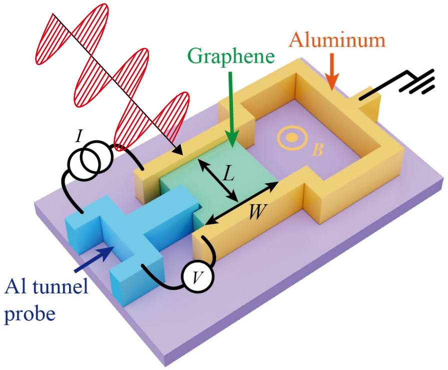
Steady Floquet–Andreev states in graphene Josephson junctions

Sein Park, Wonjun Lee, Seong Jang, Yong-Bin Choi, Jinho Park,

Woochan Jung, Gil Young Cho, Gil-Ho Lee

Department of Physics, POSTECH, Korea



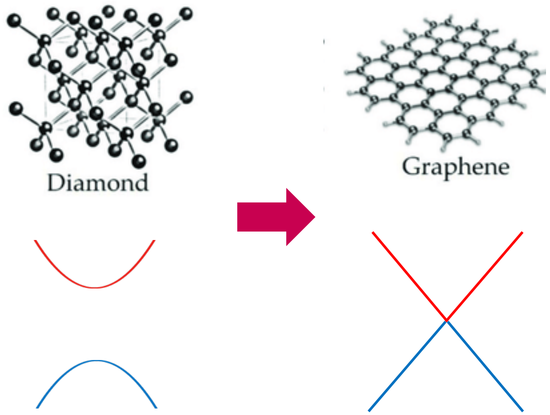
Kenji Watanabe, Takashi Taniguchi

NIMS, Japan

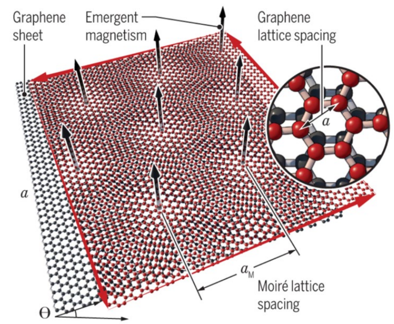
POSTECH

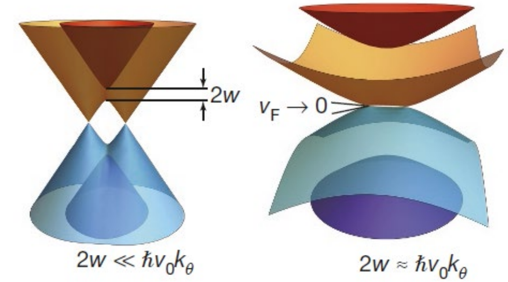
Band Engineering

Material design



Twist-angle control

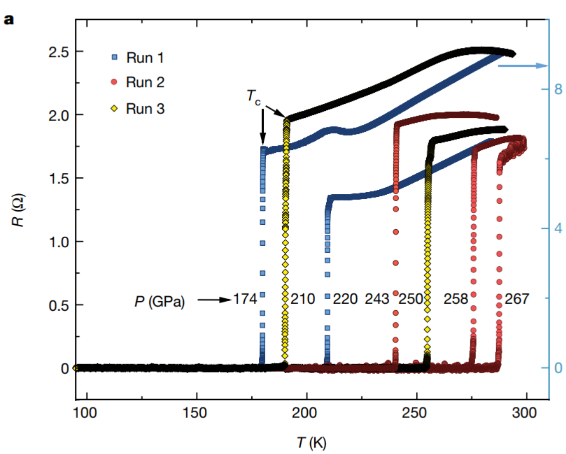




e-e correlated physics

[Science 365, 543-543 (2019)
Nature 556, 80-84 (2018)]

Pressure control

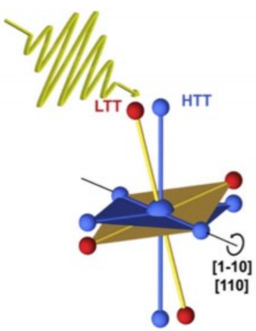


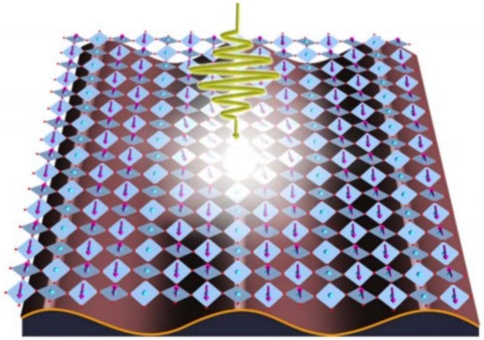
[Nature 586, 373–377 (2020)]

room-temperature superconductivity

Light control

e.g.) Floquet engineering



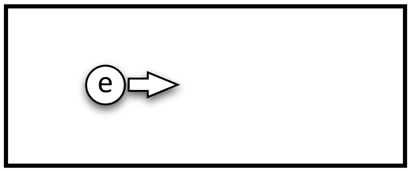


transient high-Tc superconductivity

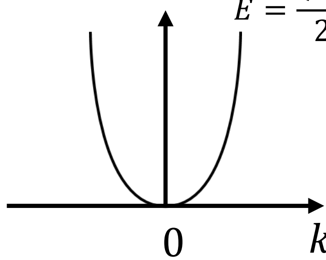
[Science 331, 189-191 (2011)]

Floquet-Bloch State

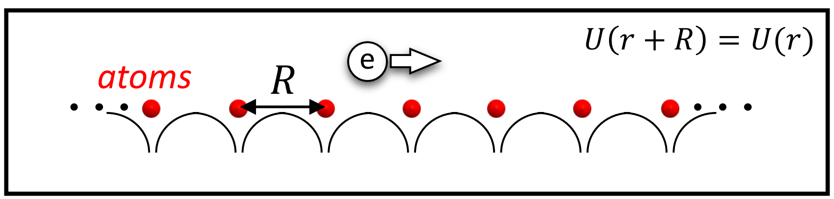
Free space



$$E = \frac{(\hbar k)^2}{2m}$$



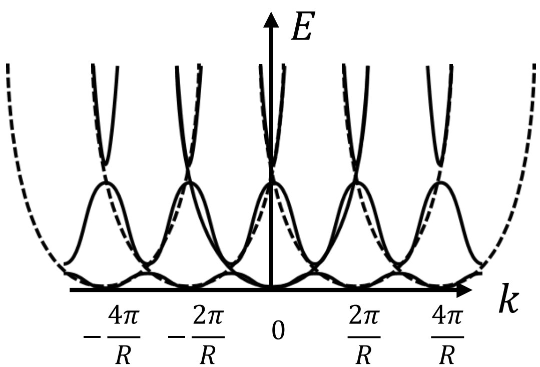
Space-periodic potential



$$H(r+R) = H(r)$$

$$\Psi_{nk}(\mathrm{r}) = \mathrm{e}^{ik\cdot r} u_{nk}(r)$$

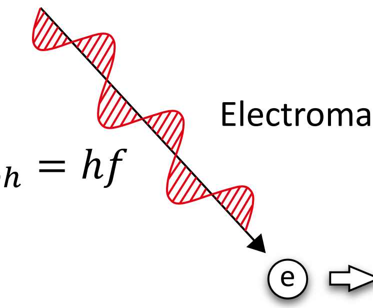
$$[x, p] = -i\hbar$$



k: quasi(crystal)-momentum

Bloch state

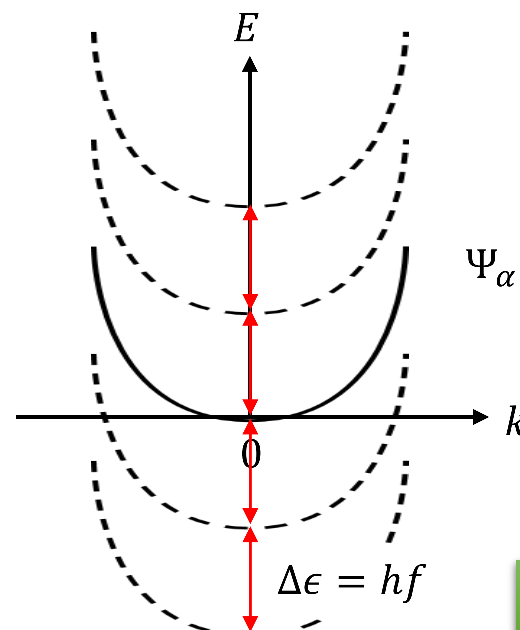
Time-periodic potential



$E_{ph} = hf$

Electromagnetic wave = 'Light'

$U(t+T) = U(t)$



$$H(t+T) = H(t)$$

$$\Psi_\alpha(t) = \mathrm{e}^{-i(\epsilon_\alpha/\hbar)t} \phi_\alpha(t)$$

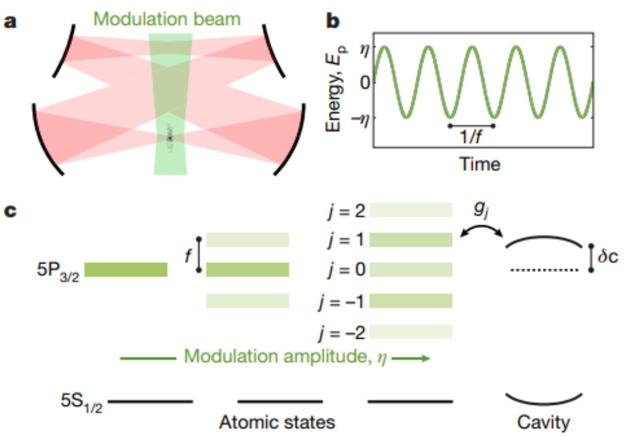
$$[E, t] = -i\hbar$$

E: quasi-energy

Floquet state

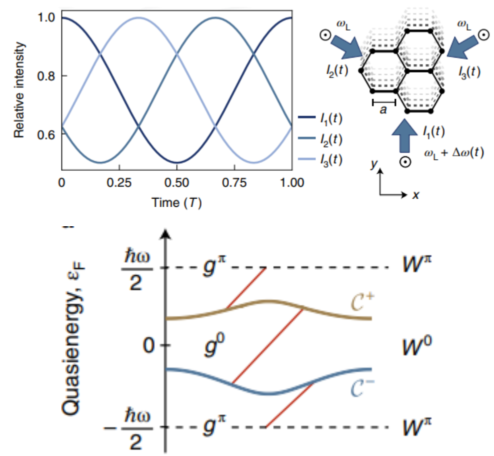
Floquet "Engineering"

Atomic Molecular Optics



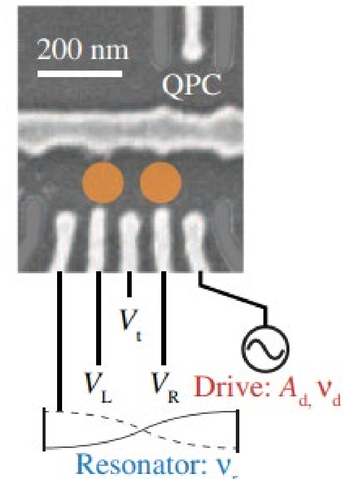
[Nature 571, 532–536 (2019)]

Floquet topological system



[Nat. Phys. 16, 1058–1063 (2020)]

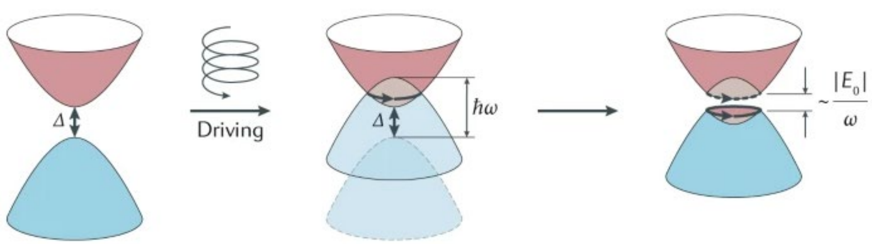
Quantum Information



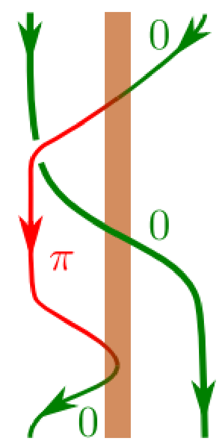
[PRL 121, 043603 (2018)]

Condensed Matter Systems

Chiral topological order



[Nat. Rev. Phys. 2 229–244 (2020)]



New braiding protocol in energy dimension

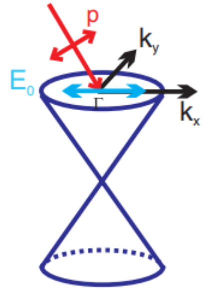
[PRB 100, 041102(R) (2019)]

