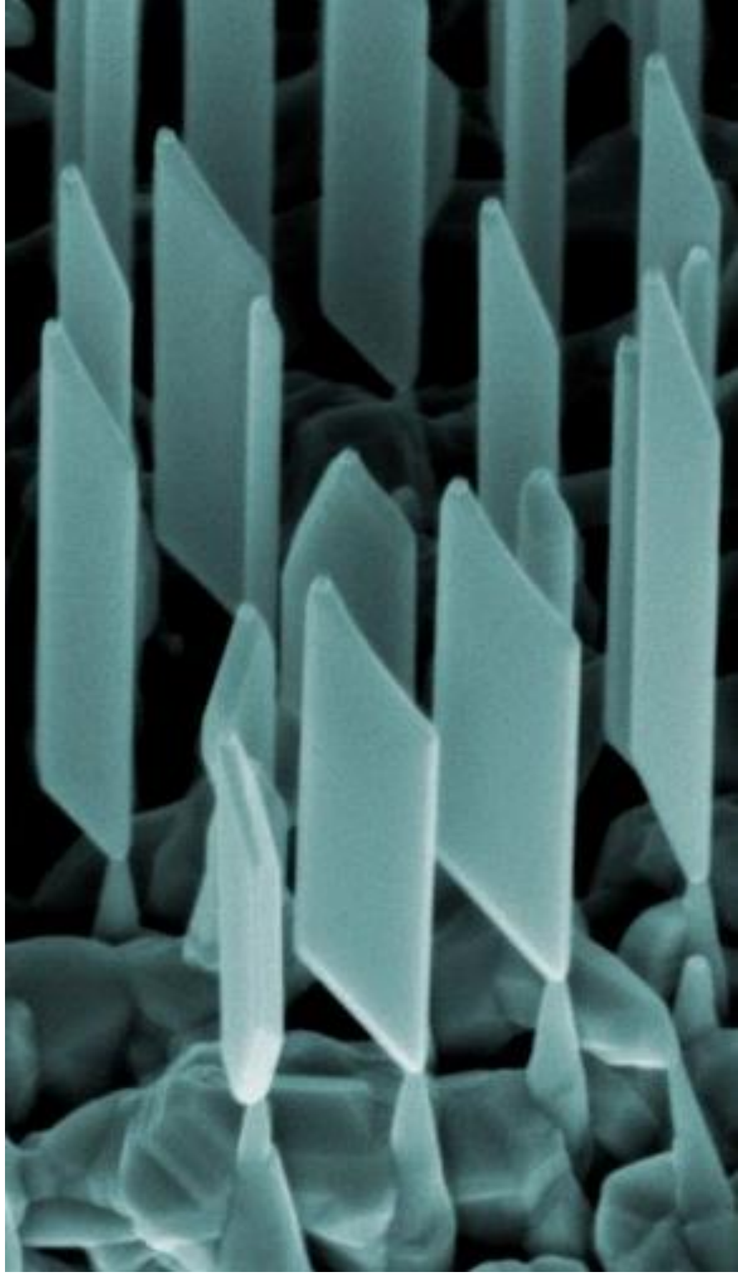
Highly transmissive InSb nanoflag Josephson junctions

Stefan Heun

NEST, Istituto Nanoscienze-CNR and Scuola Normale Superiore, Pisa, Italy



Outline of the talk

- InSb nanoflags for advanced devices
- Nanoflag-based Josephson junctions
- Josephson diode effect in InSb nanoflags
- Half-integer Shapiro steps in InSb nanoflags

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InSb is appealing for spintronics

Small bandgap	E_g=0.23 eV
Low effective mass	$m/m_0 = 0.018$
Strong SOC	$E_{SOC} \sim 200\ \mu eV$

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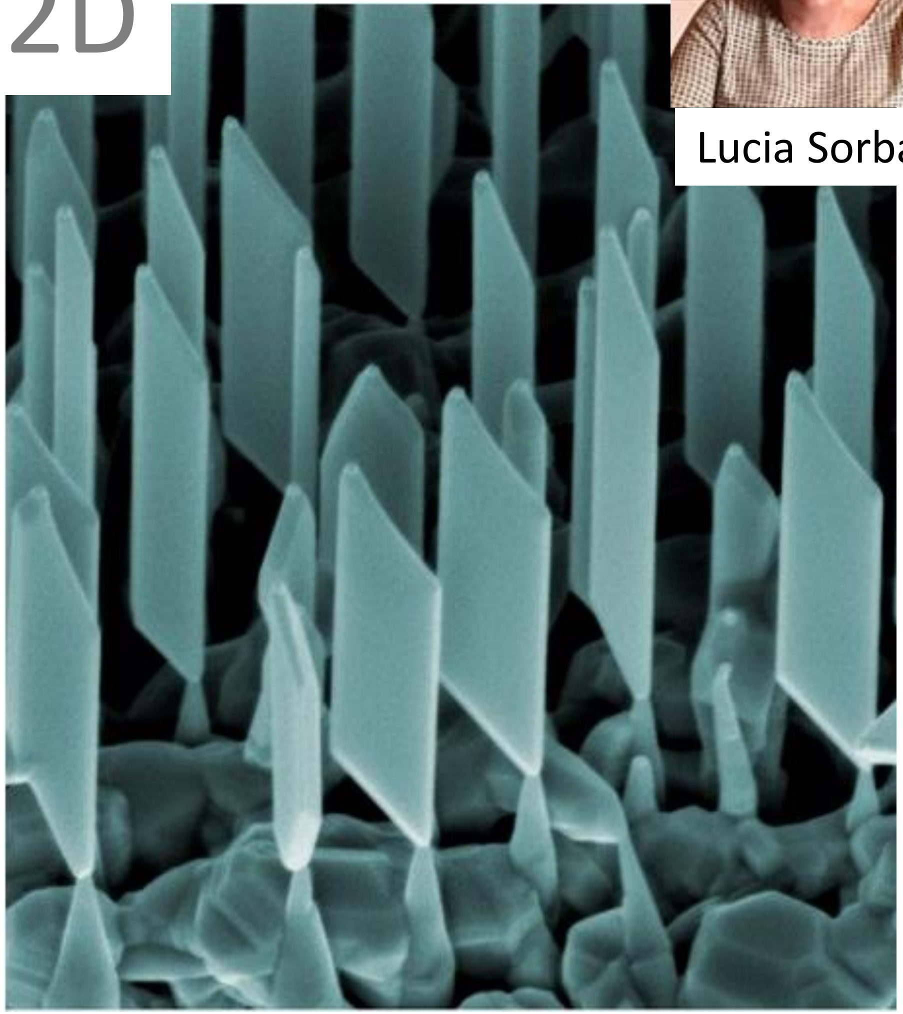
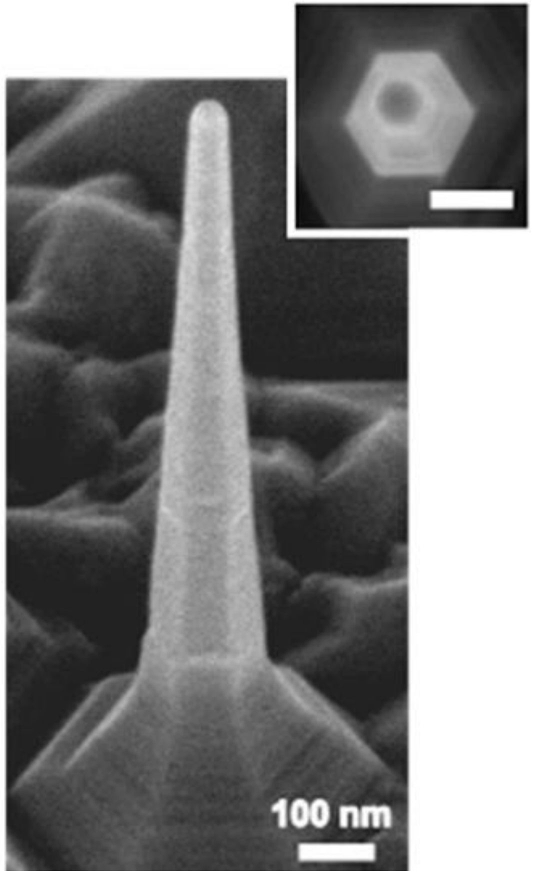
InSb is appealing for spintronics but challenging to grow 2D

