Superconducting Quantum Interference Devices based on InSb Nanoflag Josephson Junctions

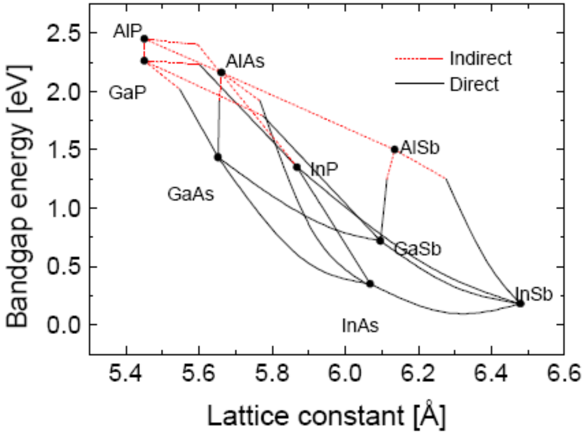
Andrea Chieppa[1], Gaurav Shukla[1], Simone Traverso[2,3], Giada Bucci[1], Valentina Zannier[1], Samuele Fracassi[2,3], Niccolò Traverso Ziani[2,3], Maura Sassetti[2,3], Matteo Carrega[3], Fabio Beltram[1], Francesco Giazotto[1], Lucia Sorba[1], **and Stefan Heun[1]**

[1]*NEST, Istituto Nanoscienze-CNR and Scuola Normale Superiore, Pisa, Italy*
[2]*Dipartimento di Fisica, Università di Genova, Genoa, Italy*
[2]*CNR-SPIN, Genoa, Italy*

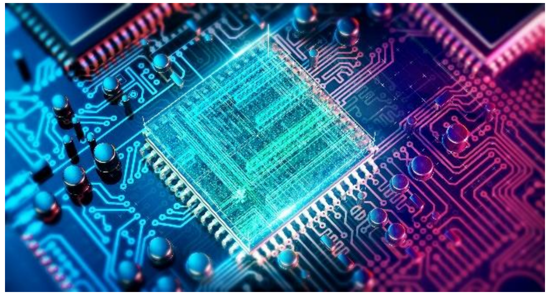
National Enterprise for nanoScience and nanoTechnology

Why InSb?

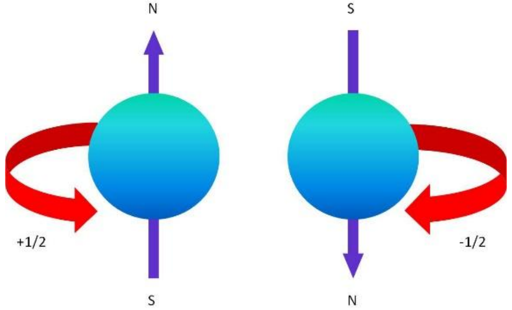
- Narrow bandgap (0.23 eV) ⟶ mid-infrared optoelectronic devices.



- High bulk electron mobility (7.7 x 10^4 $cm^2/(Vs)$), small effective mass (0.018 m_e) ⟶ high-speed and low-power electronic devices.



- Strong spin-orbit interaction (E_{SOI} $\sim 200\ \mu$eV), large Landé g-factor ($g^* \sim 50$) ⟶ spintronics and topological quantum computing.

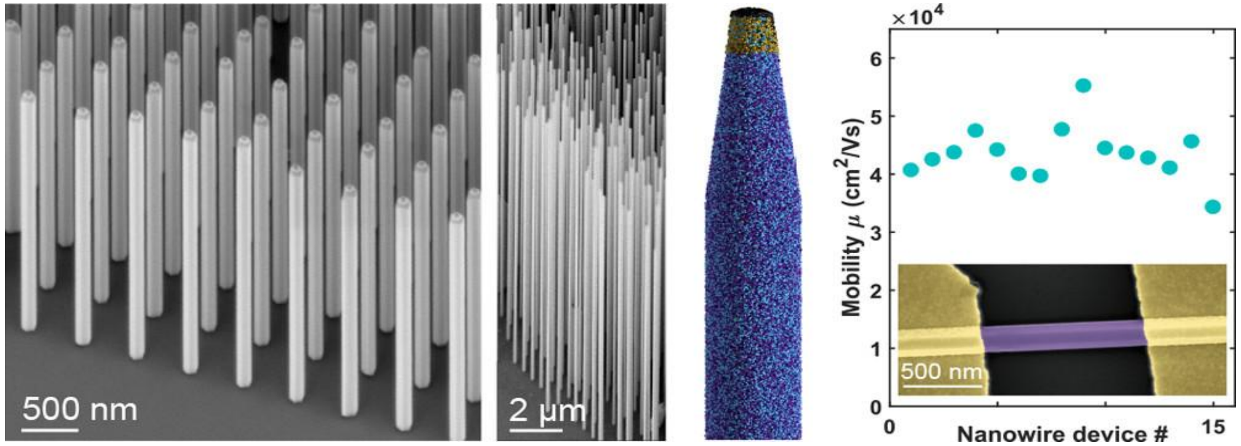


National Enterprise for nanoScience and nanoTechnology

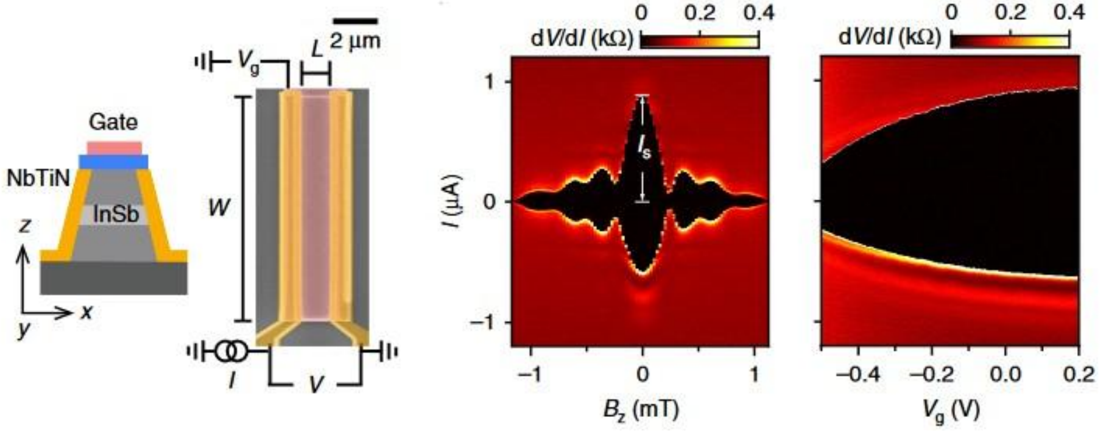
InSb nanostructures

Nano Lett. 2019, 19, 6, 3575–3582

- InSb nanowires:



- InSb quantum wells:

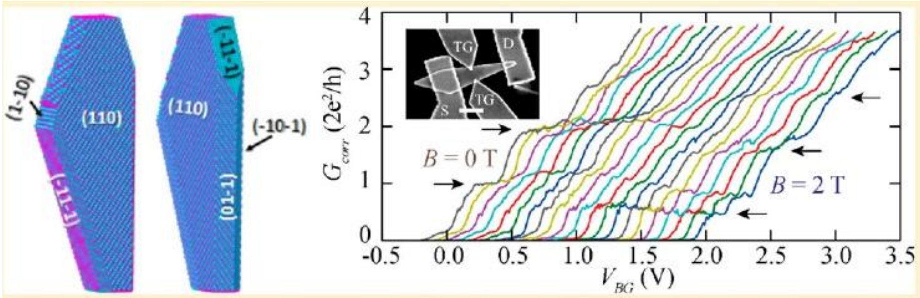


Nat Commun **10,** 3764 (2019)

A novel approach: 2D nanoflags (NFs)

Twin-Induced InSb Nanosails: A Convenient High Mobility Quantum System

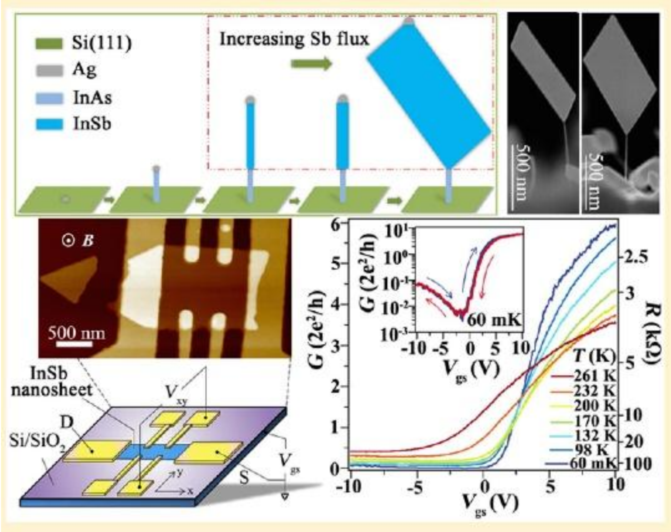
María de la Mata,[†] Renaud Leturcq,[*,‡,§] Sébastien R. Plissard,[||] Chloé Rolland,[‡] César Magén,[⊥] Jordi Arbiol,[*,†,#] and Philippe Caroff[*,‡,∇]



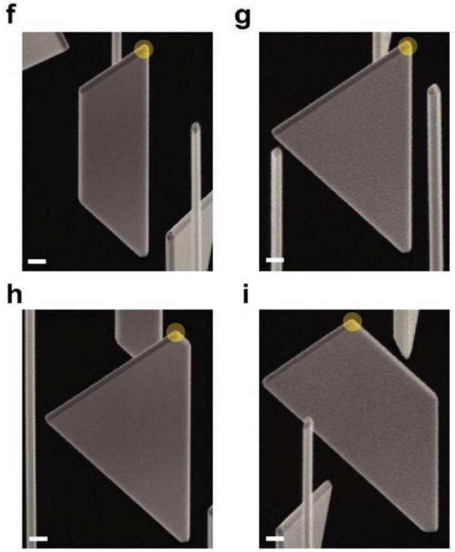
Nano Lett. 16 (2016) 825

Free-Standing Two-Dimensional Single-Crystalline InSb Nanosheets

D. Pan,[†] D. X. Fan,[‡] N. Kang,[‡] J. H. Zhi,[‡] X. Z. Yu,[†] H. Q. Xu,[*,‡] and J. H. Zhao[*,†]



Nano Lett. 16 (2016) 834



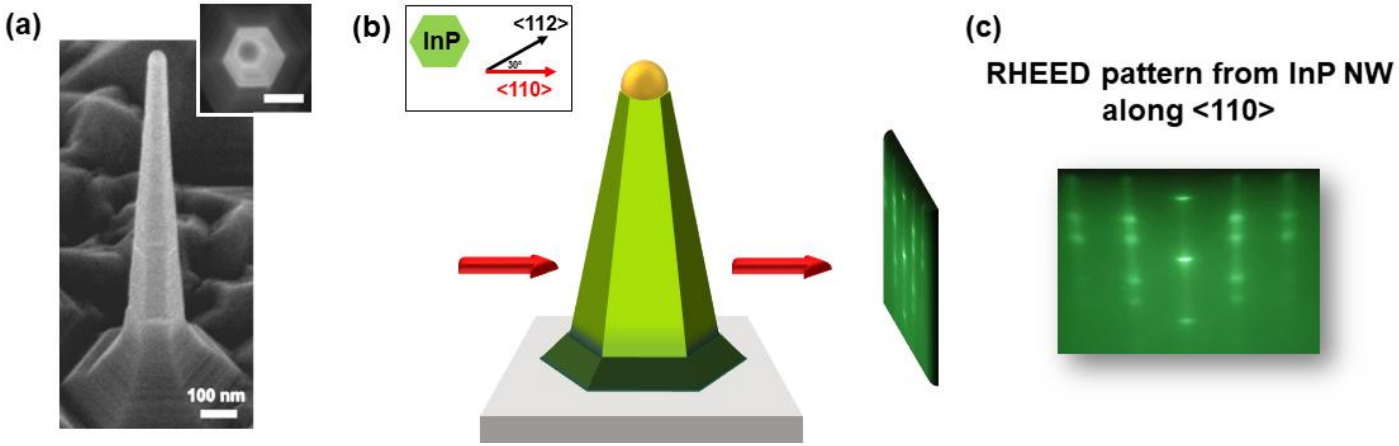
Bottom-Up Grown 2D InSb Nanostructures

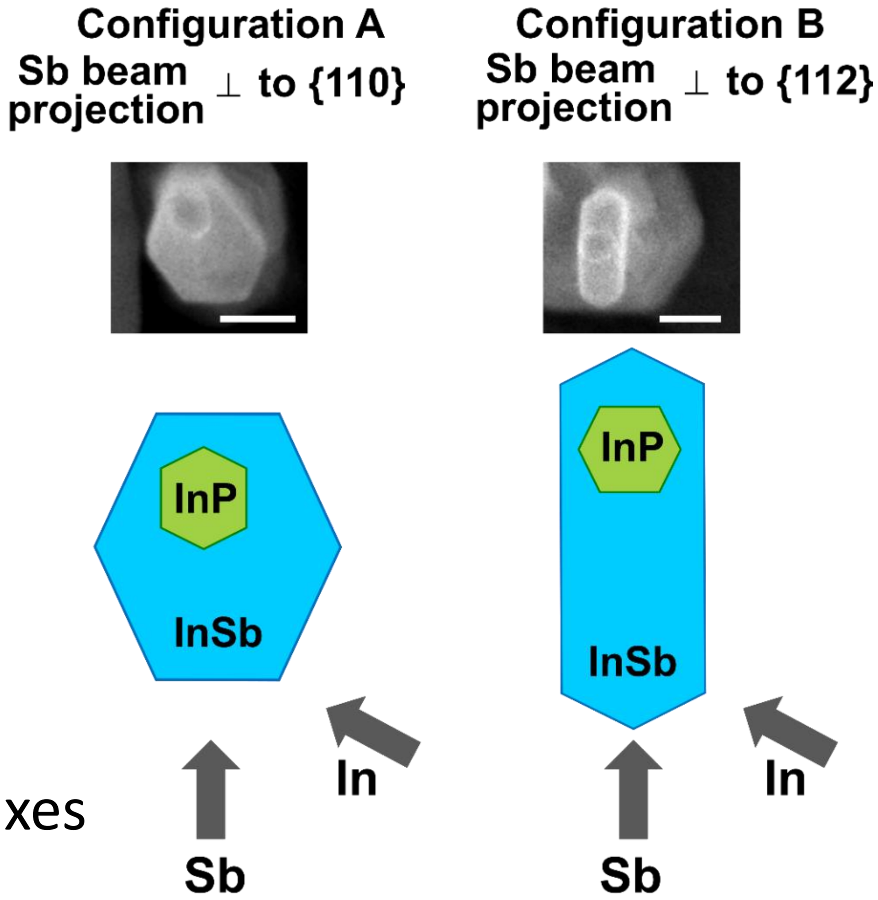
Sasa Gazibegovic, Ghada Badawy,* Thijs L. J. Buckers, Philipp Leubner, Jie Shen, Folkert K. de Vries, Sebastian Koelling, Leo P. Kouwenhoven, Marcel A. Verheijen, and Erik P. A. M. Bakkers*

Adv. Mater. 31 (2019) 1808181

From nanowires (1D) to nanoflags (2D)

Tapered InP nanowires are used as *stems*



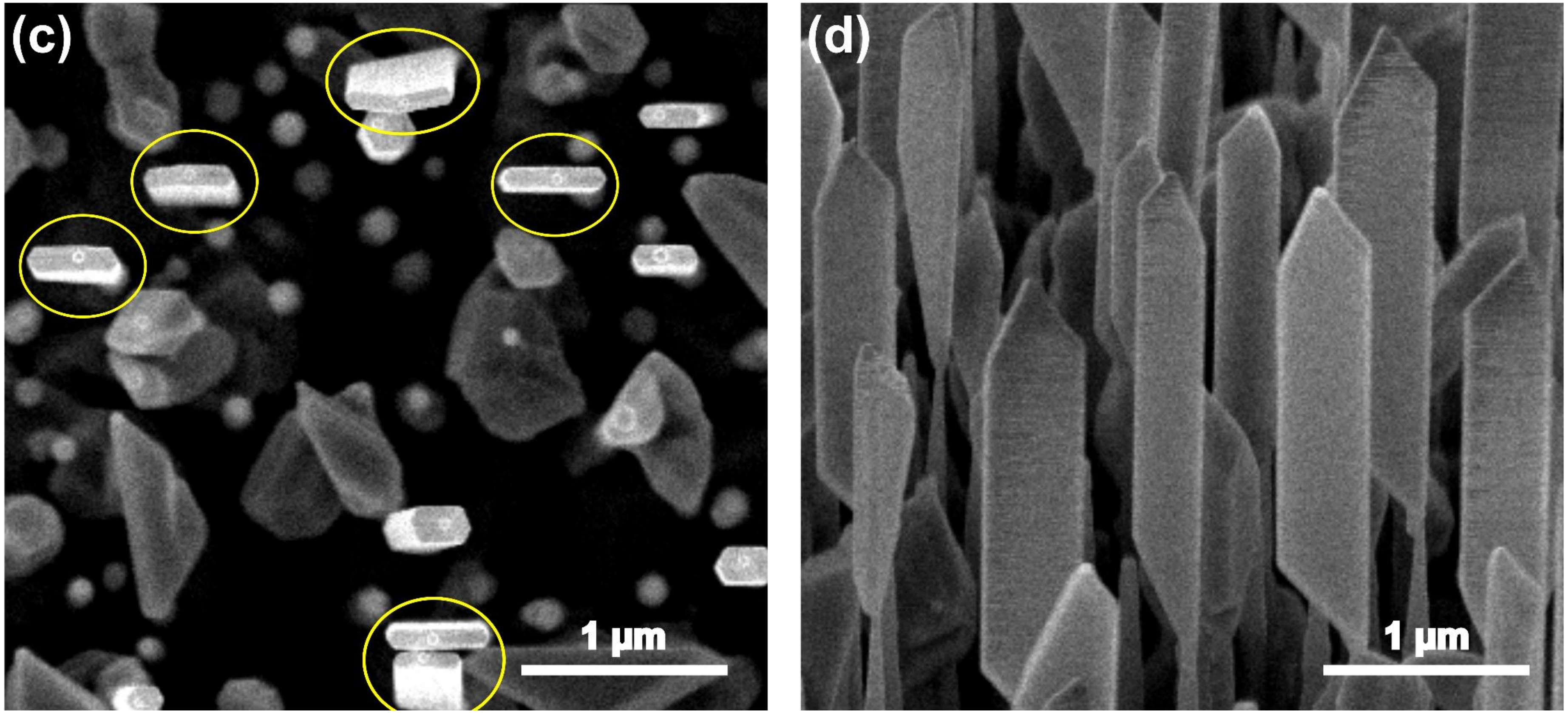


The 2D shape is obtained with directional fluxes

I. Verma et al., ACS Applied Nano Materials 4 (2021) 5825.

National Enterprise for nanoScience and nanoTechnology

Growth of InSb nanoflags by CBE



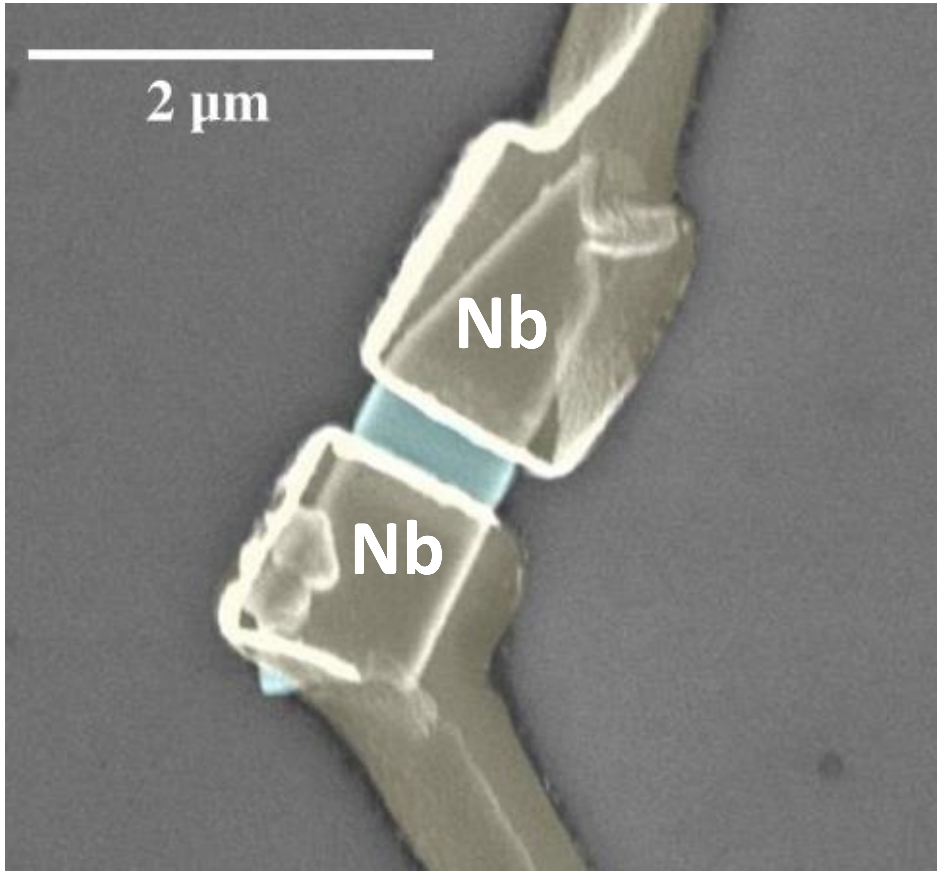
Defect-free InSb zinc blende lattice

InSb nanoflags:
Length 2-3 µm
Width 500 nm
Thickness 100 nm

I. Verma et al., ACS Applied Nano Materials 4 (2021) 5825.

InSb Nanoflags

- Single crystal, ZB structure
- length ~ 2.8 μm
- width ~ 500 nm
- thickness ~ 100 nm
- $m^* = 0.02m_e$
- $E_g = 0.23$ eV
- $|g^*| = 50$



Appl. Phys. Lett. 119 (2021) 214004.