POSTECH

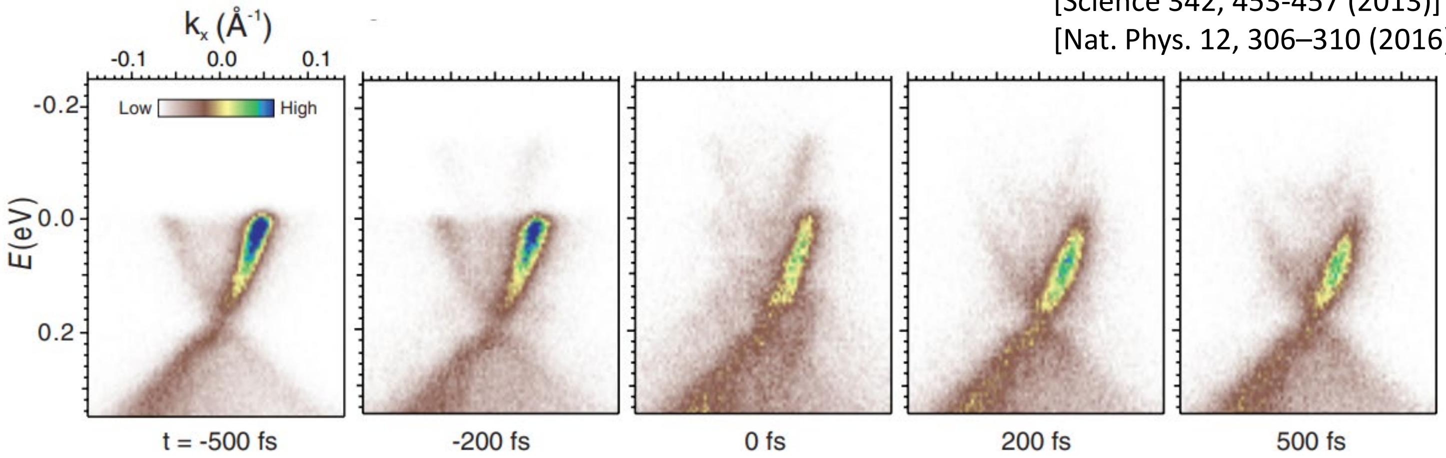
Previous Studies - ARPES

[Science 342, 453-457 (2013)]
[Nat. Phys. 12, 306–310 (2016)]

$f = 30$ THz

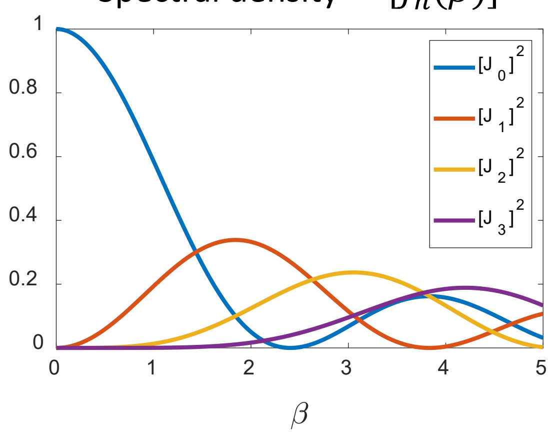


Bi_2Se_3



$\beta = ev_F|E|/\hbar\omega^2$: dimensionless parameter for Floquet interaction strength

Spectral density $\propto [J_n(\beta)]^2$



Optical light (Mid-IR, $f = 30$ THz, $hf \sim 0.12\ eV$)

↓

Strong electric field is needed. ($E \sim 10^7 V/m$)
+ Overheating problem ($P_{\text{heating}} \sim E^2$)

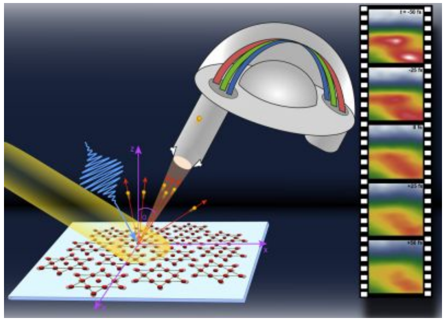
↓

Pulsed laser

↓

Time-resolved ARPES measurement

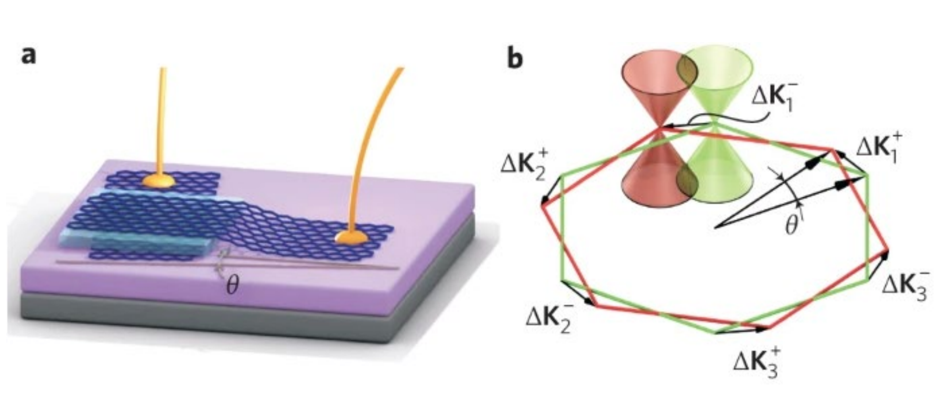
Time-resolved ARPES



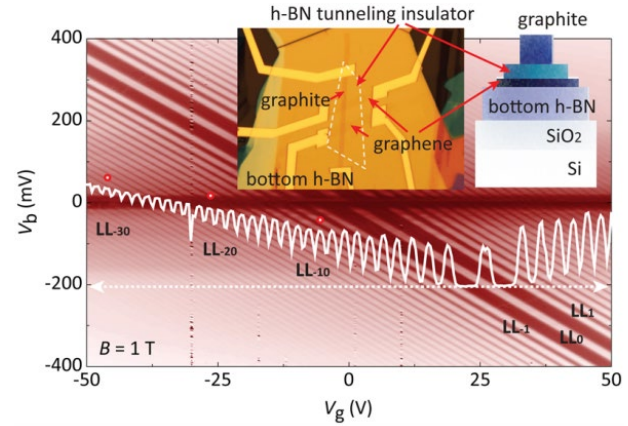
[Prof. Andrea Cavalleri's group]

Superconducting Tunneling Spectroscopy in Device

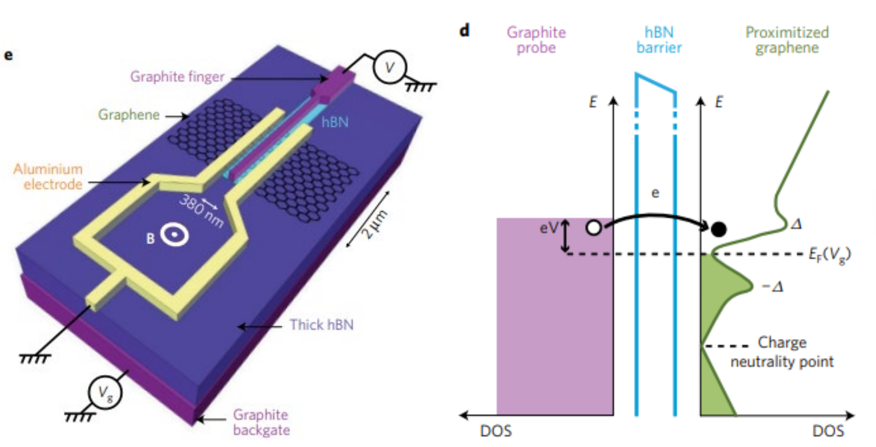
Tunneling Spectroscopy via hBN layer

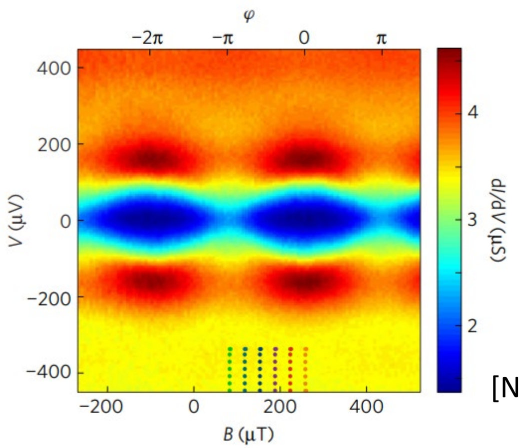


[Nat. Nano. 9, 808–813 (2014)]



[S. Jung et al., Nano Lett. 17, 206–213 (2017)]





[Nat. Phys. 13, 756-760 (2017)]

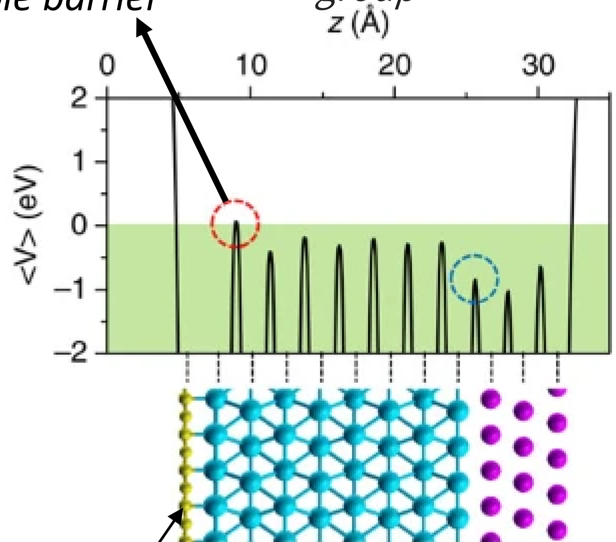
Areal averaged tunneling conductance

Making 'Bad' Contact

Graphene/Ti contact

First-principles calculations by Prof. Jhi's group

Negligible barrier

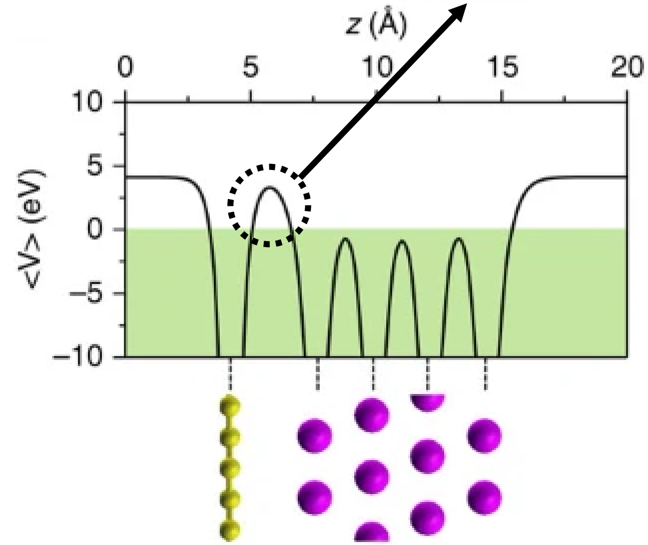


C (graphene) Ti Al

Ti adhesion layer is used for ohmic contact.

Graphene/Al contact

Potential barrier:
- Height ~ 3 eV
- Width ~ 1.5 Å



C Al

[GHL et al., Nat. Comm. 6, 6181 (2015)]

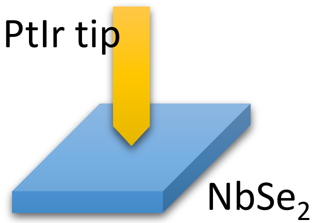
Potential barrier may act as a tunnel barrier.

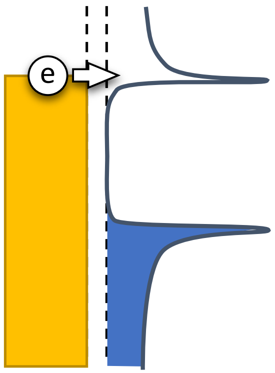
Study on CNT/Indium contact

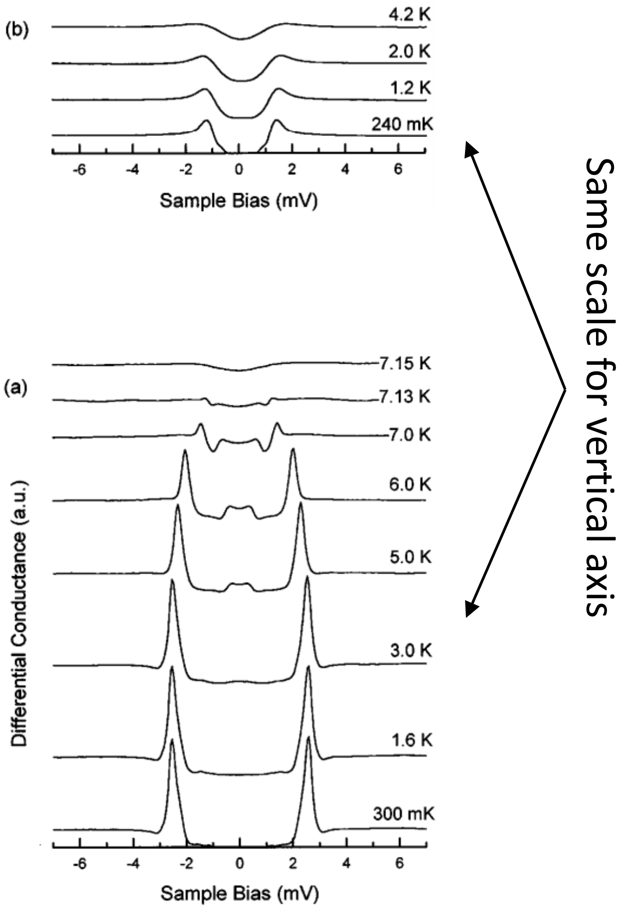
[Carbon 113, 237-242 (2017)]

