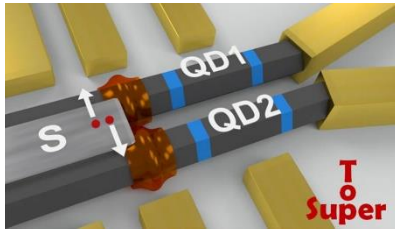
Josephson Diode Effect
in High-Mobility InSb Nanoflags

Stefan Heun

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



AndQC

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Outline of the talk

- Non-reciprocity in condensed matter systems
- InSb nanoflags for advanced devices
- Nanoflag-based Josephson junctions
- Josephson diode effect in InSb nanoflags

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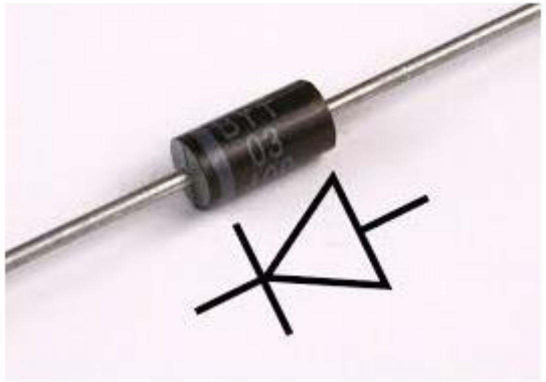
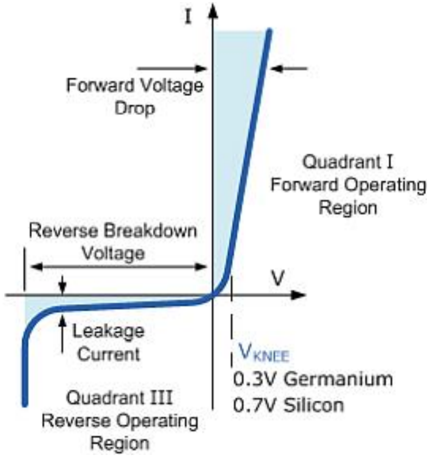
Non-reciprocal transport

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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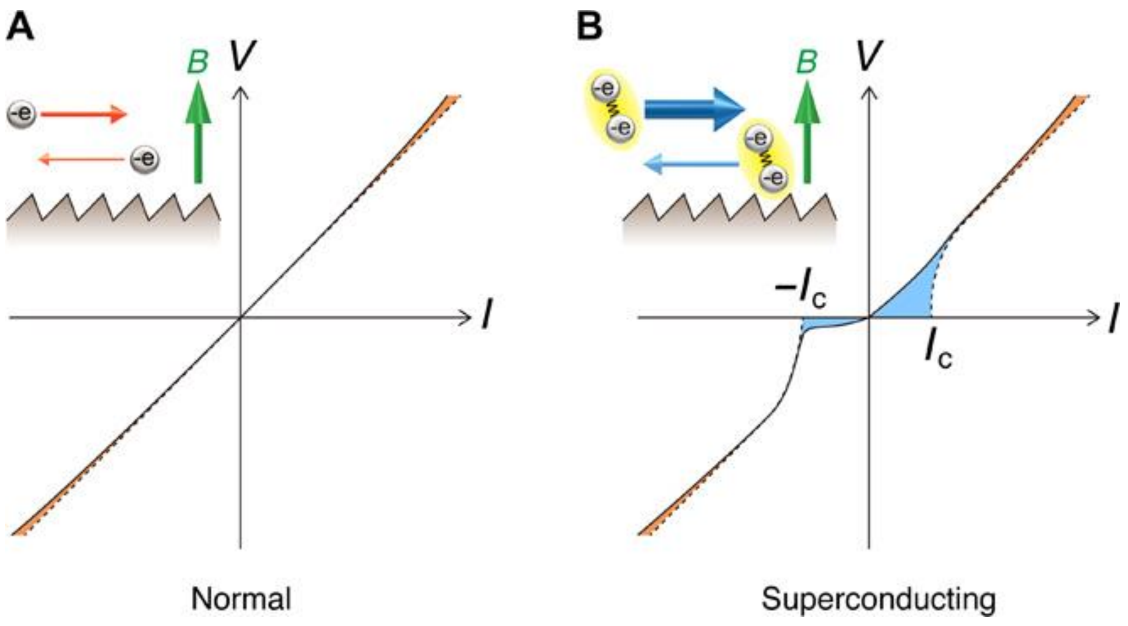
MCA in superconductors



- 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

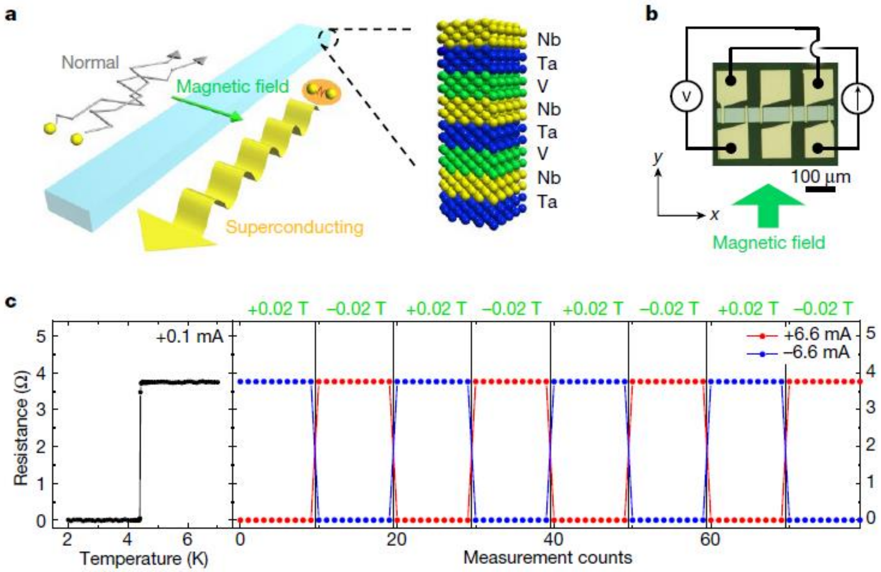
Article

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

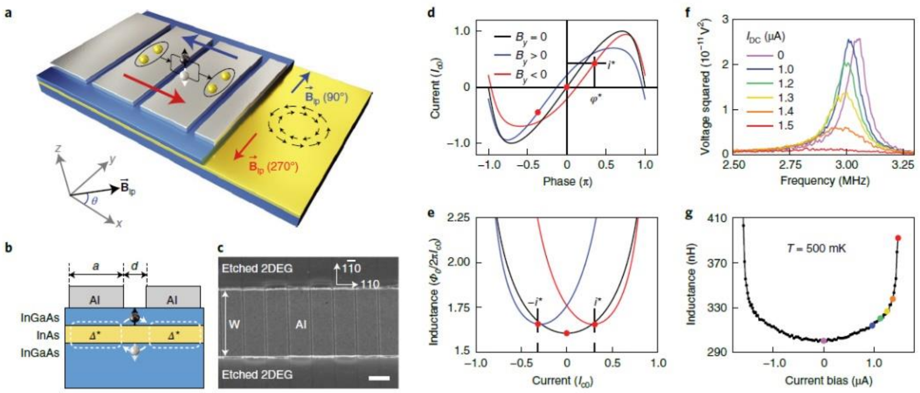


F. Ando et al., Nature 584 (2020) 373.

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.

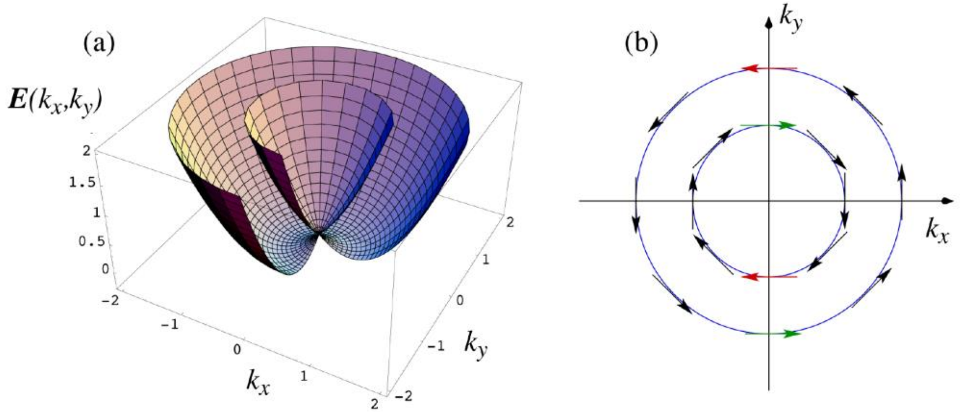
Ingredients for intrinsic SDE

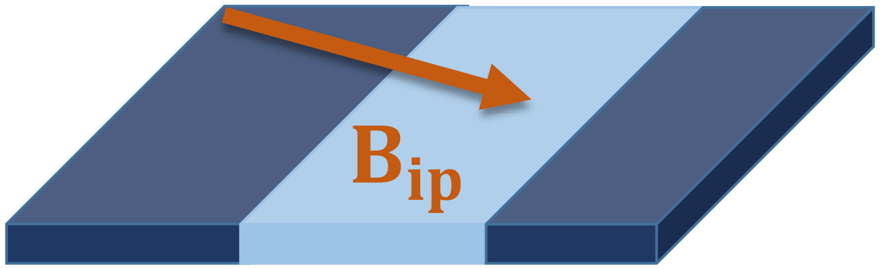
Requirements:

- 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





Outline of the talk

- Non-reciprocity in condensed matter systems
- **InSb nanoflags for advanced devices**
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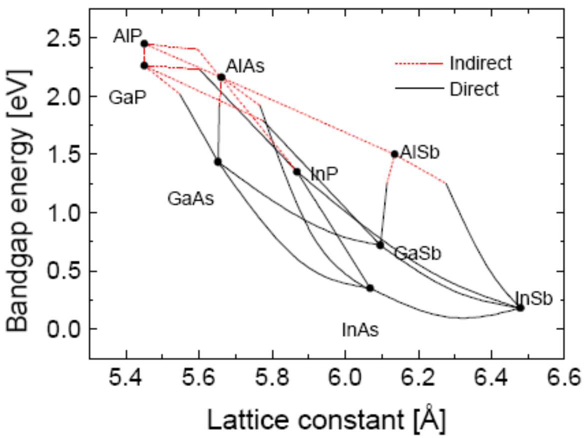
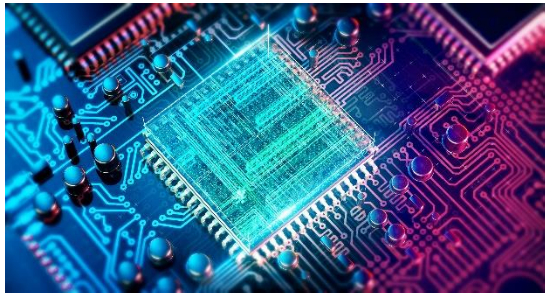
Why InSb?

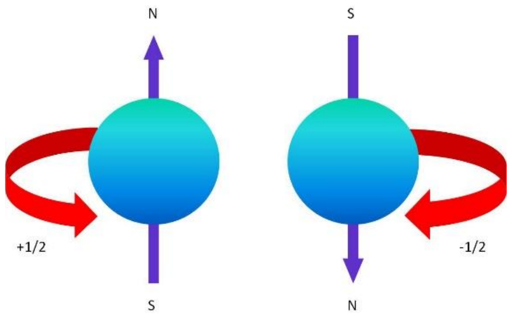
- Narrow bandgap (0.23 eV) ⟶ mid-infrared optoelectronic devices.



- 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.



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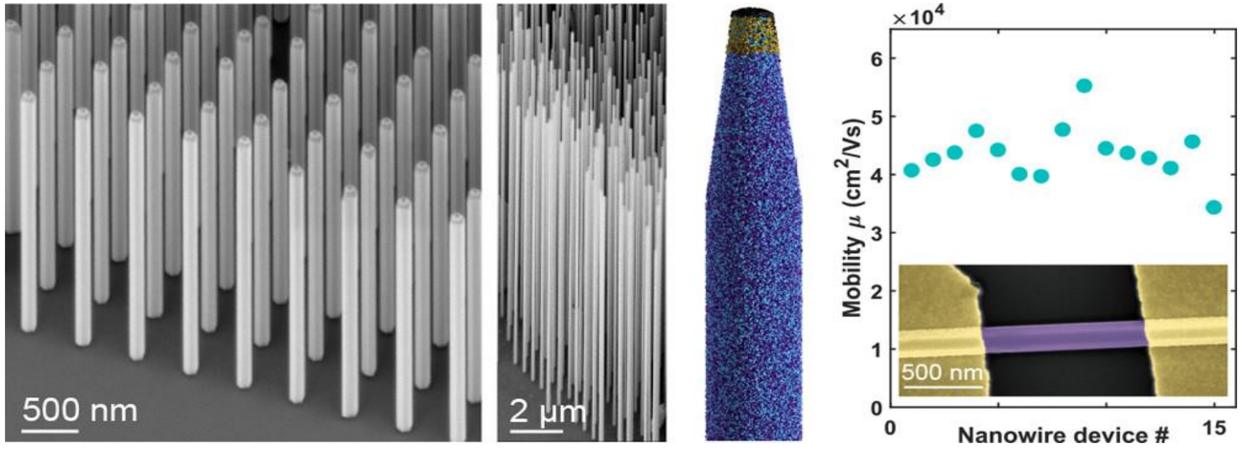
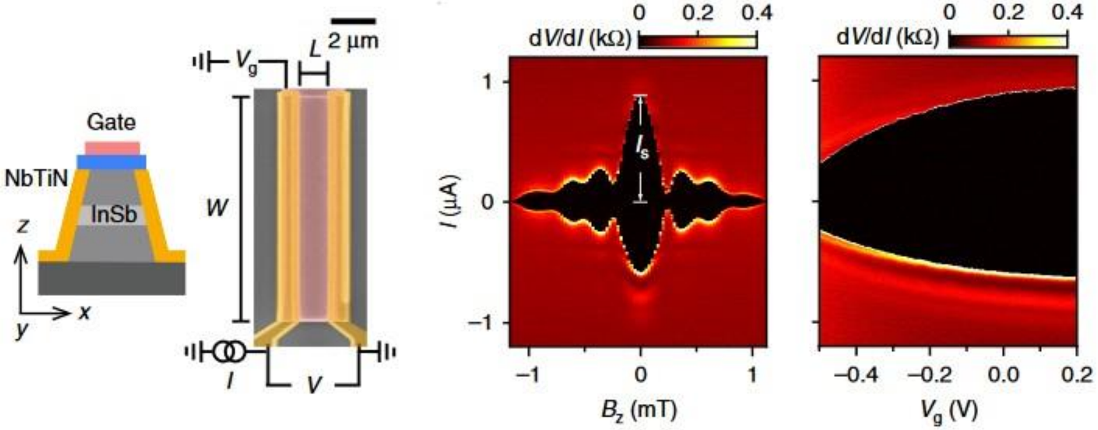
InSb nanostructures

Nano Lett. 2019, 19, 6, 3575–3582

- InSb nanowires:



- InSb quantum wells:

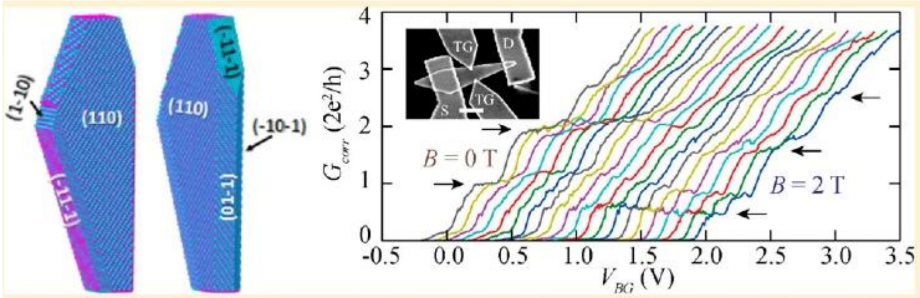


Nat Commun **10,** 3764 (2019)

A novel approach: 2D nanoflags (NFs)

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

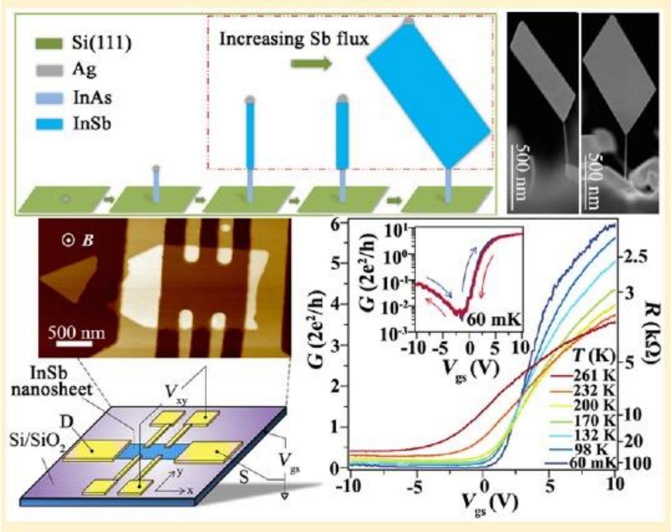
María de la Mata,† Renaud Leturcq,*,‡,§ Sébastien R. Plissard,∥ Chloé Rolland,‡ César Magén,⊥ Jordi Arbiol,*,†,# and Philippe Caroff*,‡,∇



