Calibration of Graphene-based Josephson Junction Detector for Dark Matter Search

Seunghan Lee

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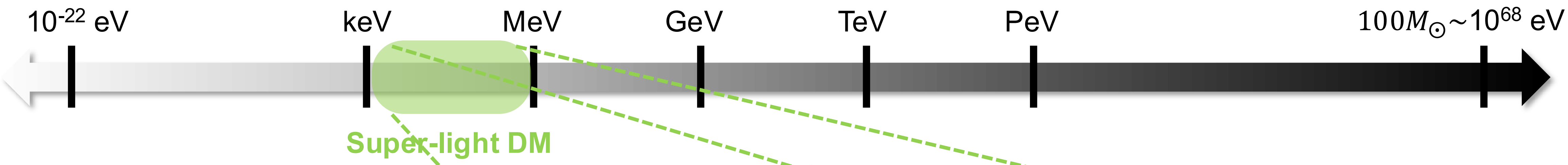
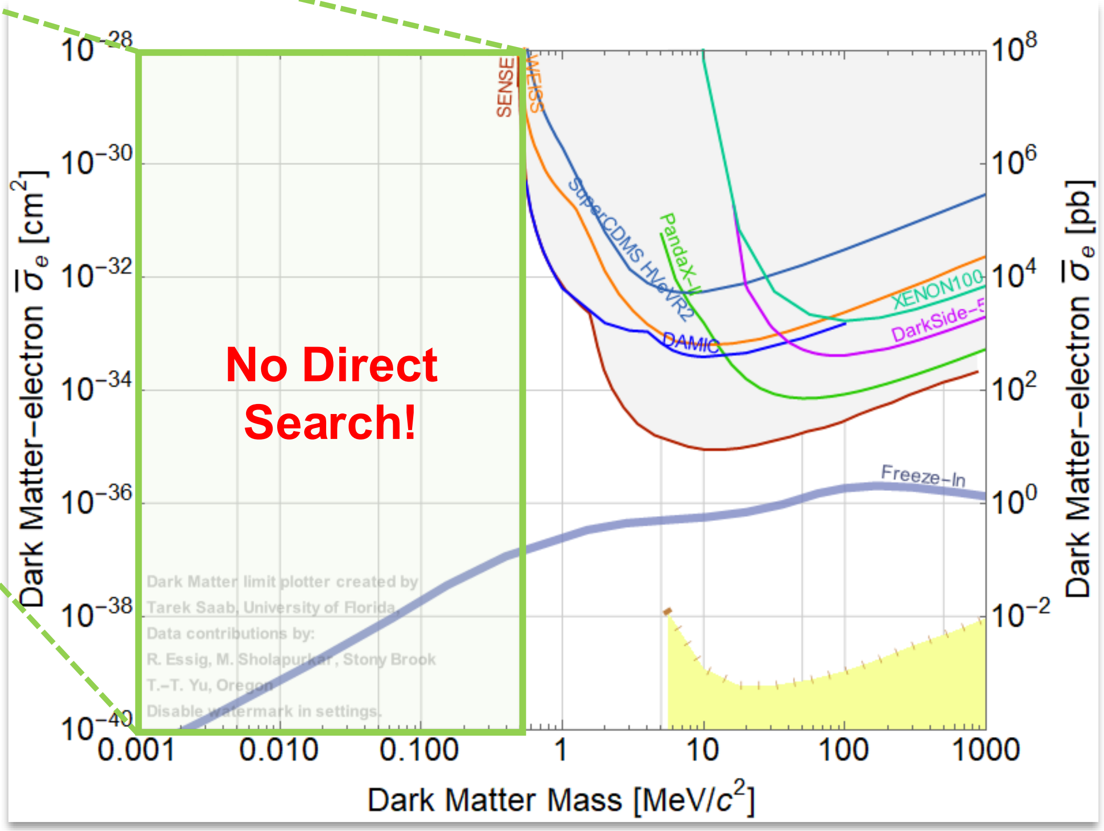
Necessity of a sensitive Detector for Dark Matter Search



❖ $\boldsymbol{E_k \sim mv^2 \sim O(\text{meV})}$ with $m\sim$keV & $v\sim10^{-3}$c

❖ **New approaches** are required!

- ✓ KID [arXiv:2403.19739 (2024)]
- ✓ SNSPD [PRL (2025)]
- ✓ TES [arXiv:2506.18982 (2025)]
- ✓ Superconducting Qubit [PRL (2021)]
- ✓ **Graphene Josephson Junction (GJJ)** [PRD 2025]



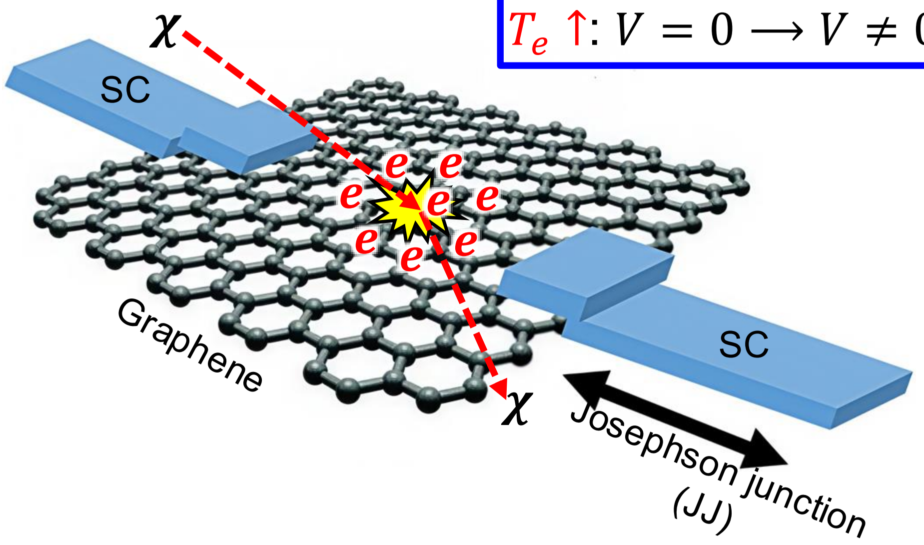
POSTECH

Our DM Search Strategy with GJJ

Graphene-based super-light invisible matter particle search

J.C. Park et al., PHYSICAL REVIEW D 112, 015002 (2025)

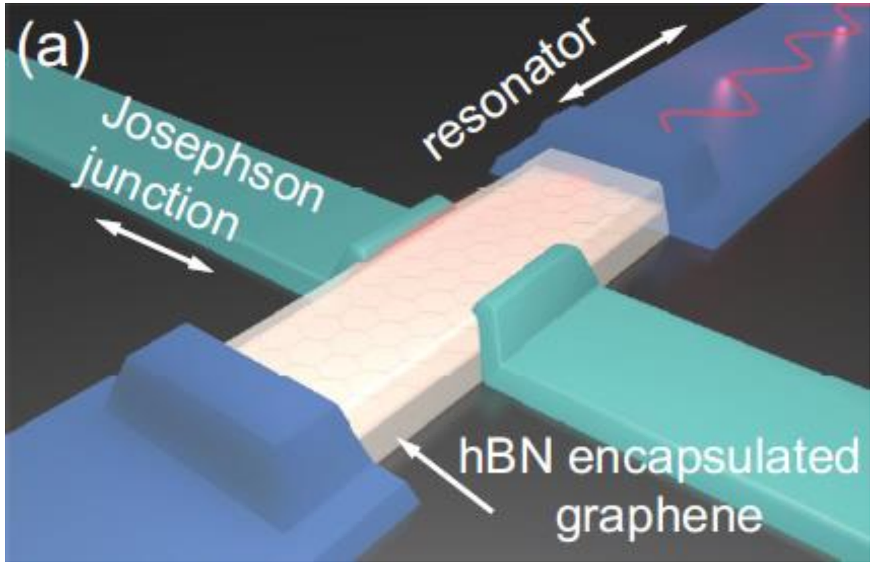
$T_e \uparrow: V = 0 \longrightarrow V \neq 0$



Super-light DM interacting with π-bond electrons

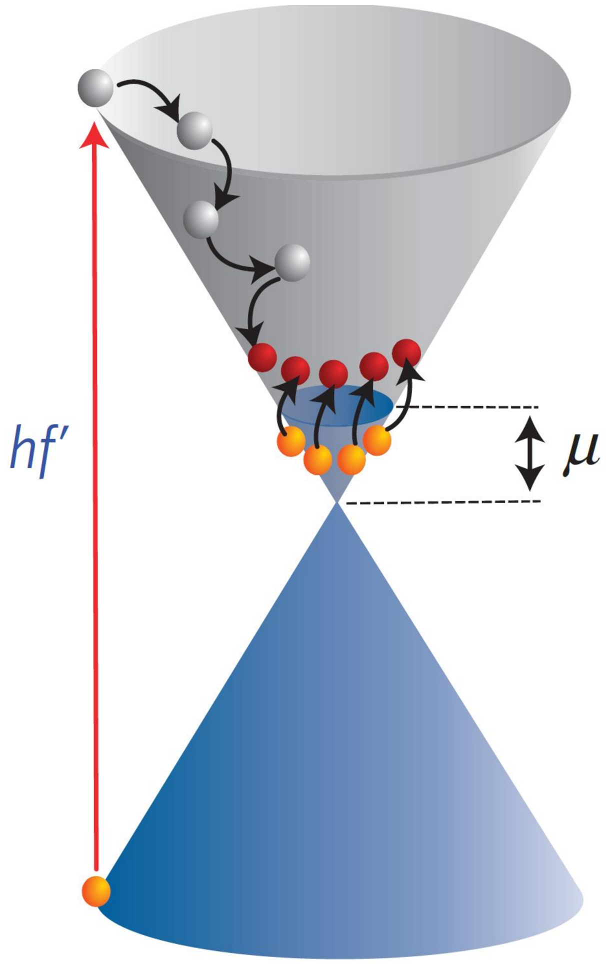
Graphene-based Josephson junction microwave bolometer

G.-H. Lee et al., Nature volume 586, pages42–46 (2020)

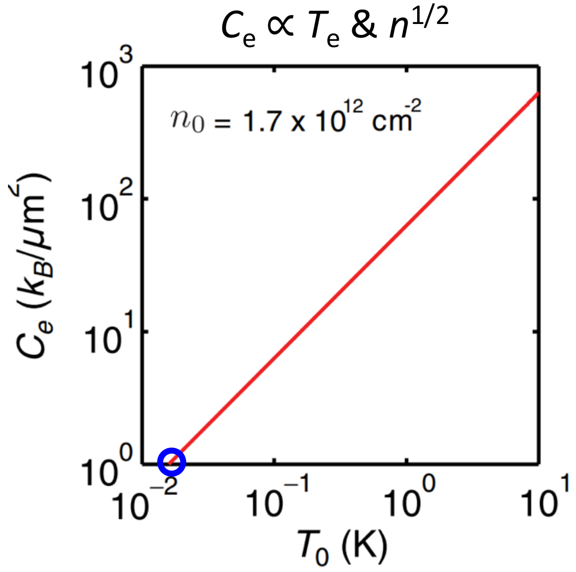


Expected E_{thres} = 0.13 meV (32 GHz)

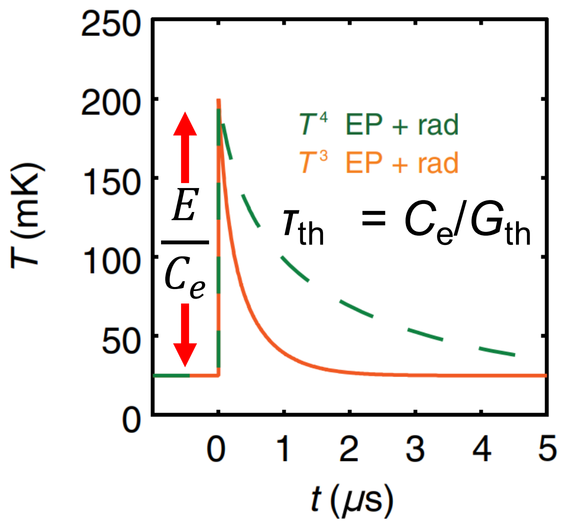
Graphene's Advantages: Focus on Thermal Properties

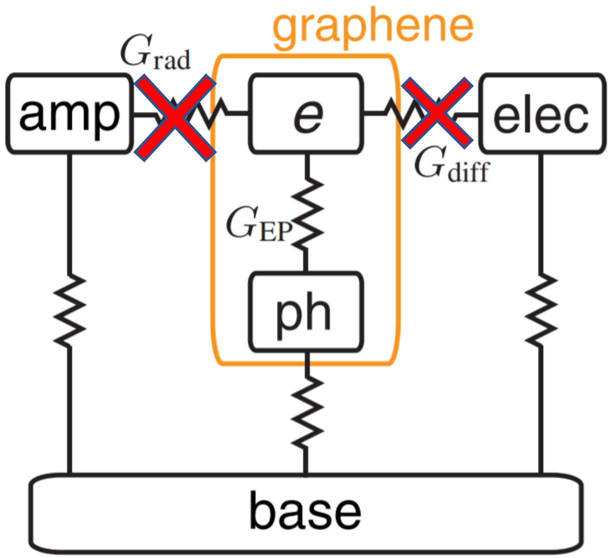


Nature Physics volume 9, pages248–252 (2013)



PHYSICAL REVIEW APPLIED 8, 024022 (2017)





[PRX **3**, 041008 (2013)]

- Shrinking density of state near the CNP → small C_e → **Higher** temperature rise
- weak thermal interaction by electron-phonon coupling (G_{EP}) → Low cooling power

∴ **Graphene is a highly promising material for thermal sensor**

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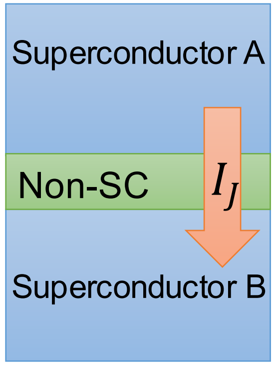
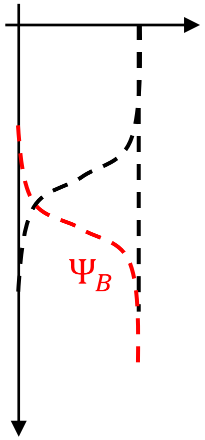
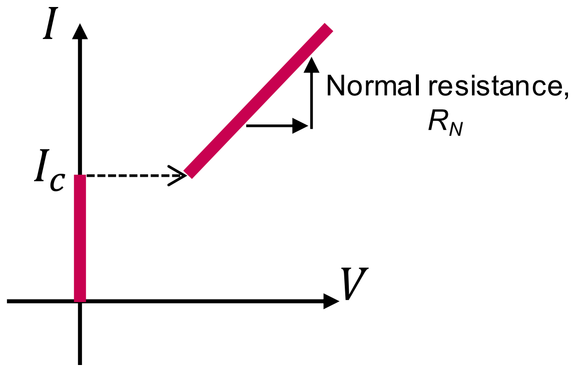
Graphene Josephson Junction

Josephson coupling



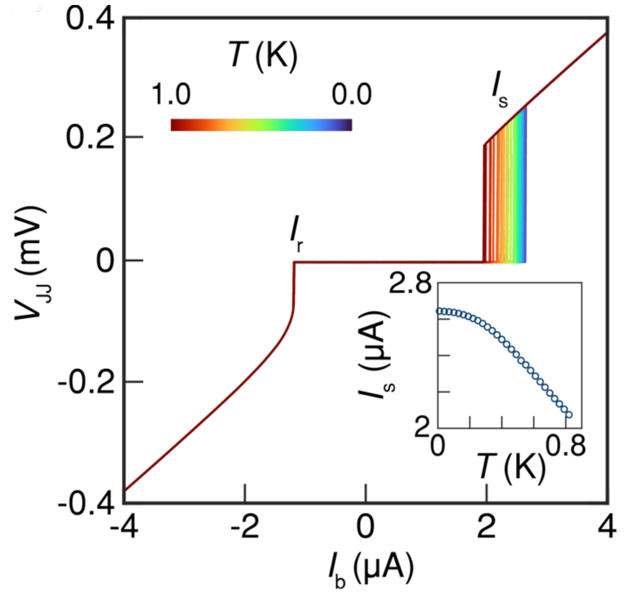


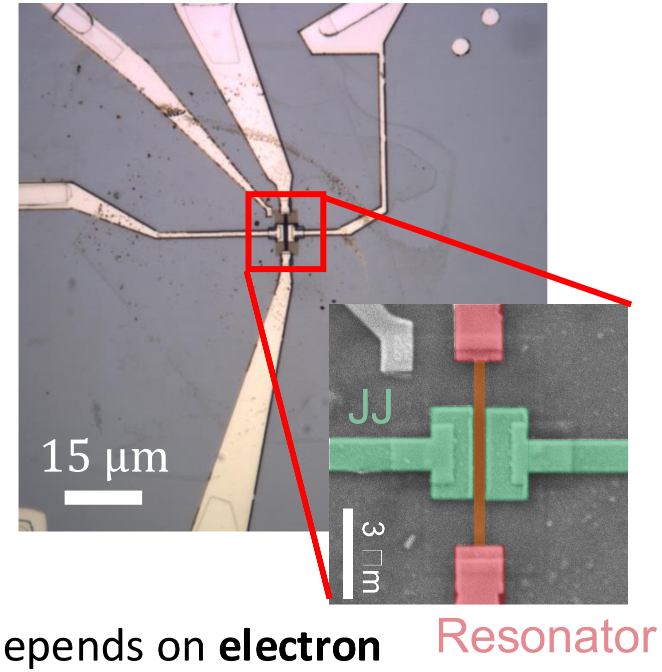
- **DC Josephson relation: $I_J = I_c \sin\phi$**
- AC Josephson relation: $\frac{d\phi}{dt} = 2eV/\hbar$