Superconducting Tunneling Spectroscopy

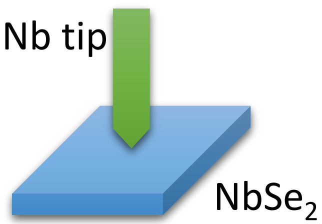
Normal metal tip

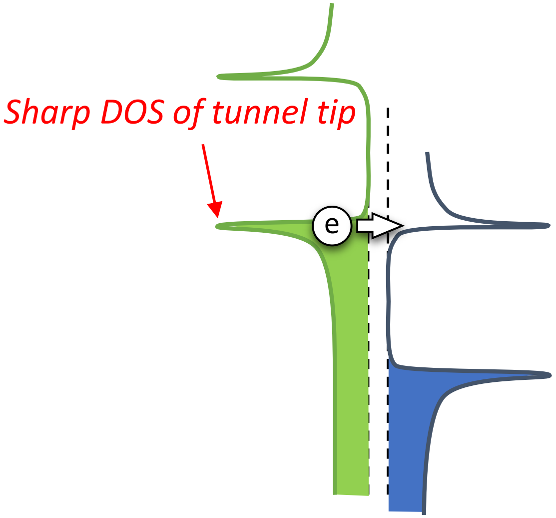






Superconductor tip



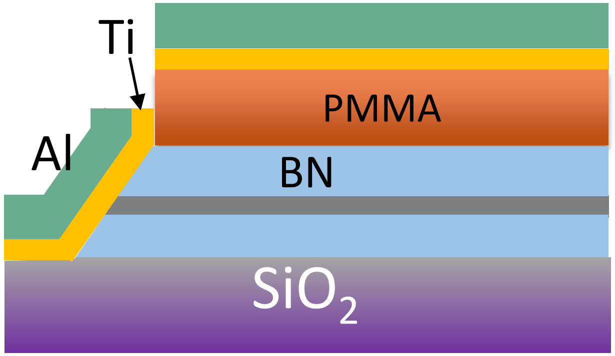


[Appl. Phys. Lett. 73, 2992 (1998)]

Superconducting tunnel probe gives better energy resolution.

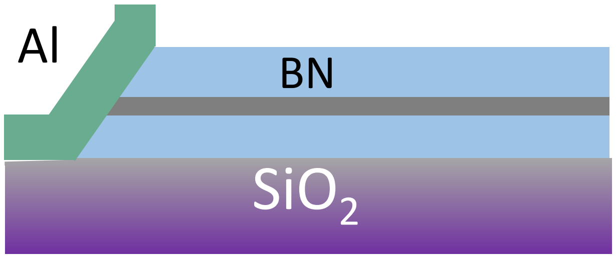
Fabrication of Side Tunnel Contact

Side ohmic contact



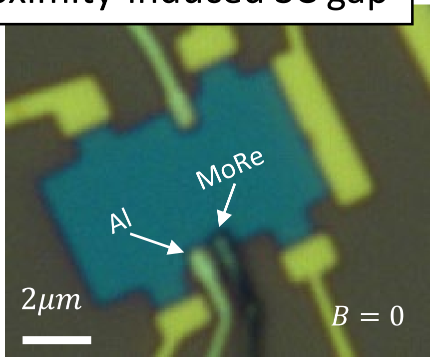
Self-aligned mask for lift-off

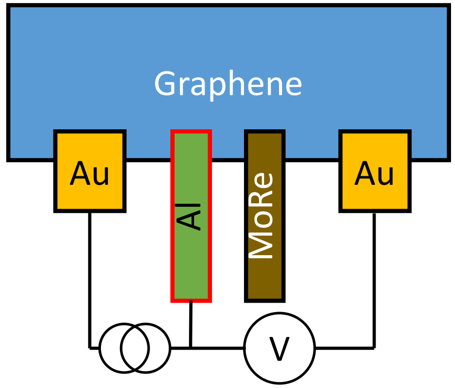
Side tunnel contact



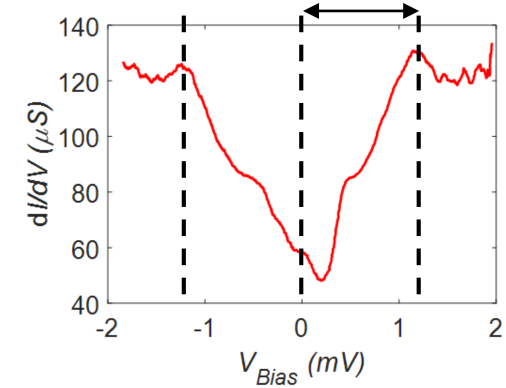
Tunneling Spectroscopy

Proximity-induced SC gap

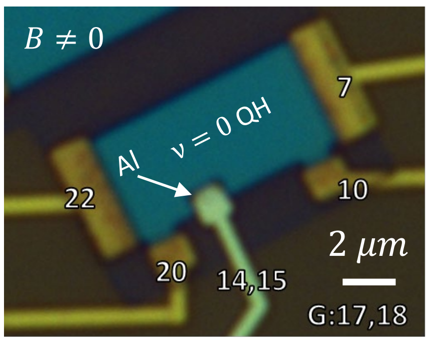




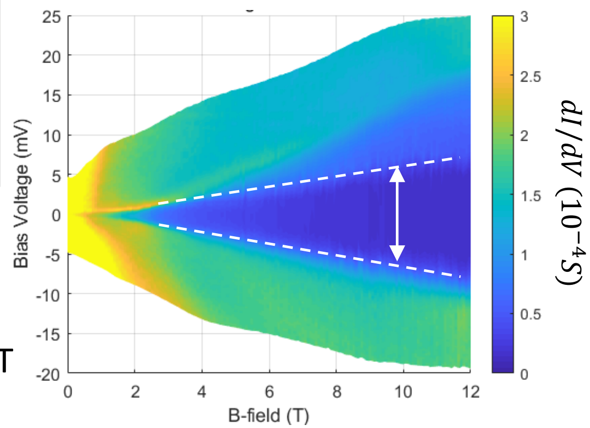
$\Delta_{\text{Al}} + \Delta_{\text{MoRe}}^{\text{ind}} \sim 1.2$ meV



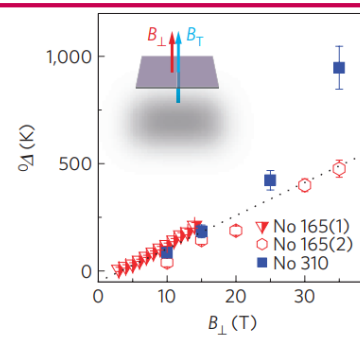
Landau gap of $\nu = 0$ Quantum Hall insulator



Dirac Point



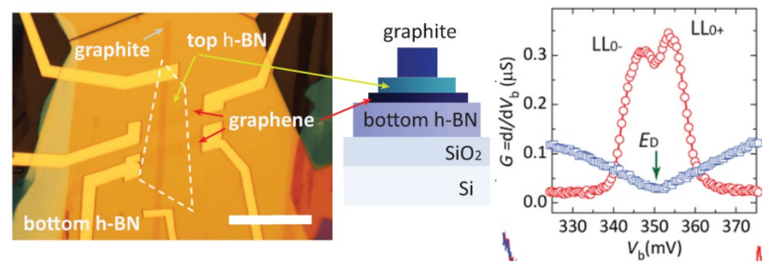
$\Delta_{\nu=0}$~10 meV @ 10 T



$\Delta_{\nu=0}$~10 meV @ 10 T

By Arrhenius fitting

[A. F. Young et al., Nat. Phys. 8, 550–556 (2012)]

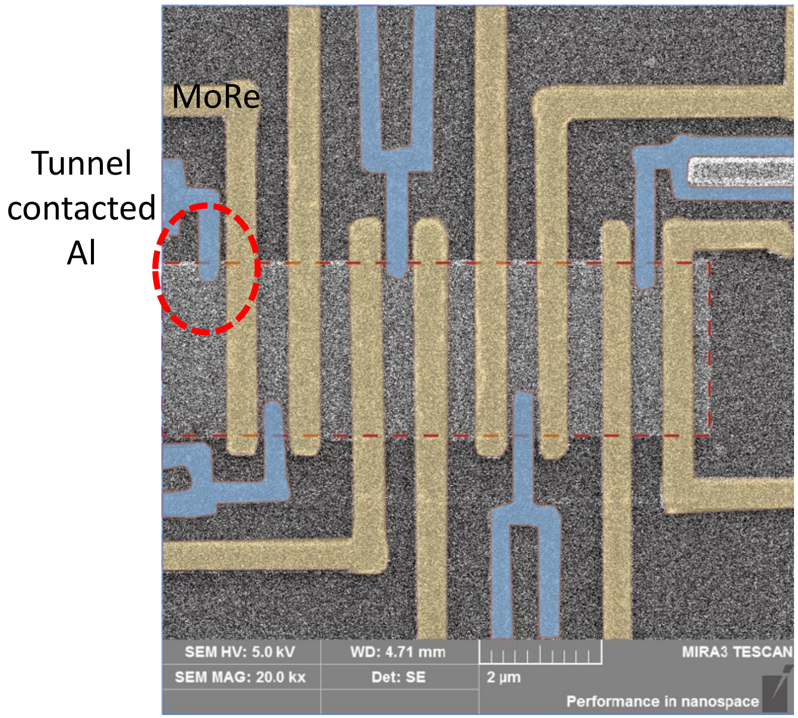


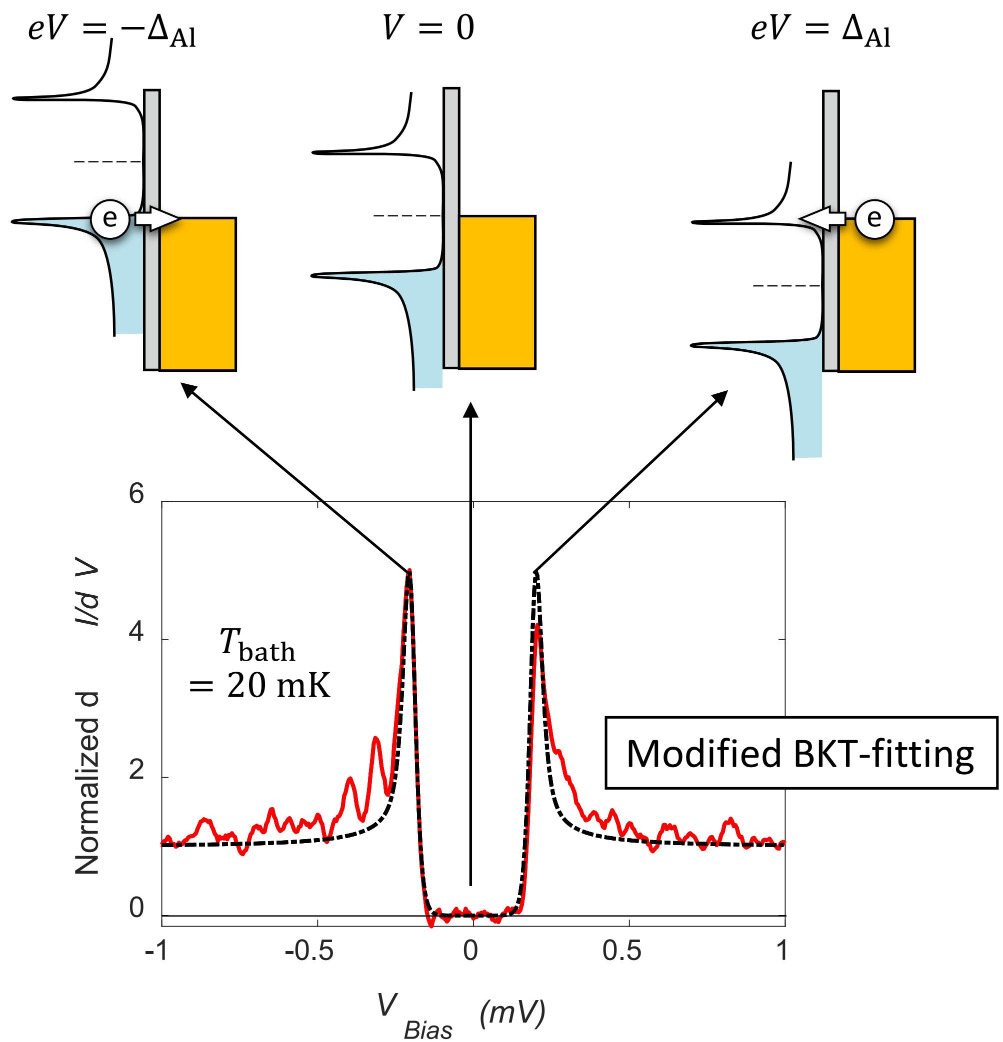
$\Delta_{\nu=0}$~20 meV @ 1 T

[S. Jung et al., Nano Lett. 17, 206–213 (2017)]