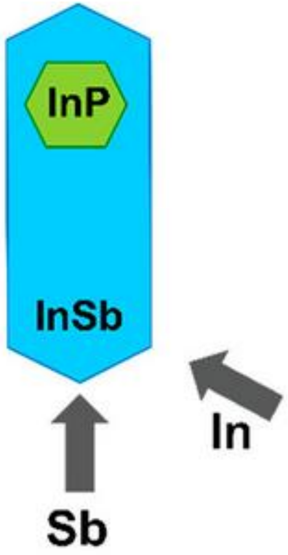


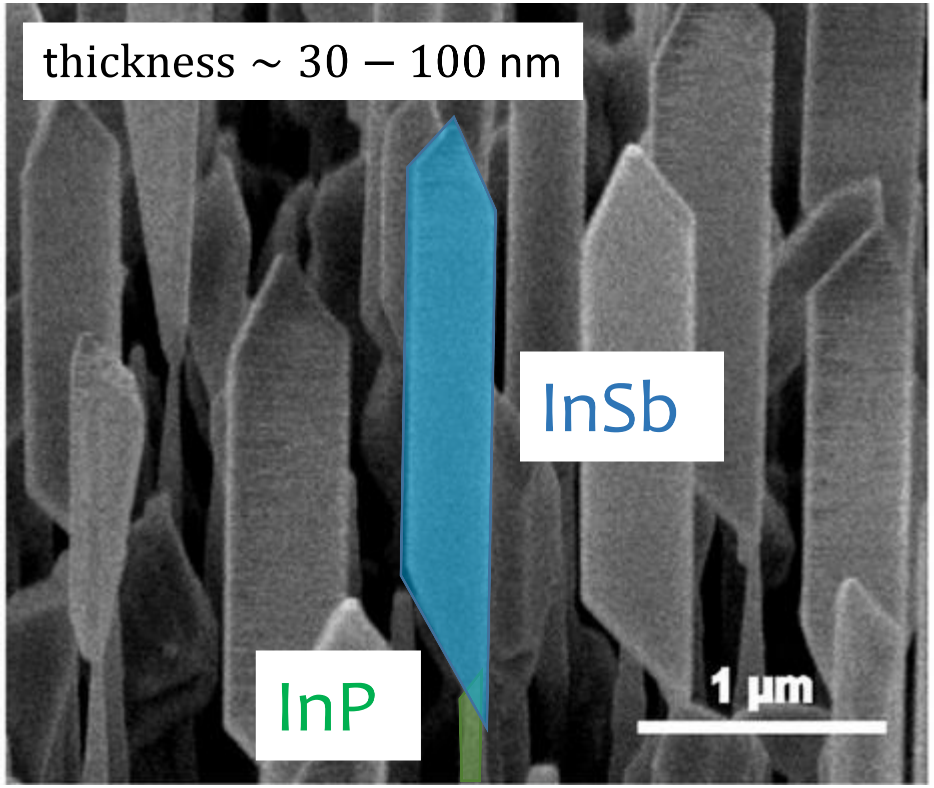

Lucia Sorba

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	

Nanoflags are grown via Chemical Beam Epitaxy







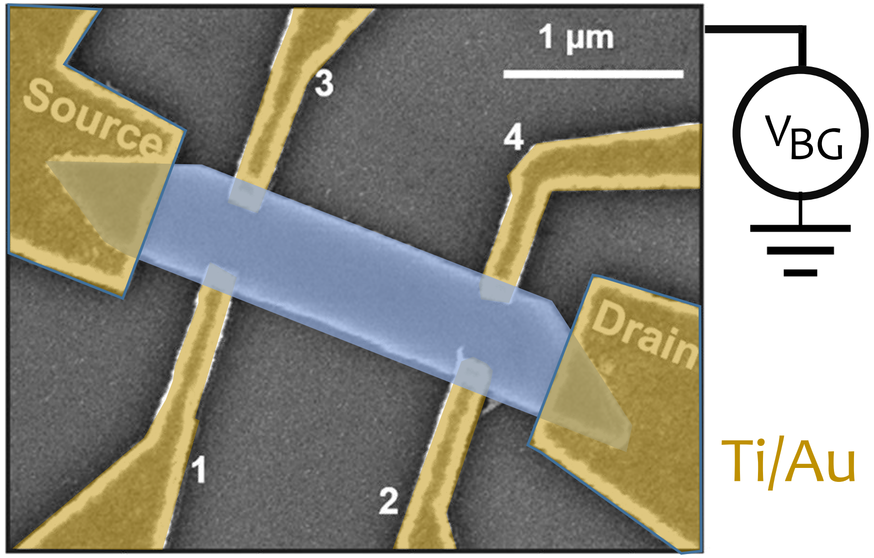
Defect-free InSb zinc blende lattice

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

NFs show high mobility and giant g*-factor

@ T = 4.2 K

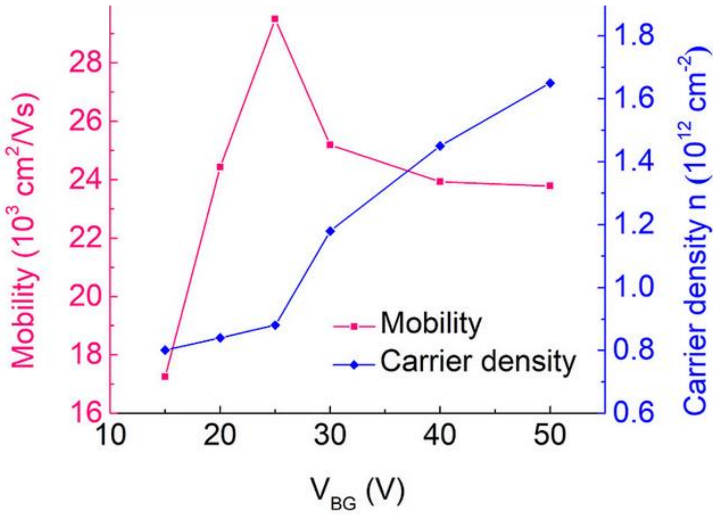
Ti/Au



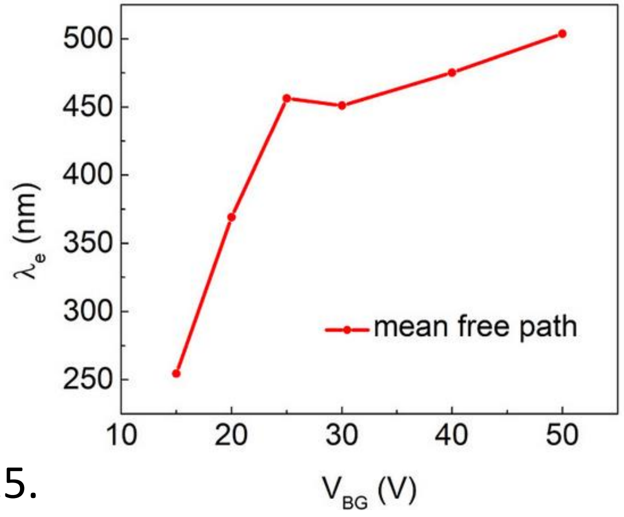
Ti/Au

@ T = 250 mK

$g^* \sim 44$



$\mu_e \sim 29500\ cm^2/Vs$



$\lambda_{mfp} \sim 500$ nm

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

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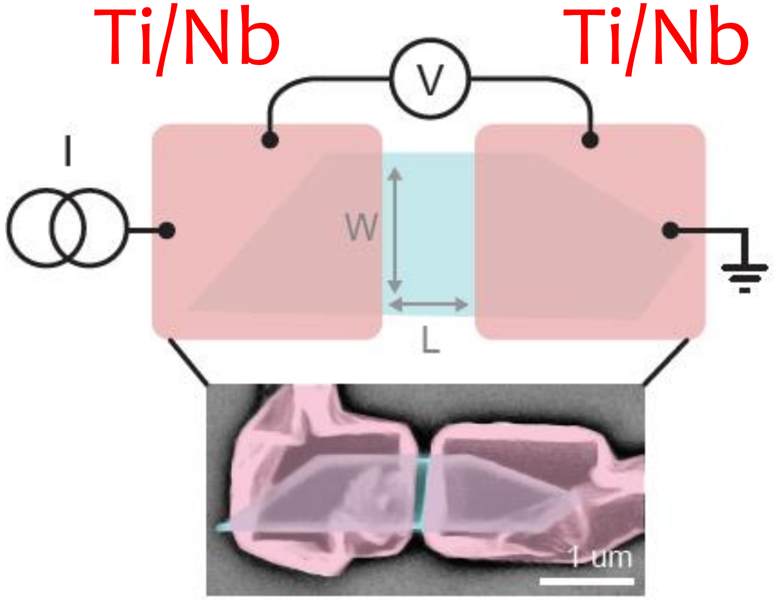
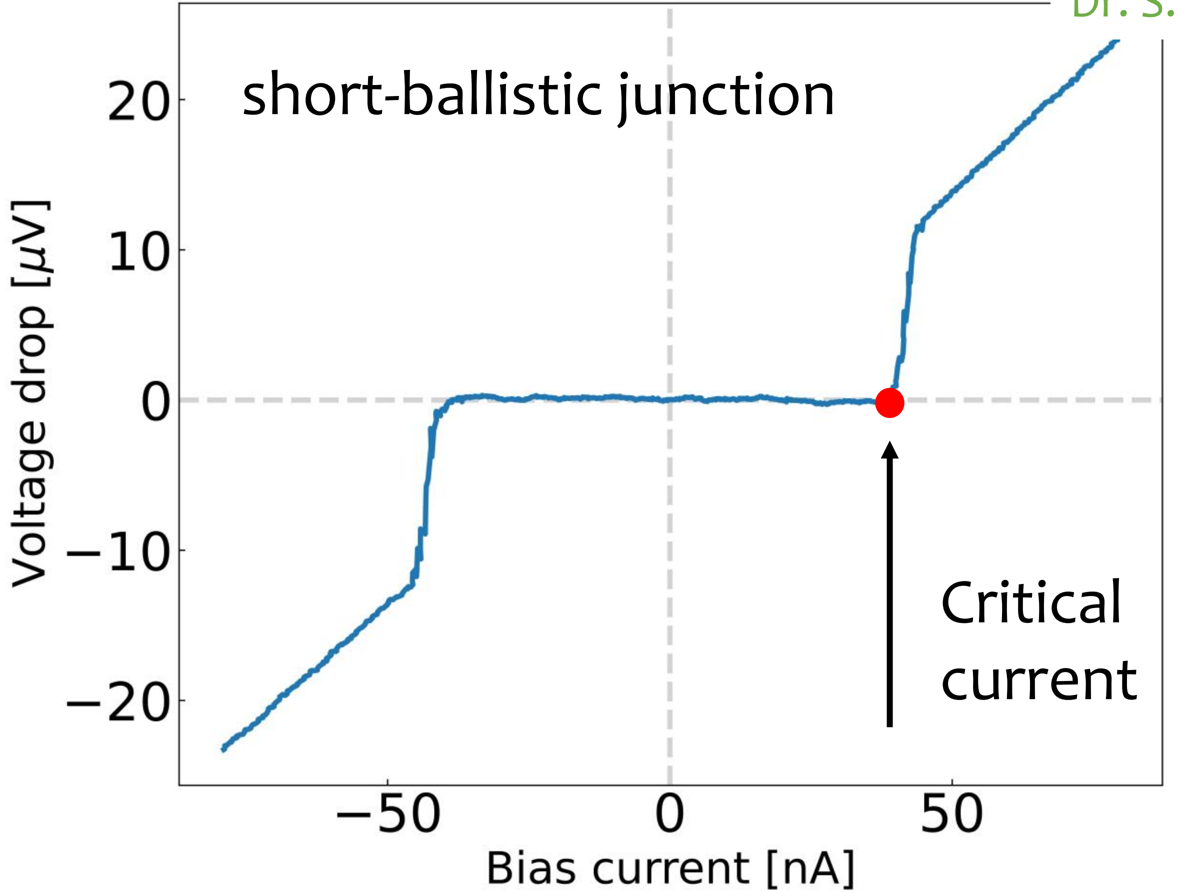
- Half-integer Shapiro steps in InSb nanoflags

The devices show supercurrent



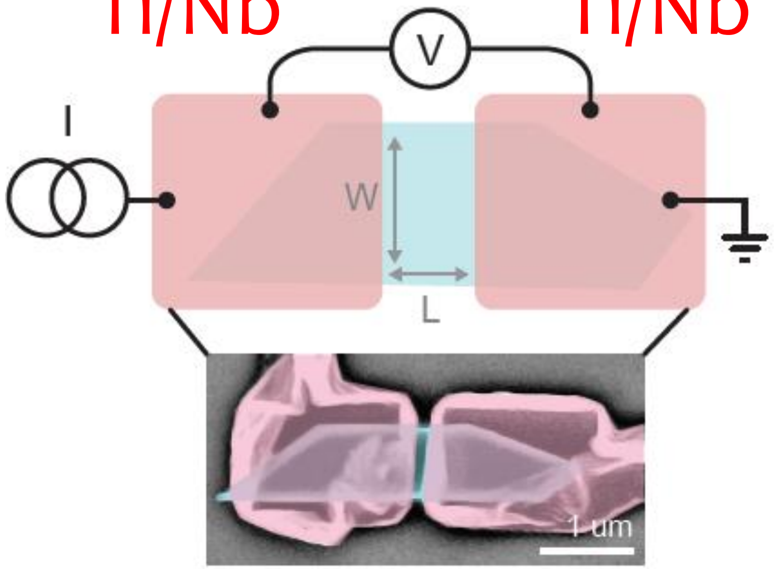
λ_{mfp}	500 nm
L	200 nm
ξ_S	750 nm

Dr. S. Salimian



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

The devices show gate-tunable supercurrent



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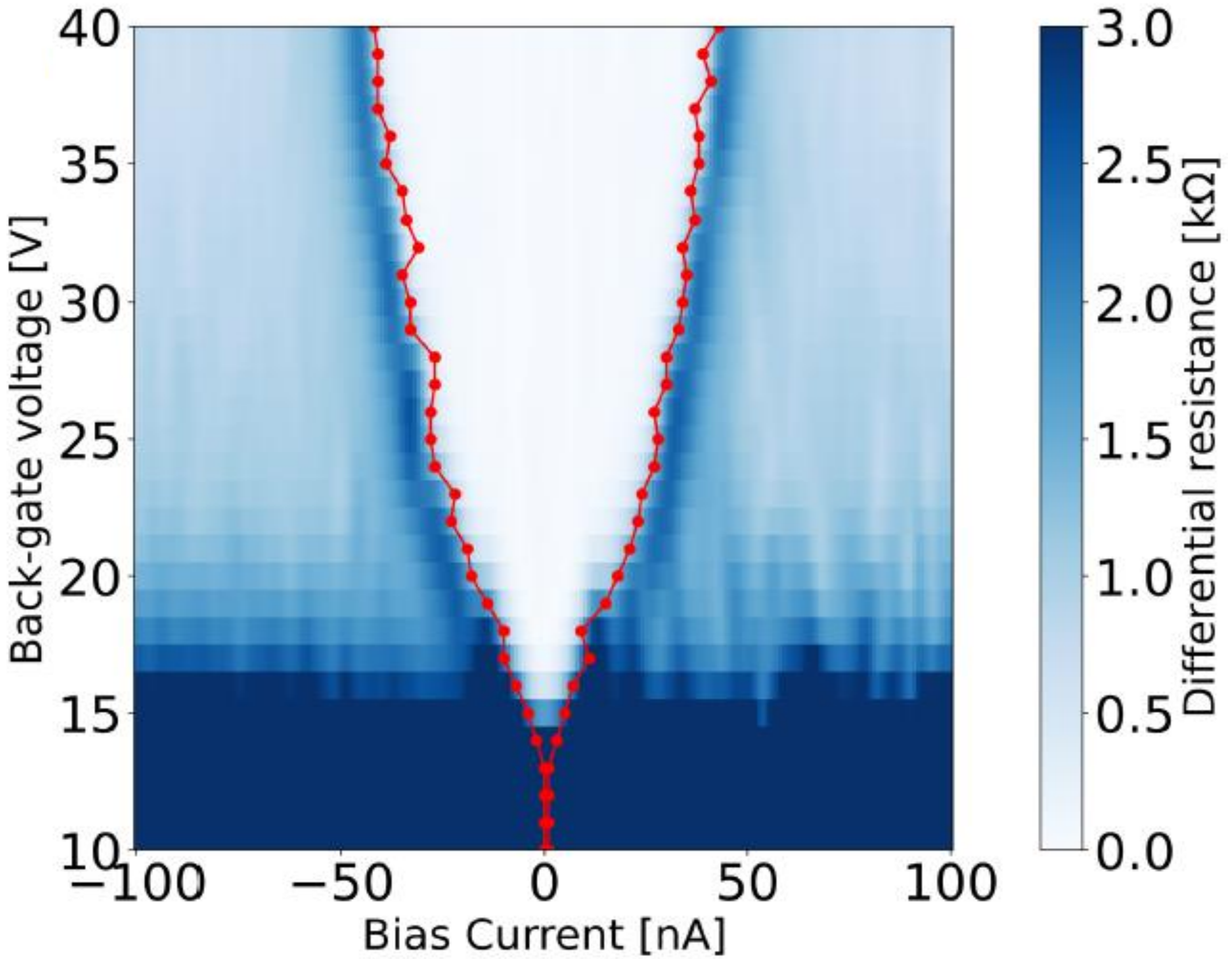
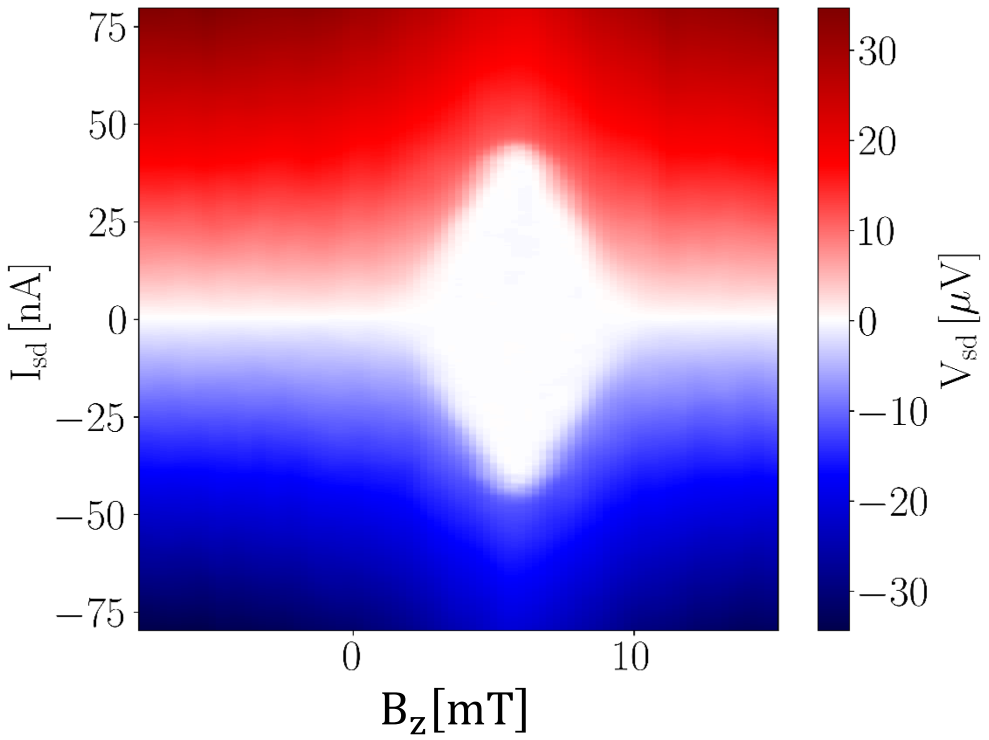
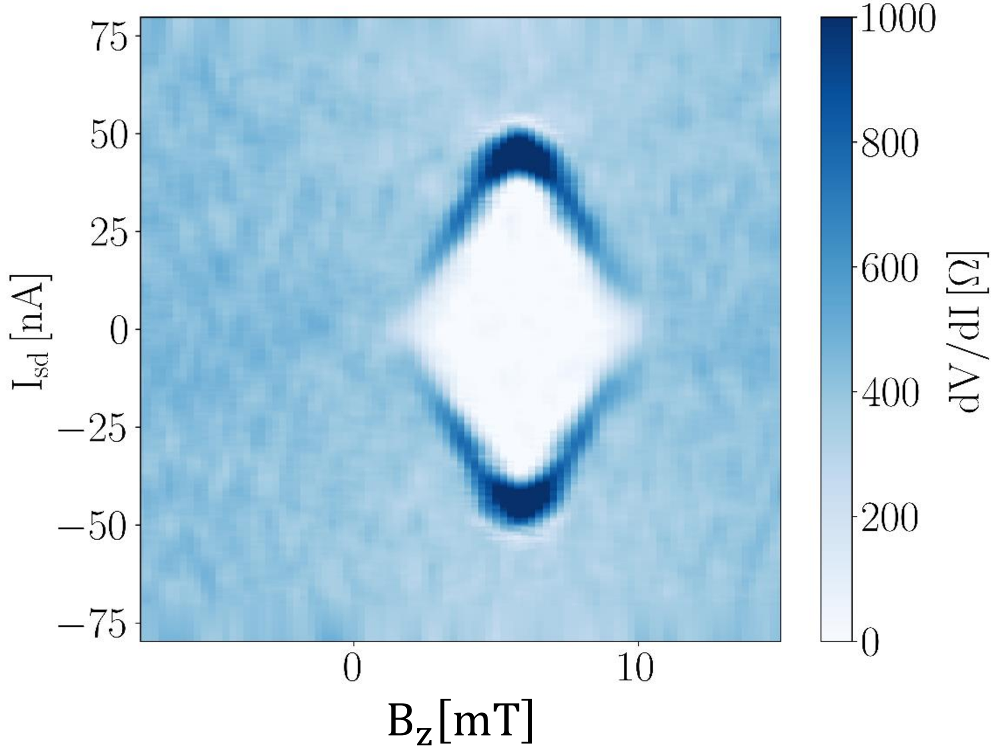


