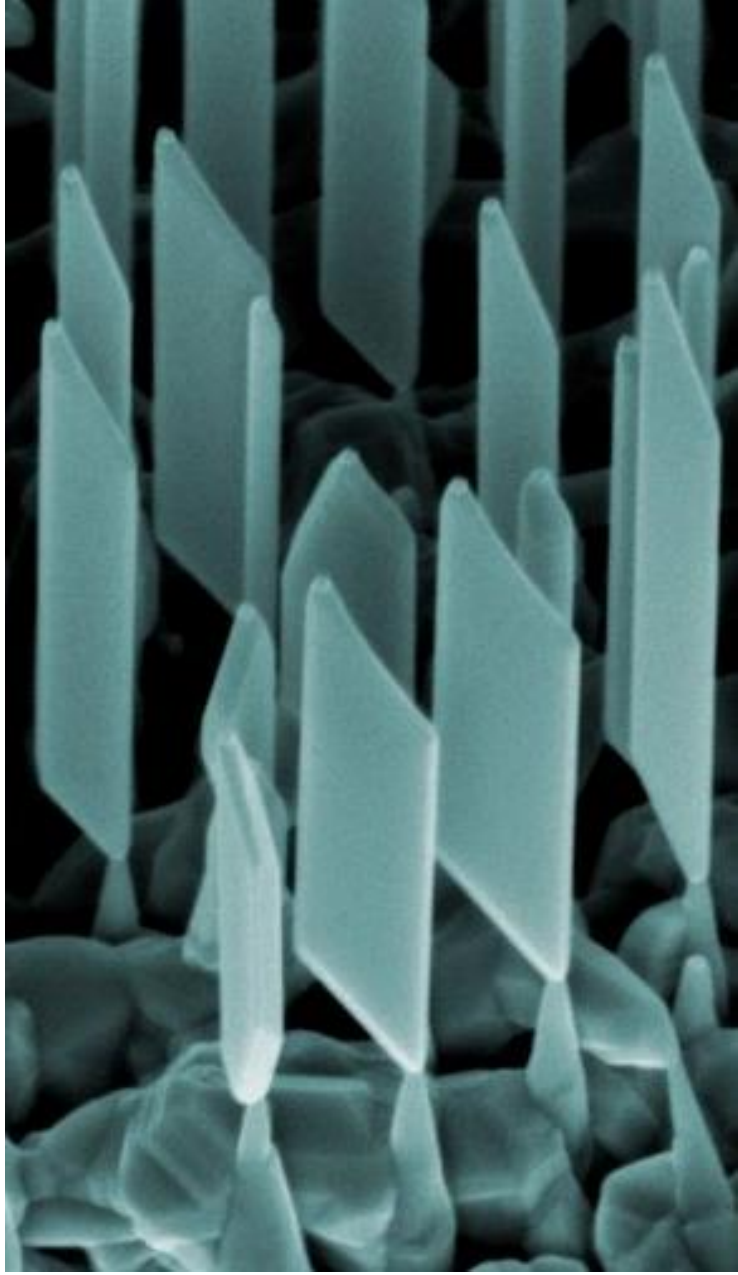
Half-integer Shapiro Steps in Highly Transmissive InSb Nanoflag Josephson Junctions

Andrea Iorio[1], Alessandro Crippa[1], Bianca Turini[1], Sedighe Salimian[1], Matteo Carrega[2], Luca Chirolli[1], Valentina Zannier[1], Lucia Sorba[1], Elia Strambini[1], Francesco Giazotto[1], and **Stefan Heun**[1]

[1]*NEST, Istituto Nanoscienze-CNR and Scuola Normale Superiore, Pisa, Italy*
[2]*CNR-SPIN, Via Dodecaneso 33, 16146 Genoa, Italy*



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InSb is appealing

Small bandgap	E_g=0.23 eV
Low effective mass	m/m_0 = 0.018
Strong SOC	E_{SOC} ~ 200 μeV

InSb is appealing but challenging to grow 2D

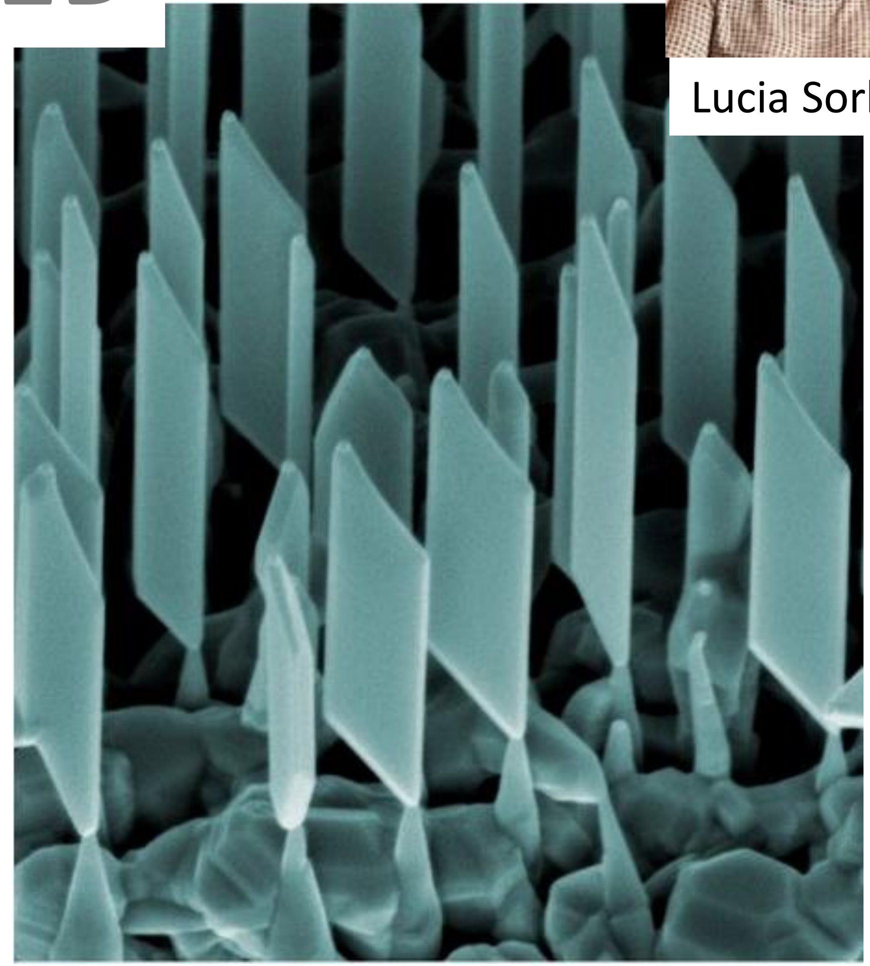
Lucia Sorba

Small bandgap E_g=0.23 eV

Low effective mass m/m_0 = 0.018

Strong SOC E_{SOC} ~ 200 μeV

High-mobility 2D nanostructures



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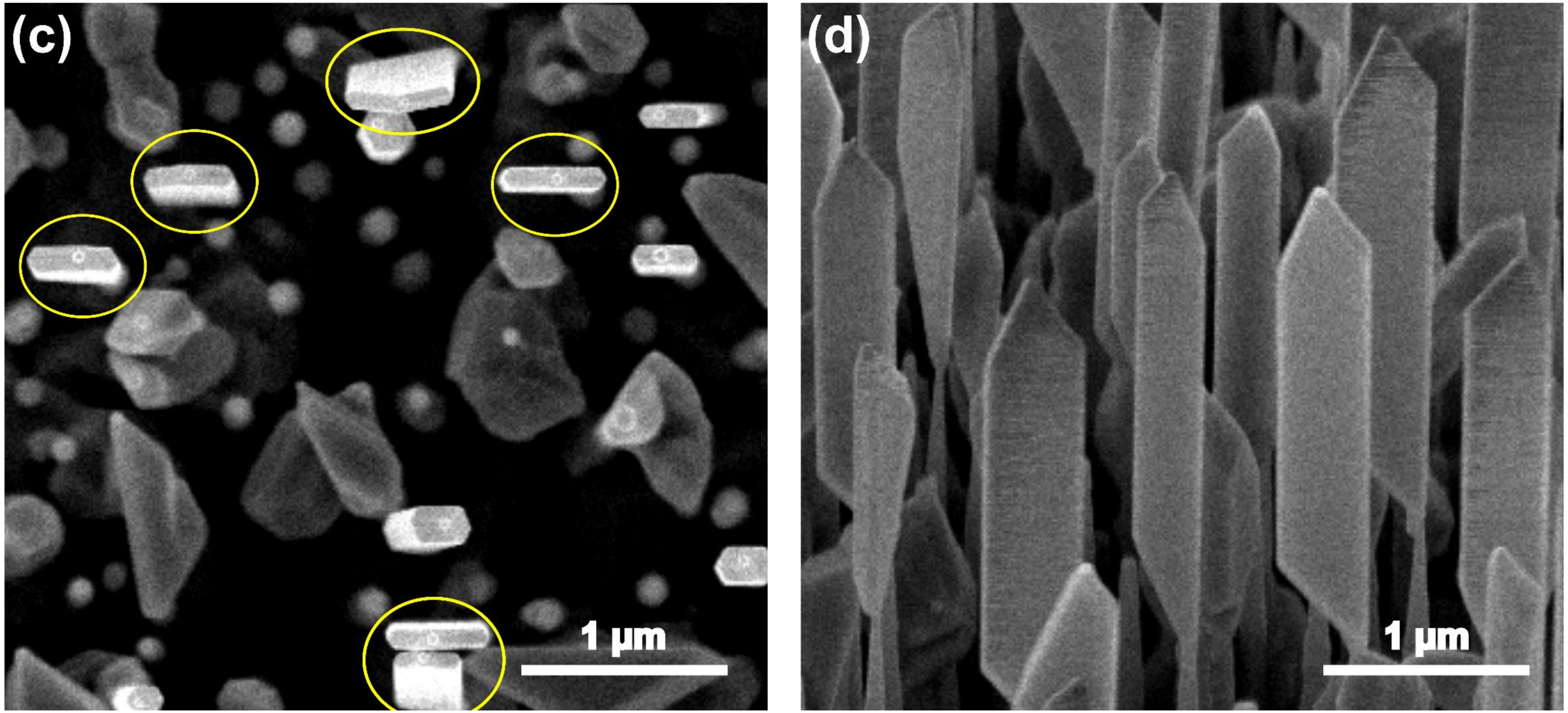
Growth of InSb nanoflags by CBE



Isha Verma

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.