BTK Fitting for Tunneling Differential Conductance

After optimizing fabrication conditions,



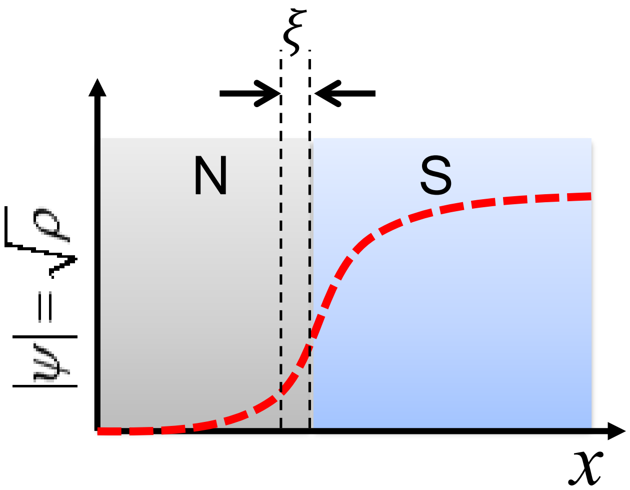


- Dynes parameter: $\gamma = 2.1 \times 10^{-4}$
- SC gap: $\Delta_{\mathrm{Al}} = 0.2\ \mathrm{meV}$
- Electron Temperature: $T_{\mathrm{e}} = 140\ \mathrm{mK}$

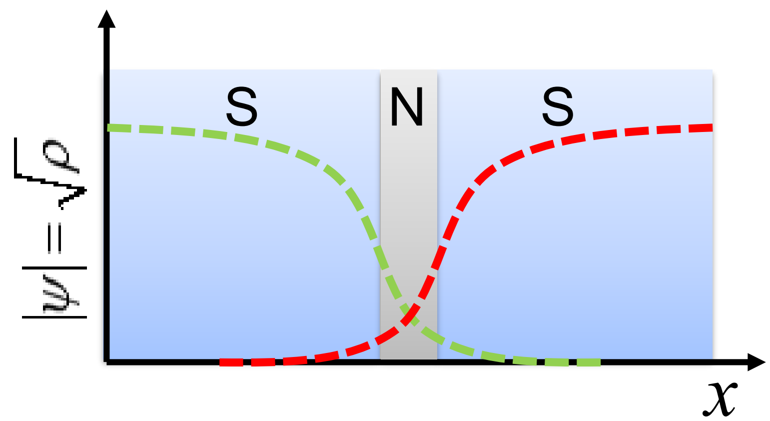
Andreev Bound State

Proximity Josephson Junction

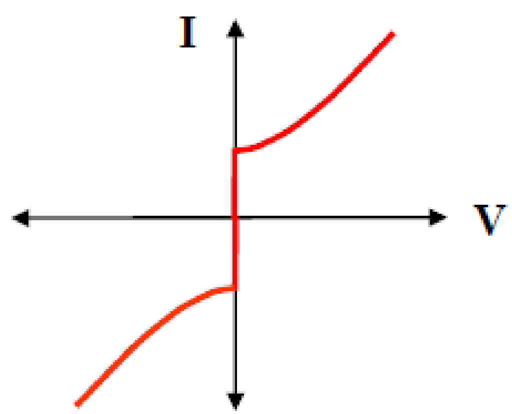
In mesoscopic point of view,



Proximity effect

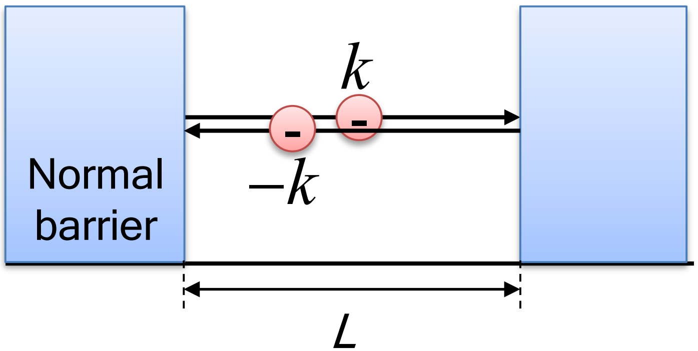


Proximity Josephson coupling



Andreev Bound State (ABS)

c.f.) Particle in a box problem



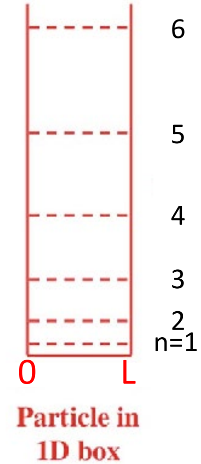
Bohr-Sommerfeld quantization: $2kL = 2\pi n$

$$\downarrow$$

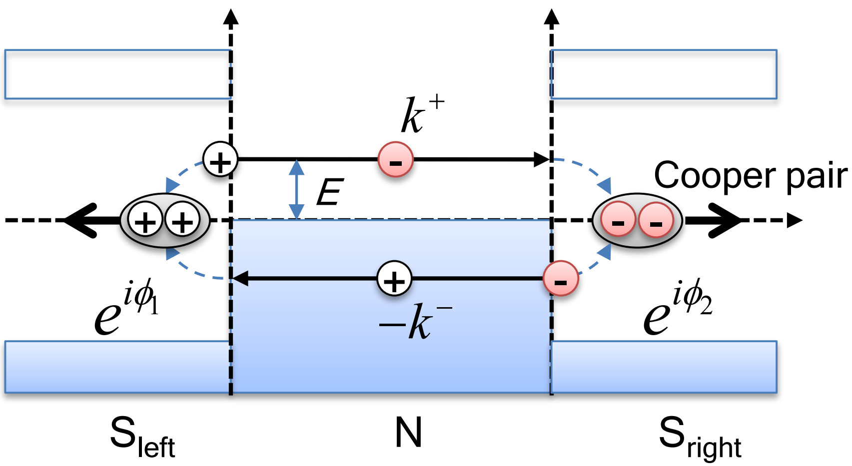
$$k_n = \frac{n\pi}{L}$$

$$\downarrow$$

Bound state energy: $E_n = \left(\frac{\hbar k_n}{2m}\right)^2 = n^2\left(\frac{h}{2mL^2}\right)^2$



In microscopic point of view,



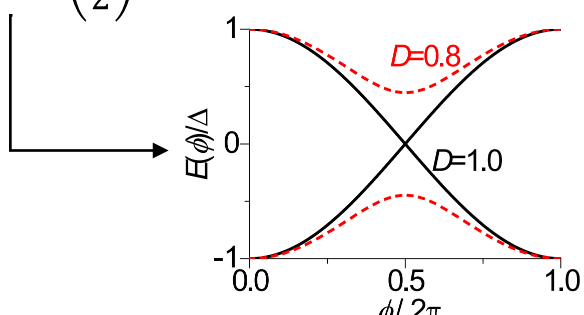
Bohr-Sommerfeld quantization:

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

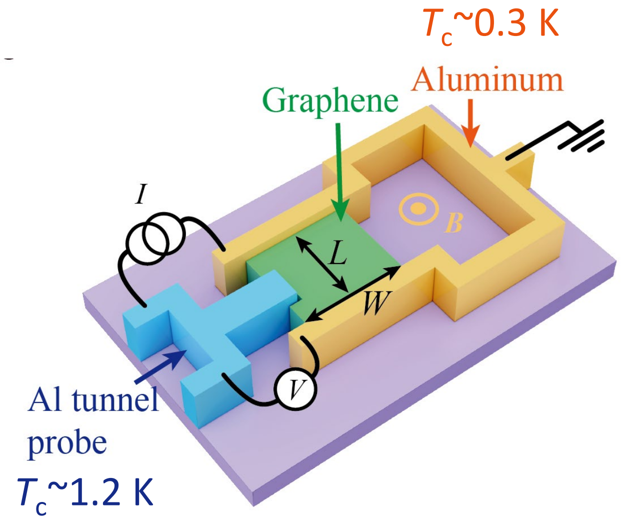
Phase difference : $\phi \equiv \phi_2 - \phi_1$
Momentum: $k^{\pm} = k_F \pm E/\hbar v_F$
Transparency at S/N interface: D

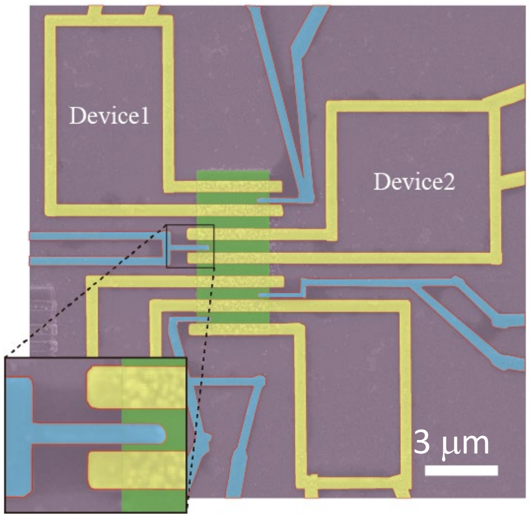
$$\downarrow$$

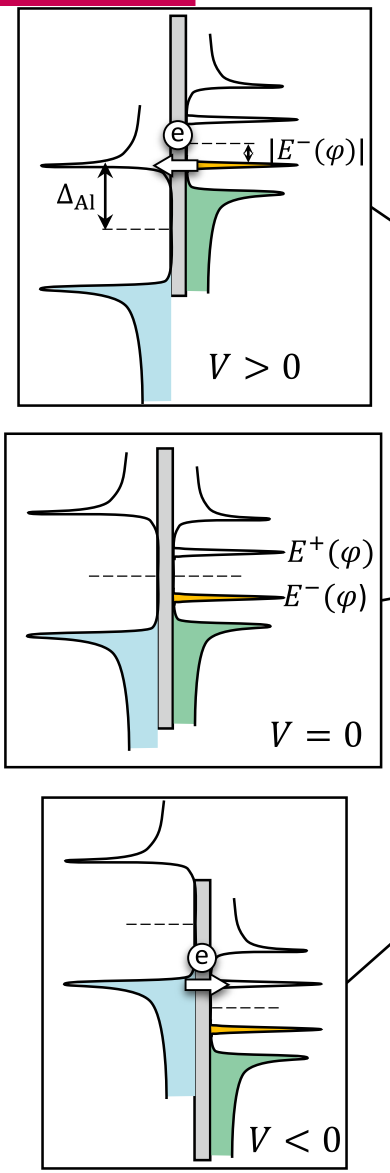
$$E^{\pm} = \pm\Delta\cos\left(\frac{\phi}{2}\right)$$

