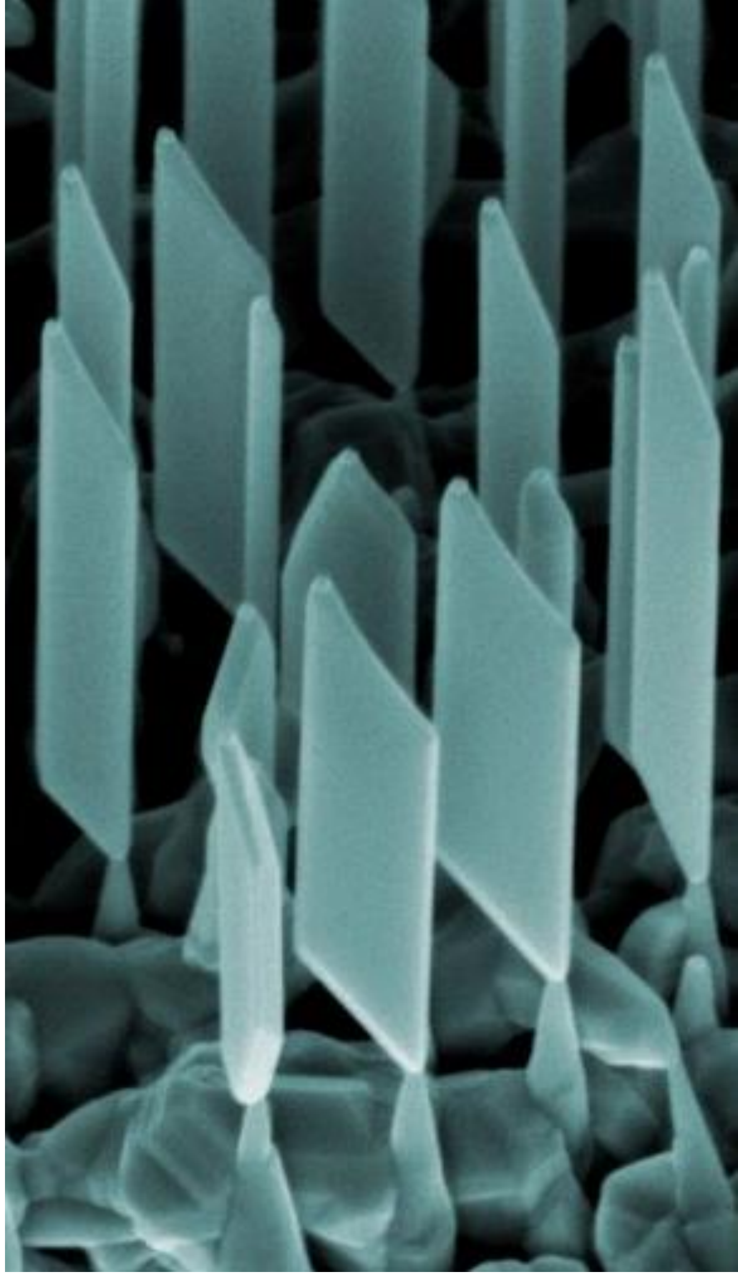
Hybrid superconductor-semiconductor Josephson junctions for quantum technologies

Stefan Heun

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



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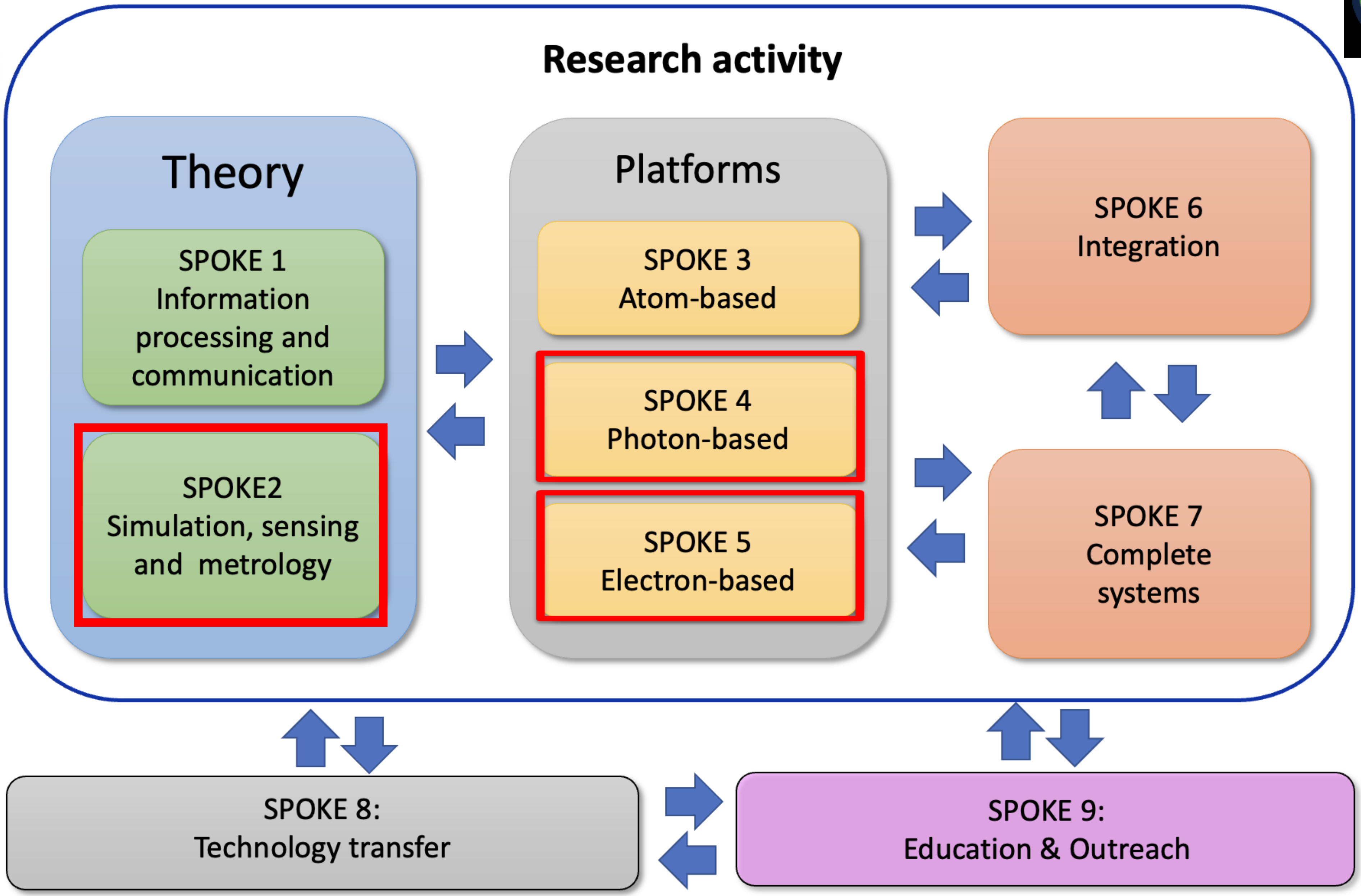
NQSTI
National Quantum Science and Technology Institute



Activities Spoke 5

A5.1	Tunable emerging electronic configurations in hybrid/topological systems
A5.2	Novel nanomaterials for hybrid architectures
A5.3	Phase-sensitive architectures (SQUIPTs)
A5.4	Quantum energy management
A5.5	Tailored defects and molecules for QT
A5.6	Quantum interfacing, control and readout
A5.7	Innovative characterization techniques to probe quantum nature and performance (Ultra-fast and quantum-enhanced TEM of collective exitation)

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SCUOLA NORMALE SUPERIORE

InSb Nanoflag-based JJs

Growth activity

Isha Verma

Daniele Ercolani

Valentina Zannier

Lucia Sorba

Devices

Sedighe Salimian

Theory

Matteo Carrega (CNR-SPIN)

Luca Chirolli

Transport

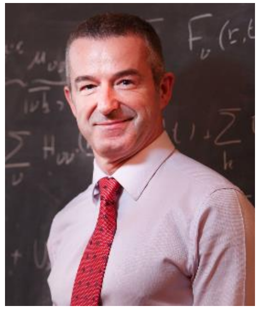
Bianca Turini

Andrea Iorio

Alessandro Crippa

Elia Strambini

Francesco Giazotto



Fabio Beltram

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Why InSb?

Small bandgap E_g=0.23 eV

Low effective mass m/m_0 = 0.018

Strong SOC E_{SOC} ~ 200 μeV

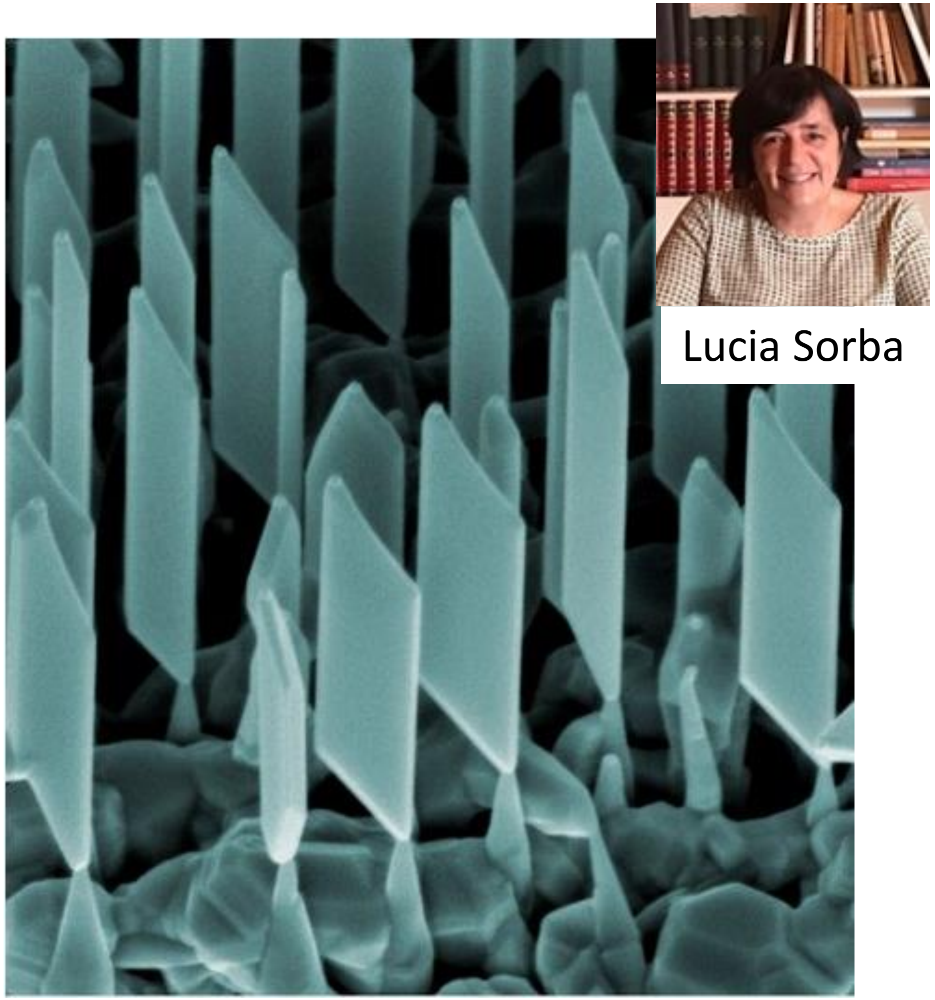
Why InSb?