Talk by Gaurav Shukla on Thursday at 12:00

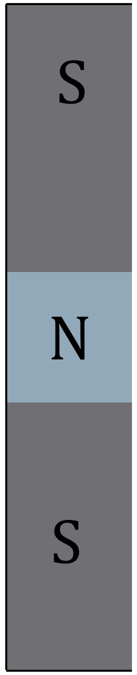
Introduction to SQUIDs (Superconducting Quantum Interference Devices)

From Josephson Junctions to SQUIDs

SNS Josephson Junctions

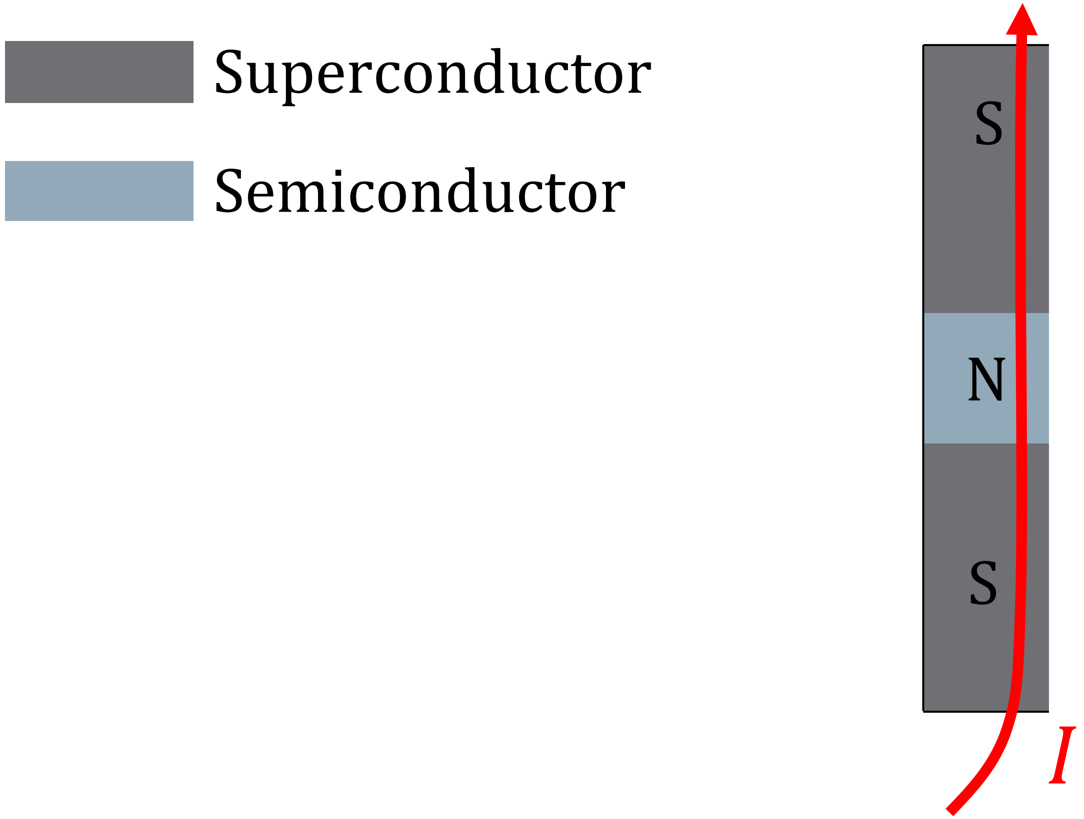
Superconductor

Semiconductor



N = normal material non superconducting

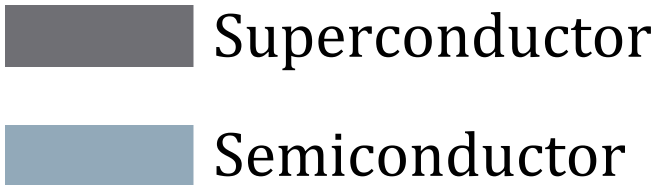
SNS Josephson Junctions

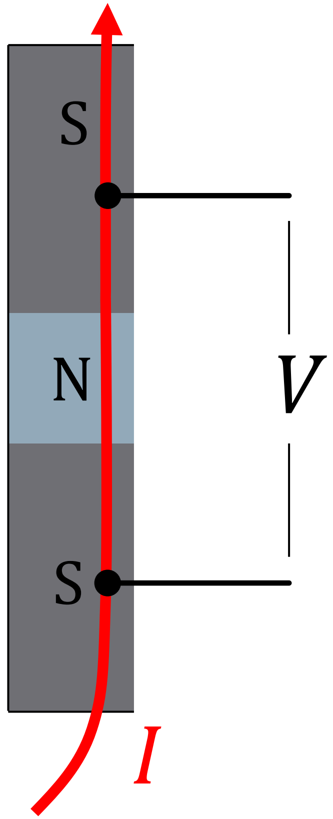


- Josephson Effect

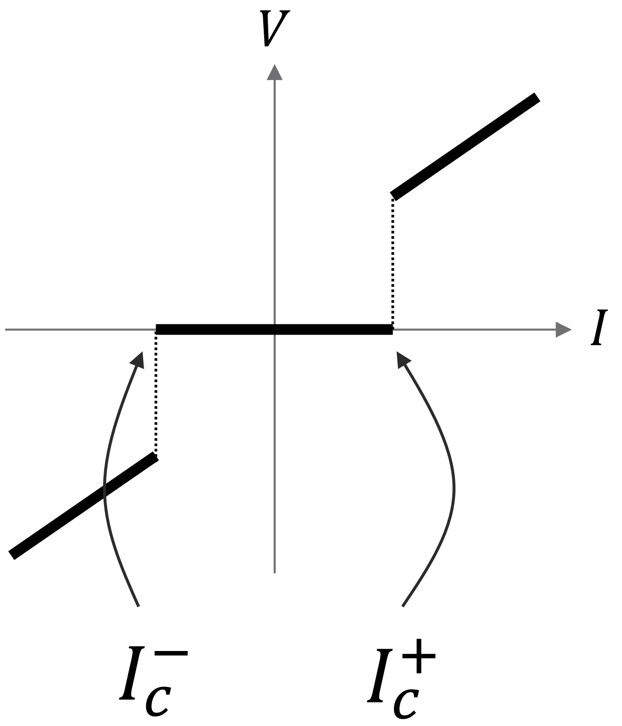
N = normal material non superconducting

SNS Josephson Junctions



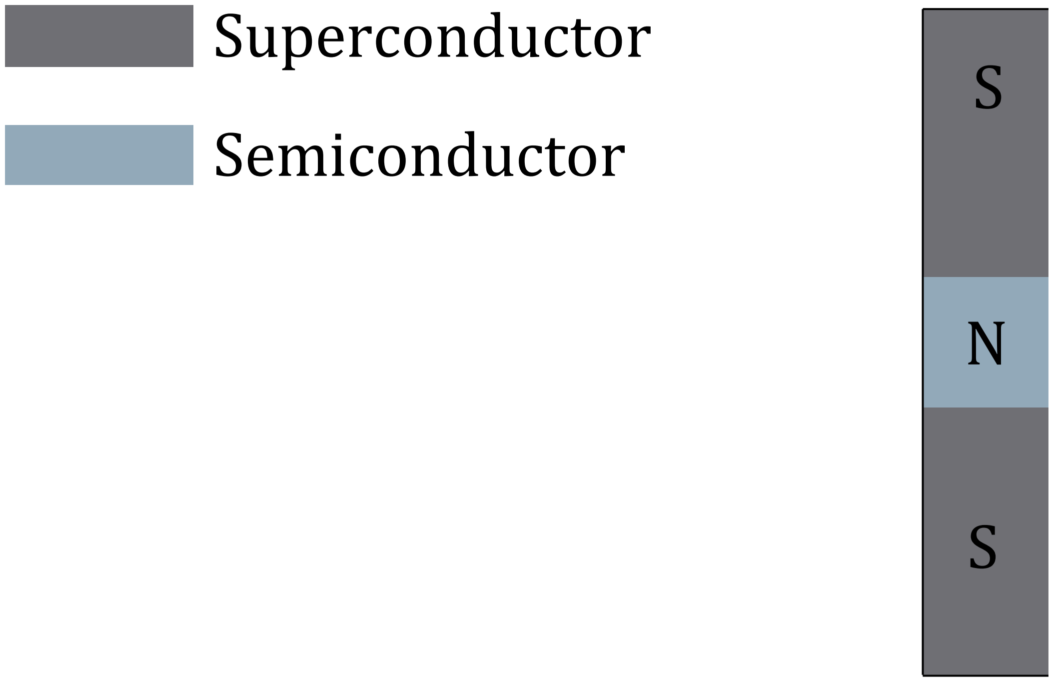


- Josephson Effect

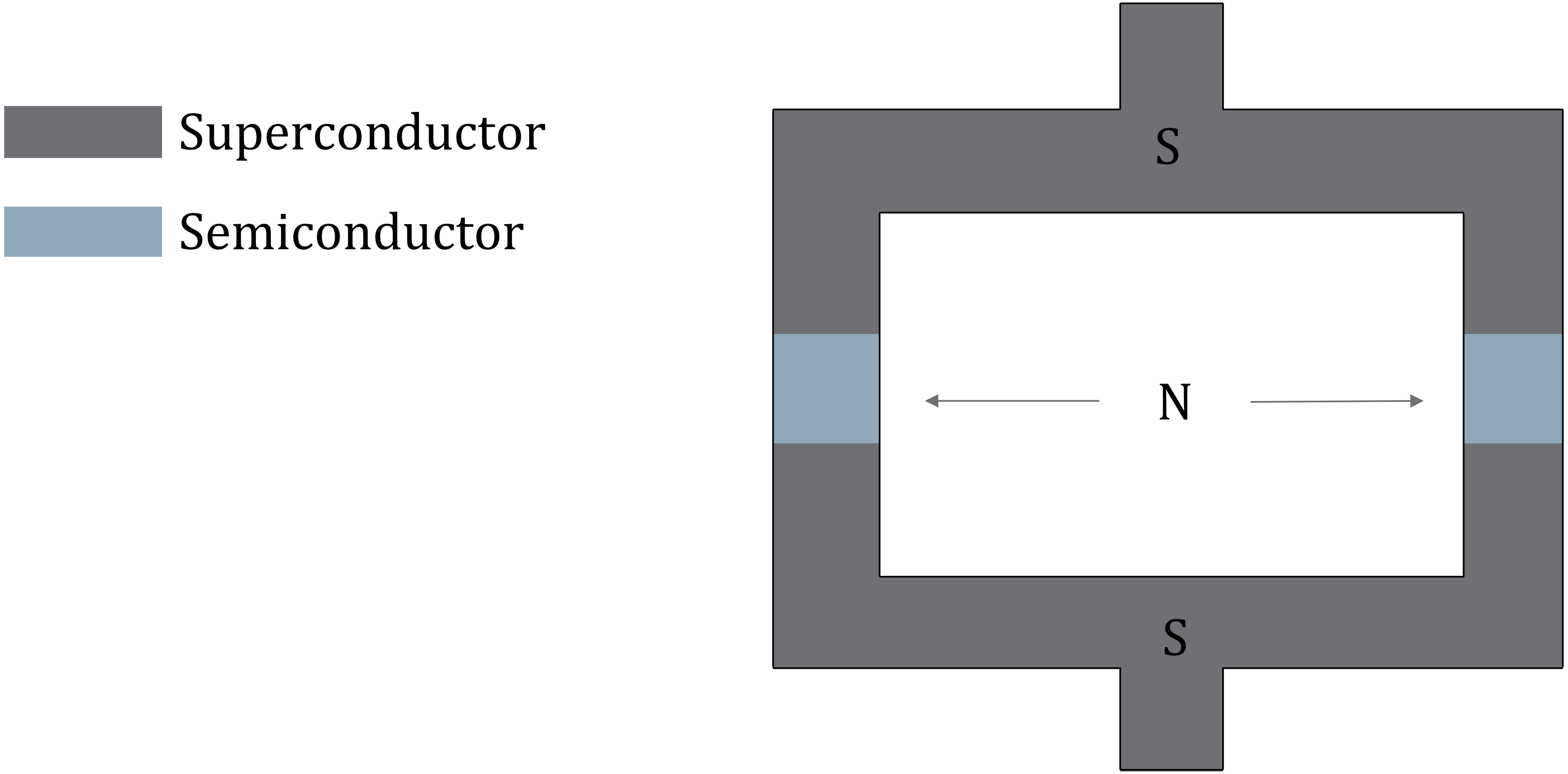


N = normal material non superconducting

SQUID based on SNS Josephson Junctions

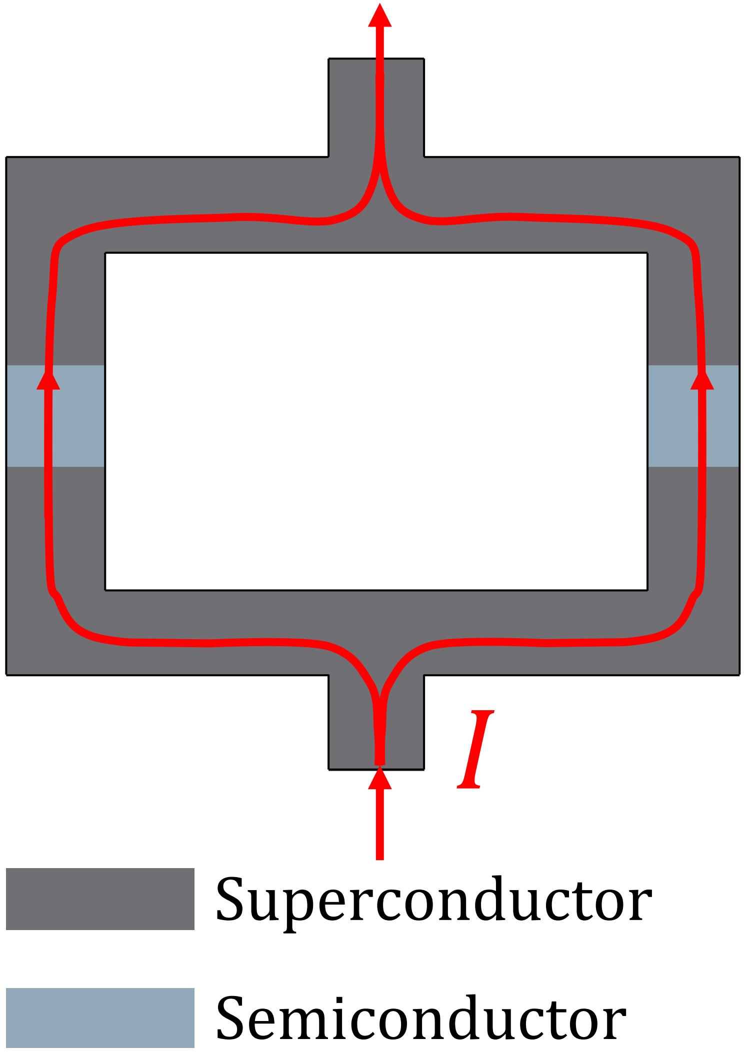


SQUID based on SNS Josephson Junctions



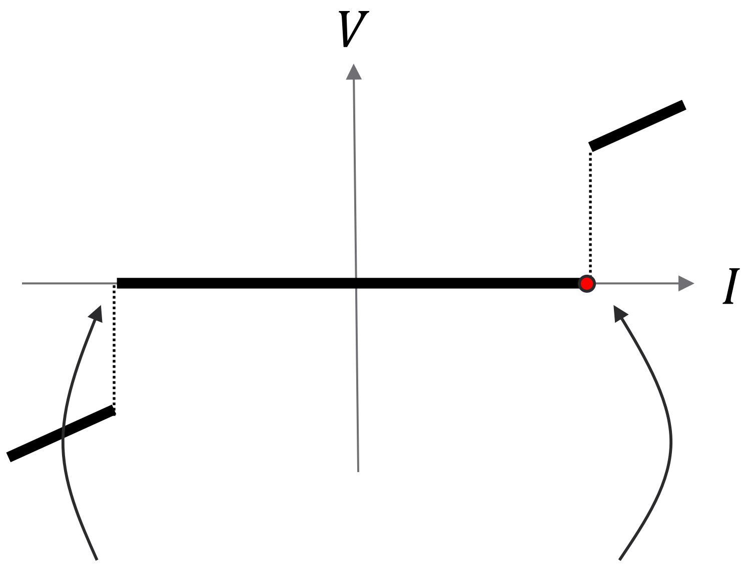
SQUID based on SNS Josephson Junctions

- Josephson Effect



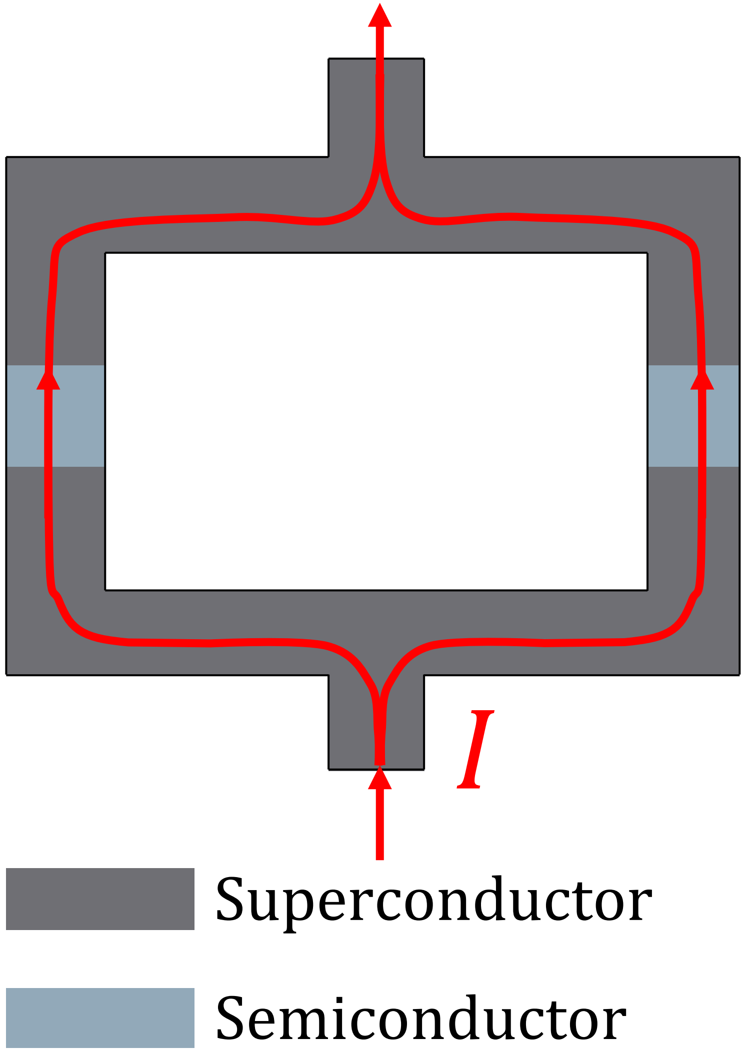
SQUID based on SNS Josephson Junctions

- Josephson Effect



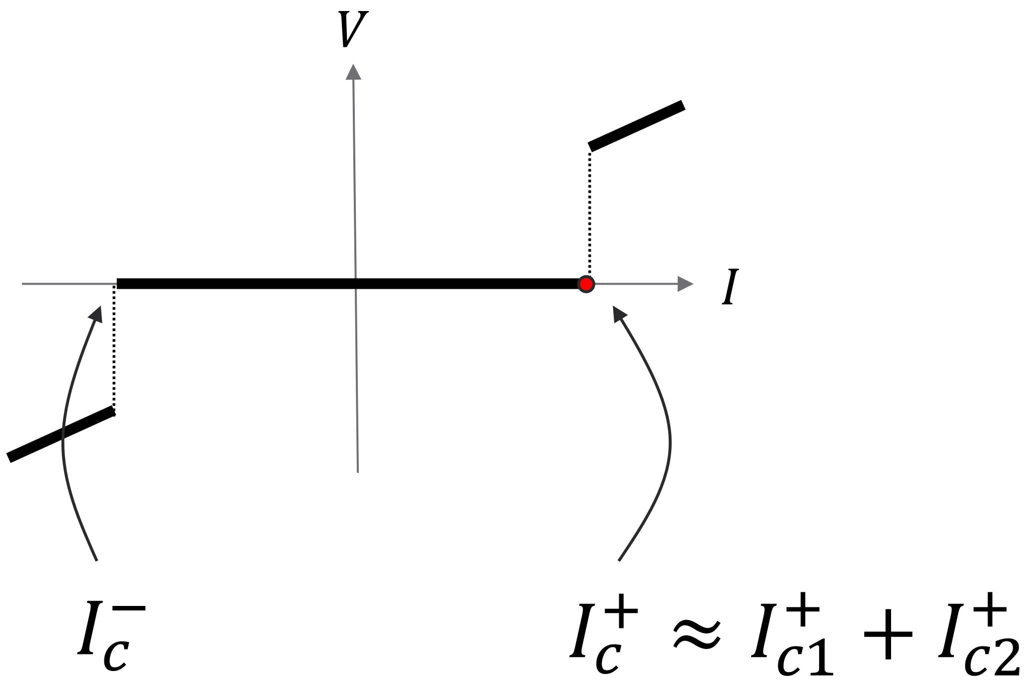
I_c^-

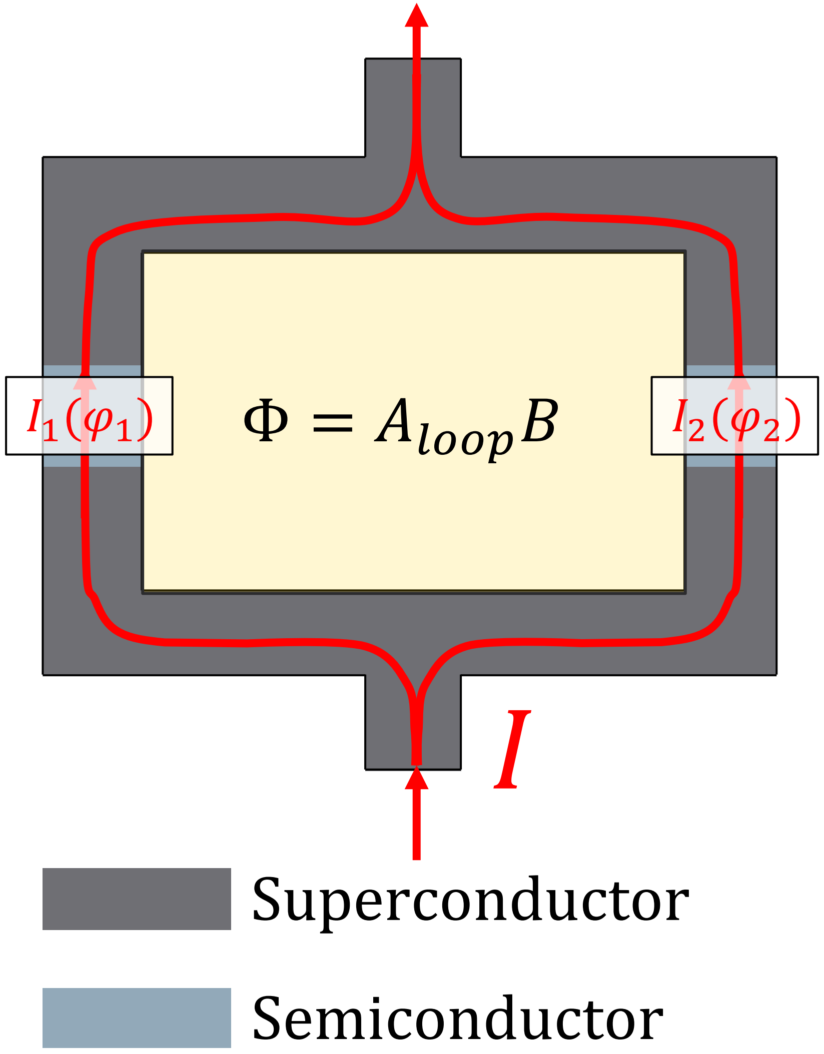
$I_c^+ \approx I_{c1}^+ + I_{c2}^+$