S. Salimian et al., Appl. Phys. Lett. 119, 214004 (2021).

Magnetic Interference Pattern

T = 250 mK





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

Magnetic Interference Pattern

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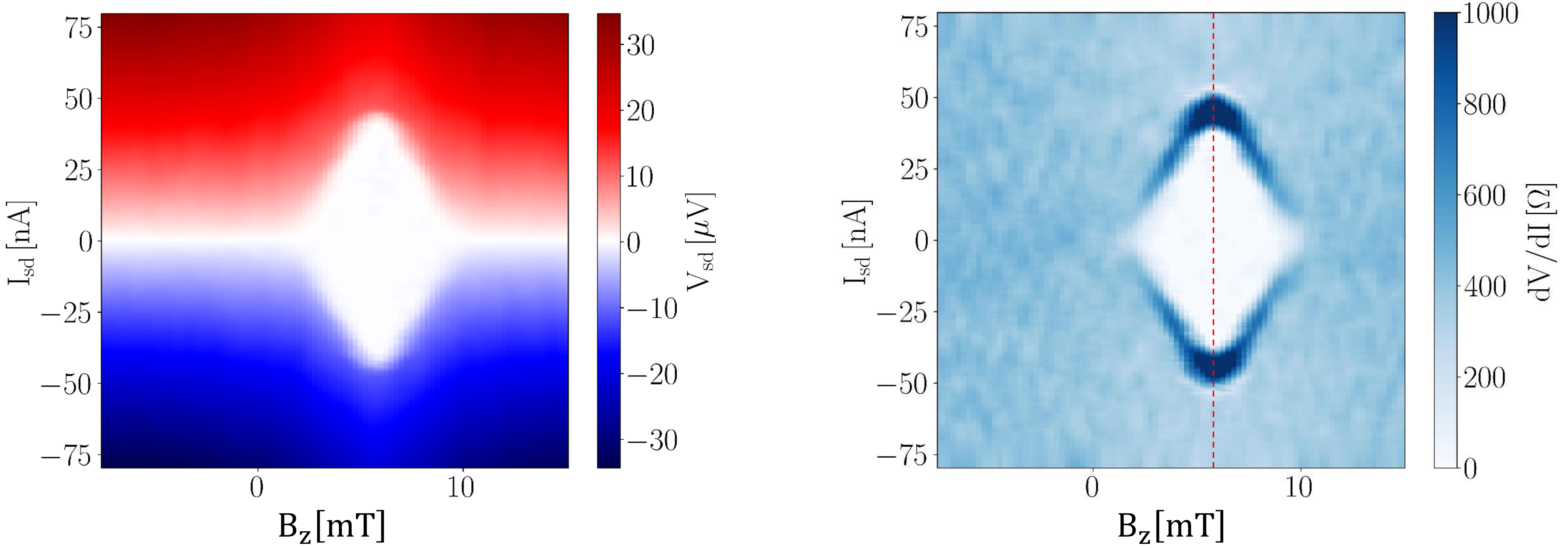


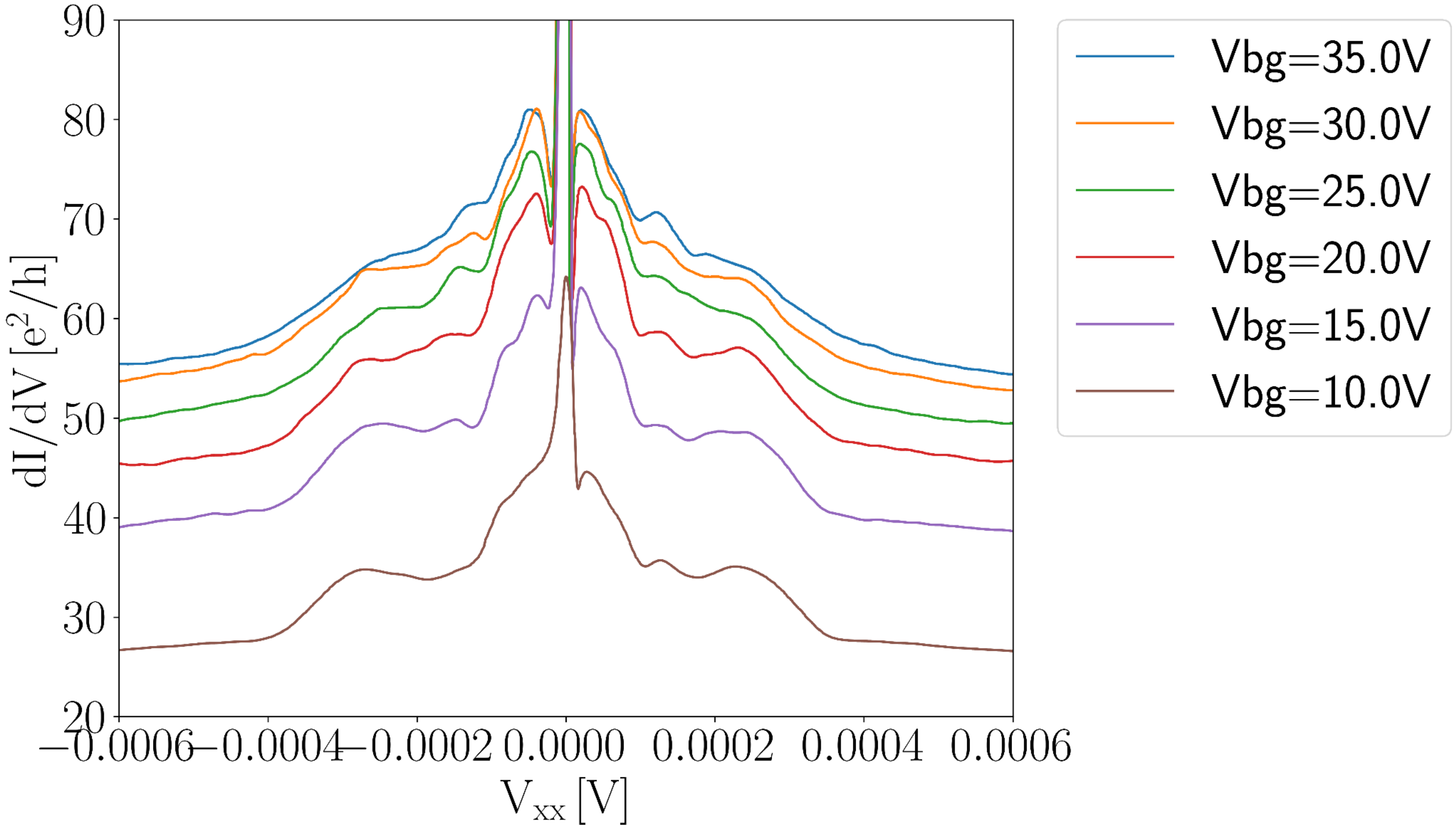
Why no sides lobes in the Fraunhofer pattern?

- Even-odd effect? (de Vries et al., Phys. Rev. Res. 1 (2019) 032031)
- Narrow junction? (Cuevas & Bergeret, Phys. Rev. Lett. 99 (2007) 217002)

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

Multiple Andreev Reflections

T = 250 mK



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

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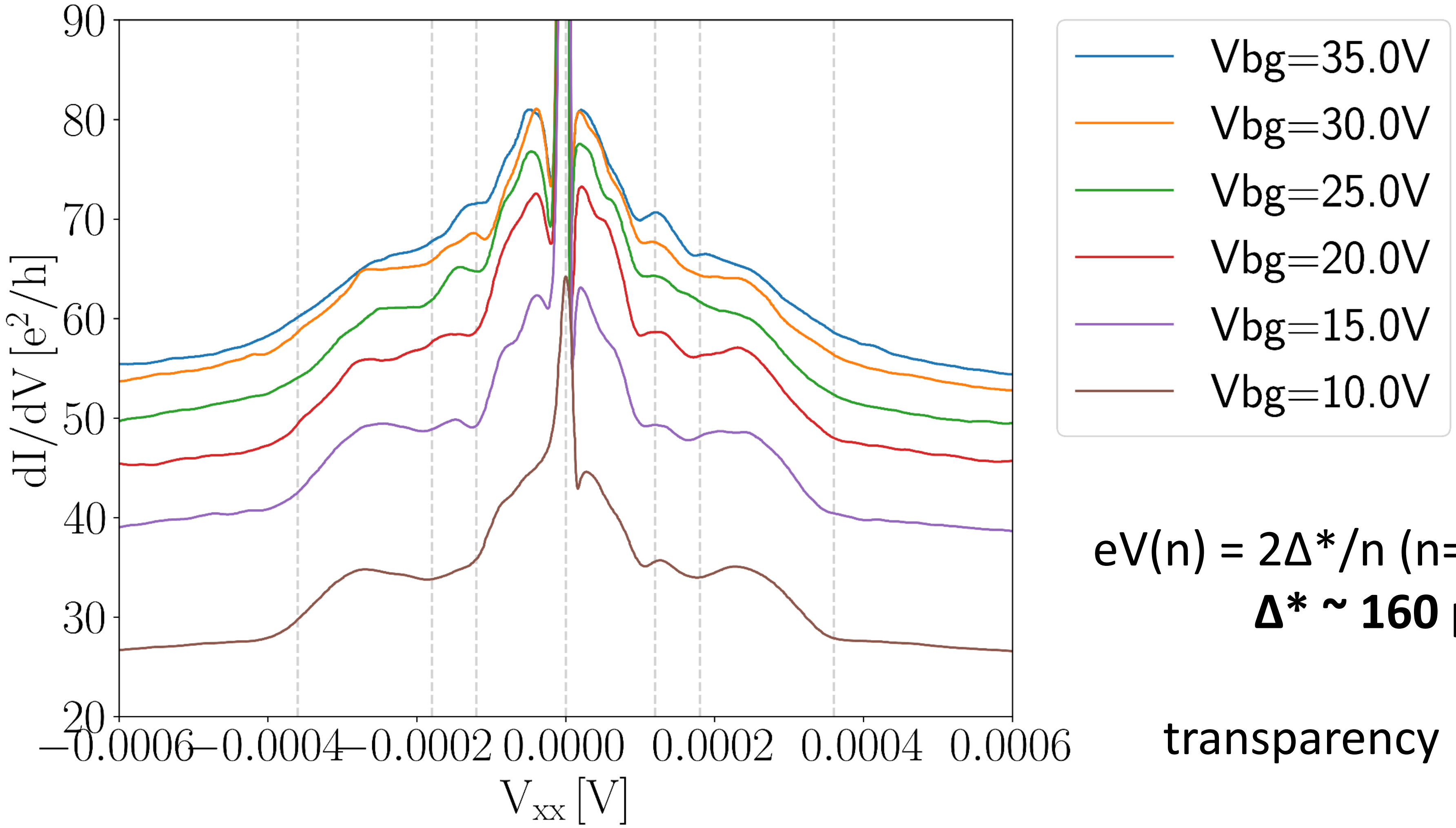
Multiple Andreev Reflections

T = 250 mK



Michal P. Nowak

$eV(n) = 2\Delta^*/n$ (n=1, 2, 3 . . .)

Δ^* ~ 160 μeV

transparency τ = 0.94

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

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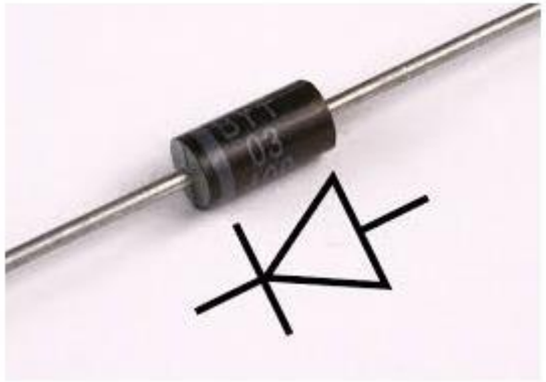
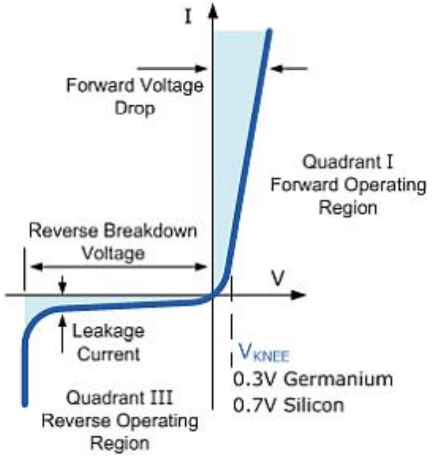
Non-reciprocal transport

Semiconductor diode with pn-junction





The p-n junction is at the basis of classical electronics.