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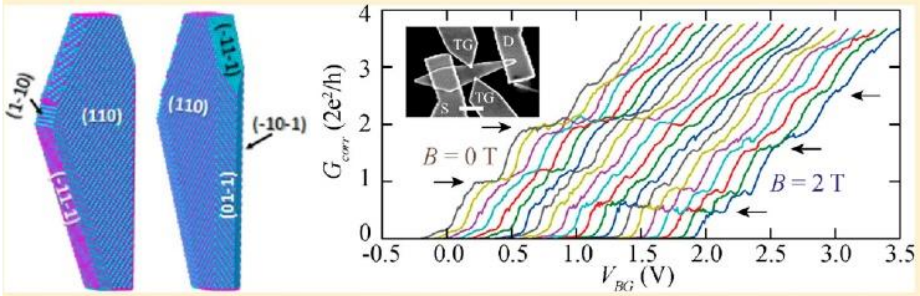
A novel approach: 2D nanoflags (NFs)

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

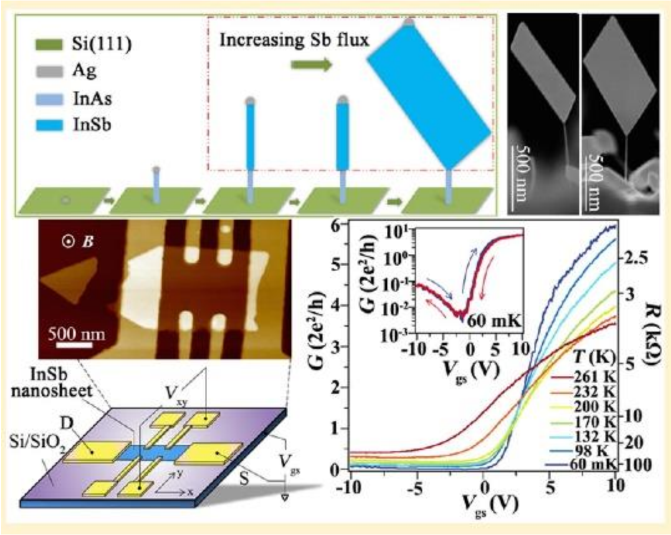
María de la Mata,† Renaud Leturcq,*,‡,§ Sébastien R. Plissard,∥ Chloé Rolland,‡ César Magén,⊥ Jordi Arbiol,*,†,# and Philippe Caroff*,‡,∇



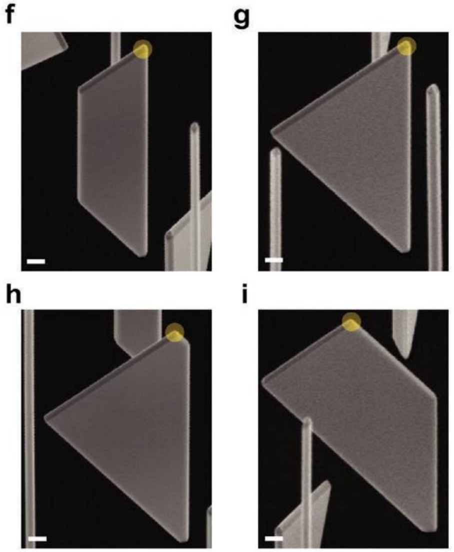
Nano Lett. 16 (2016) 825

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

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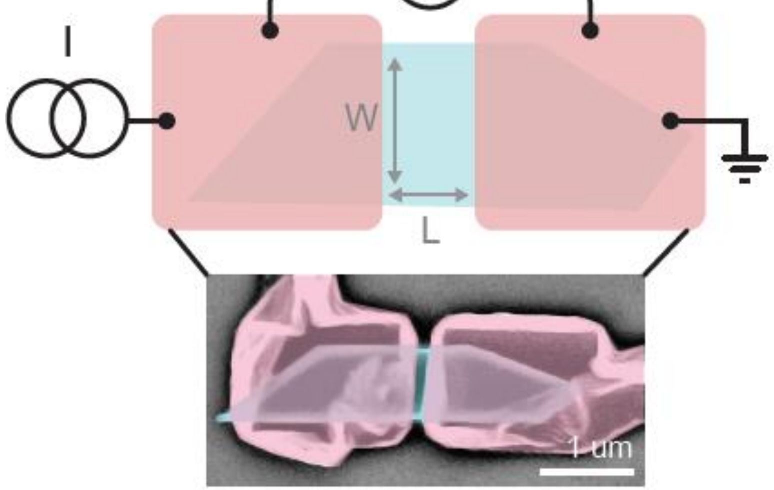
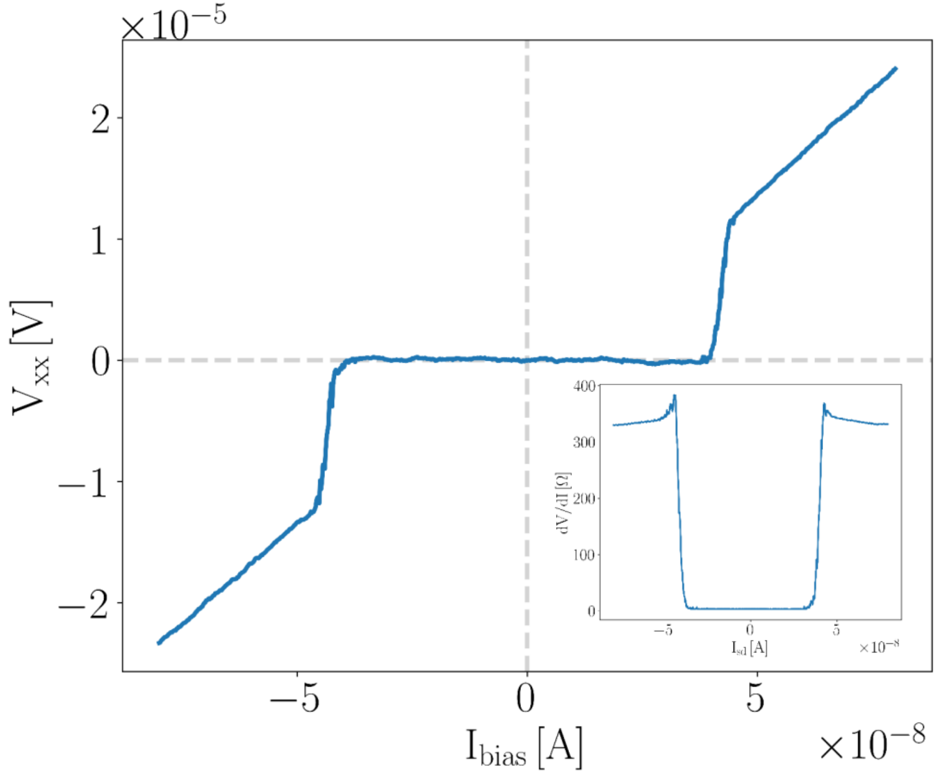
InSb nanoflag-based Josephson junctions