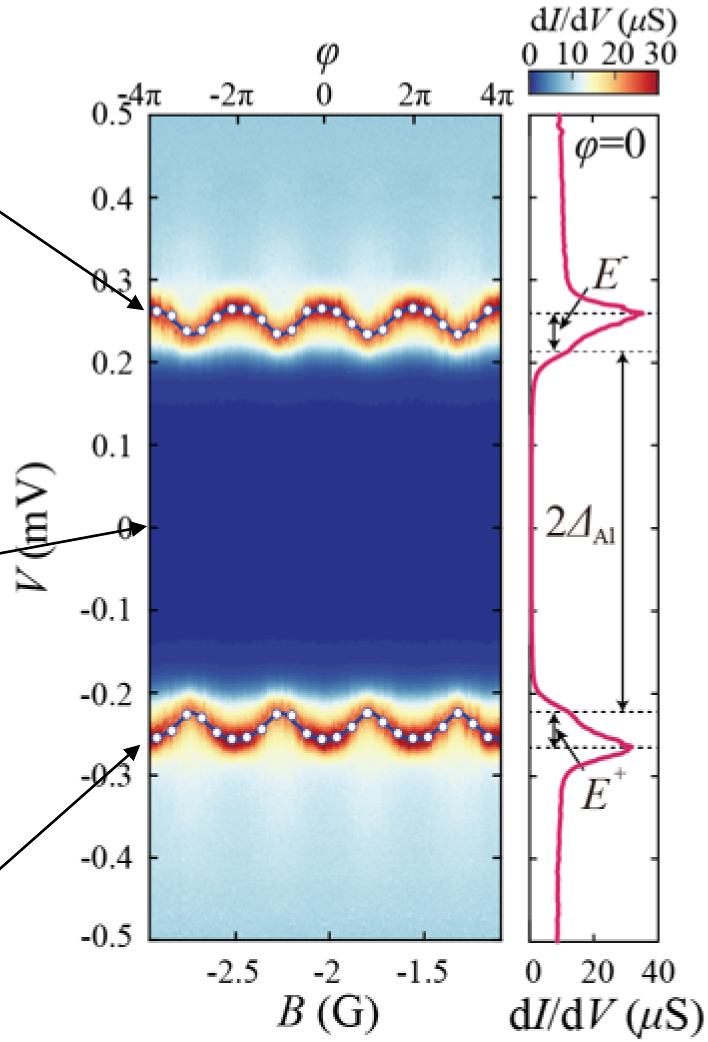


ABS in Graphene Josephson Junction



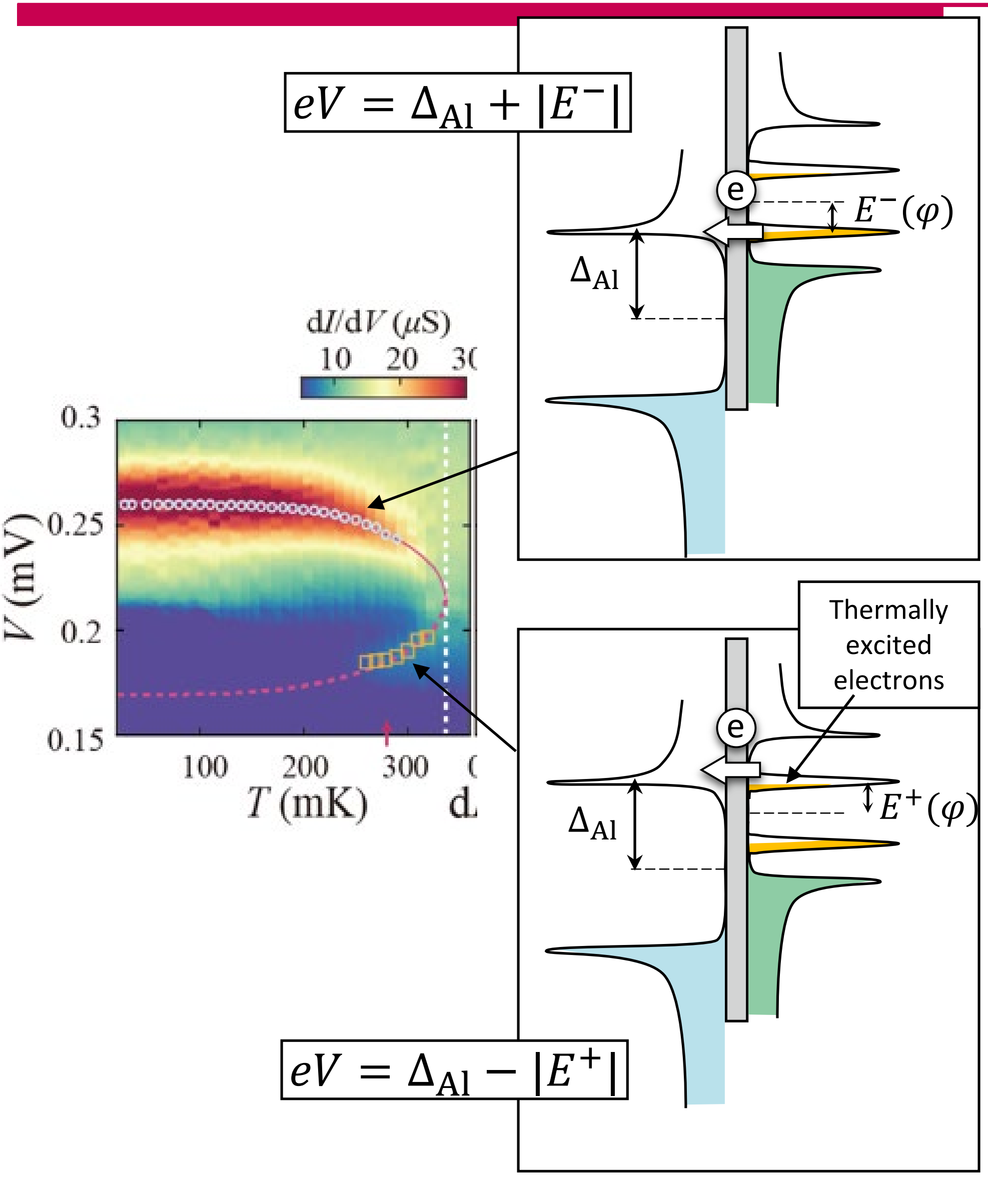




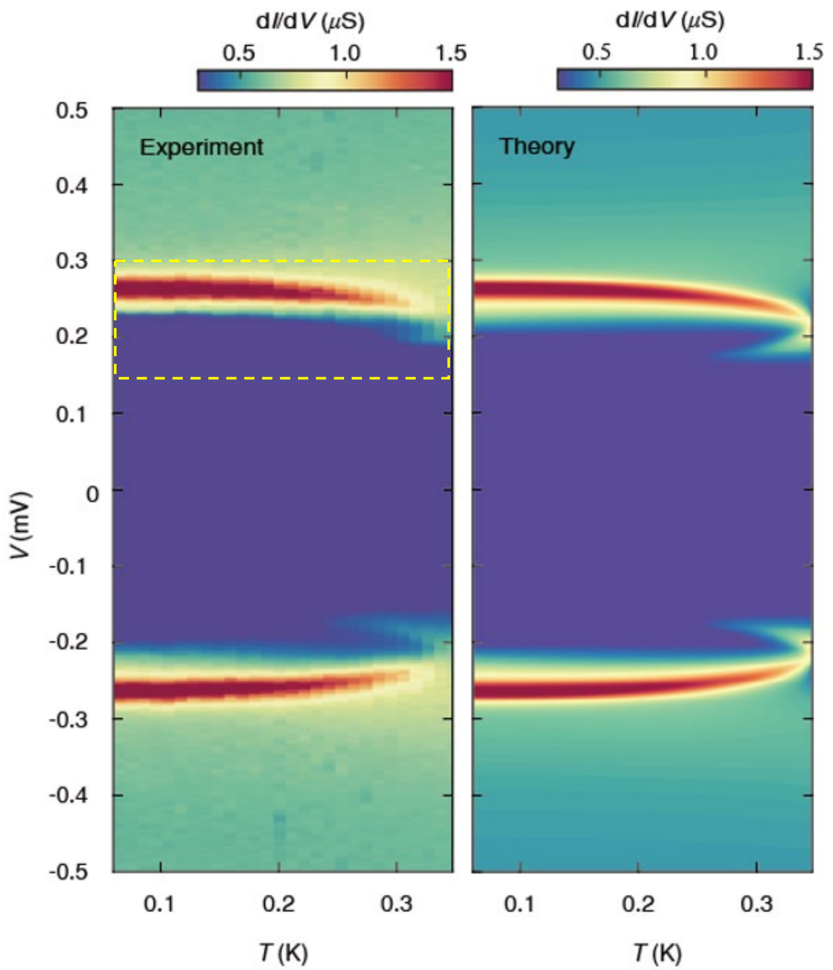


[S. Park *et al.*, *Nature* **603**, 421–426 (2022)]

Temperature Dependence

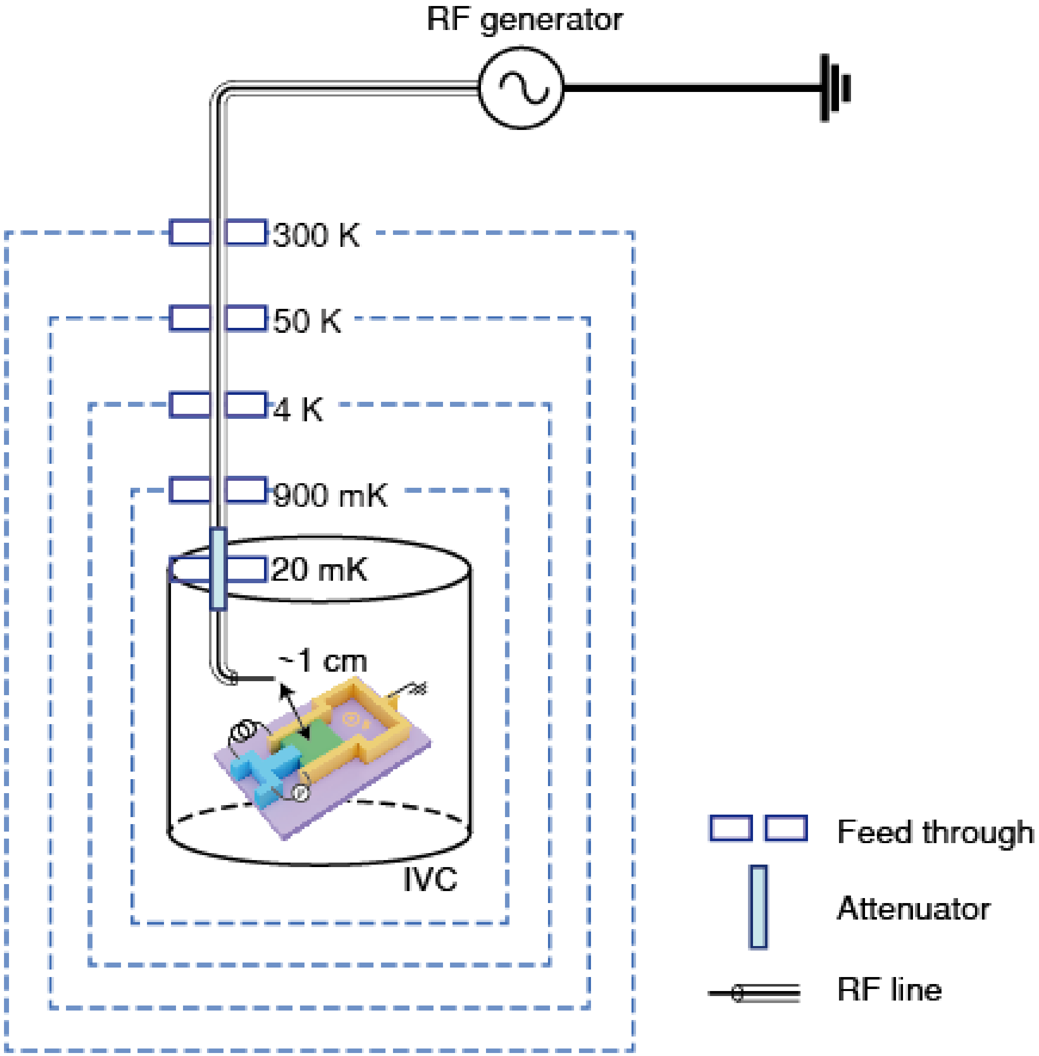


Theoretical calculation



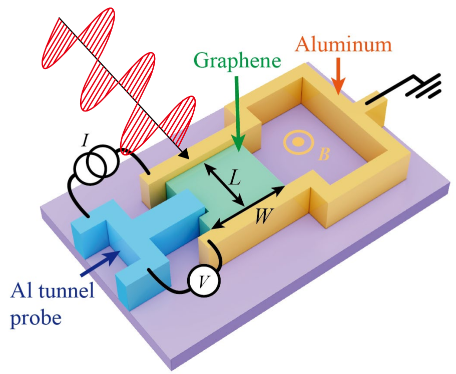
Floquet-Andreev State

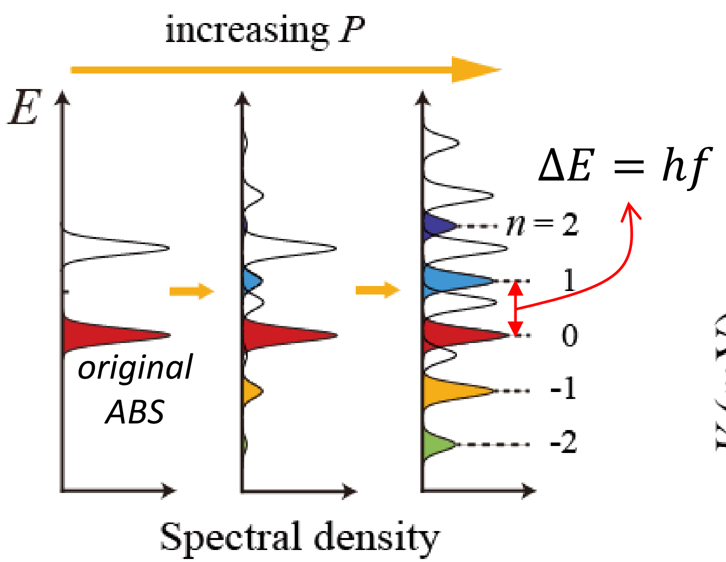
Experimental Setup for Microwave Irradiation