Magneto-chiral anisotropy (MCA)

- Magnetochiral anisotropy caused by breaking of spatial-inversion and time-reversal symmetries
- $R = R_0[1 + \gamma \hat{\mathbf{e}}_\mathbf{z}(\mathbf{B} \times \mathbf{I})]$
- Elusive in CM systems
- $\gamma \sim \left(\frac{E_{SOI}}{E_F}\right) \sim 10^{-3}$ to 10^{-2} T^{-1} A^{-1}

Rikken et al., *Phys. Rev. Lett*. 87, 236602

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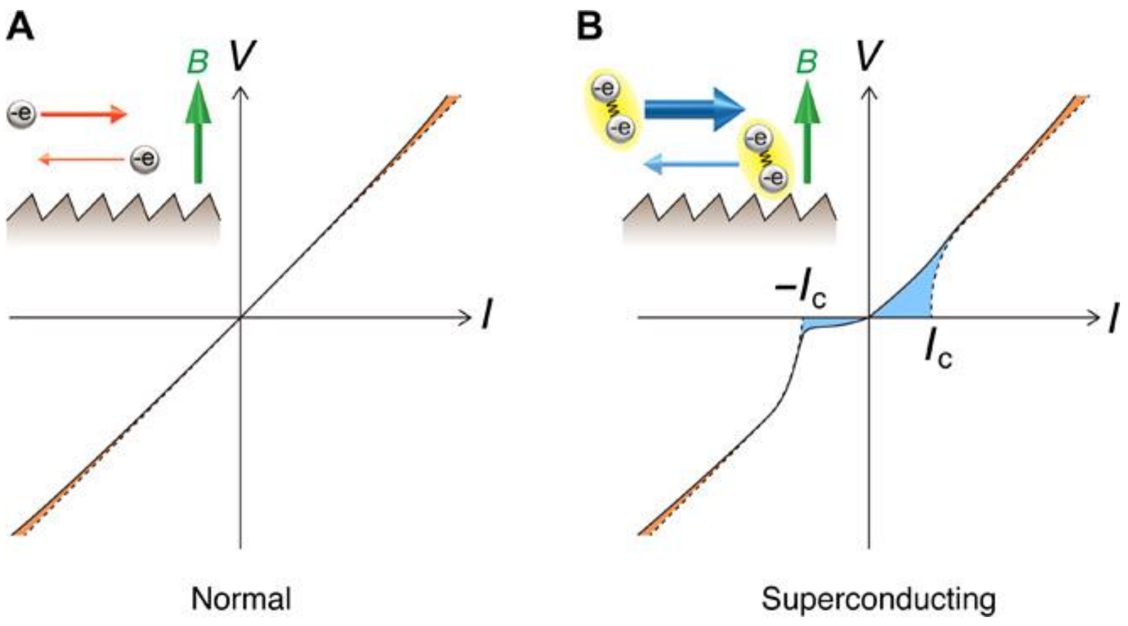
MCA in superconductors



- Superconducting order defines a new energy scale:

$$E_F \gg \Delta \sim \text{meV}$$

- MCA is strongly enhanced (10^5) in the resistive state
- What happens to the supercurrent?

SUPERCURRENT DIODE EFFECT

Wakatsuki, R. et al., *Sci. Adv.* 3, e1602390 (2017)

Superconducting Diode Effect

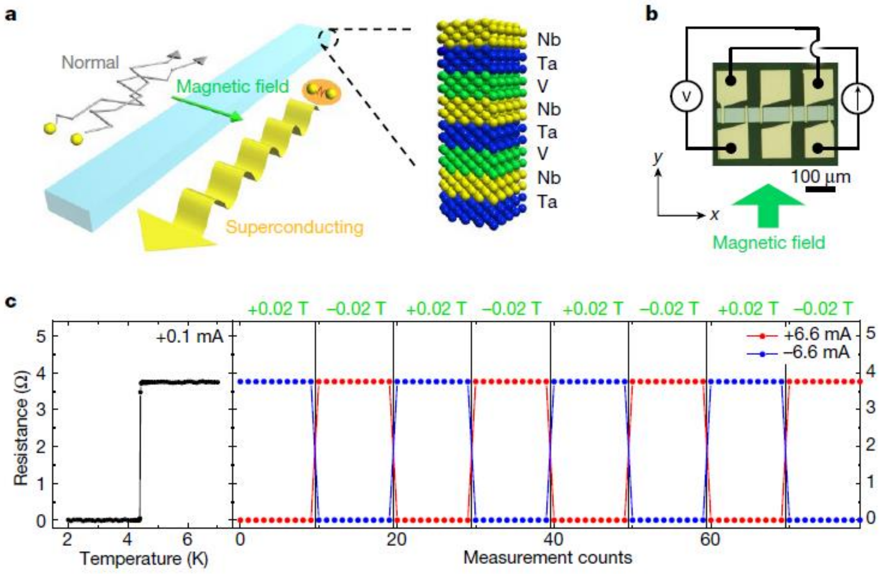
Article

Observation of superconducting diode effect

https://doi.org/10.1038/s41586-020-2590-4
Received: 14 March 2020
Accepted: 23 June 2020
Published online: 19 August 2020
Check for updates

Fuyuki Ando[1], Yuta Miyasaka[1], Tian Li[1], Jun Ishizuka[2], Tomonori Arakawa[3,4], Yoichi Shiota[1], Takahiro Moriyama[1], Youichi Yanase[2] & Teruo Ono[1,4] ✉

Nonlinear optical and electrical effects associated with a lack of spatial inversion symmetry allow direction-selective propagation and transport of quantum particles, such as photons[1] and electrons[2–9]. The most common example of such nonreciprocal

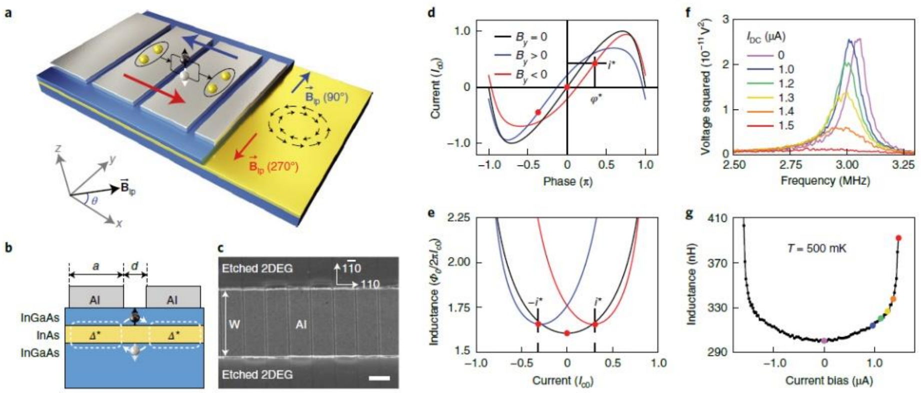


F. Ando et al., Nature 584 (2020) 373.

nature nanotechnology
ARTICLES
https://doi.org/10.1038/s41565-021-01009-9
Check for updates

Supercurrent rectification and magnetochiral effects in symmetric Josephson junctions

Christian Baumgartner[1,8], Lorenz Fuchs[1,8], Andreas Costa[2], Simon Reinhardt[1], Sergei Gronin[3,4], Geoffrey C. Gardner[3,4], Tyler Lindemann[4,5], Michael J. Manfra[3,4,5,6,7], Paulo E. Faria Junior[2], Denis Kochan[2], Jaroslav Fabian[2], Nicola Paradiso[1] ✉ and Christoph Strunk[1]



C. Baumgartner et al., Nat. Nano 17 (2022) 39.

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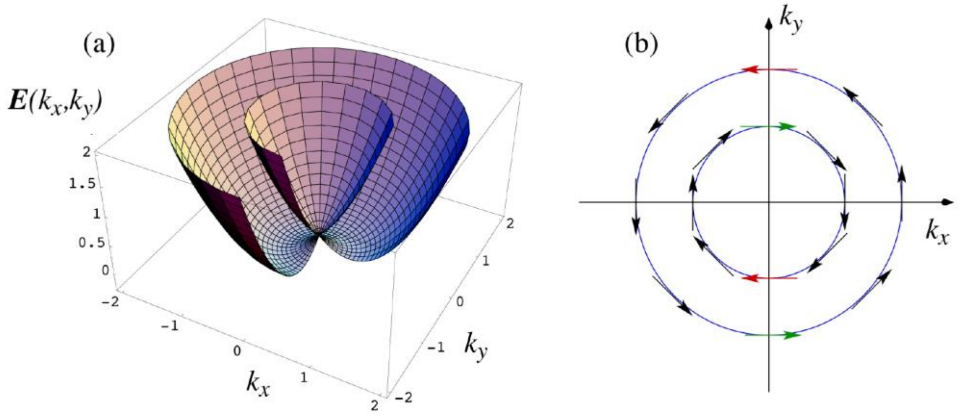
Ingredients for intrinsic SDE

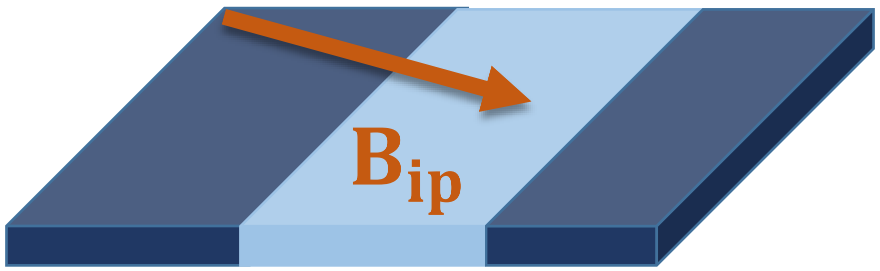
Requirements:

- Breaking of TR symmetry
- Breaking of I symmetry
- Robust superconducting order

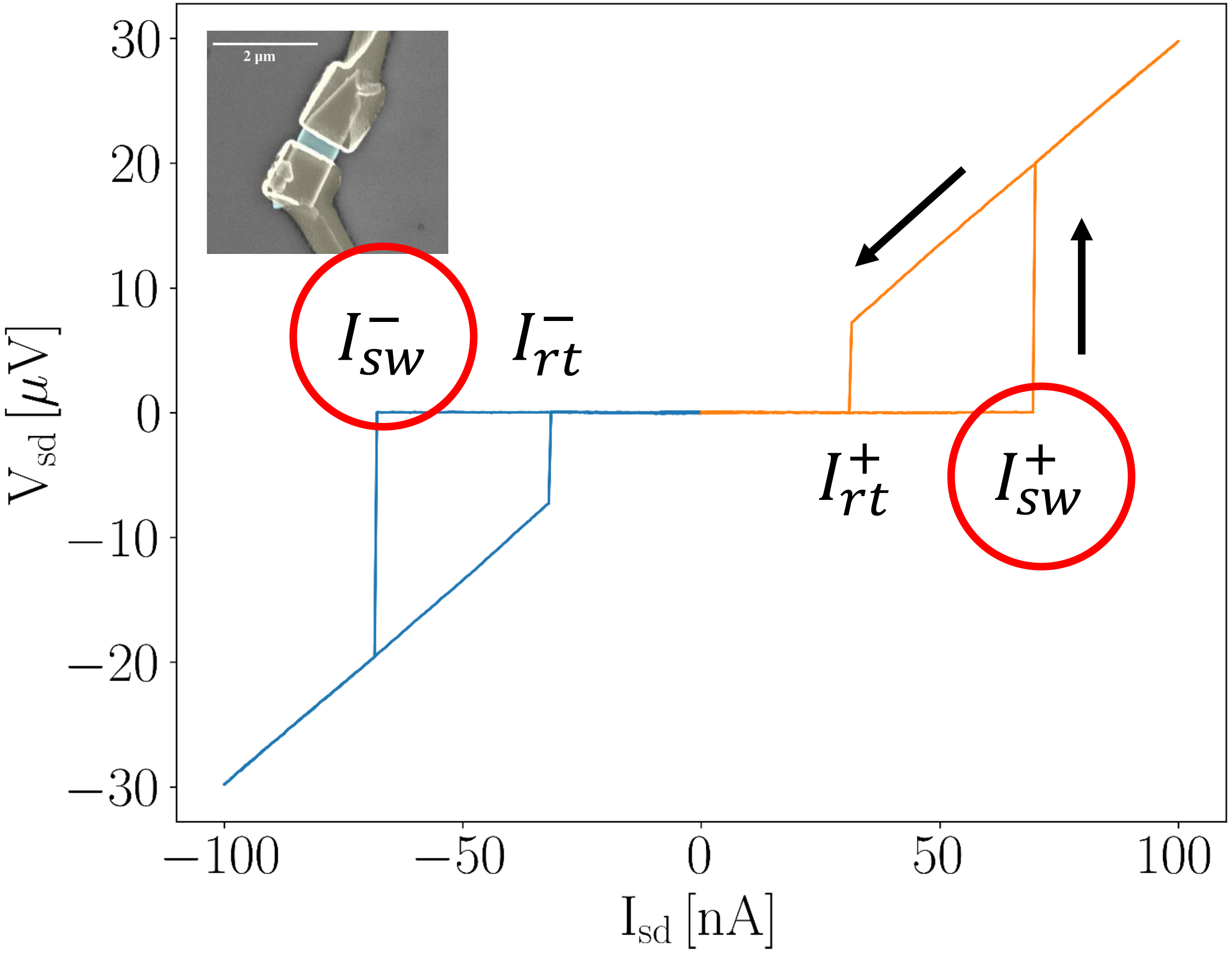
Ideal candidate:
strong SOI and large effective g-factor