λ_{mfp}	500 nm
L	200 nm
ξ_S	750 nm

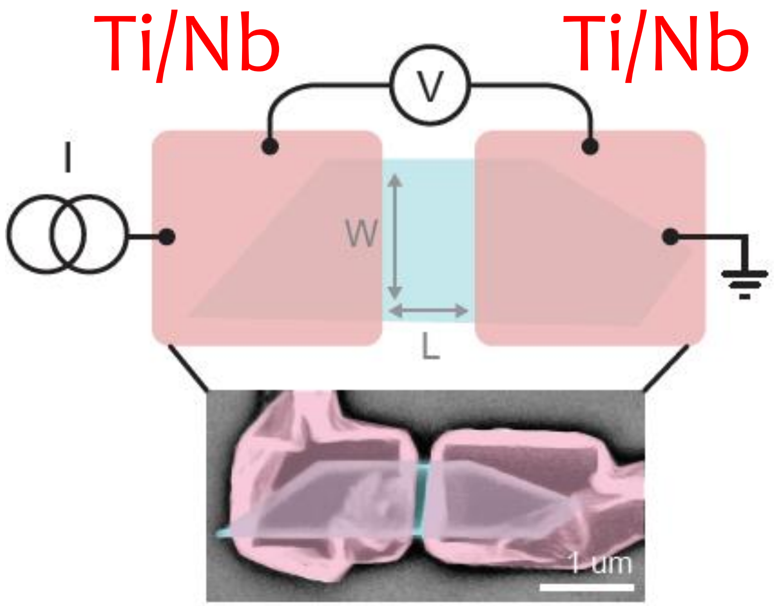
short-ballistic junction



Sedighe Salimian

S. Salimian et al., Appl. Phys. Lett. 119, 214004 (2021).

Gate-tunable supercurrent



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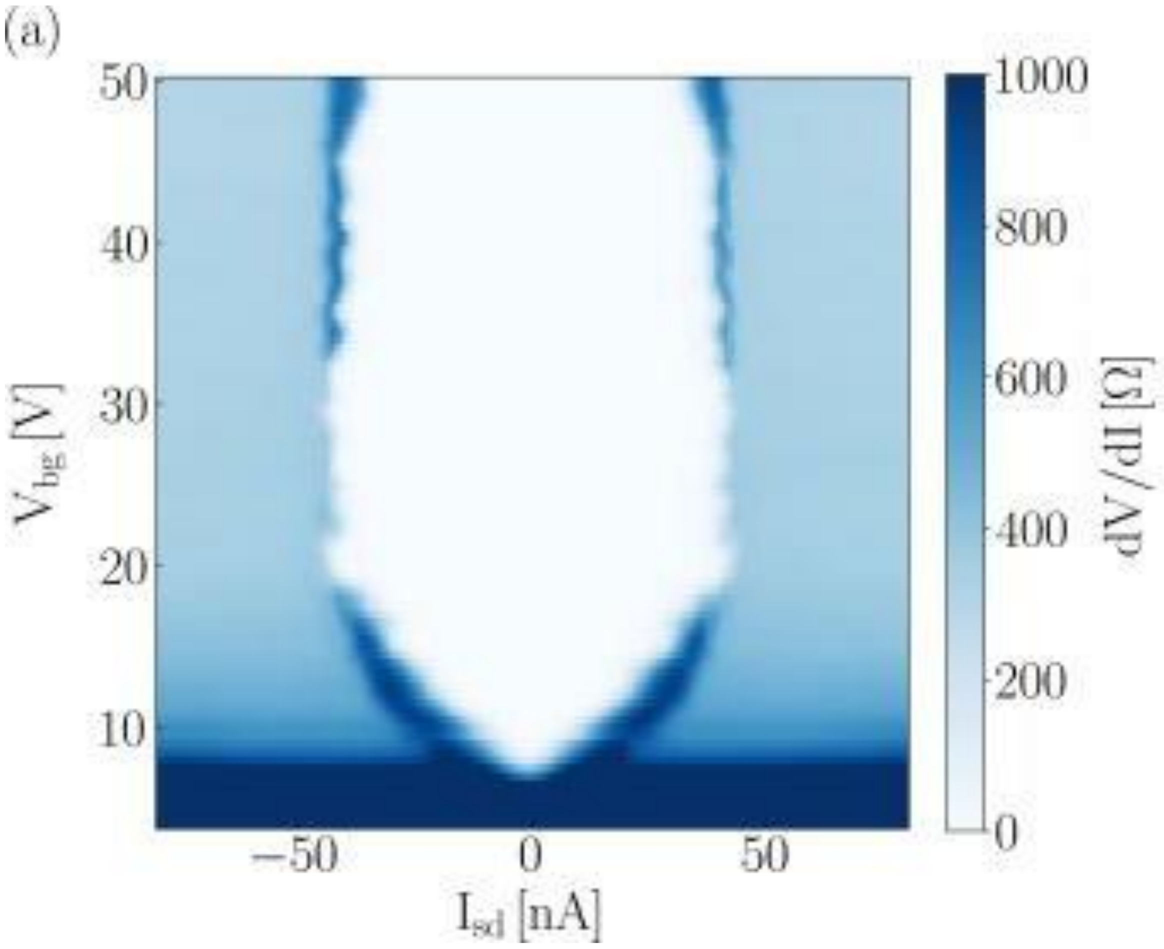

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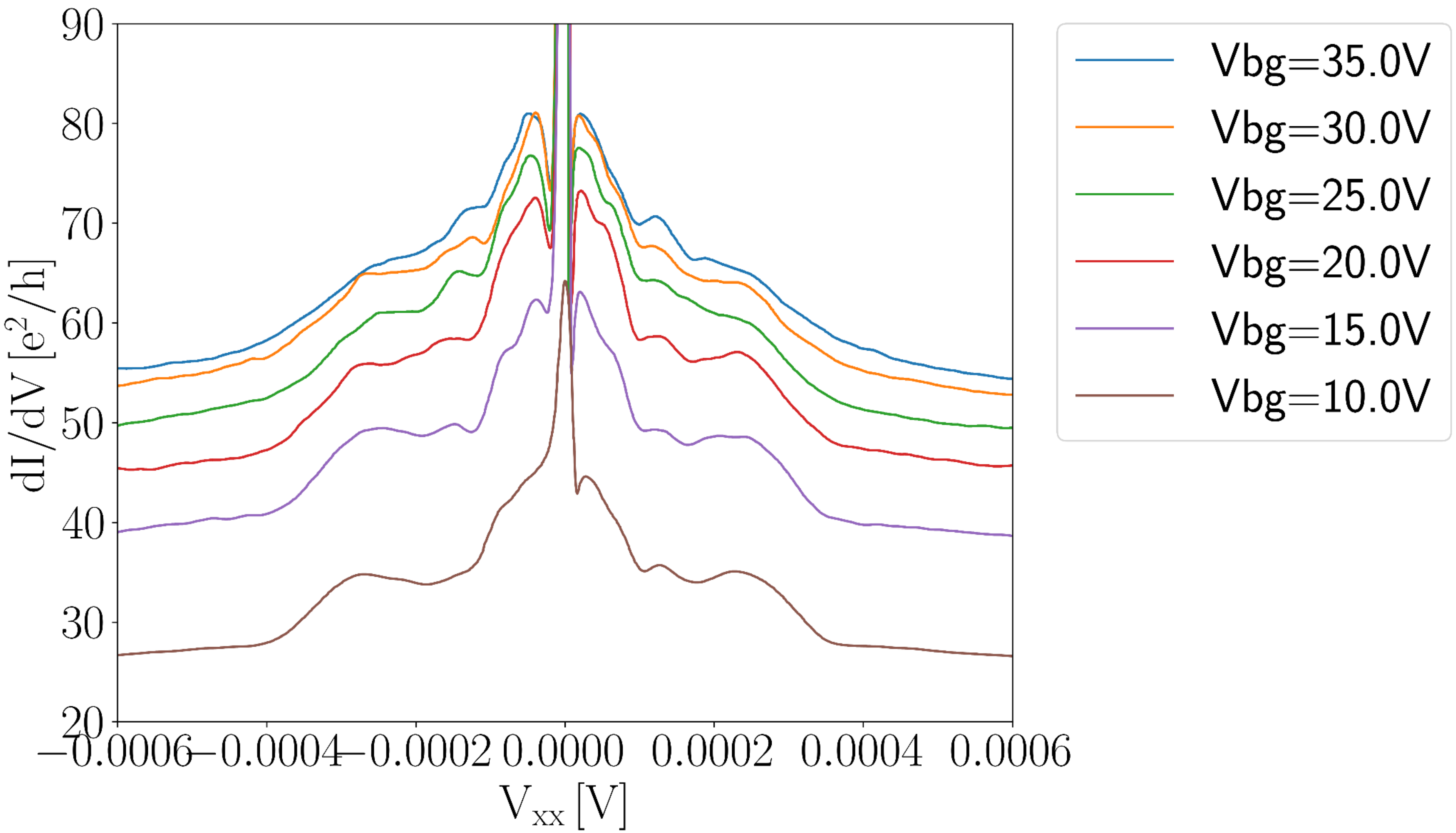
Multiple Andreev Reflections



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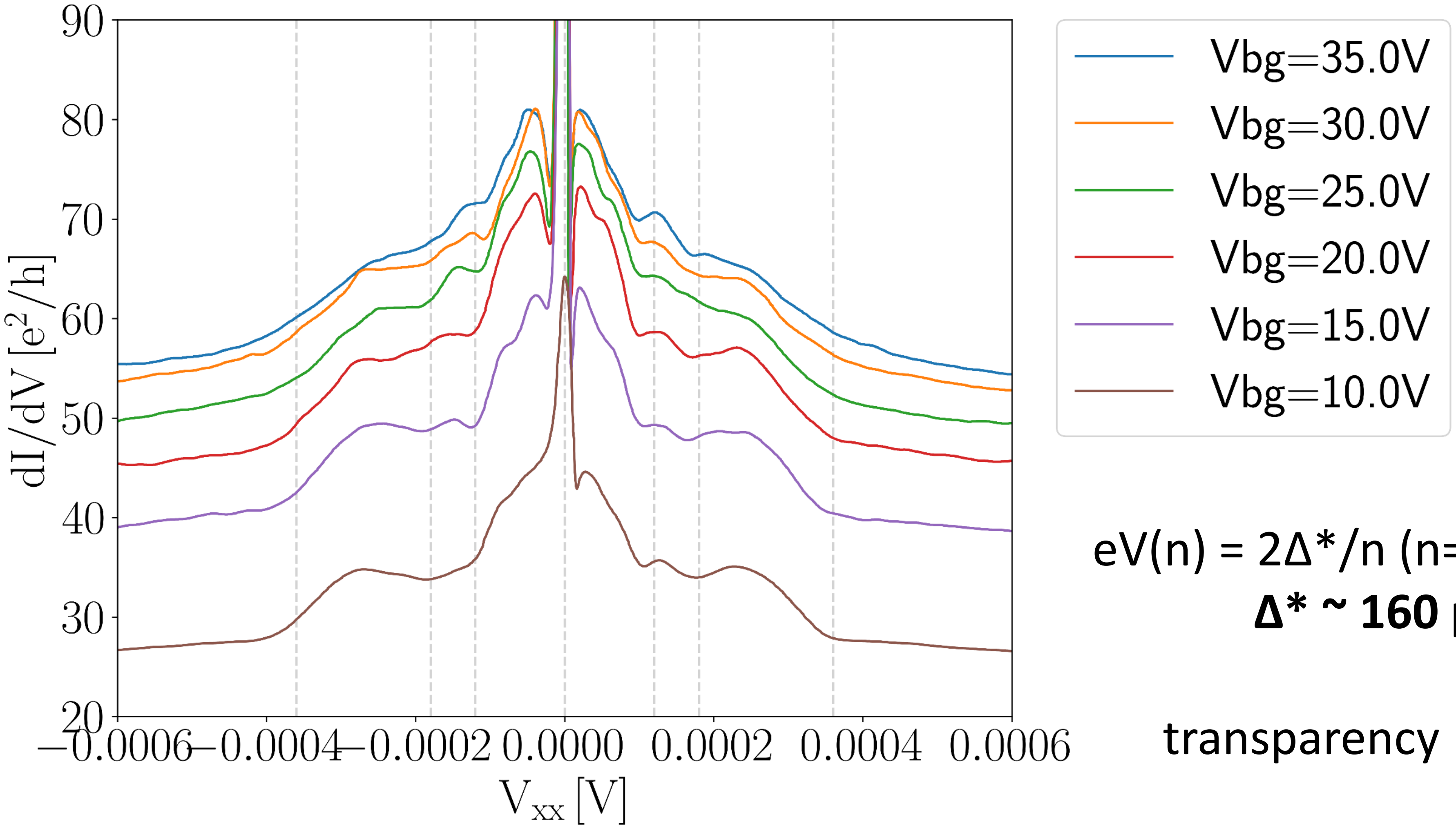


Michal P. Nowak

eV(n) = 2Δ*/n (n=1, 2, 3 . . .)