SQUID based on SNS Josephson Junctions

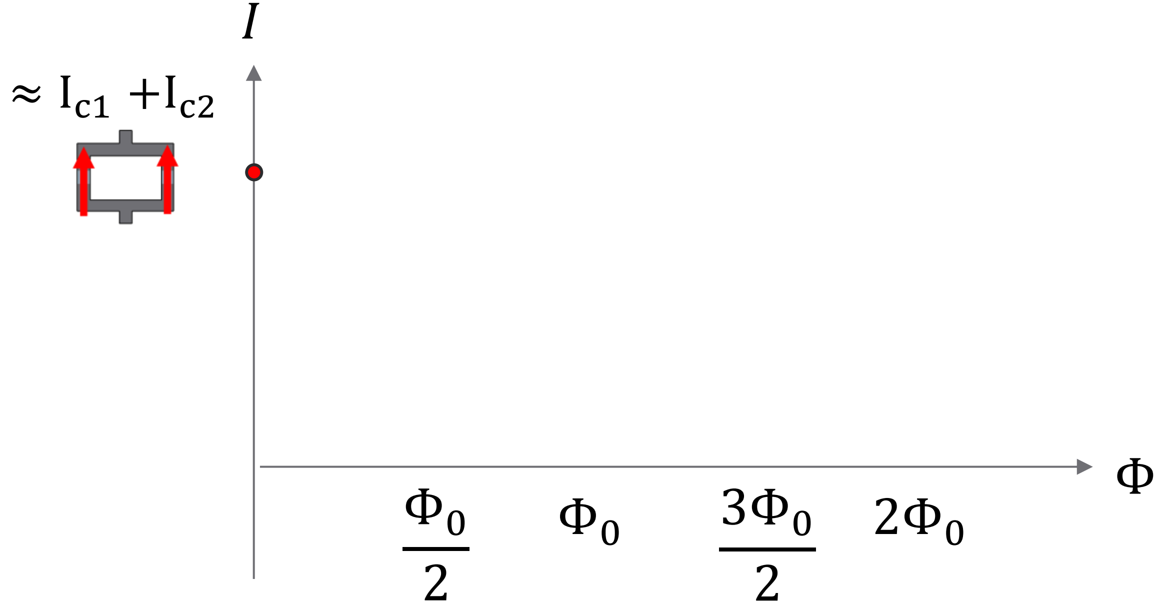
- Josephson Effect
- Flux quantization → $I_c(\Phi)$

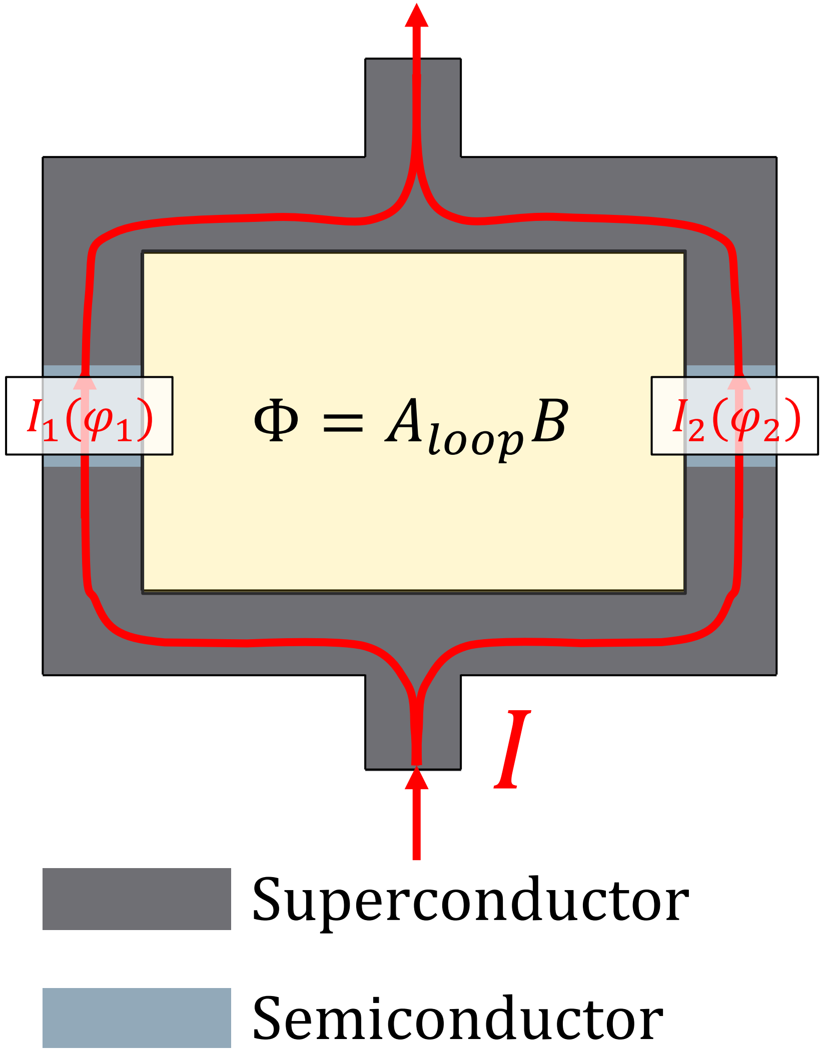




SQUID based on SNS Josephson Junctions

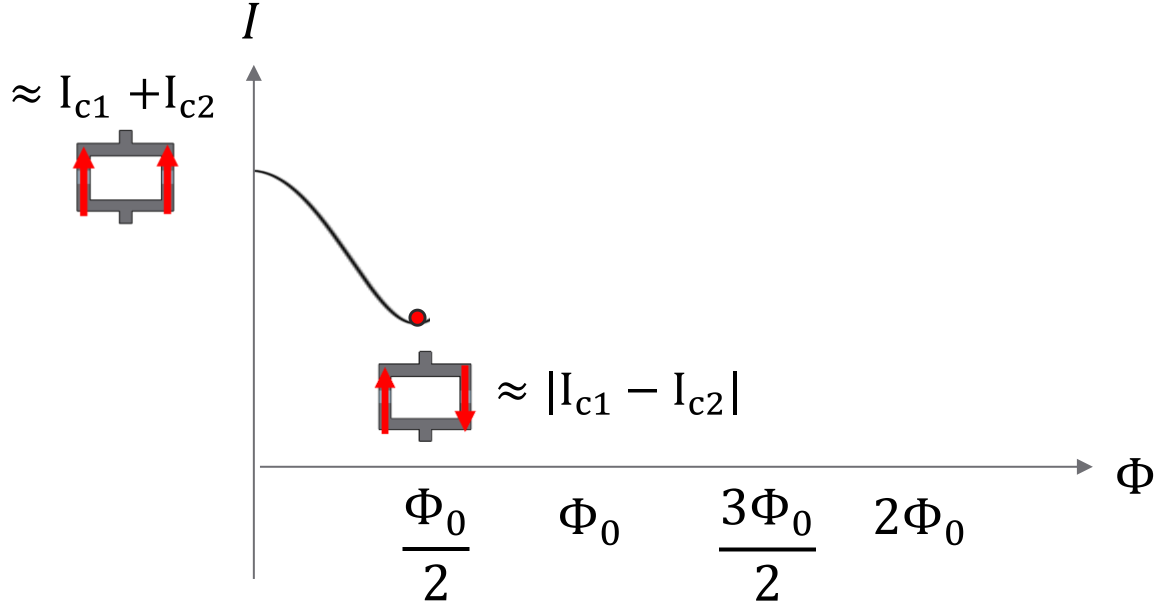
- Josephson Effect
- Flux quantization → $I_c(\Phi)$

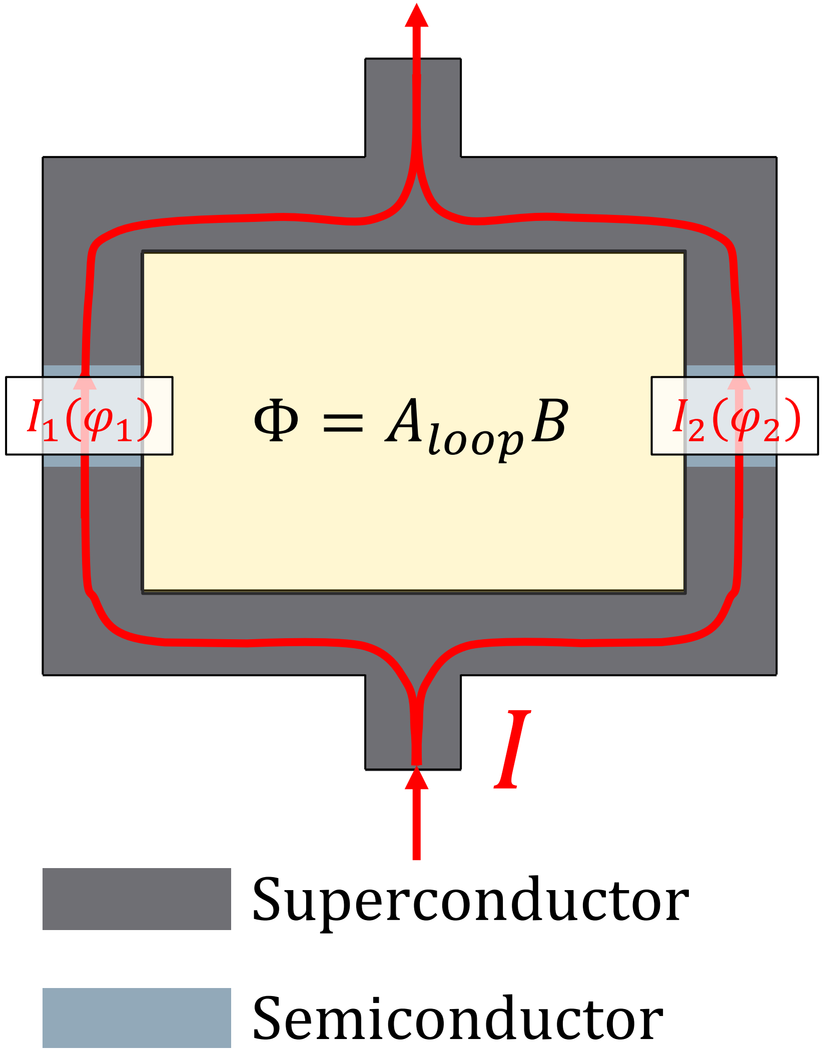




SQUID based on SNS Josephson Junctions

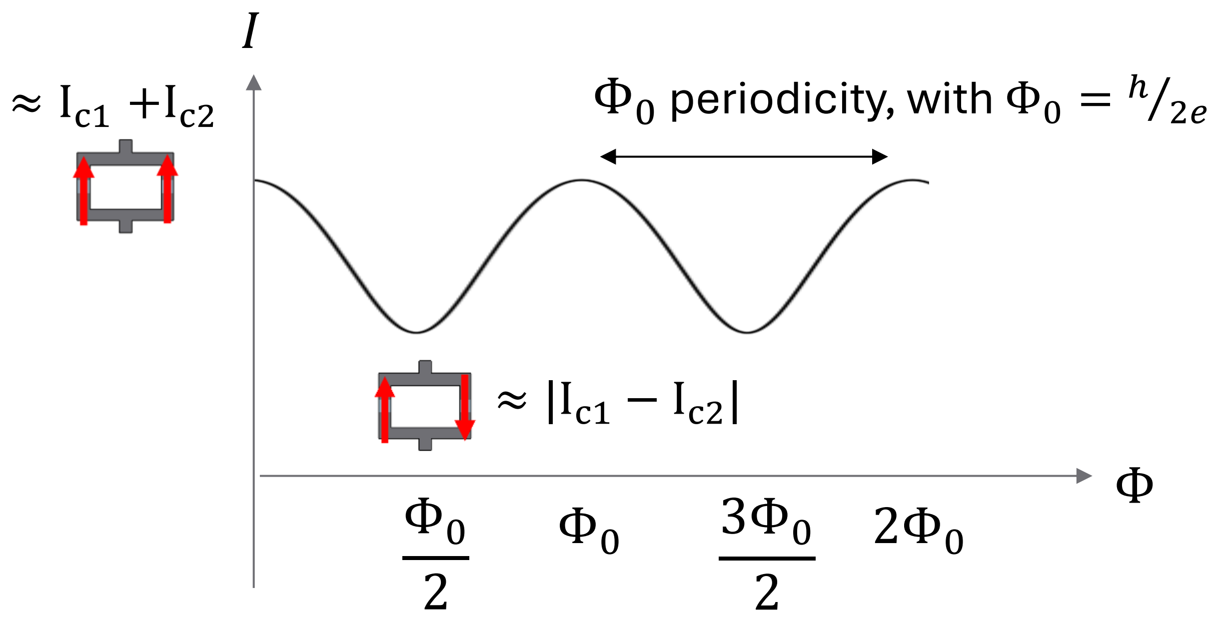
- Josephson Effect
- Flux quantization → $I_c(\Phi)$

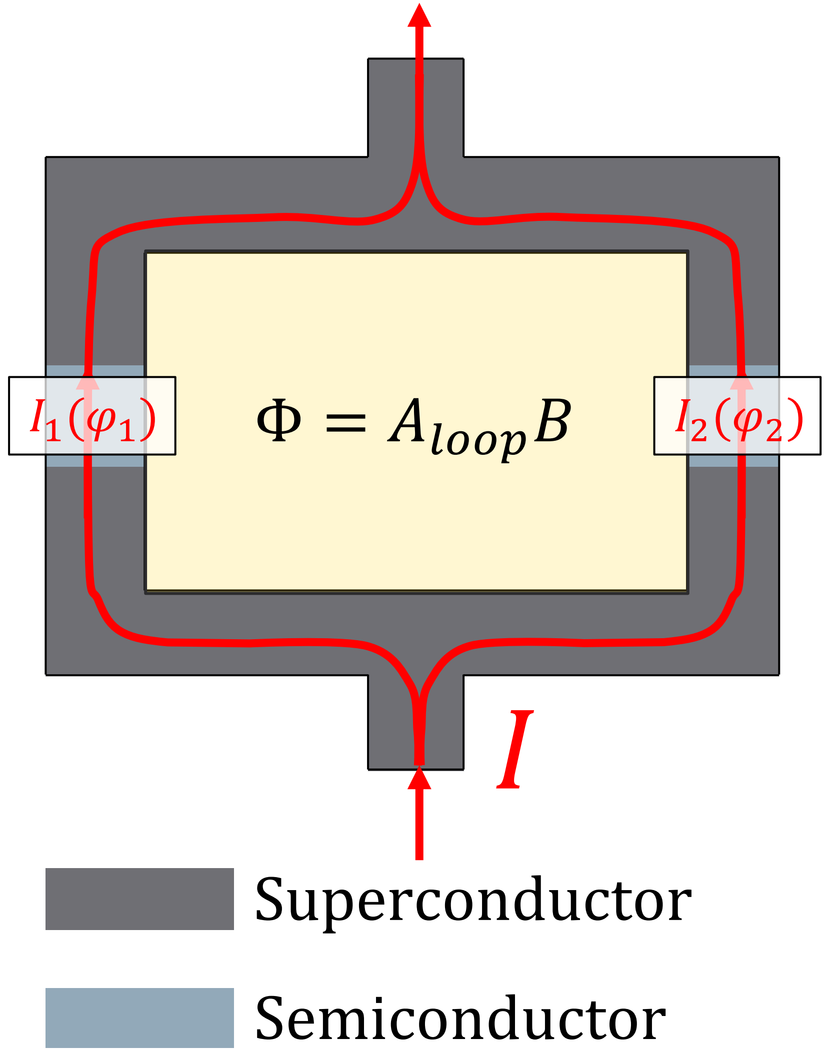




SQUID based on SNS Josephson Junctions

- Josephson Effect
- Flux quantization → $I_c(\Phi)$



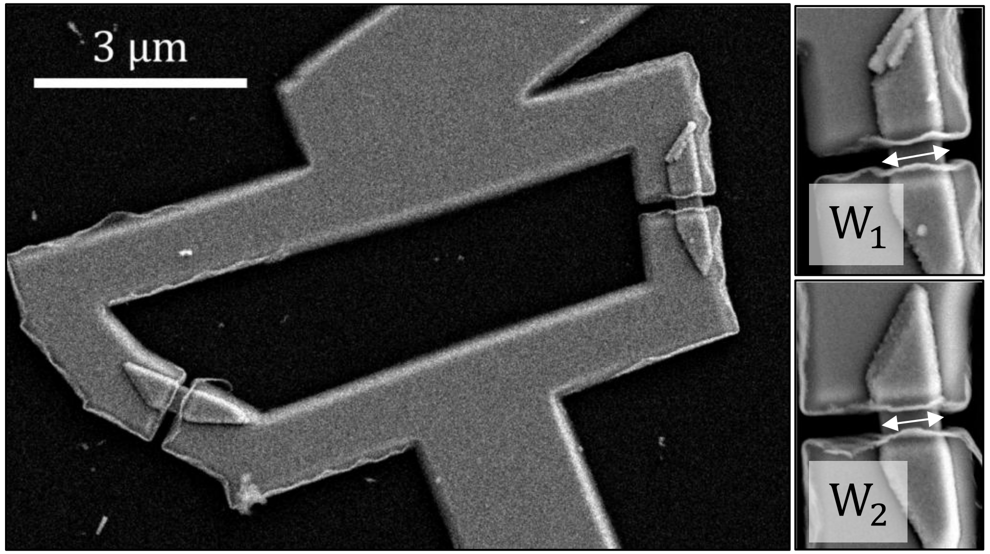


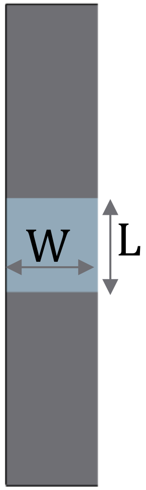
SQUIDs based on InSb nanoflags

Experimental Results

Scanning electron micrographs

Symmetric SQUID

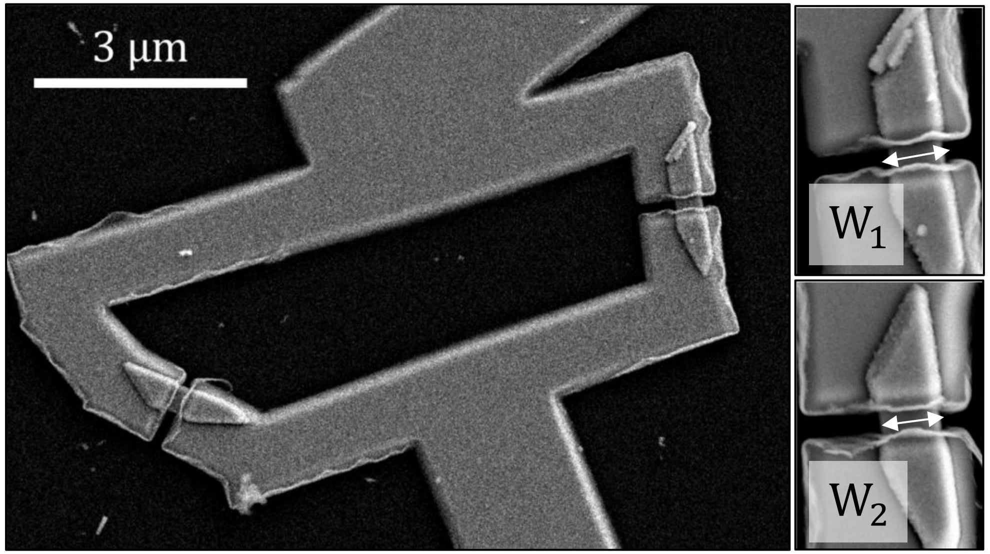


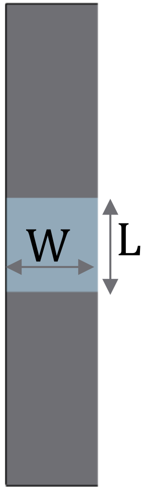


- $L \approx 200$ nm
- $W_1 = W_2 \approx 0.4$ µm

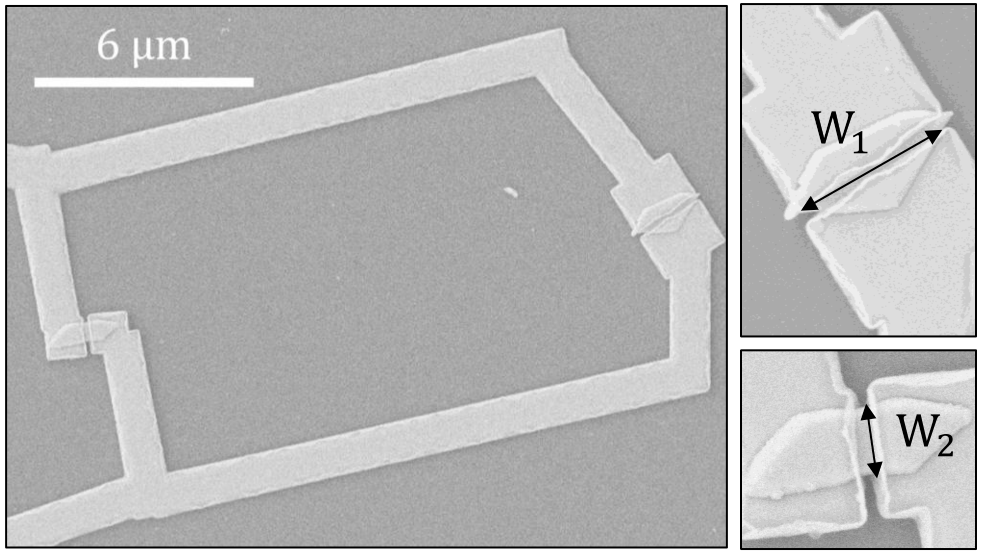
Scanning electron micrographs

Symmetric SQUID





Asymmetric SQUID

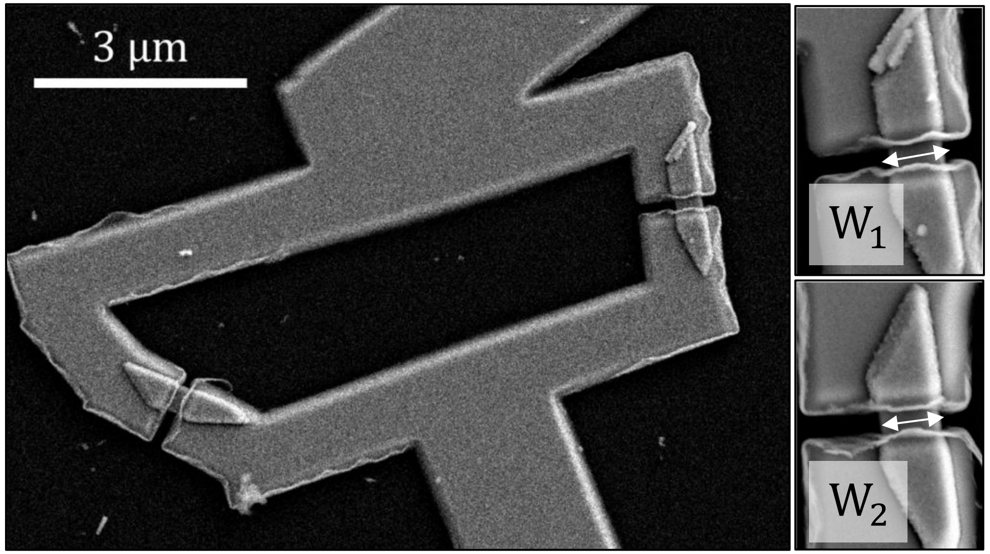


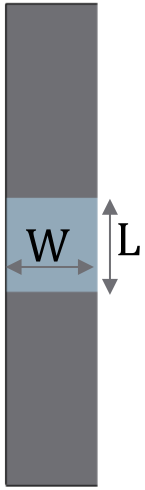
- $L \approx 200$ nm
- $W_1 = W_2 \approx 0.4$ µm