Small bandgap E_g=0.23 eV

Low effective mass $m/m_0 = 0.018$

Strong SOC $E_{SOC} \sim 200\ \mu eV$

High-mobility 2D nanostructures



Lucia Sorba

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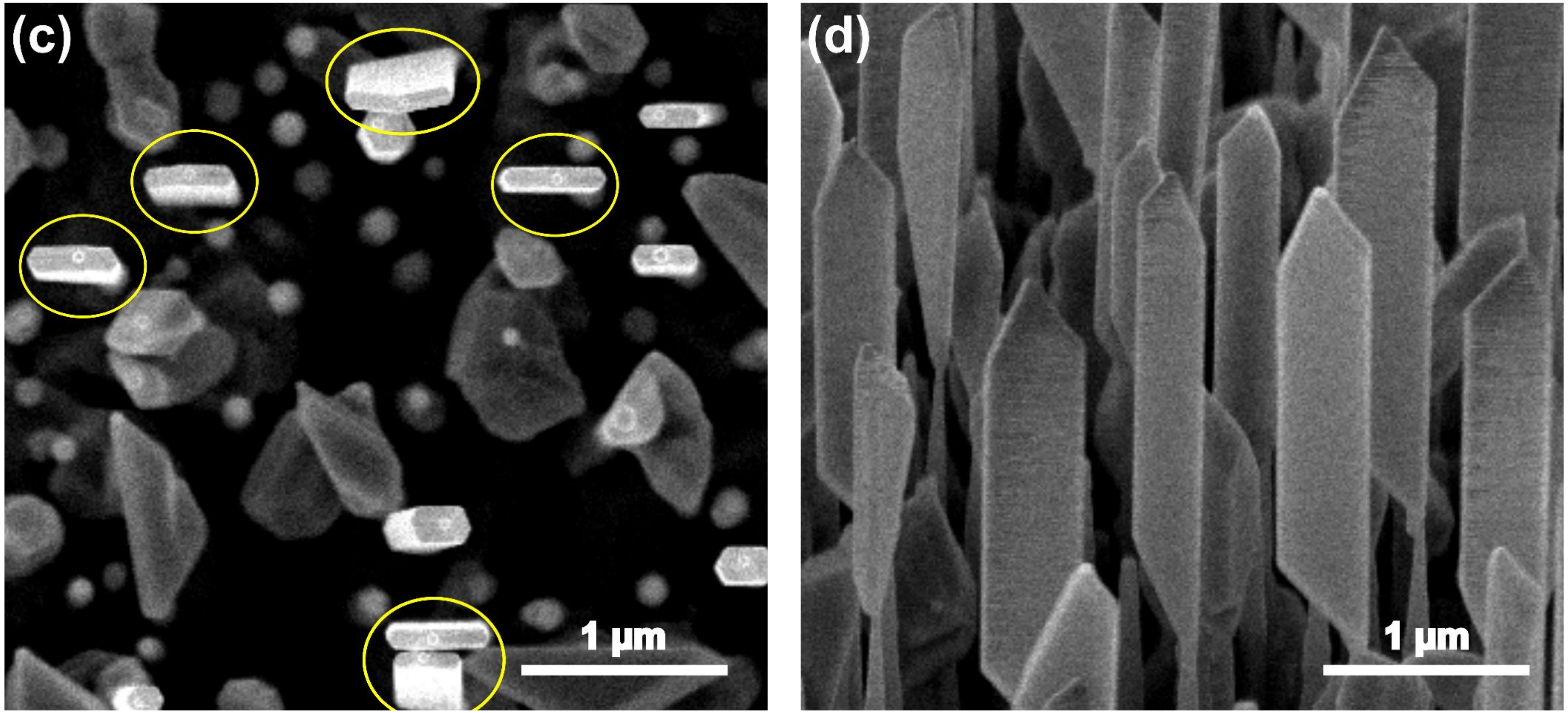
Growth of InSb nanoflags by CBE



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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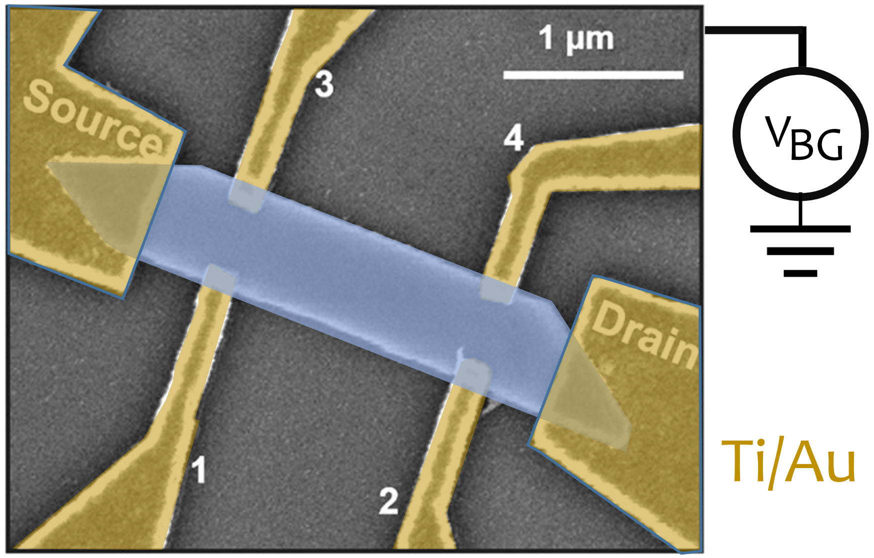
NFs show high mobility and giant g*-factor

@ T = 4.2 K

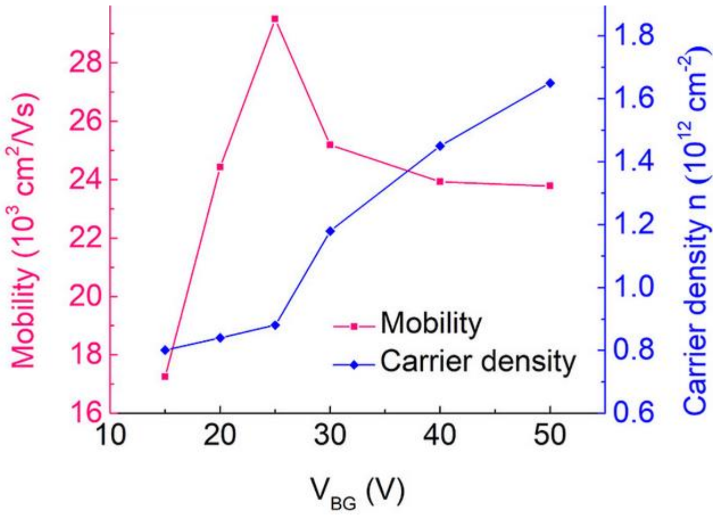
Ti/Au



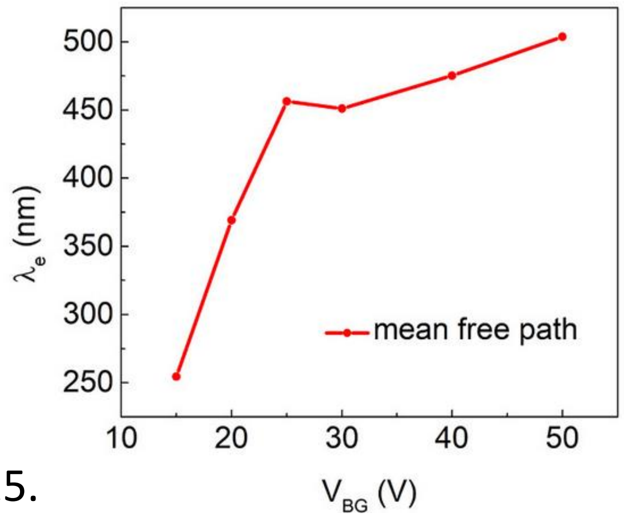
Ti/Au

@ T = 250 mK

$g^* \sim 44$



$\mu_e \sim 29500\ \mathrm{cm}^2/\mathrm{Vs}$



$\lambda_{mfp} \sim 500\ \mathrm{nm}$

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

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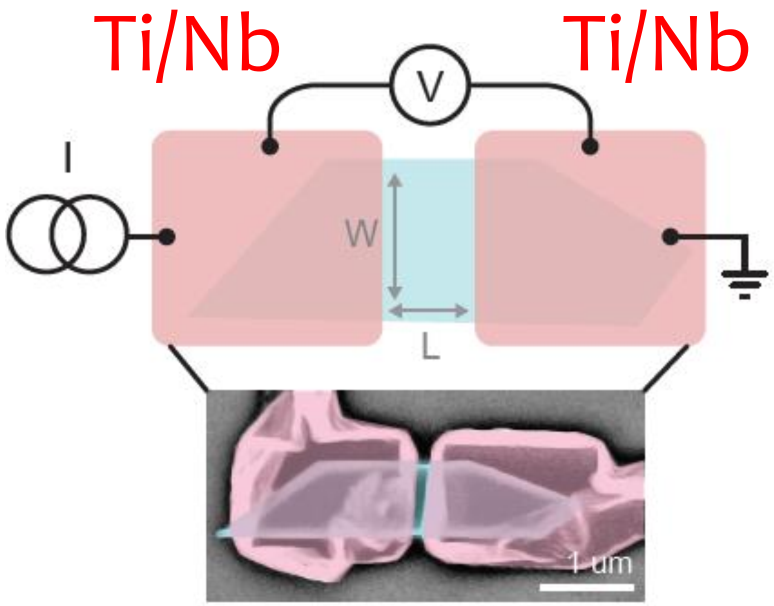
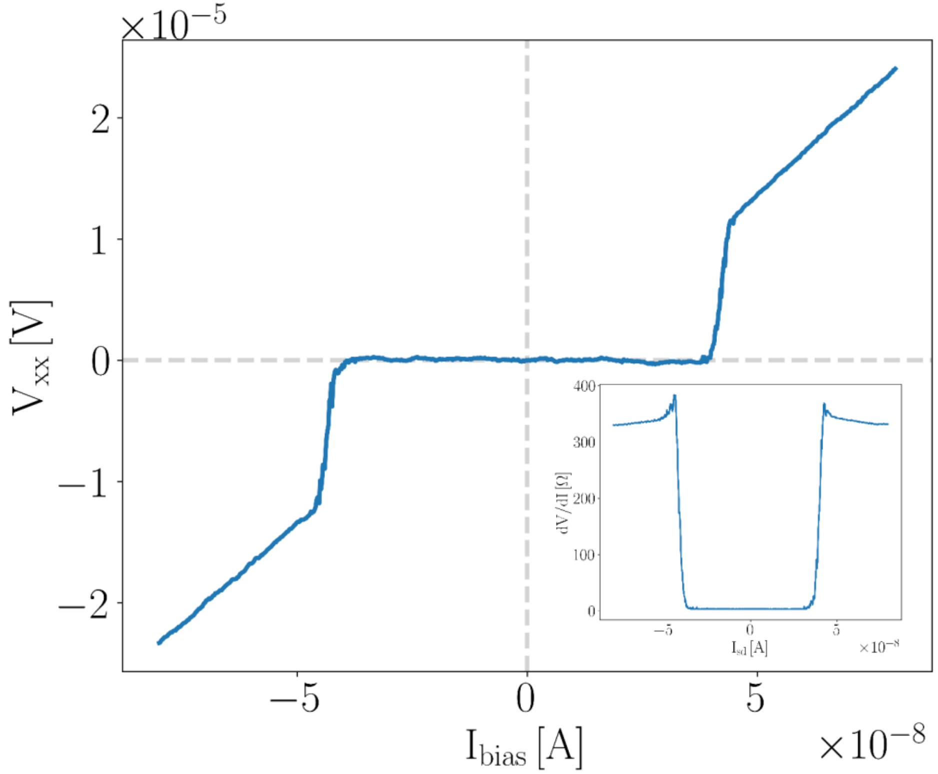
InSb nanoflag-based Josephson junctions