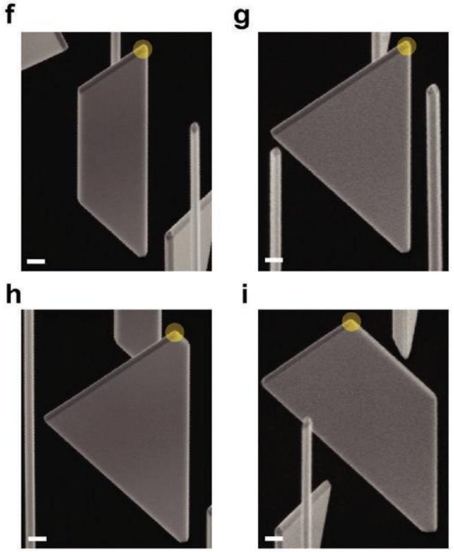
Nano Lett. 16 (2016) 825

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

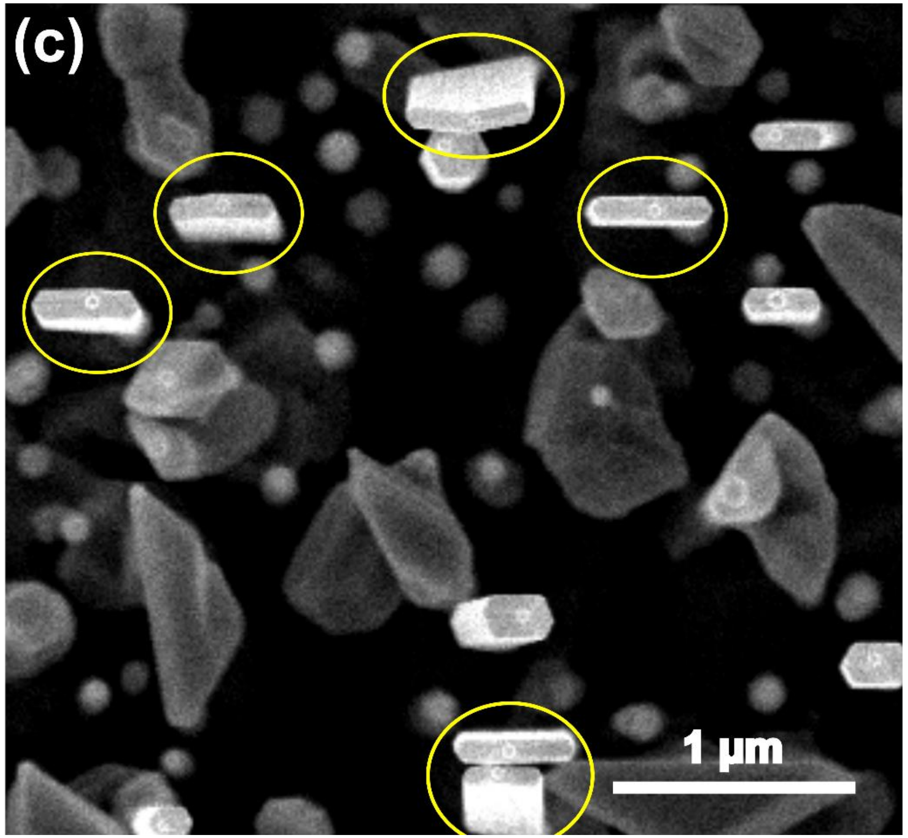


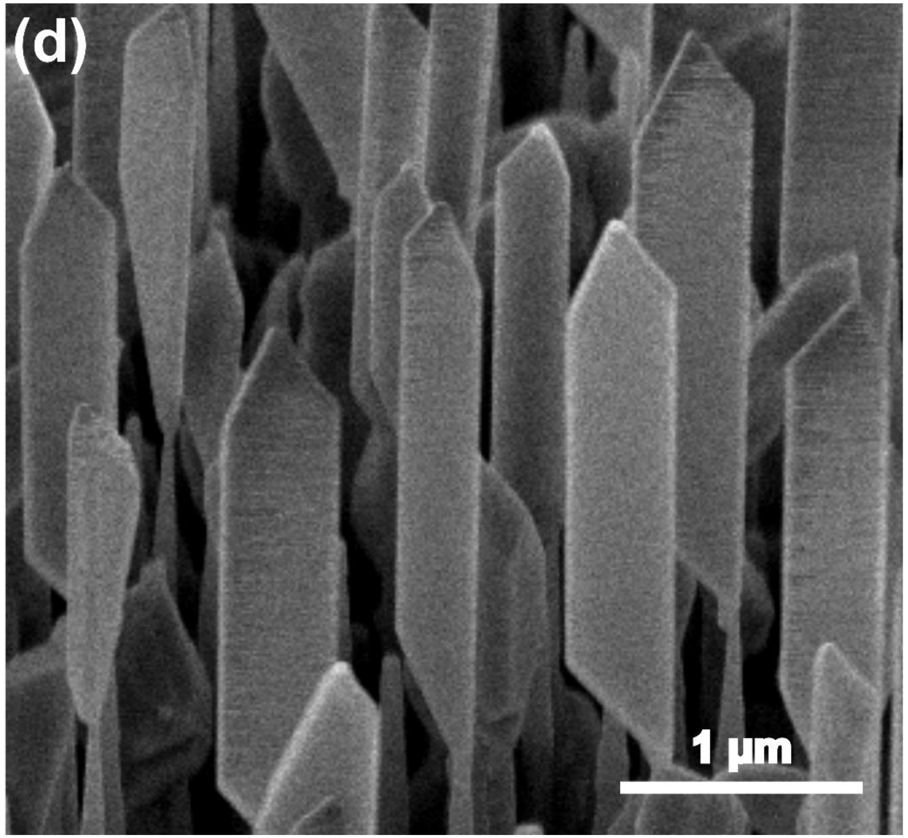
Bottom-Up Grown 2D InSb Nanostructures

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

Growth of InSb nanoflags by CBE





Isha Verma

Defect-free InSb zinc blende lattice

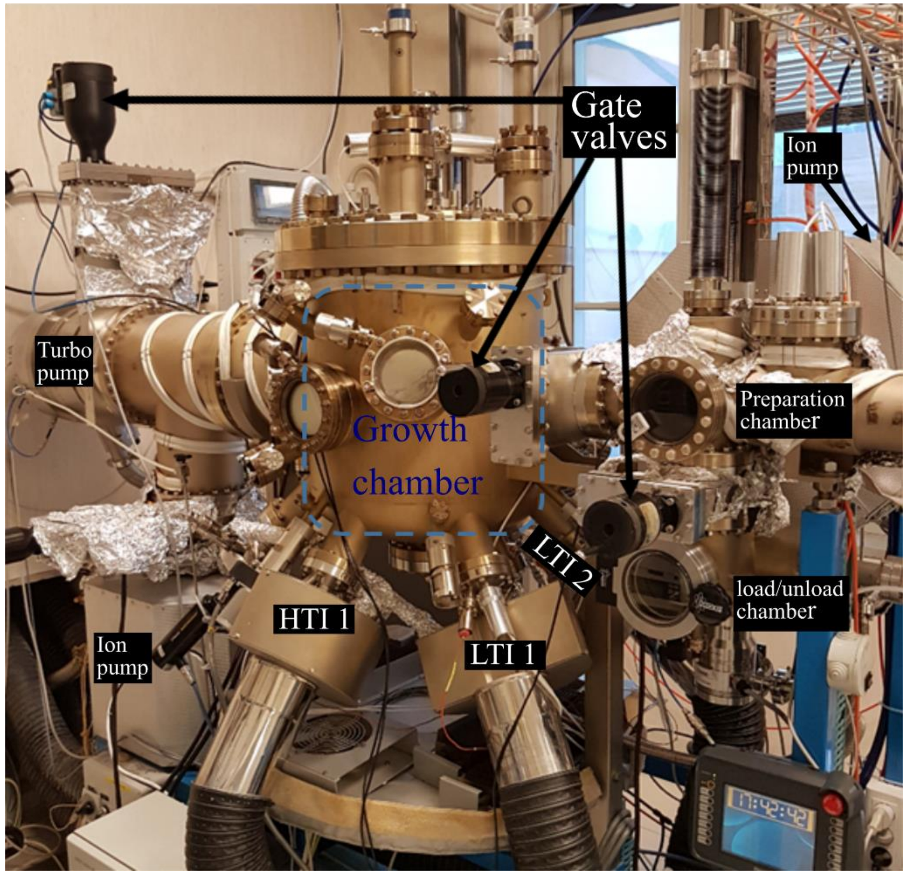
InSb nanoflags:
Length 2-3 µm
Width 500 nm
Thickness 100 nm

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

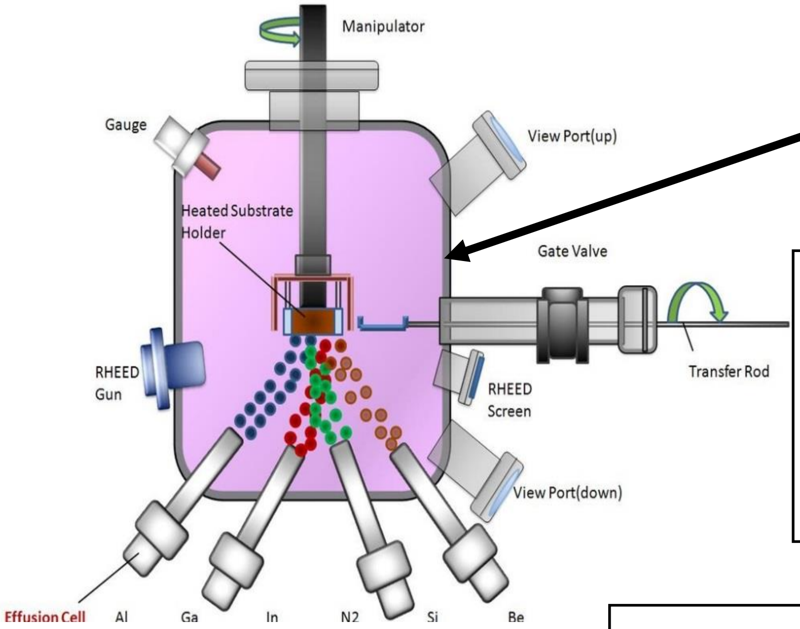
Chemical Beam Epitaxy (CBE)

CBE system at NEST lab

Riber Compact-21 CBE for the growth of III-V NWs



Schematic of CBE



Ultra High Vacuum (UHV) growth chamber (base pressure: 10^{-9} Torr)

Metal-organic precursors

Group III : TM**In**, TE**Ga**, TM**Al**

Group V : TB**As**, TB**P**, TDMA**Sb**, TM**Sb**

n-doping : TB**Se**

Advantages of CBE system

Direct control of fluxes

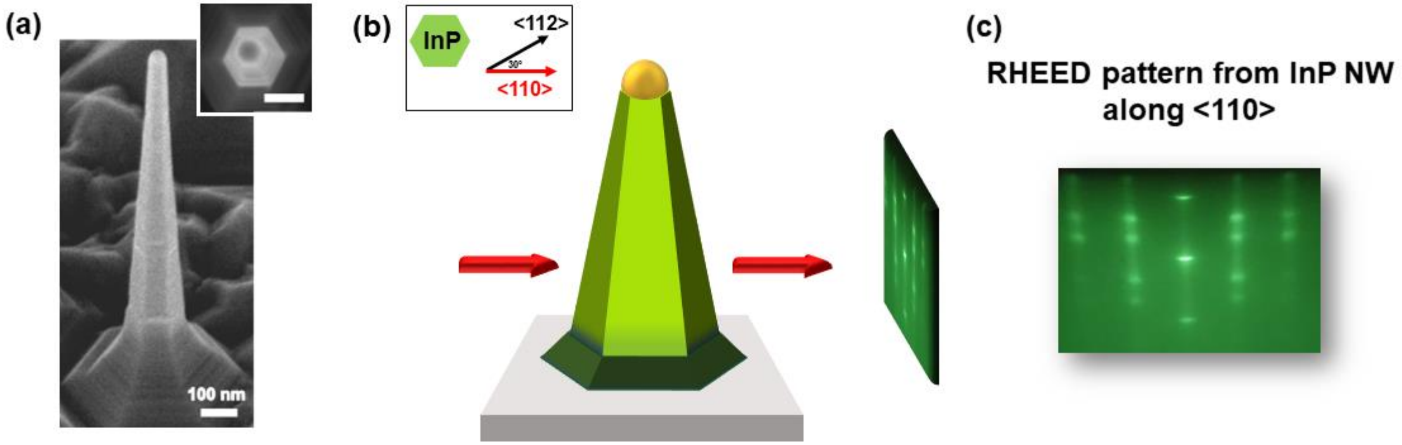
Monolayer thickness control

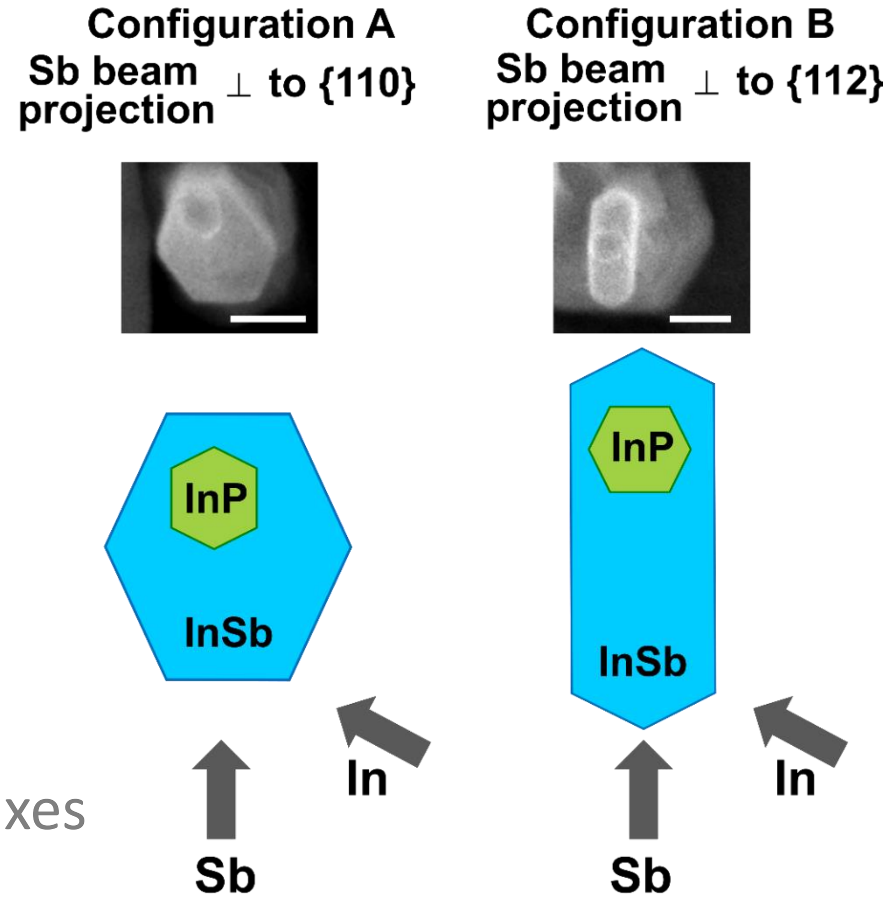
Abrupt interfaces

Good control of composition and doping profiles

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.

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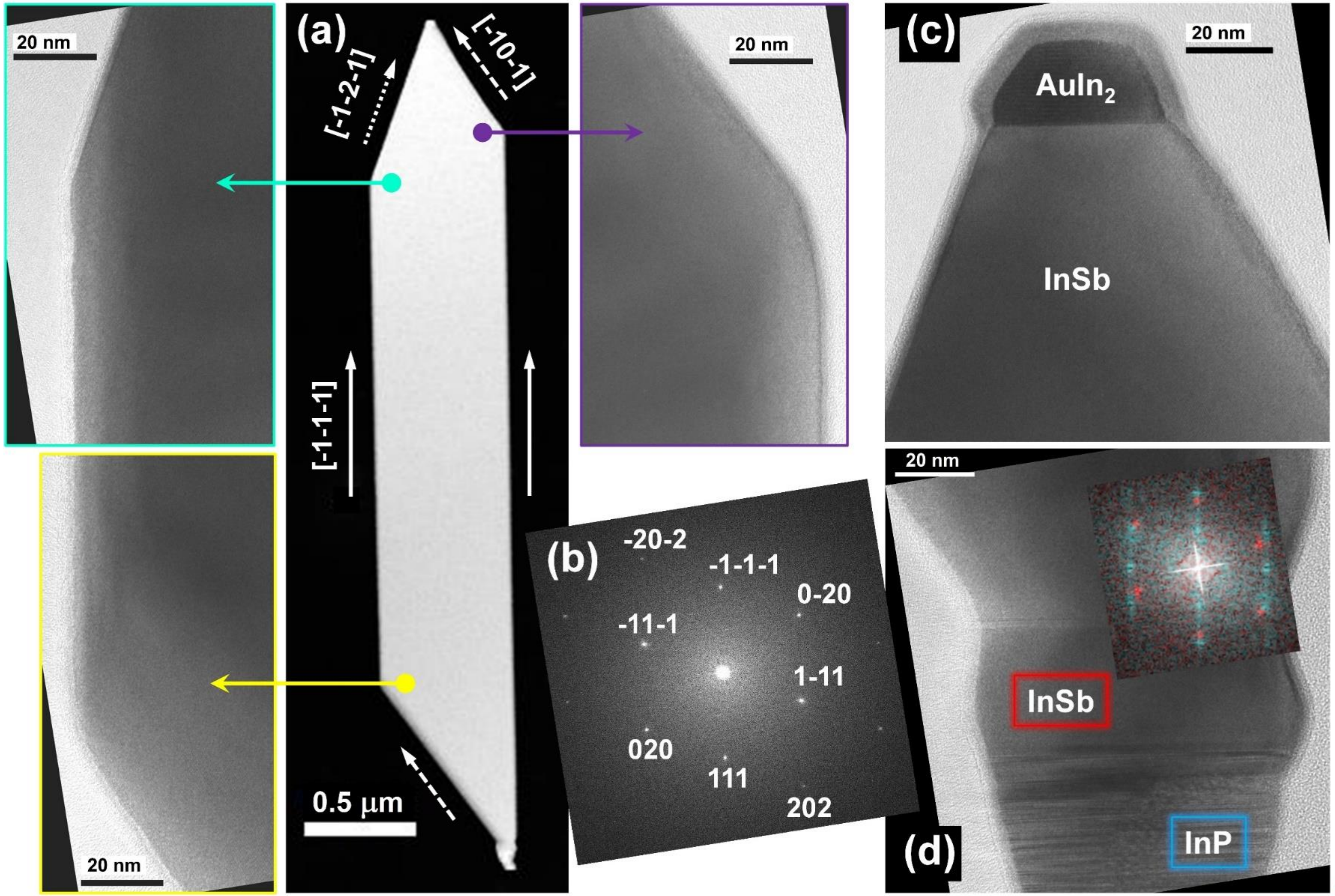
HRTEM of InSb nanoflags

Defect-free InSb zinc blende lattice, completely relaxed.