SNS junction + SOI + Zeeman field





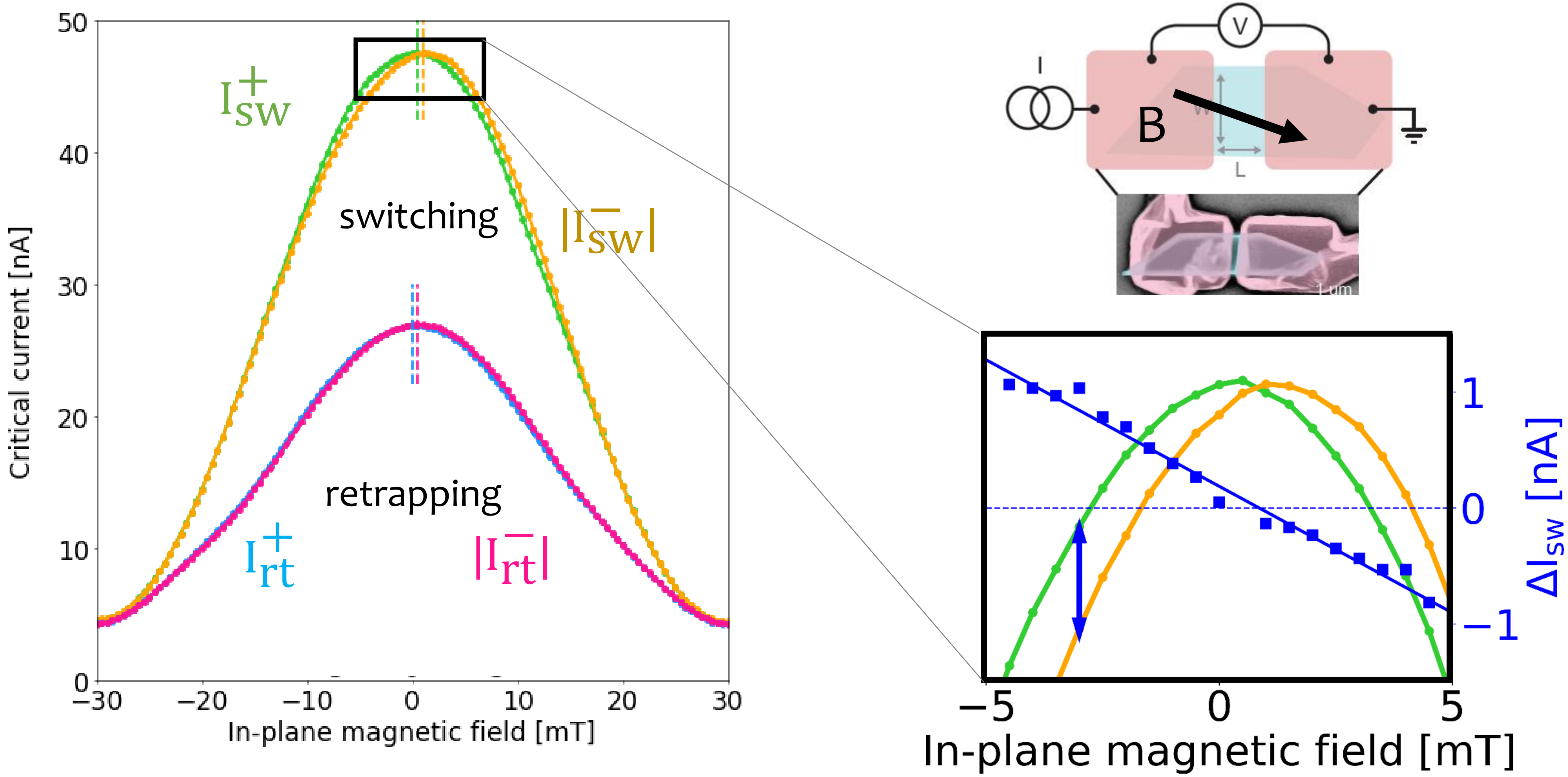
Supercurrent at 30 mK



Bianca Turini

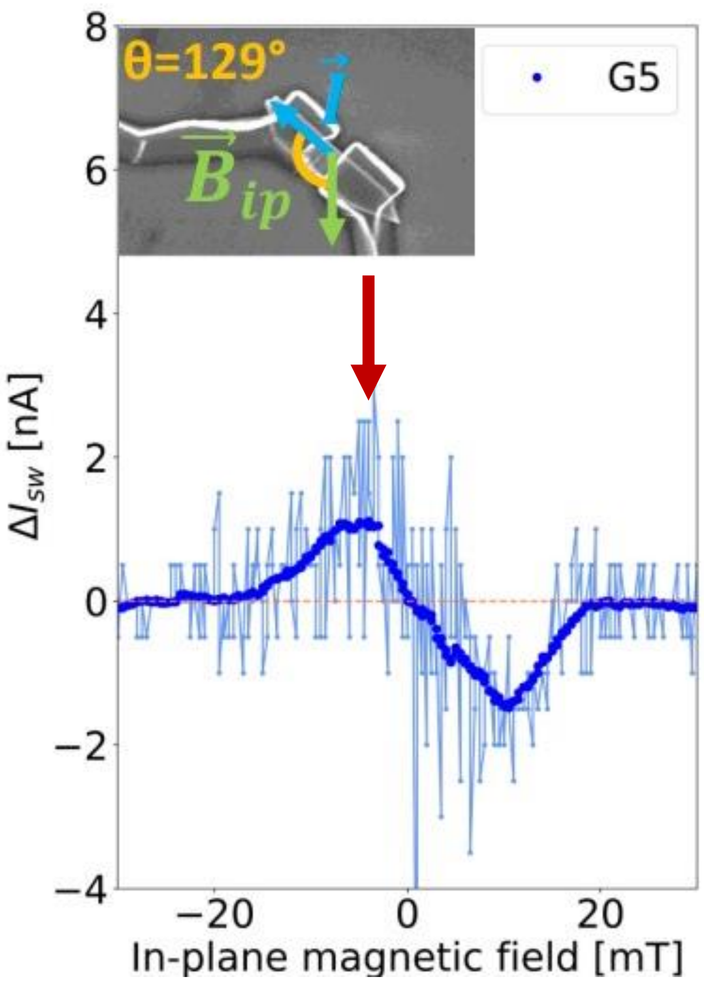
B. Turini et al., Nano Lett. 22, 8502 (2022).

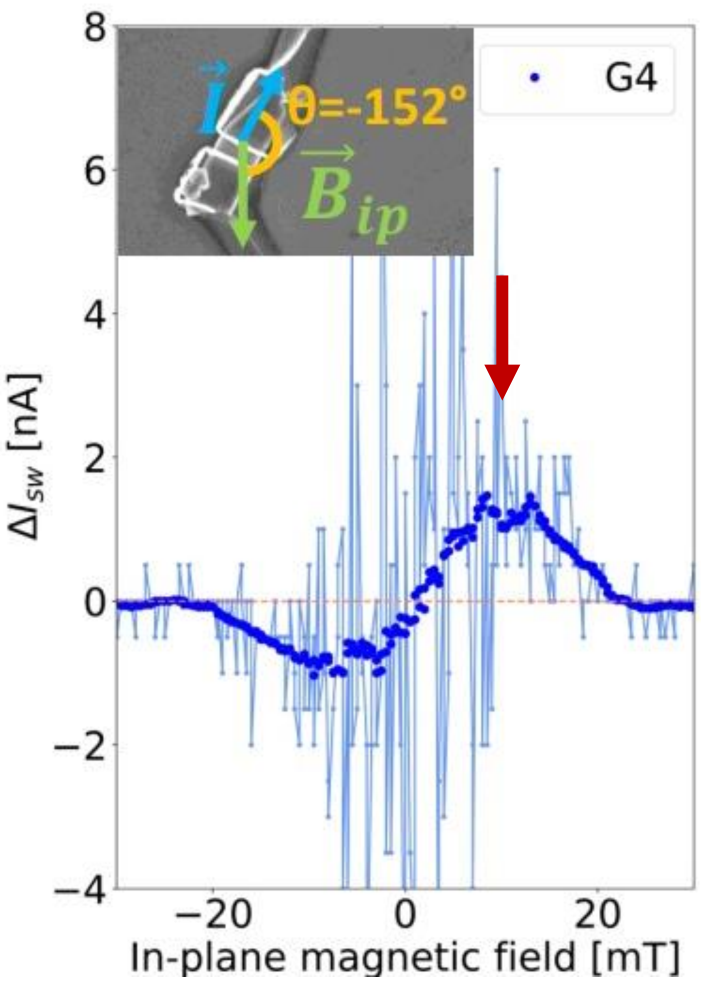
JDE is driven by the magnetic field



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

Switching current asymmetry





$$\Delta I_{sw} = I_{sw}^{+} - |I_{sw}^{-}|$$

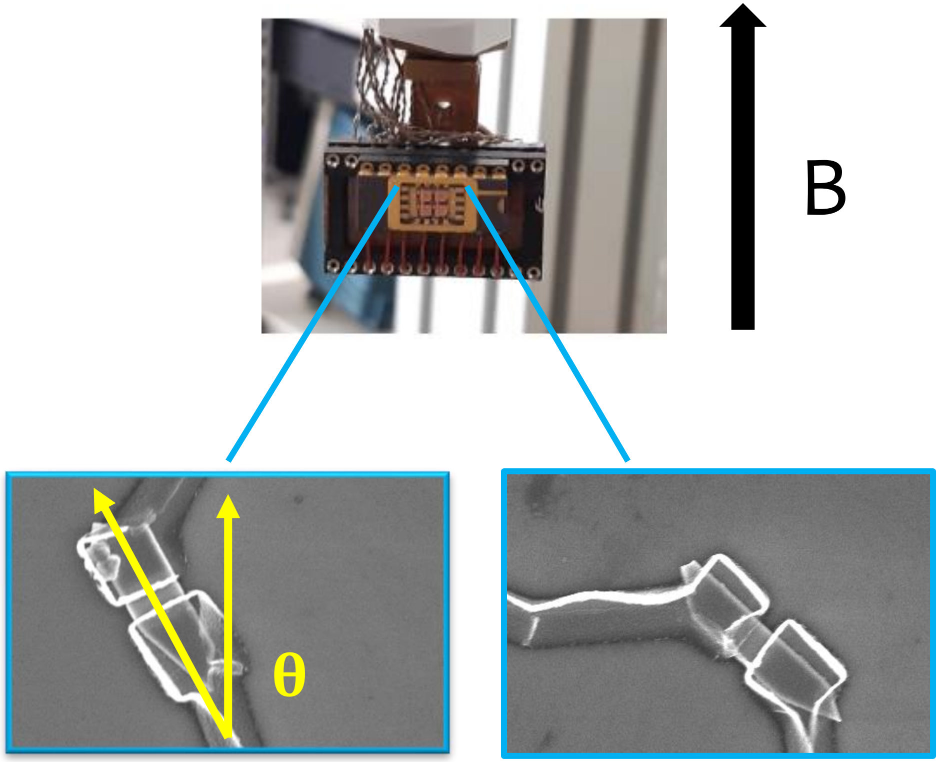
Main features:

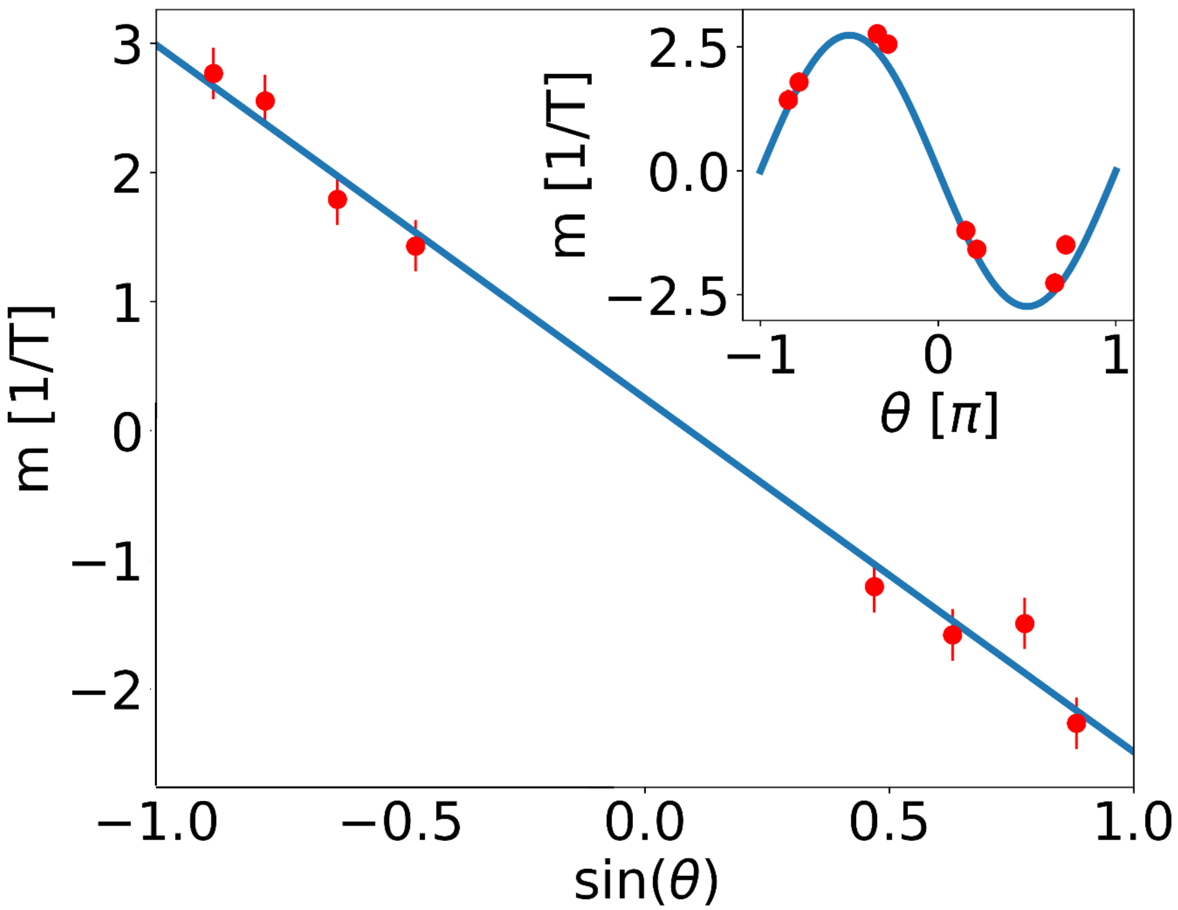
- antisymmetric behavior
- linear around $B = 0$
- rounded maximum
- suppression at $\mathrm{B} \gtrsim 20$ mT
- θ-dependent polarity

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

JDE depends on the in-plane angle due to Rashba coupling

Rasmussen *et al.*, PRB (2016)