*Phase difference: $\phi \equiv \phi_B - \phi_A$
*critical current: I_c
*flux quantum: $\Phi_0 = h/2e$

Graphene Josephson Junction(GJJ) critical current **Temp. Dep.**





- Switching current, $\langle I_s \rangle$, strongly depends on **electron temperature of graphene**.

d$\langle I_s \rangle$/dT **~-0.5 μA/K**

- Switching happens very fast, **within ~10 ps.**

ω_p **~ 100 GHz**

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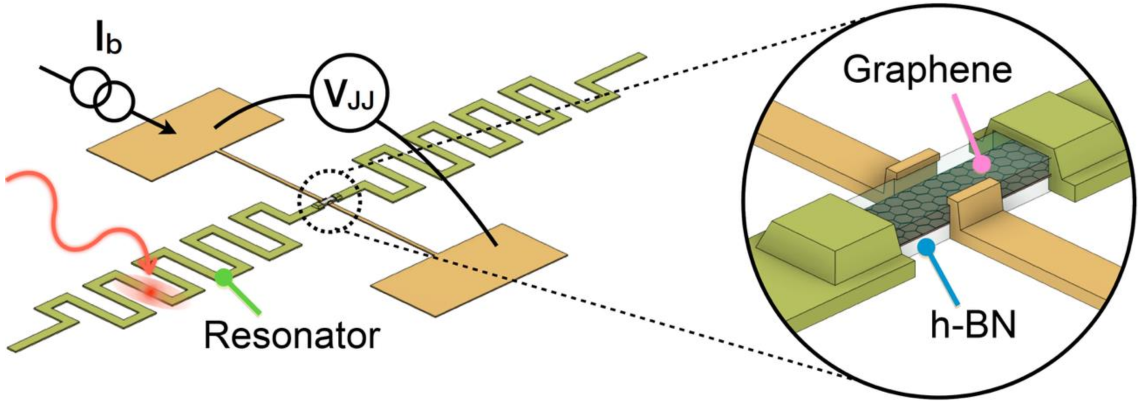
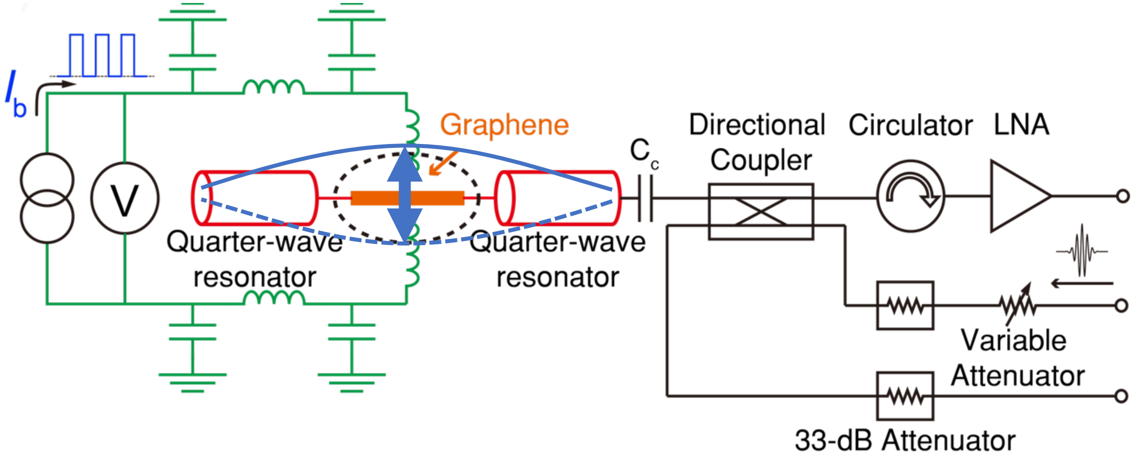
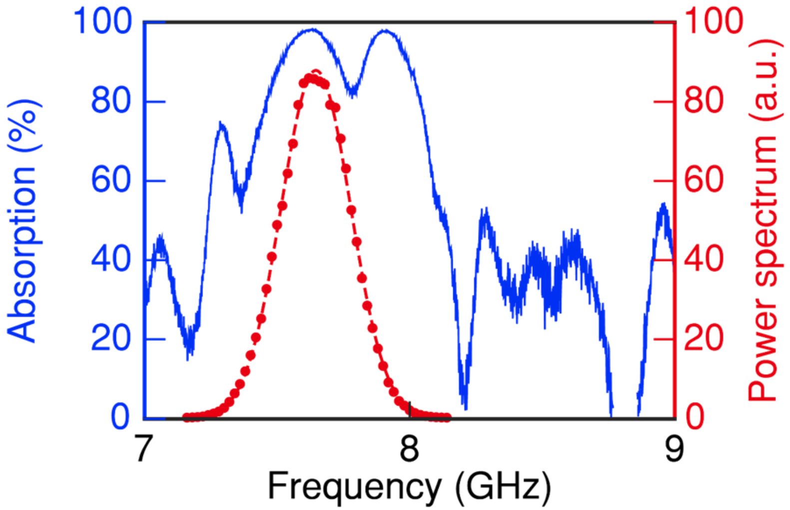
Proposal: Calibration of GJJ Detector with Microwave Pulse

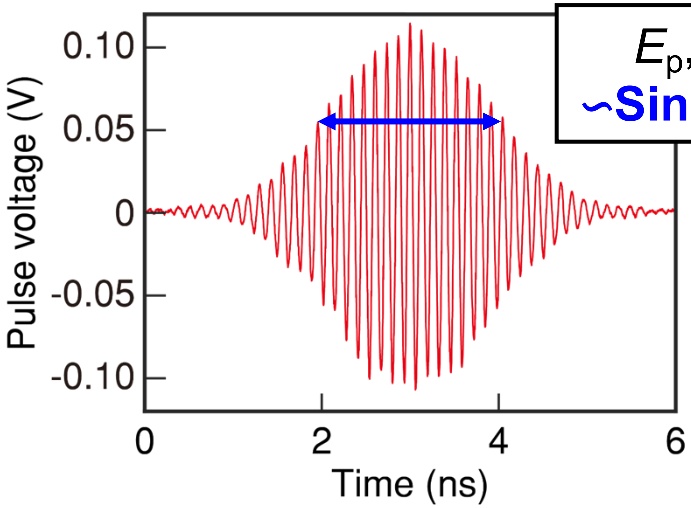
Josephson Junctions in the Age of Quantum Discovery
arXiv:2505.12724 [quant-ph]







t_p = 2 ns << τ_{th} = C_e/G_{th} = 18.5 ns



E_p, f tunable 1 ns Pulse
~Single energy deposition

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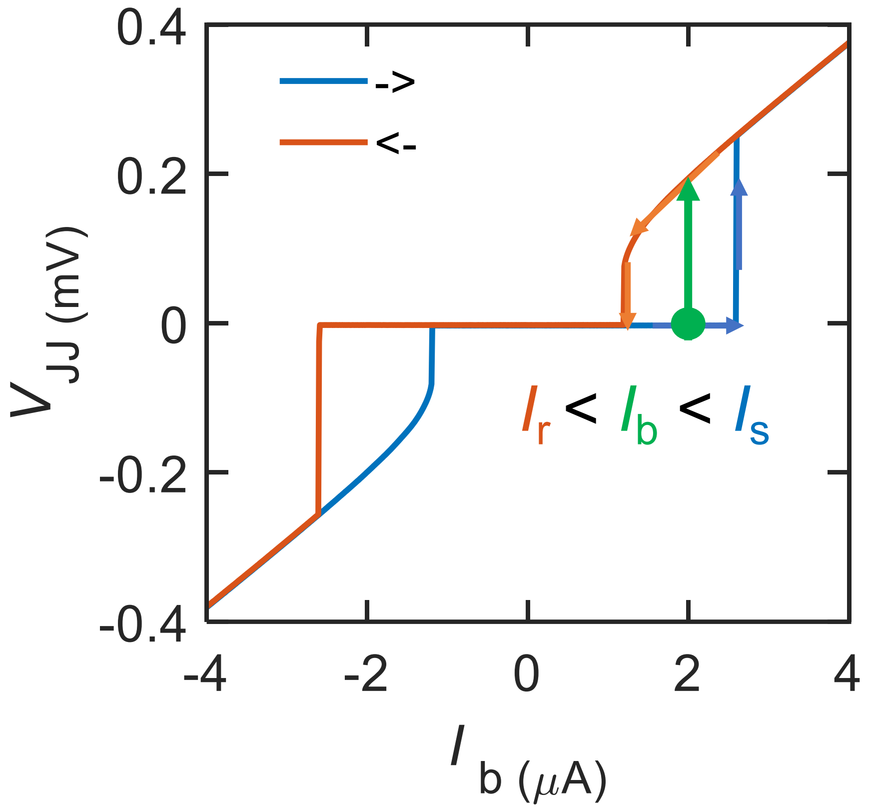
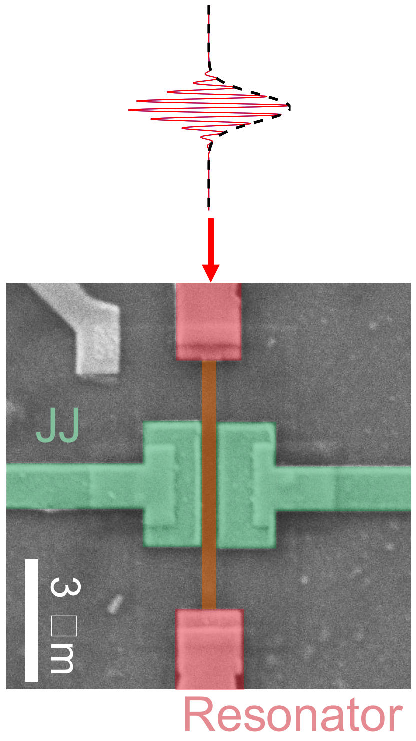
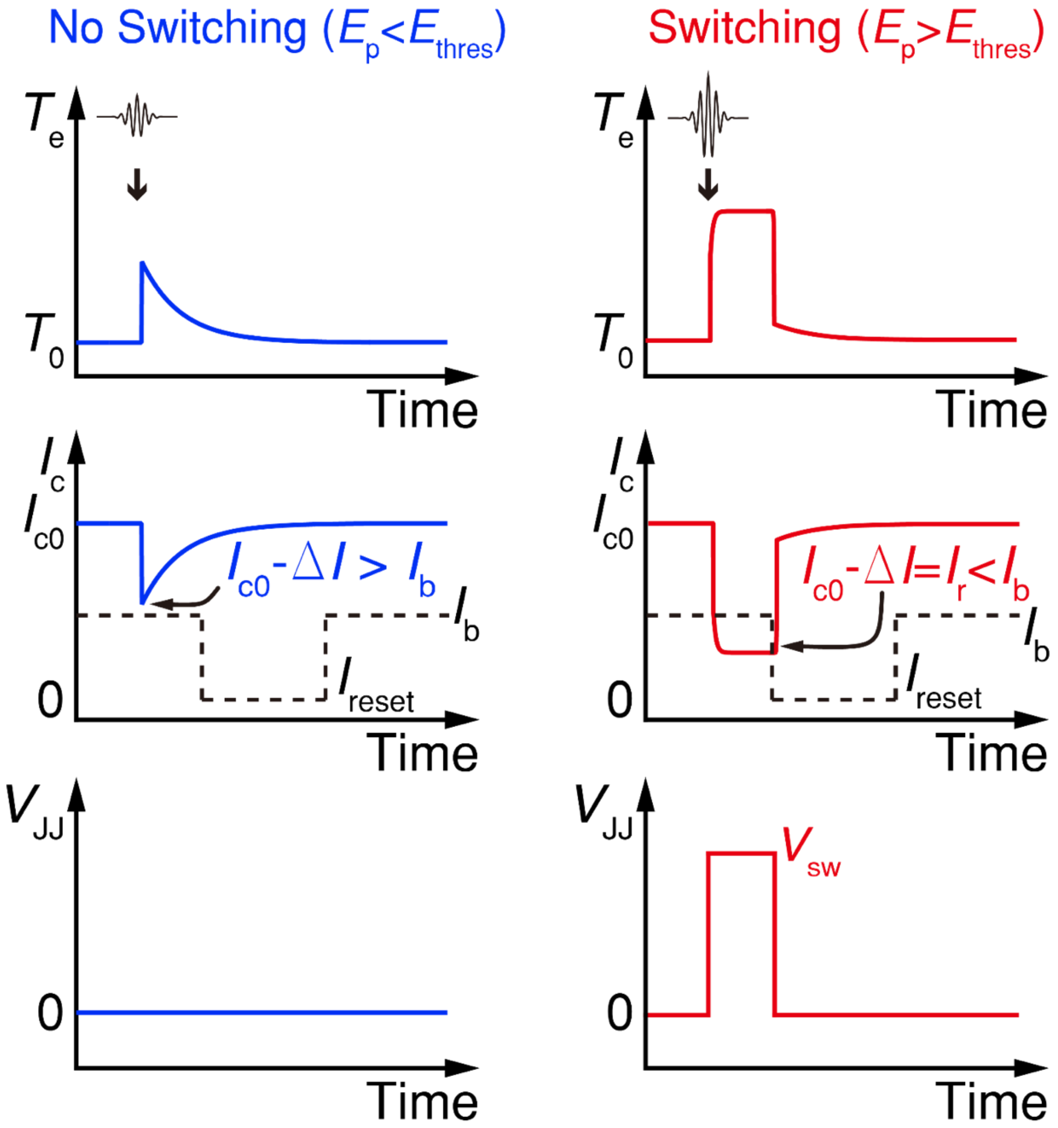
Proposal: Calibration of GJJ Detector with Microwave Pulse