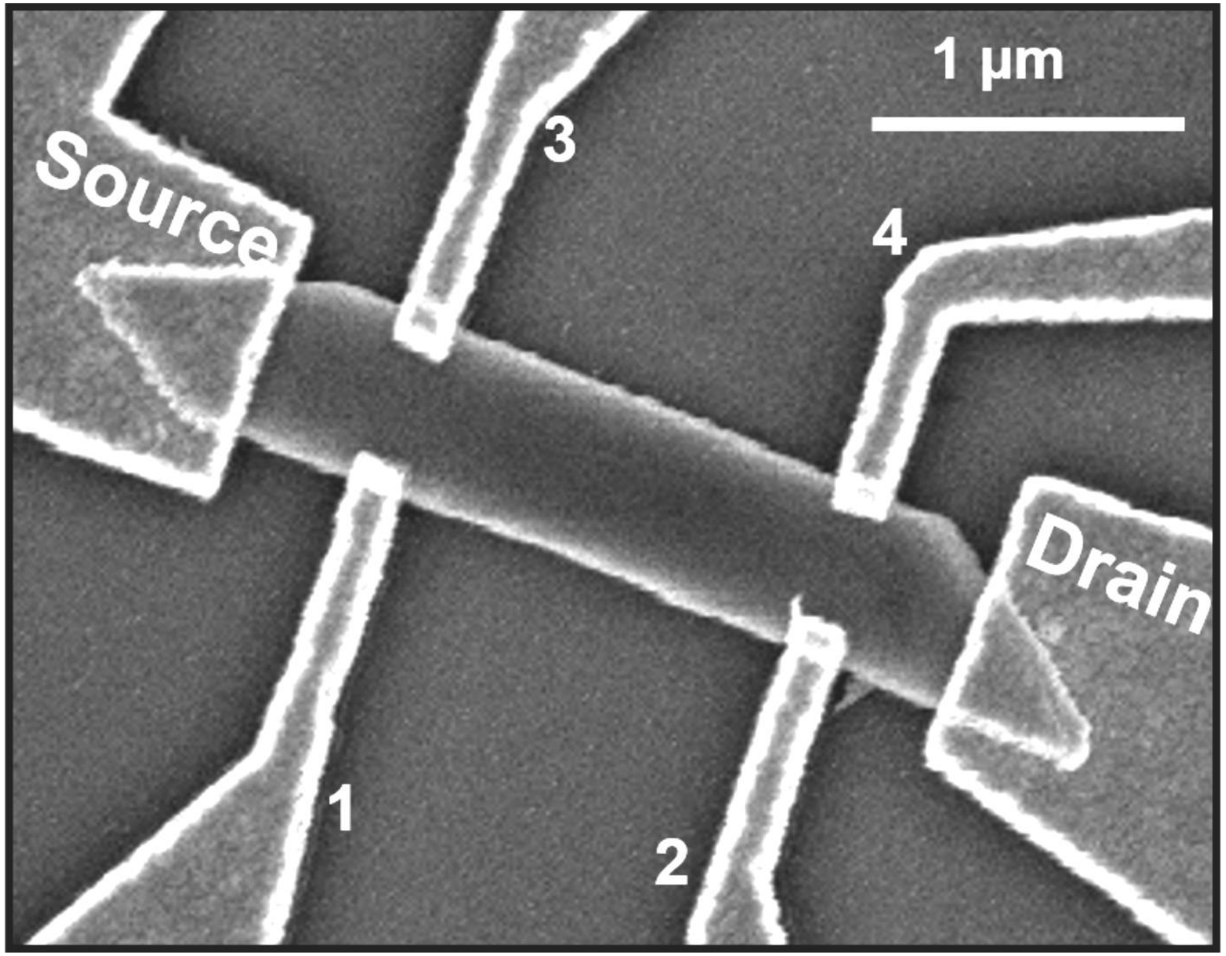
EDX confirms chem. composition of metal alloy seed particle as $AuIn_2$.

EDX confirms the purity, stoichiometry, and homogeneity of InSb.

The NF base (between InP and InSb is highly defected, with a mixed WZ/ZB stacking, but after 10 nm InSb the perfect ZB structure is recovered.

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

InSb Nanoflag Hall-bar device



L = 1.5 µm
W = 325 nm
d = 100 nm

10 nm Ti/190 nm Au
Substrate: Si/SiO_2

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

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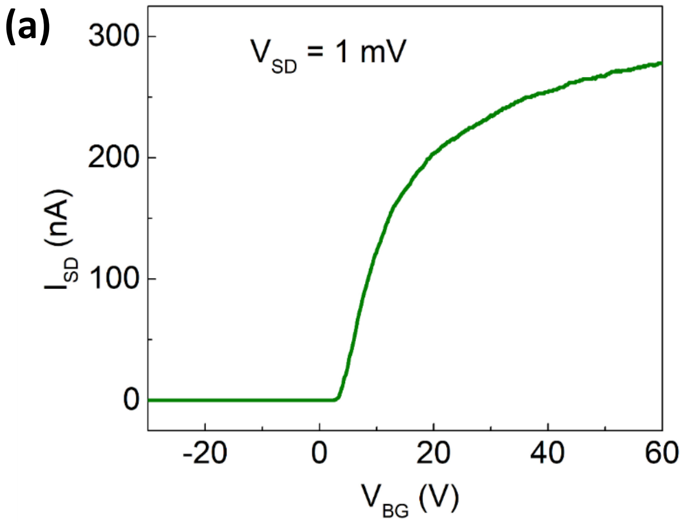
InSb NF mobility

T = 4.2 K



Field-effect :

n-type conduction

$\mu_{FE} = 2.8 \times 10^4$ cm²/Vs

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

InSb NF mobility

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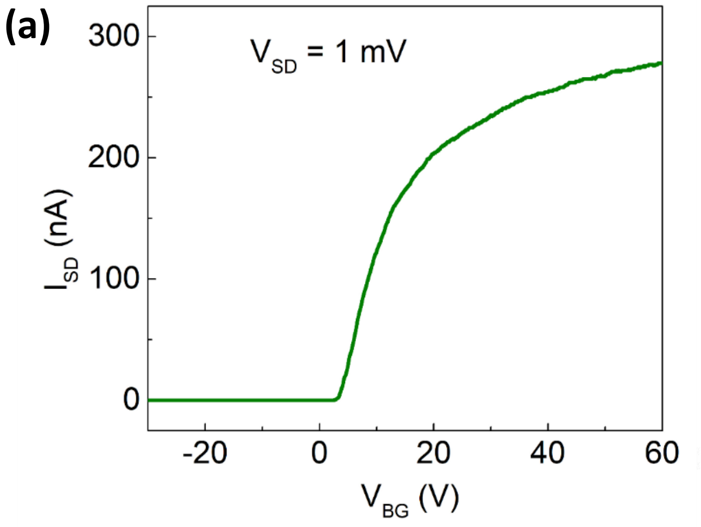

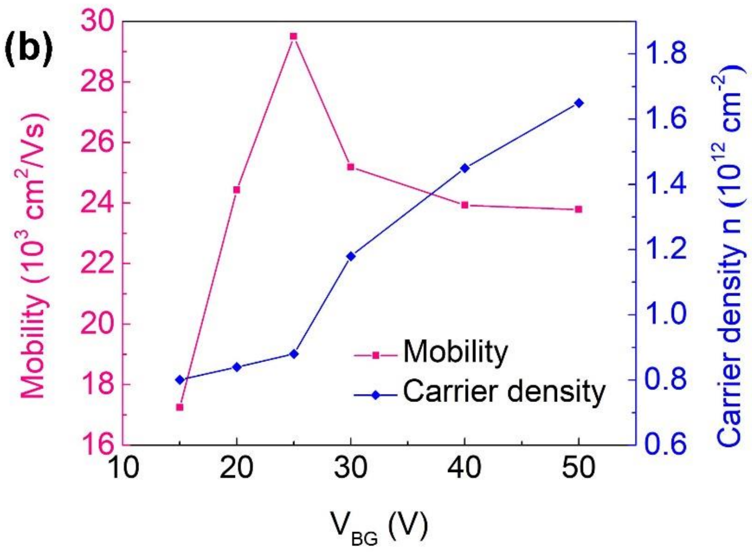

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Hall mobility:

$\mu_H = 2.95 \times 10^4$ cm^2/Vs

@ n = 8.5 x 10^{11} cm^{-2}

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

InSb NF mobility

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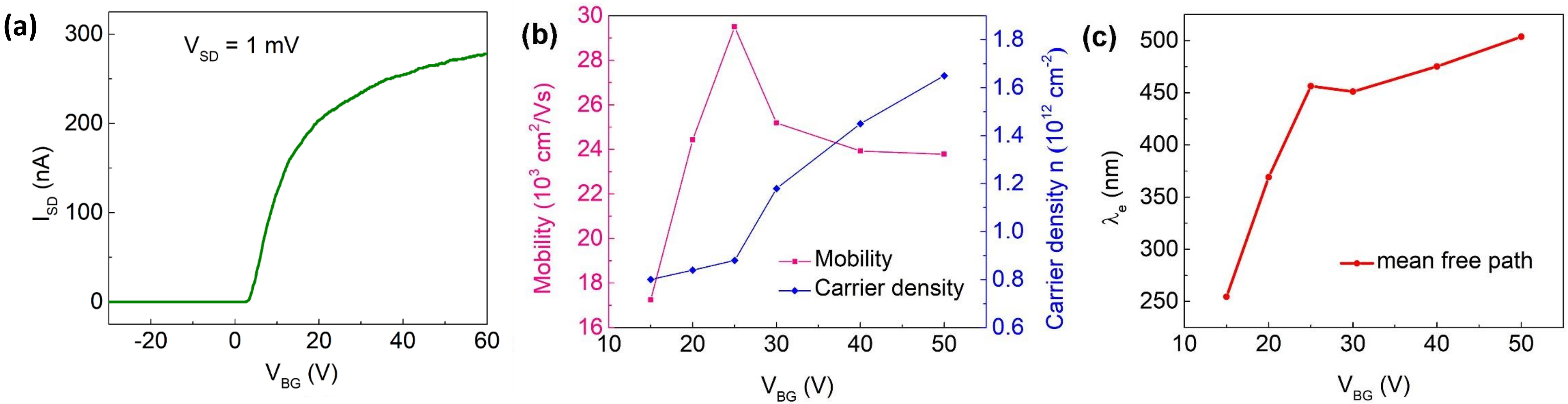

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Mean free path:

$\lambda \sim 500$ nm

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

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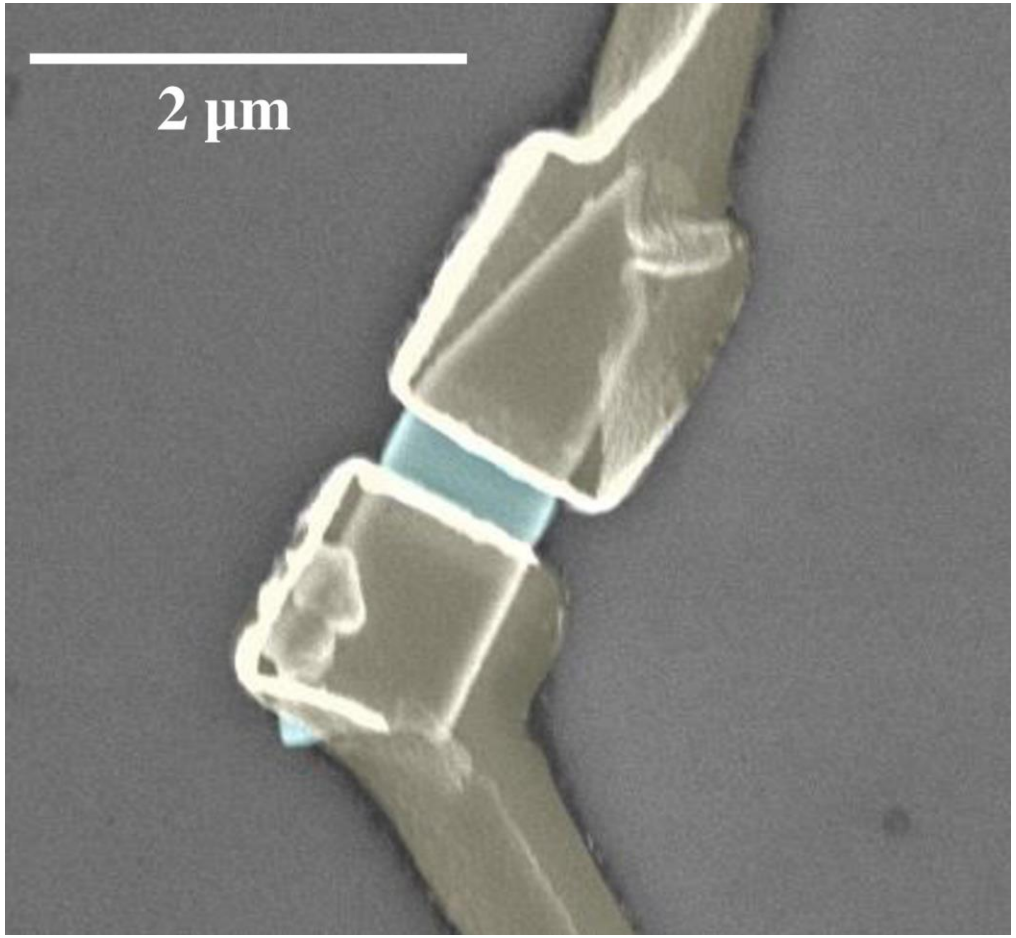
Nb/Ti-InSb Nanoflag-based JJs



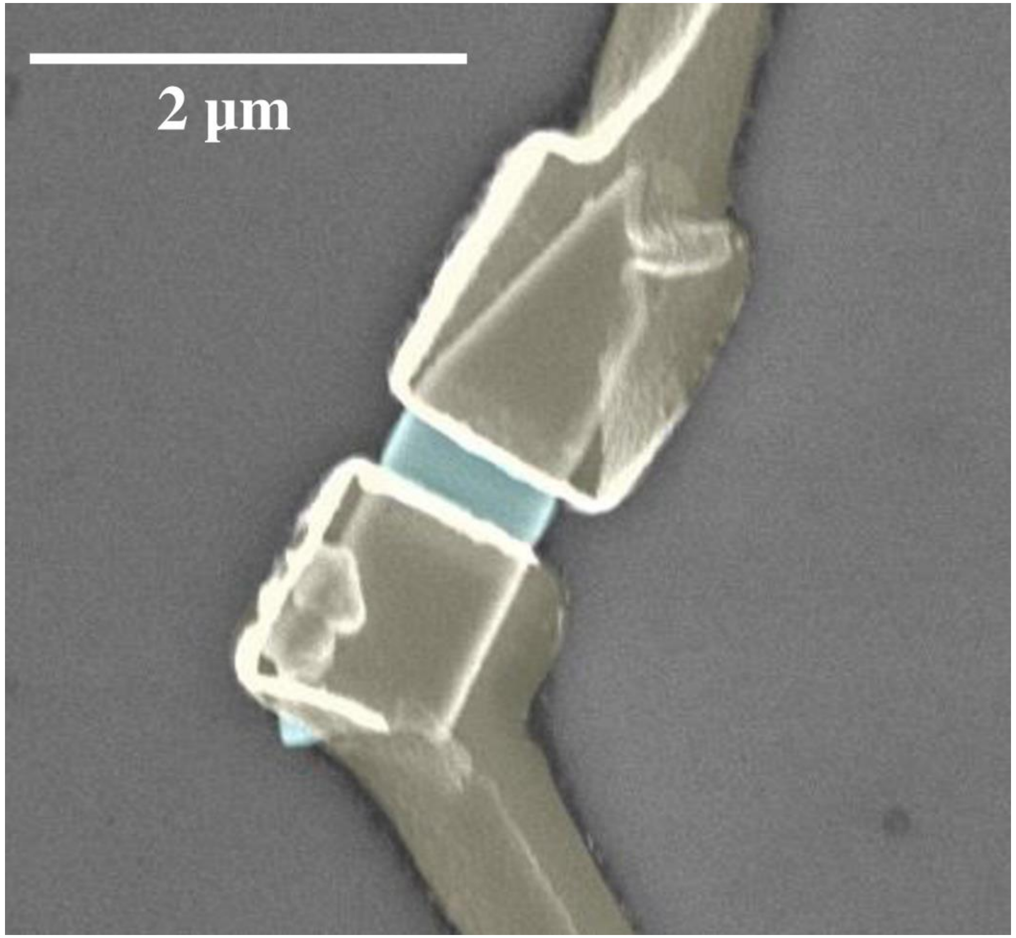
10 nm Ti/150 nm Nb
Substrate: Si/SiO_2

L = 200 nm
W = 700 nm

Sedighe Salimian

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

Nb/Ti-InSb Nanoflag-based JJs



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L = 200 nm
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T_c = 8.44 K → Δ = 1.28 meV


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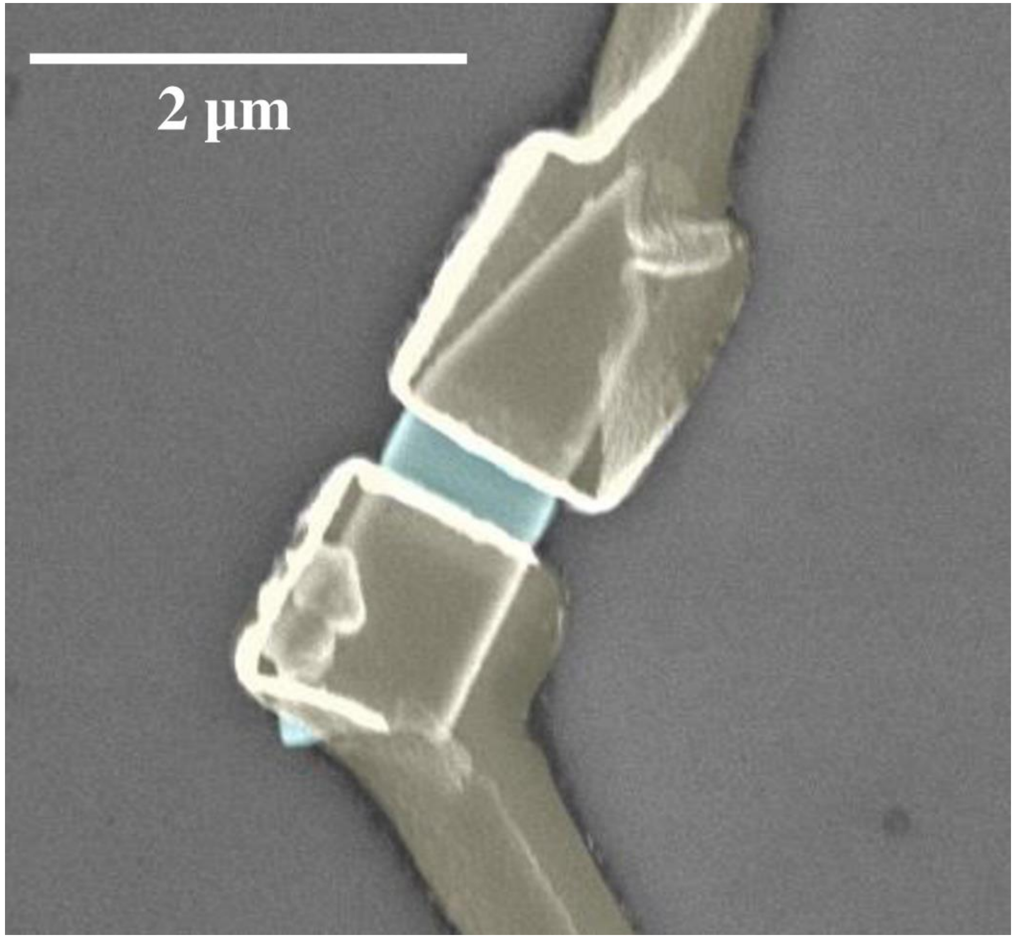