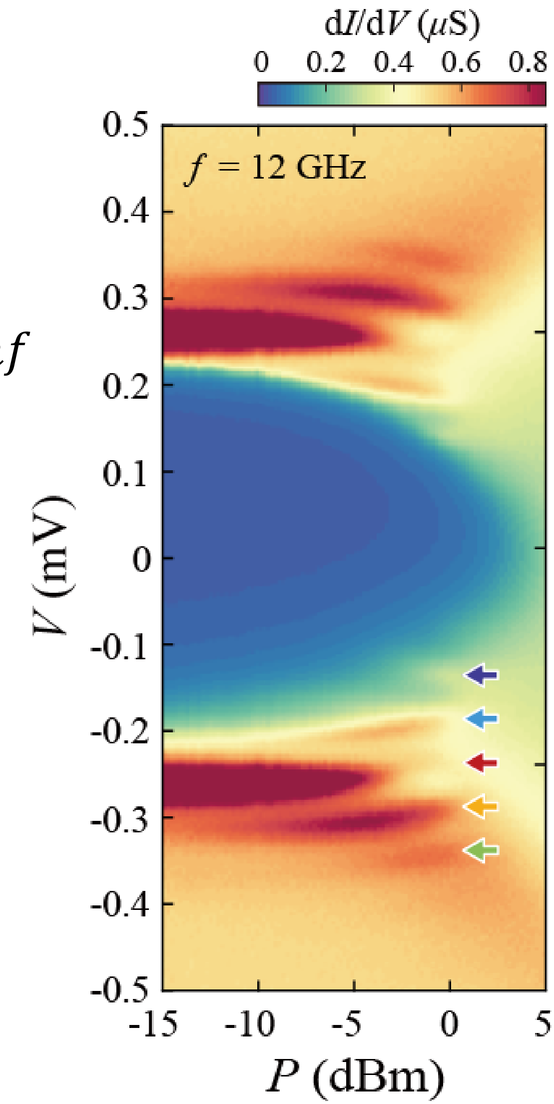


(Steady) Floquet-Andreev State

continuous microwave

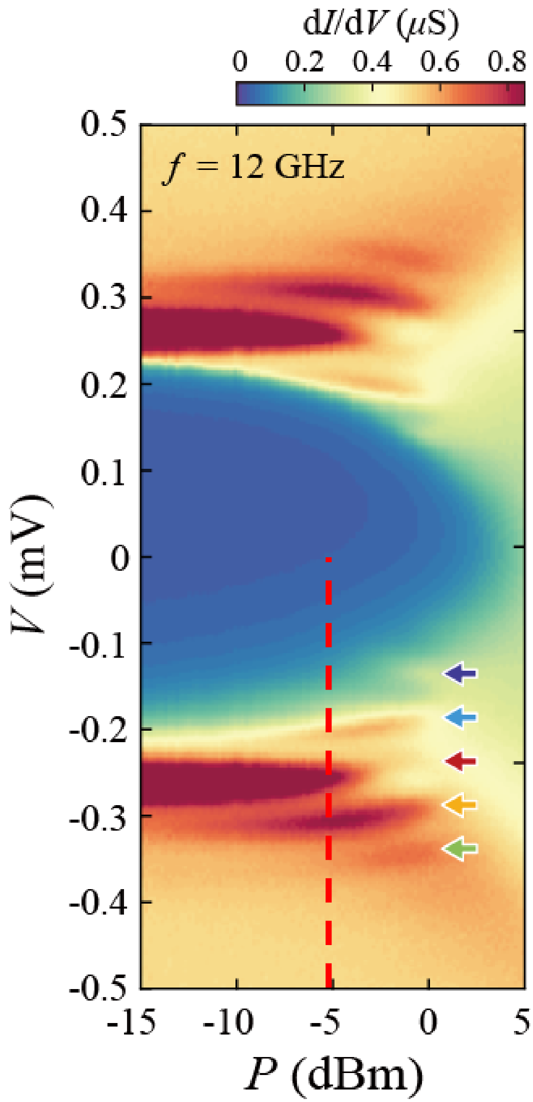




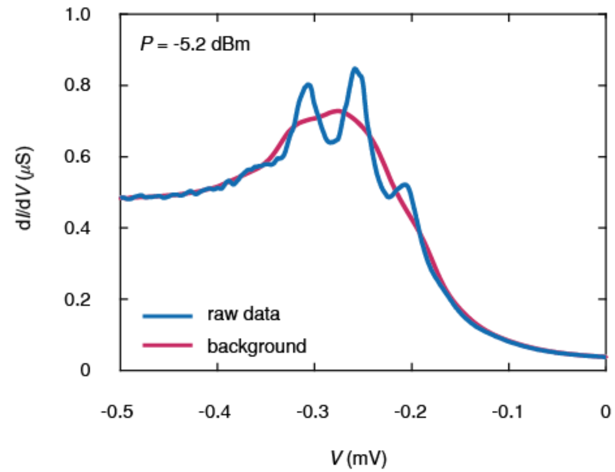


Replicas of ABS appears
under *continuous* MW irradiation

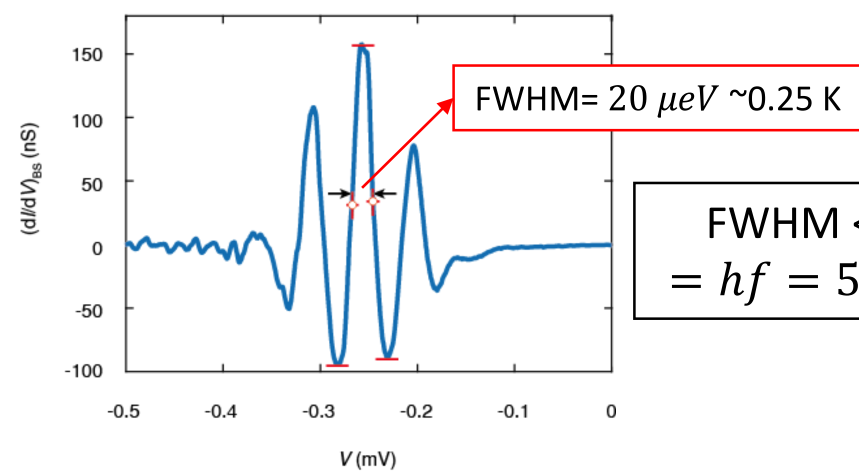
Energy Resolution of Tunnel Probe



Line cut of dI/dV



Background substrated



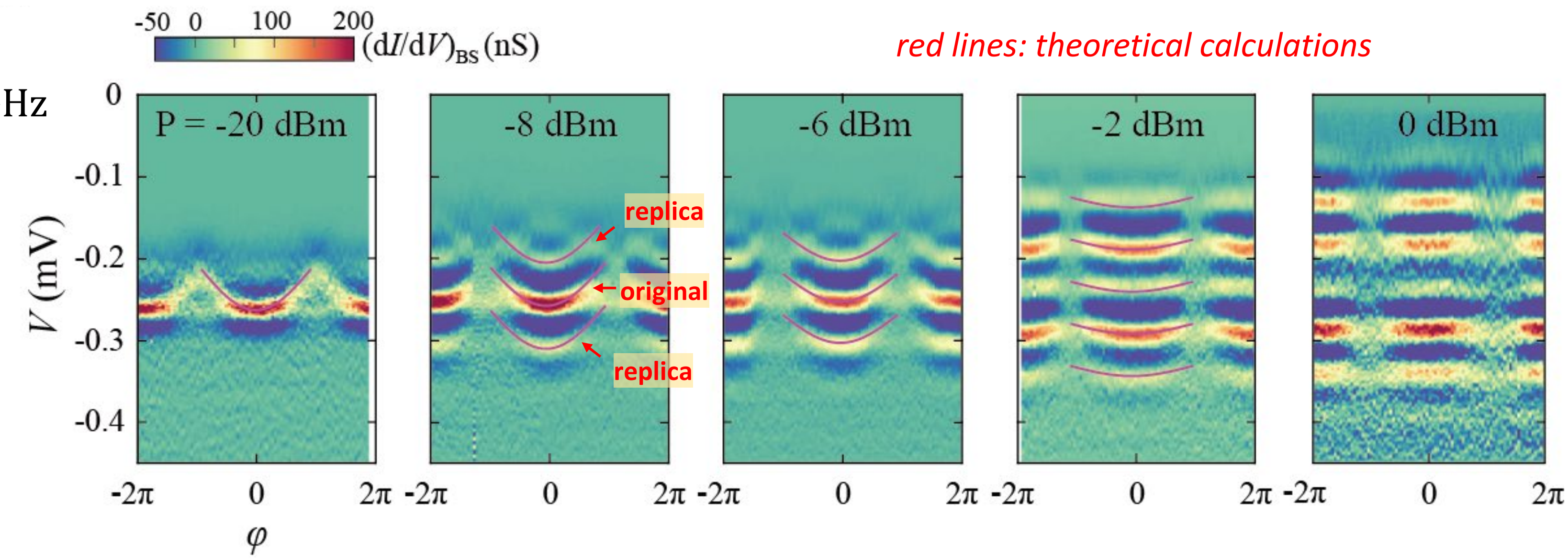
FWHM < ΔE
$= hf = 50\ \mu eV$

POSTECH

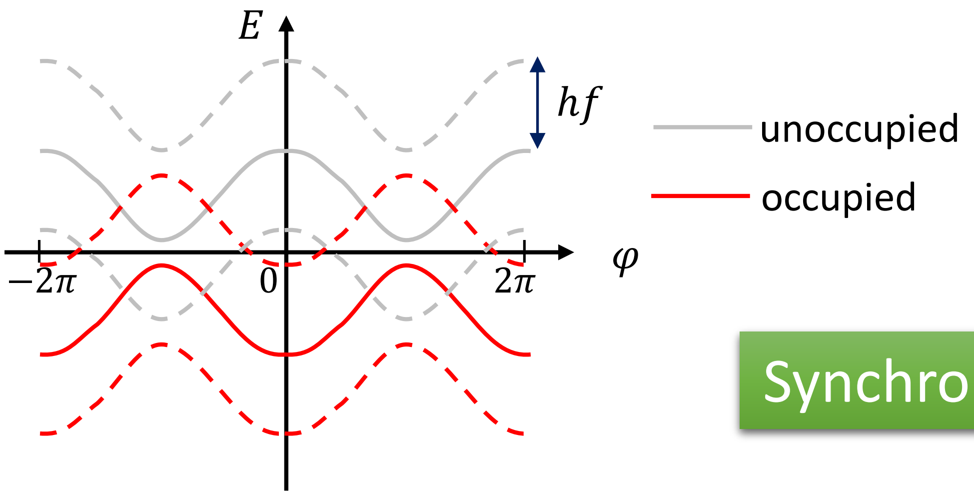
Magnetic Field Dependence

red lines: theoretical calculations

$f = 12$ GHz

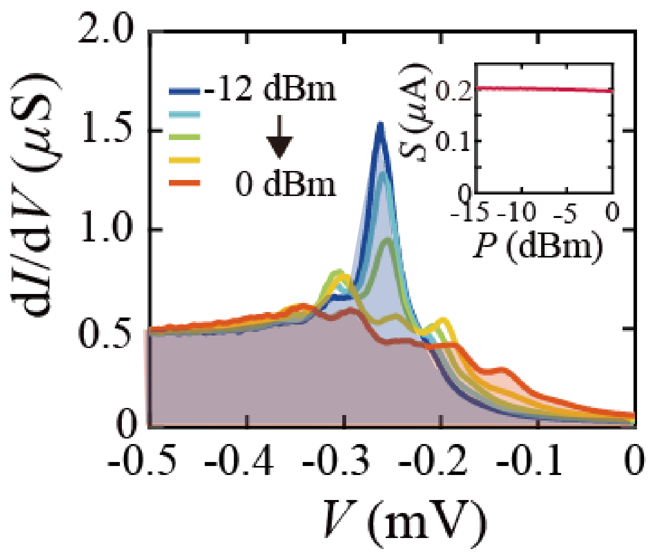


At higher *P*, device heating occurs.