- $L \approx 200$ nm
- $W_1 \approx 1.7$µm
- $W_2 \approx 0.5$ µm

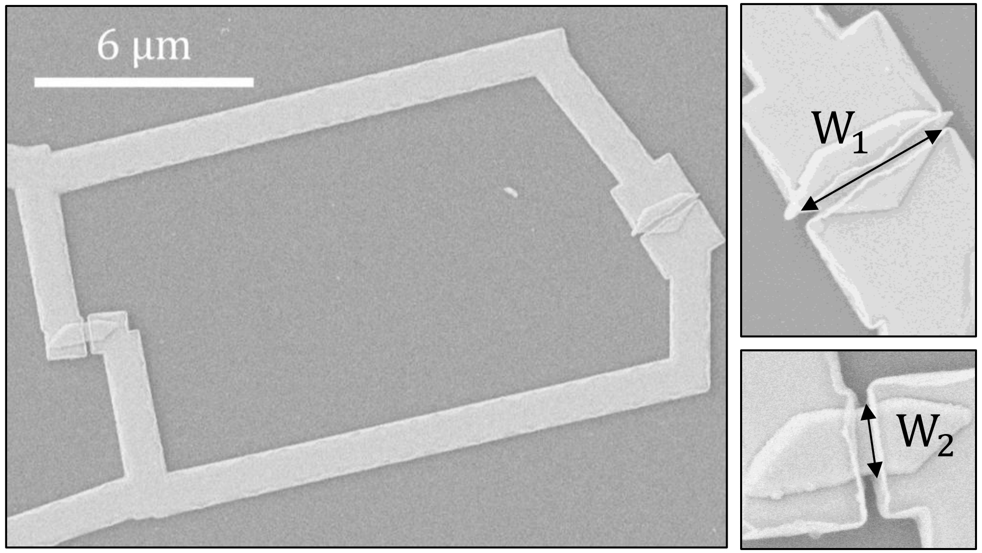
Scanning electron micrographs

Symmetric SQUID

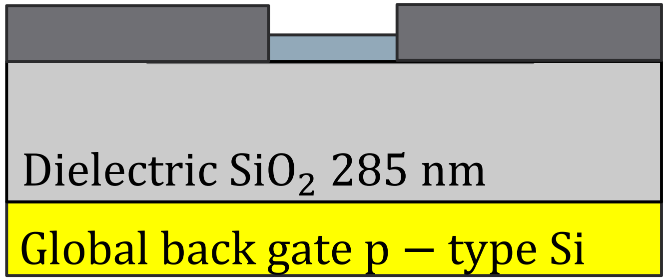




Asymmetric SQUID



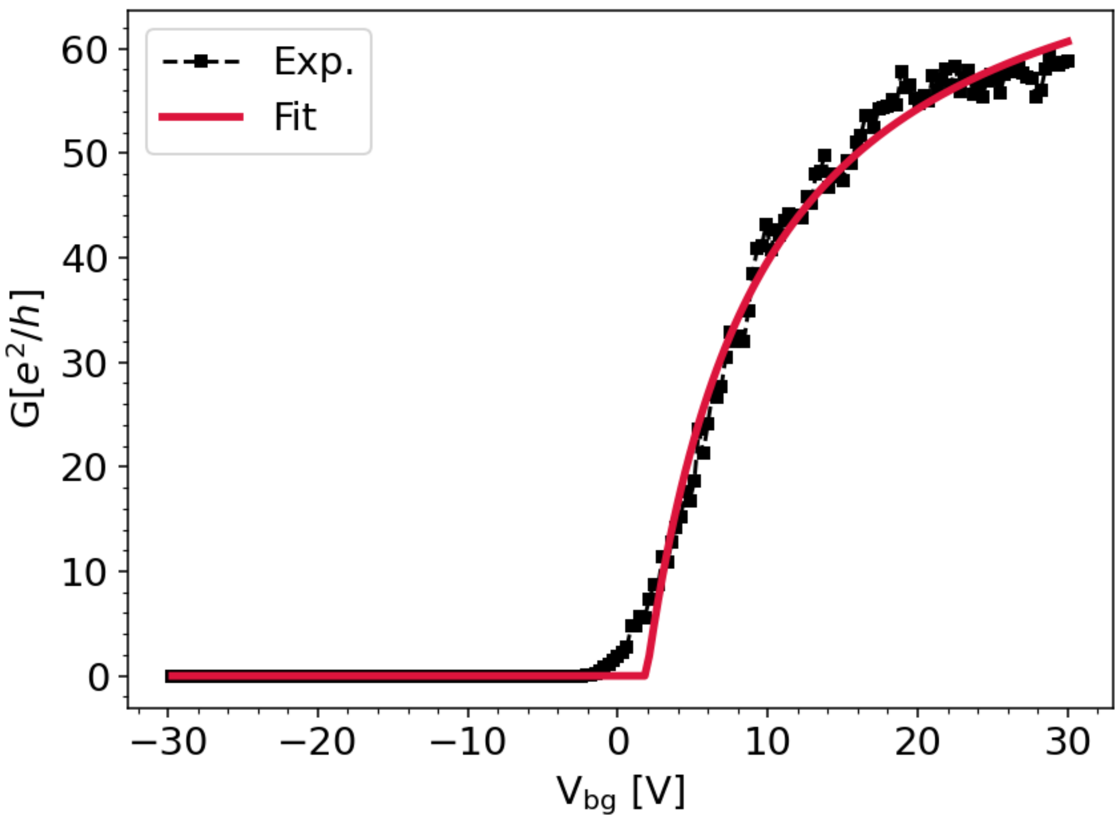
- $L \approx 200$ nm
- $W_1 = W_2 \approx 0.4$ μm



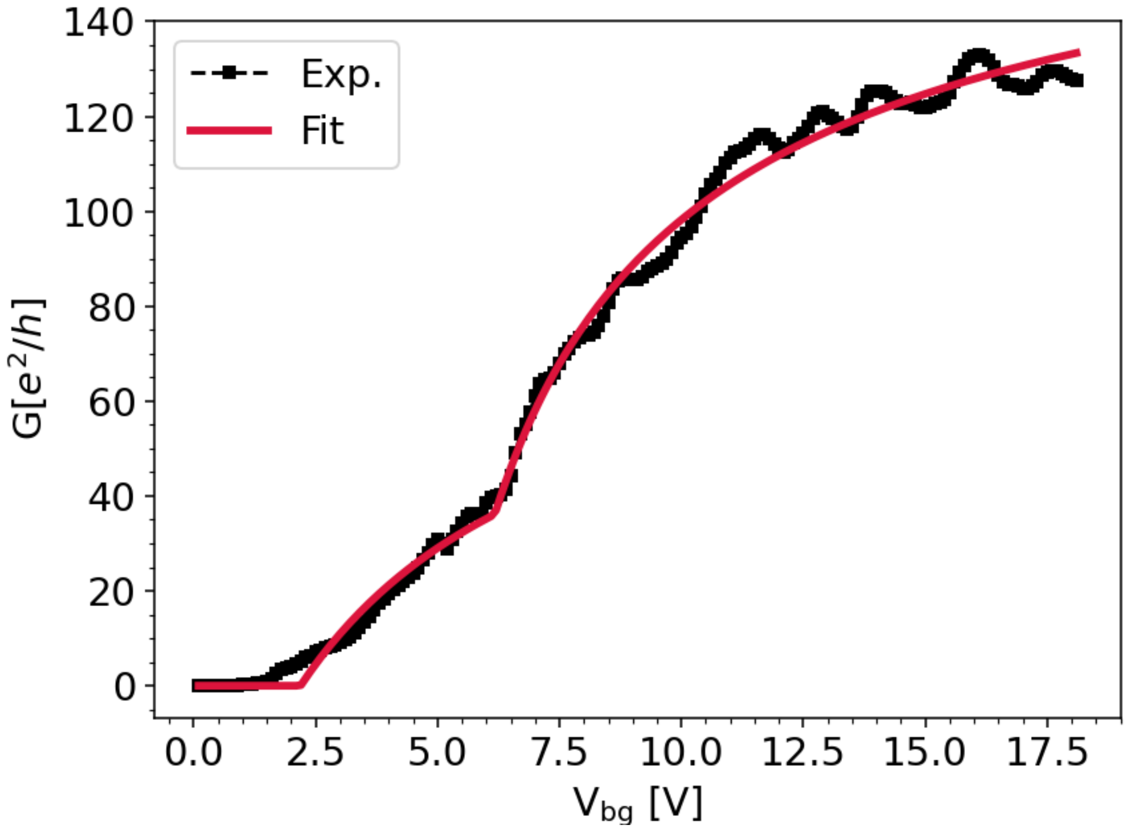
- $L \approx 200$ nm
- $W_1 \approx 1.7$μm
- $W_2 \approx 0.5$ μm

SQUID conductance $G = G_{JJ1} + G_{JJ2}$

Symmetric SQUID



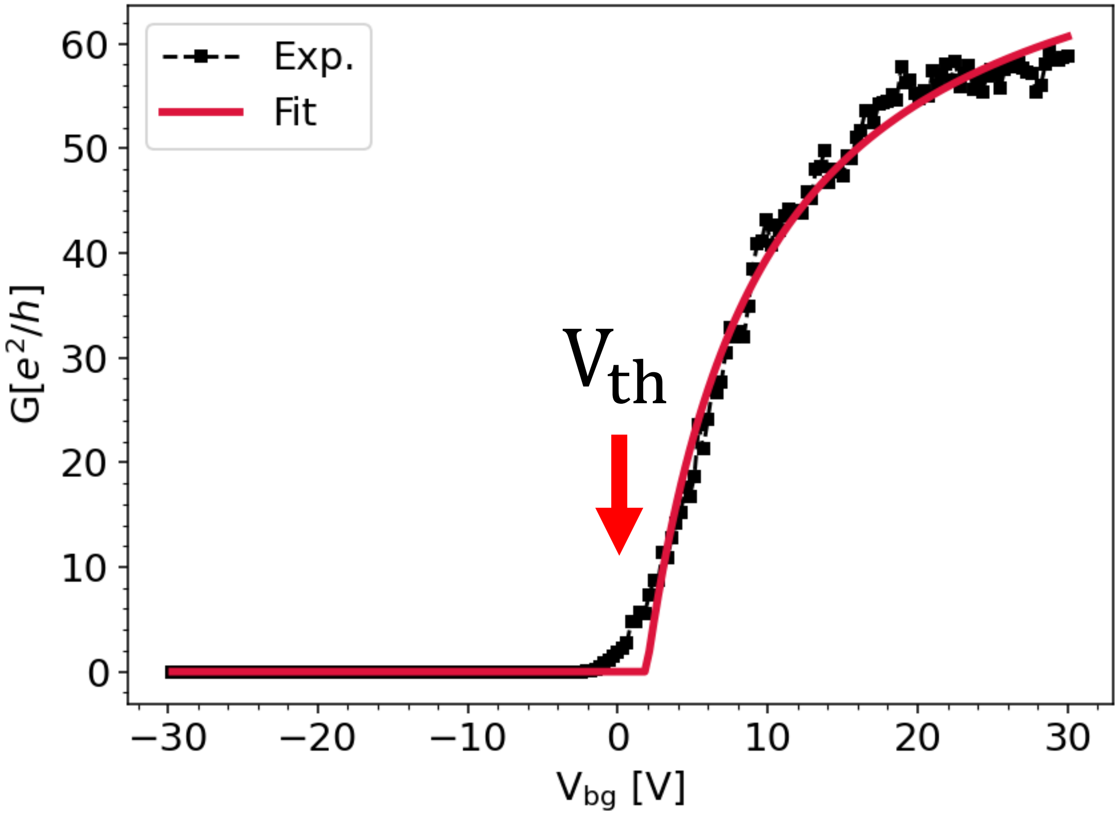
Asymmetric SQUID



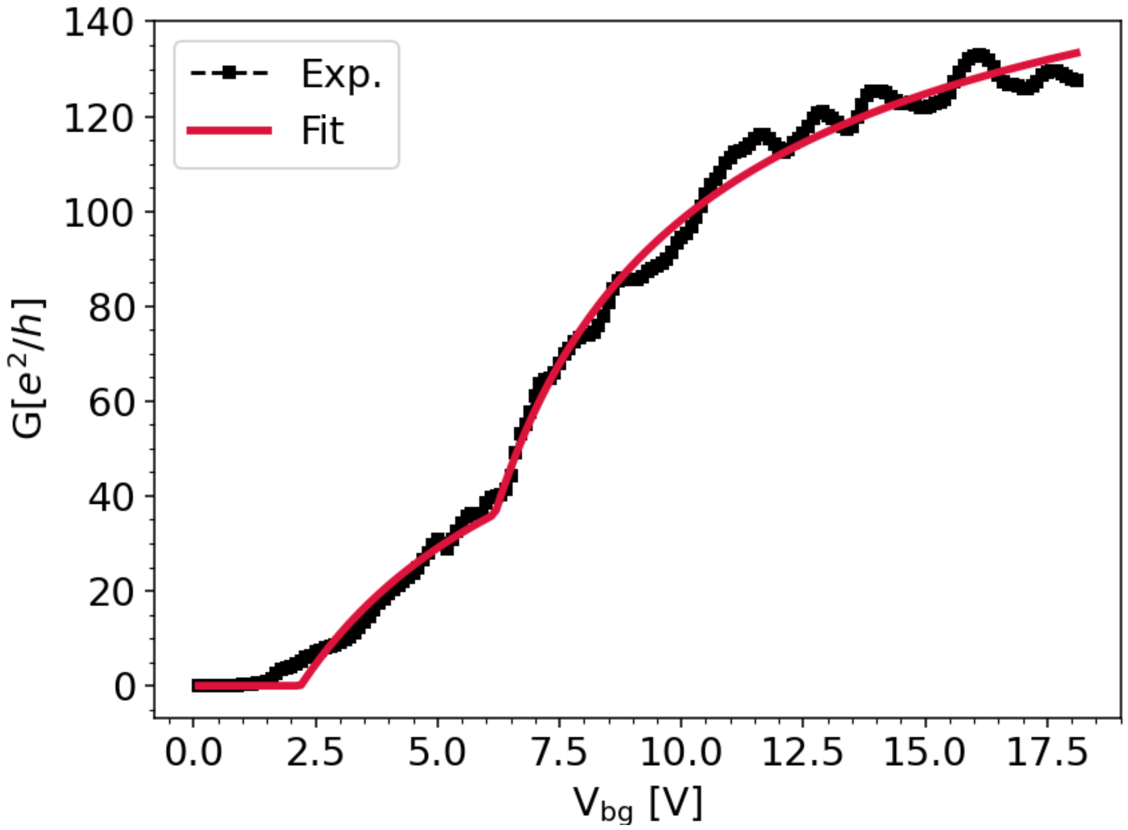
$T = 2\ \mathrm{K}$

SQUID conductance $\mathrm{G} = \mathrm{G}_{\mathrm{JJ1}} + \mathrm{G}_{\mathrm{JJ2}}$