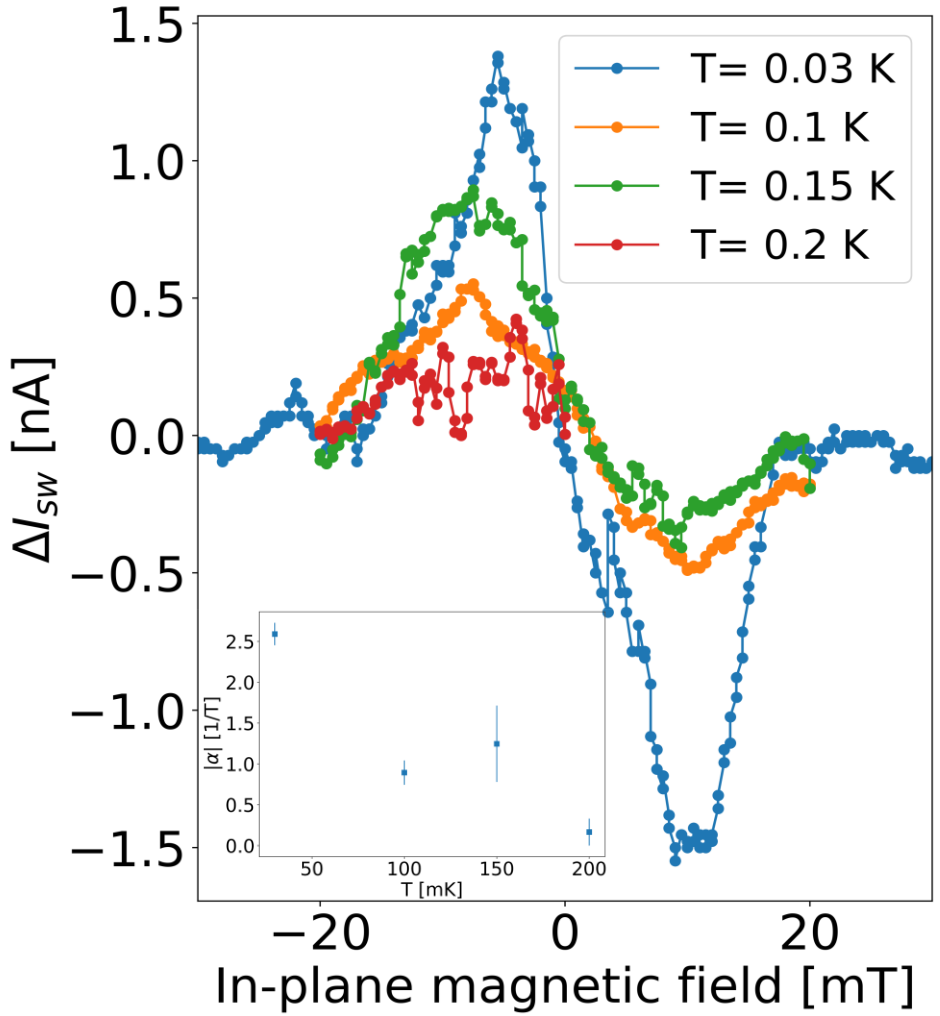


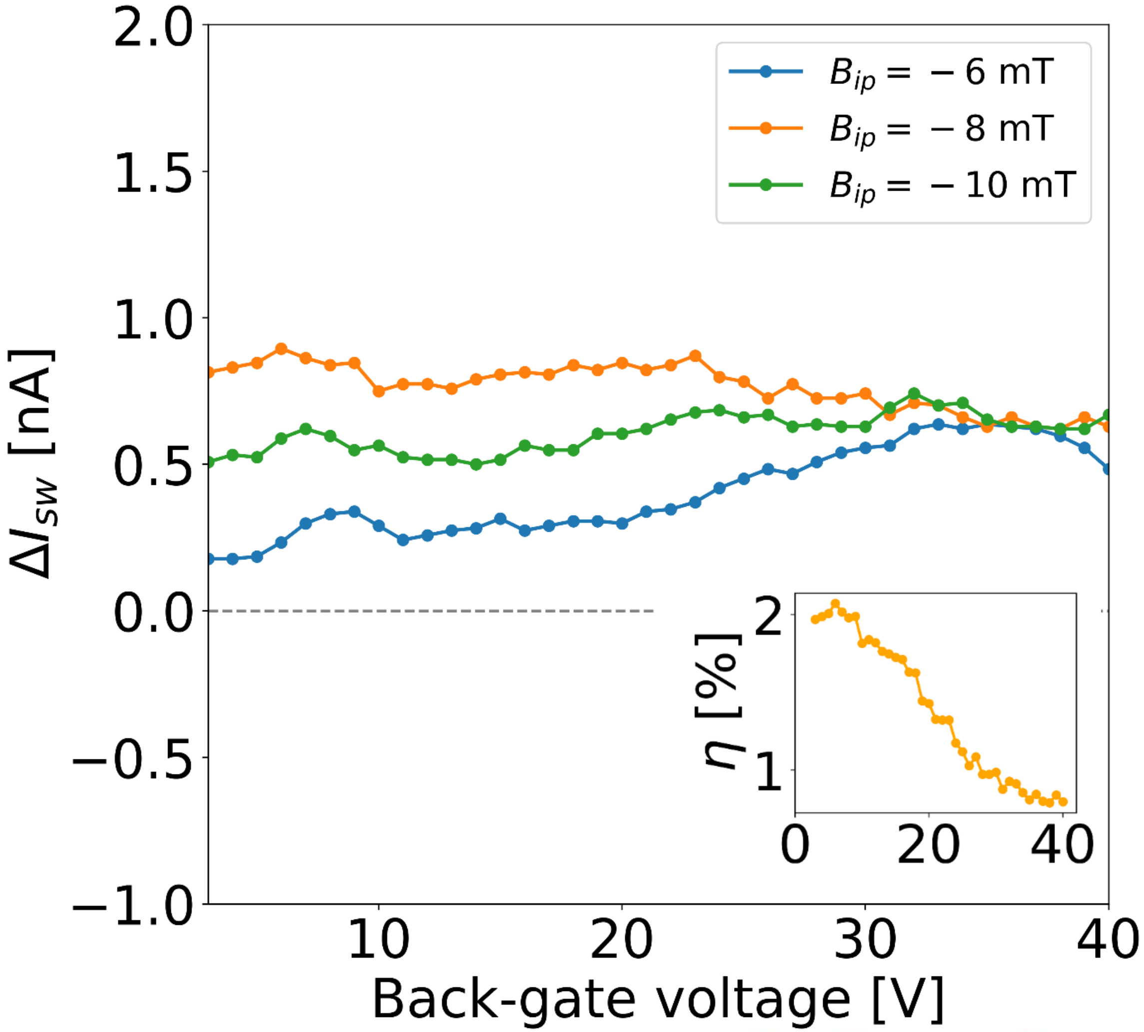


B. Turini et al., Nano Lett. 22, 8502 (2022).

JDE depends on temperature and back-gate voltage

$\eta = \Delta I_{sw}/(I_c^+ + I_c^-)$





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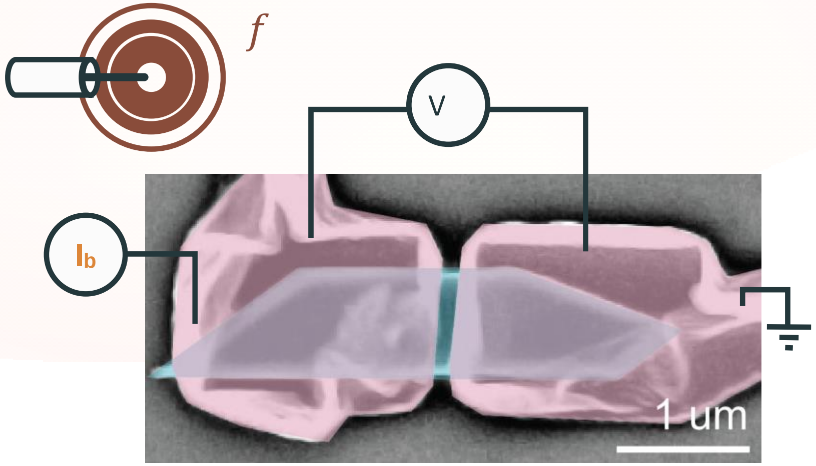
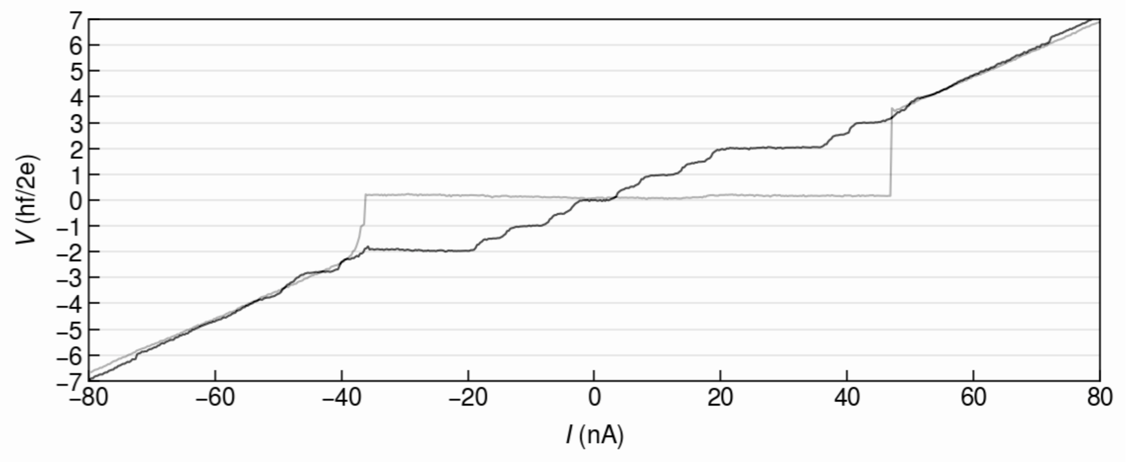
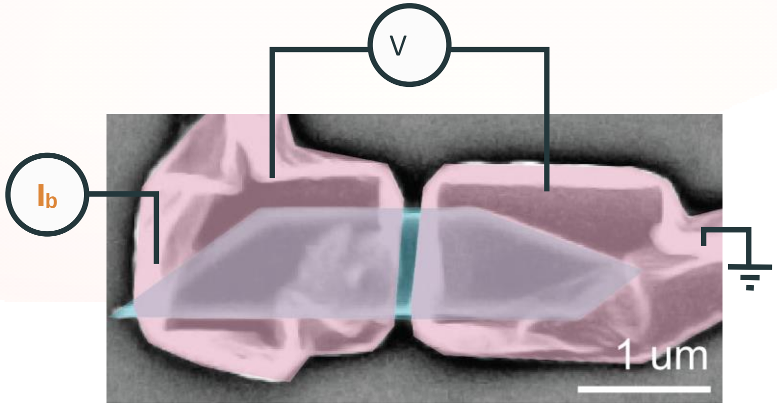
Half-integer Shapiro steps



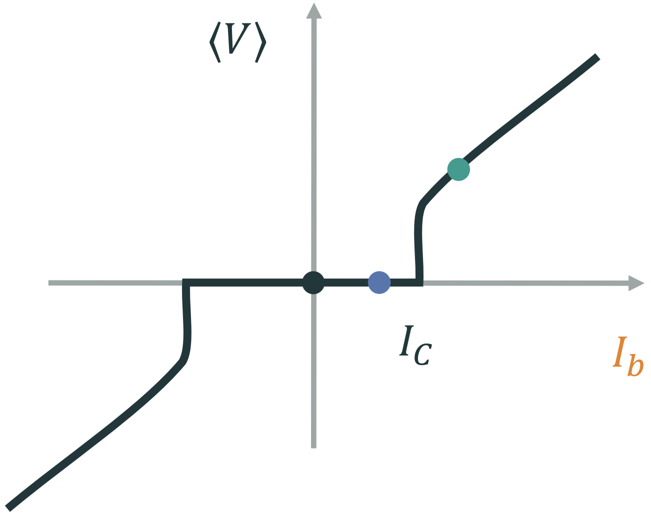


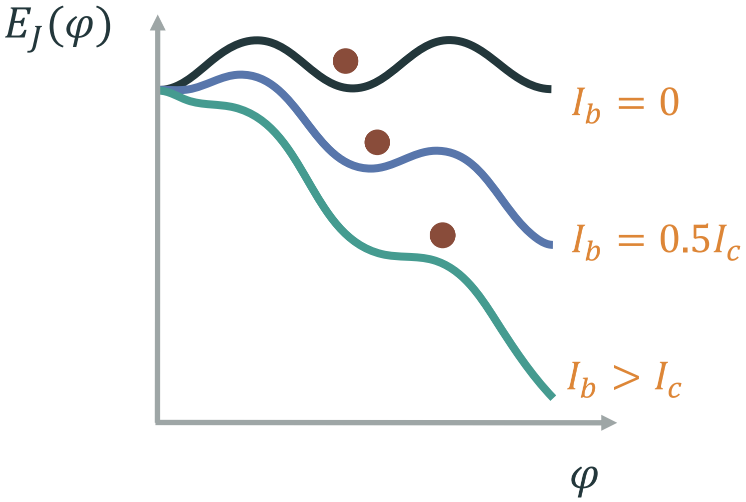
A. Iorio et al., Phys. Rev. Research 5, 033015 (2023).

Half-integer Shapiro steps



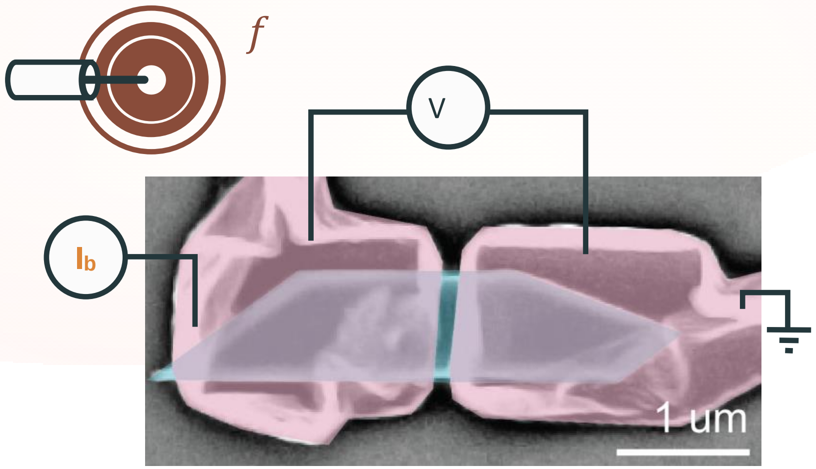
$$V = \frac{\hbar}{2e}\dot{\varphi}$$





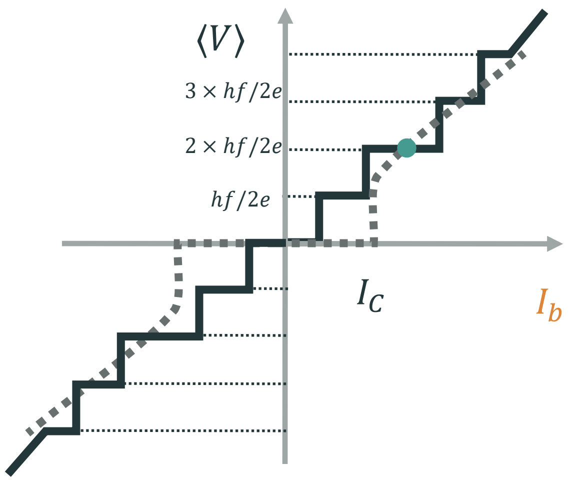
A. Iorio et al., Phys. Rev. Research 5, 033015 (2023).