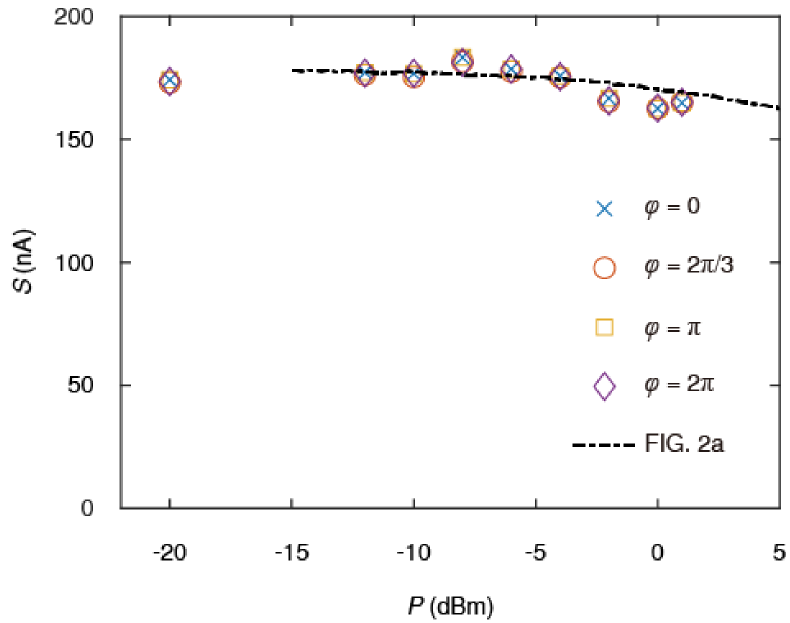


Synchronized oscillations with φ

Sum Rule



Sum-rule for various phase

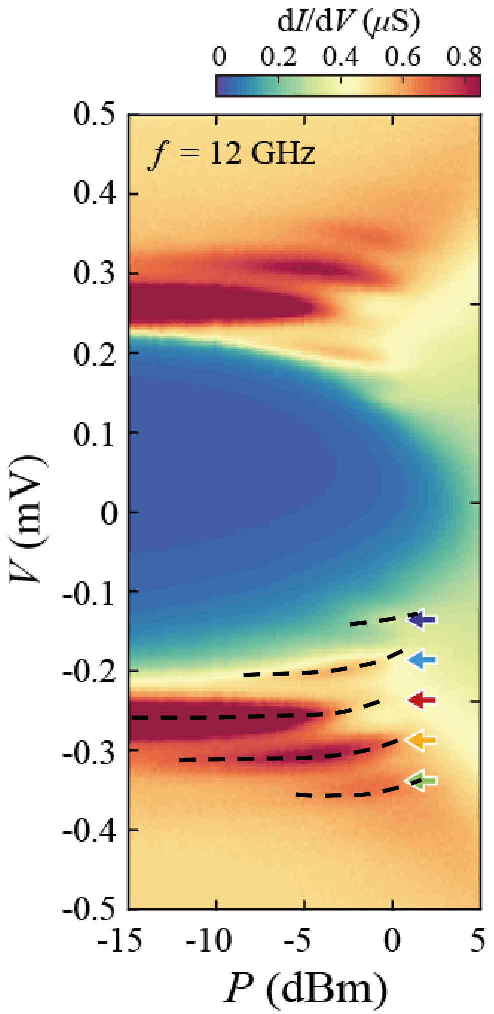


$$S = \int_0^{\infty} (dI/dV)\, dV = const.$$

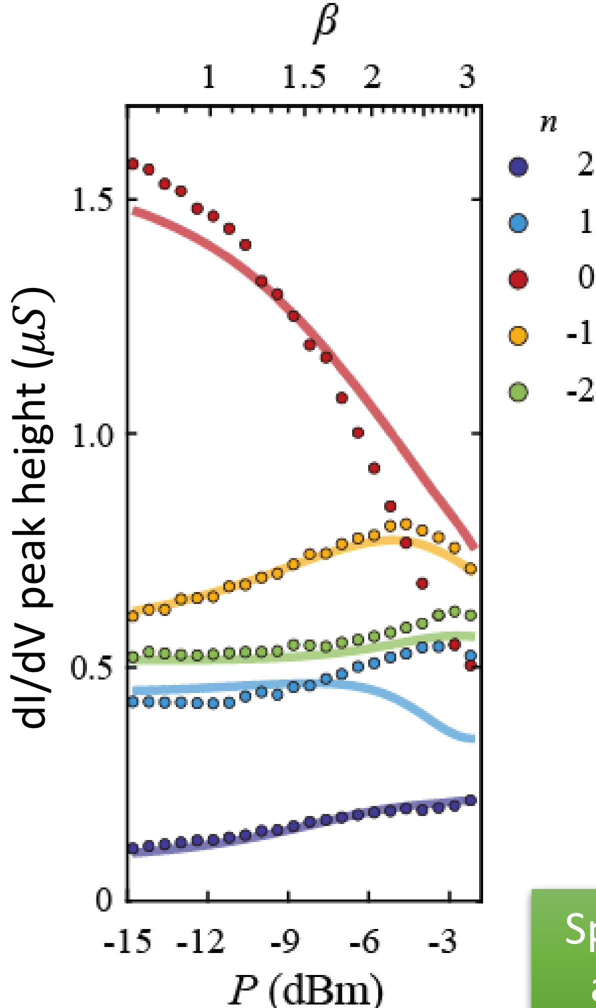
[PRL 122, 13060 (2019)]

Sum-rule could be checked thanks to steadiness of Floquet states.

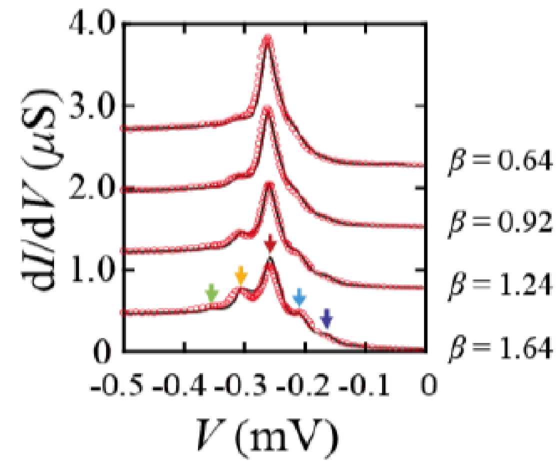
Microwave Power Dependence



P-dependence fitting



Line-cut fitting



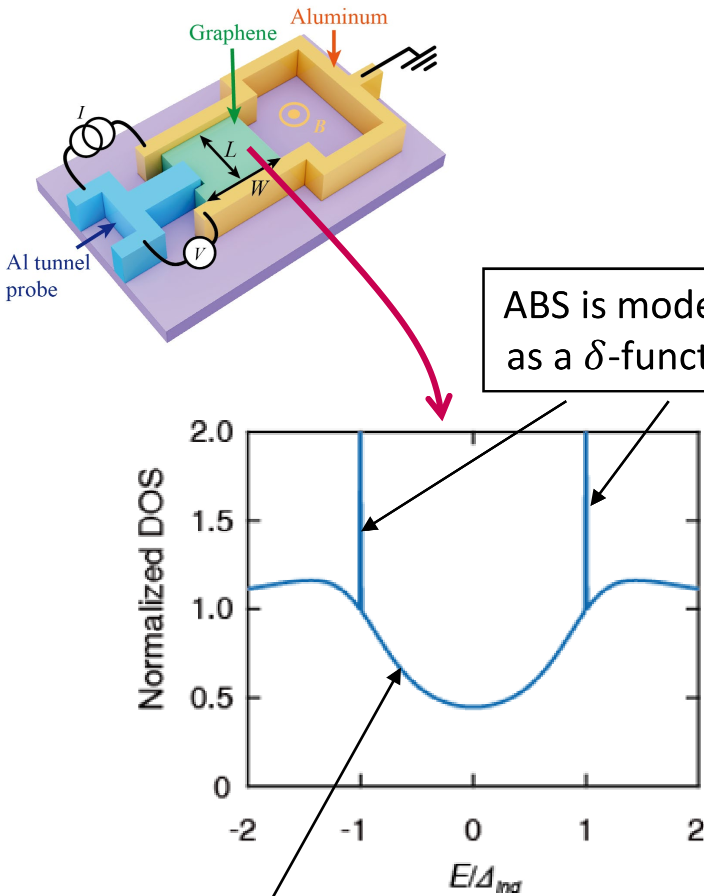
$$\overline{J_n} \equiv \frac{2}{\pi}\int_0^{2\pi} |J_n(\beta\cos\theta)|^2\, d\theta$$

Polarization averaged

$$E \sim 1\ \mathrm{V/m} \ll 10^7\,\mathrm{V/m}$$

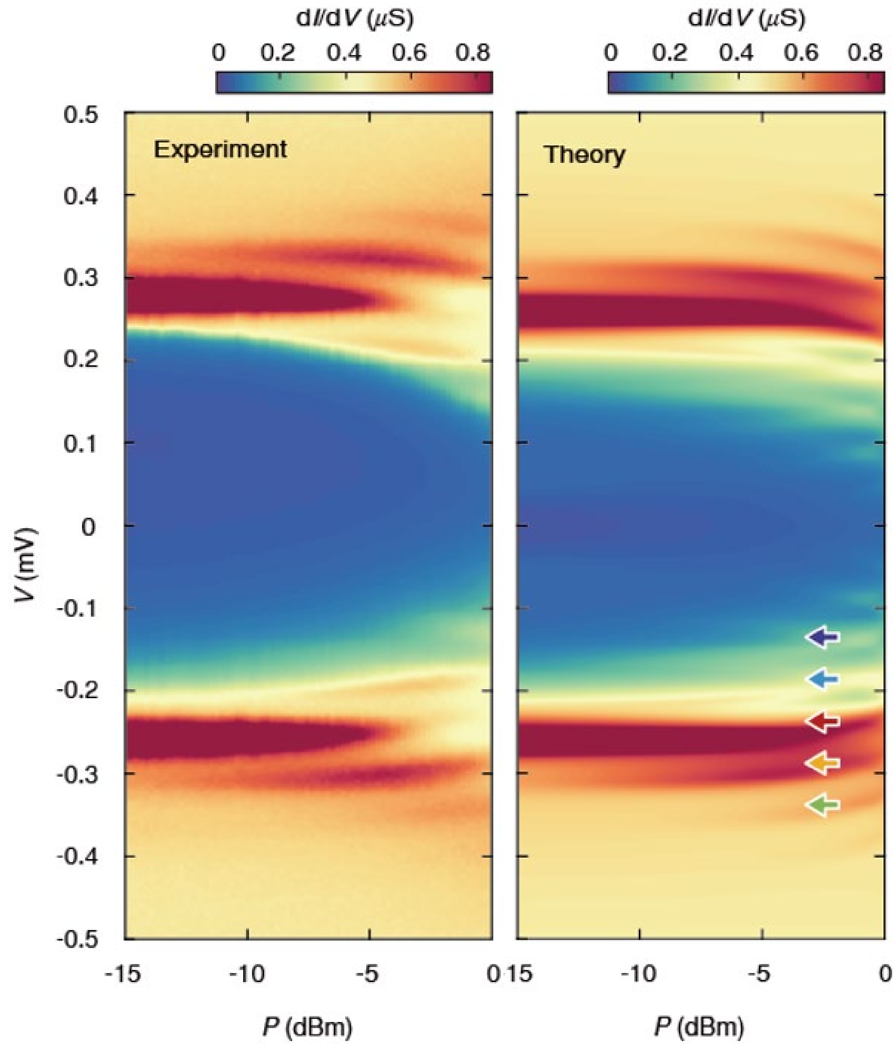
Spectral density follows polarization-averaged squared Bessel function.

Theoretical Calculations

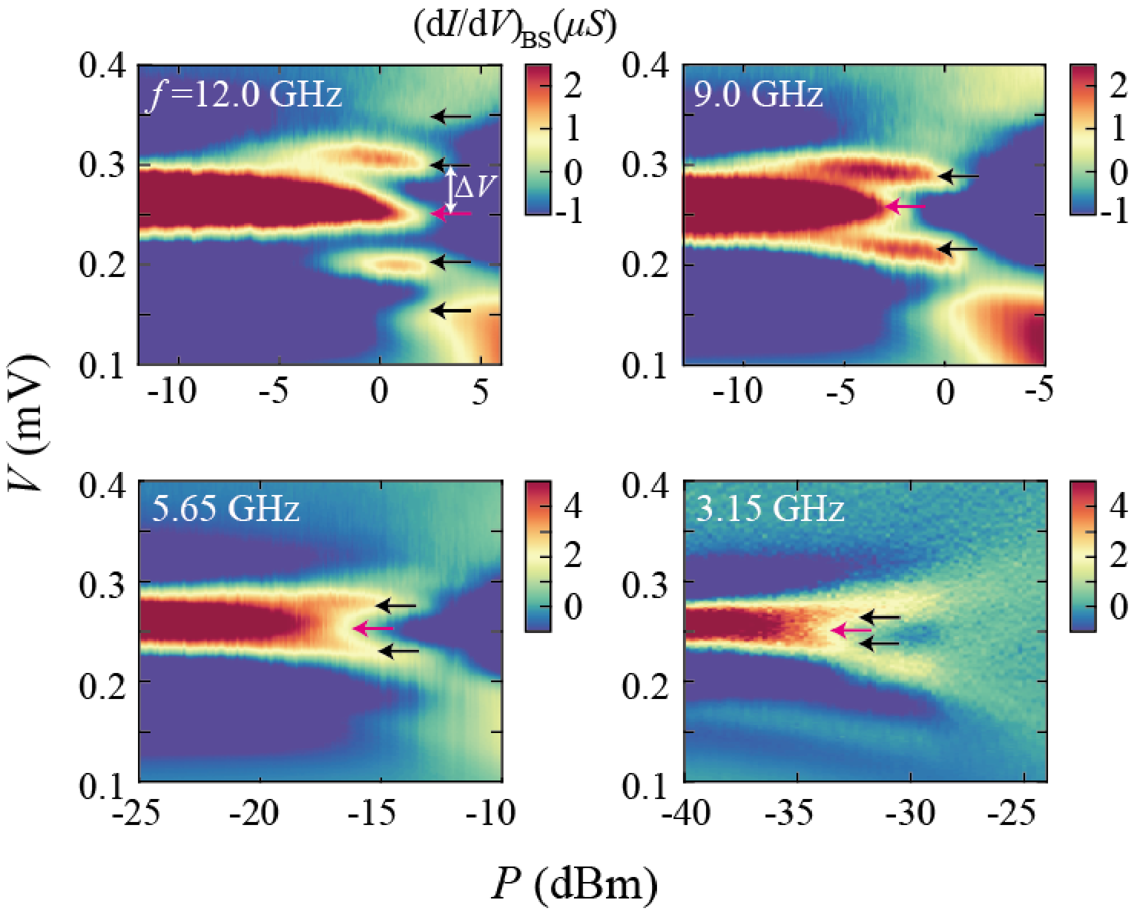


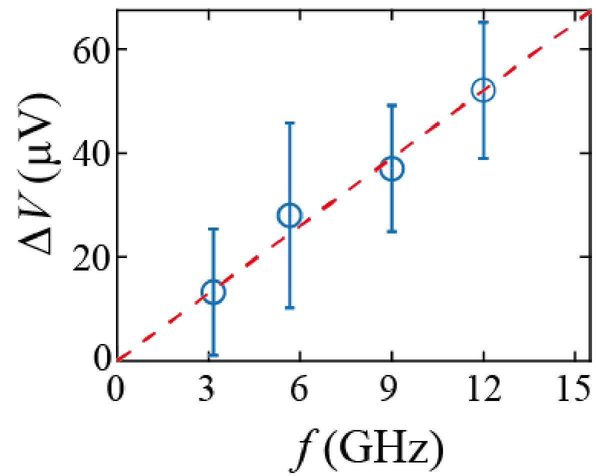
ABS is modelled as a δ-function.

Background comes from the proximity-induced superconductivity.