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λ_e = 500 nm → ballistic regime

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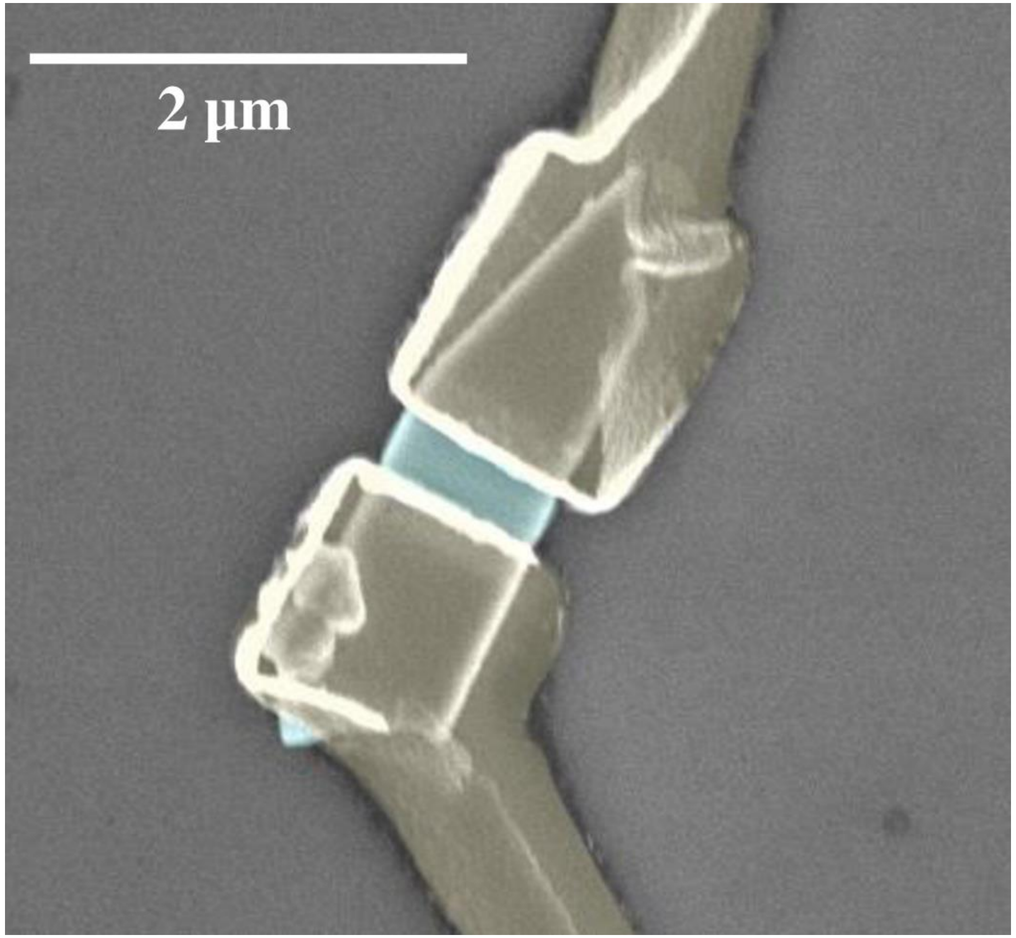

10 nm Ti/150 nm Nb
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L = 200 nm
W = 700 nm

T_c = 8.44 K → Δ = 1.28 meV

λ_e = 500 nm → ballistic regime

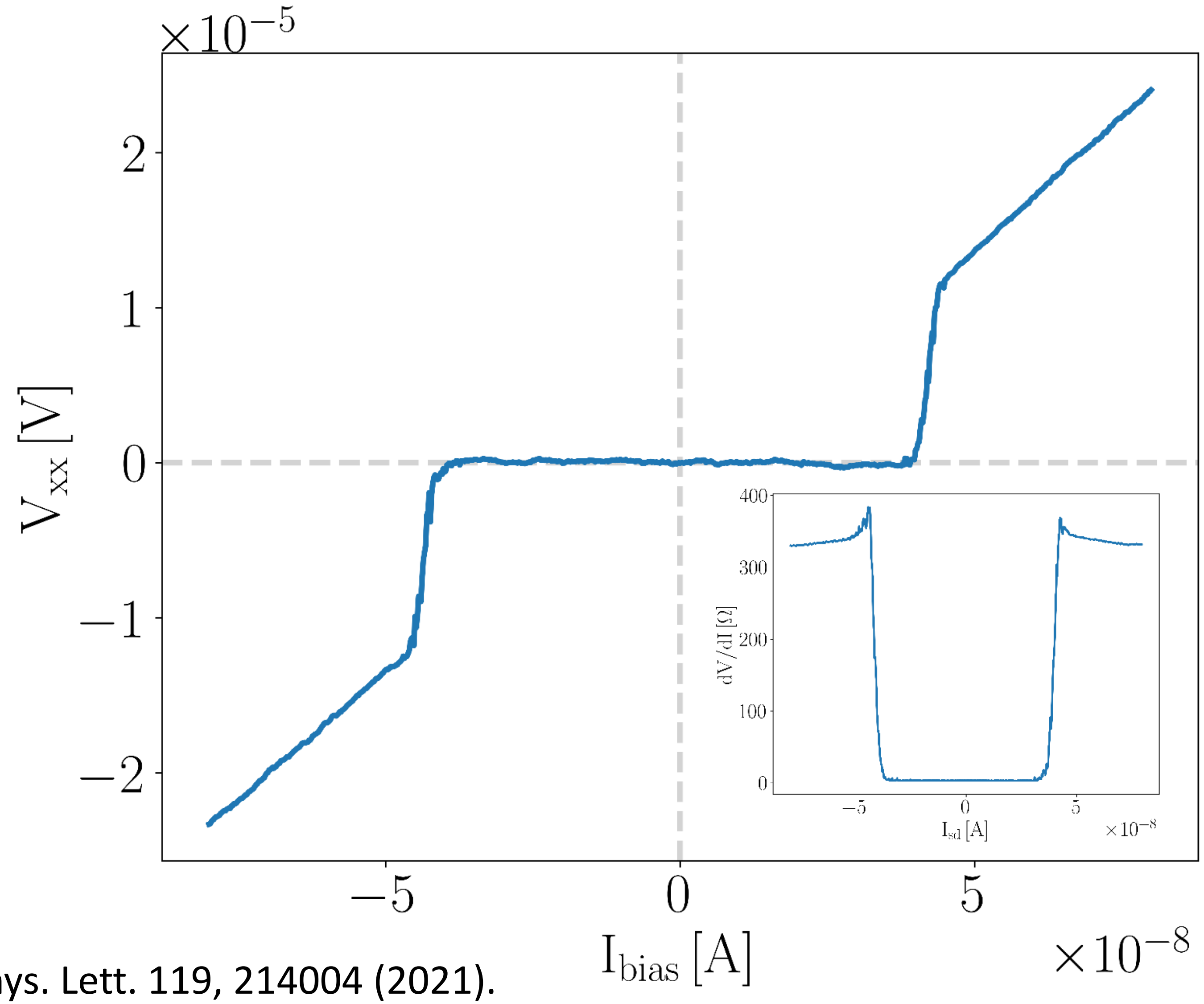
$\xi_s = \hbar v_F/\Delta \sim 750$ nm → short junction

Sedighe Salimian

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

V-I shows supercurrent

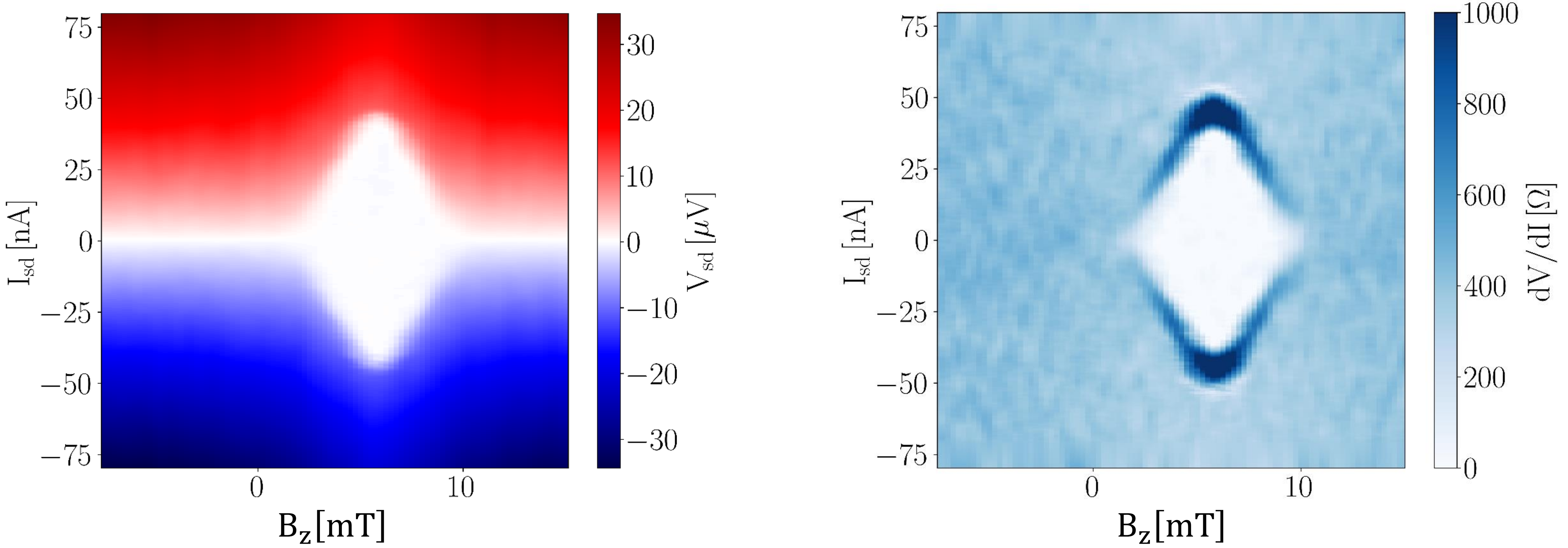
T = 250 mK



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

Magnetic Interference Pattern

T = 250 mK



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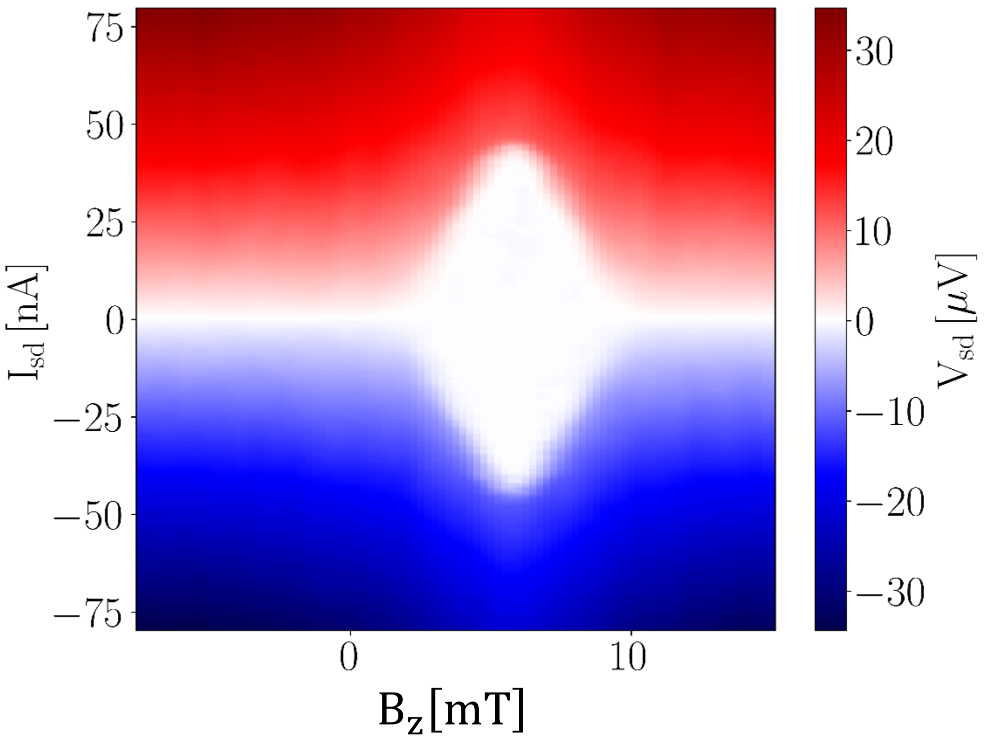
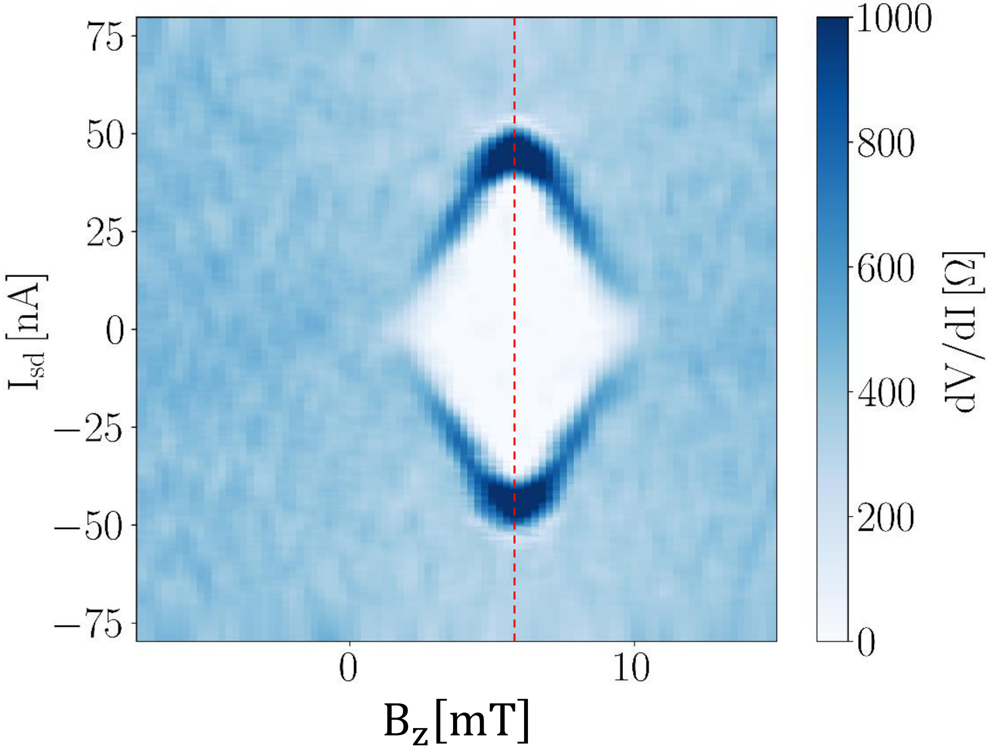




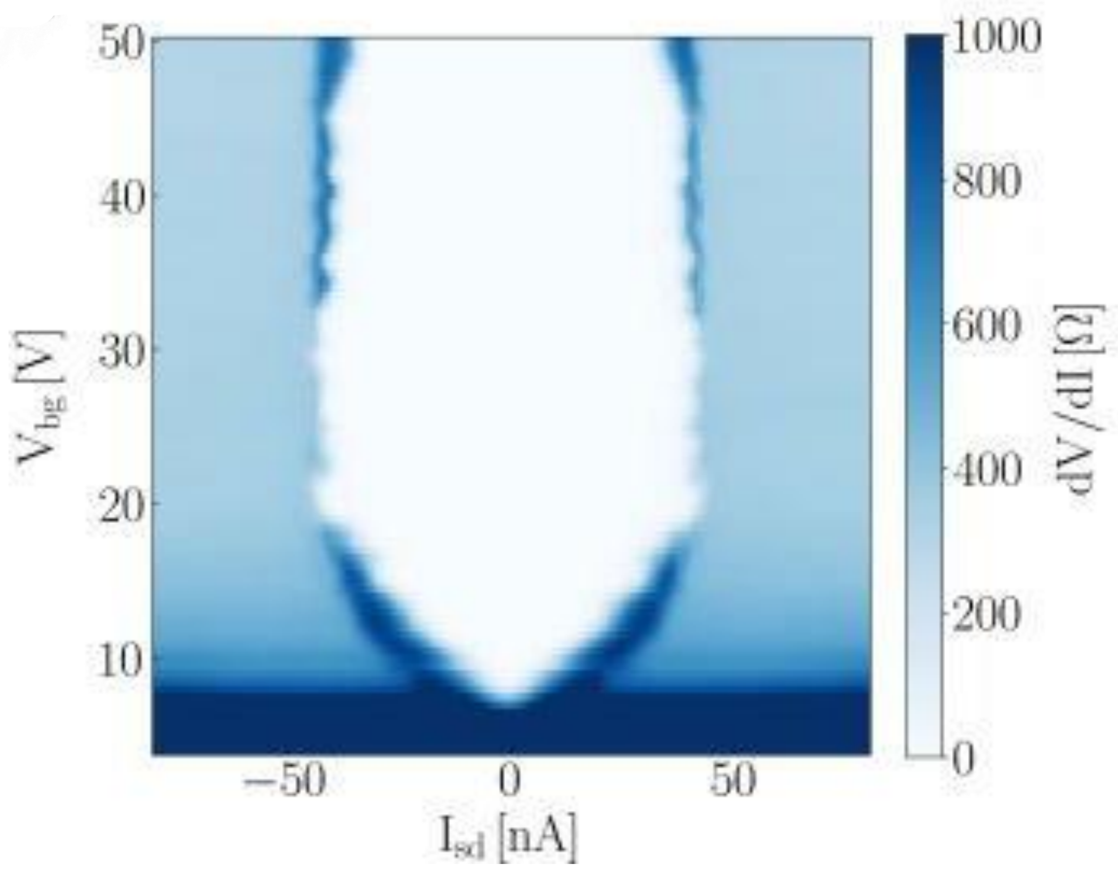
Why no sides lobes in the Fraunhofer pattern?