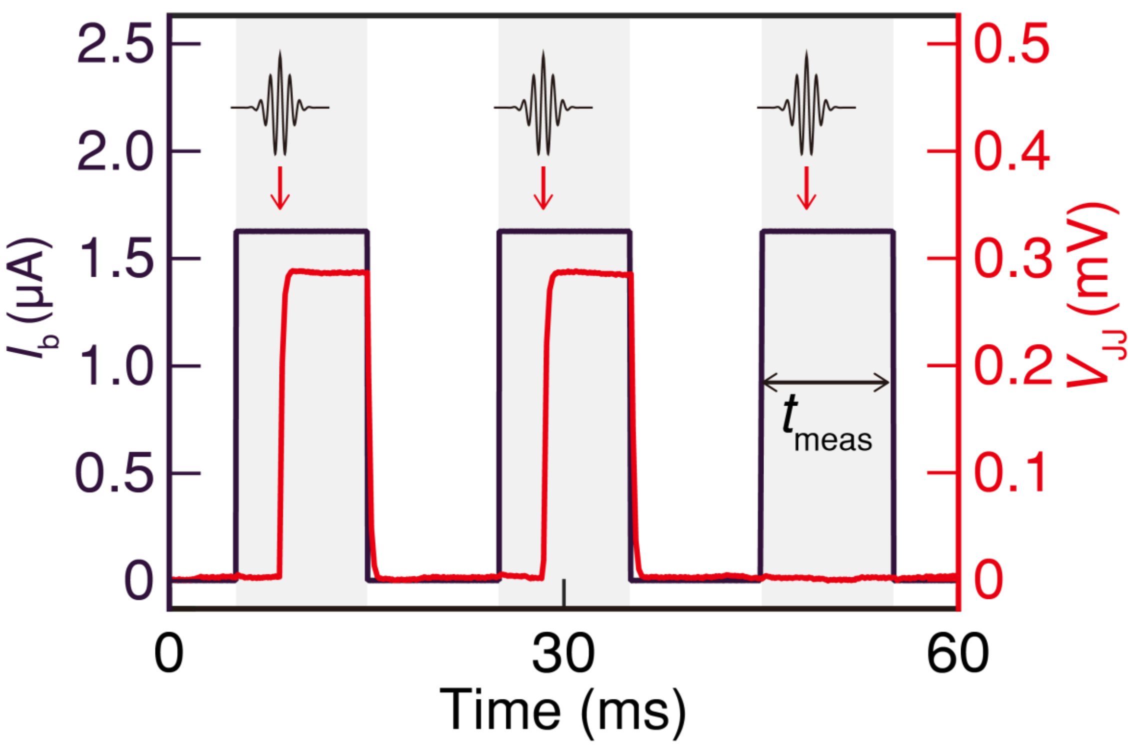


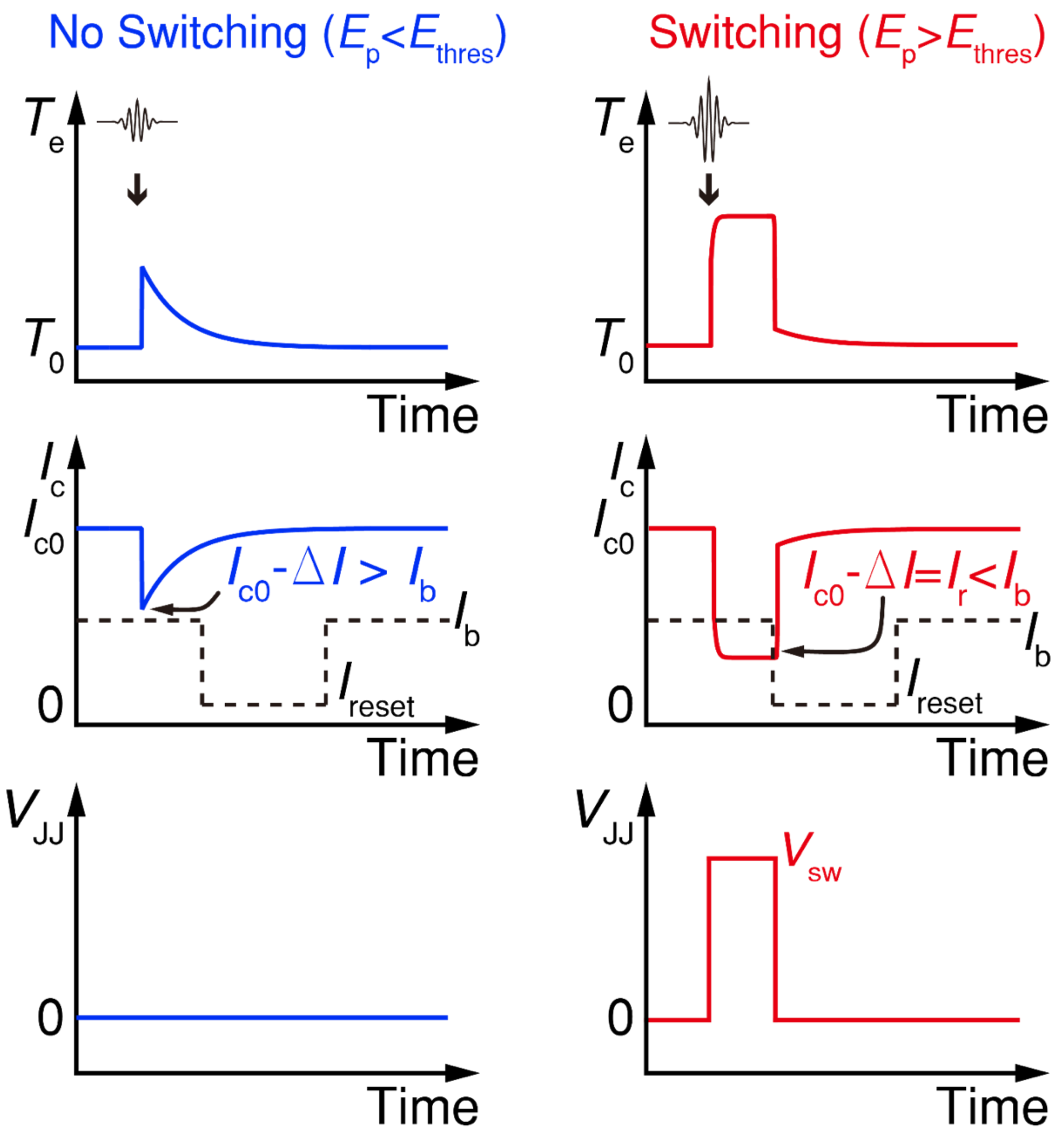




Proposal: Calibration of GJJ Detector with Microwave Pulse

η= Voltage Jump / Trial
=2/3=66.6%





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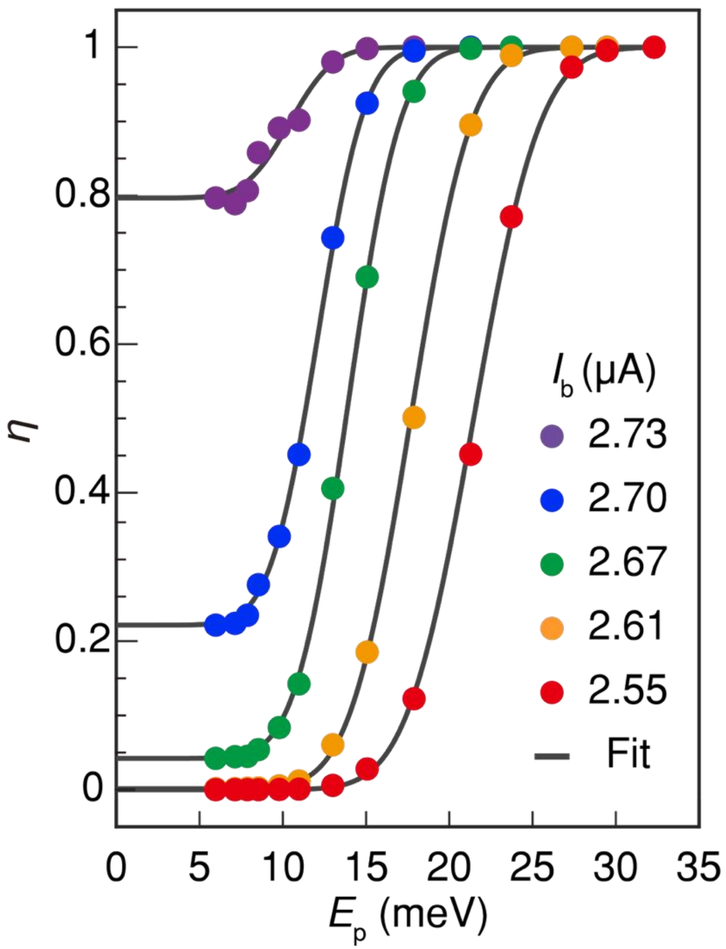
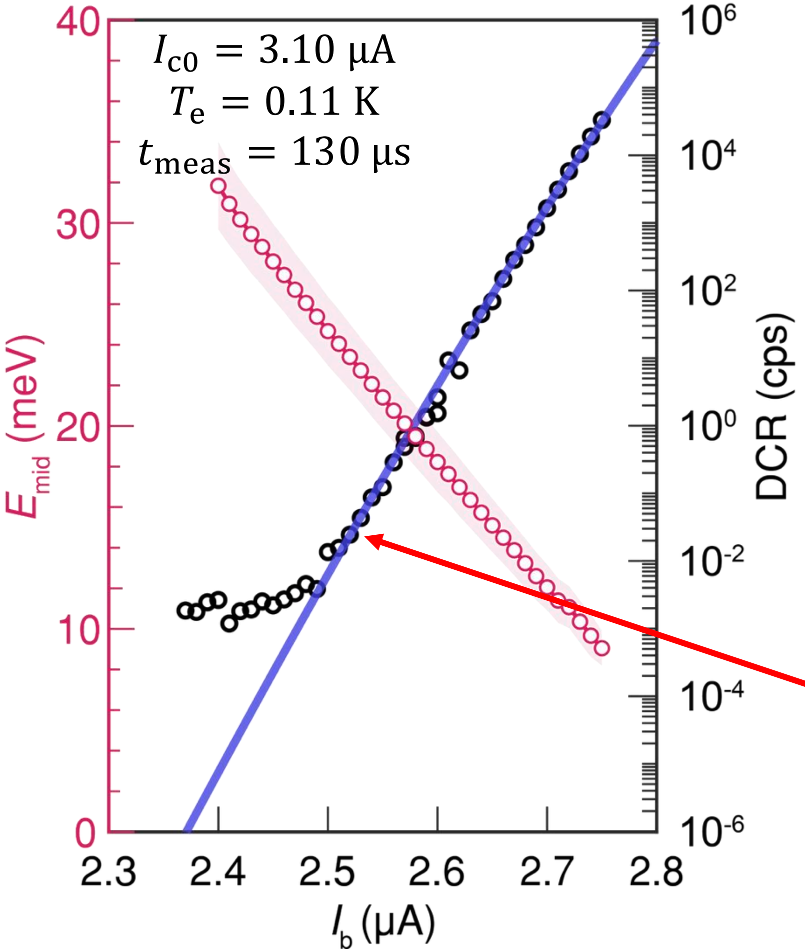
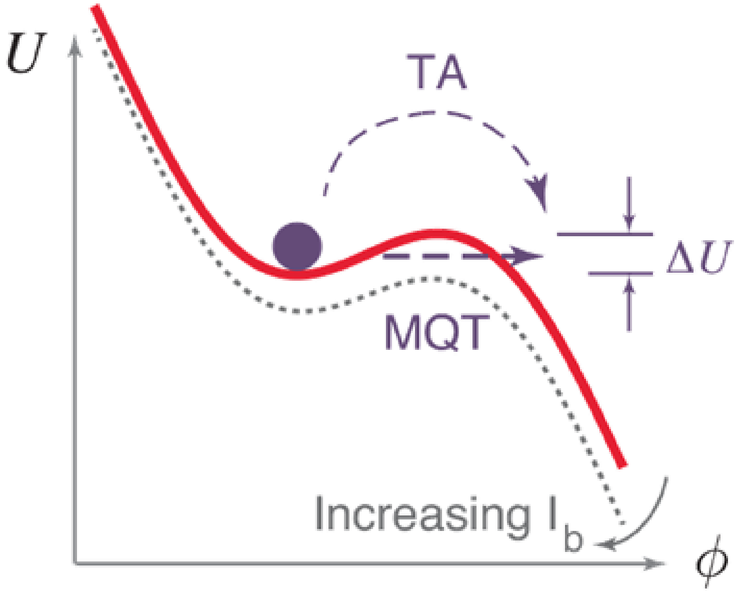
Calibration of GJJ Detector with Microwave Pulse & Dark count

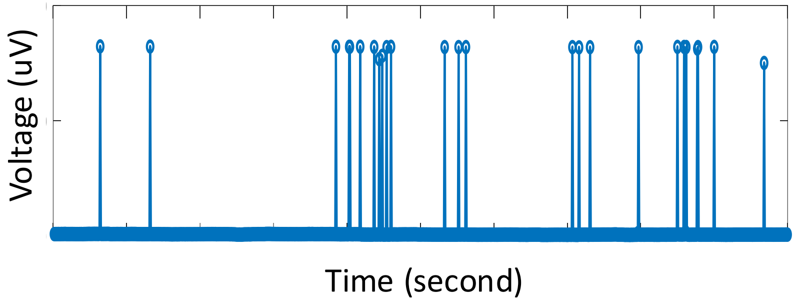


$$\eta(E_P) = \eta_{\mathrm{floor}} + \frac{A}{2}\left[1 + \mathrm{erf}\frac{(E_p - E_{\mathrm{mid}})}{\sqrt{2}\sigma}\right]$$

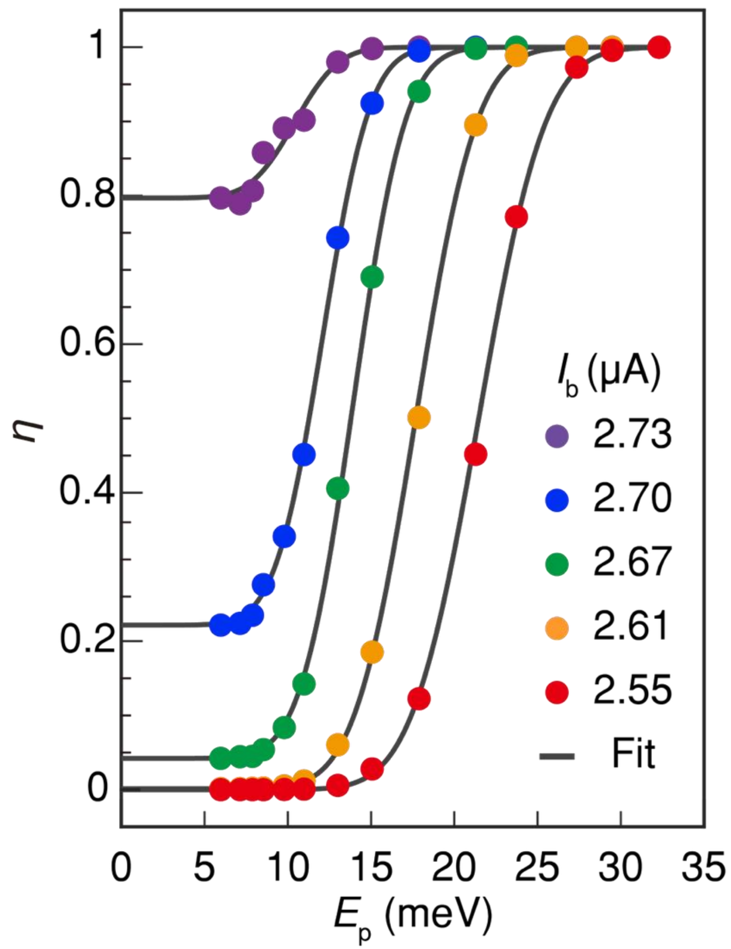




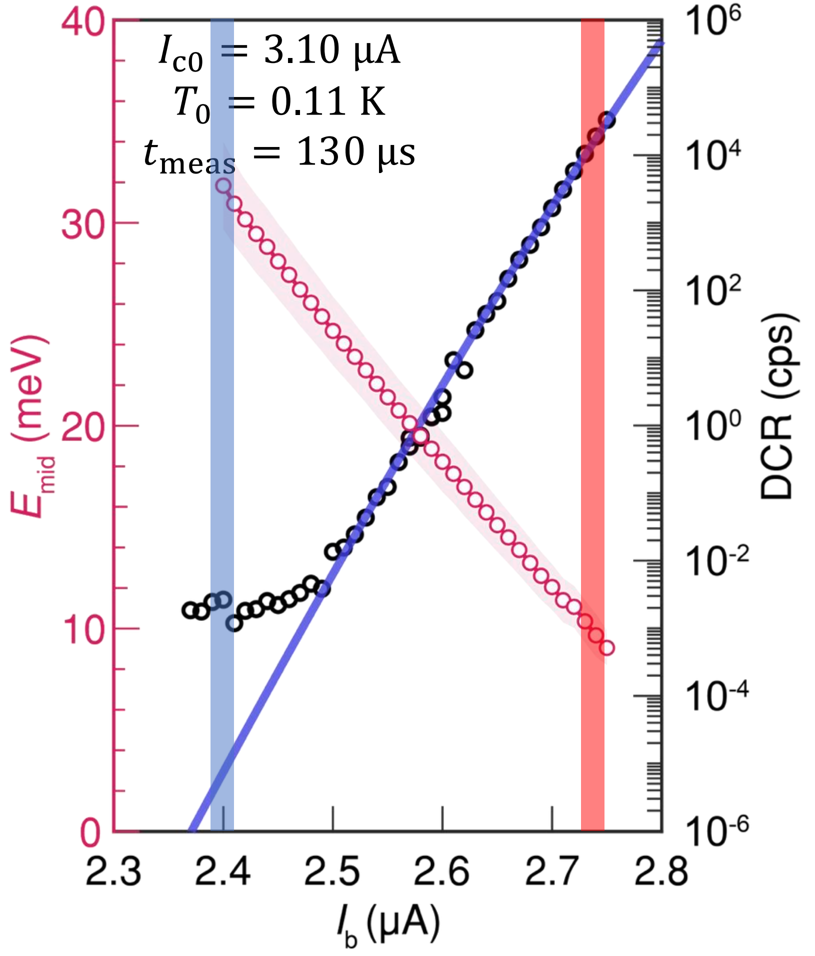
❖ Fix I_b and wait JJ switches

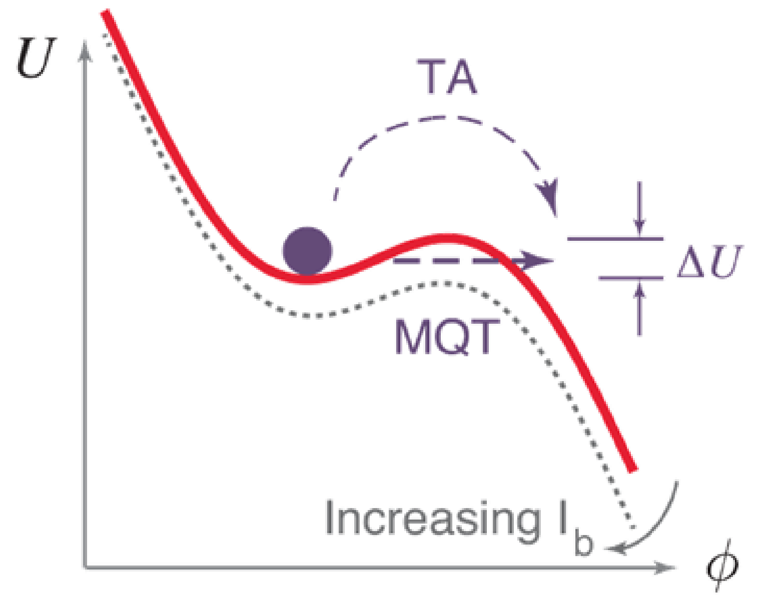


Calibration of GJJ Detector with Microwave Pulse & Dark count



$$\eta(E_P) = \eta_{\text{floor}} + \frac{A}{2}\left[1 + \text{erf}\frac{(E_p - E_{\text{mid}})}{\sqrt{2}\sigma}\right]$$





