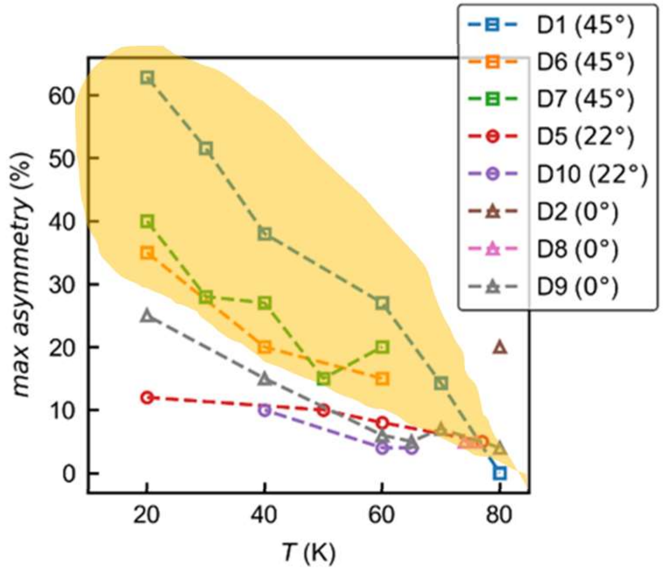
Non-reciprocal transport in 45 degree twisted BSCCO JJ :

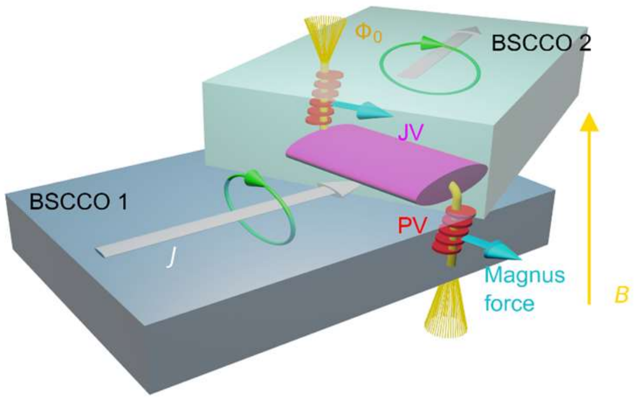
Related results from Kim group @ Harvard -- S. Y. F. Zhao et al., Science 10.1126/science.abl8371 (2023).

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

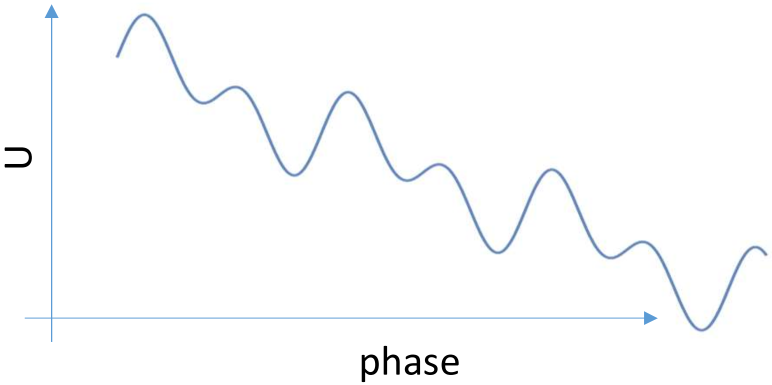
$$\text{Asymmetry} = \left(\frac{I_c^+ - |I_c^-|}{I_c^+ + |I_c^-|}\right) \times 100\ \%$$

JJ Diode – asymmetry a strong function of the twist angle





- coupling between Josephson and Abrikosov vortices



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

Summary

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

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

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