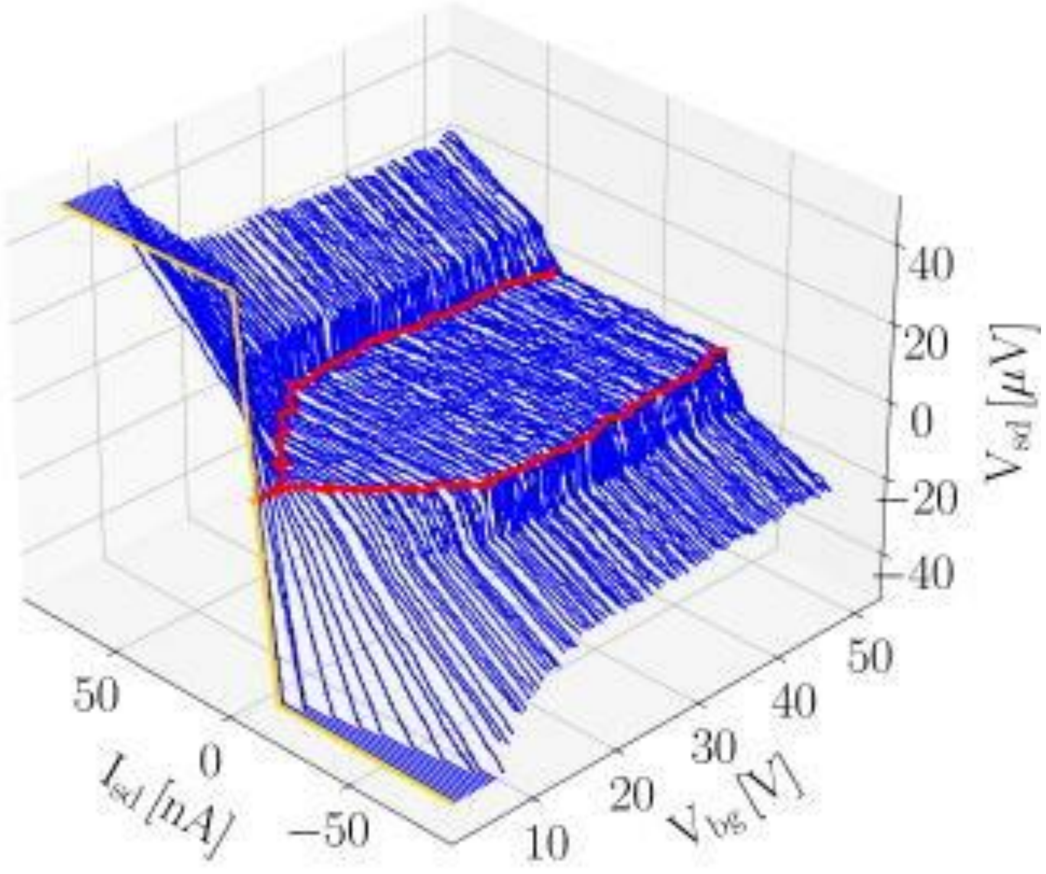
- Even-odd effect? (de Vries et al., Phys. Rev. Res. 1 (2019) 032031)
- Narrow junction? (Cuevas & Bergeret, Phys. Rev. Lett. 99 (2007) 217002)

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

Gate-controlled supercurrent

T = 250 mK

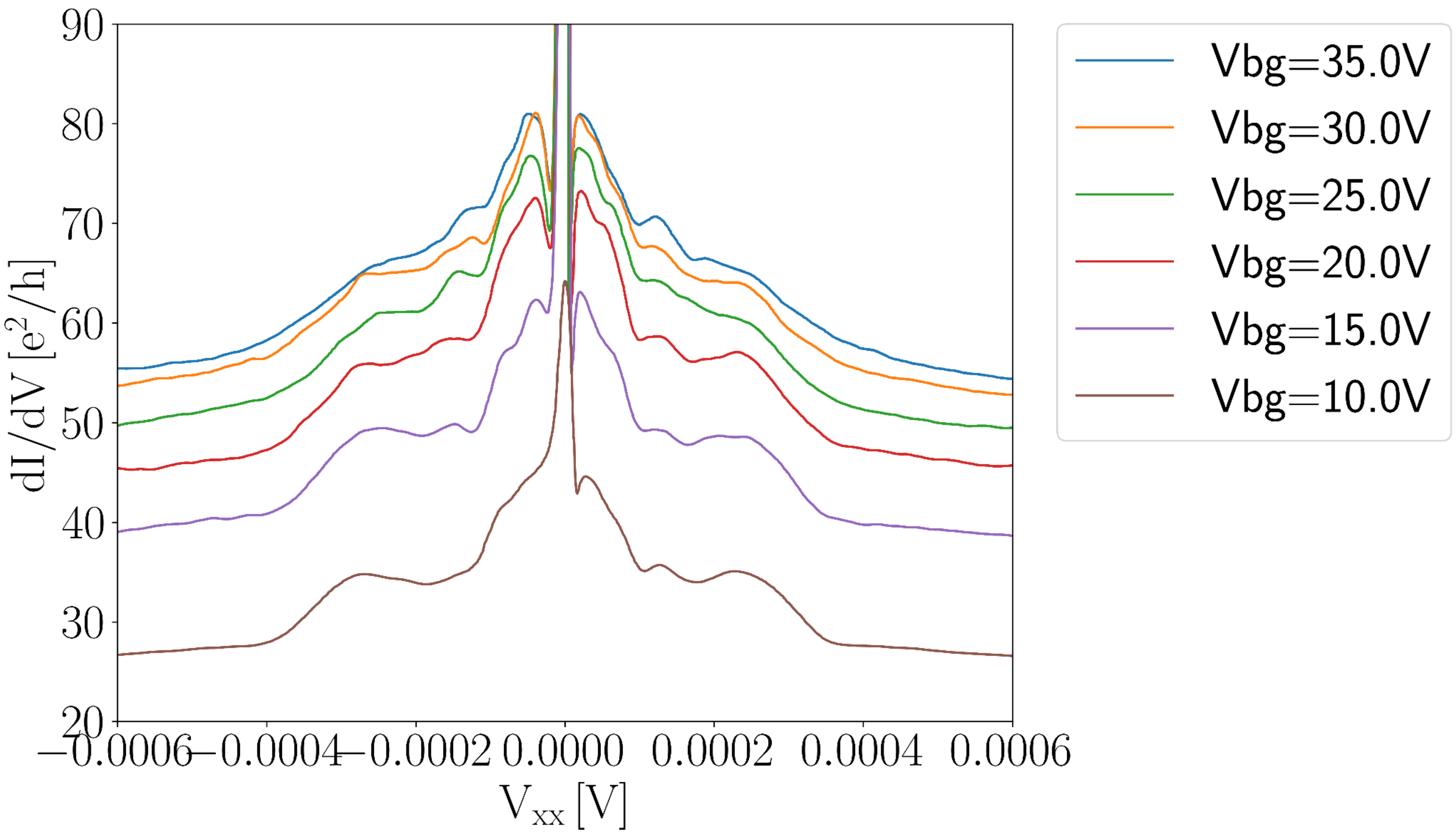




S. Salimian et al., Appl. Phys. Lett. 119, 214004 (2021).

Multiple Andreev Reflections

T = 250 mK



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Multiple Andreev Reflections

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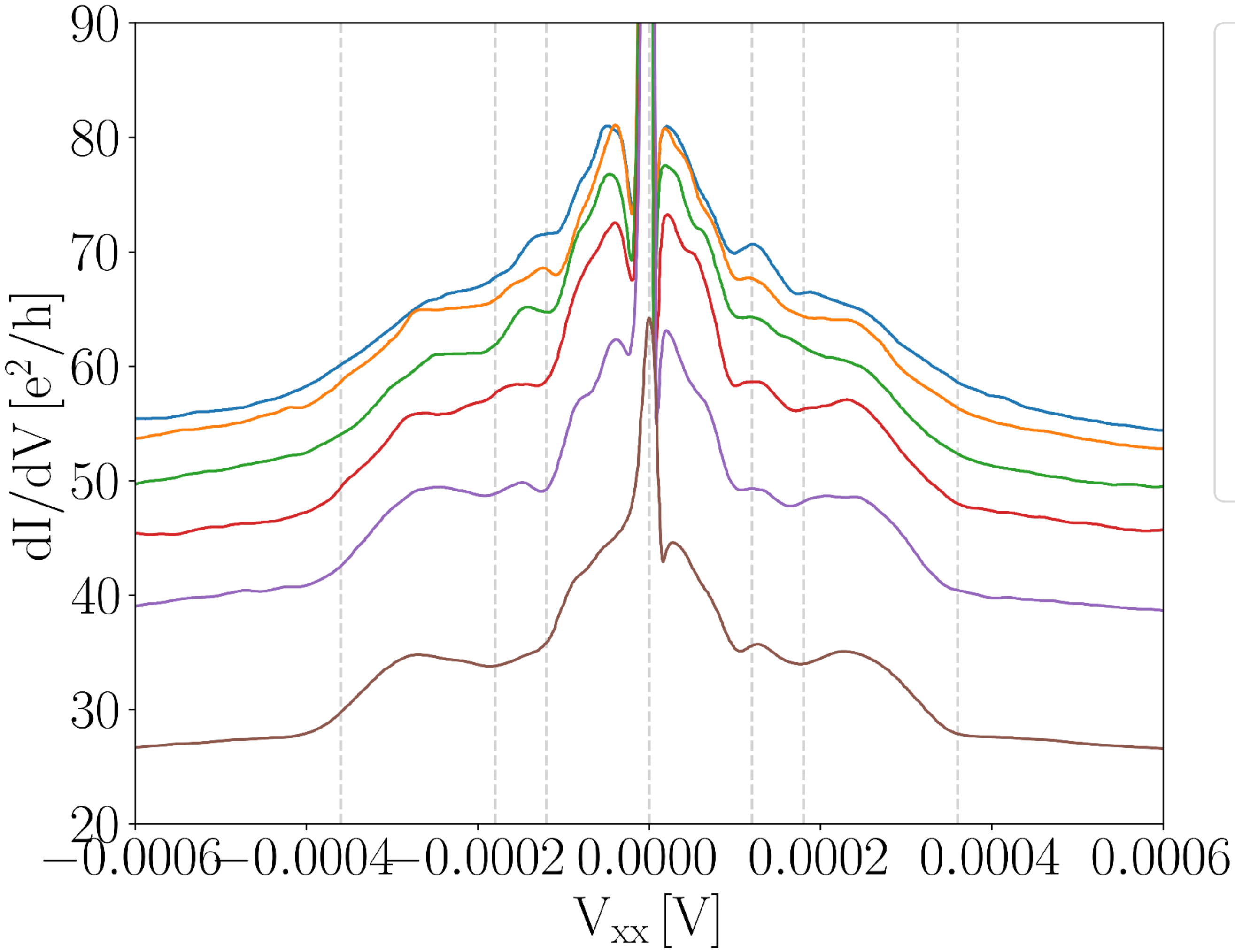

Michal P. Nowak

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).

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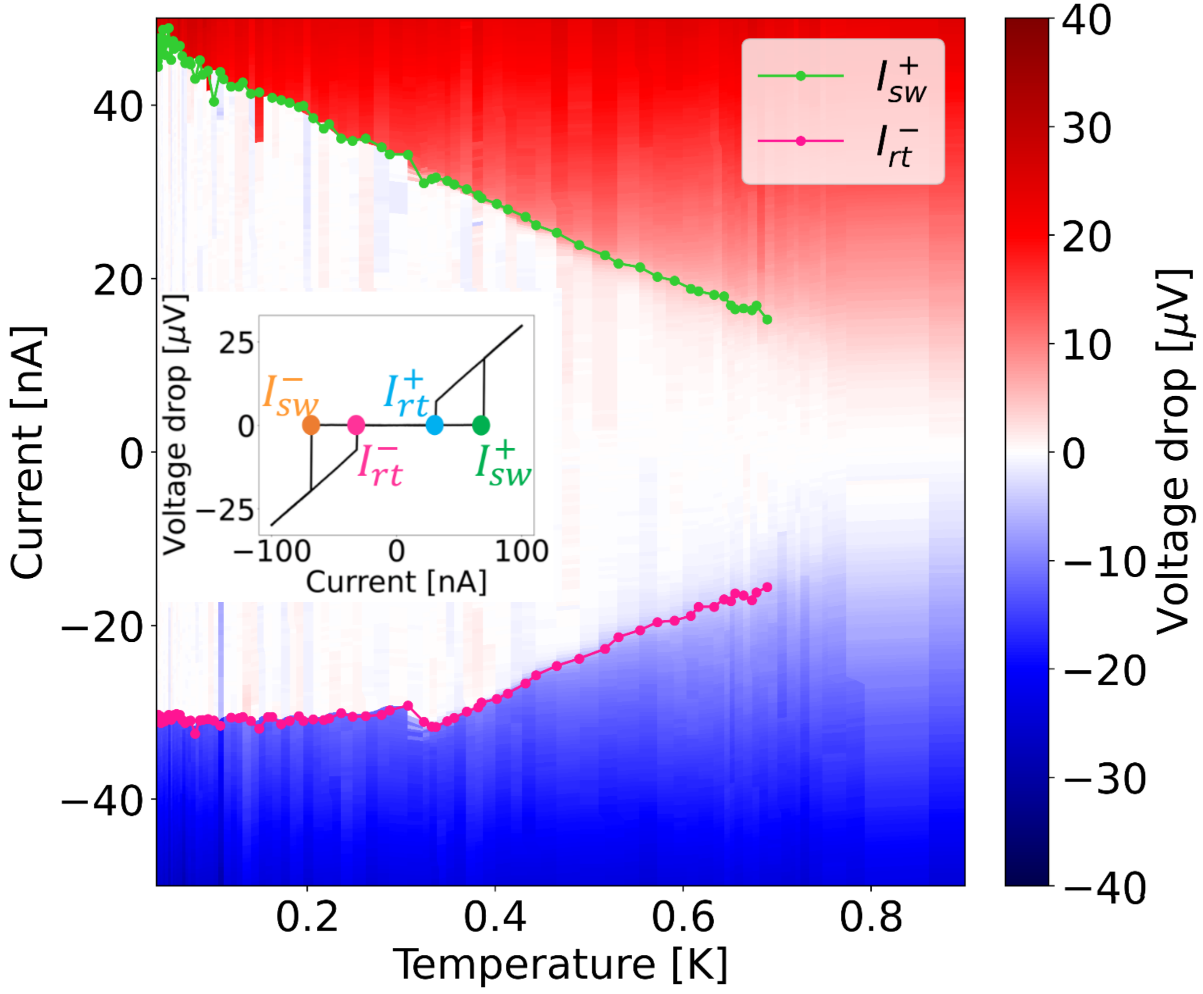
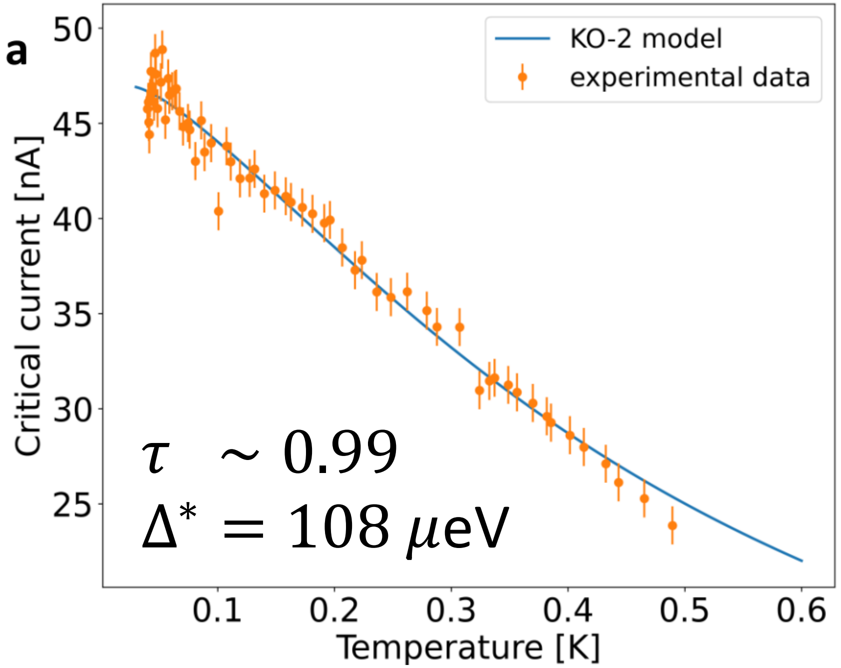
Temperature dependence

T = 30 mK



KO-2 model:

$$I(\varphi) = I_0 f(\varphi) = I_0 \frac{\bar{\tau} \sin\varphi \tanh\left[\frac{\Delta^*}{2k_B T}\sqrt{1-\bar{\tau}\sin^2\left(\frac{\varphi}{2}\right)}\right]}{2\sqrt{1-\bar{\tau}\sin^2\left(\frac{\varphi}{2}\right)}}$$