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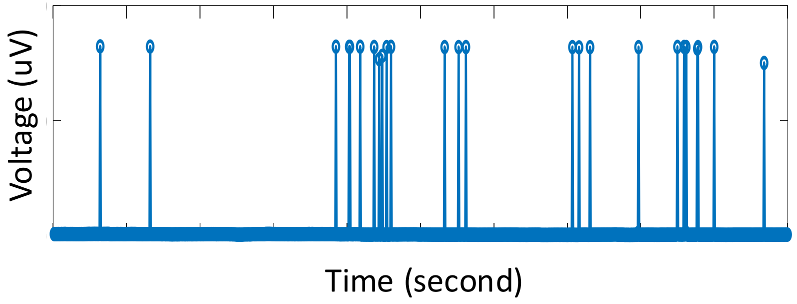

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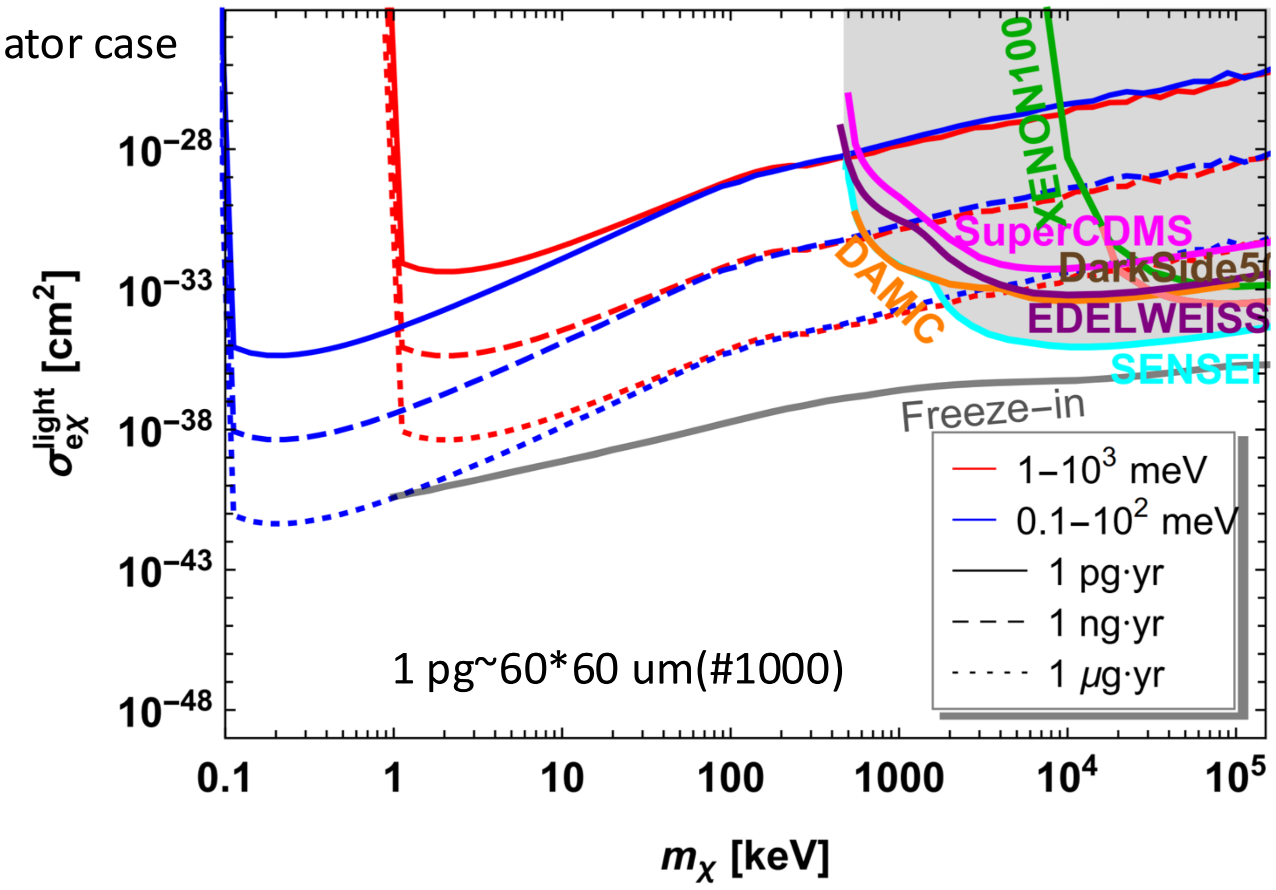
Path to a dark matter science run

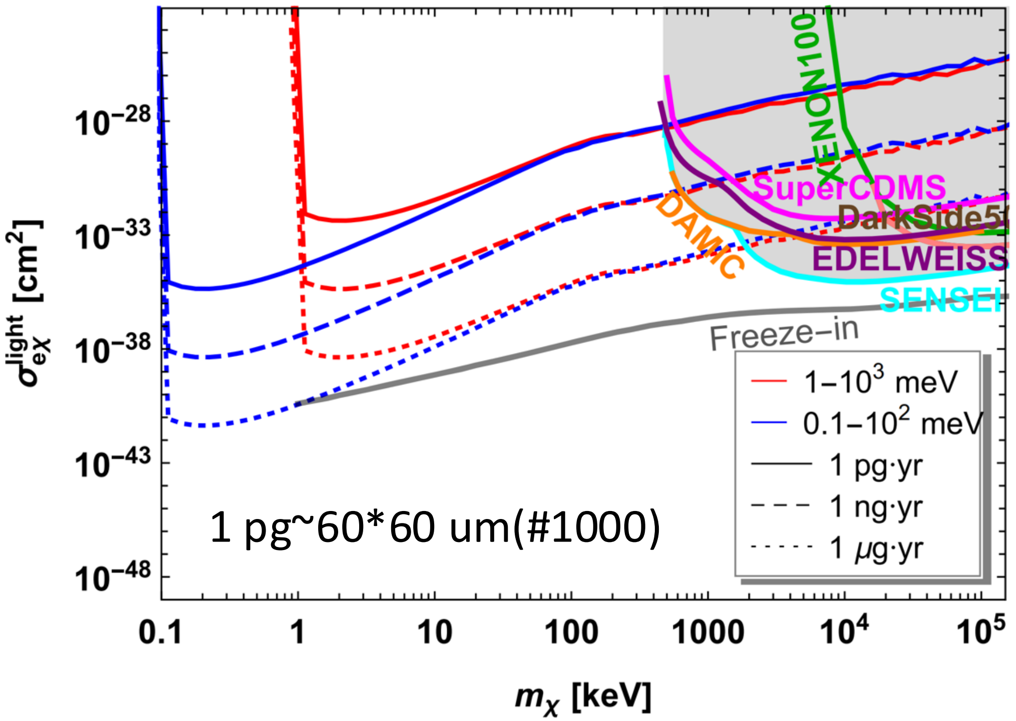
Light mediator case



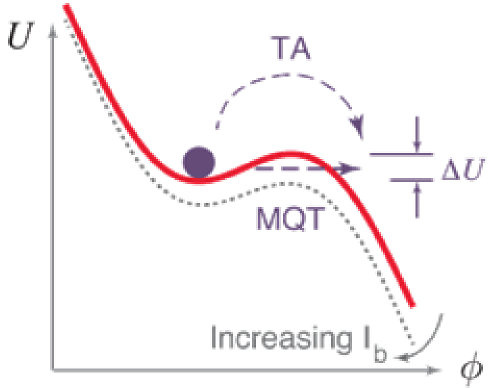
2. Longer **measurement time**
3. larger-scale detector

1. Better Detector **Sensitivity**

Path to a dark matter science run

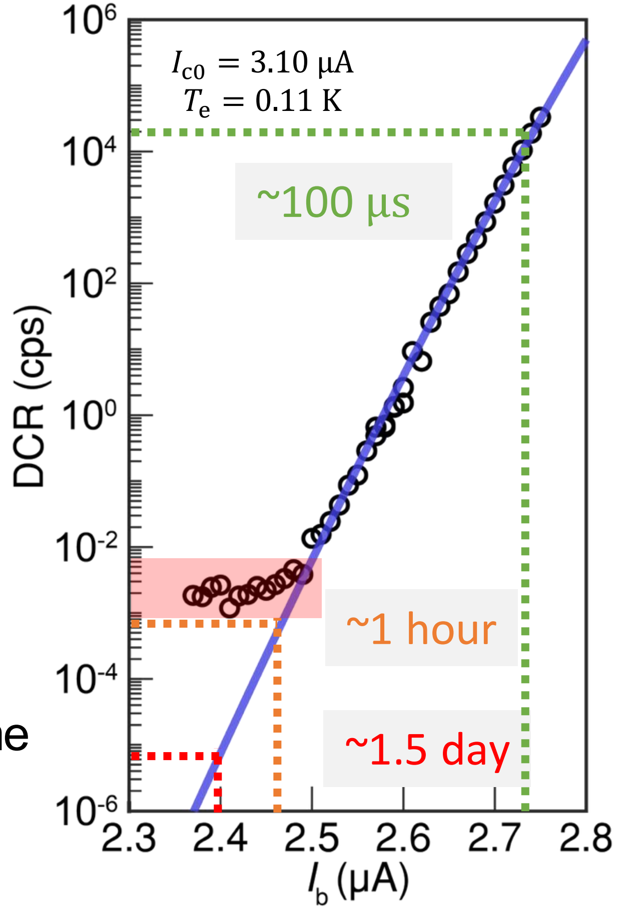


1. Better Detector Sensitivity



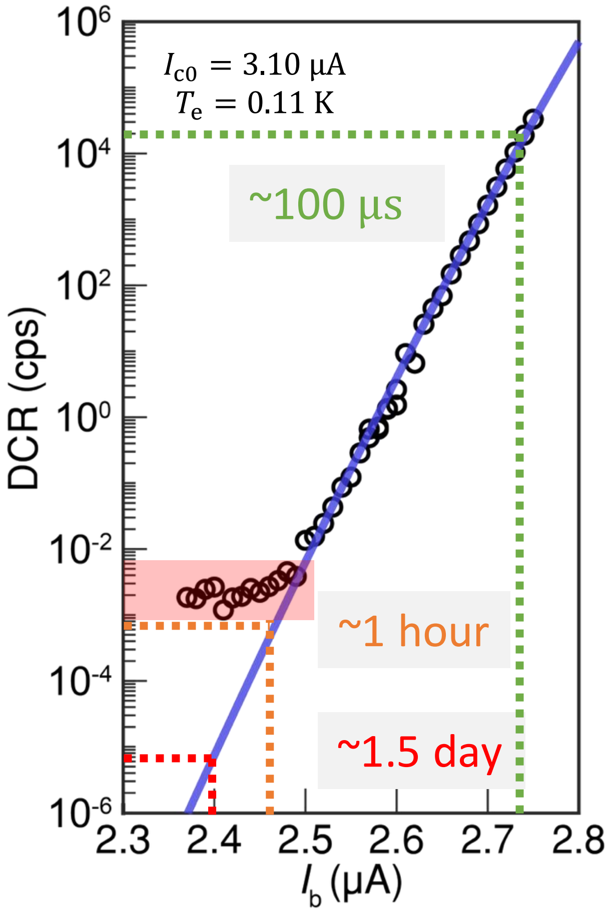
2. Longer **measurement time**
3. larger-scale detector

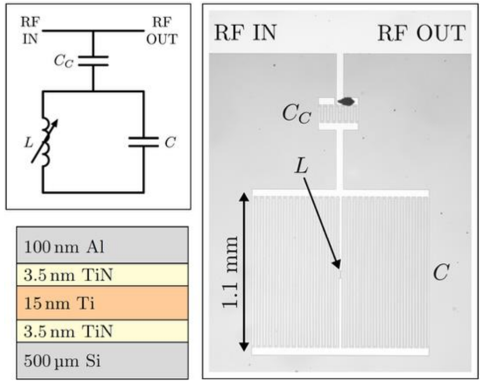
Limited measurement time by **LEE**

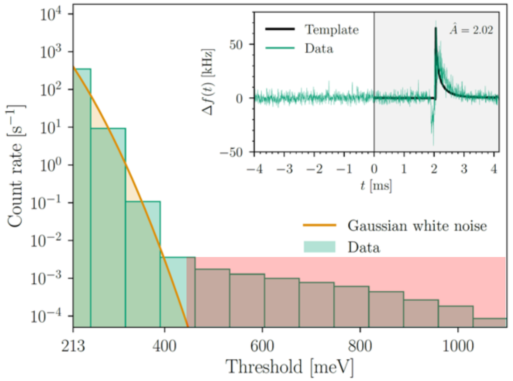


Why?

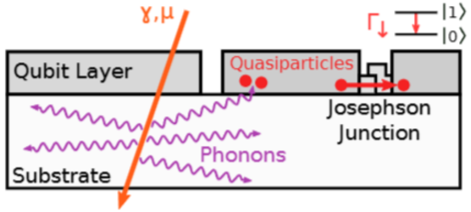
Low Energy Excess (LEE) Background



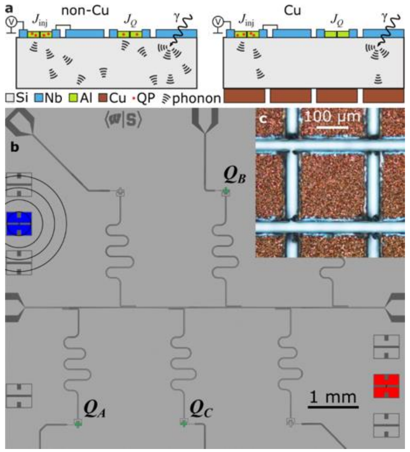




arXiv:2403.19739v1 [hep-ph]



[McEwen, M. *et al.*, Nature Physics (2021)]



Nature Communications
volume 13, Article number: 6425 (2022)

Cosmic rays & Chip interaction

⬇

High energy phonon

⬇

Excess Quasiparticles

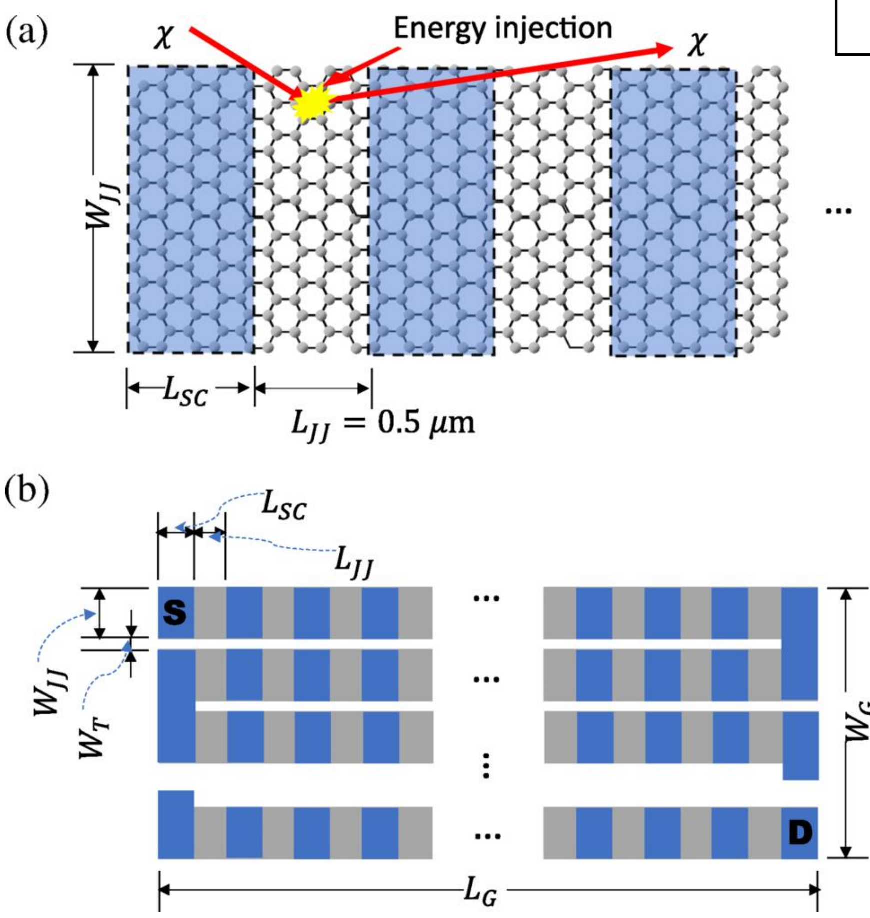
⬇

Strategy: Reducing area of SC

Why? → quasiparticles can tunnel through Josephson junctions ➔ Decoherence/Dark count

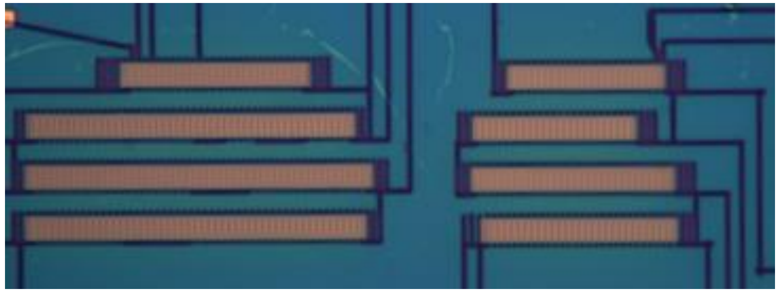
Scaling Up: Larger-Scale Detector Arrays (# of JJ)