λ_{mfp}	500 nm
L	200 nm
ξ_S	750 nm

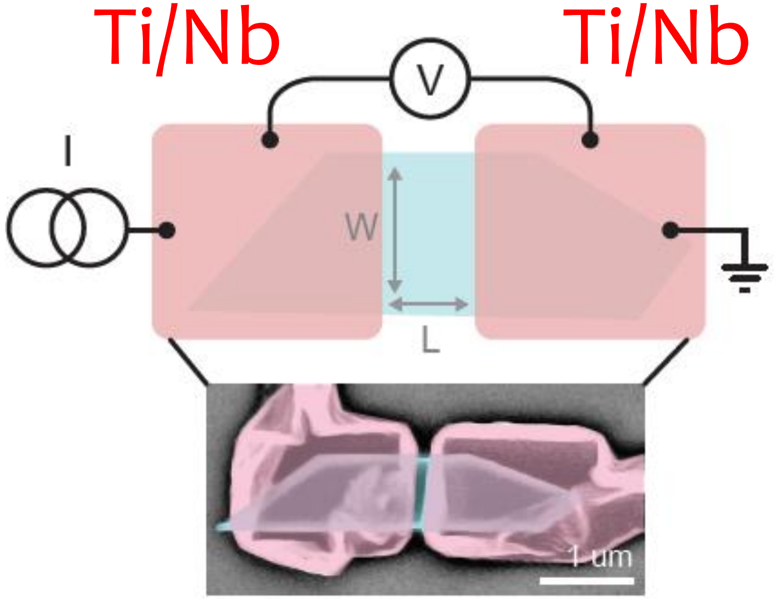
short-ballistic junction



Sedighe Salimian

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

Gate-tunable supercurrent



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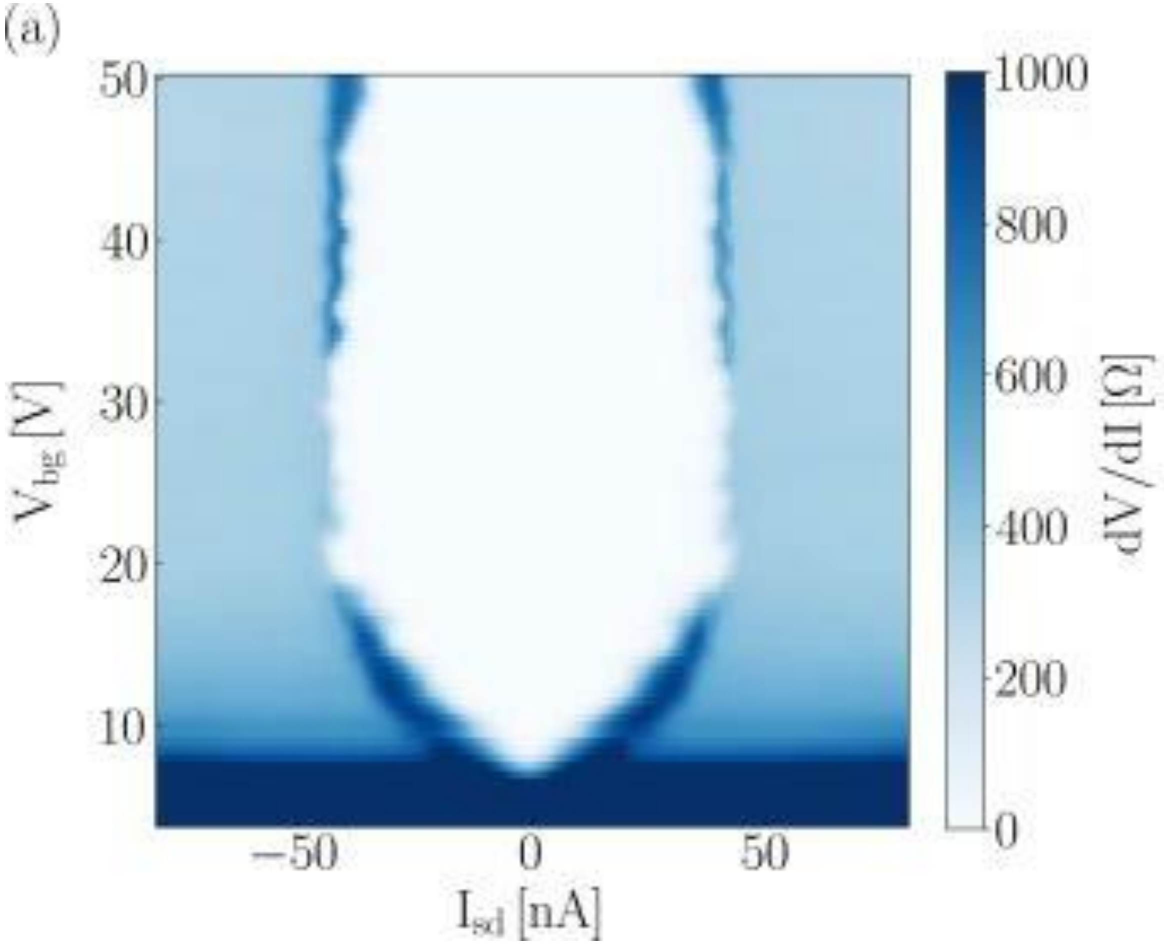

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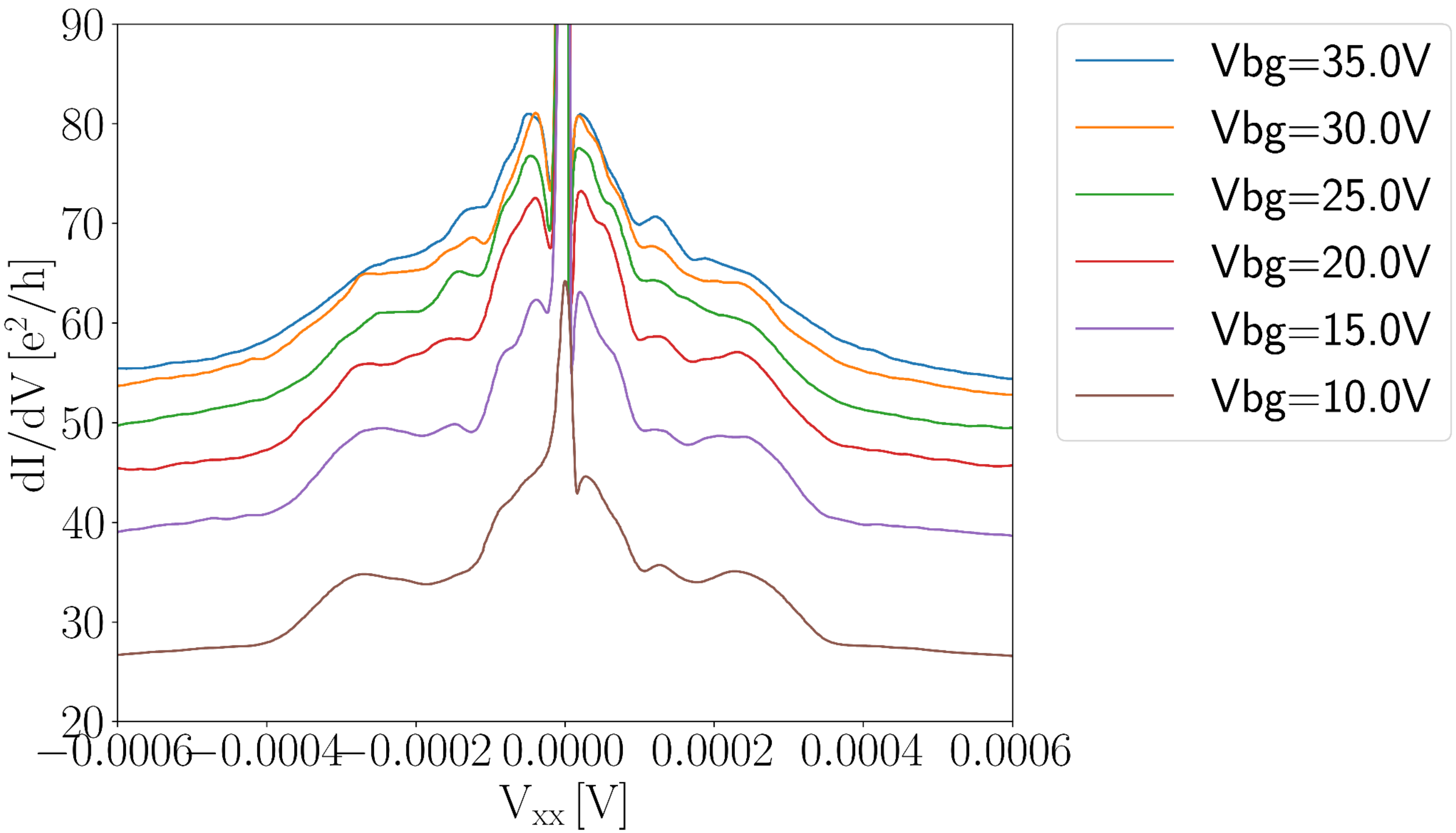
Multiple Andreev Reflections