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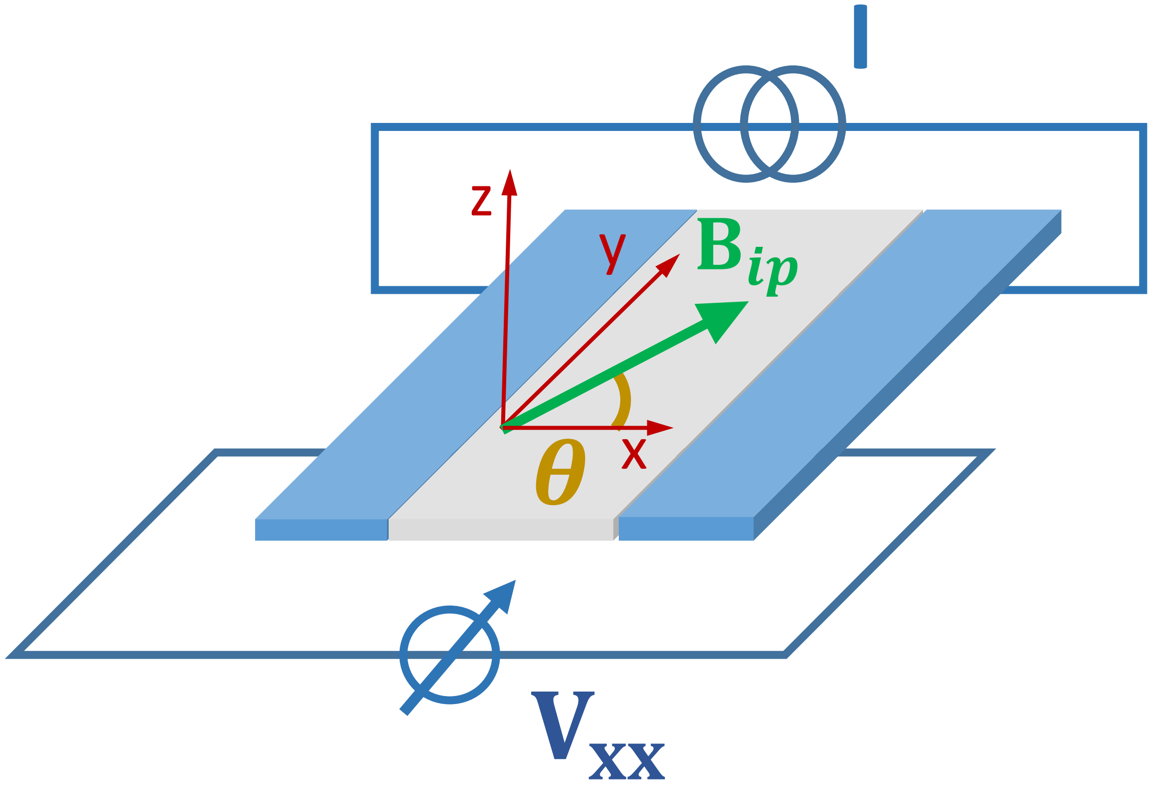
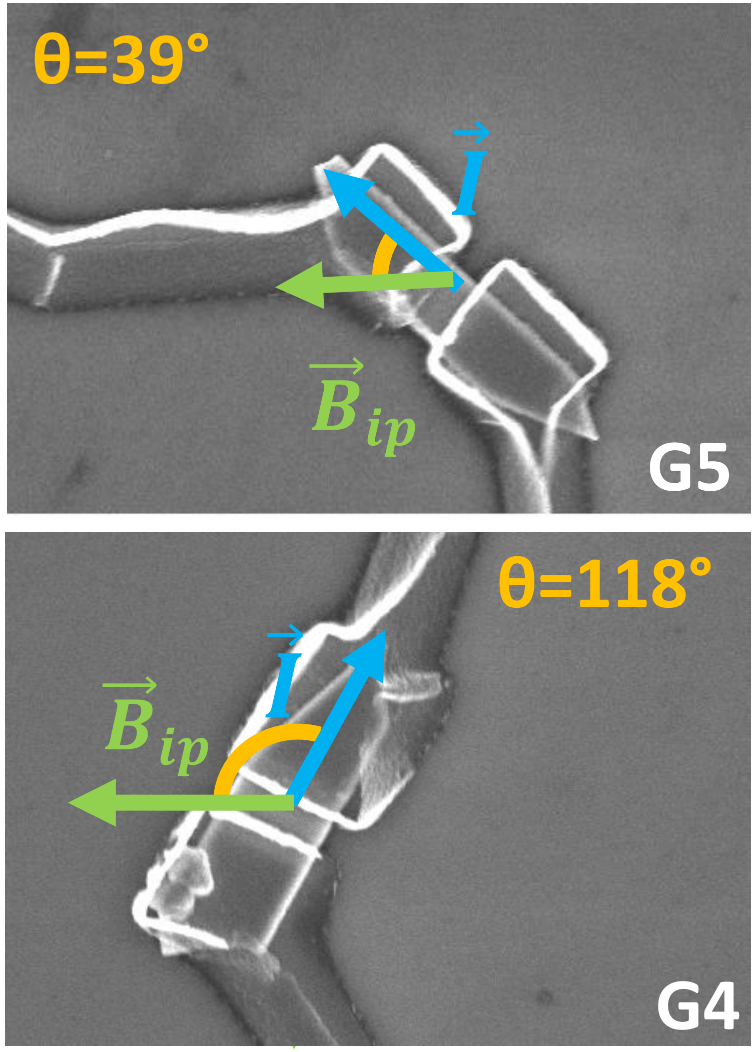
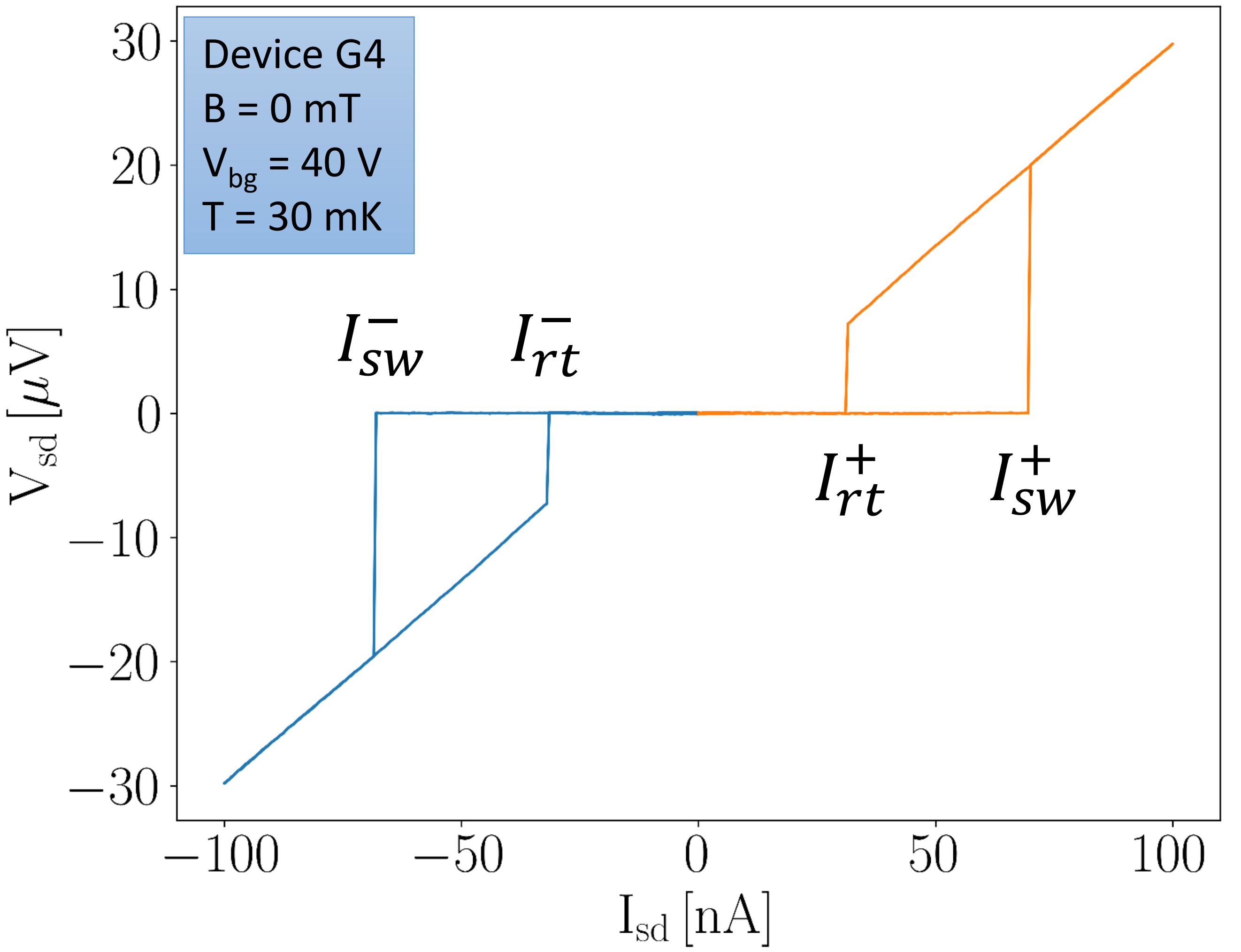
Design of the experiment





B. Turini et al., arXiv:2207.08772, Nano Letters, in press.

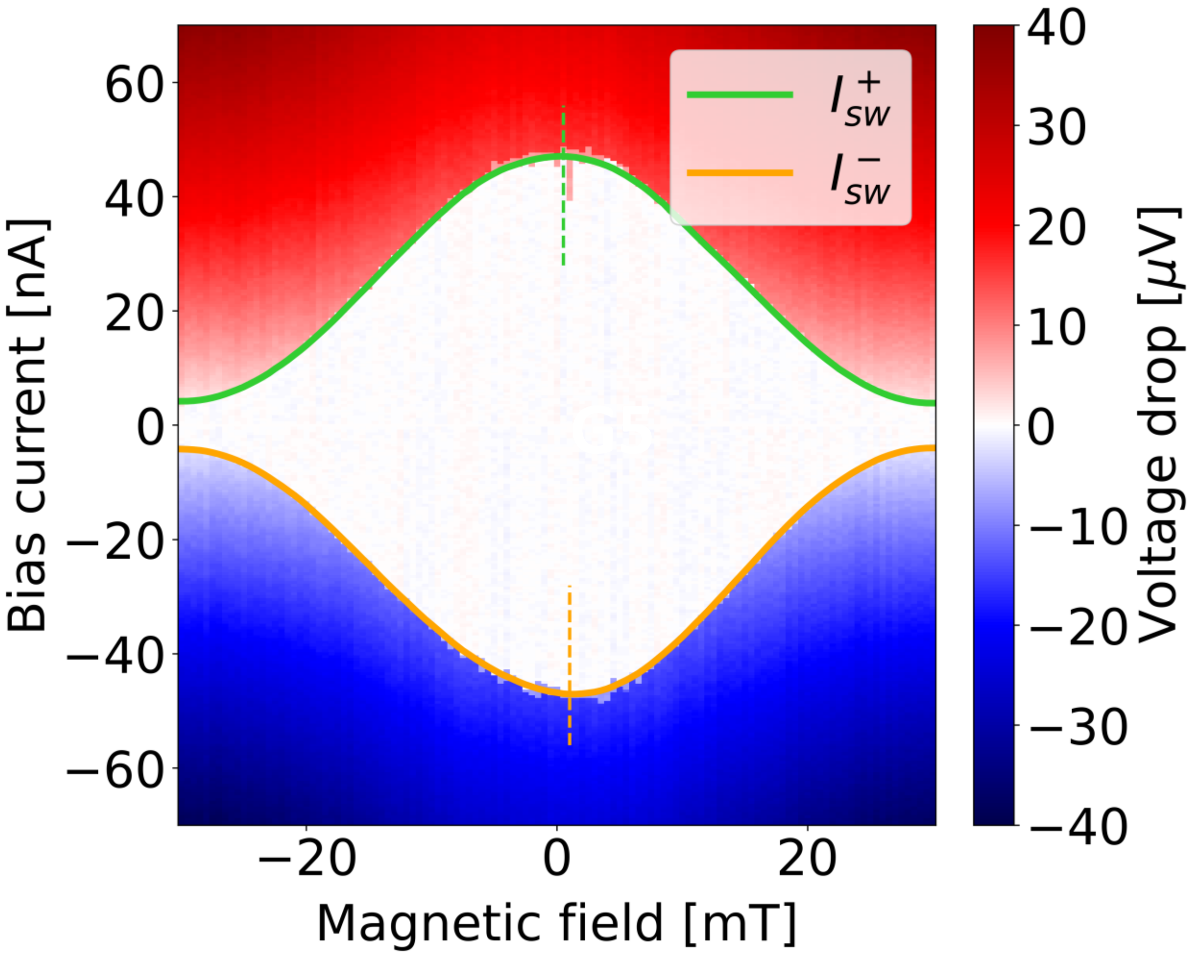
Supercurrent at 30 mK

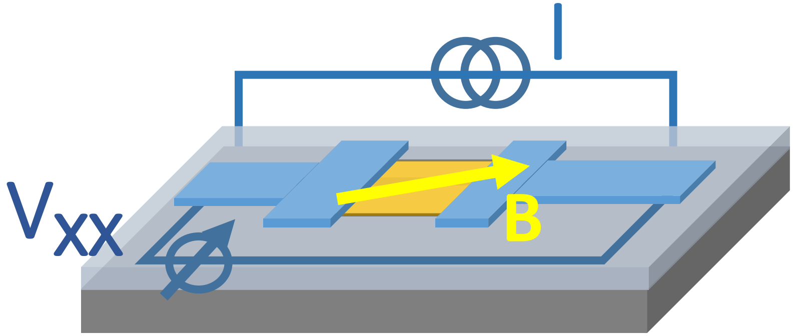


Bianca Turini

B. Turini et al., arXiv:2207.08772, Nano Letters, in press.

Magnetic field-driven JDE





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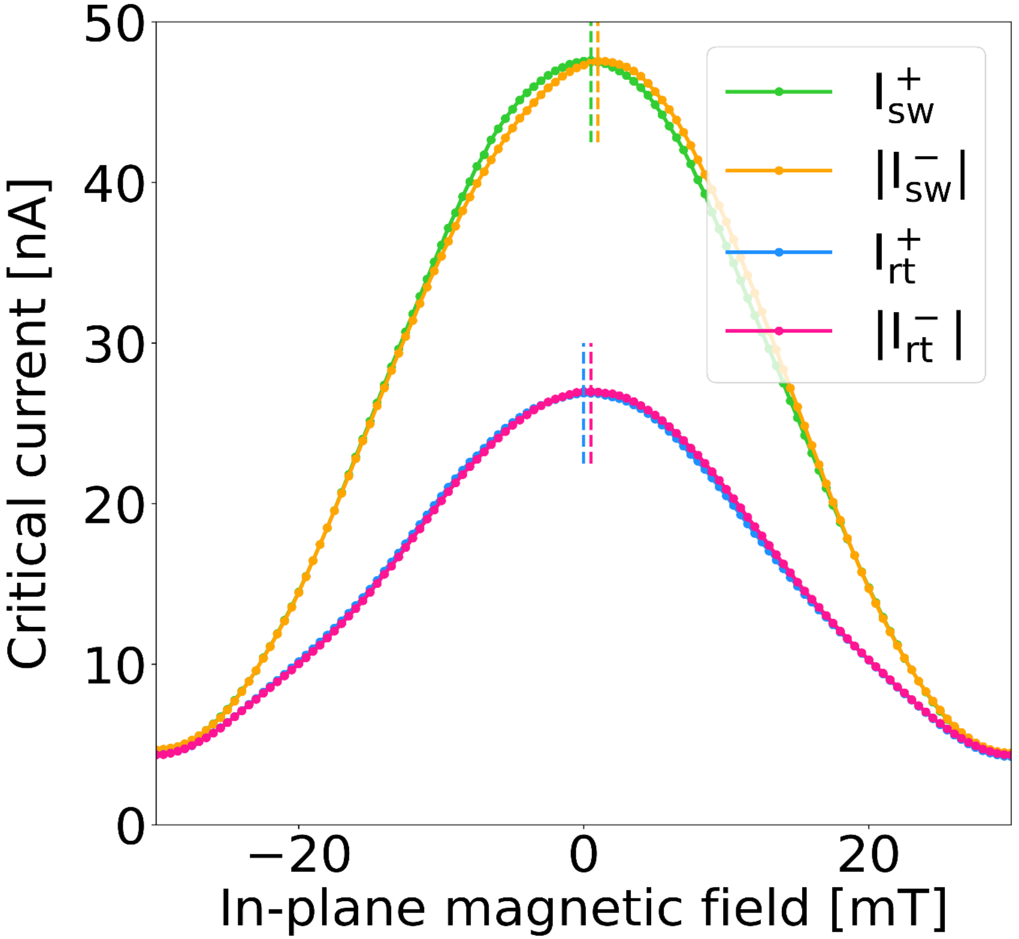