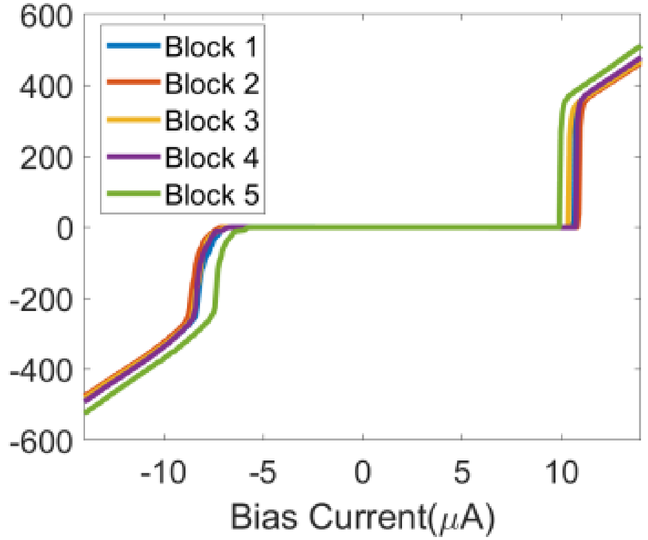
1 pg~60*60 um (#1000)



Uniform Josephson junctions in series
→nanofabrication technology

216 GJJs connected in series

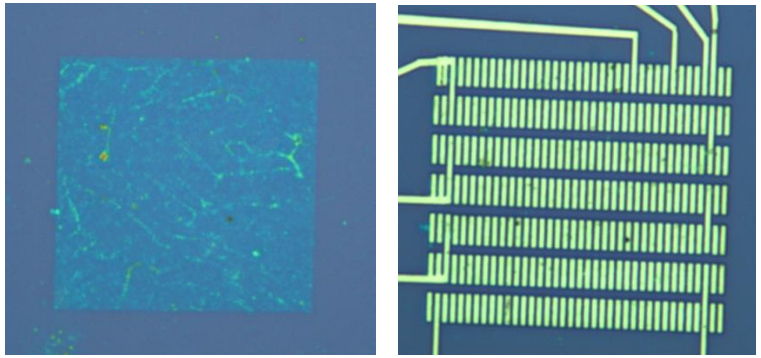


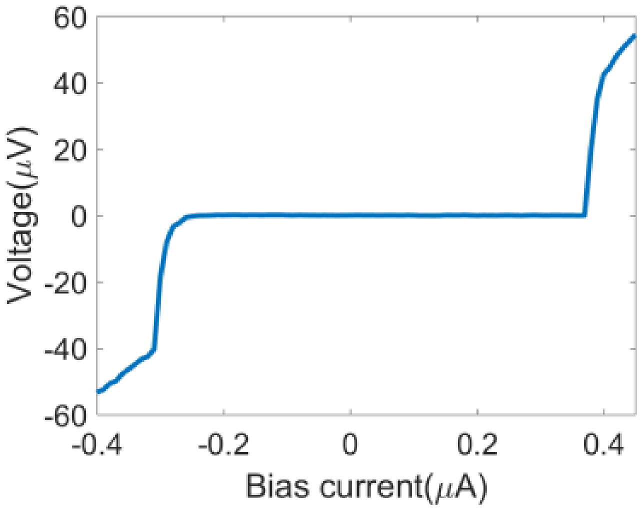


Almost same I-V curve when scaled

large-scale graphene sheet
→ CVD graphene

231 GJJs connected in series

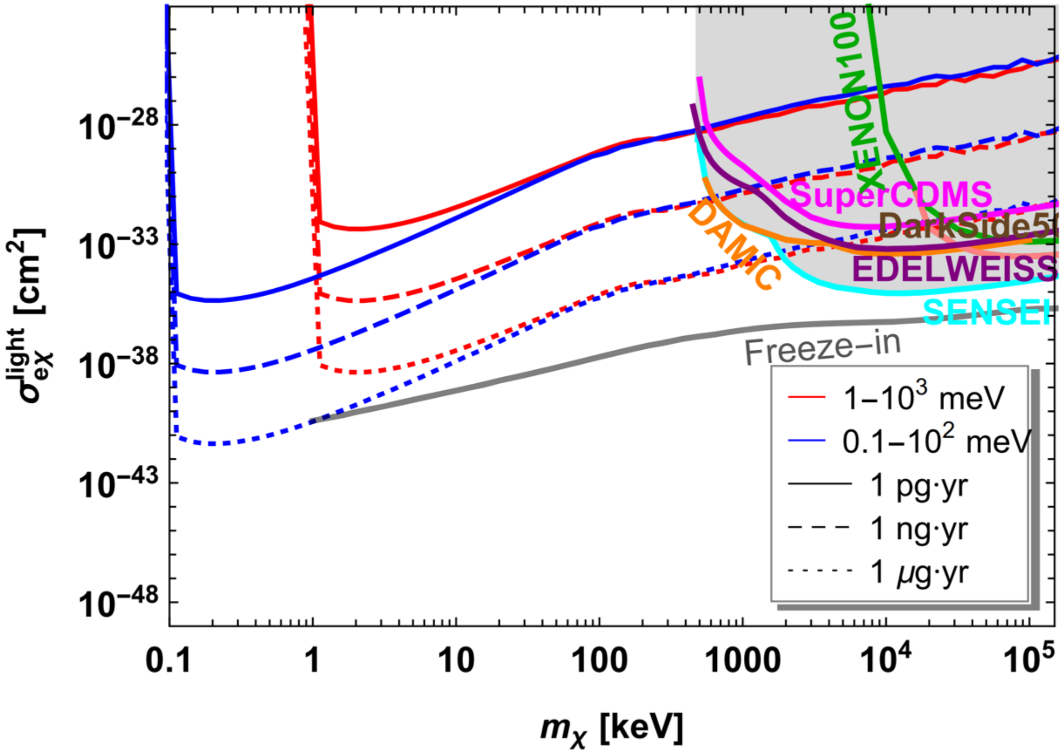




POSTECH

Conclusion

- **Calibration of GJJ Detector**
  - ✓ $E_{mid} \fallingdotseq 9.7$ meV with DCR~3*10^4 Hz, $E_{mid} \fallingdotseq 31$ meV with DCR~1*10^{-3} Hz
  - ✓ Thermal parameter extraction C_e = 12.5 ± 1.69 yJ/K(16.1) & τ_{th} = 18.5 ns & $\Sigma_{ep} = 0.81\ \mathrm{Wm^{-2}K^{-3}}$



Path to a dark matter science run

1. Better Detector Sensitivity

- Optimization of $|dI_c/dT|$ for GJJ
- Reduce G_{EP} & C_e

2. Scaling Up: Larger-Scale Detector Arrays

- large-scale graphene sheet
- Uniform GJJ in series

3. Low energy excess background

- Reducing area of SC

Acknowledgement

POSTECH, Korea

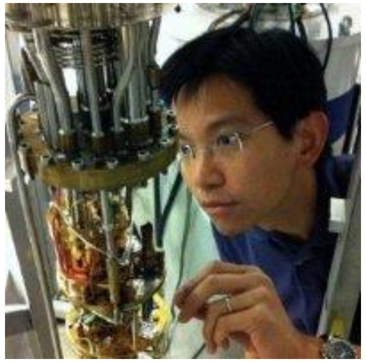
- <u>Seunghan Lee</u>
- <u>Gil-Ho Lee</u>


- Seong Jang
- Woochan Jung
- Jayeon Kim
- Seongeun Jeon



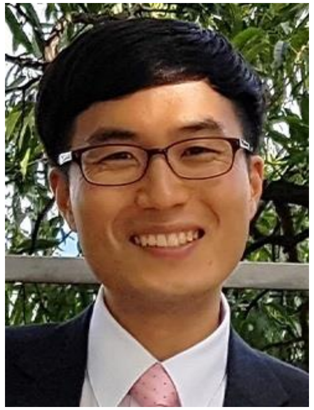

Northeastern University, USA

- Kin Chung Fong



Chungnam National University, Korea

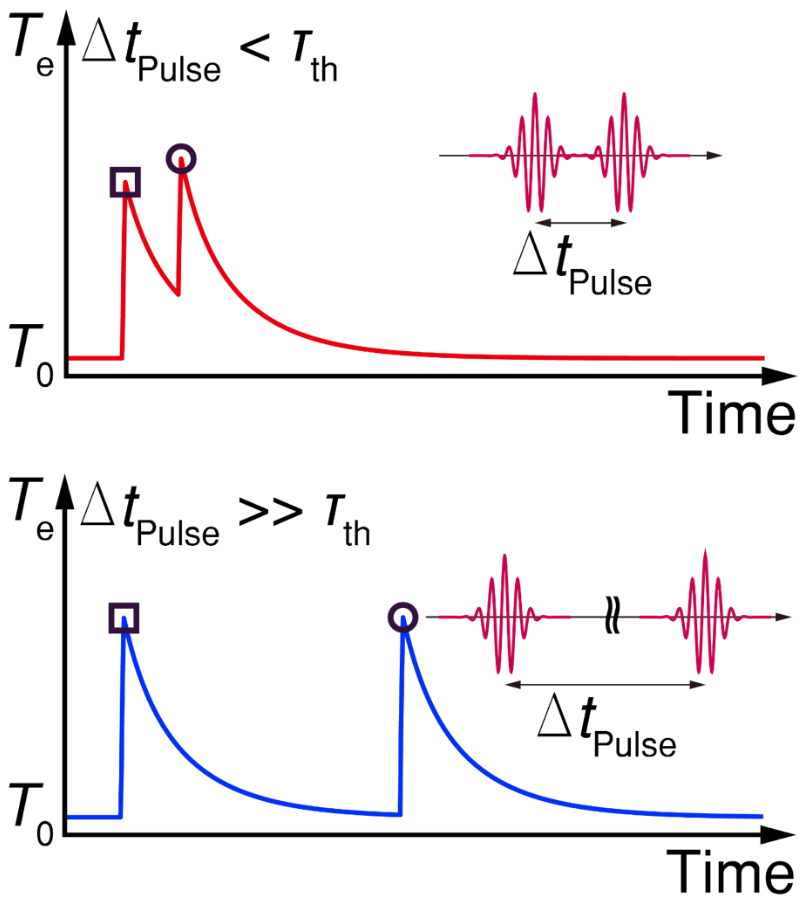
- Jong-Chul Park

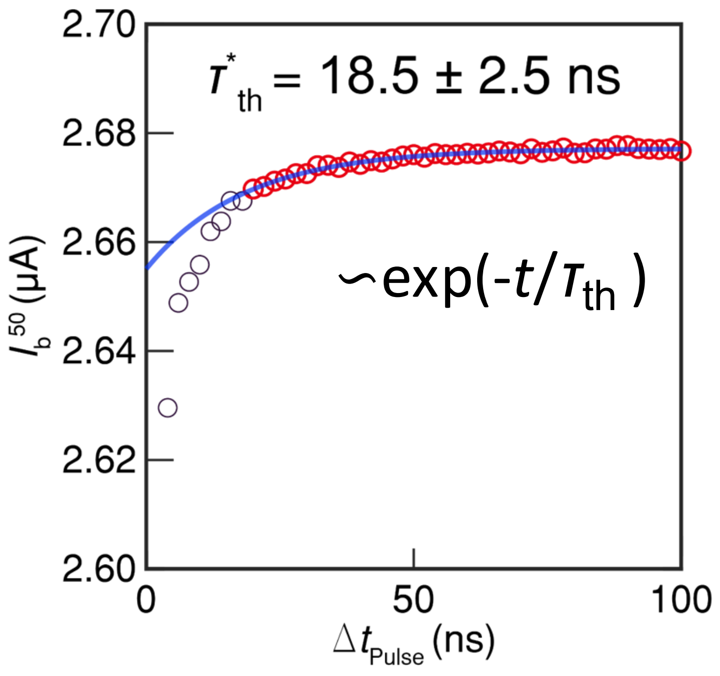


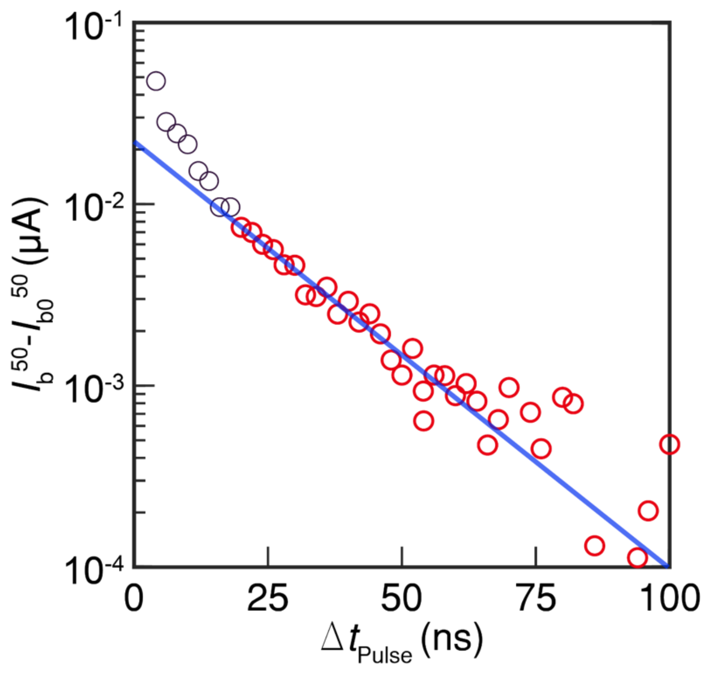
Thank you!

Supple.

Thermal Relaxation Time Measurement: Time-Resolved Two Pulse Method







$C_e = G_{th} * \tau_{th}$

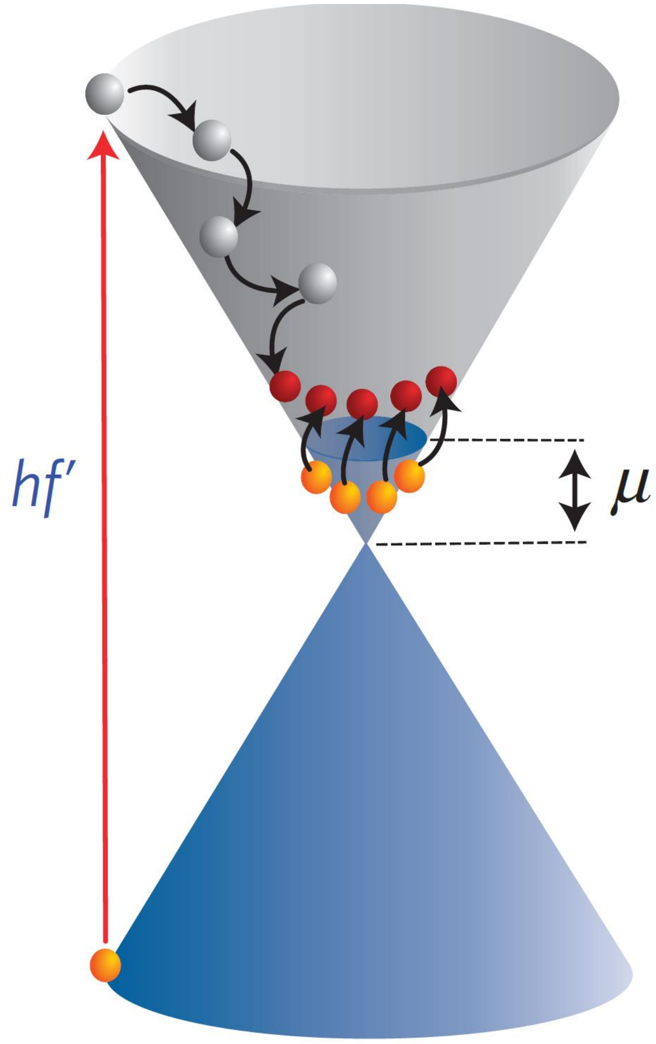
= 12.5 ± 1.69 yJ/K(16.1)= 0.9 ± 0.1 k_B(1.2)

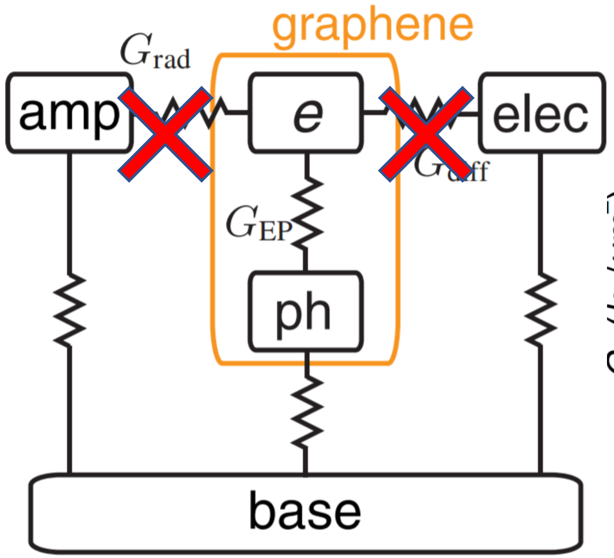
Measure the switching probability varying Δt