Symmetric SQUID



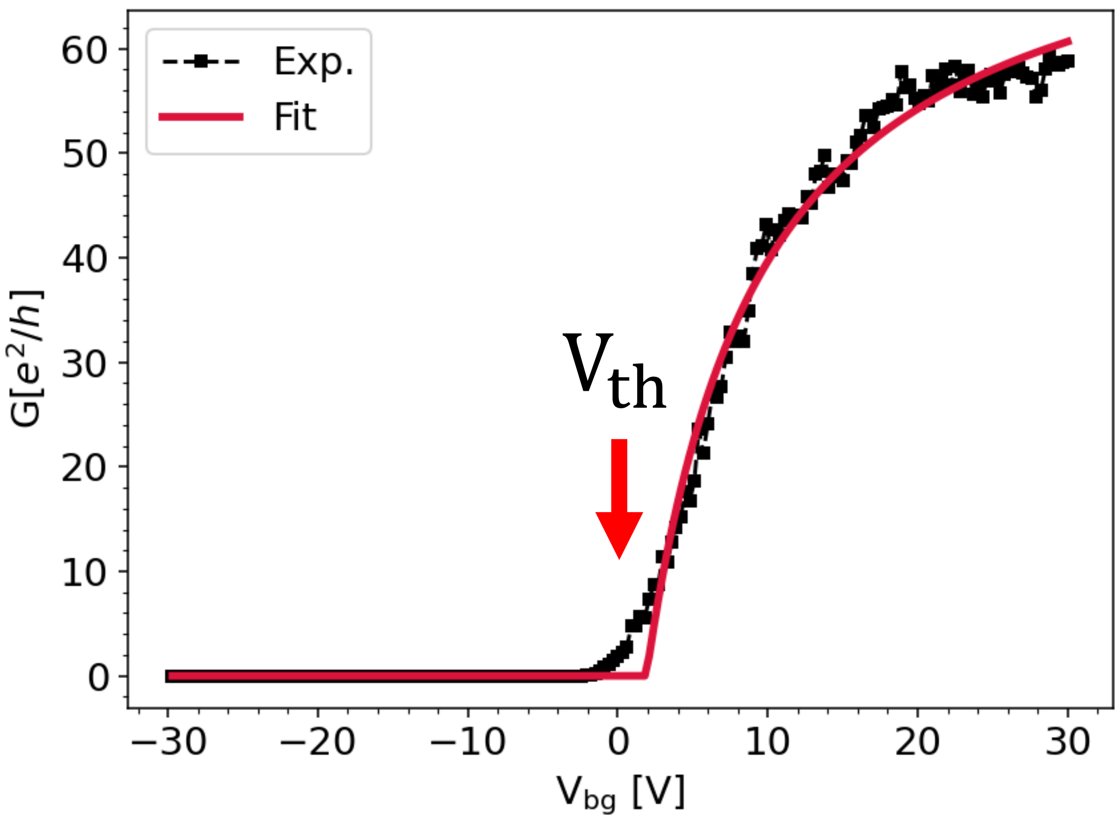
Asymmetric SQUID



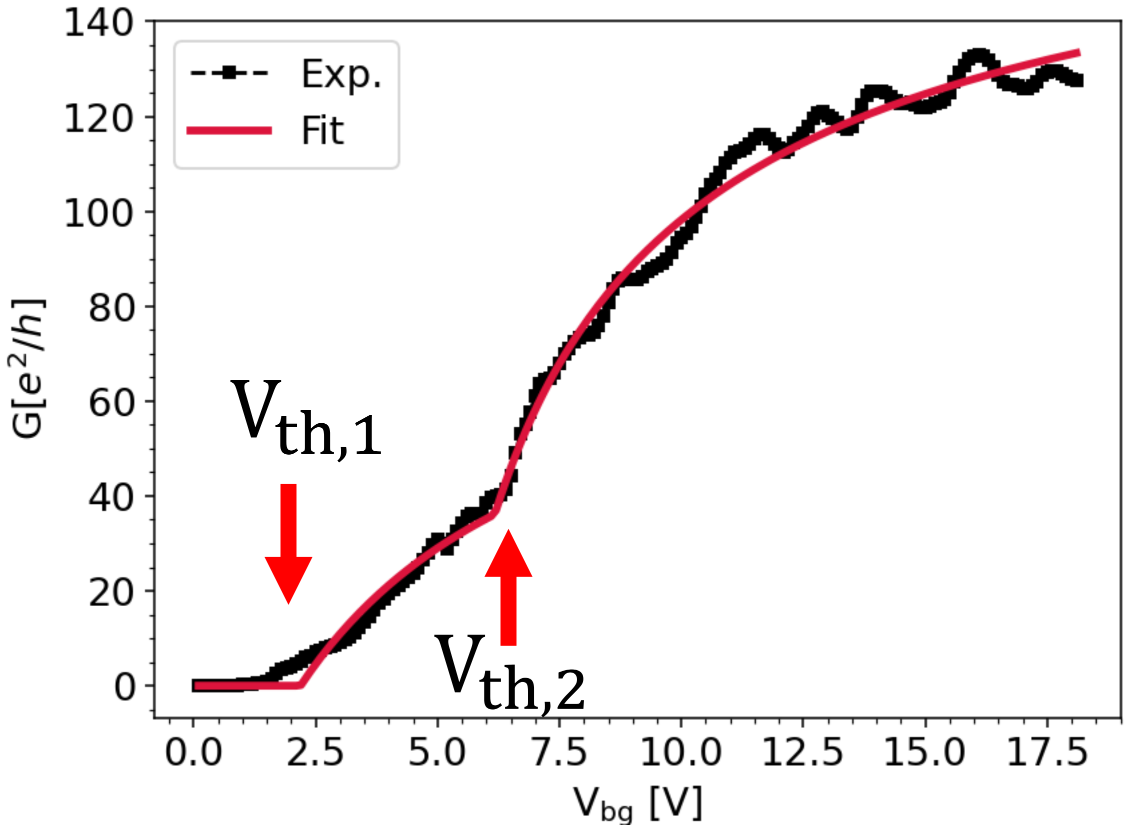
$T = 2$ K

SQUID conductance $G = G_{JJ1} + G_{JJ2}$

Symmetric SQUID



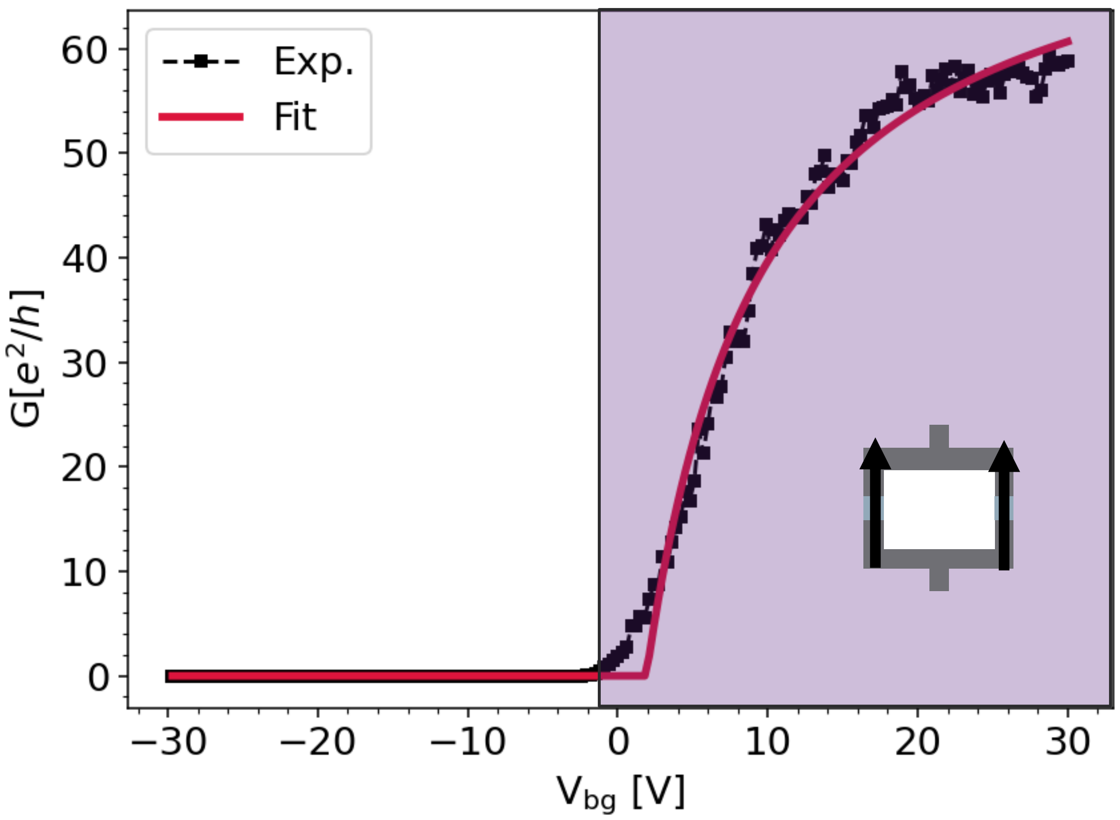
Asymmetric SQUID



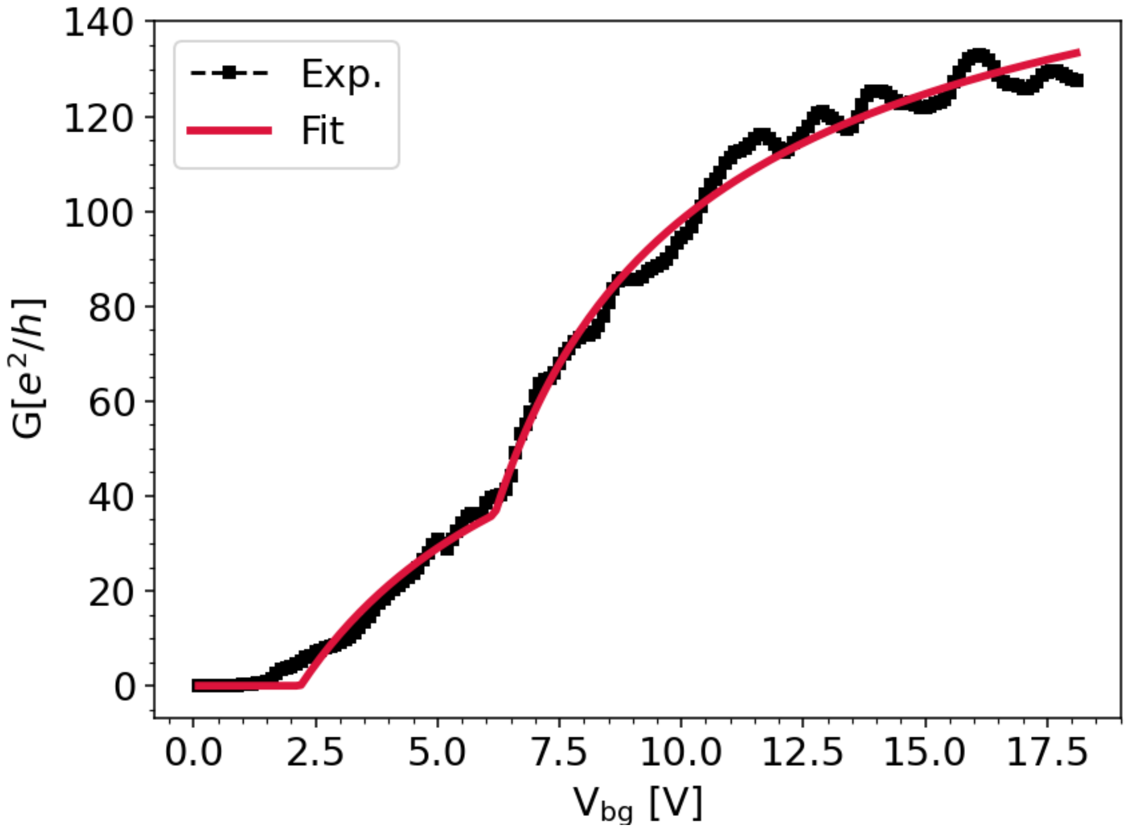
$T = 2\ \mathrm{K}$

SQUID conductance $G = G_{JJ1} + G_{JJ2}$

Symmetric SQUID



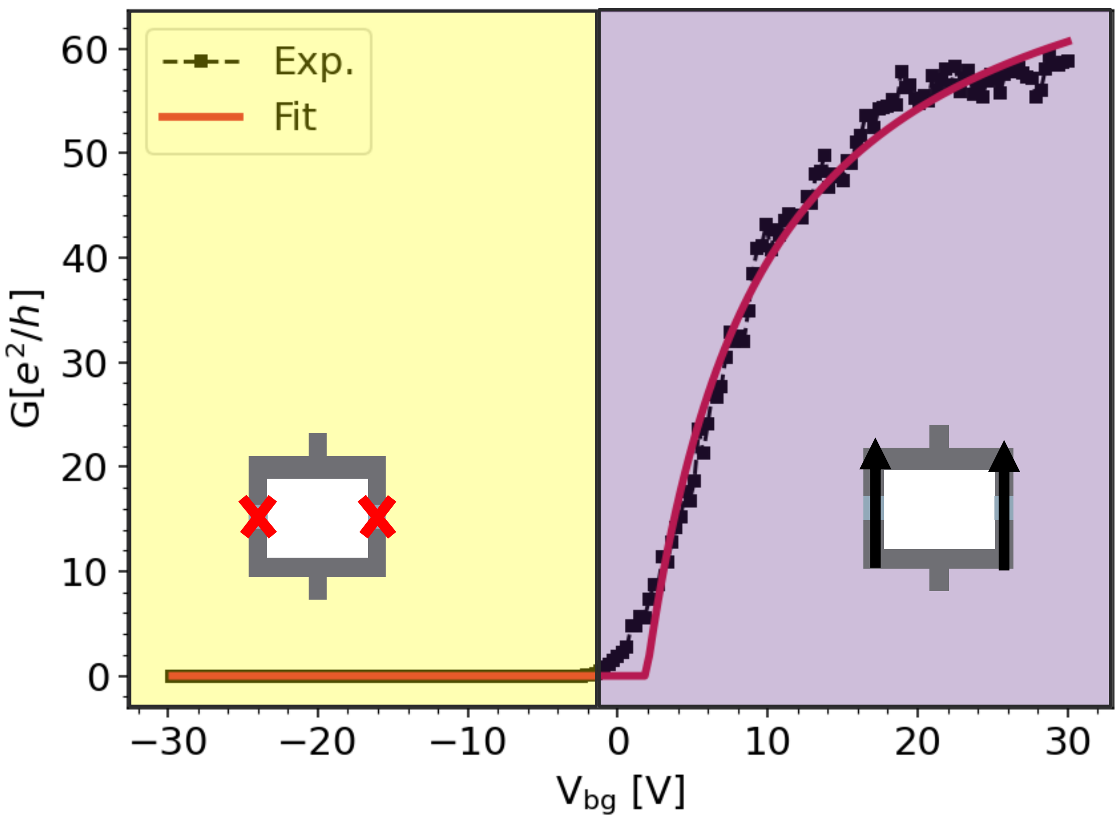
Asymmetric SQUID



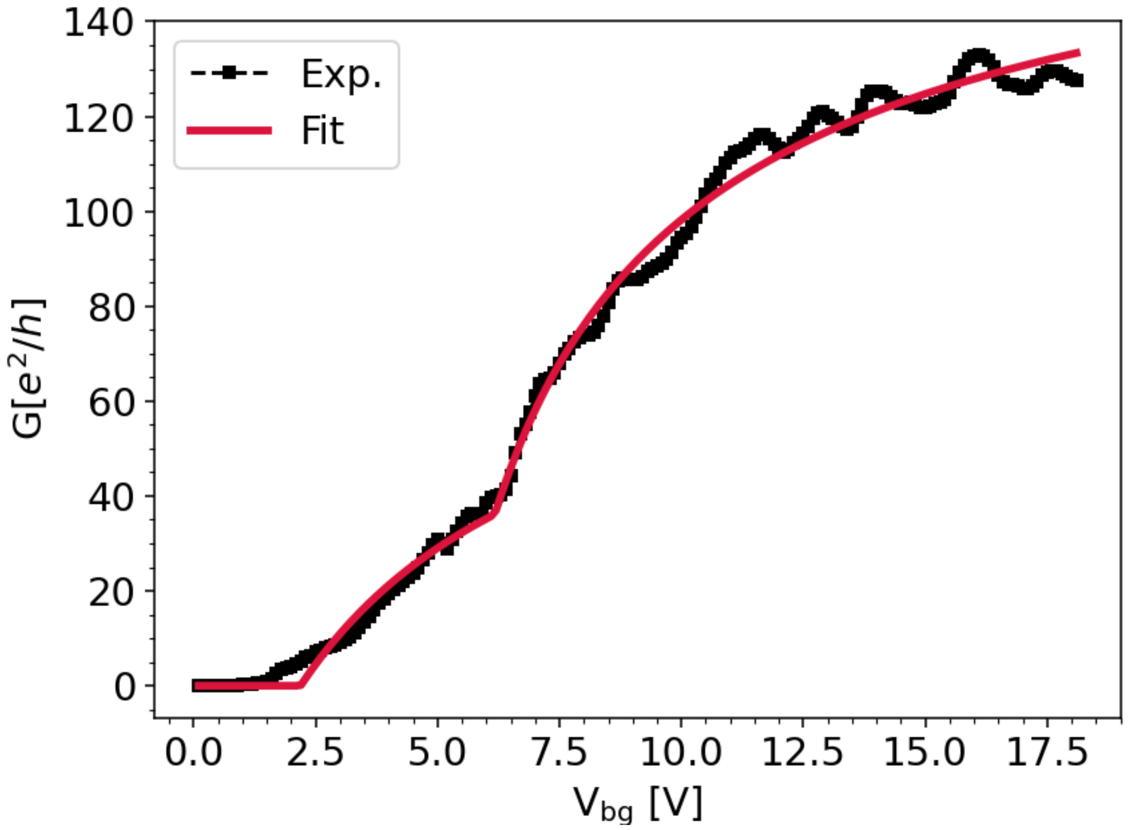
$T = 2$ K

SQUID conductance $G = G_{JJ1} + G_{JJ2}$

Symmetric SQUID



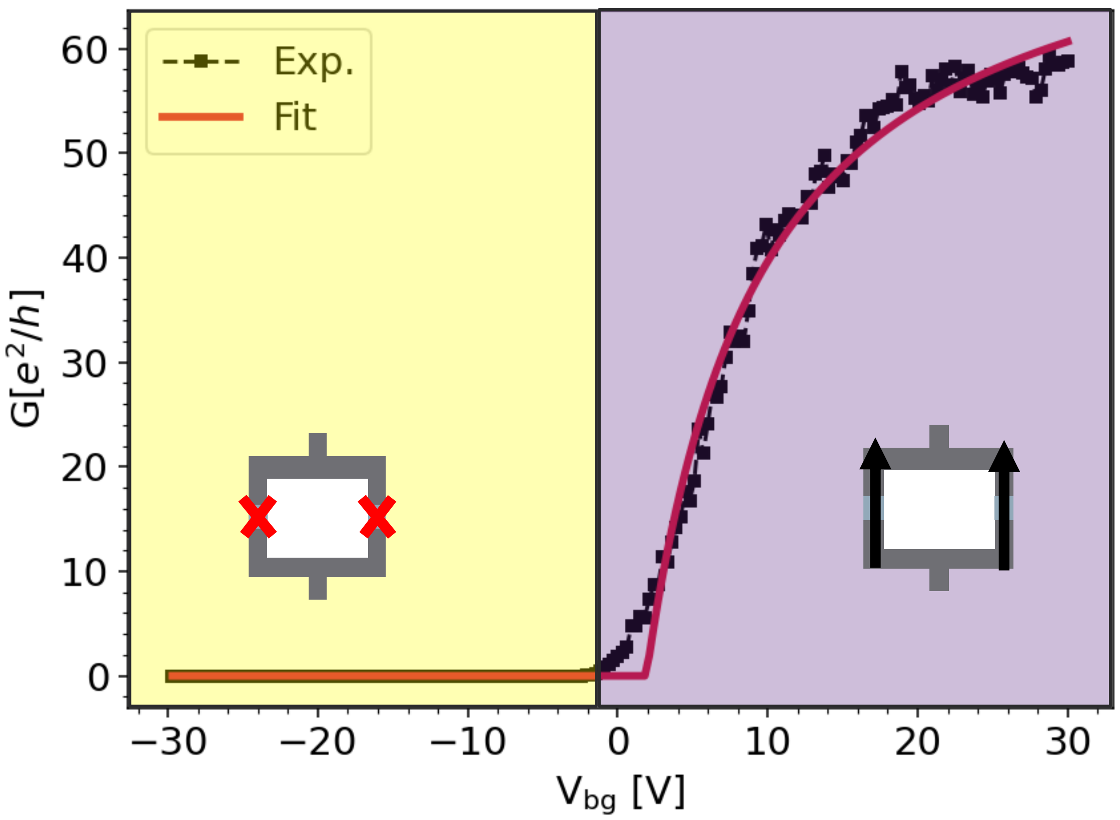
Asymmetric SQUID



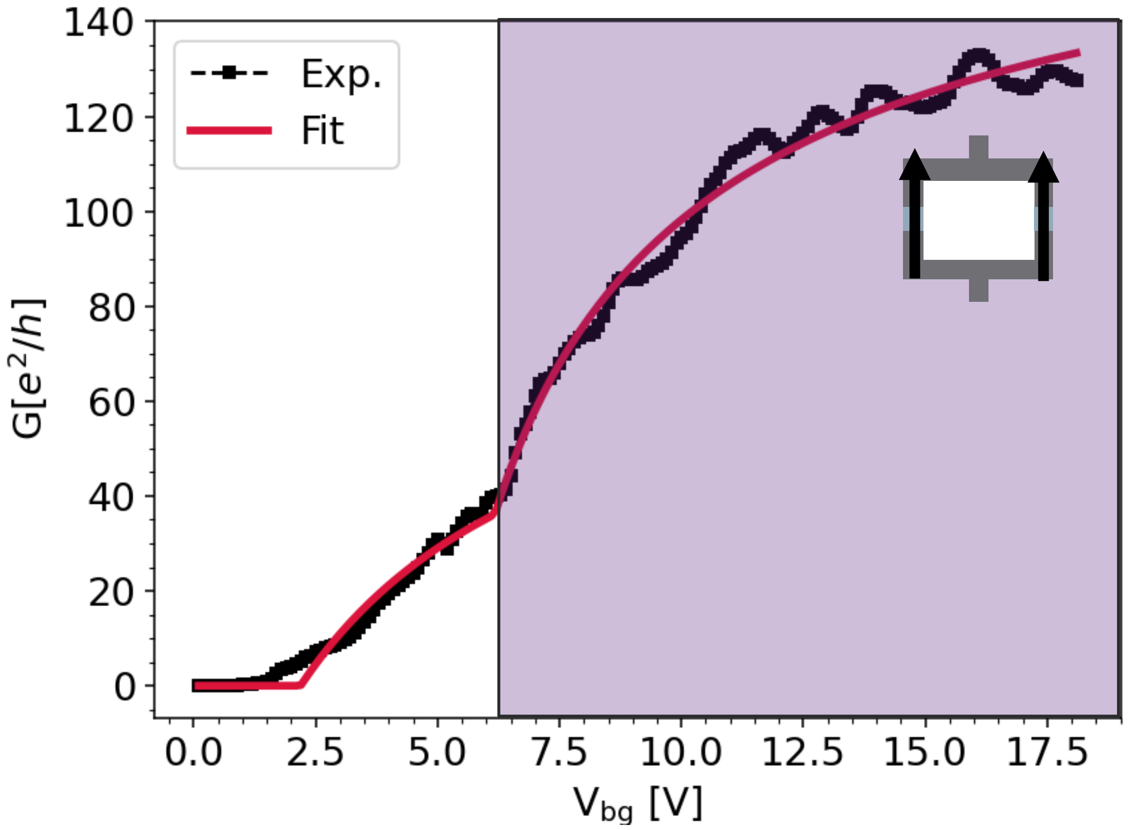
$T = 2$ K

SQUID conductance $G = G_{JJ1} + G_{JJ2}$