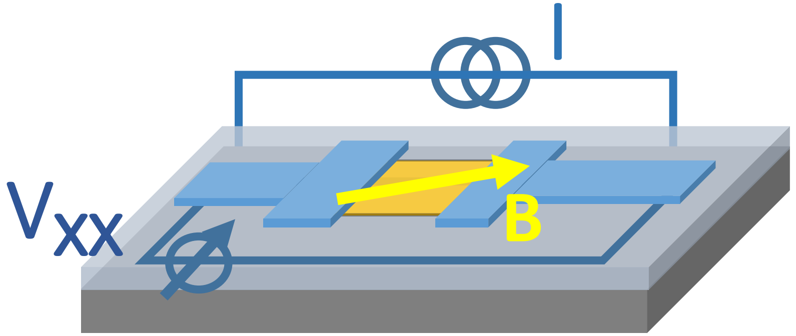

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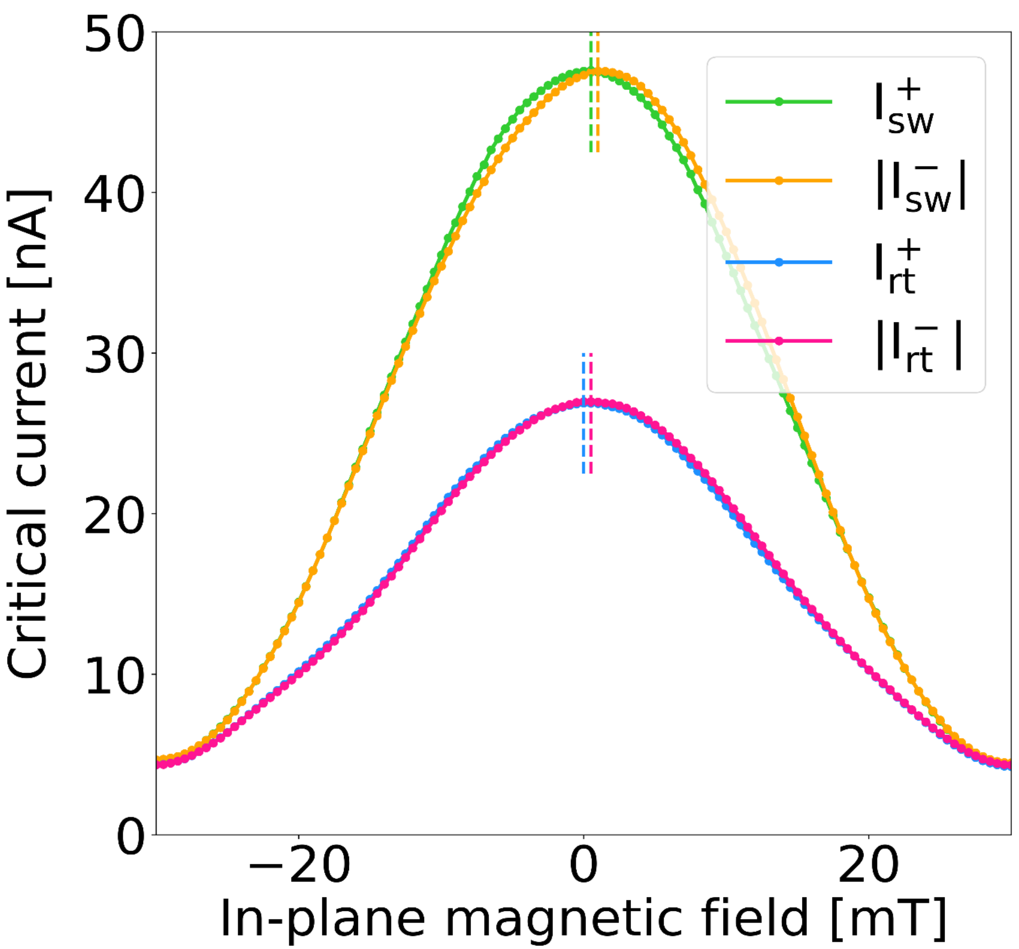
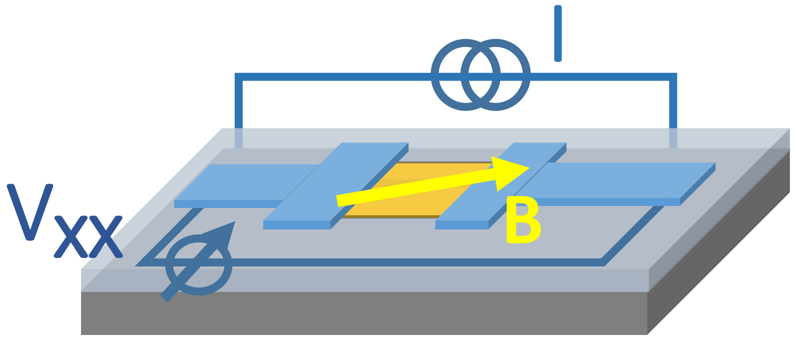
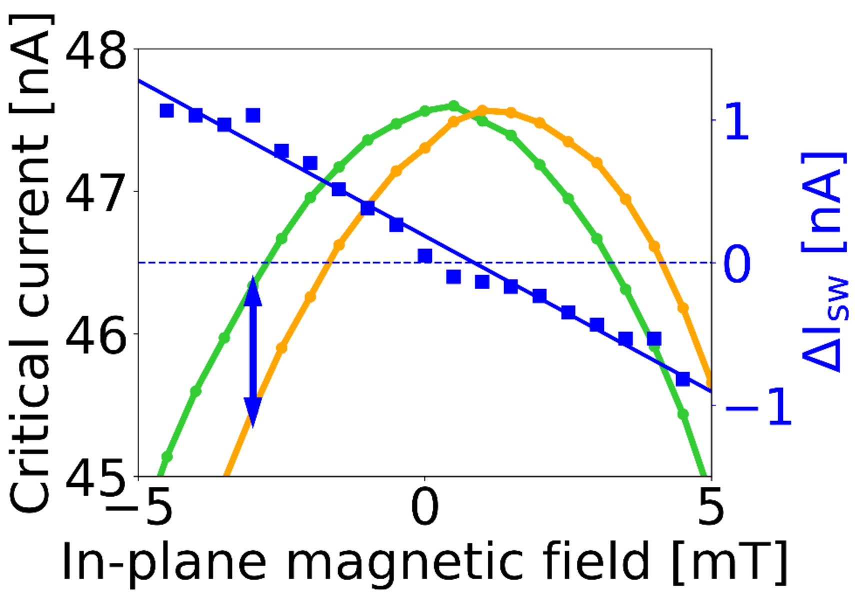
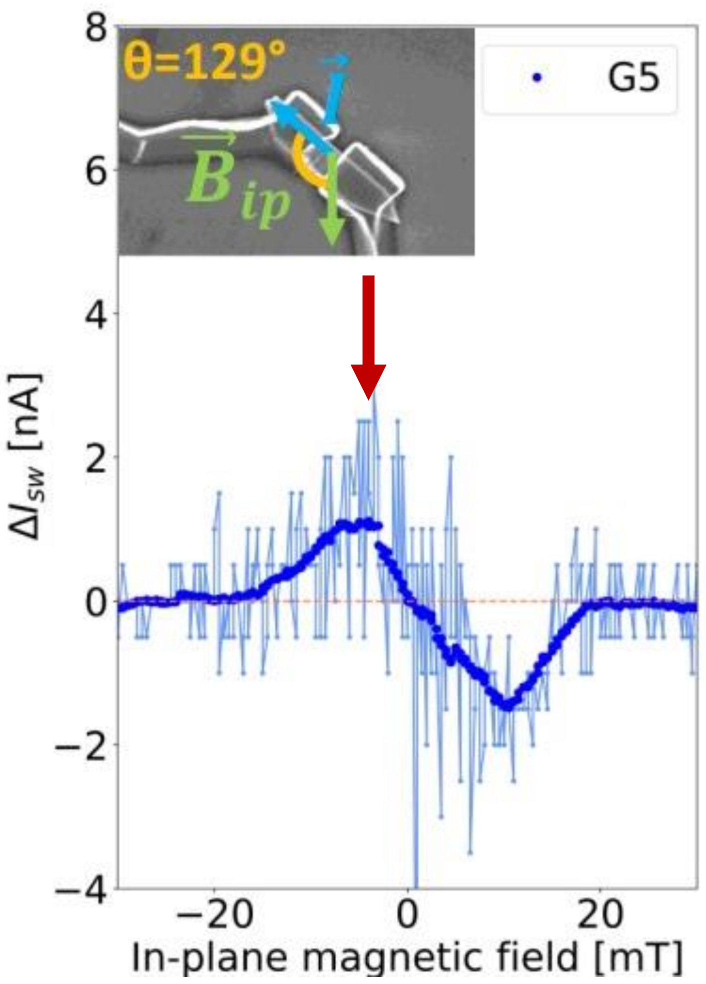


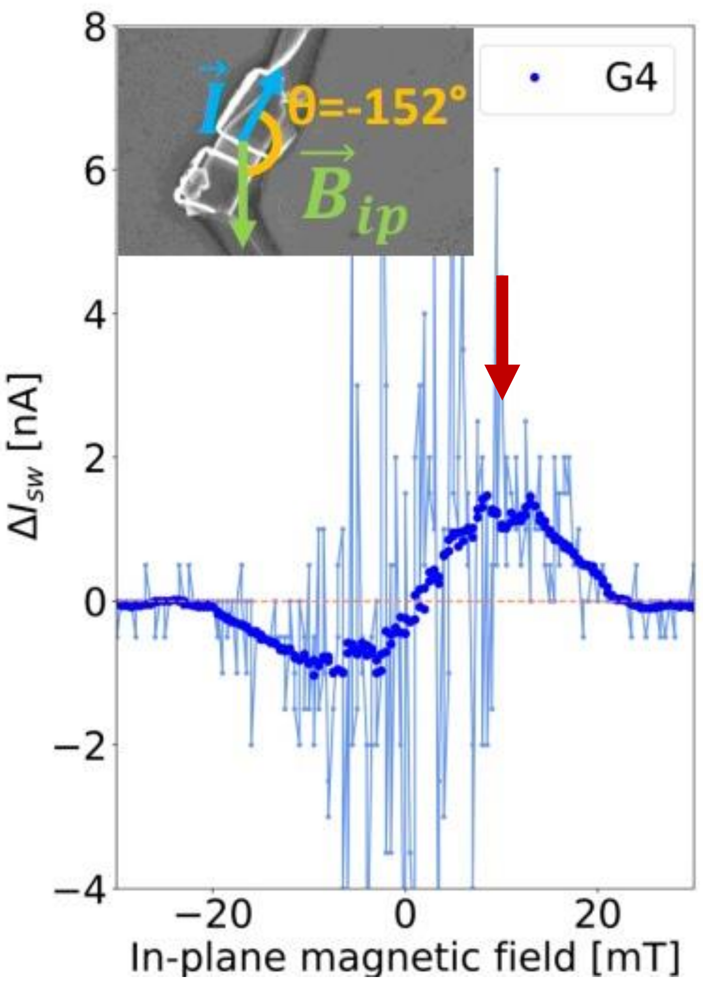




B. Turini et al., arXiv:2207.08772, Nano Letters, in press.

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., arXiv:2207.08772, Nano Letters, in press.

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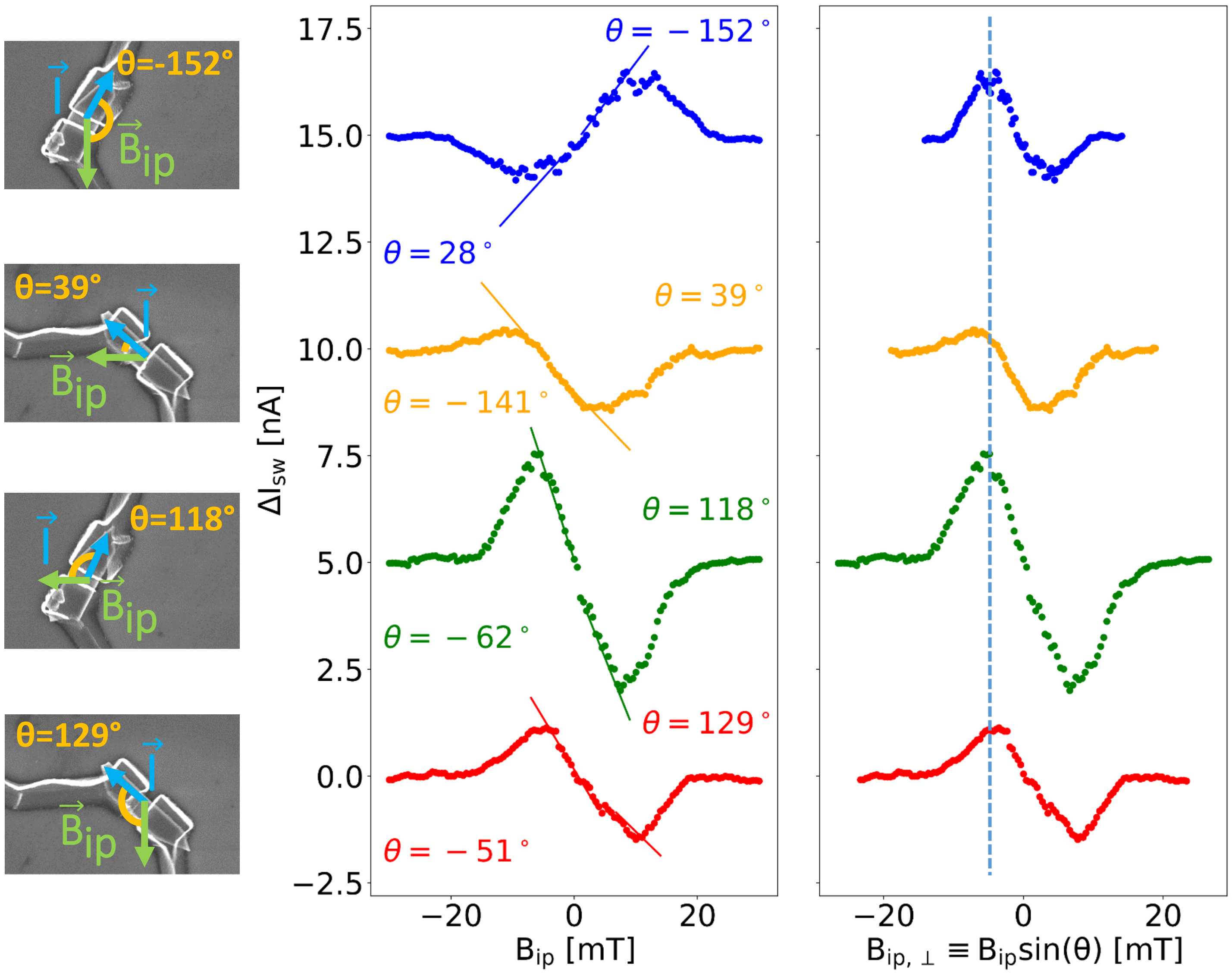
Dependence on the angle



$$\Delta I_{sw} \propto |\boldsymbol{B} \times \boldsymbol{I}|$$

Dominant Rashba spin-orbit coupling

B. Turini et al., arXiv:2207.08772, Nano Letters, in press.

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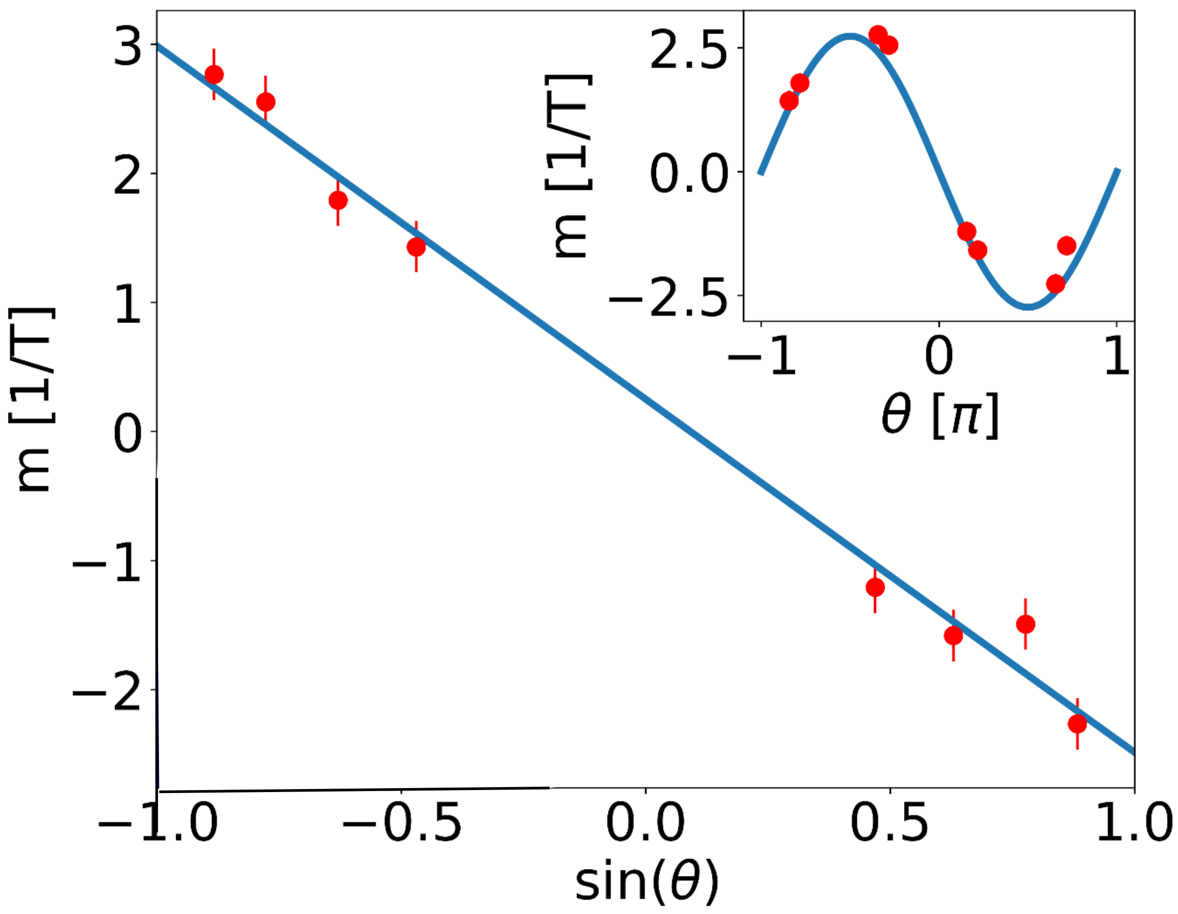
Field-driven JDE



Diode rectification coefficient η in the SO-dominated regime:

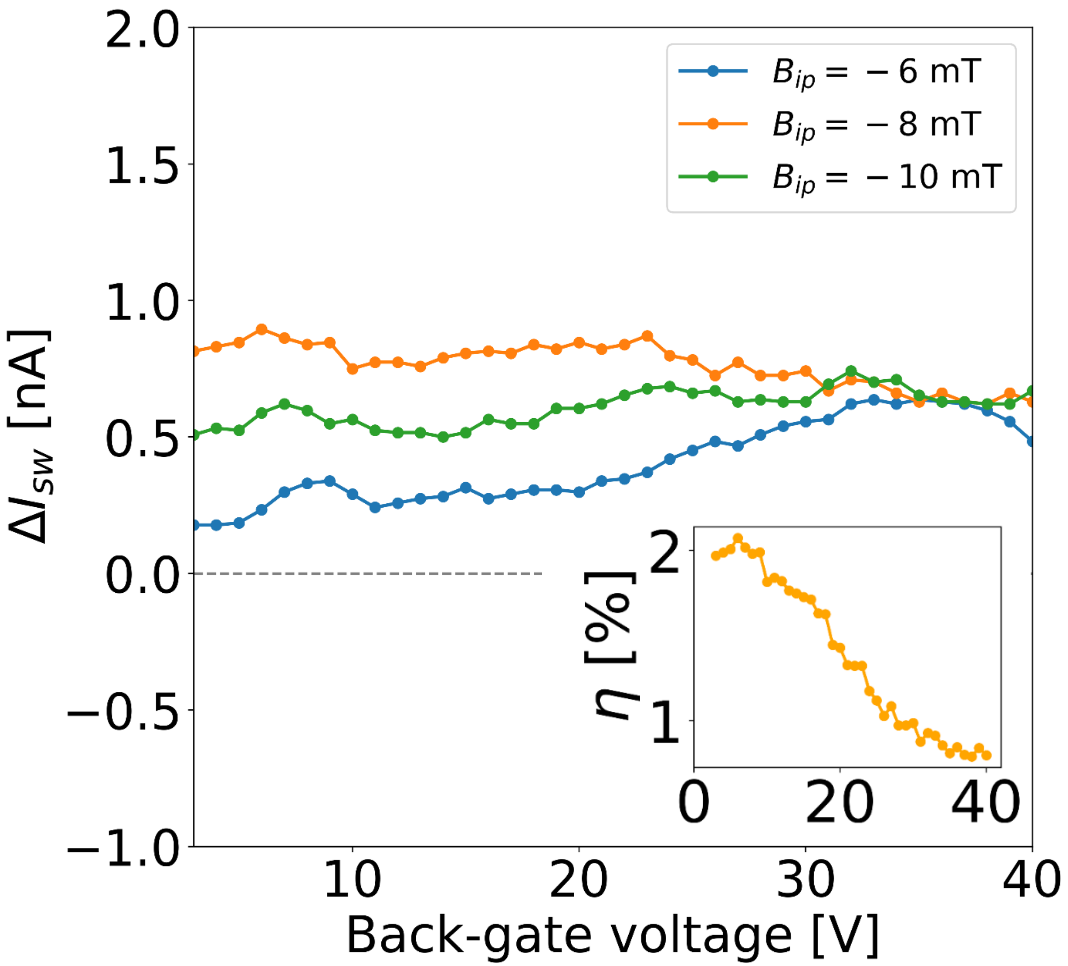
$$\eta = \frac{\Delta I_c}{I_c^+ + |I_c^-|} = \frac{2g^* \mu_B}{\pi \Delta^*} B \equiv \alpha B.$$