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

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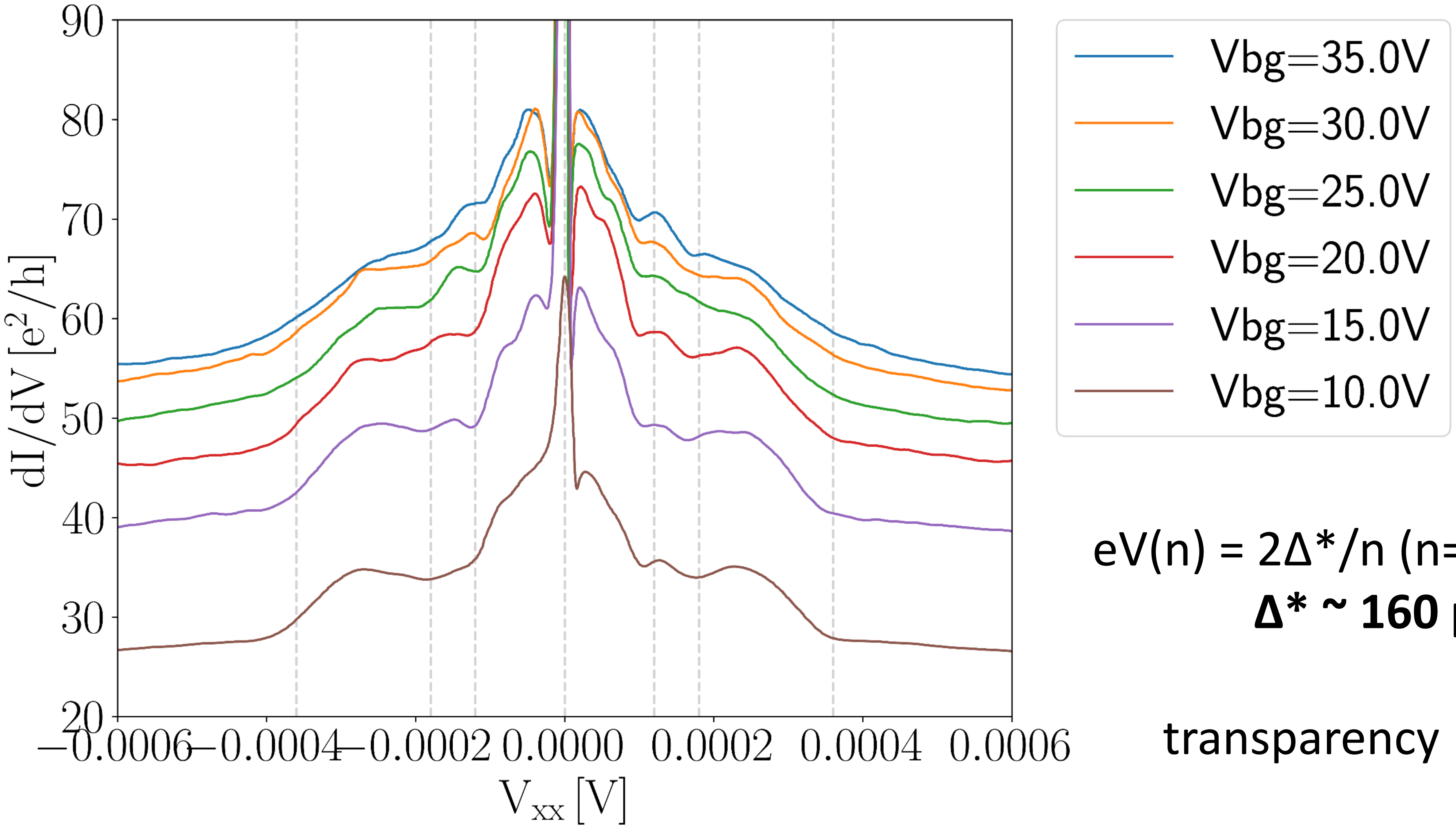

Michal P. Nowak

$eV(n) = 2\Delta^*/n$ (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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Josephson Diode Effect

Bianca Turini

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

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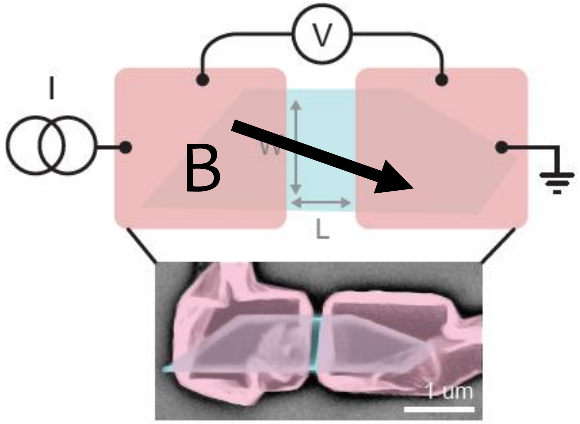
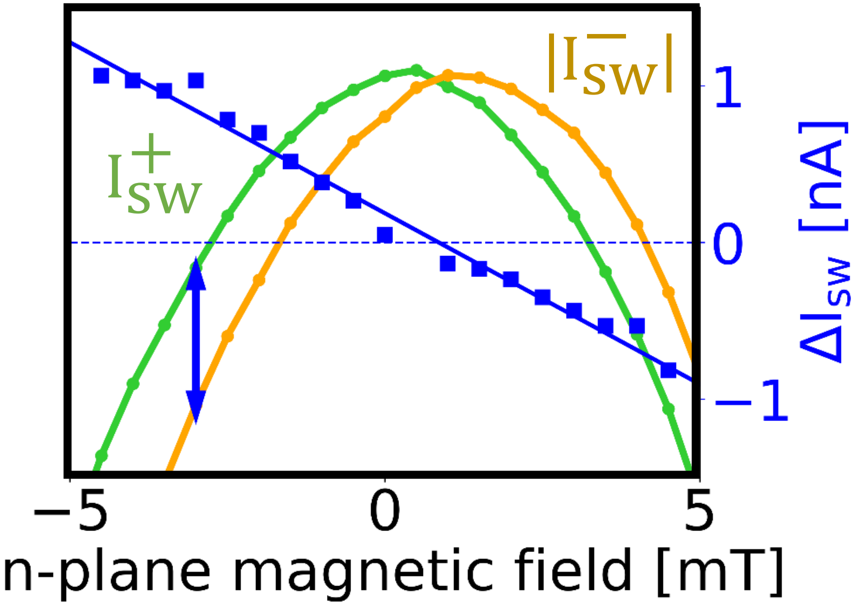
Josephson Diode Effect





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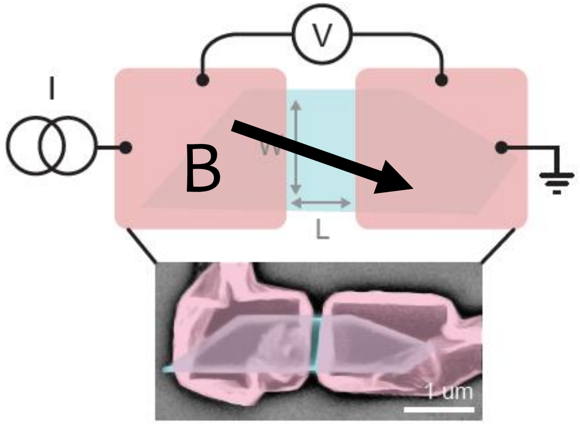