Symmetric SQUID



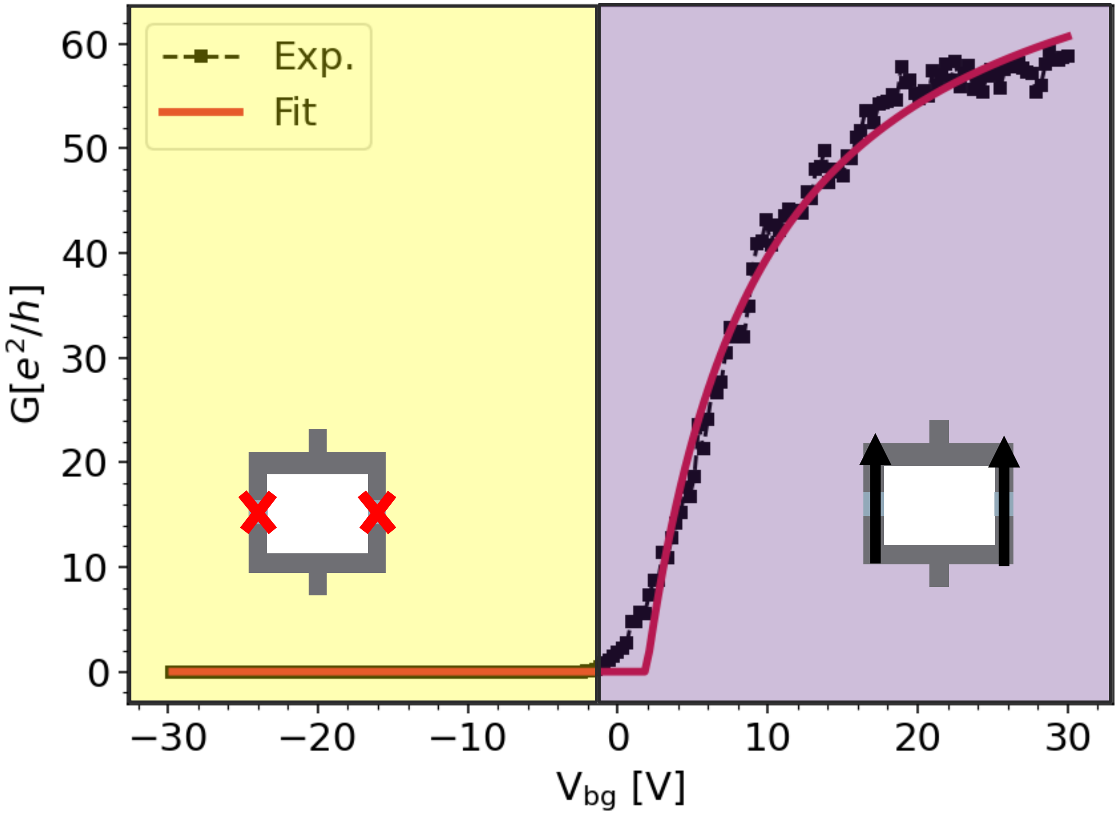
Asymmetric SQUID



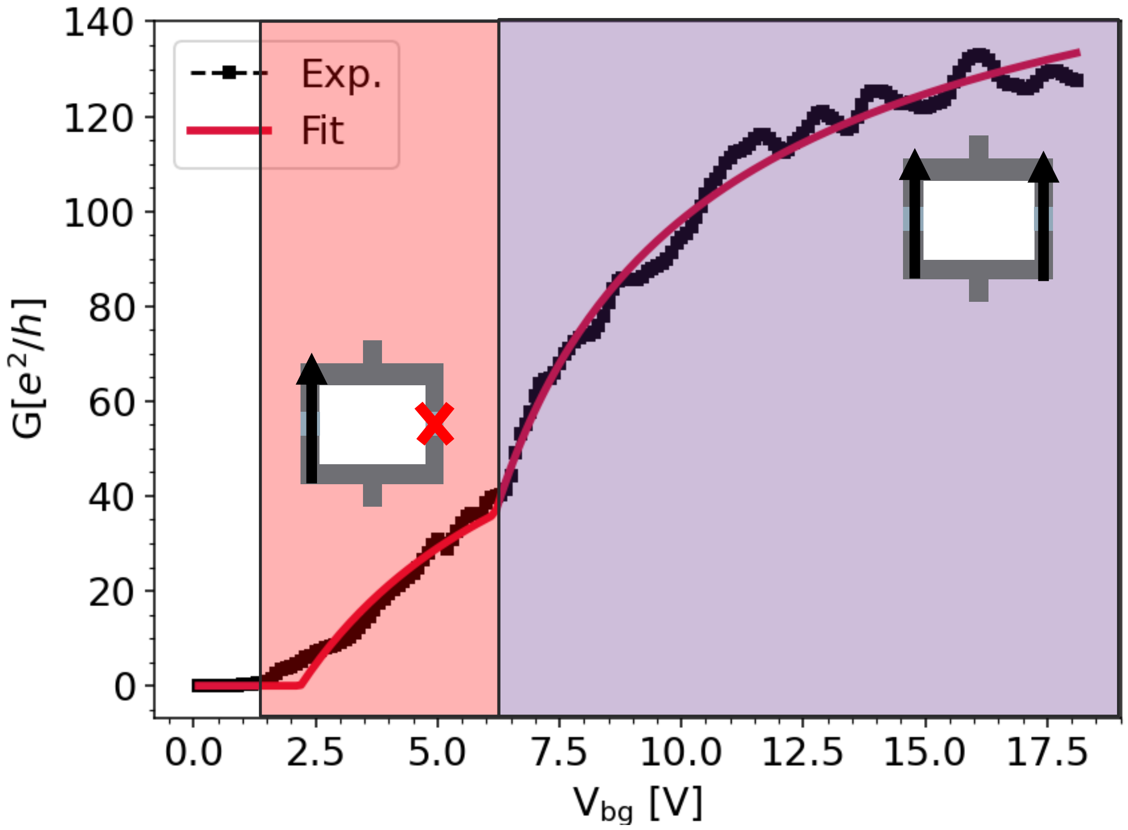
$T = 2\ \mathrm{K}$

SQUID conductance $G = G_{JJ1} + G_{JJ2}$

Symmetric SQUID

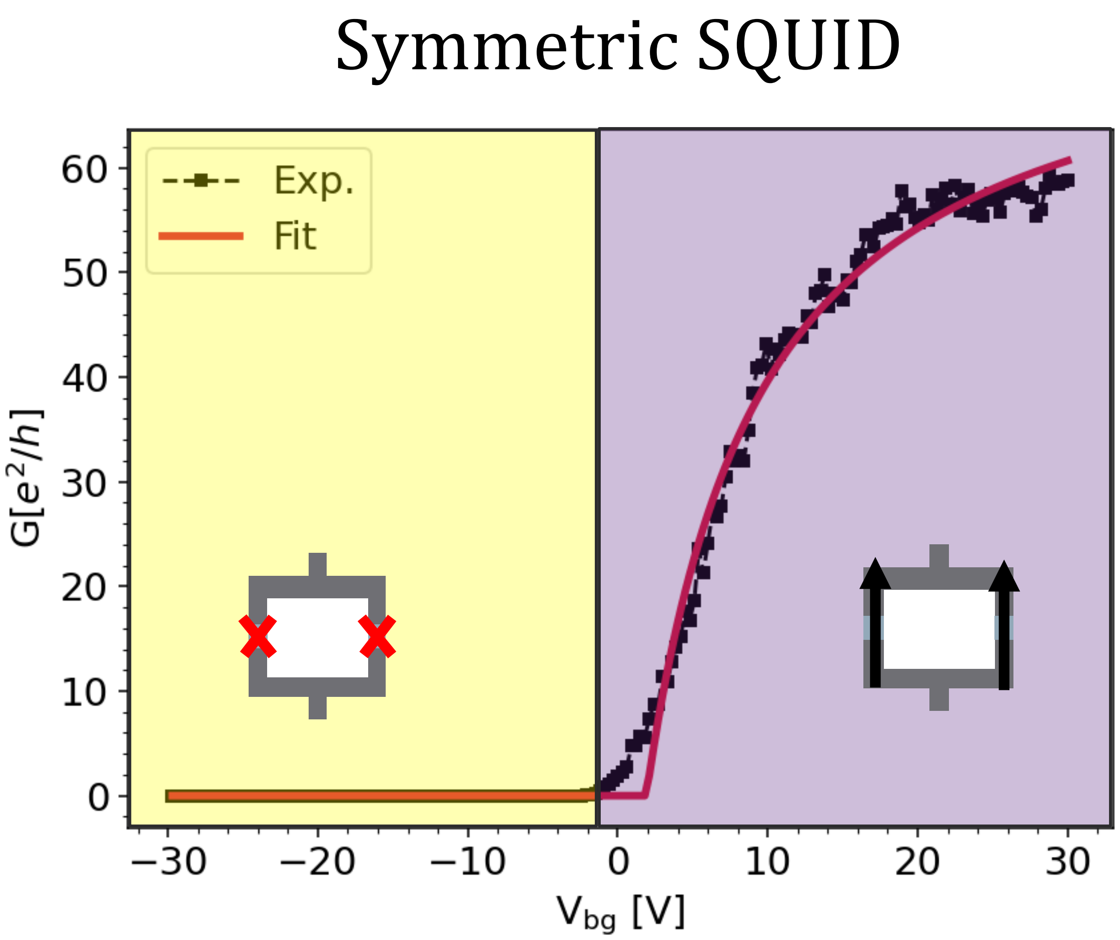


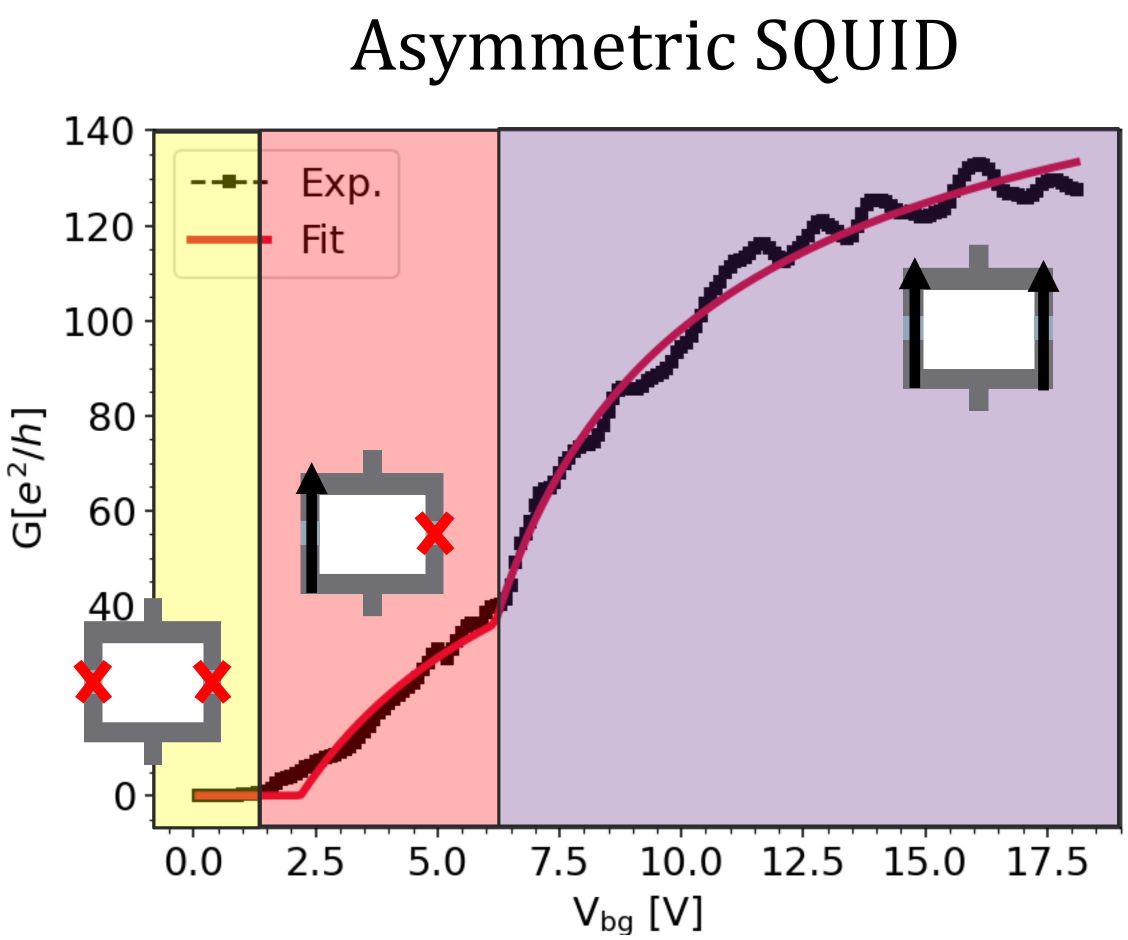
Asymmetric SQUID



$T = 2\ \mathrm{K}$

SQUID conductance $G = G_{JJ1} + G_{JJ2}$



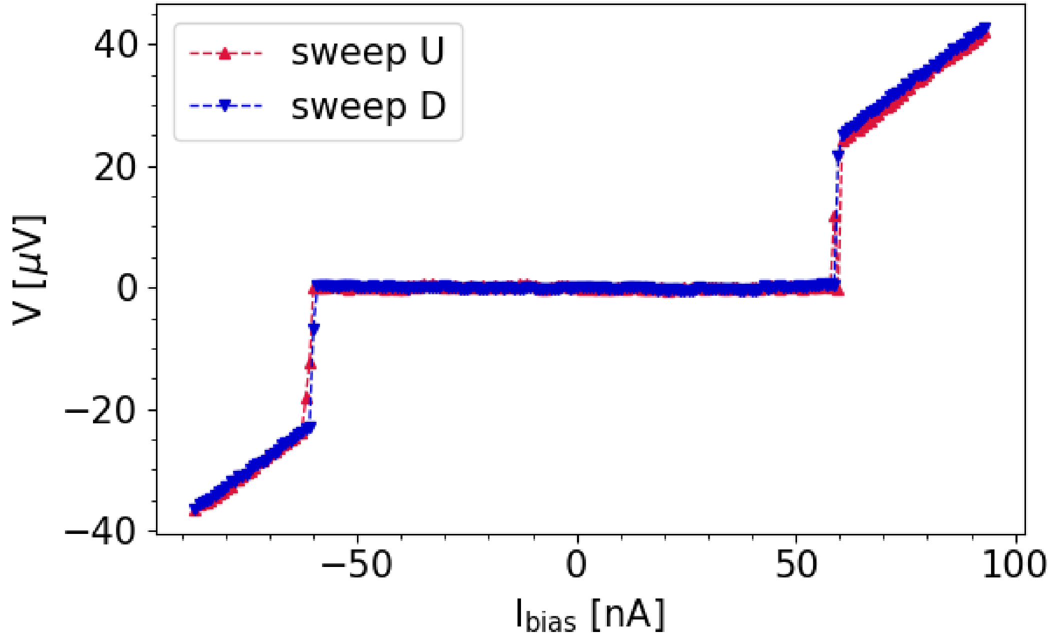


$T = 2\ \mathrm{K}$

VI traces @ $T = 350$ mK

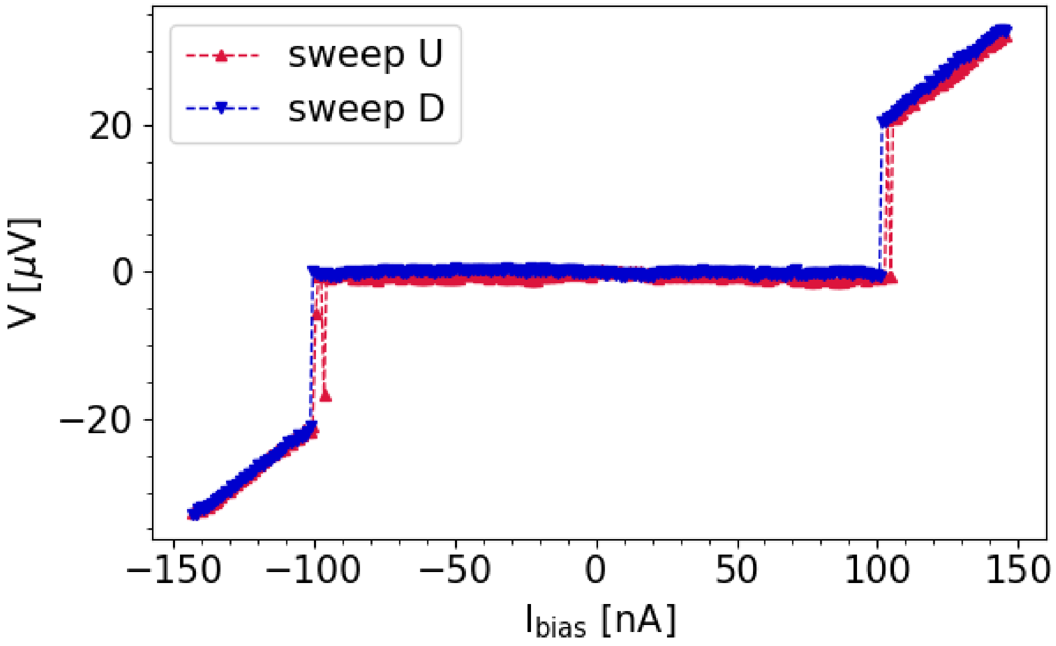
Symmetric SQUID

$V_{bg} = 20.0$ V



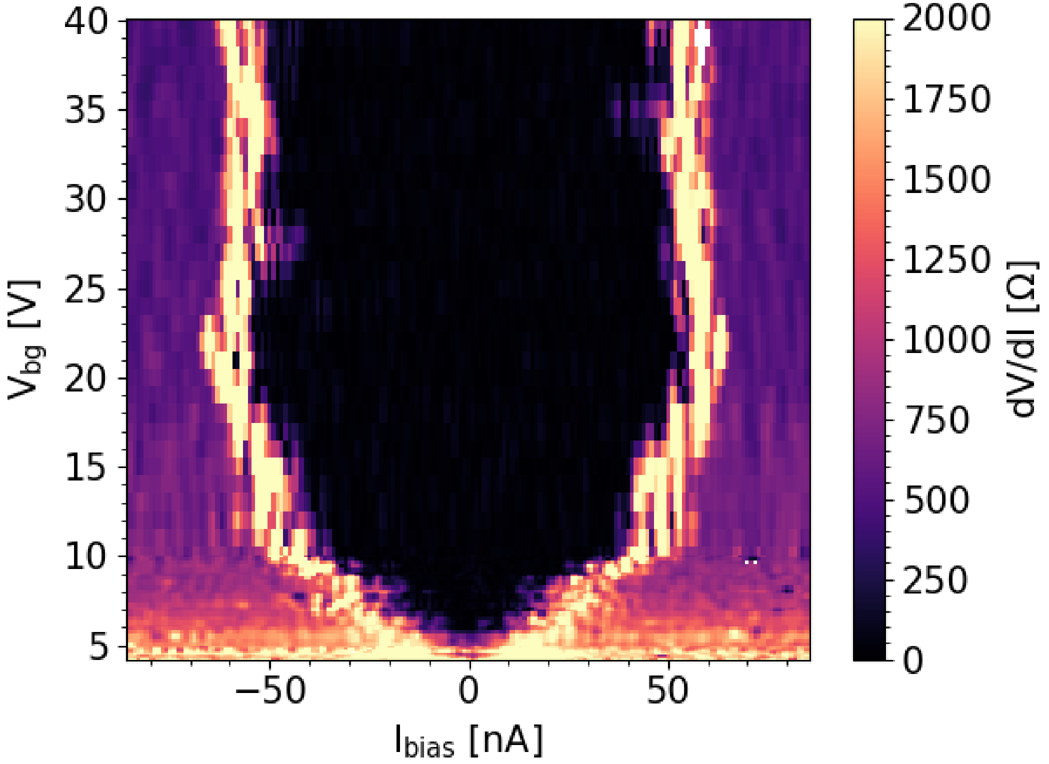
Asymmetric SQUID

$V_{bg} = 18.0$ V

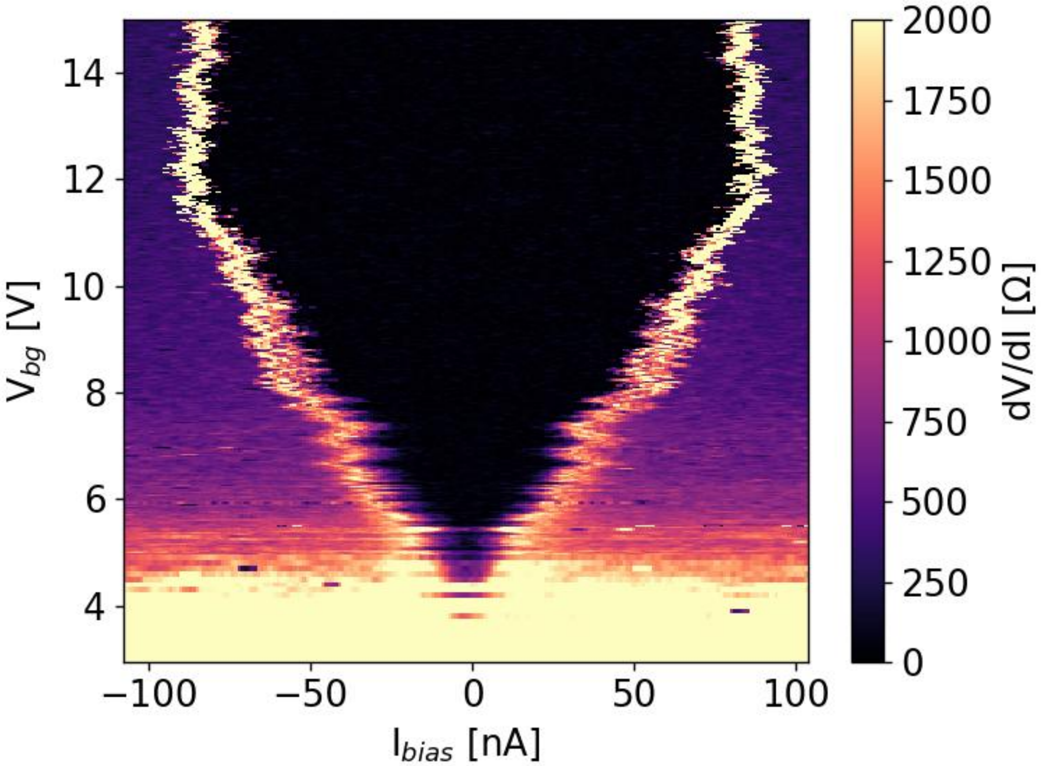


SQUID JoFETs (Josephson Field Effect Transistor)