Δ* ~ 160 μeV

transparency τ = 0.94

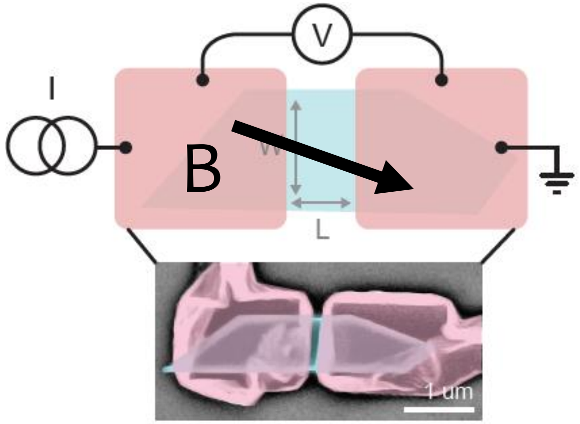
S. Salimian et al., Appl. Phys. Lett. 119, 214004 (2021).

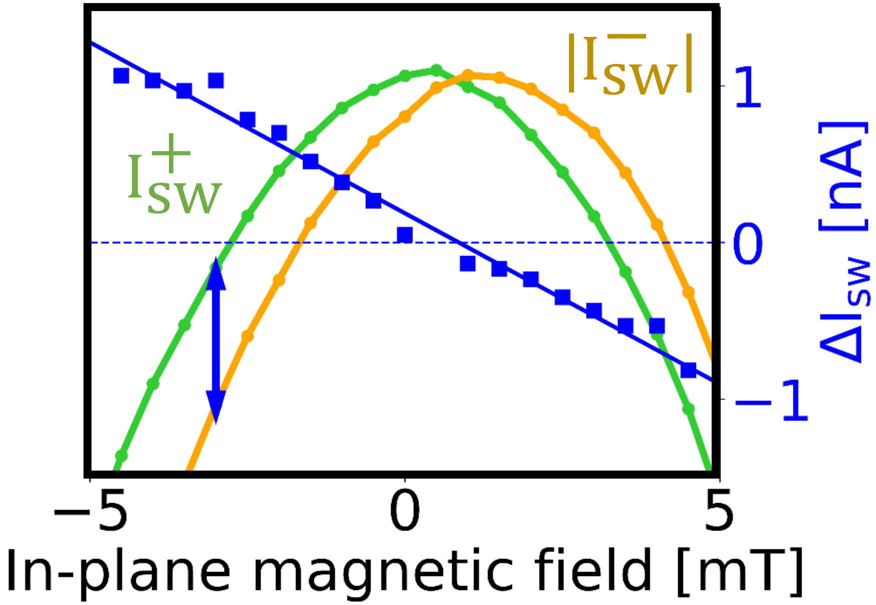
Josephson Diode Effect

Bianca Turini

B. Turini et al., Nano Lett. 22, 8502 (2022).

Josephson Diode Effect





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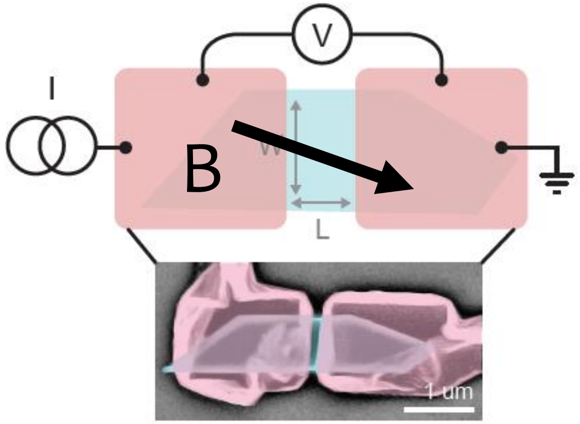
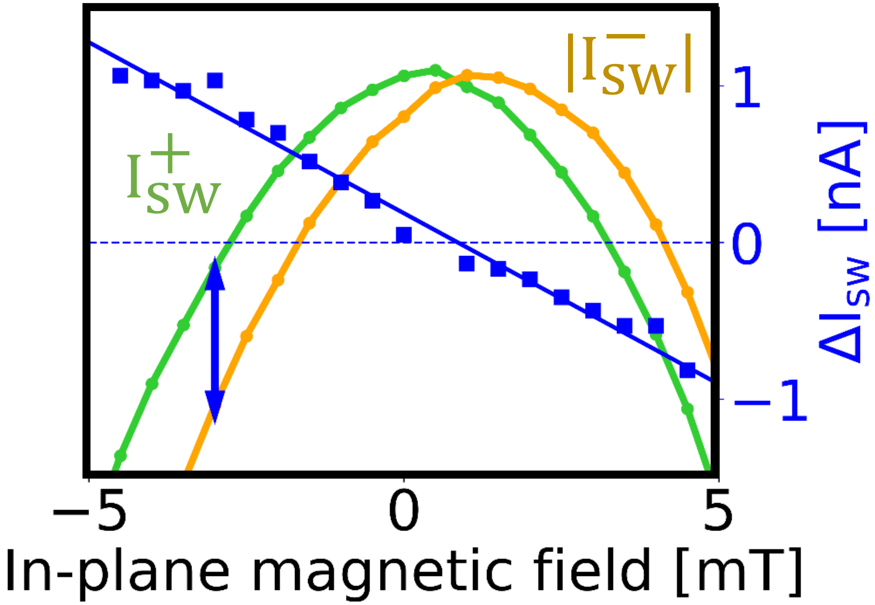
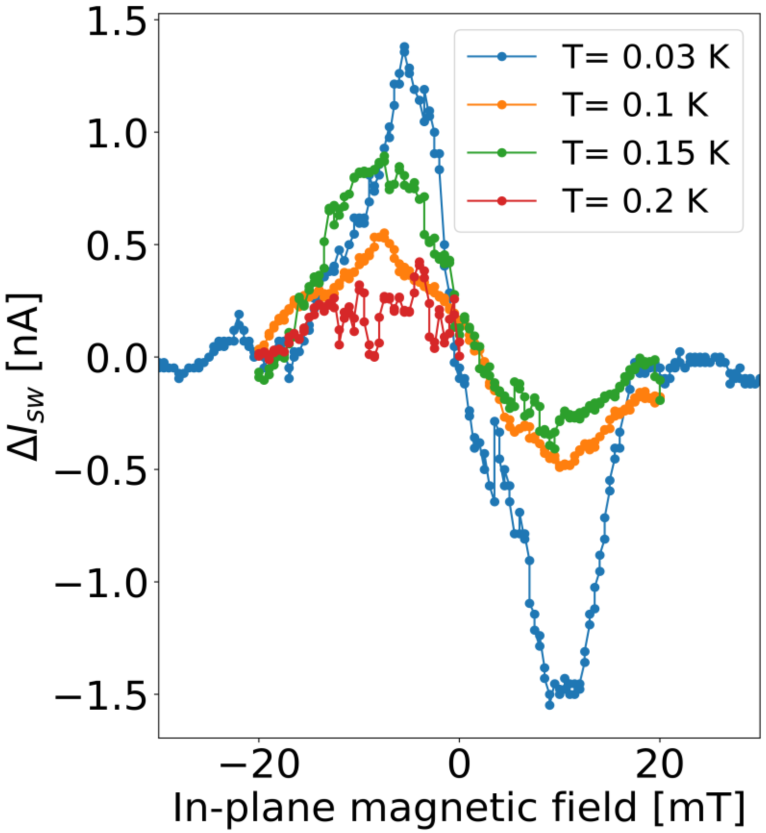
Josephson Diode Effect







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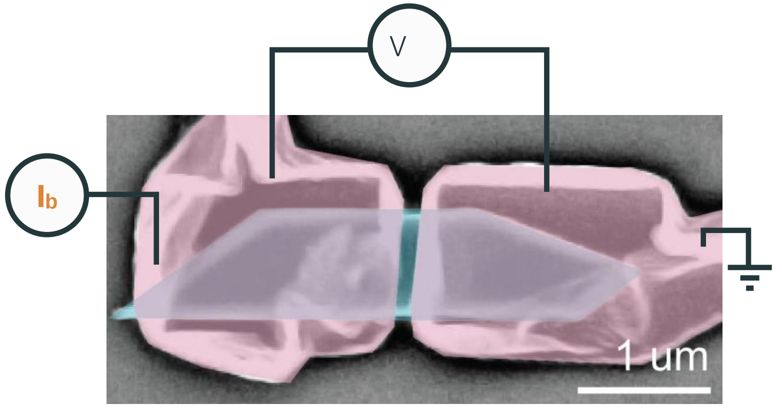
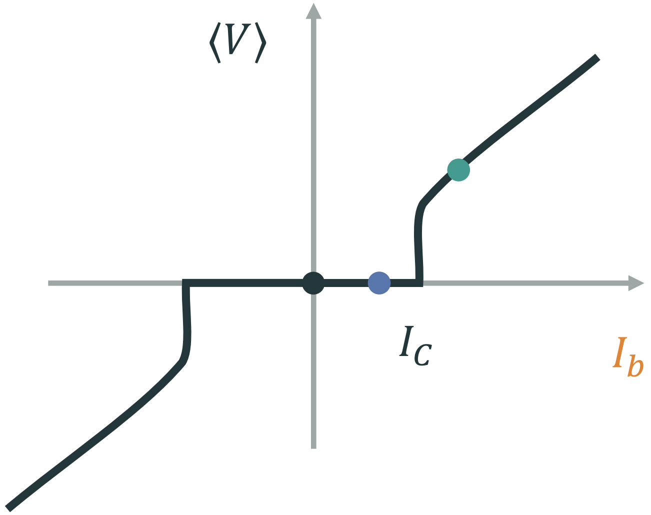
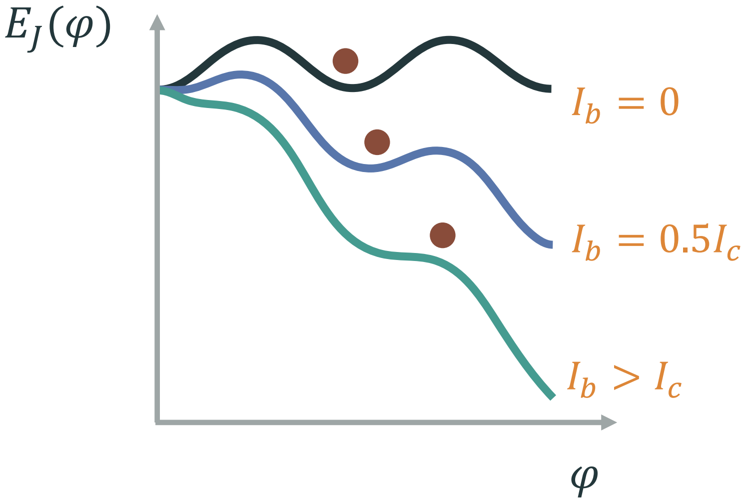
Shapiro steps