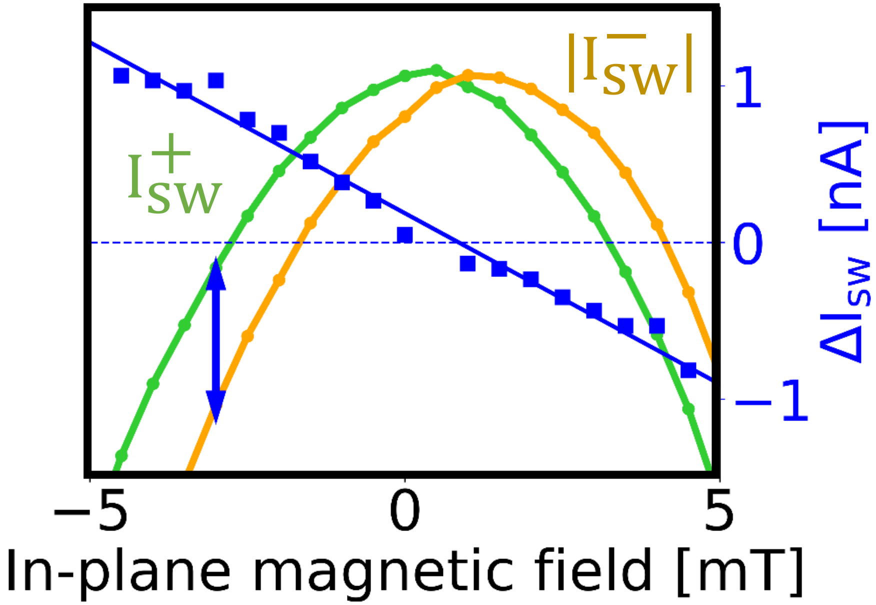

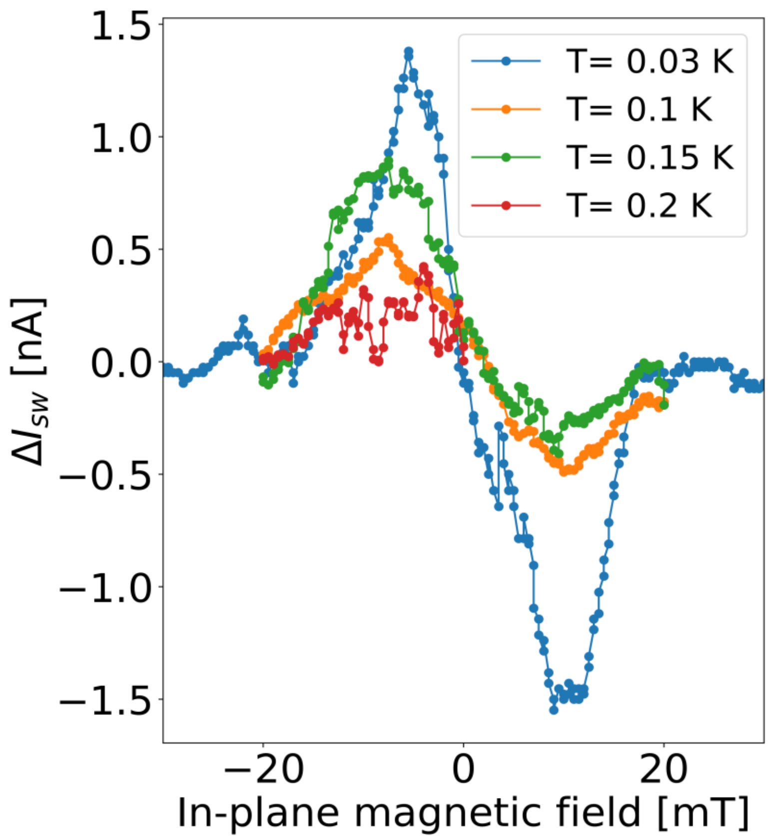

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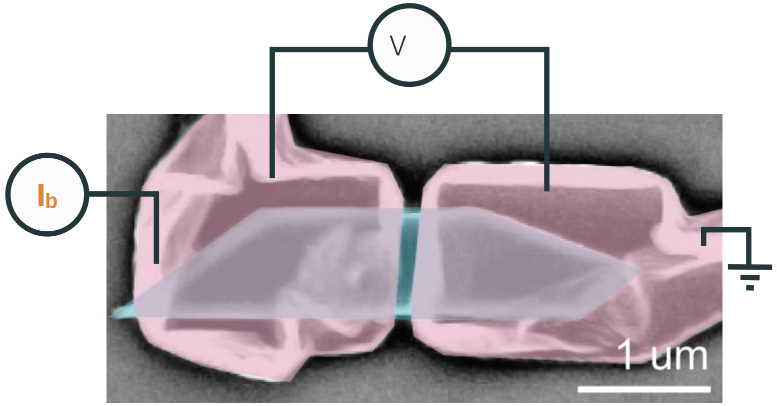
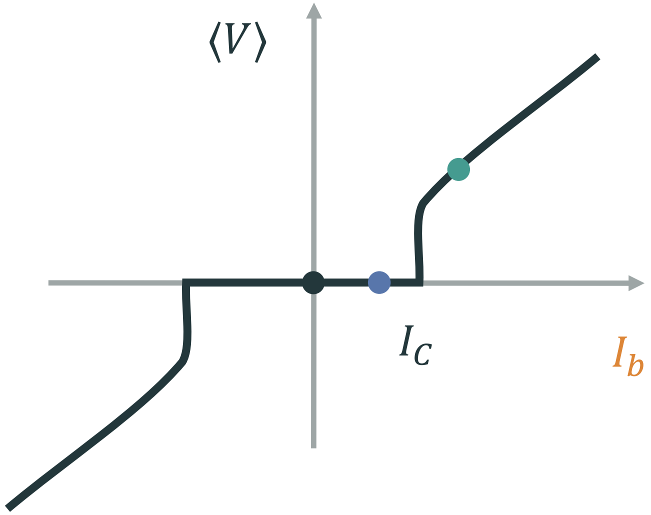
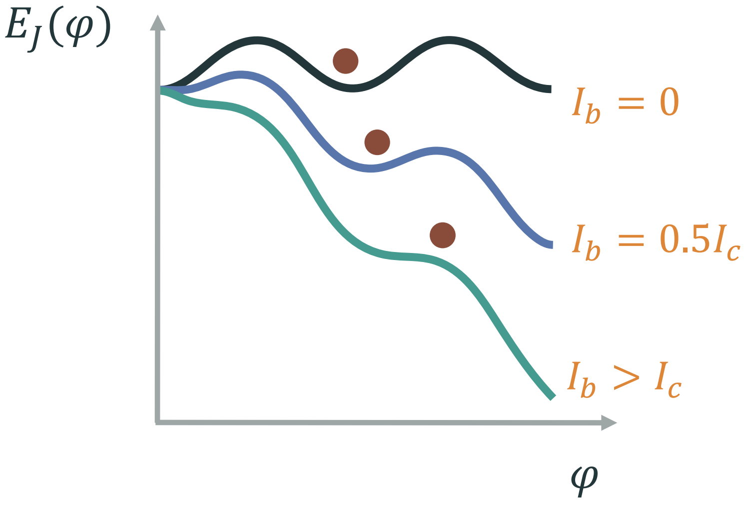
Shapiro steps



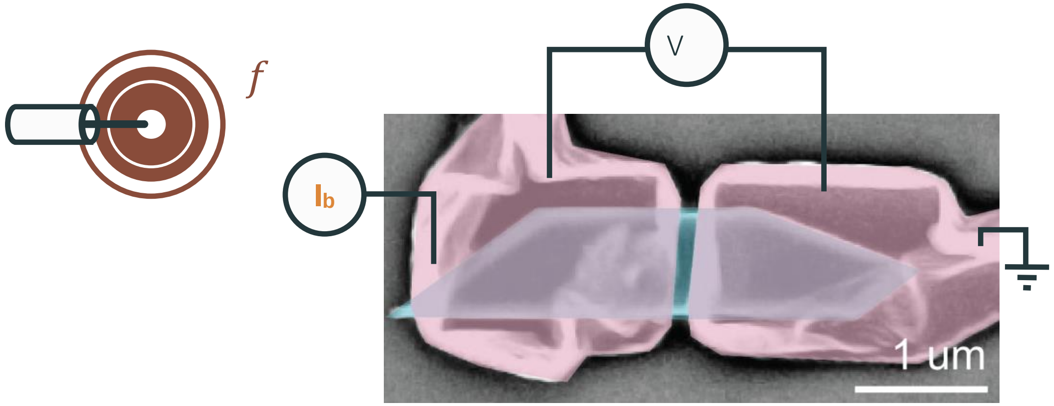
$$V = \frac{\hbar}{2e}\dot{\varphi}$$





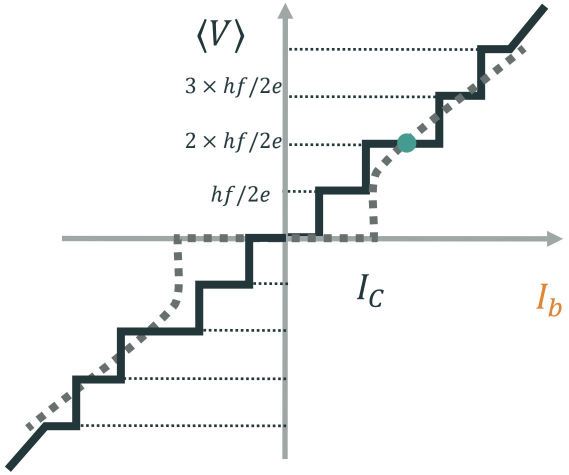
A. Iorio et al., Phys. Rev. Research 5, 033015 (2023).

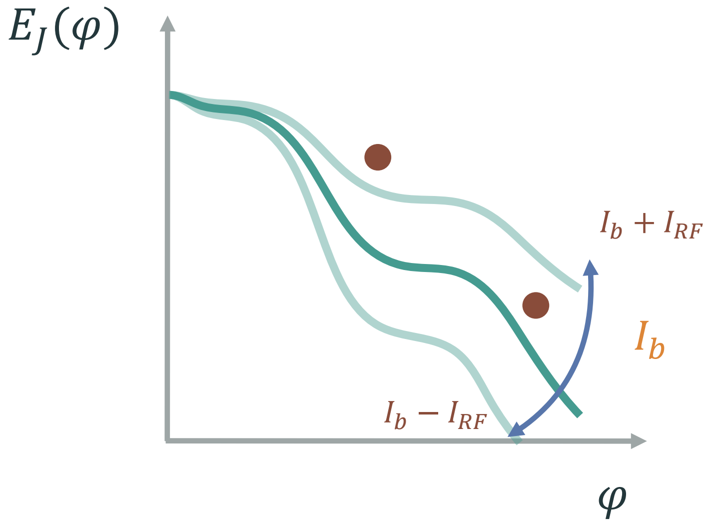
Shapiro steps



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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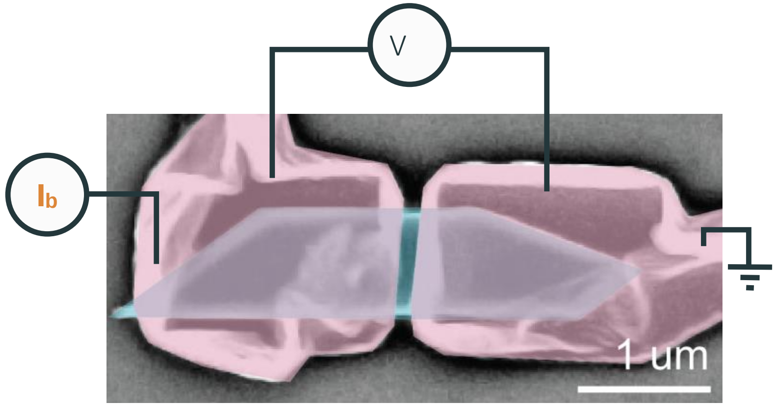
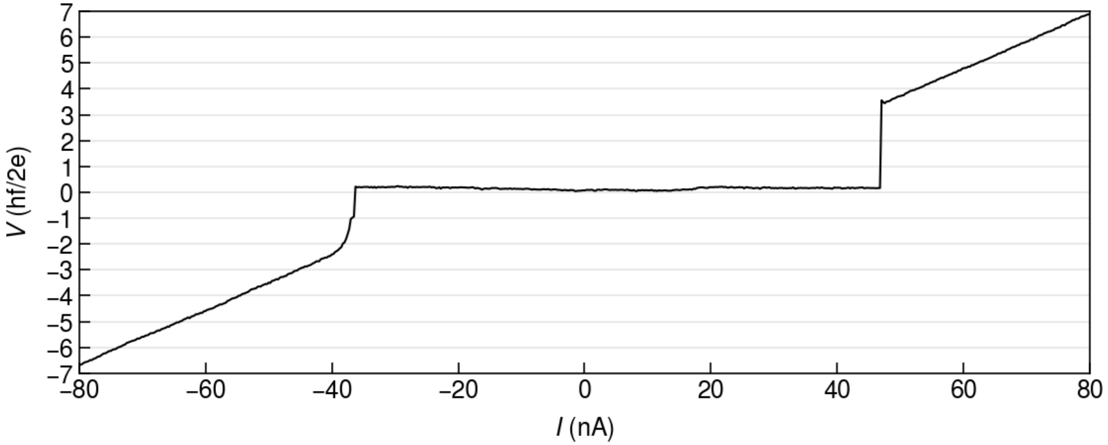
Half-integer Shapiro steps





Andrea Iorio

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

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

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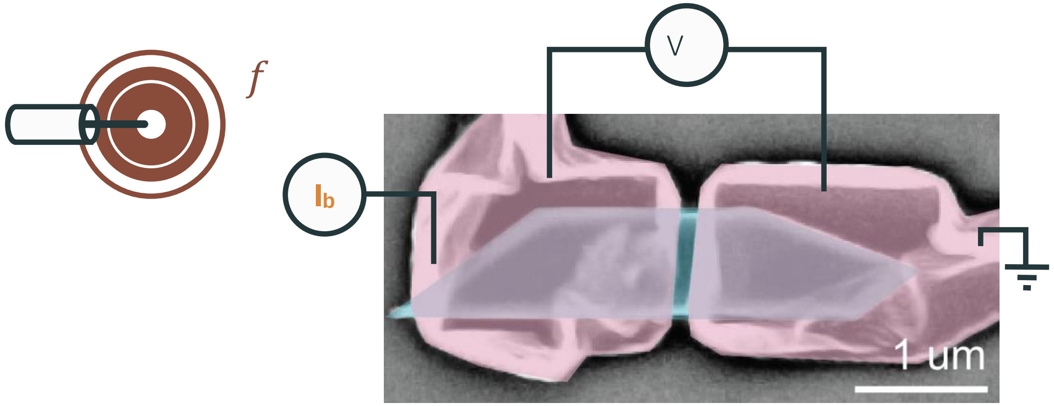
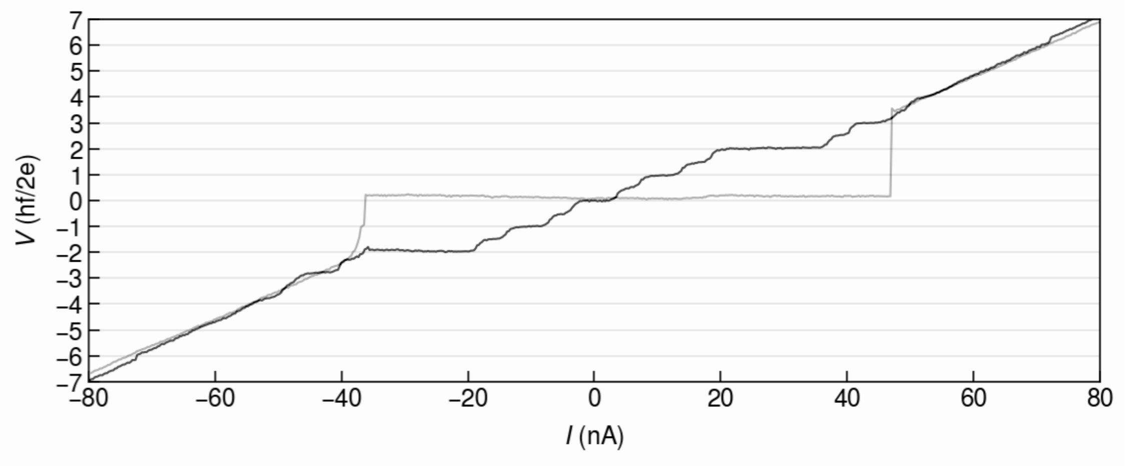
Half-integer Shapiro steps