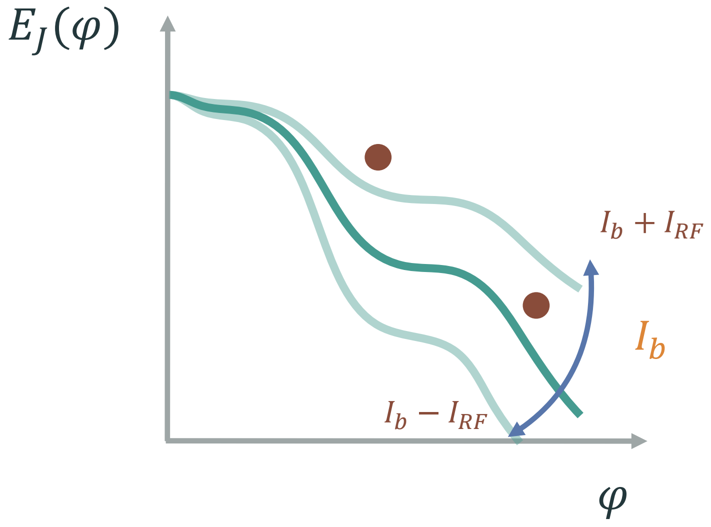
Half-integer Shapiro steps



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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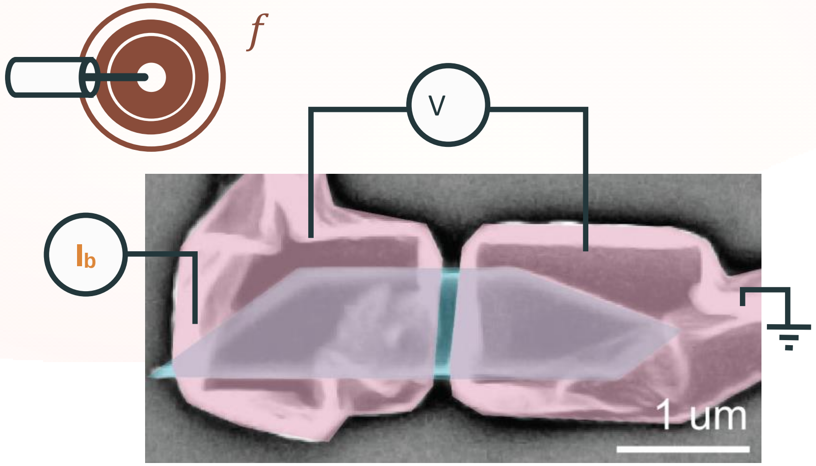
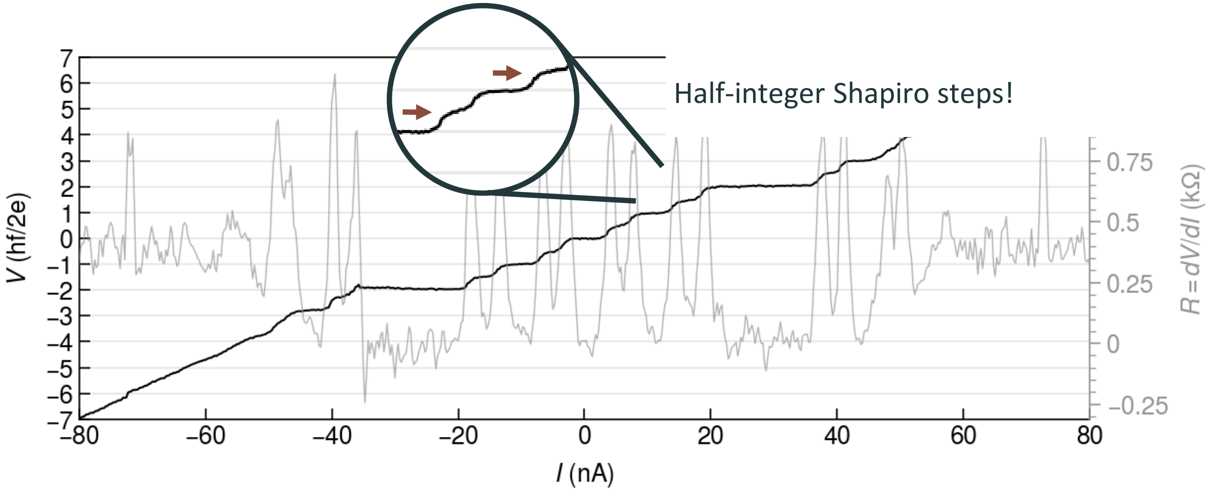
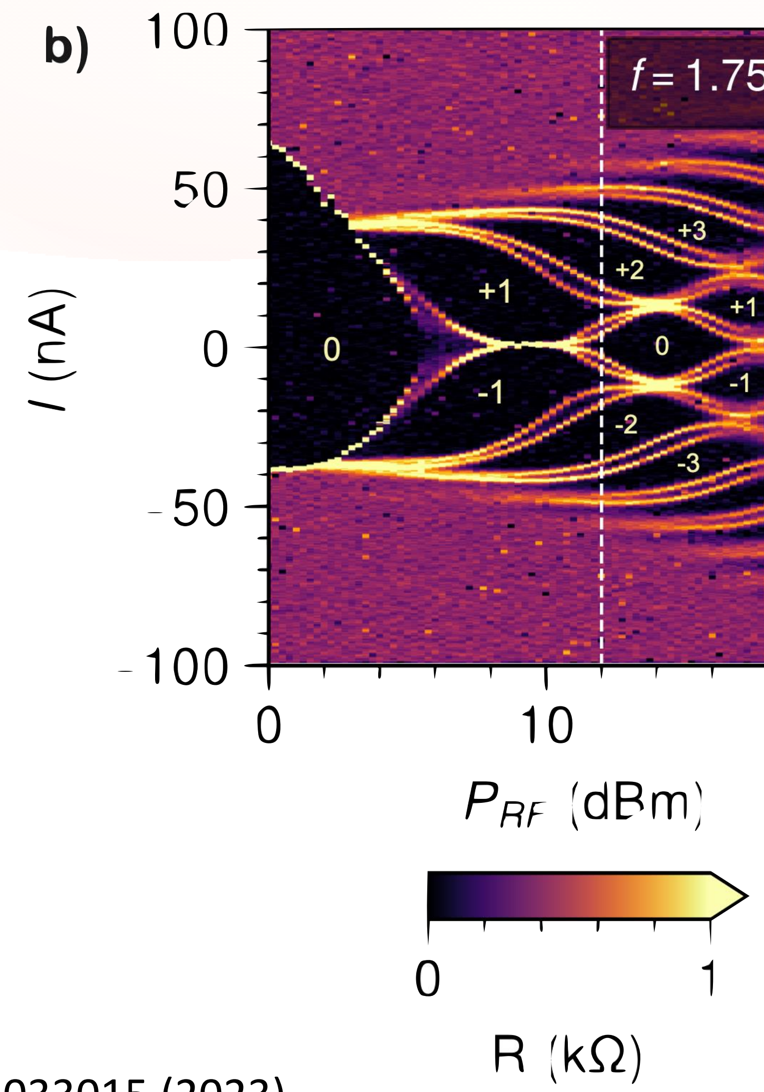




Shapiro steps – Quantized voltage plateaus $V = \frac{hf}{2e}n$

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

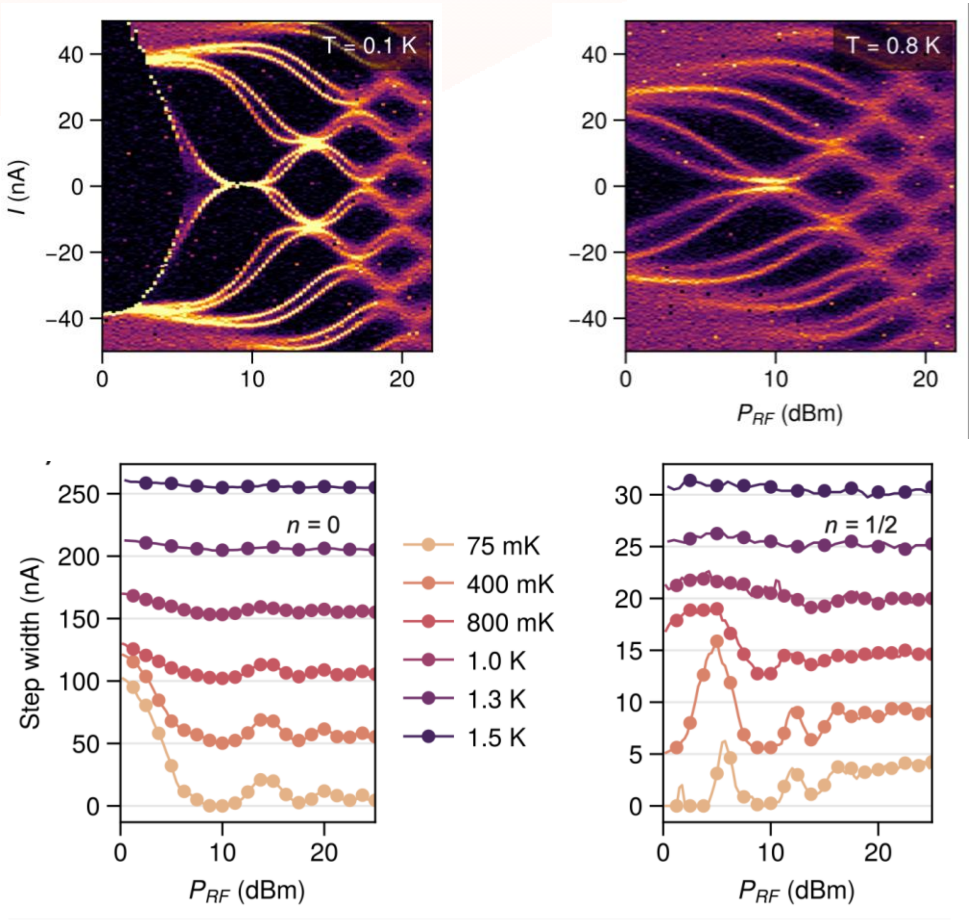
Half-integer Shapiro steps



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

Half-integer Shapiro steps

A non-monotonic temperature dependance



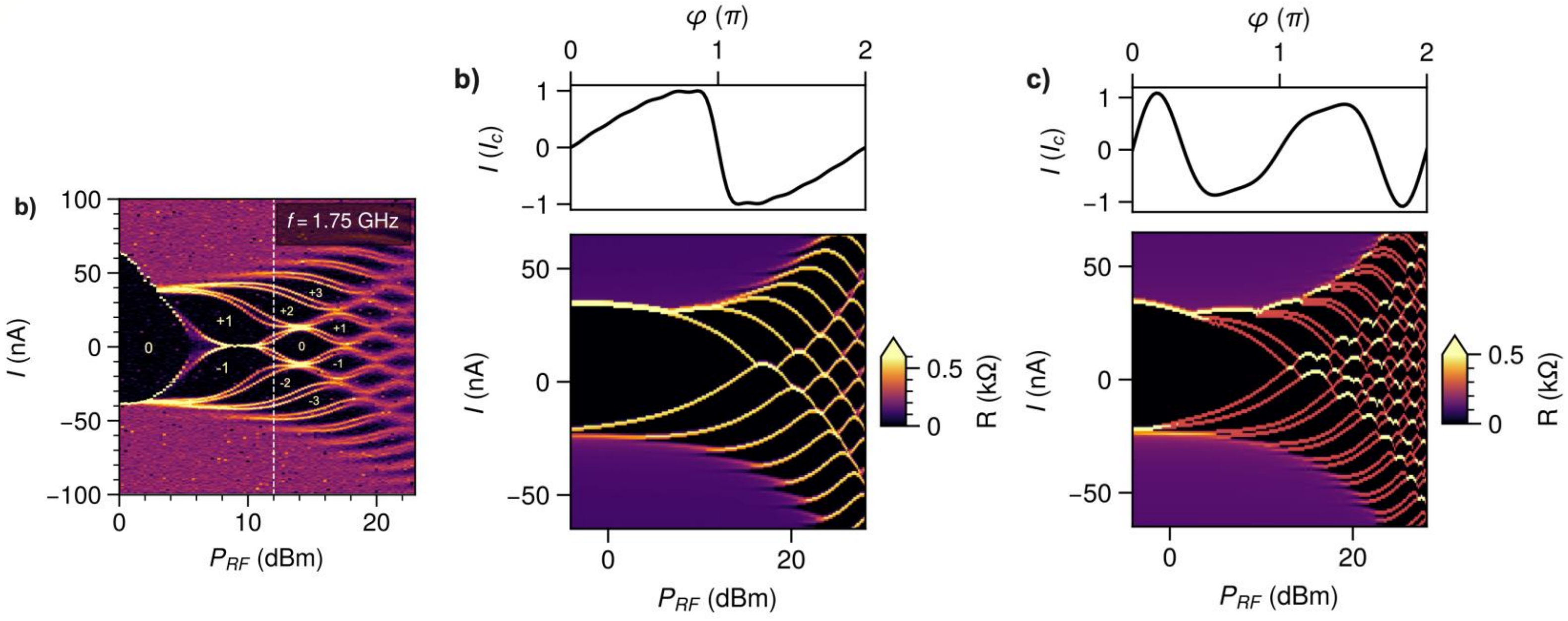
A. Iorio et al., Phys. Rev. Research 5, 033015 (2023).

Half-integer Shapiro steps

How to have half-integer steps?

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

RCSJ simulations

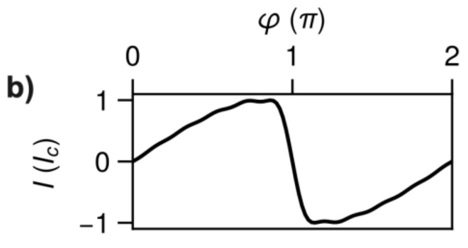


A. Iorio et al., Phys. Rev. Research 5, 033015 (2023).

Half-integer Shapiro steps

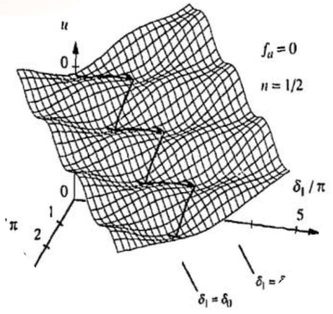
Potential mechanisms for $\sin(2\varphi)$

Higher harmonic in the equilibrium CPR



- ✓ Common given explanation
- ✗ Weaker half-steps
- ✗ Half-steps decrease with T

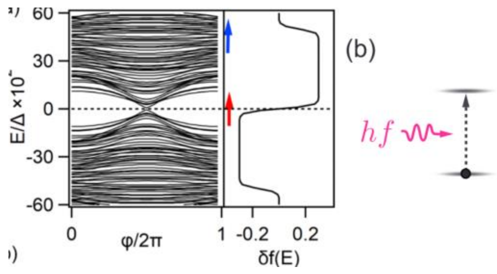
SQUID-like



- ✓ 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)

Non-equilibrium excitations



- ✓ $\sin(2\varphi)$ only when driving
- ✓ Half-steps non-monotonic in T
- ! Still some gaps with the theory

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).