Frequency Dependence

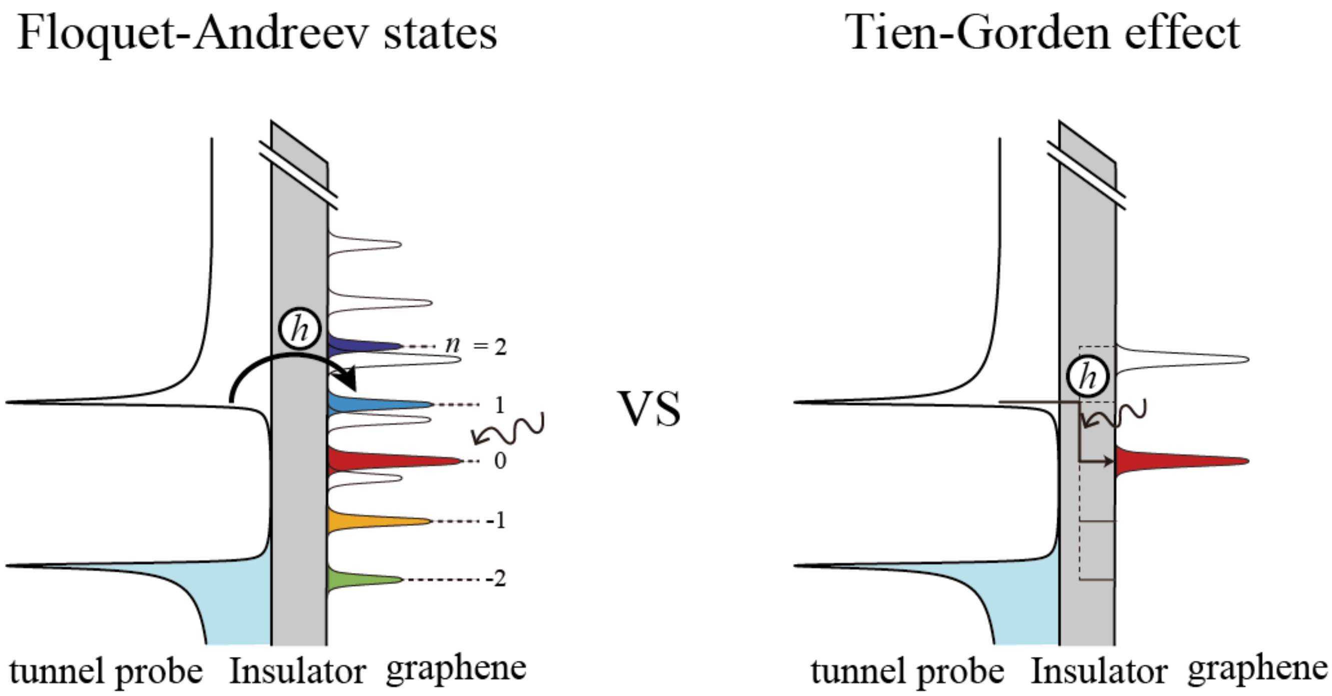




$$\Delta V = hf$$

Tien-Gordon Model v.s. Floquet Model

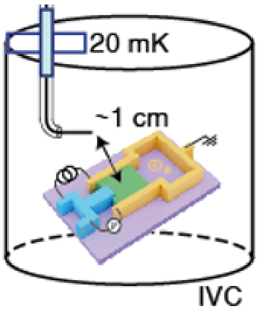
Tien-Gordon model for photo-assisted tunneling

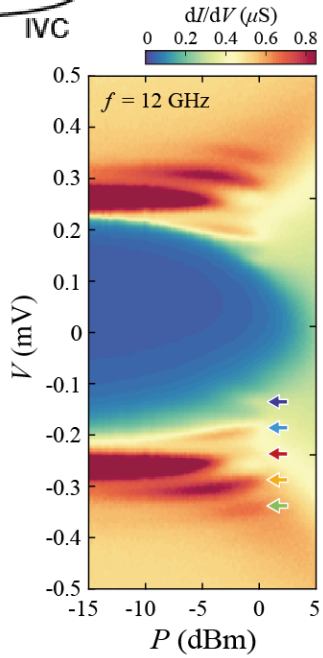


Improving Microwave Coupling

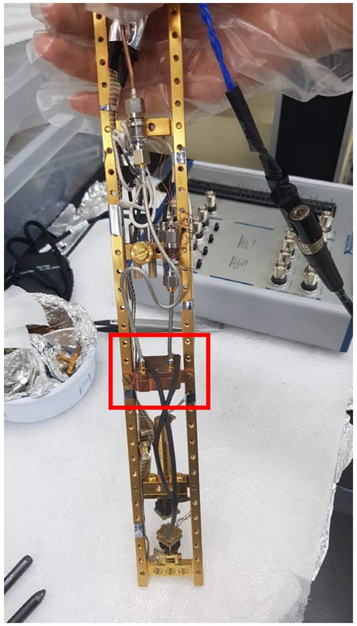
[Junho Suh, Jinwoong Cha (KRISS)]

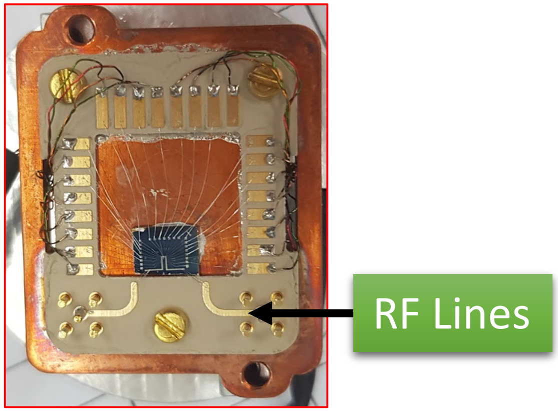
showering coupling scheme

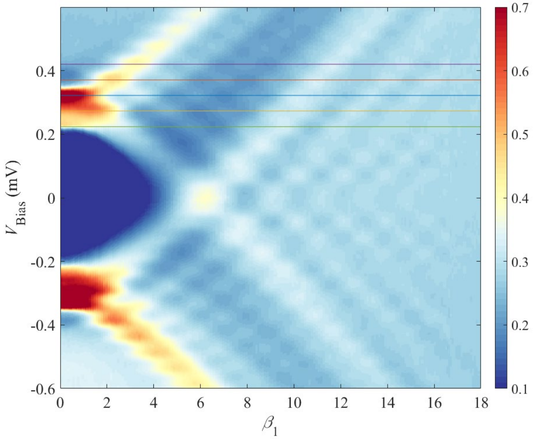




Flux-line coupling scheme



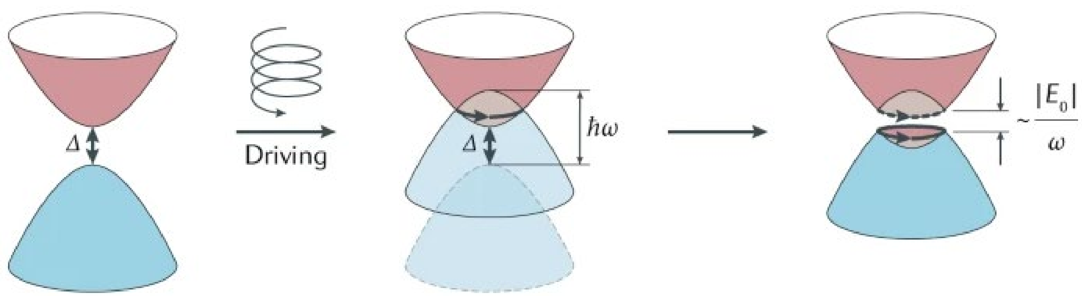


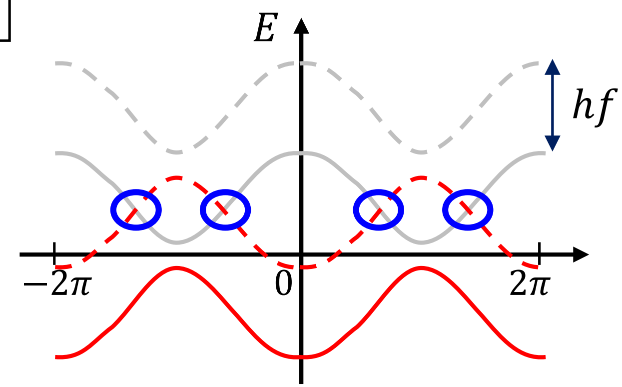


Higher Floquet states w/o heating

Outlook

Circular polarization light for topological phase transition

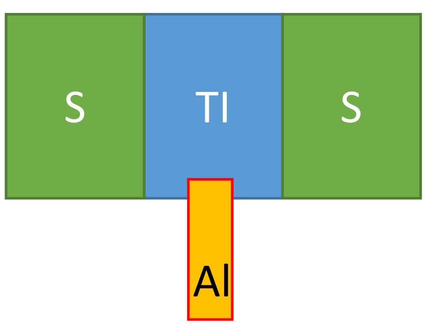


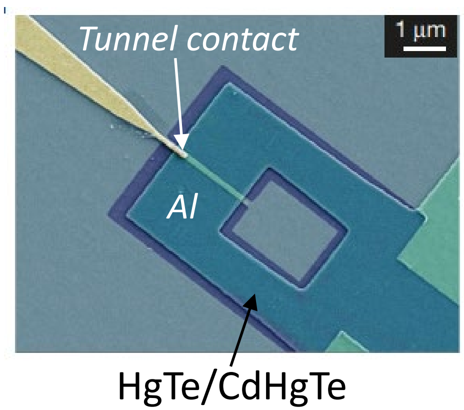


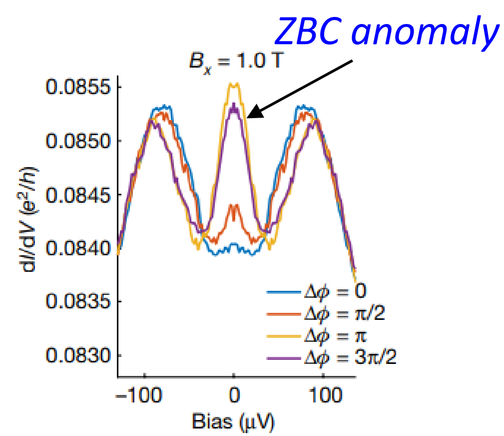
[Nat. Rev. Phys. 2, 229–244 (2020)]

Studying topological Josephson junctions

Looking for Majorana fermions



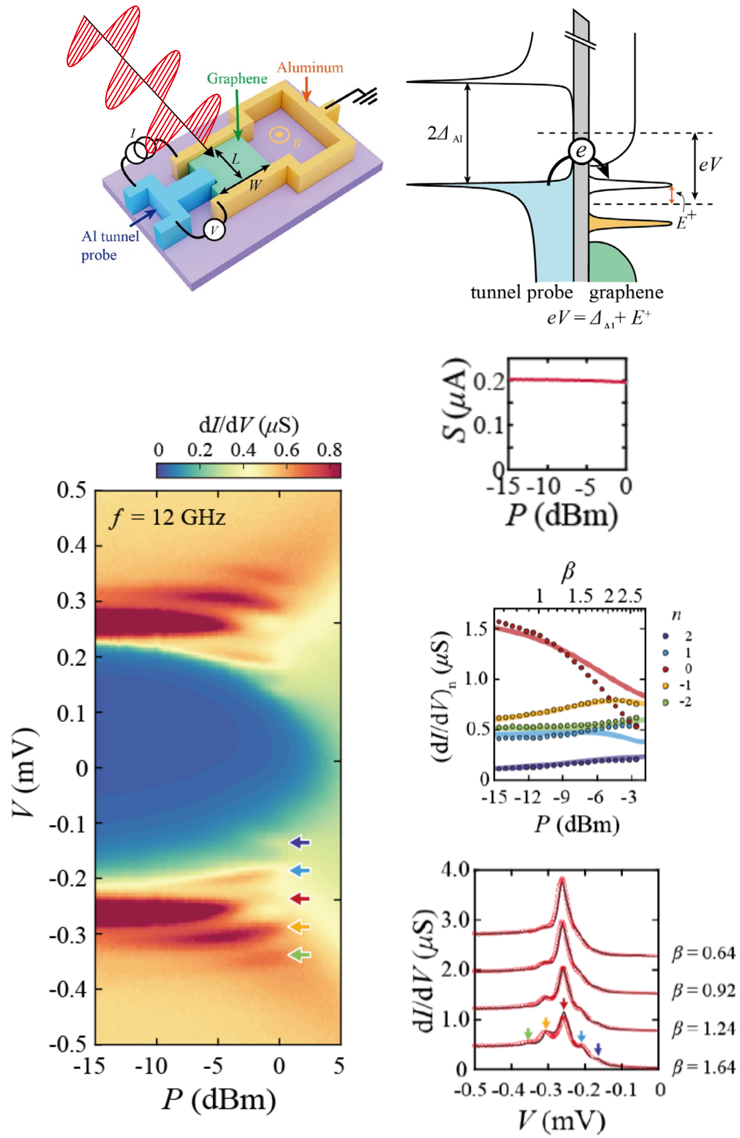




[Nature 569, 93–98 (2019)]

Summary

- Superconducting tunnelling spectroscopy with high energy resolution of ~ 20 μV
- Observed Andreev bound state (ABS) of graphene Josephson junction
- Observed *steady* Floquet-Andreev state by irradiating *continuous* microwave
- Quantitative analysis
  - Sum-rule
  - Fitting Power dependence (squared Bessel function)
  - Fitting dI/dV curves
- Side tunnel contact method may be applicable to other 2D materials.



Tunneling Spectroscopy on ABS

[J-D. Pillet *et al.*, Nat. Phys. 6, 965–969 (2010)]