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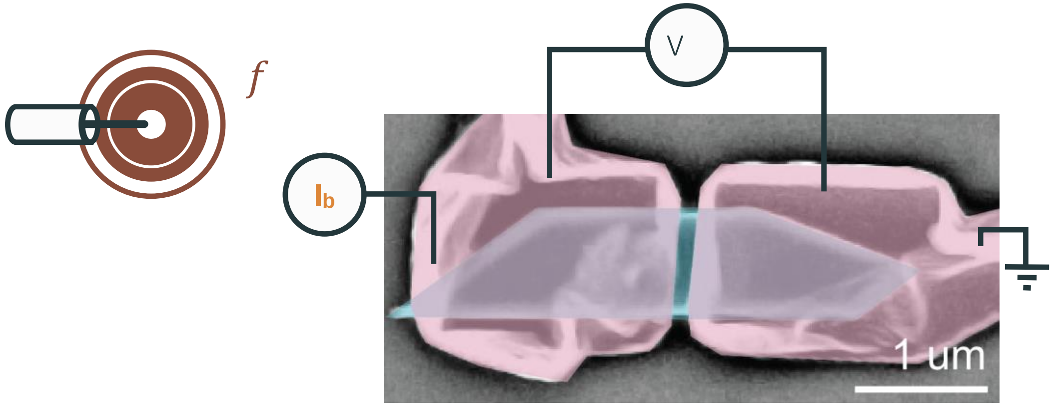

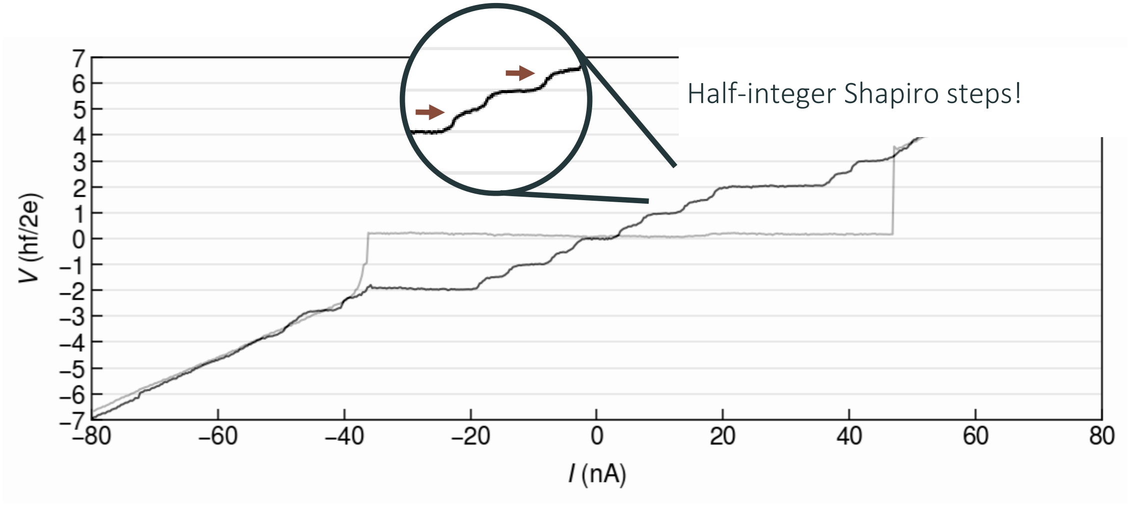

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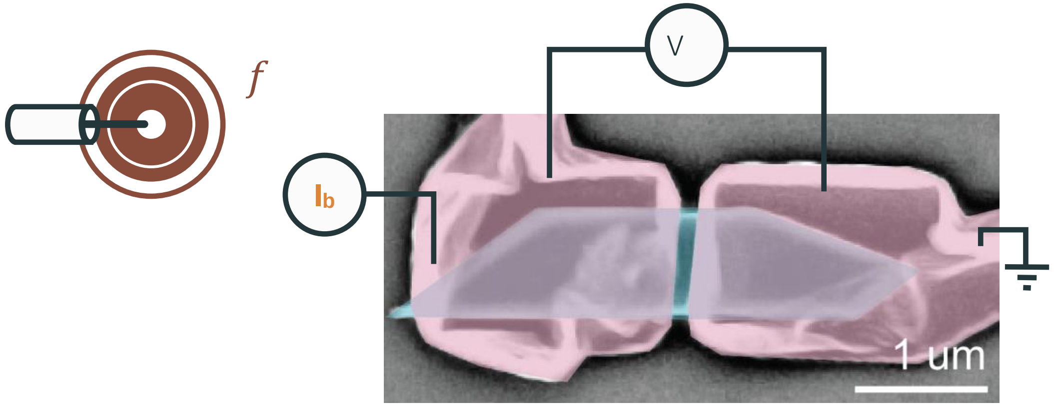

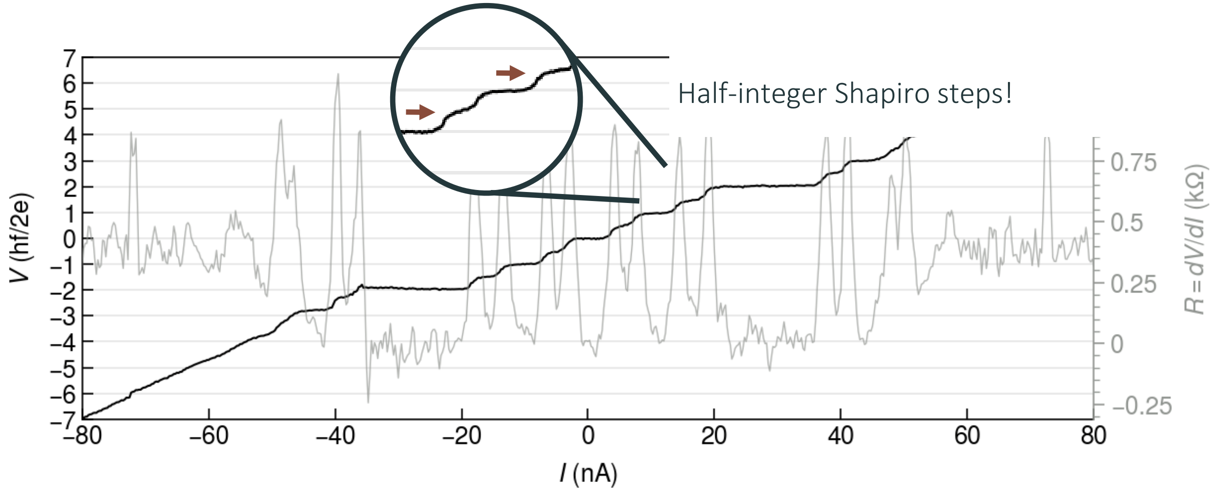

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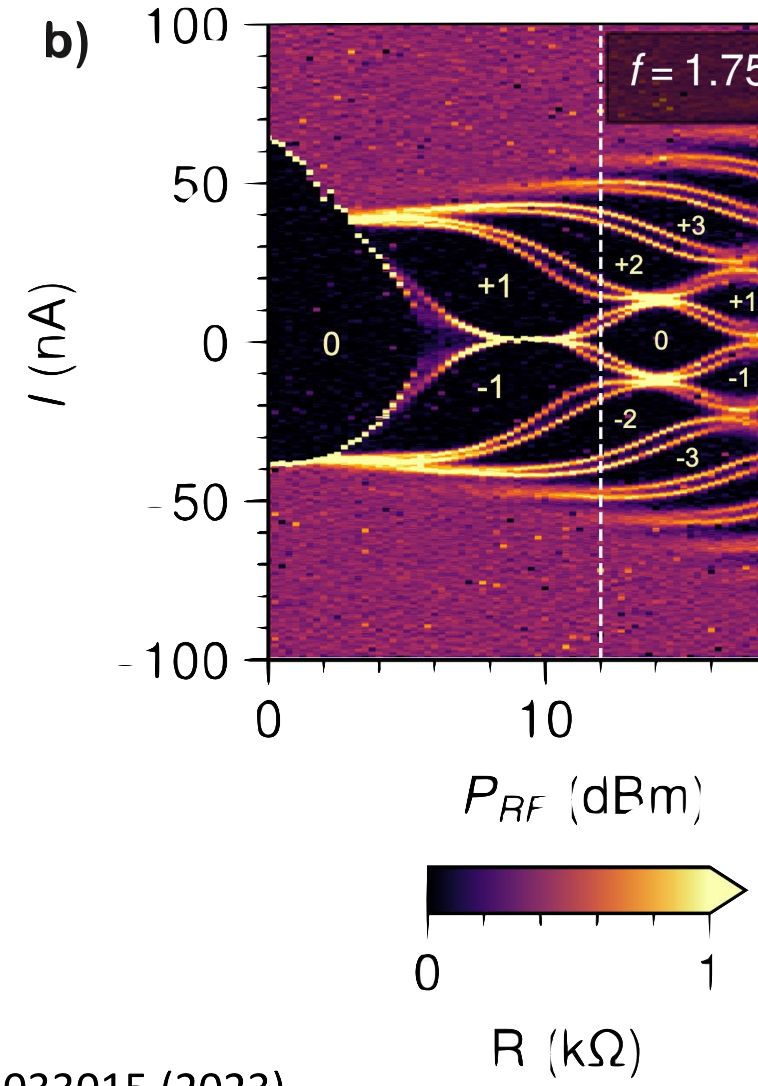