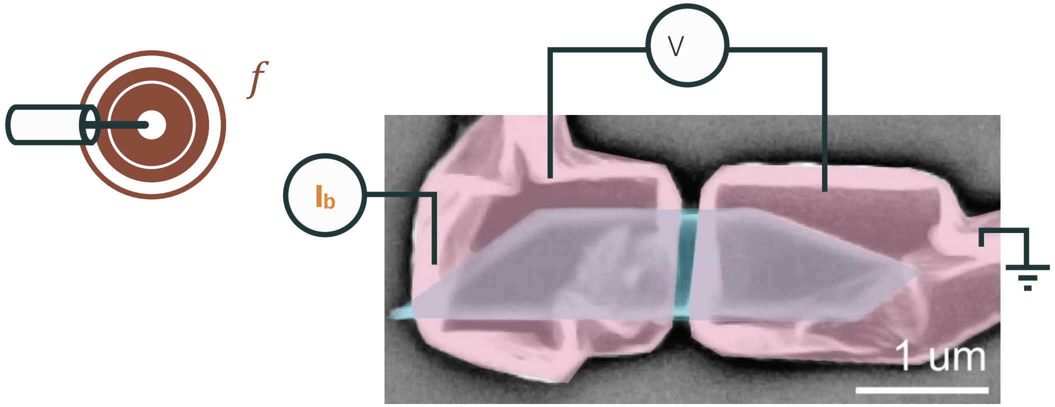
$$V = \frac{\hbar}{2e}\dot{\varphi}$$





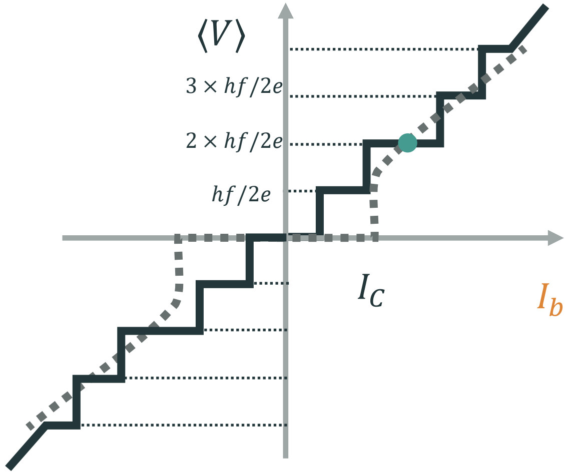
A. Iorio et al., Phys. Rev. Research 5, 033015 (2023).

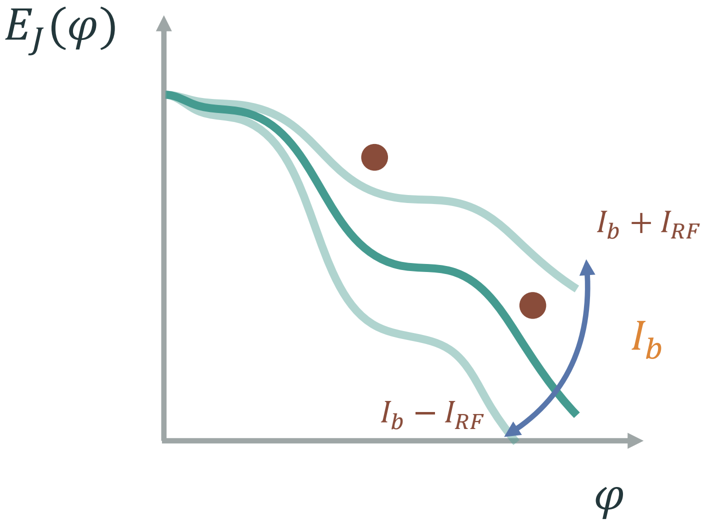
Shapiro steps



If particle rolls n minima in a period $T = 2\pi/f$, then $\dot{\varphi} = 2\pi n f$

$$V = \frac{\hbar}{2e}\dot{\varphi} = \frac{hf}{2e}n$$





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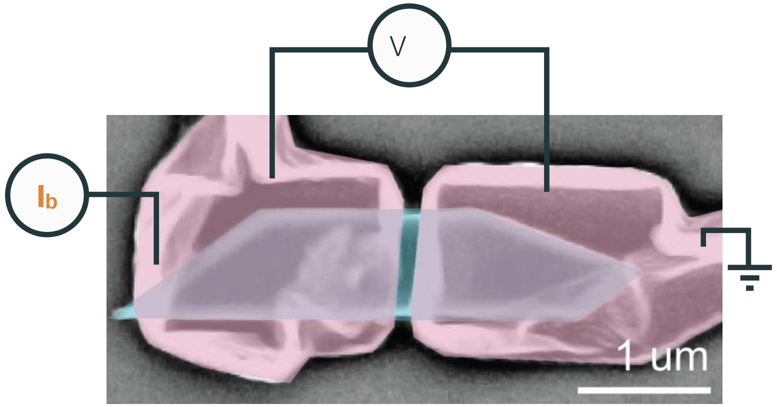
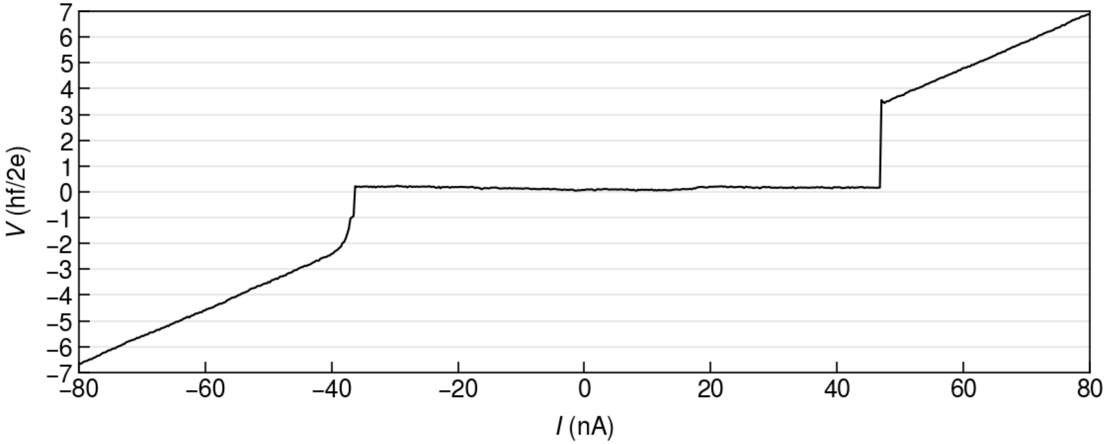
Half-integer Shapiro steps



Andrea Iorio



Shapiro steps – Quantized voltage plateaus $V = \frac{hf}{2e} n$

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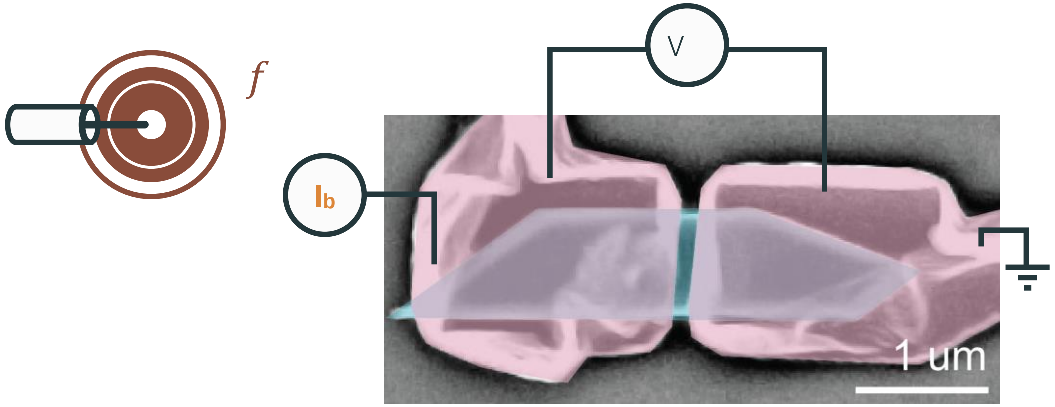