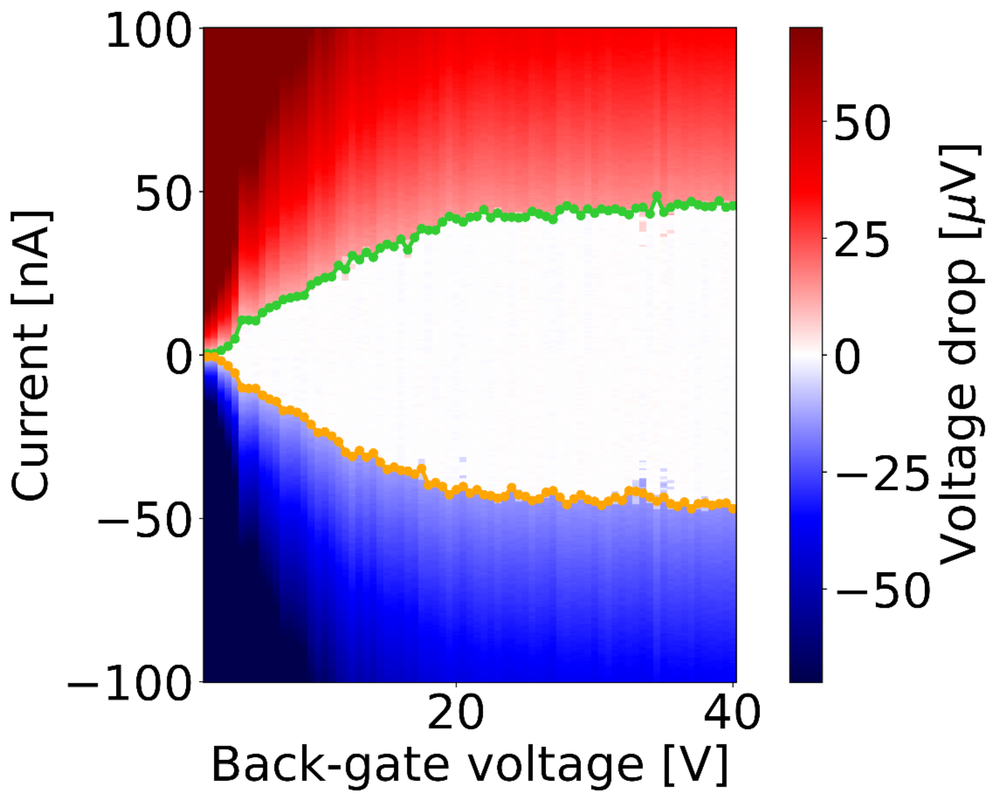
$$\alpha_{exp} = -3.0 \pm 0.2\, T^{-1}$$

Dolcini *et al.*, Phys. Rev. B 92, 03542 (2015)
Davydova *et al.*, Science Advances 8, eabo0309 (2022)

B. Turini et al., arXiv:2207.08772, Nano Letters, in press.

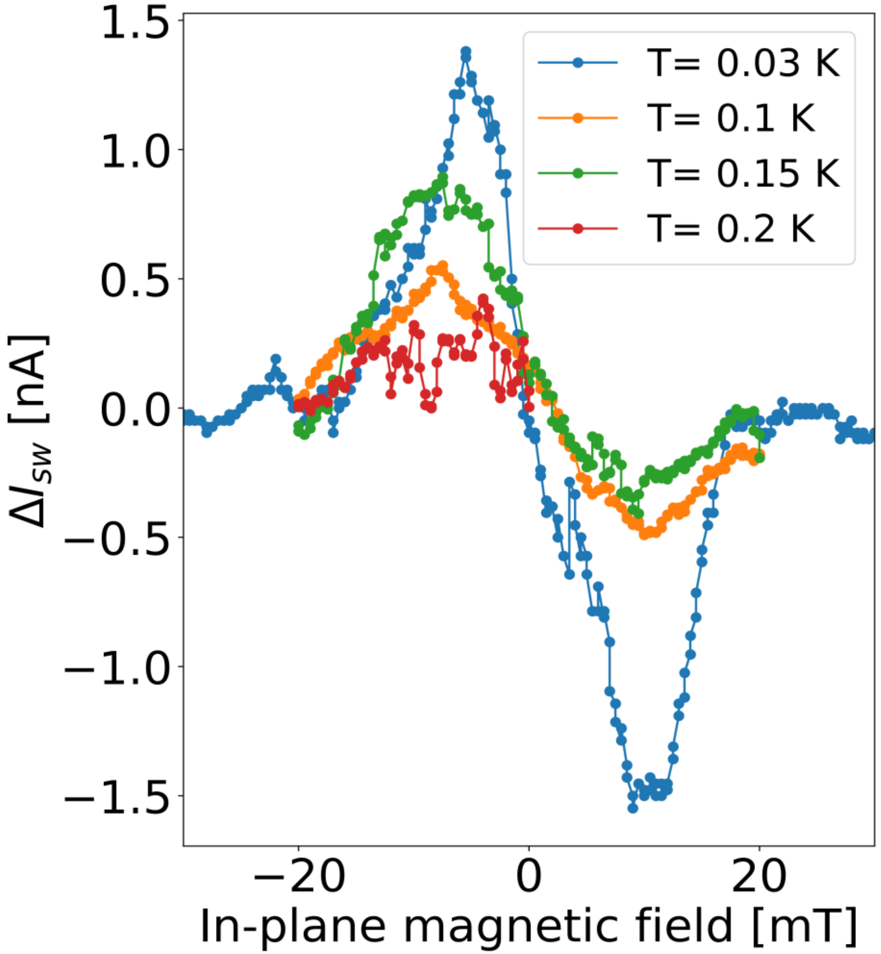
Back-gate dependence

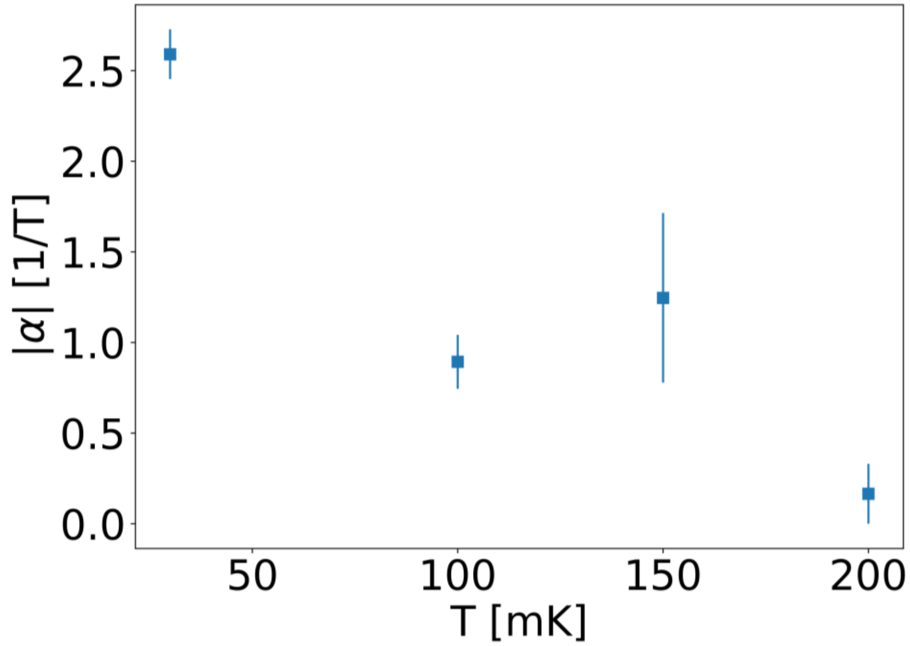




B. Turini et al., arXiv:2207.08772, Nano Letters, in press.

Temperature dependence



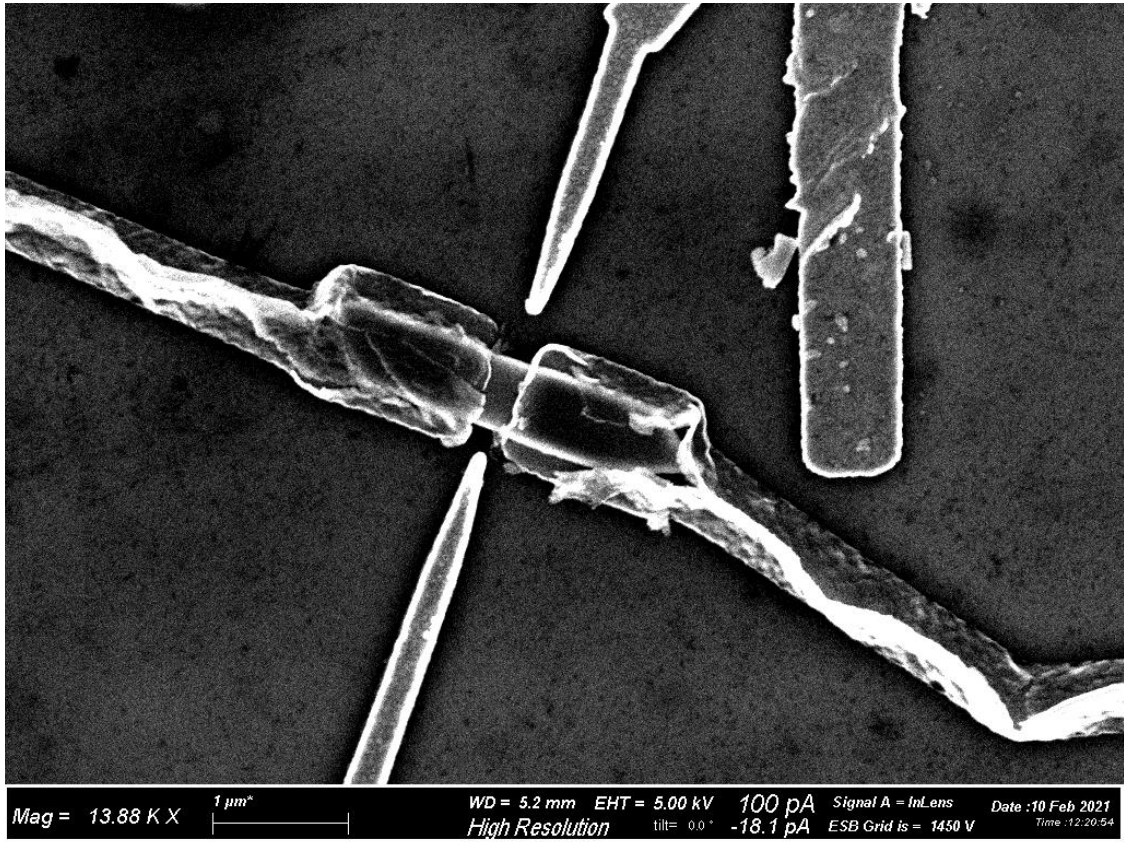


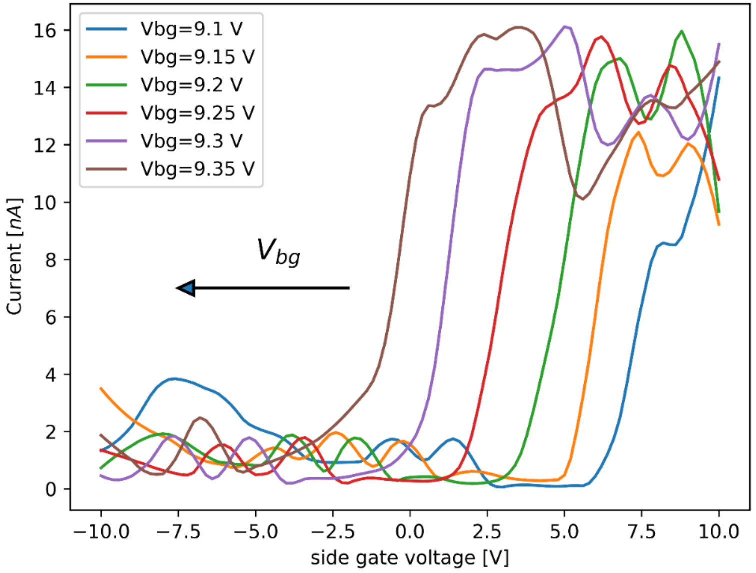
B. Turini et al., arXiv:2207.08772, Nano Letters, in press.

Outlook: gate-controlled SOI

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

Bianca Turini   Federico Paolucci





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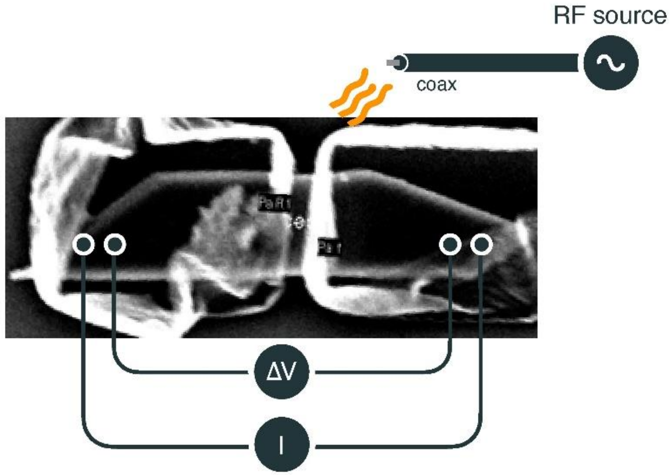
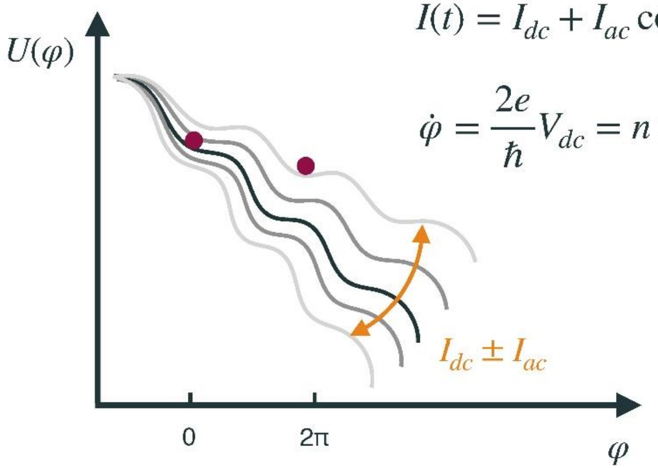
Outlook: Shapiro steps in InSb nanoflags

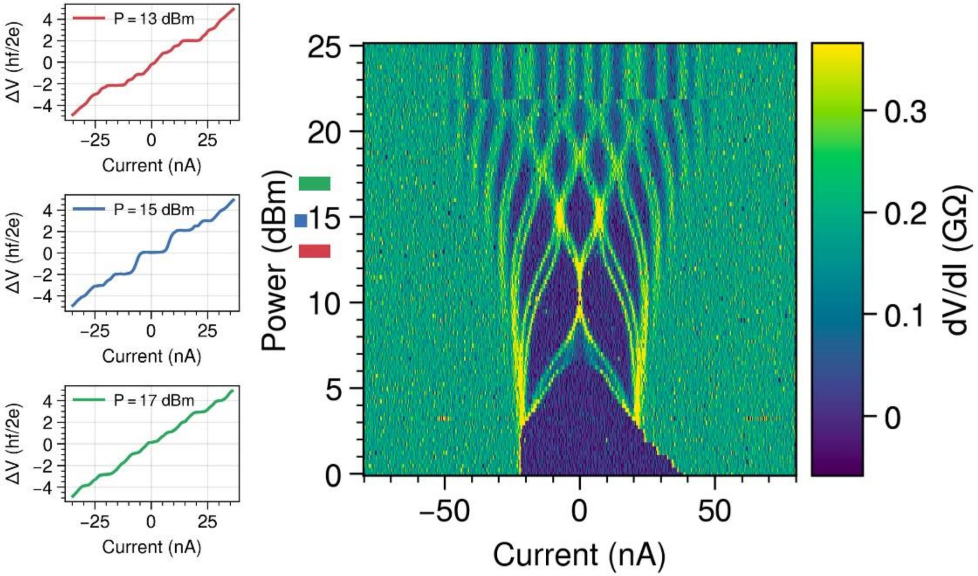
Andrea Iorio

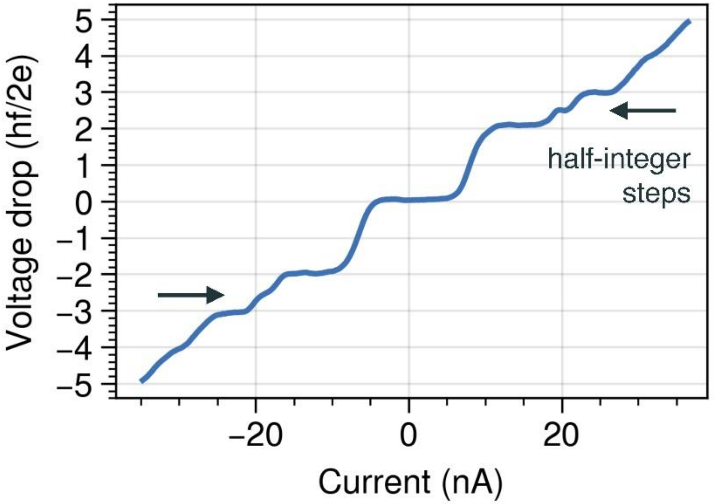


$$I(t) = I_{dc} + I_{ac}\cos(\omega_{ac} t)$$

$$\dot{\varphi} = \frac{2e}{\hbar} V_{dc} = n \times 2\pi f_{ac}$$







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