Symmetric SQUID



Asymmetric SQUID

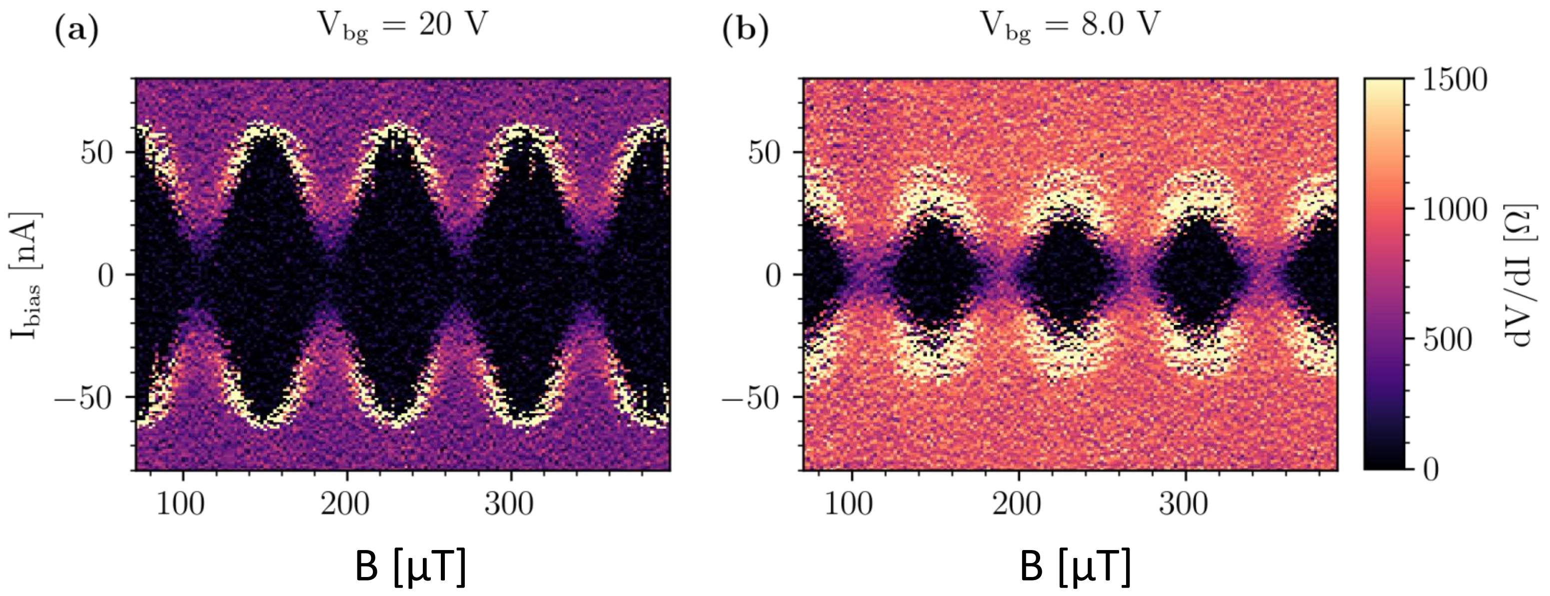


Back gate control of supercurrent

$T = 350\ \text{mK}$

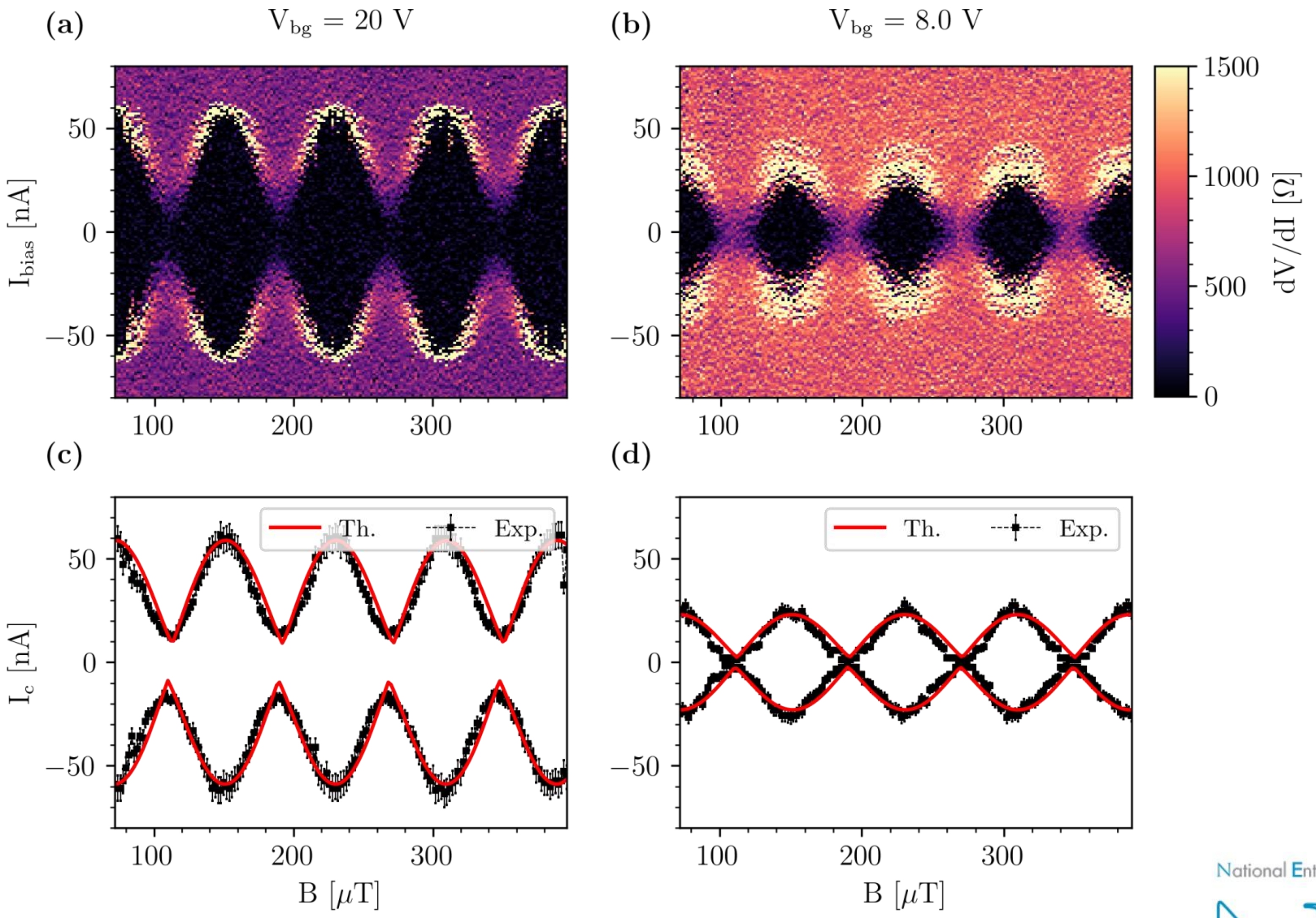
Interference in the symmetric SQUID

Interference vs. back gate



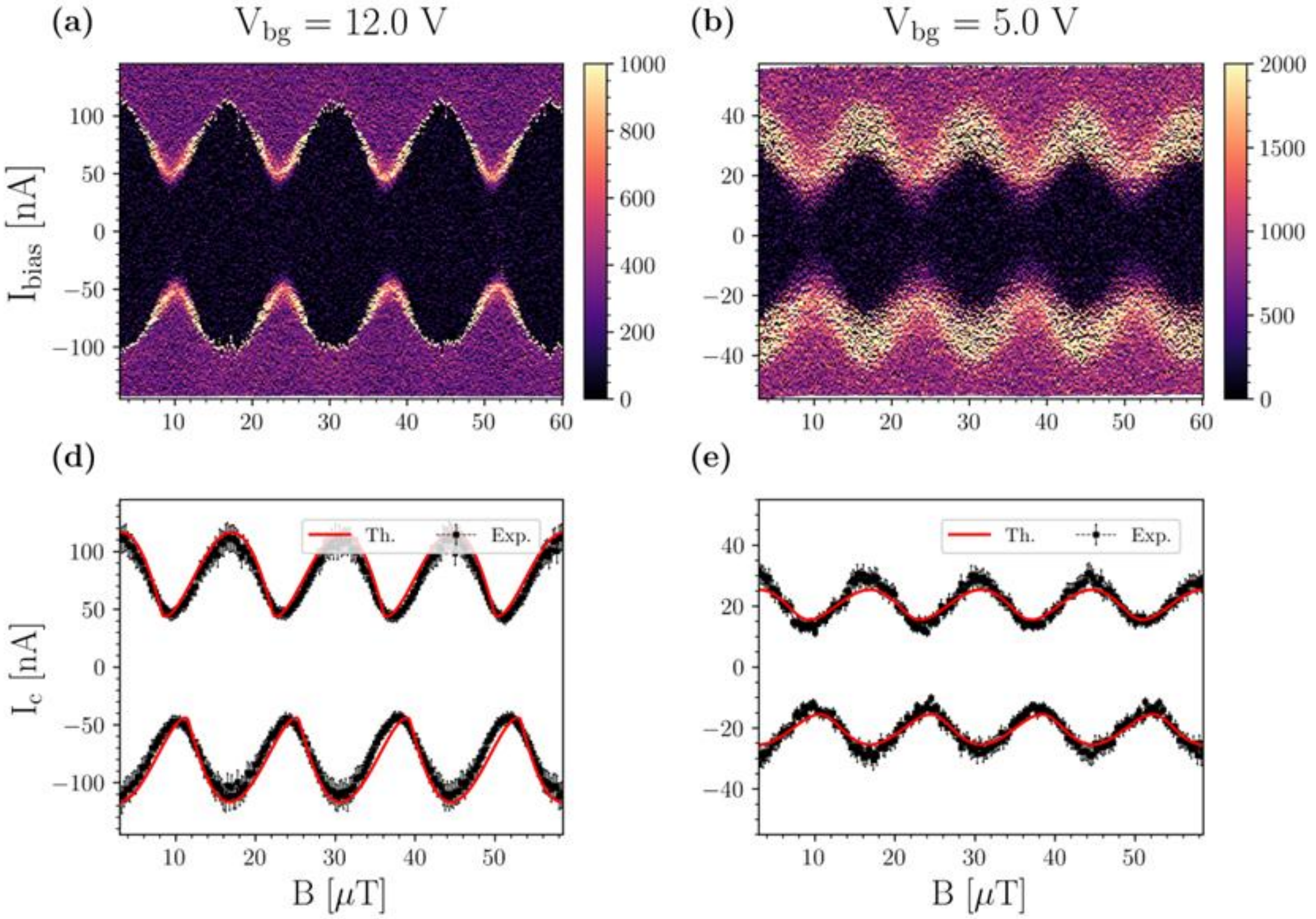
A. Chieppa et al., arXiv:2504.18965 [cond-mat.mes-hall].

Interference vs. back gate



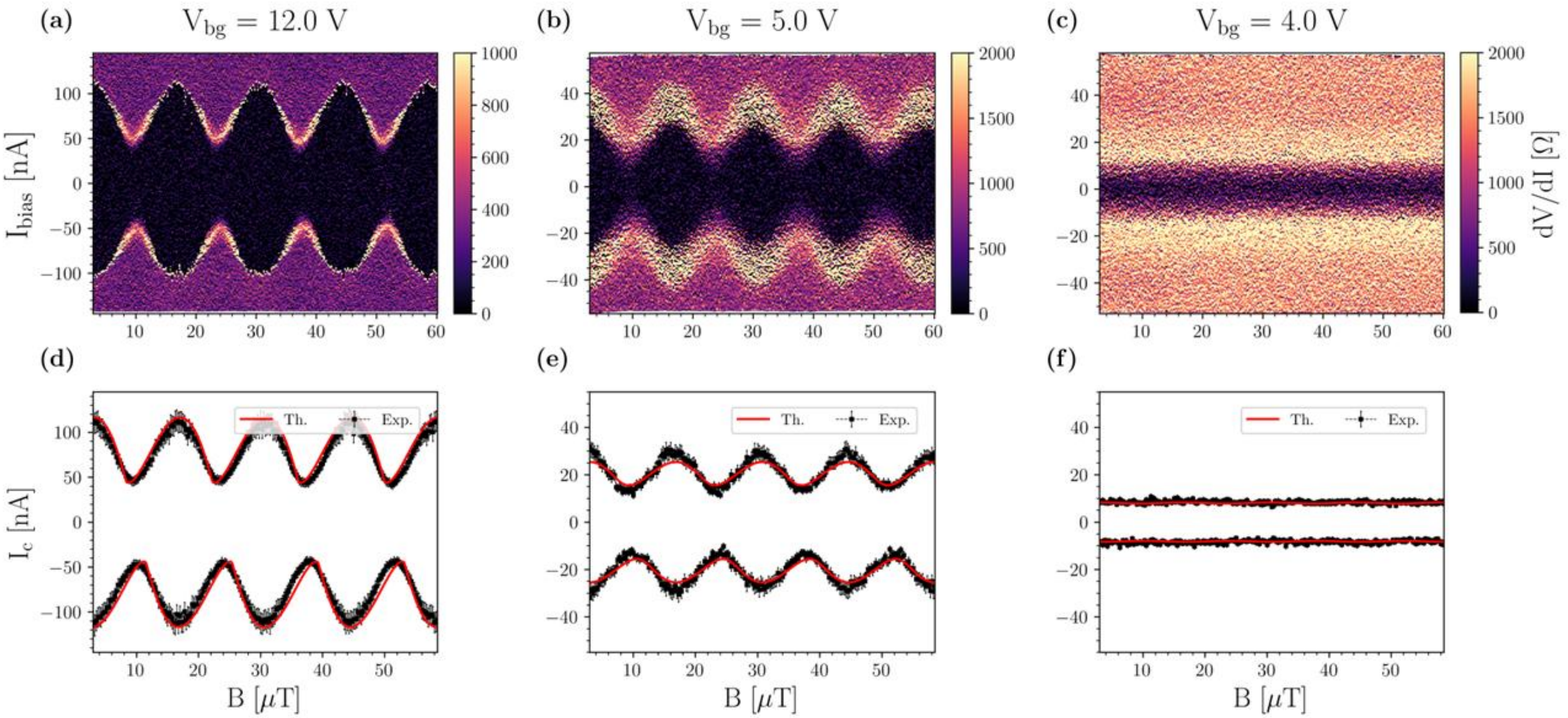
Results for the asymmetric SQUID

Interference vs. back gate



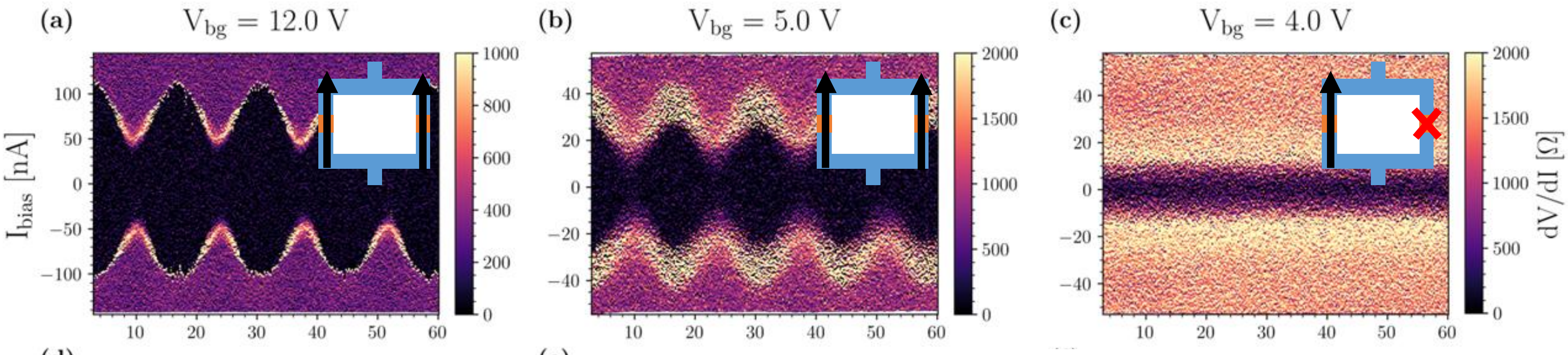
A. Chieppa et al., arXiv:2504.18965 [cond-mat.mes-hall].

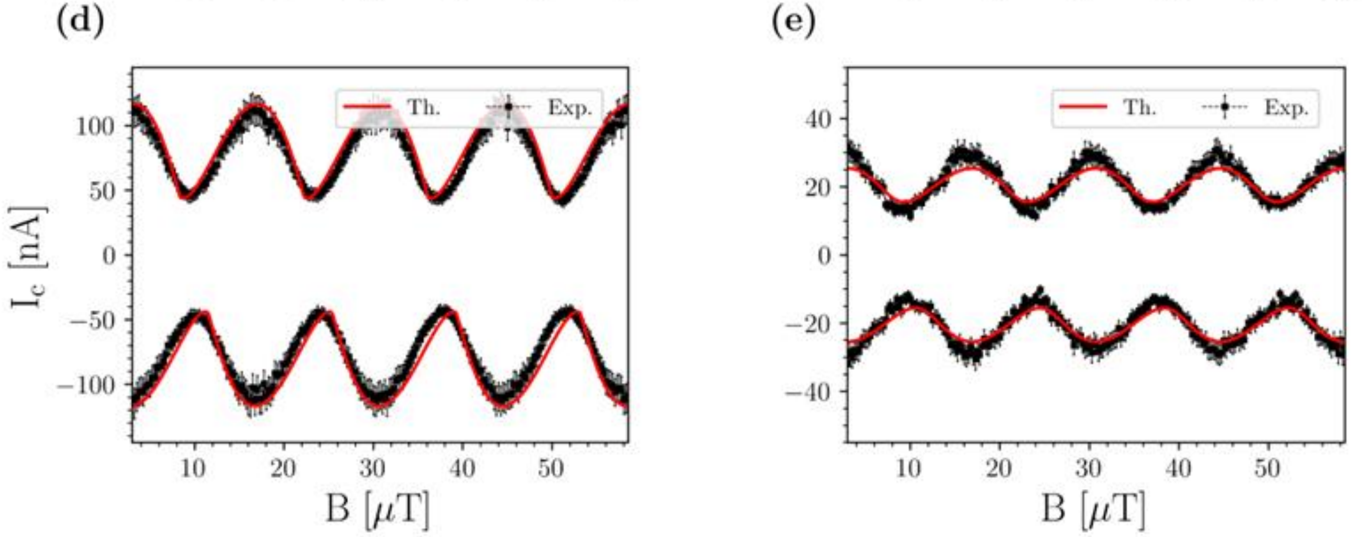
Interference vs. back gate



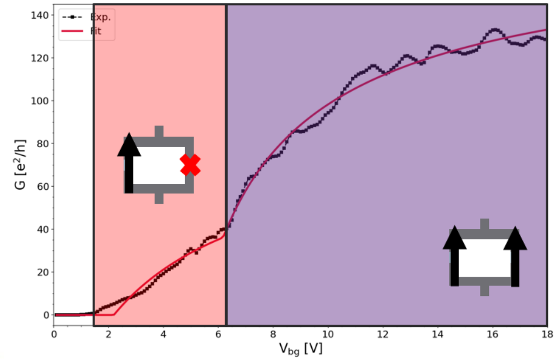
A. Chieppa et al., arXiv:2504.18965 [cond-mat.mes-hall].