Half-integer Shapiro steps

Almost four contemporary papers

March 10, 2023

Half-integer Shapiro steps in highly transmissive InSb nanoflag Josephson junctions

A. Iorio,[1,*] A. Crippa,[1] B. Turini,[1,†] S. Salimian,[1] M. Carrega,[2] L. Chirolli,[1] V. Zannier,[1] L. Sorba,[1]
E. Strambini,[1] F. Giazotto,[1] and S. Heun[1,‡]

April 23, 2023

Large Second-Order Josephson Effect in Planar Superconductor-Semiconductor Junctions

P. Zhang,[1] A. Zarassi,[1] L. Jarjat,[2] V. Van de Sande,[3] M. Pendharkar,[4] J.S. Lee,[5] C.P. Dempsey,[4] A.P. McFadden,[4]
S.D. Harrington,[6] J.T. Dong,[6] H. Wu,[1] A.-H. Chen,[7] M. Hocevar,[7] C.J. Palmstrøm,[4,5,6] and S.M. Frolov[1,*]

June 8, 2023

Charge-4e supercurrent in an InAs-Al superconductor-semiconductor heterostructure

Carlo Ciaccia,[1,*] Roy Haller,[1] Asbjørn C. C. Drachmann,[2,3] Tyler Lindemann,[4,5]
Michael J. Manfra,[4,5,6,7] Constantin Schrade,[2] and Christian Schönenberger[1,8]

June 12, 2023

Radio frequency driven superconducting diode and parity conserving Cooper pair transport in a two-dimensional germanium hole gas

Marco Valentini[1,*], Oliver Sagi[1], Levon Baghumyan[1], Thijs de Gijsel[1,2], Jason Jung[2], Stefano Calcaterra[3],
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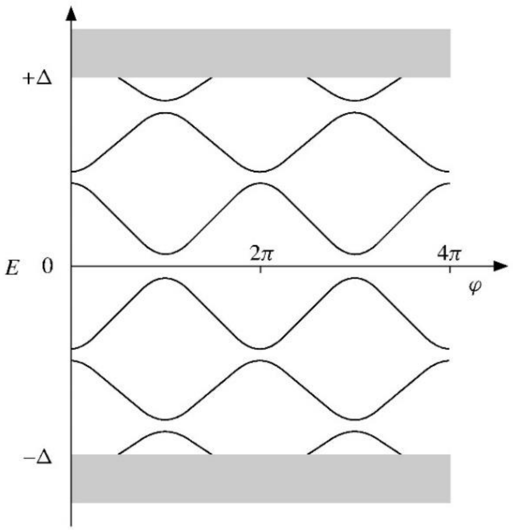
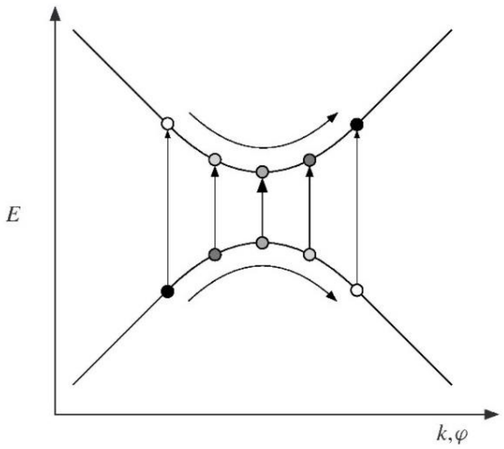
23

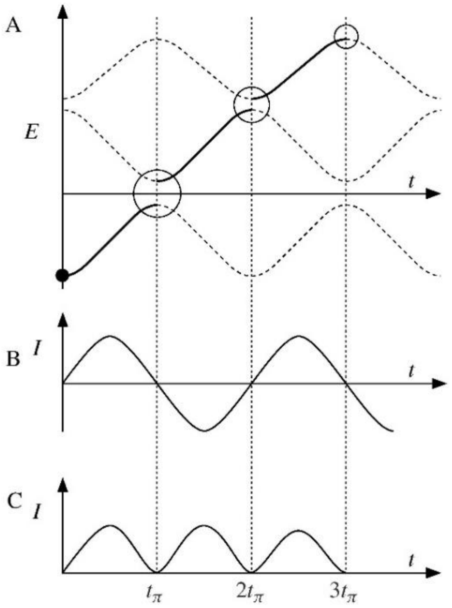
A. Iorio et al., Phys. Rev. Research 5, 033015 (2023).

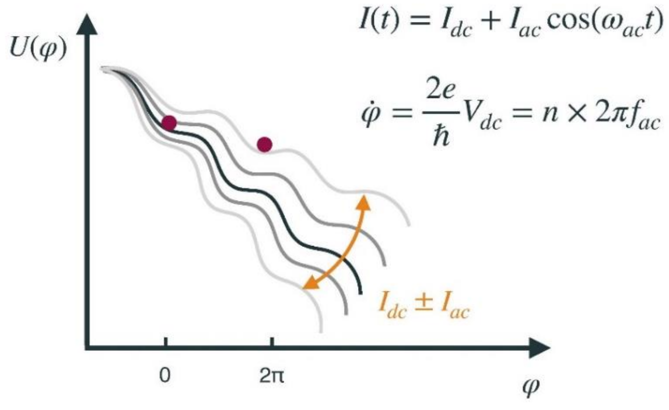
Half-integer Shapiro steps (non-equilibrium)

- Non-equilibrium occupation probability of Andreev Bound States
  - Strong 2φ-periodic oscillations at twice the Josephson frequency
  - Giving rise to half-integer Shapiro-steps









Schematic Andreev Bands

Josephson frequency $\omega_J = \frac{d\varphi}{dt} = \frac{2eV}{\hbar}$

$$I = \frac{2e}{\hbar} \cdot \frac{dE}{d\varphi}$$

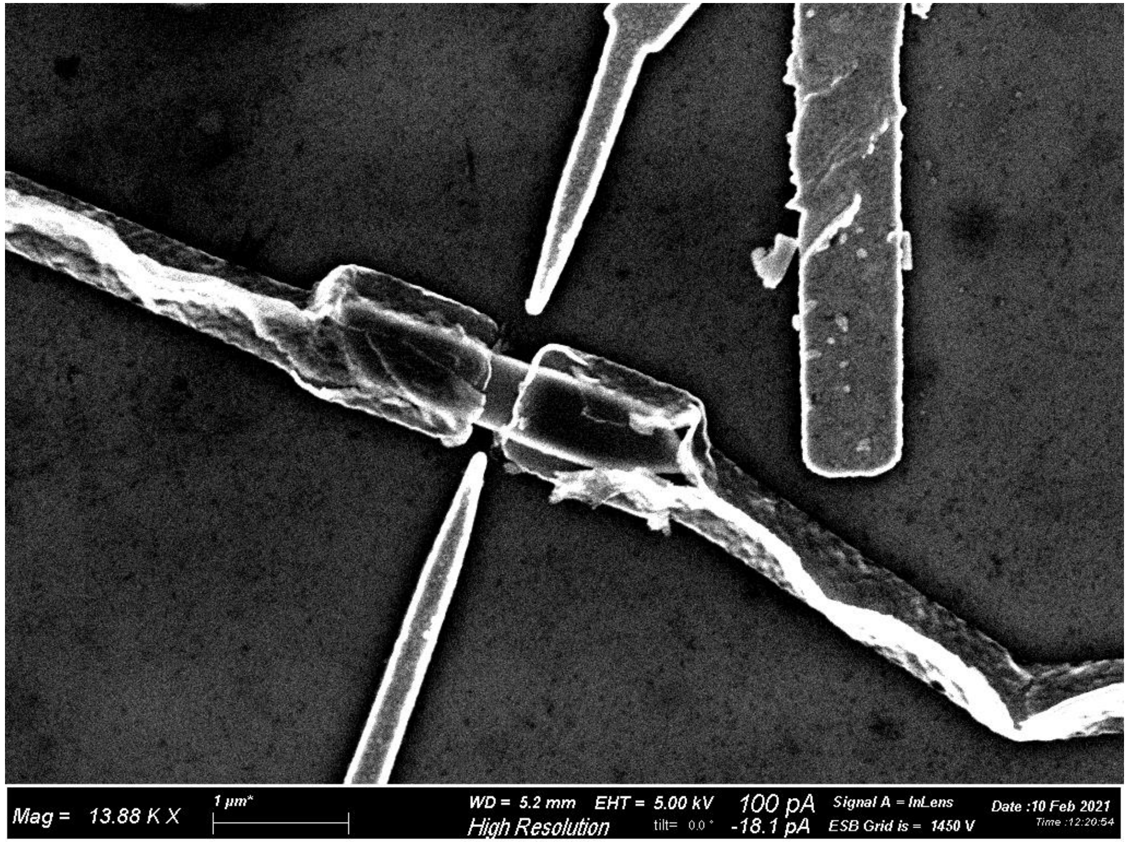
H. Kroemer, Superlattices and Microstructures 25 (1999) 877.

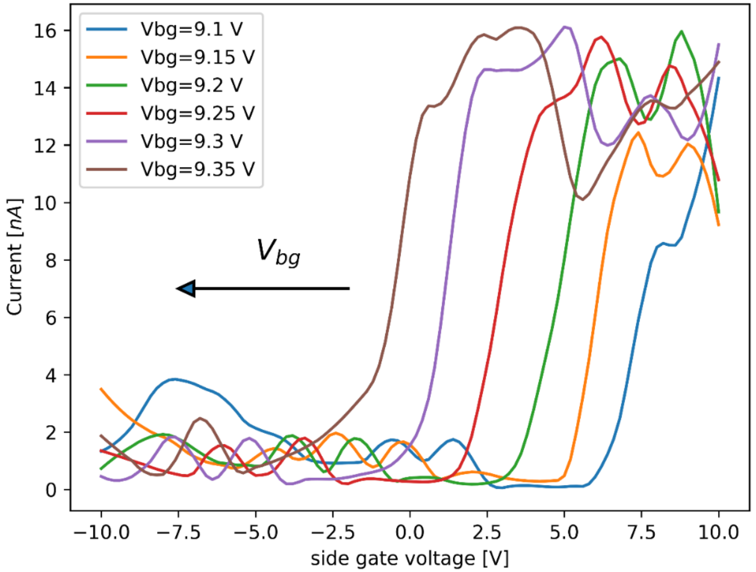
Outlook: gate-controlled SOI

Idea: tune the effective geometry and the SO coupling with side gates

Bianca Turini

Federico Paolucci





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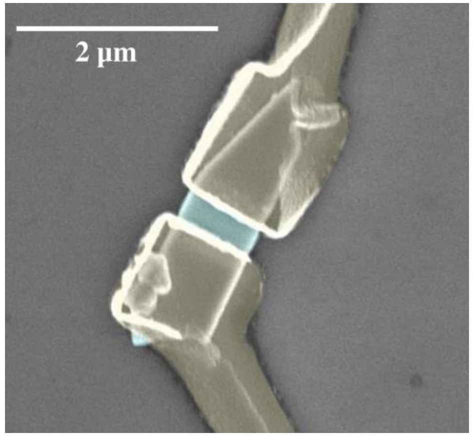
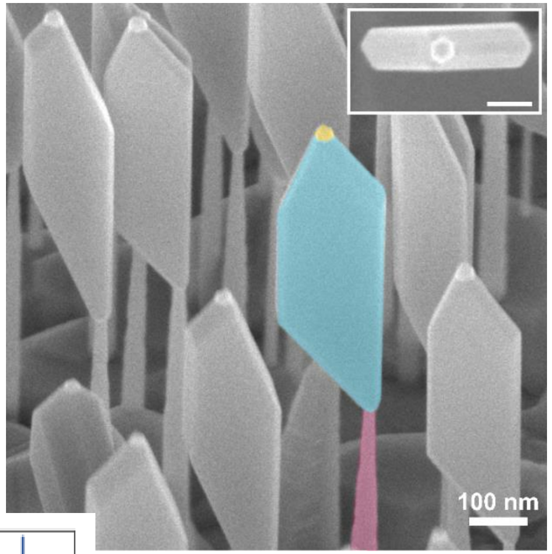
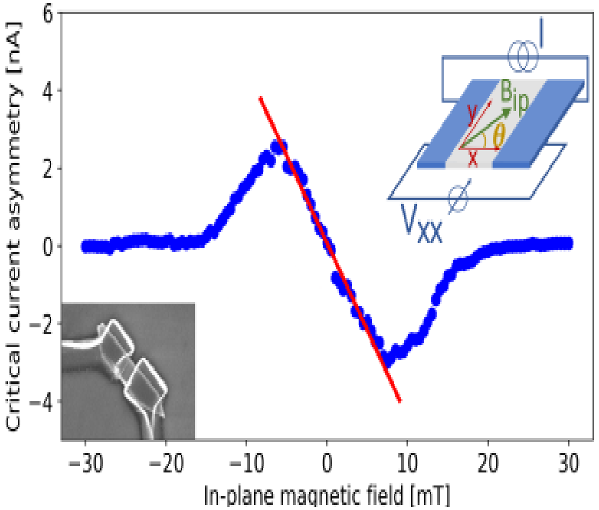
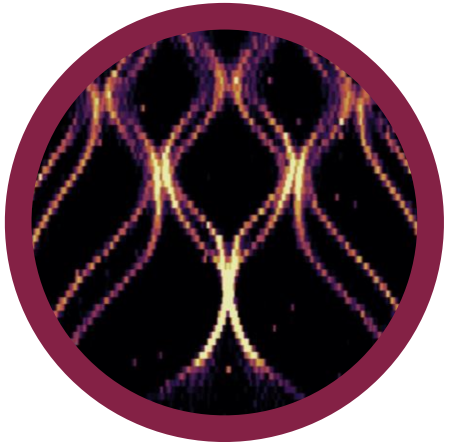
Summary

- Free-standing 2D InSb nanoflags via CBE:
  - Defect-free zinc blende crystal structures
  - High-mobility devices
- 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)









People Involved

CNRNANO PISA NEST

Growth activity

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Valentina Zannier

Lucia Sorba

Devices

Sedighe Salimian

Theory

Matteo Carrega
Luca Chirolli

Transport

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Alessandro Crippa

Elia Strambini

Francesco Giazotto

Acknowledgments:

AndQC

MUR PRIN

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Postdoc Position Available

- We are looking for a postdoc for the ongoing work on these InSb nanoflags.
- Mainly device fabrication and low-temperature magneto-transport.
- Please contact me: Stefan Heun (stefan.heun@nano.cnr.it)

Thank you for your attention!

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