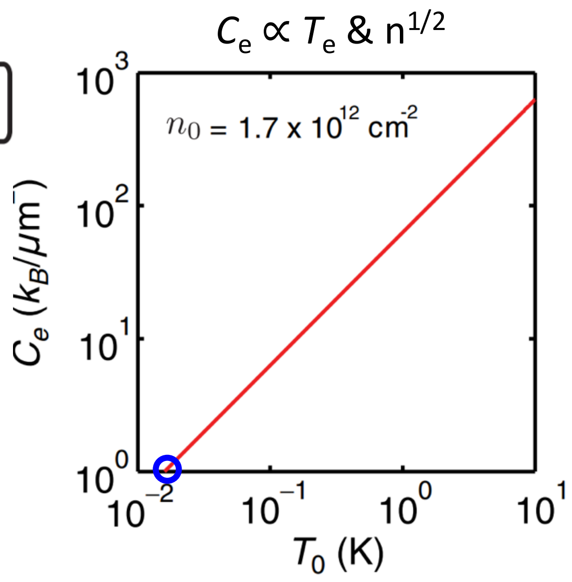
→ Estimate the **thermal relaxation time**

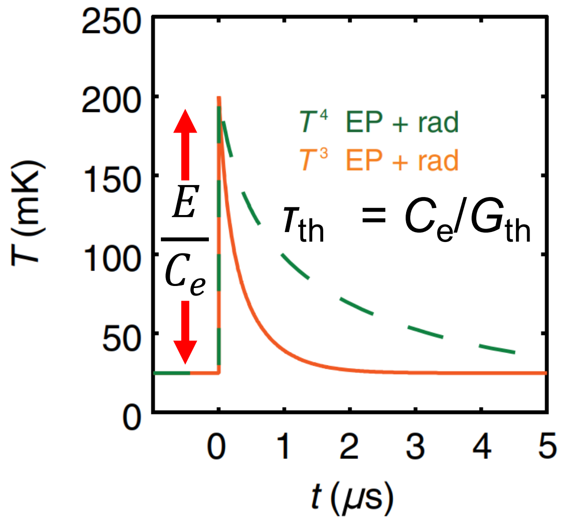
Graphene's Advantages: Focus on Thermal Properties

PHYSICAL REVIEW APPLIED 8, 024022 (2017)









- ➢ Linear Dispersion Relation → Broad absorption bandwidth
- ➢ Fast electron–electron interaction time **(~10 fs)**

[Nat.Phys. **9**, 248 (2013)]

- ➢ Shrinking density of state near the CNP

→ small C_e → **Higher** temperature rise & **Faster** cooldown

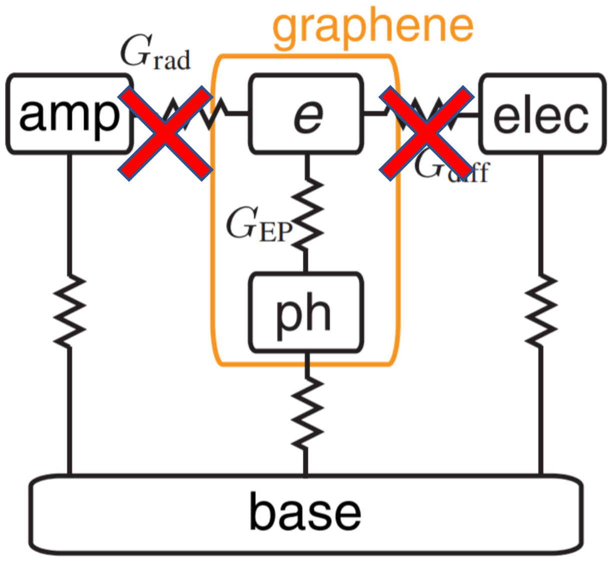
[PRX **3**, 041008 (2013)]

- ➢ graphene enables good SC contacts

Nature Physics volume 9, pages 248–252 (2013)

Graphene's Advantages: Focus on Thermal Properties

PHYSICAL REVIEW APPLIED 8, 024022 (2017)



G_{ep}

The thermal interaction by electron-phonon coupling

$G_{rad} \cong r_0 k_B B, for\ B < k_B T/h$

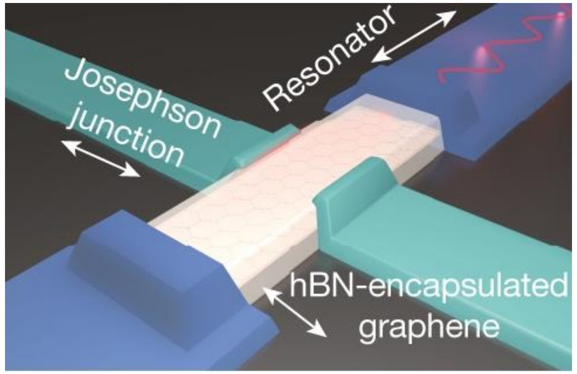
very <u>small</u>

G_{diff}

Andreev reflection suppress the thermal diffusion

at the superconductor to graphene contact.

$$\boxed{G_{th} = (\cancel{G_{diff}} + \cancel{G_{rad}} + G_{ep}) \sim G_{ep}}$$

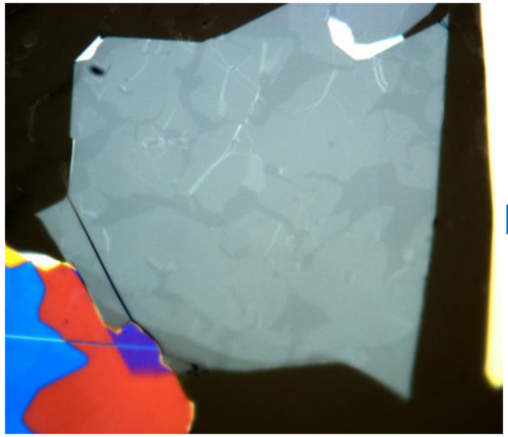


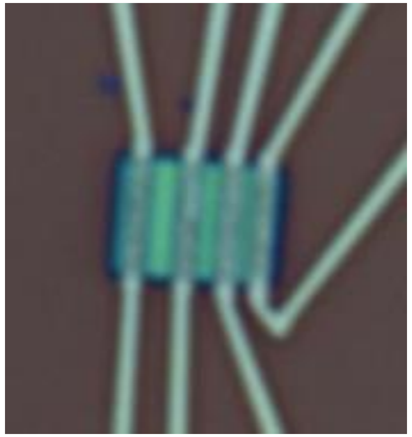
∴ Weak electron-phonon coupling + Small heat capacity

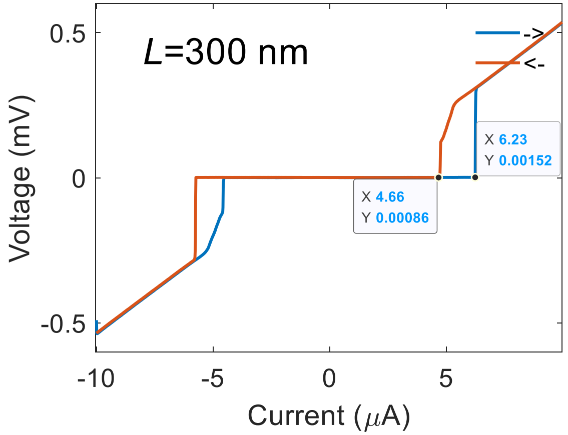
➔ **Graphene is a highly promising material for Sensor**

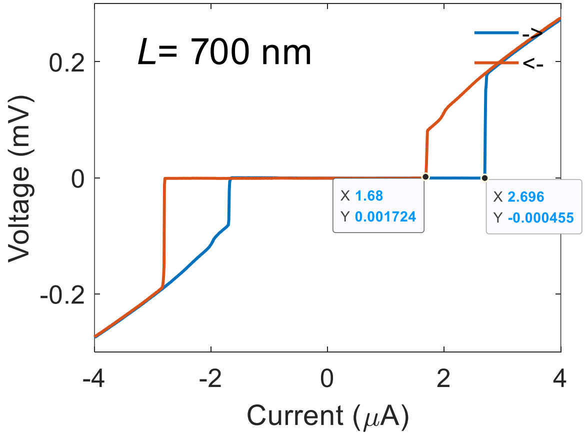
Fabrication of Large-scale Graphene

❖ CVD-grown Graphene with exfoliated hBN

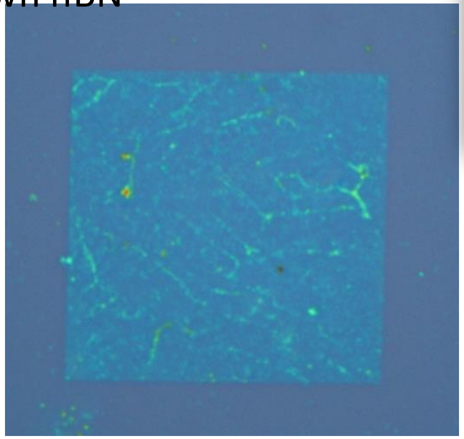






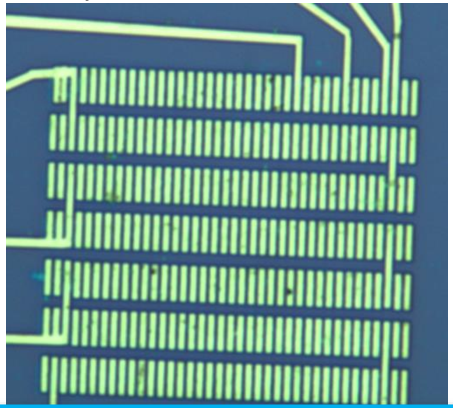


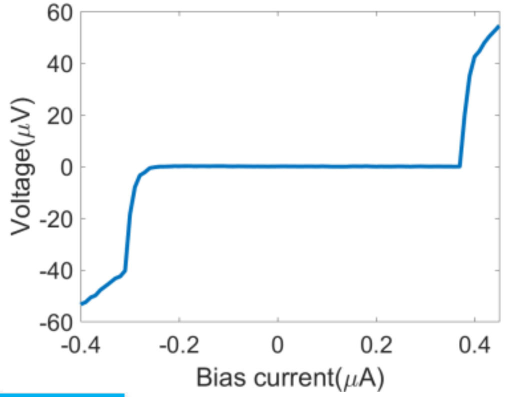
❖ CVD-grown Graphene with CVD grown hBN



hBN/Graphene/hBN stack

231 GJJ array





Seong Jang

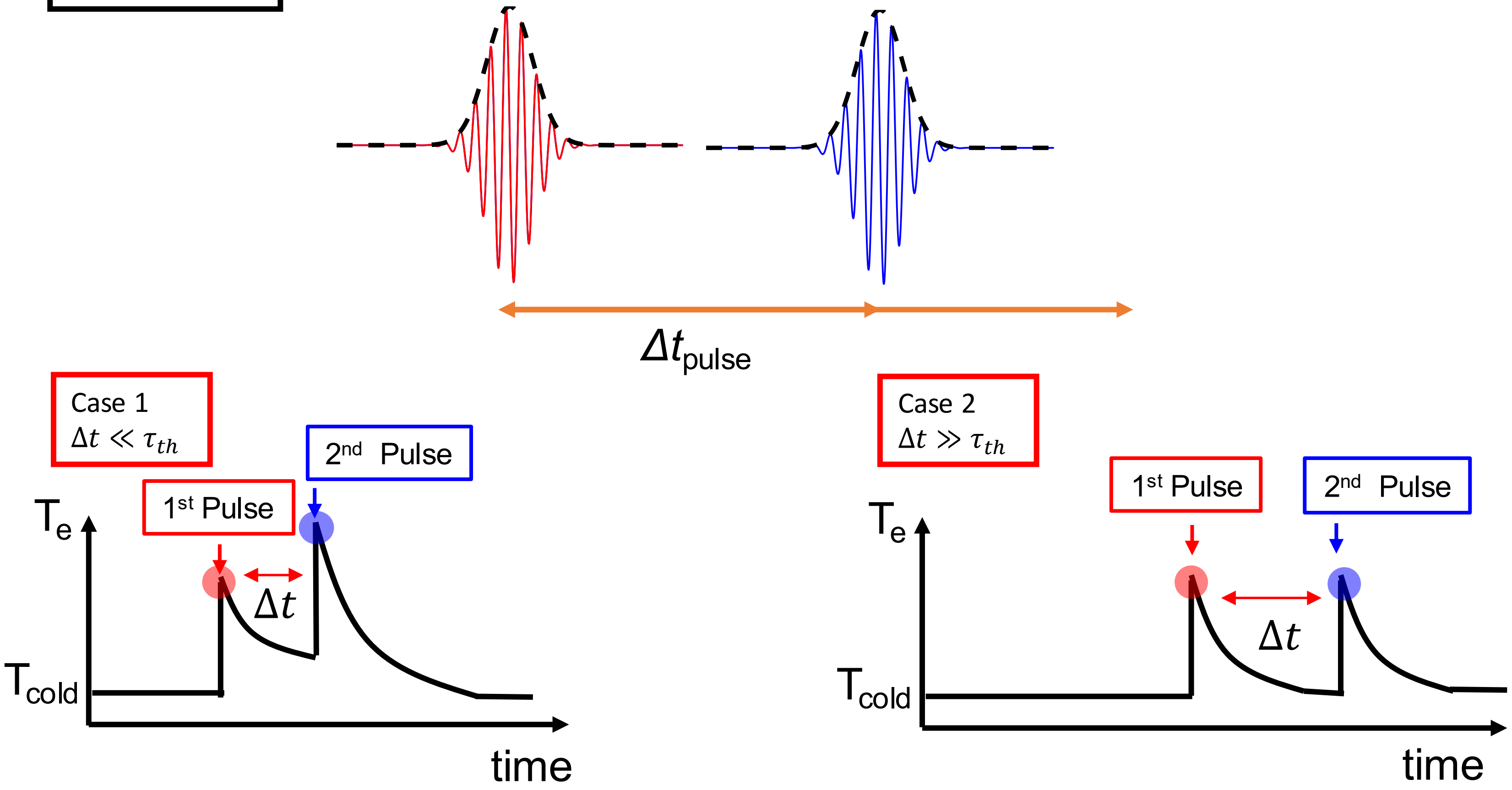
Chae-Gun Lee

GJJs were demonstrated with CVD-grown large-scale graphene.

POSTECH

Thermal Relaxation Time Measurement

Method



Measure the detection eff. varying Δt_{pulse}

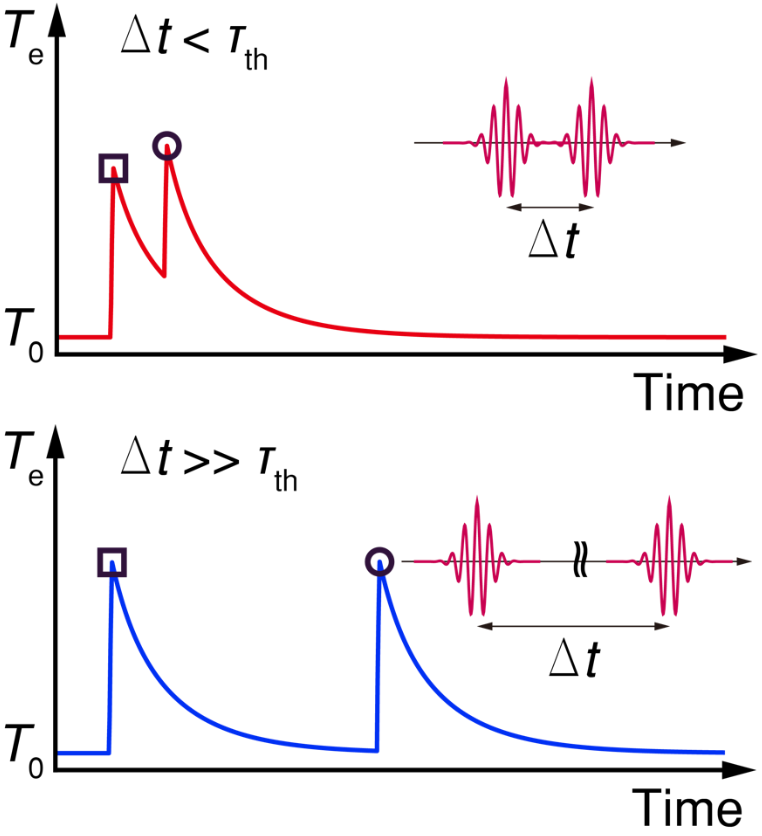
→ Estimated the τ_{th}

POSTECH

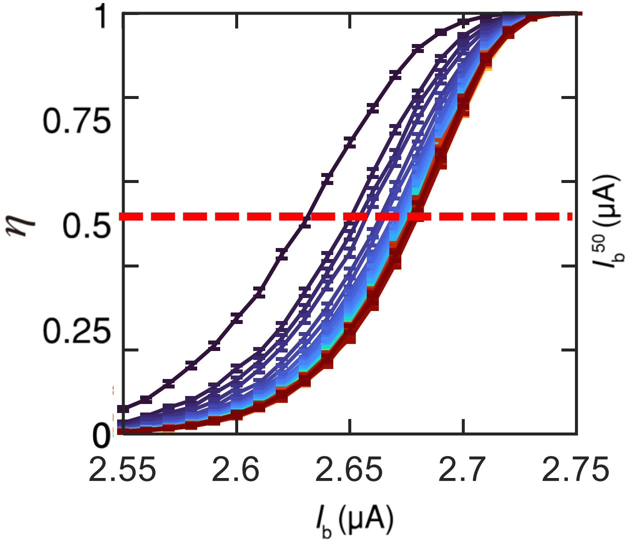
Thermal Relaxation Time Measurement: Time-Resolved Two Pulse Method