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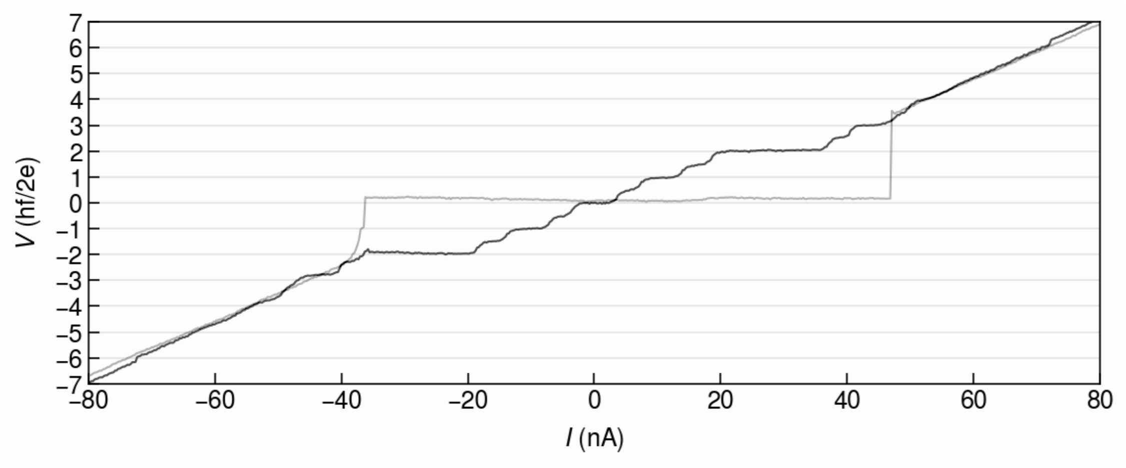

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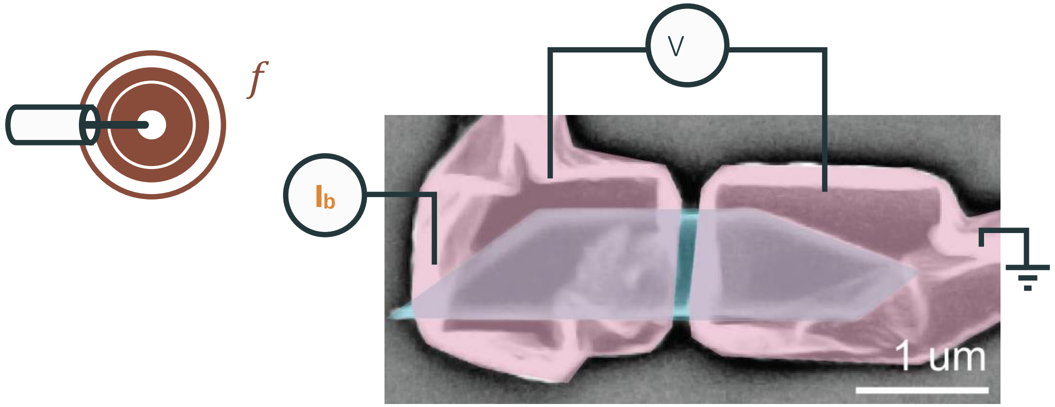

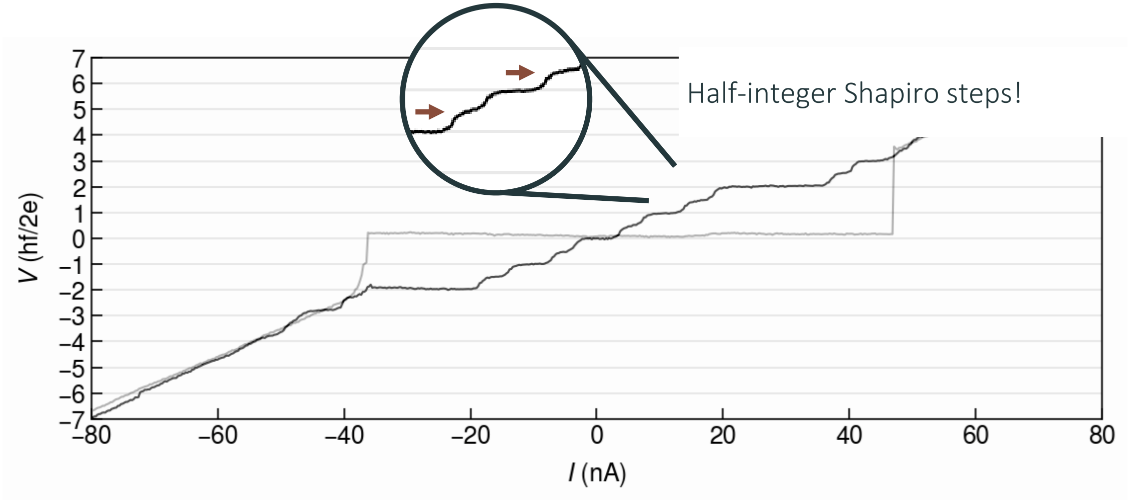

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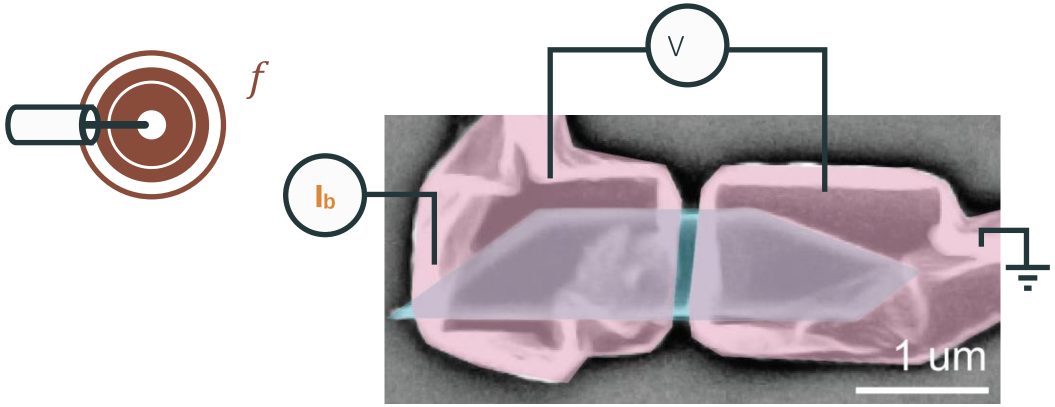

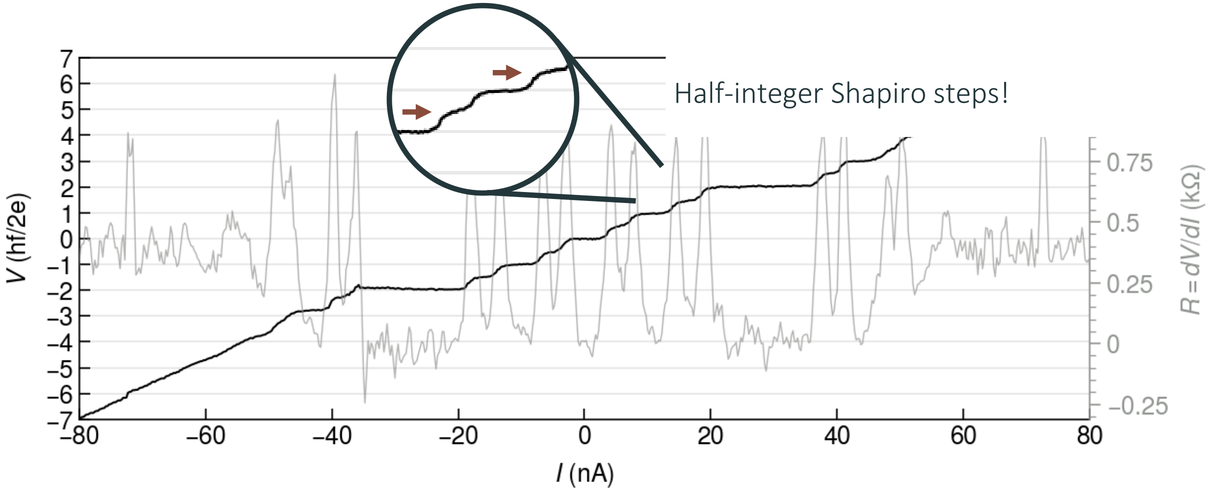

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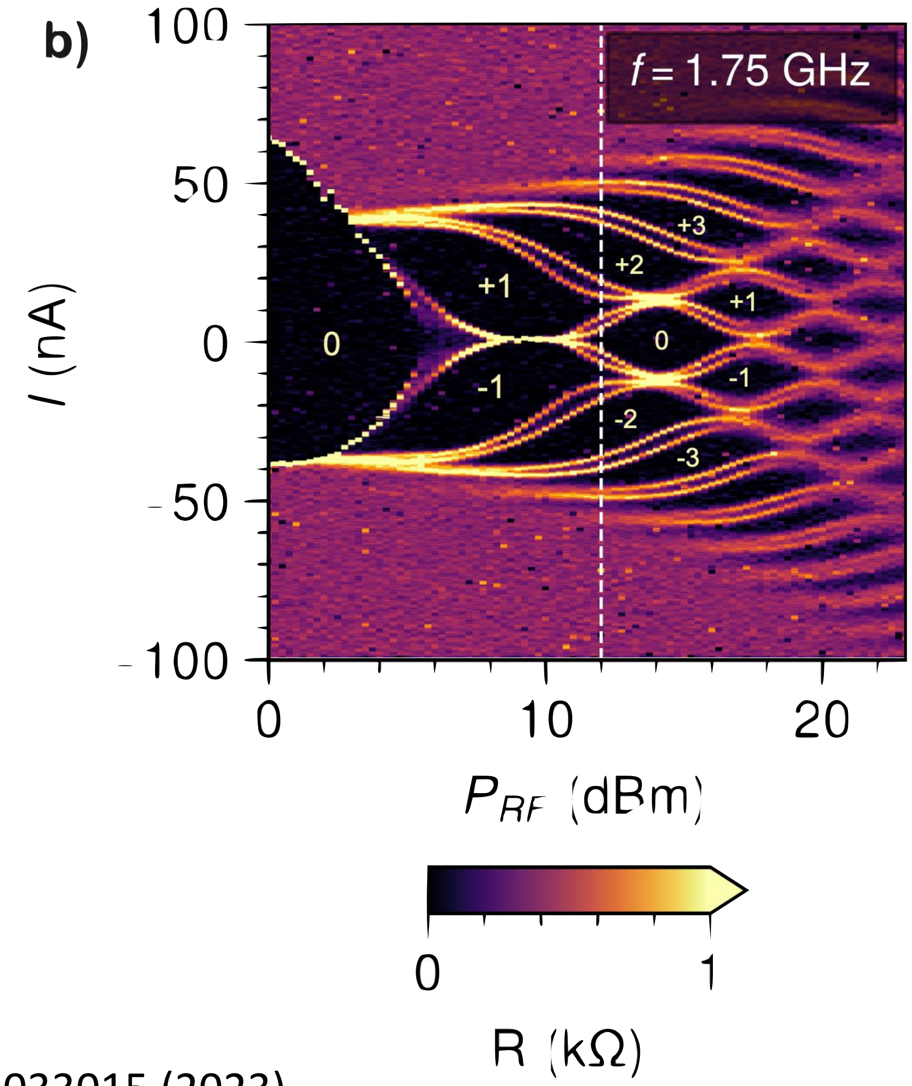