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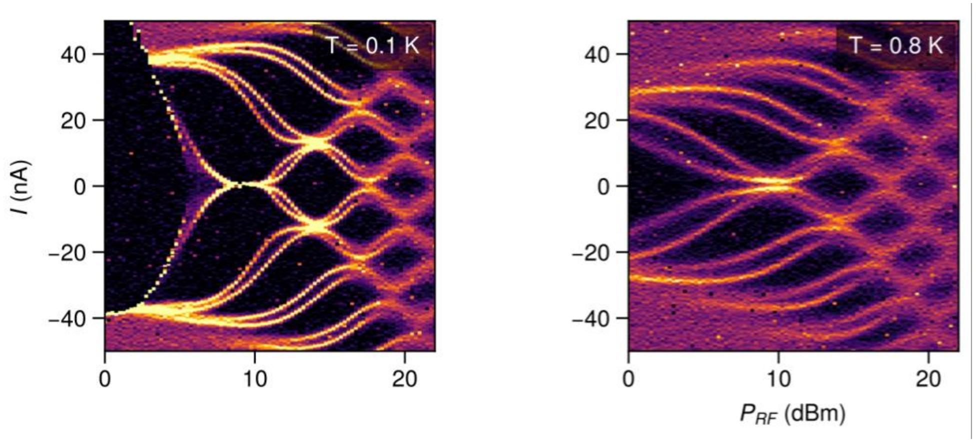
Half-integer Shapiro steps

A non-monotonic temperature dependance



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Half-integer Shapiro steps

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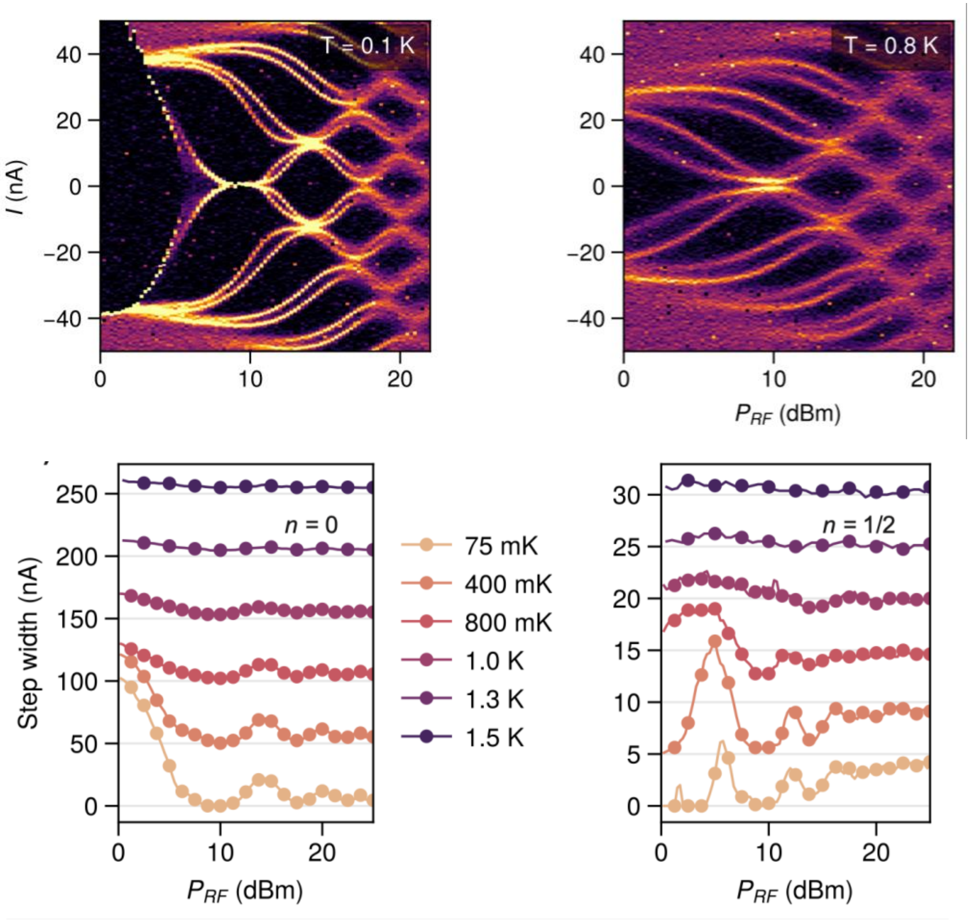

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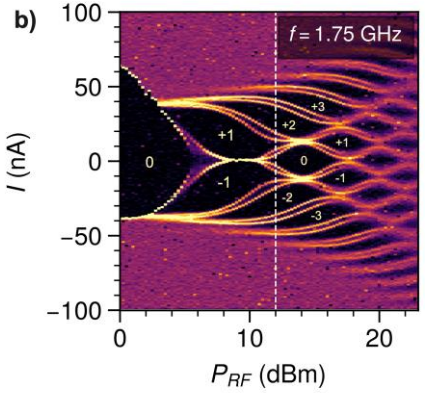
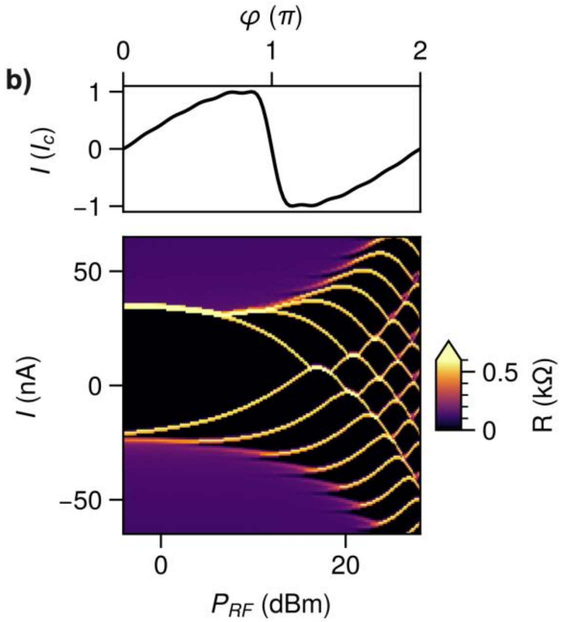
Half-integer Shapiro steps

How to have half-integer steps?



RCSJ simulations



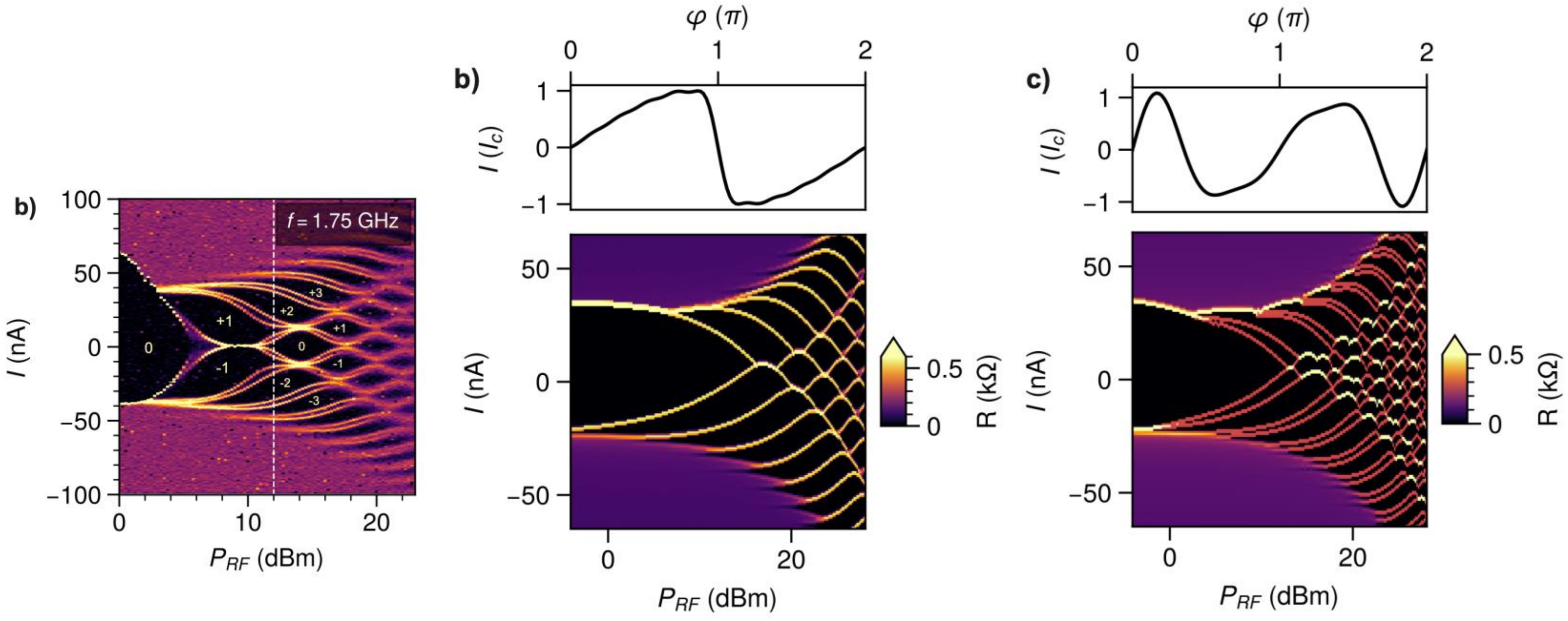
A. Iorio et al., Phys. Rev. Research 5, 033015 (2023).

Half-integer Shapiro steps

How to have half-integer steps?

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

RCSJ simulations



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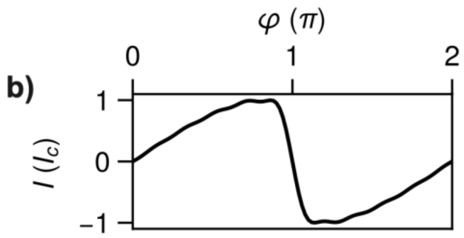
Half-integer Shapiro steps

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

Higher harmonic in the equilibrium CPR



- ✅ Commonly 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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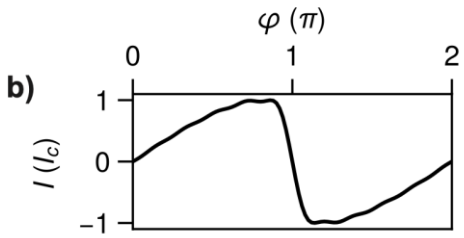

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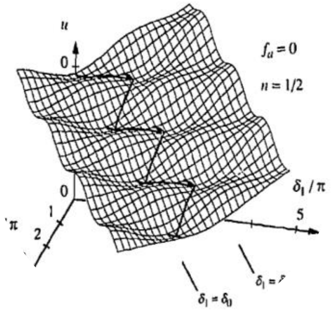
SQUID-like



- ✔ 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

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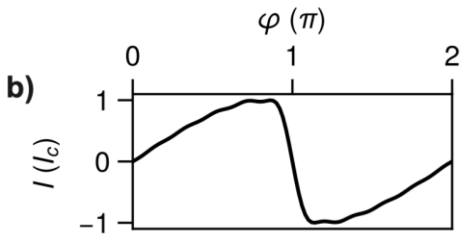

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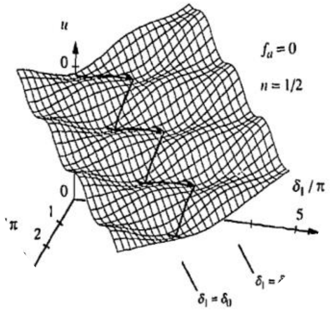