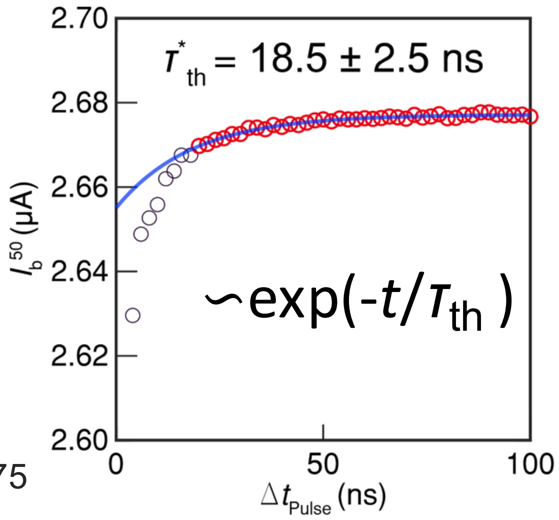
T_0 = 110 mK

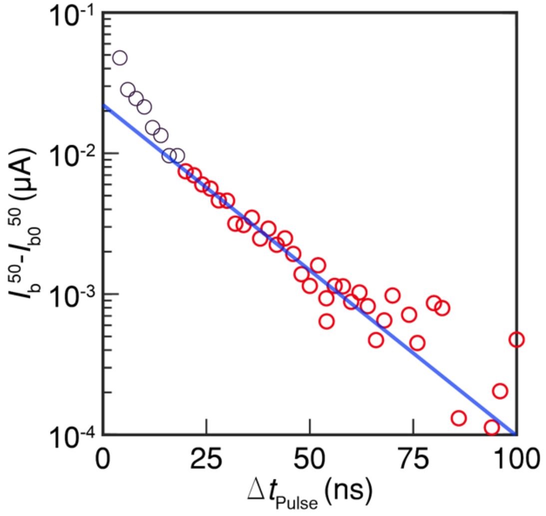
T_e vs t → T_{peak} vs t → η vs t



Δt = 4 ns ~ 100 ns







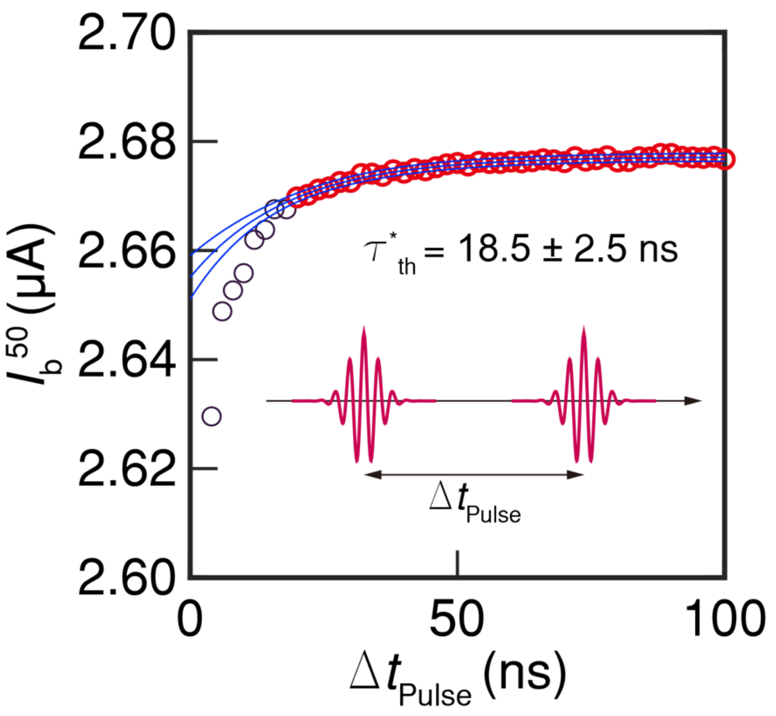
$$C_e = G_{th} * \tau_{th} = 61.7\ \text{fW/K} * 18.5\ \text{ns}$$

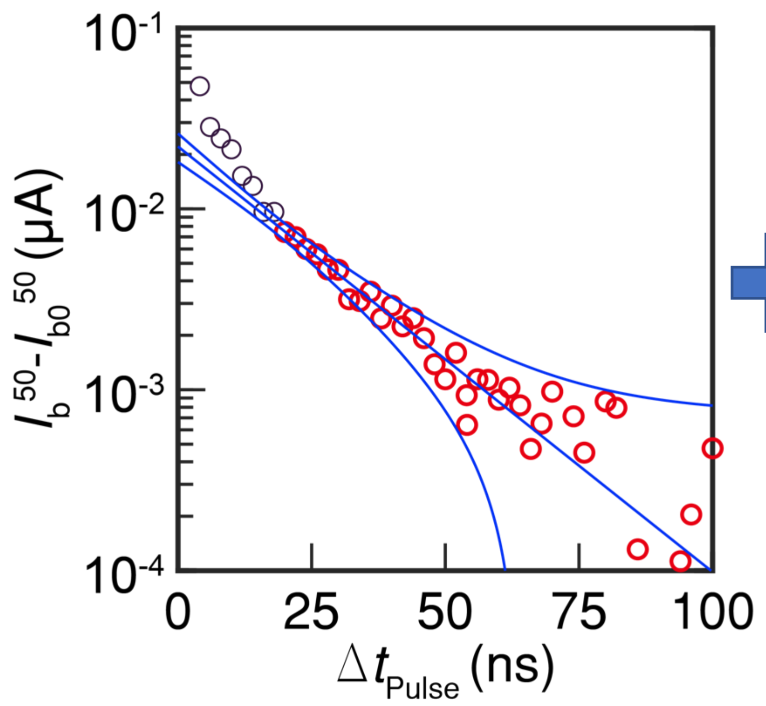
$$= 1.14\ \text{zJ/K}(= 82.6\ k_B) >> C_{e,th} = 0.177\ \text{zJ/K}\ (= 12.8\ k_B)$$

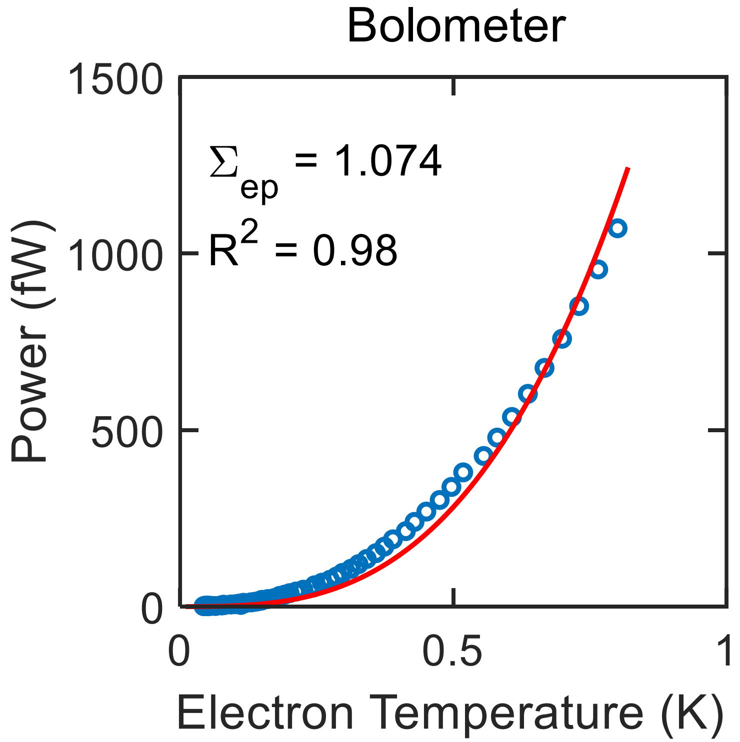
Measure η varying Δt

→ Estimate the τ_{th}

Thermal Relaxation Time Measurement



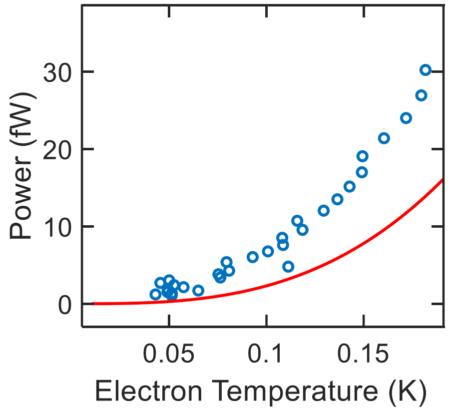




T_e^1 T_e^2 T_e^{-1}

$$C_e = G_{th} * \tau_{th}$$

= 12.5 ± 1.69 yJ/K(16.1)= 0.9 ± 0.1 k_B(1.2)

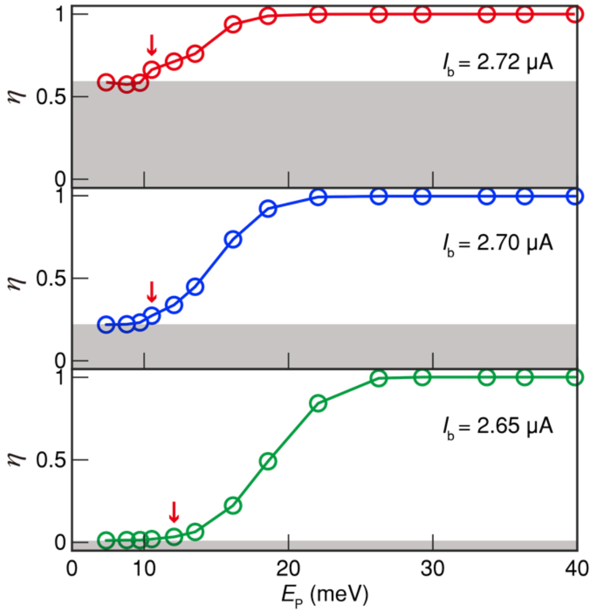


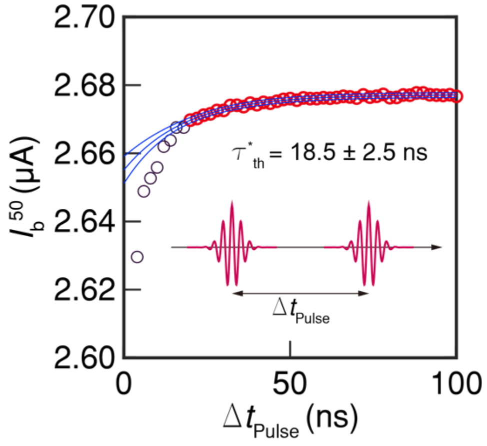
Σ_{ep} =1.07 W/m^{2}K^3 (0.01)

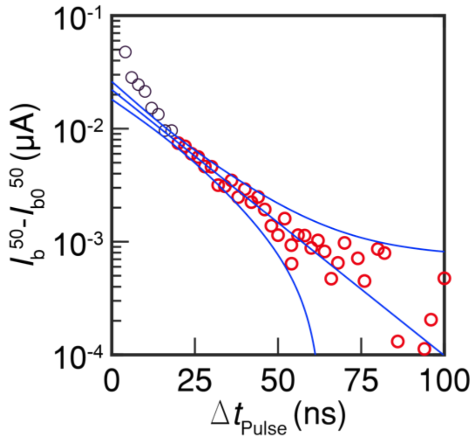
→ G_{th} = $A\Sigma_{ep}T_e^2$ = 674 aW/K

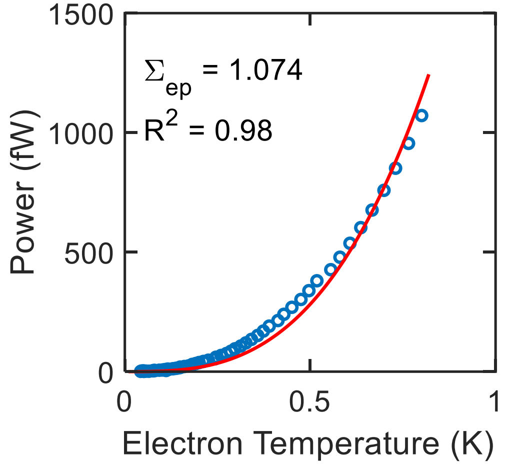
POSTECH

Summary









Calorimeter → E_{thres} = 10.5 meV (2.2 meV)

Two-pulse method → τ_{th} = 18.5 ns

Bolometer

→ G_{th} = 674 aW/K

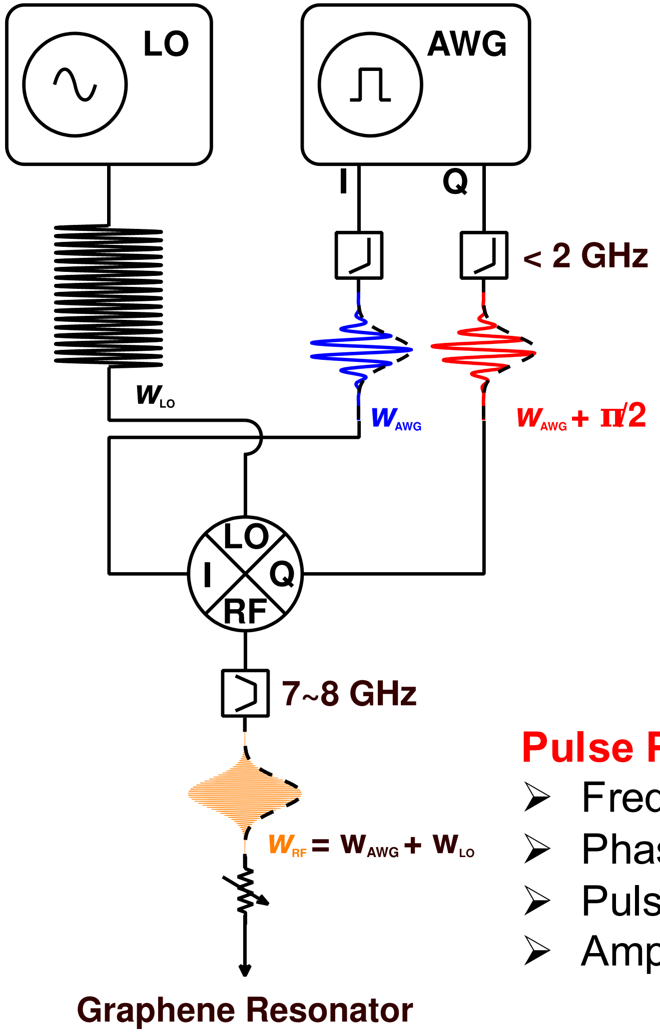
Σ_{ep} =1.1 W/m^{2}K^3(0.01)

$C_e = G_{th} * \tau_{th}$ = 12.5 ± 1.69 yJ/K(16.1)= 0.9 ± 0.1 k_B(1.2)

The system that enables **these measurements to be performed simultaneously.**

Pulse Generation

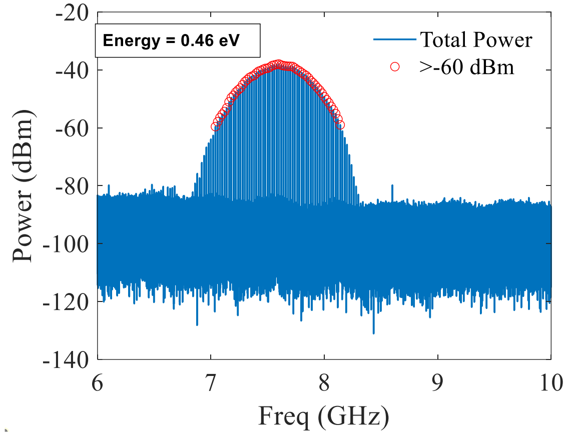
Single sideband mixing



Pulse Parameters

- Frequency
- Phase
- Pulse shape
- Amplitude

Spectrum Analyzer

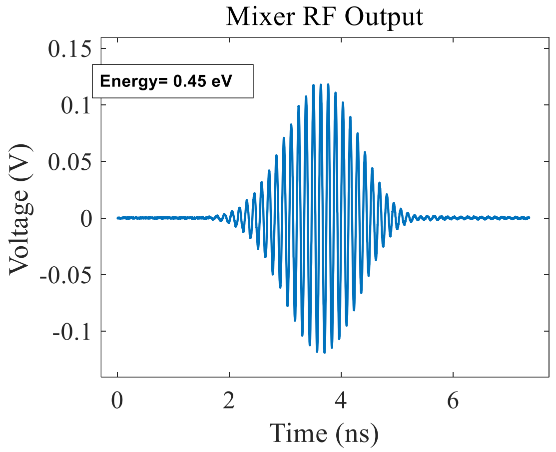


Pulse Energy Calculation

Effective Power=Power > -60 dBm

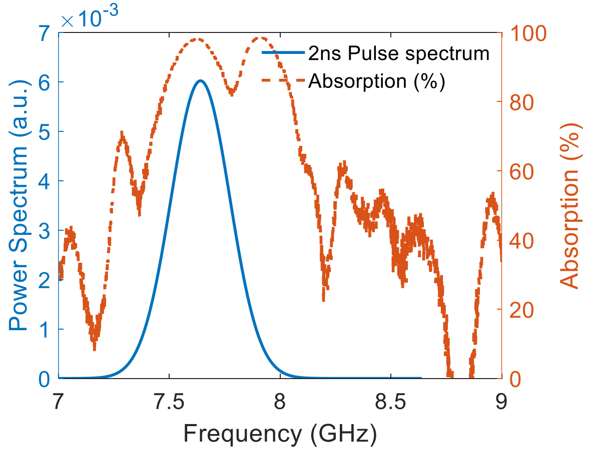
Sum(Effective Power)*Repetition Time

Oscilloscope



Pulse Energy Calculation

$$\text{Energy} = \Sigma \frac{V^2}{R} \Delta t$$



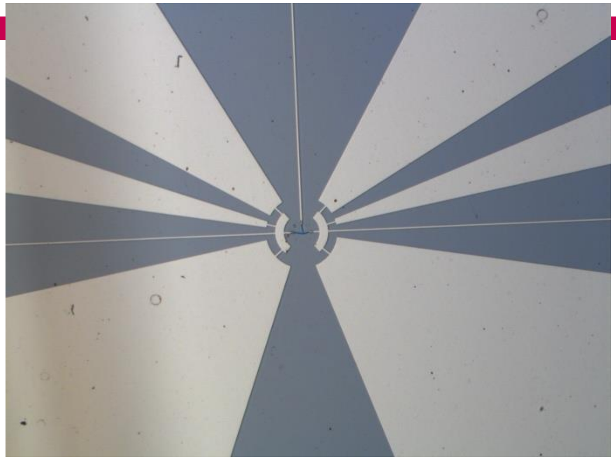
Absorption Ratio Cal.