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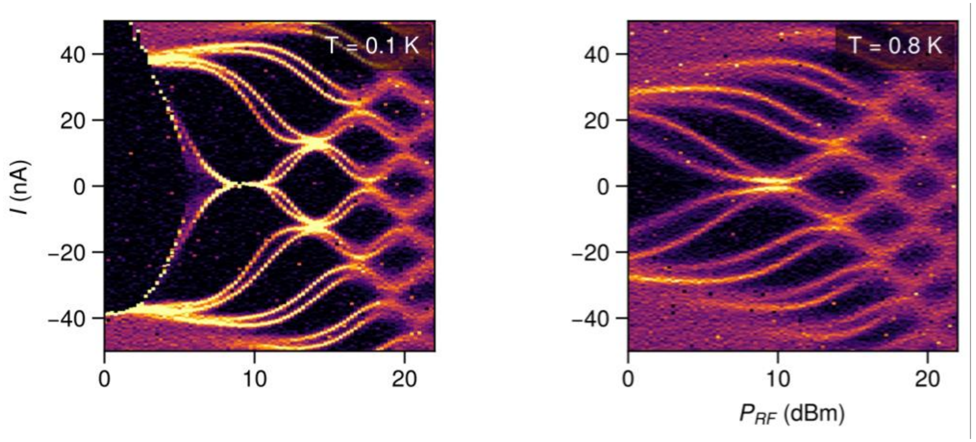
Half-integer Shapiro steps

A non-monotonic temperature dependance



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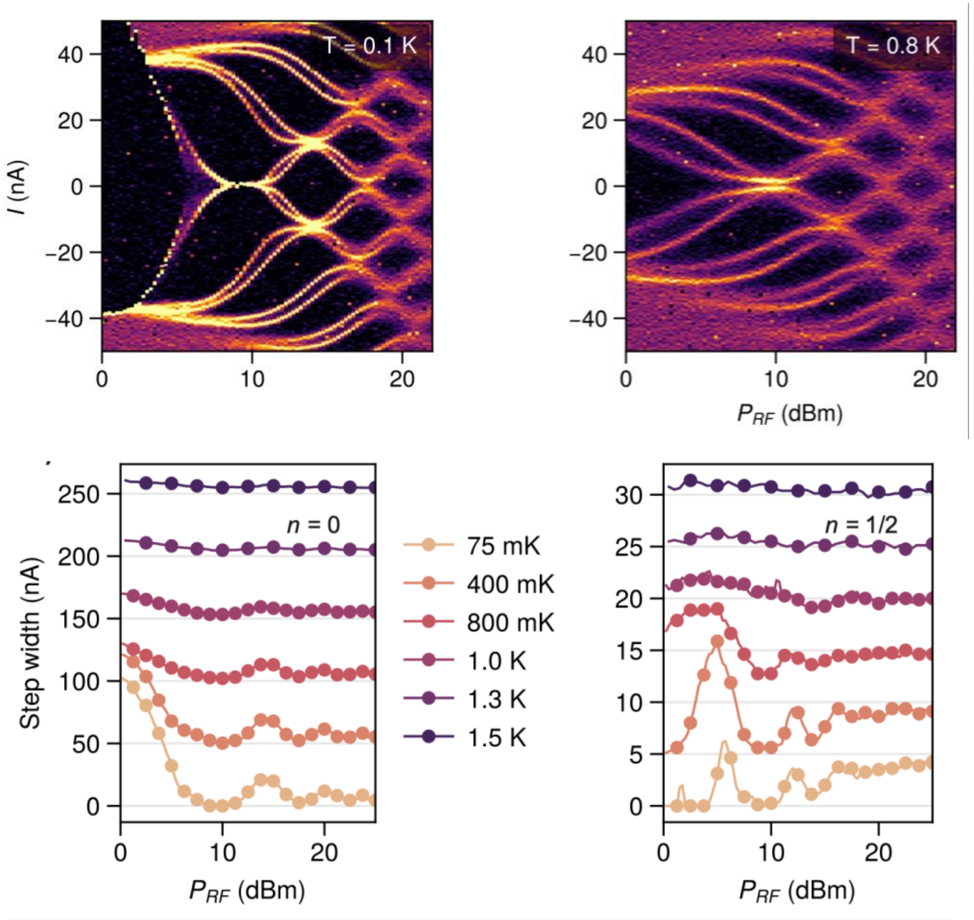
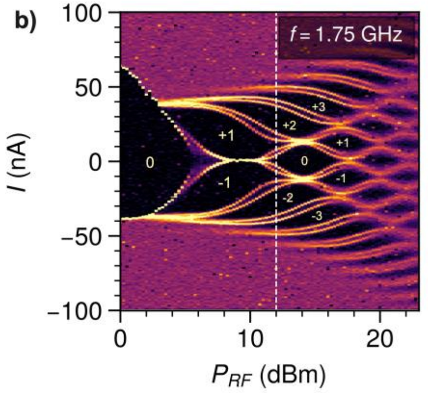


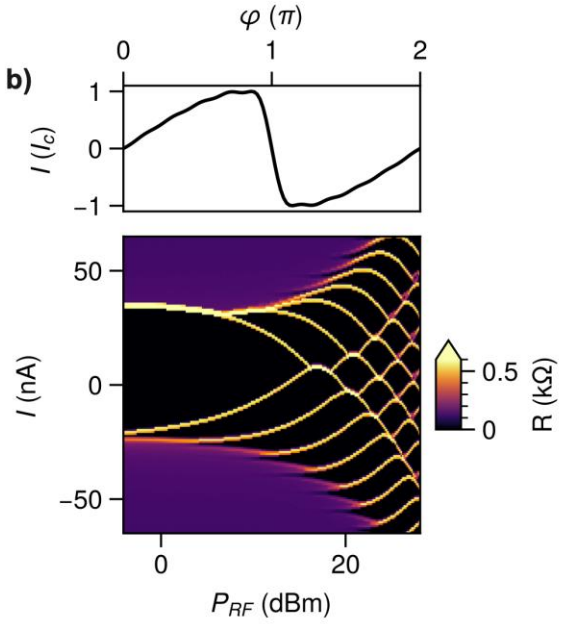
A. Iorio et al., Phys. Rev. Research 5, 033015 (2023).

Half-integer Shapiro steps

How to have half-integer steps?

RCSJ simulations





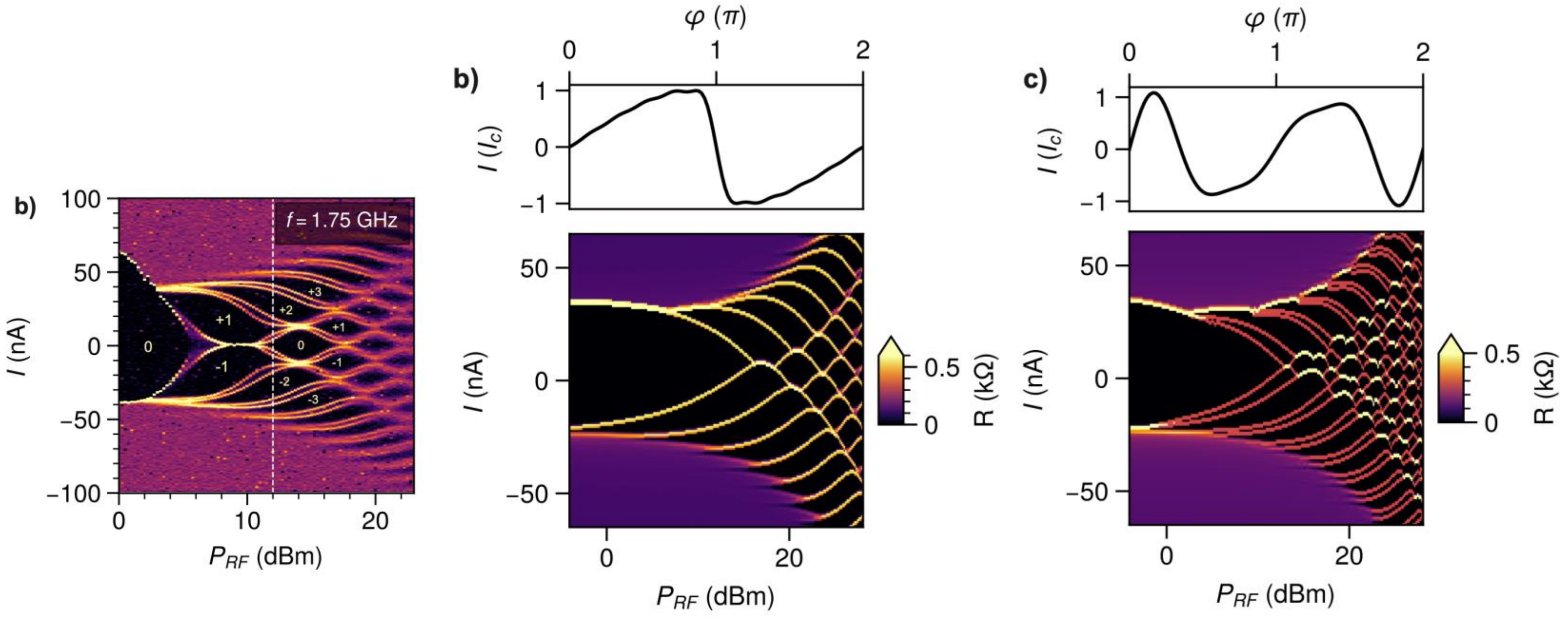
A. Iorio et al., Phys. Rev. Research 5, 033015 (2023).