Interference vs. back gate





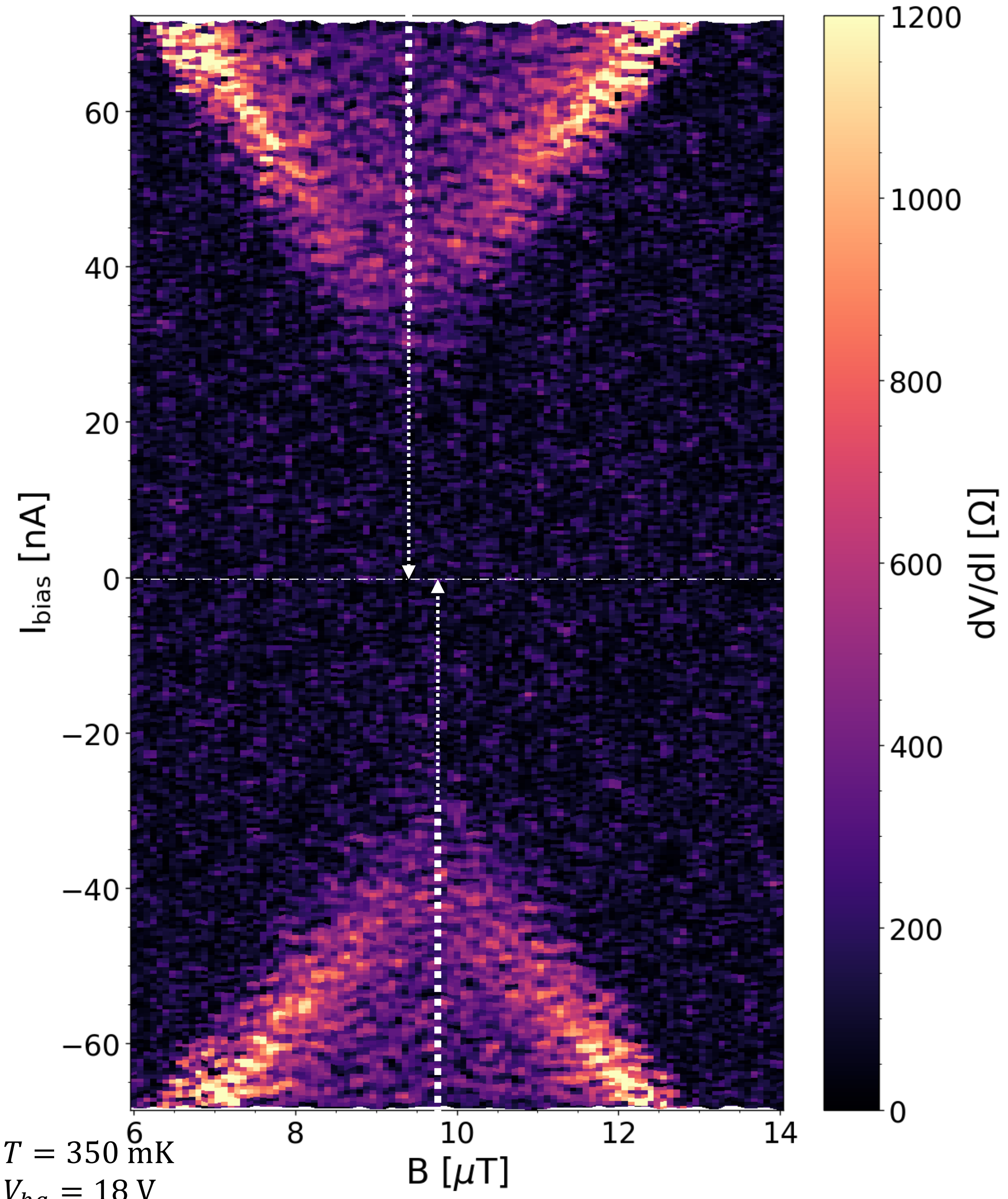
Loss of interference



A. Chieppa et al., arXiv:2504.18965 [cond-mat.mes-hall].

Non-reciprocal transport

Josephson Diode Effect

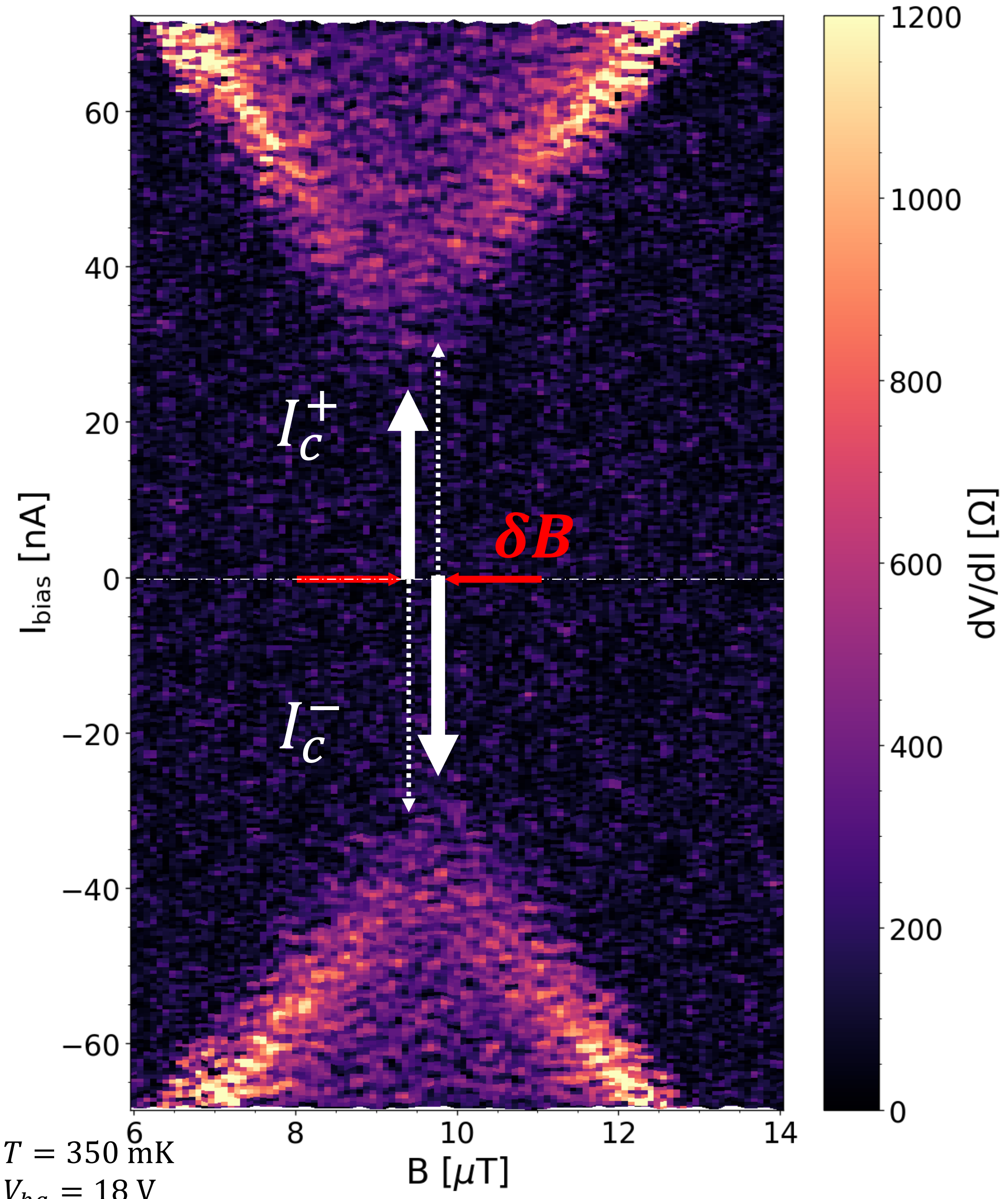


$T = 350$ mK
$V_{bg} = 18$ V

Josephson Diode Effect in SQUIDs

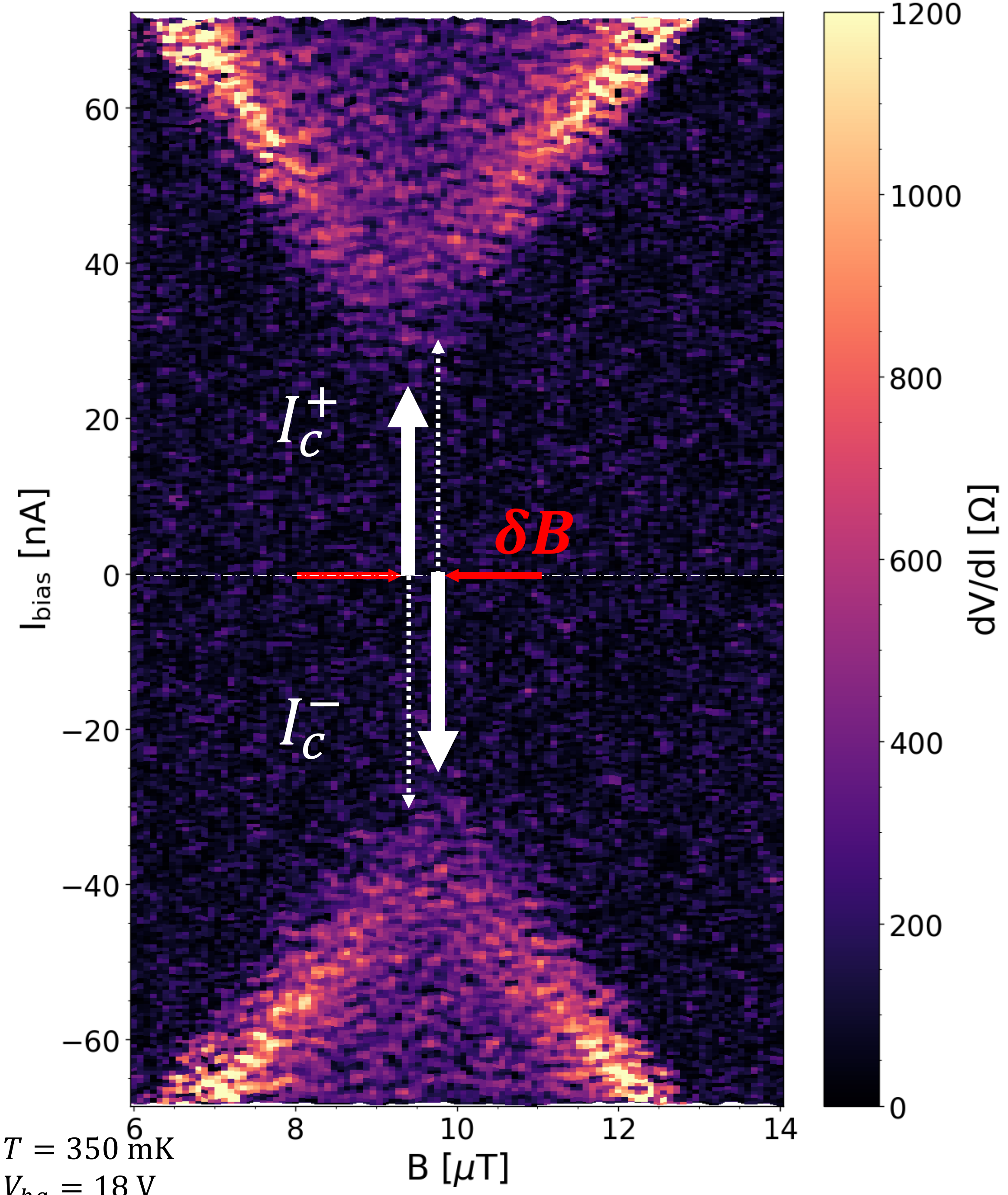
- Minima in I_{c+}, I_{c-} for different magnetic fields

Josephson Diode Effect in SQUIDs



$T = 350$ mK
$V_{bg} = 18$ V

- Minima in I_{c+}, I_{c-} for different magnetic fields



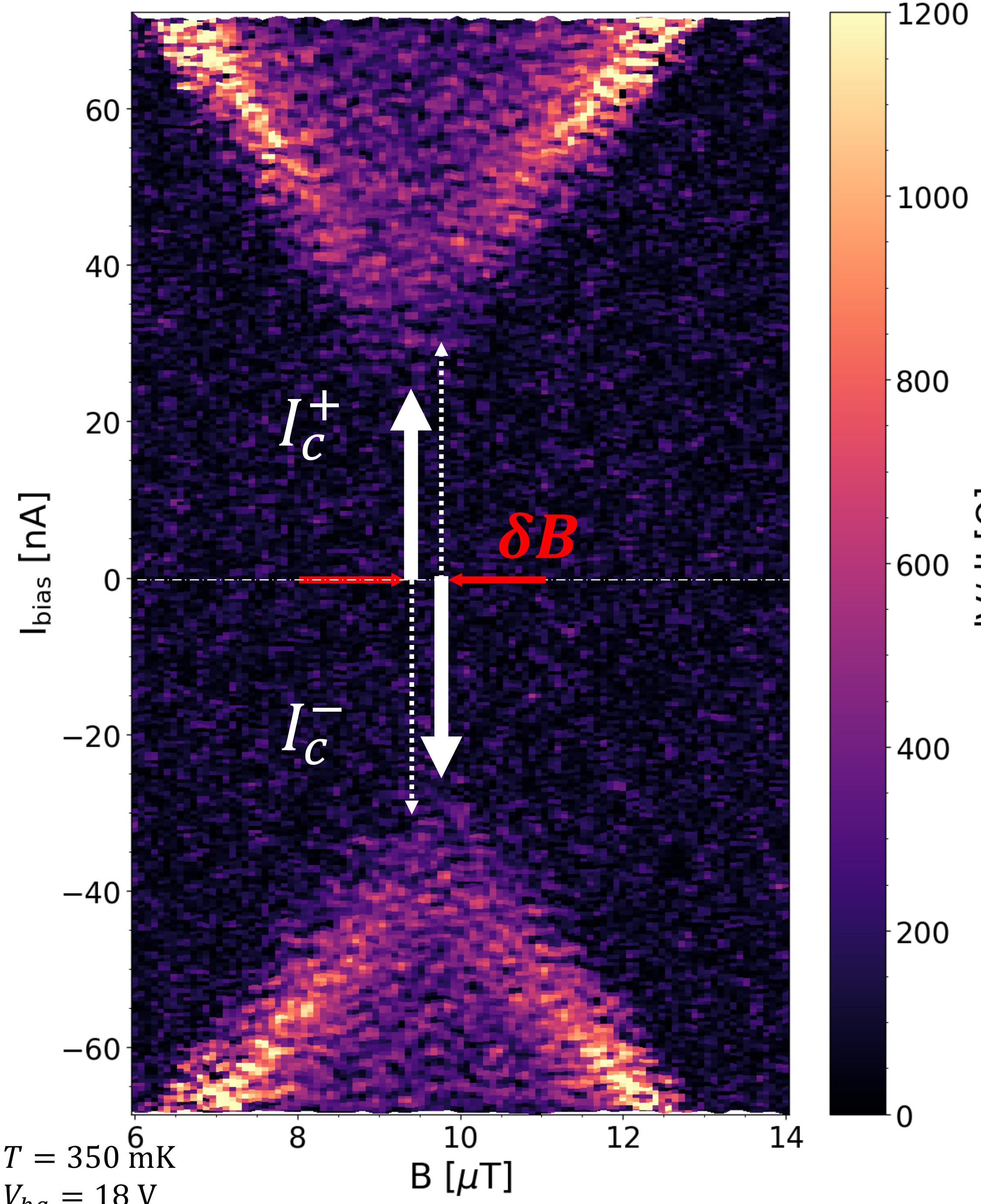
$T = 350$ mK
$V_{bg} = 18$ V

Josephson Diode Effect in SQUIDs

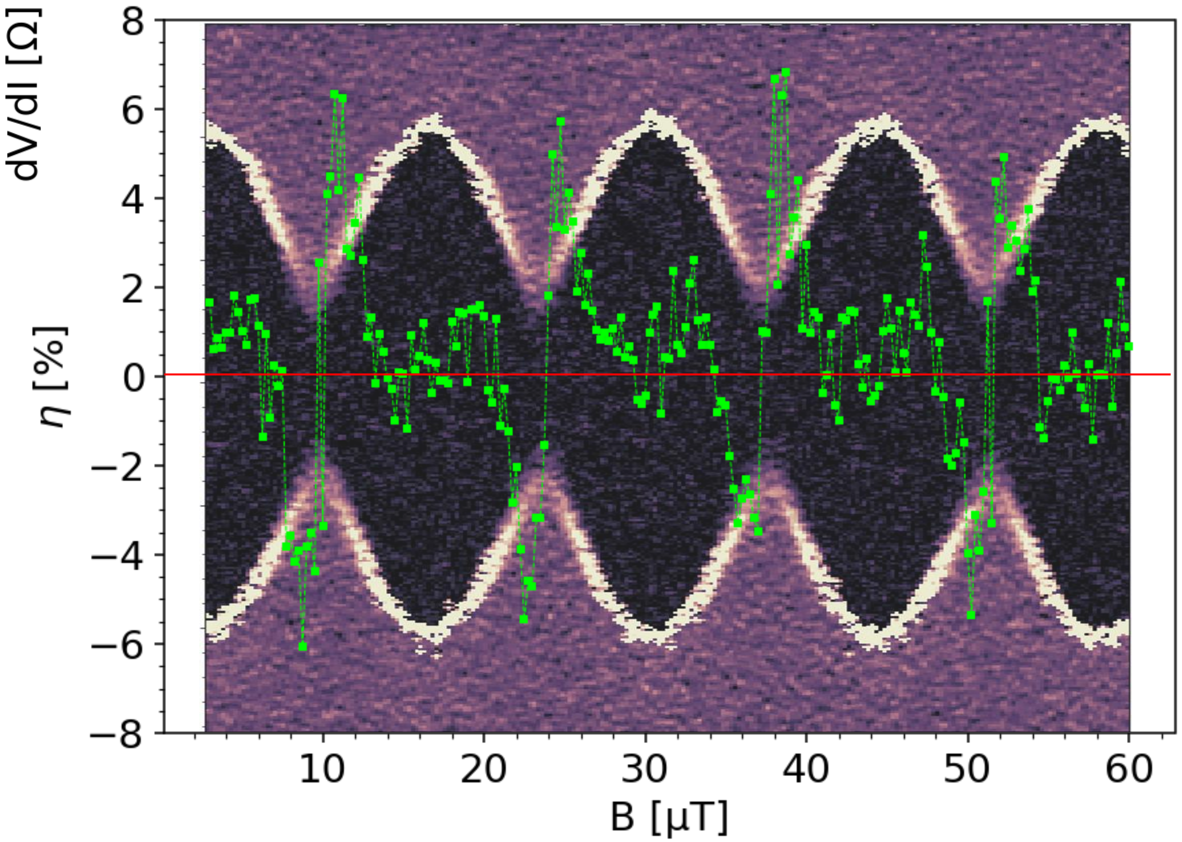
- $\eta[\%] = \frac{I_{c+} - |I_{c-}|}{I_{c+} + |I_{c-}|} \cdot 100$

Josephson Diode Effect in SQUIDs

- $\eta[\%] = \frac{I_{c+} - |I_{c-}|}{I_{c+} + |I_{c-}|} \cdot 100 \approx 6\%$



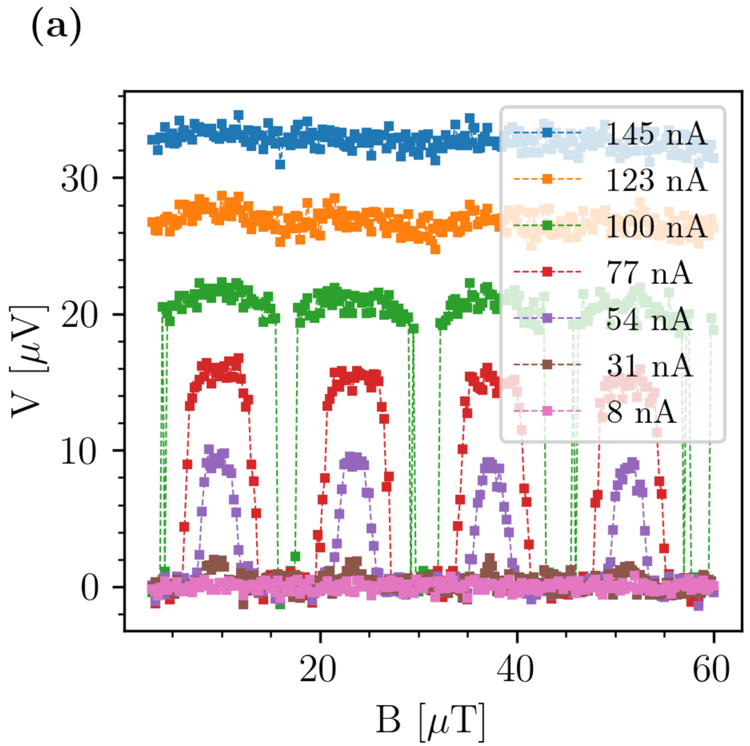
$T = 350$ mK
$V_{bg} = 18$ V



Magnetometer performance

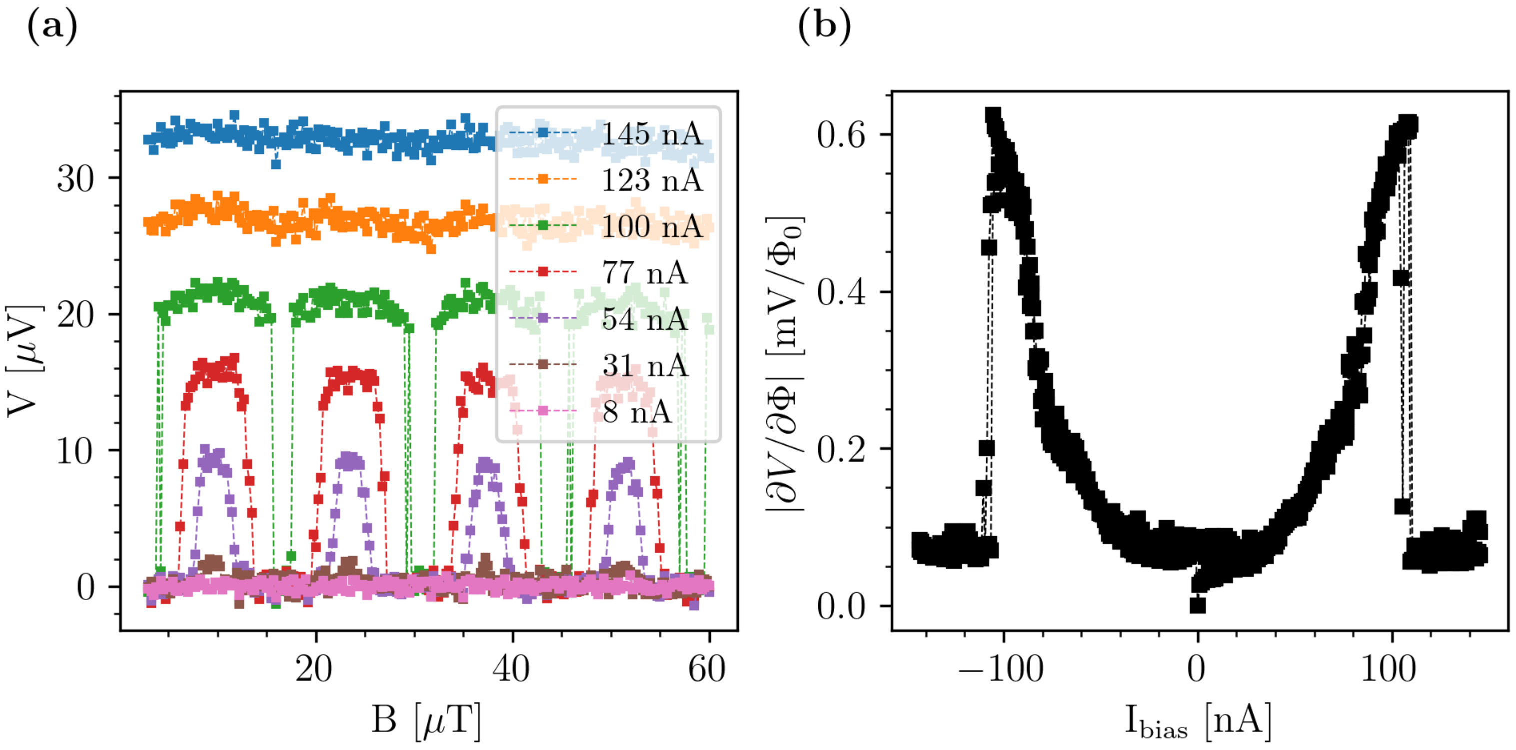
SQUID as a flux-to-voltage transducer

Transfer function characteristics



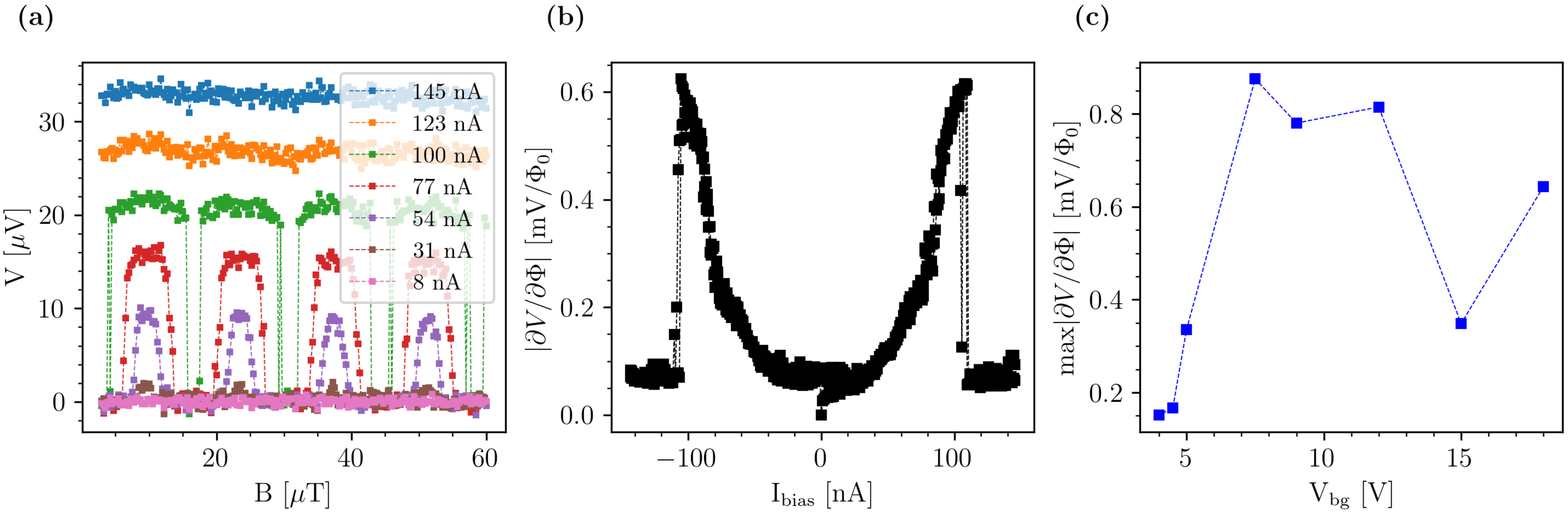
A. Chieppa et al., arXiv:2504.18965 [cond-mat.mes-hall].

Voltage responsivity $V_\Phi = {}^{\partial V}/_{\partial \Phi}$



A. Chieppa et al., arXiv:2504.18965 [cond-mat.mes-hall].

Maximum responsivity vs. back gate



Magnetic flux noise amplitude $S_{\Phi}^{1/2} = 4.4 \times 10^{-6}\, \Phi_0/\sqrt{\mathrm{Hz}}$

A. Chieppa et al., arXiv:2504.18965 [cond-mat.mes-hall].

Conclusions

- SQUIDs realized using InSb nanoflag Josephson junctions.
- Symmetric and asymmetric geometries were implemented.
- Theoretical framework accounts for all observations.
- Transparency of the junctions can be modulated by a back gate.
- Non-reciprocal transport demonstrated (Josephson Diode Effect).
- SQUID performance as magnetometer has been evaluated.

Thank you for your attention!

National Enterprise for nanoScience and nanoTechnology

NEST