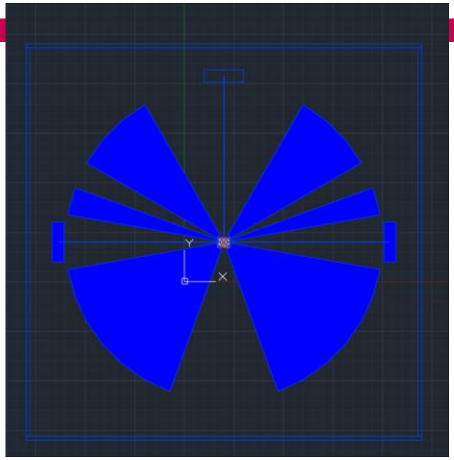
$$E_{absorption} = E_{Input} * Absorption\ Ratio$$

https://blog.minicircuits.com/iq-mixers-image-reject-down-conversion-single-sideband-ssb-up-conversion/

POSTECH

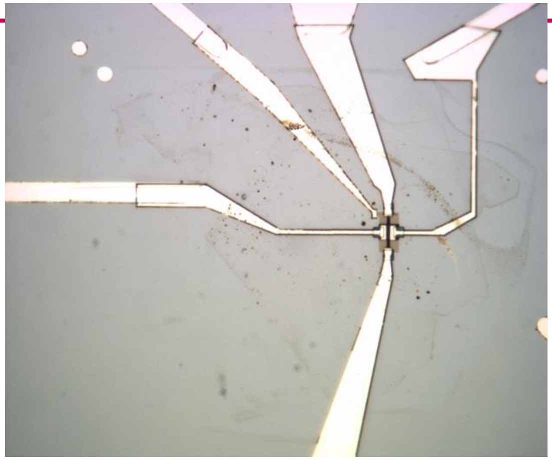
[LEE03]

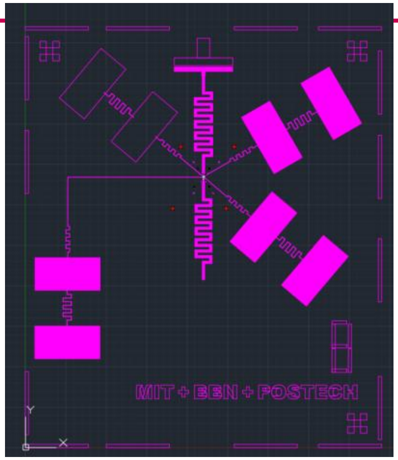




10 mm

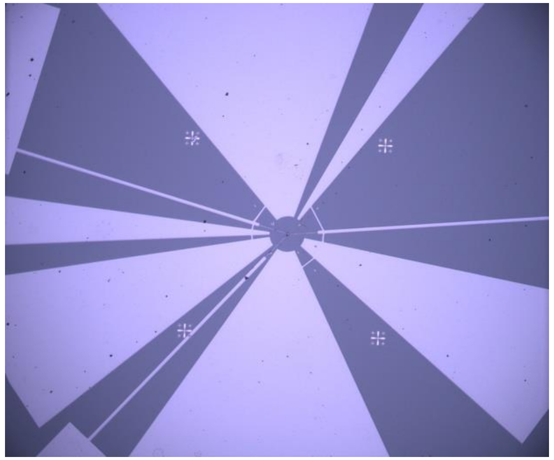
[mSPD12]

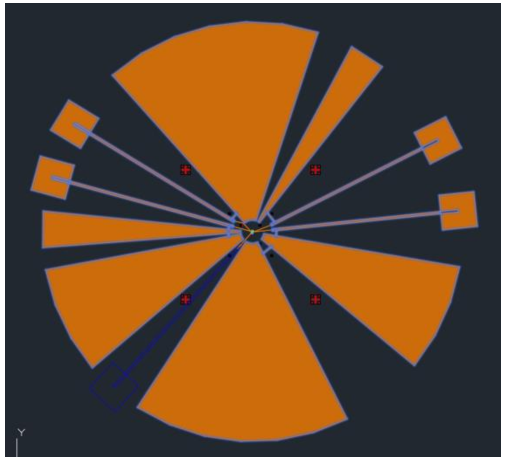




10.9 mm

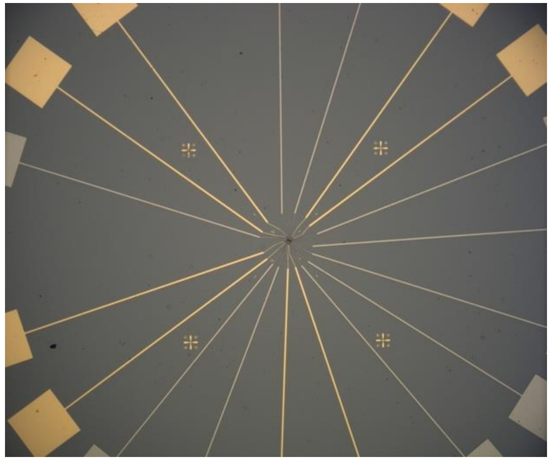
[LEE02]

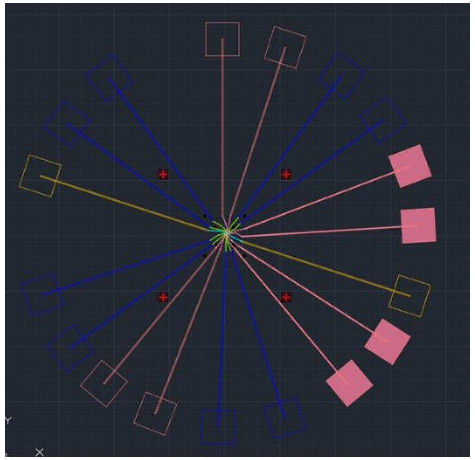




2 mm

[LEE01]





2 mm

*** SC 면적비 : mSPD12 : LEE03 : LEE02 : LEE01 = 0.36 : 1 : 0.11 : 0.002**

mSPD: 1.0×10^{7} um^2 ,LEE03 : 2.8×10^{7} um^2 ,LEE02 : 2.98×10^{6} um^2, LEE#1 : 5.2×10^{4} um^2

그래핀과 contact이 된 전극은 색을 채워 표시

Future Directions

- **Sensitivity Enhancement**

➢ Reduce electron–phonon coupling

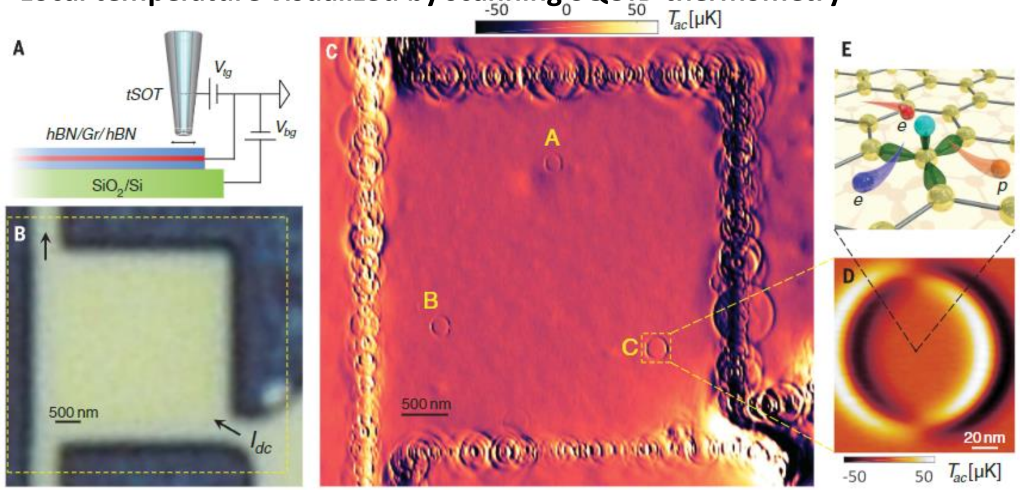
➢ Improve $dI_c dT$

Thermal Properties

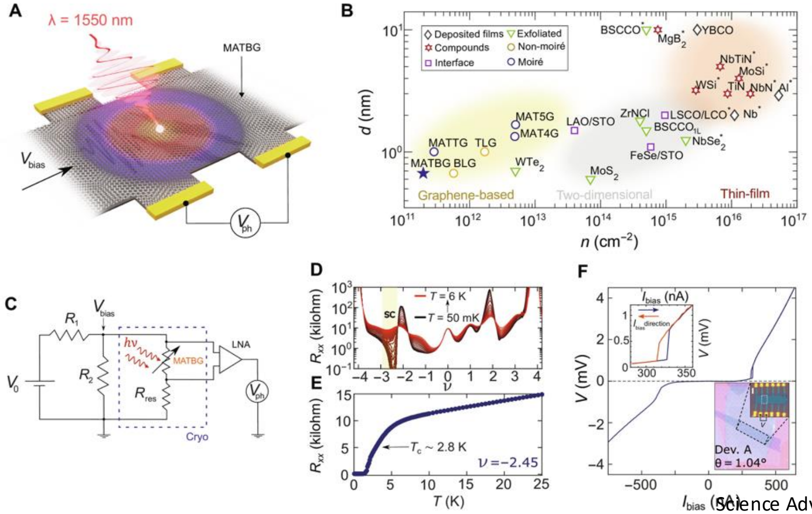
➢ Exploration of alternative 2D materials (e.g., twisted graphene)

Halbertal et al.,Science358, 1303–1306 (2017)

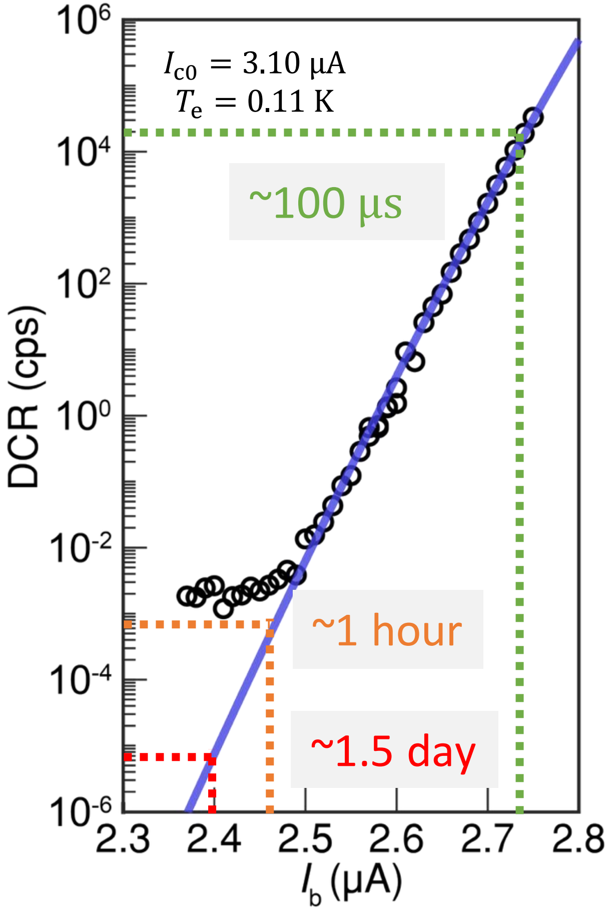
Local temperature visualized by scanning SQUID thermometry



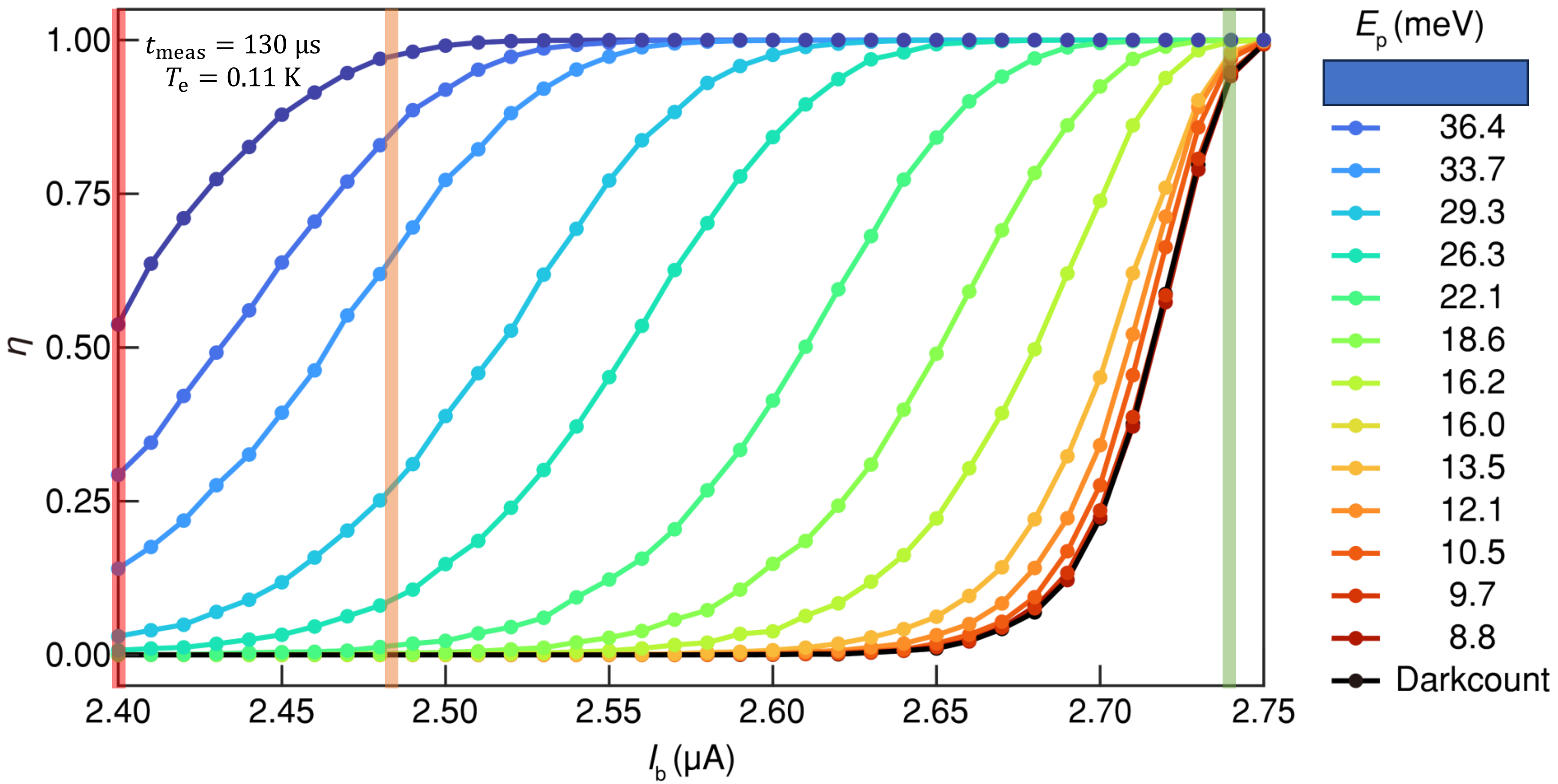
Atomic disorders at the edges could greatly enhance the value of $\boldsymbol{\Sigma}$.



Science AdvancesVolume 10, Issue 38



$I_{c0} = 3.10$ μA
$T_e = 0.11$ K
~100 μs
~1 hour
~1.5 day
DCR (cps)
I_b (μA)



$t_{meas} = 130$ μs
$T_e = 0.11$ K
η
I_b (μA)
E_p (meV)
36.4
33.7
29.3
26.3
22.1
18.6
16.2
16.0
13.5
12.1
10.5
9.7
8.8
Darkcount