Half-integer Shapiro steps

How to have half-integer steps?

Need for a $\sin(2\varphi)$ CPR

RCSJ simulations

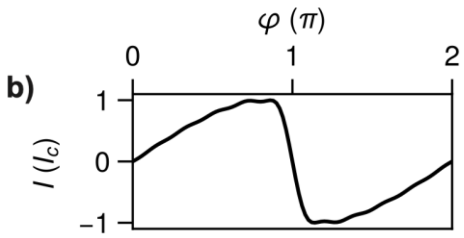


A. Iorio et al., Phys. Rev. Research 5, 033015 (2023).

Half-integer Shapiro steps

Potential mechanisms for $\sin(2\varphi)$

Higher harmonic in the equilibrium CPR



- ✔ Common given explanation
- ✘ Weaker half-steps
- ✘ Half-steps decrease with T

A. Iorio et al., Phys. Rev. Research 5, 033015 (2023).

Half-integer Shapiro steps

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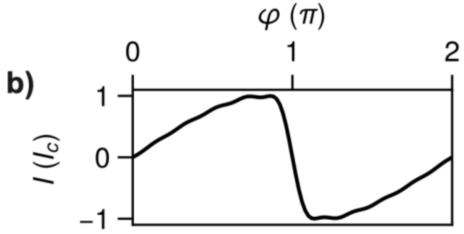

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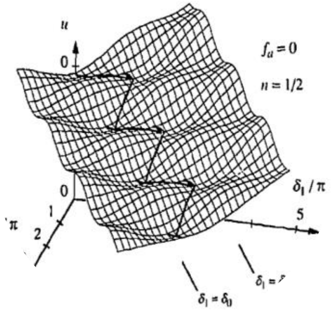
SQUID-like



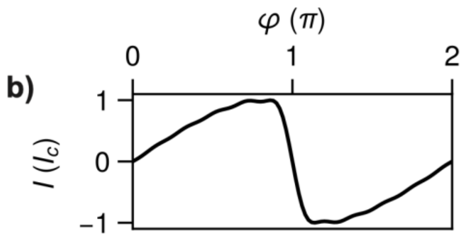
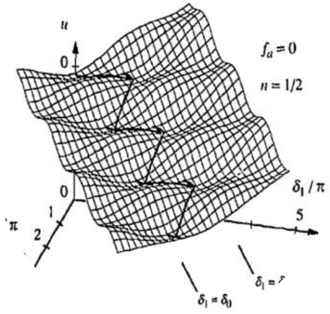
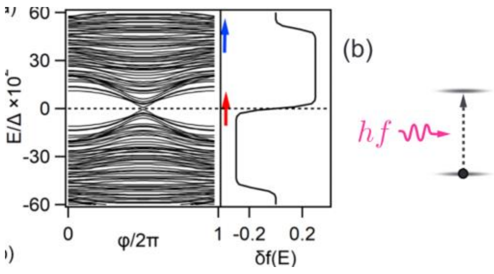
- ✔ Robust half-steps
- ✘ Different geometry
- ✘ B-field dependent

Physical basis for half-integral Shapiro steps in a dc SQUID. Physica C: Superconductivity 245.3-4 (1995)

A. Iorio et al., Phys. Rev. Research 5, 033015 (2023).

Half-integer Shapiro steps

Potential mechanisms for $\sin(2\varphi)$

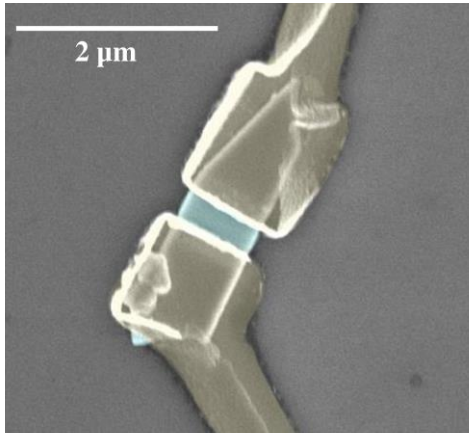
Higher harmonic in the equilibrium CPR	SQUID-like	Non-equilibrium excitations
		
✔ Common given explanation	✔ Robust half-steps	✔ $\sin(2\varphi)$ only when driving
✘ Weaker half-steps	✘ Different geometry	✔ Half-steps non-monotonic in T
✘ Half-steps decrease with T	✘ B-field dependent	! Still some gaps with the theory

Physical basis for half-integral Shapiro steps in a dc SQUID. Physica C: Superconductivity 245.3-4 (1995)

Theory of microwave-assisted supercurrent in quantum point contacts. Physical review letters 105.11 (2010)
Microwave photoassisted dissipation and supercurrent of a phase-biased graphene-superconductor ring. Physical Review Research 3.3 (2021)

A. Iorio et al., Phys. Rev. Research 5, 033015 (2023).

Summary



- InSb nanoflag-based Josephson junctions:
  - High-transparency of the interfaces
  - Ballistic transport
  - Gate-controlled supercurrent
- Josephson diode effect:
  - First observation of the JDE in InSb
  - Magnetic field-driven rectification
  - Relevance of Rashba SOC in the system
- Half-integer Shapiro steps:
  - Shapiro steps are still an open-topic in SNS devices
  - Controllable manipulation of bound states excitations (Andreev qubits)

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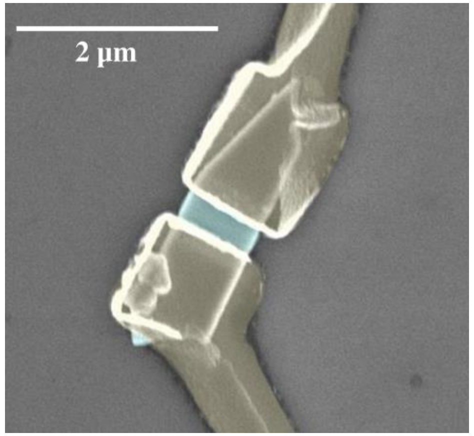

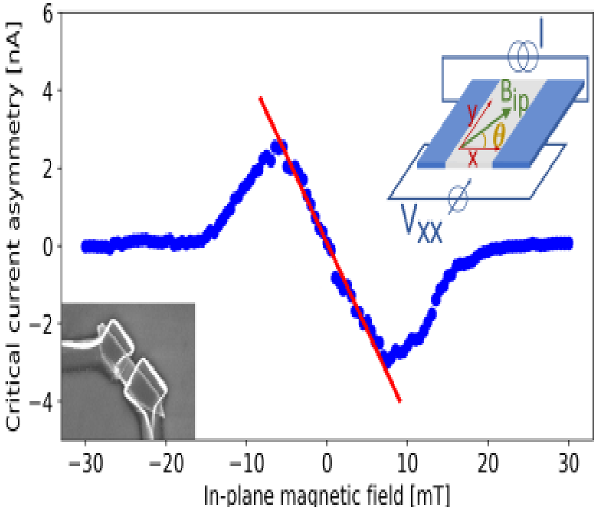

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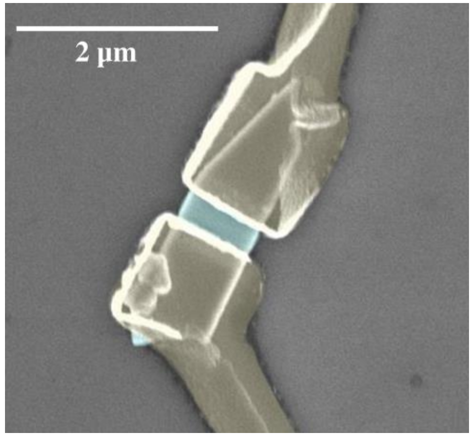
Summary



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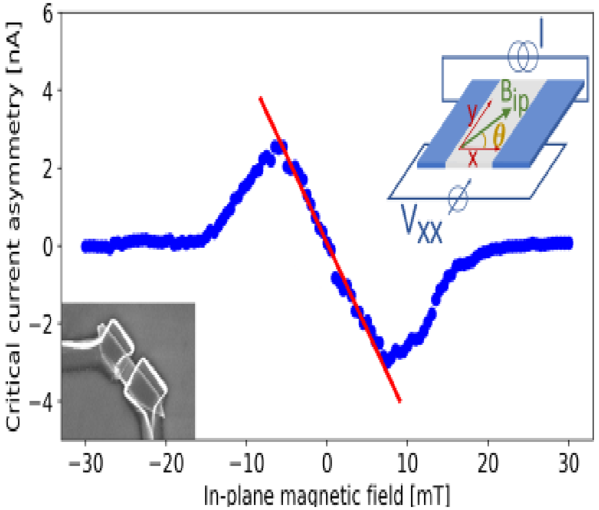
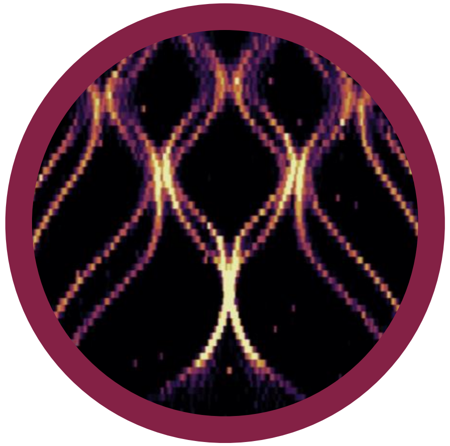




People Involved

CNRNANO PISA NEST

Growth activity


Isha Verma


Valentina Zannier


Lucia Sorba

Devices


Sedighe Salimian

Theory


Matteo Carrega
Luca Chirolli

Transport

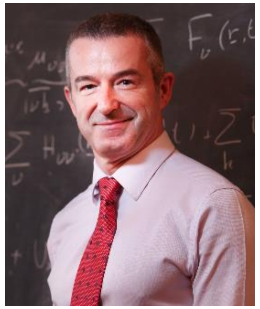

Bianca Turini


Andrea Iorio


Alessandro Crippa


Elia Strambini


Francesco Giazotto


Fabio Beltram

Acknowledgments:

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