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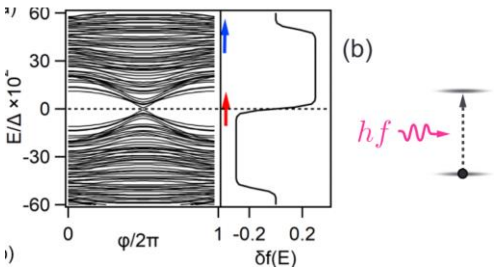
Non-equilibrium excitations



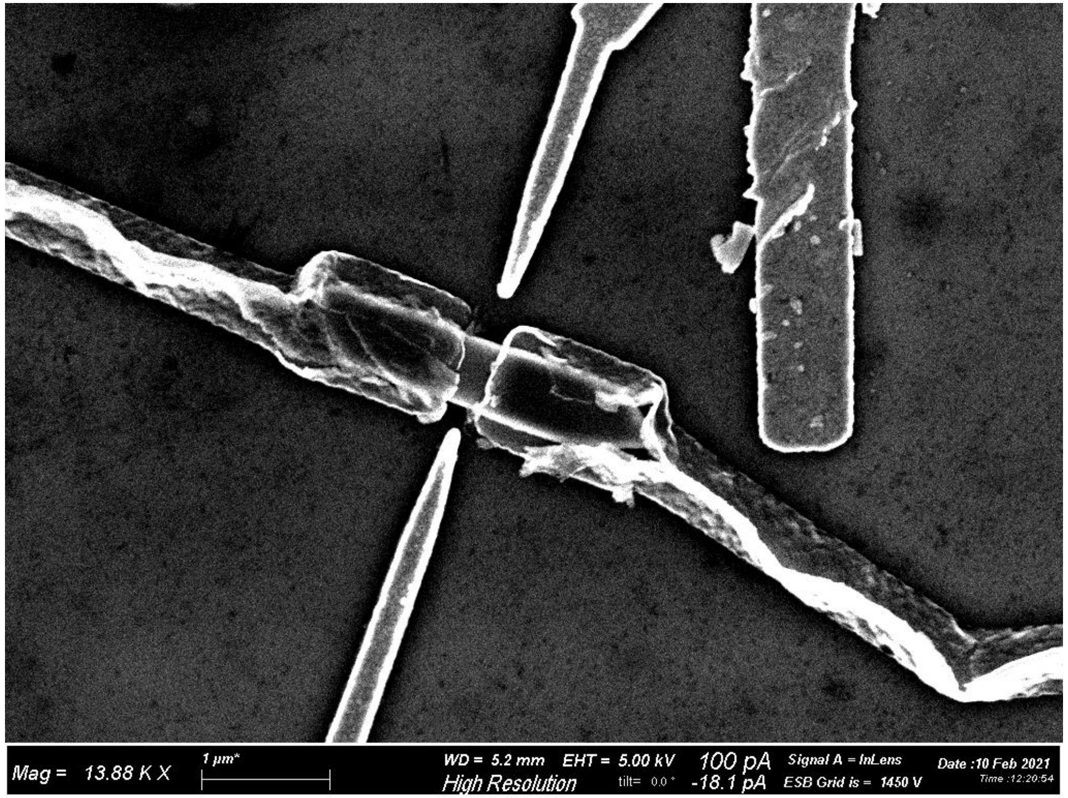
- ✓ $\sin(2\varphi)$ only when driving
- ✓ Half-steps non-monotonic in T
- ! Still some gaps with the theory

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)

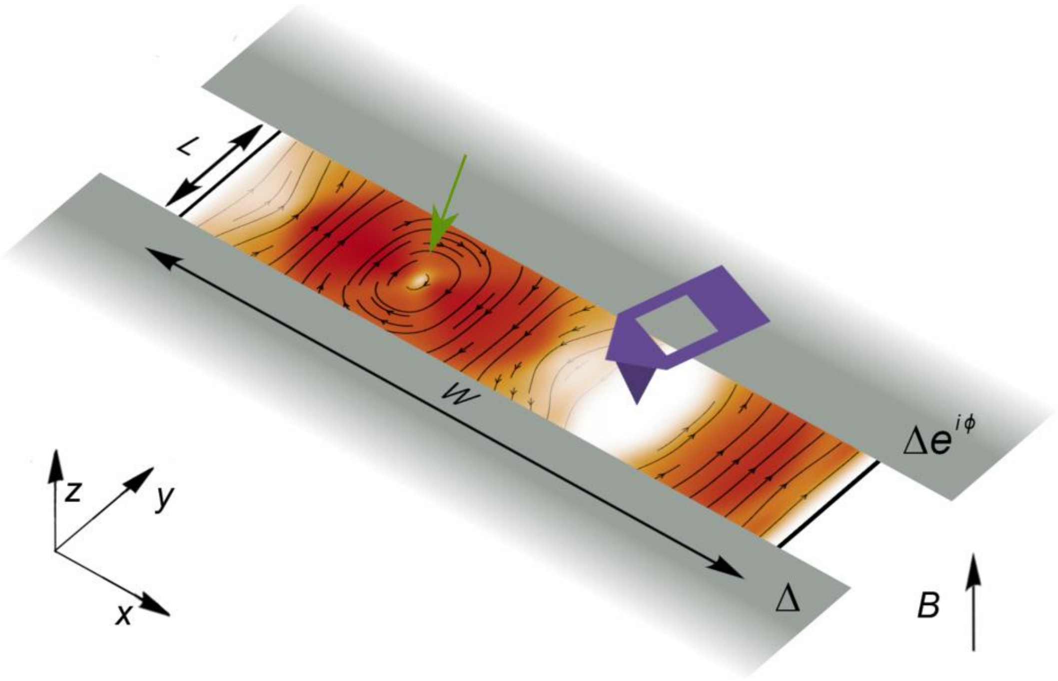
A. Iorio et al., Phys. Rev. Research 5, 033015 (2023).

Outlook

Gate-controlled JJs

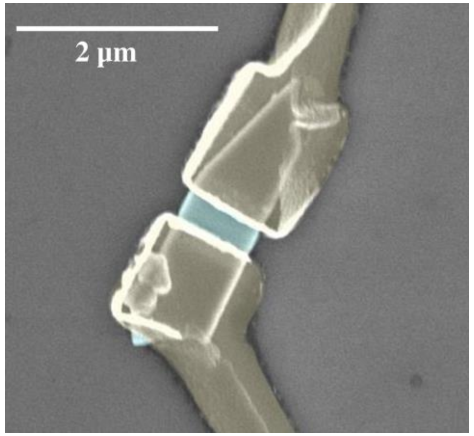


SGM on these JJs



K. Kaperek et al., Phys. Rev. B 106 (2022) 035432
S. Fracassi et al., arXiv:2403.17894
Appl. Phys. Lett. 124 (2024); doi: 10.1063/5.0210660

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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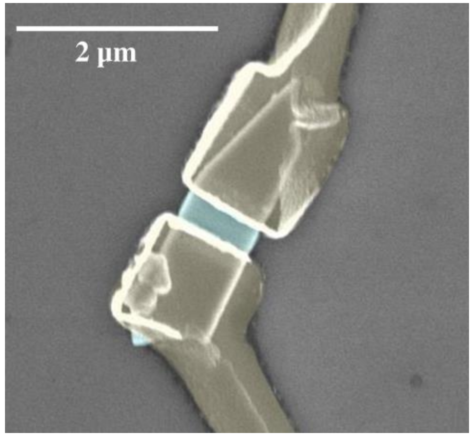

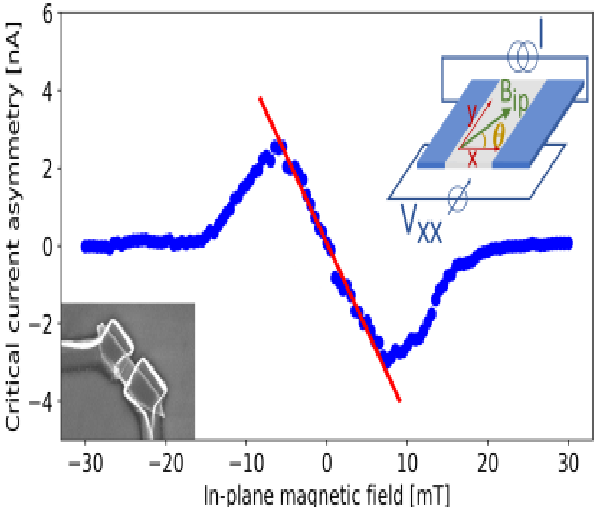

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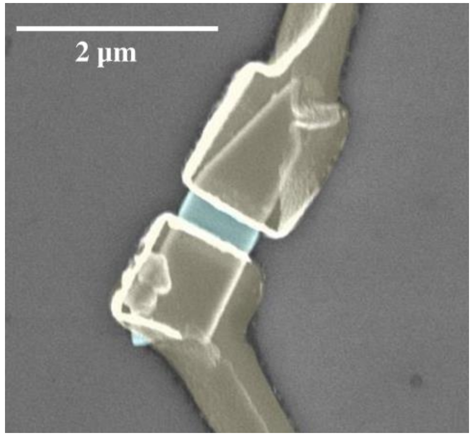

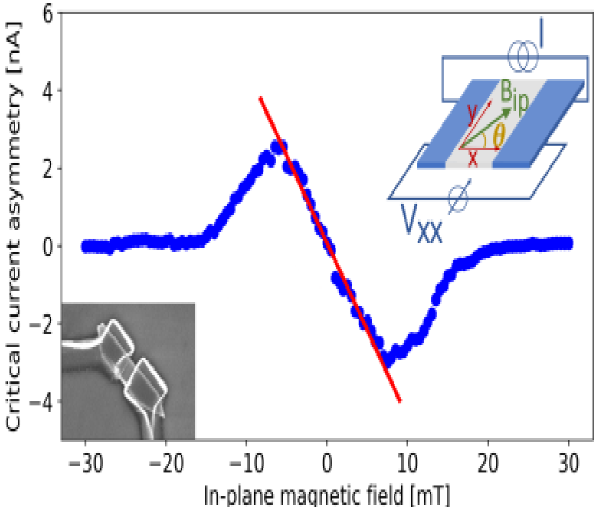

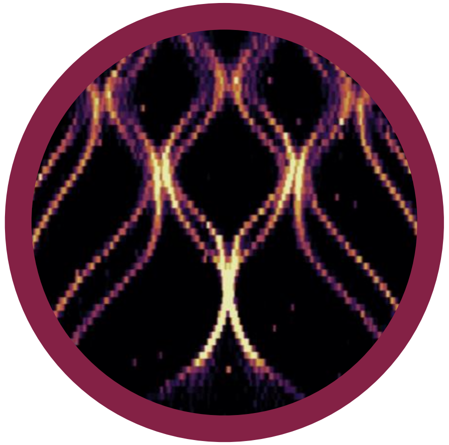

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Thank you for your attention!

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