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Josephson diode effect in high-mobility InSb nanoflags

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National Enterprise for nanoScience and nanoTechnology

NEST

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-reciprocity in condensed matter systems**
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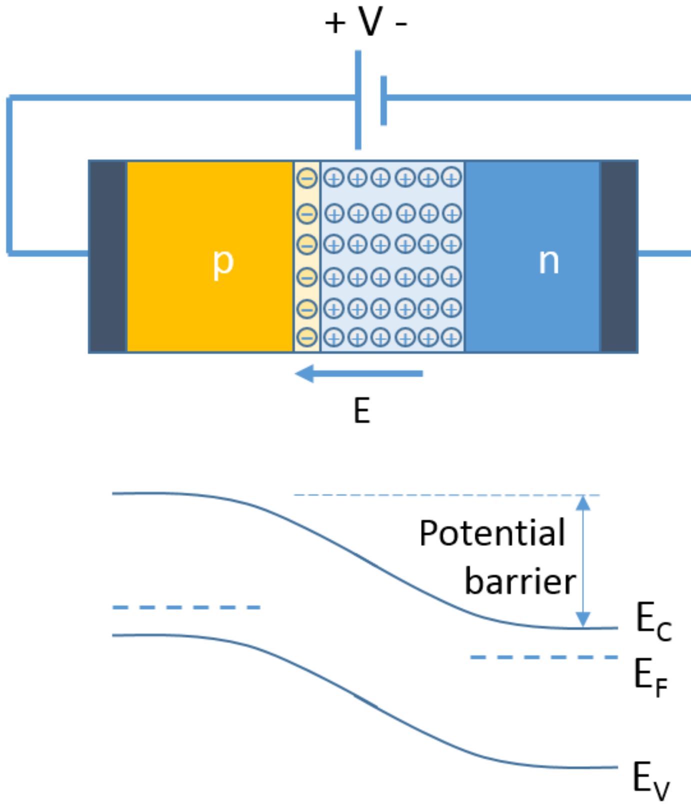
Non-reciprocity: a familiar concept



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

Magneto-chiral anisotropy:

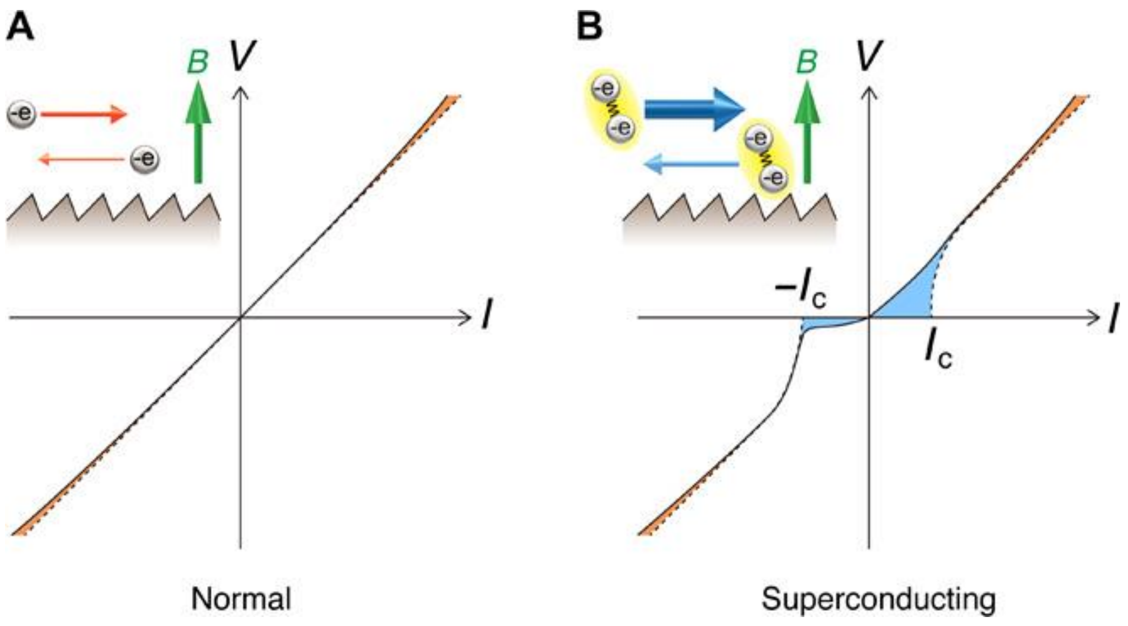
$$R = R_0(1 + \gamma_{MCA}\, \hat{e}_z \vec{B} \times \vec{I})$$

- Non-linear effect
- TRS-breaking required
- Elusive in CM systems

$$\gamma_{MCA} \left(\frac{E_{SOI}}{E_G}\right) \sim 10^{-3}\text{-}10^{-2}\ \mathrm{T}^{-1}\ \mathrm{A}^{-1}$$

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

MCA in superconductors



- Superconducting order defines a new energy scale:

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

- 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)

First observations of SDE

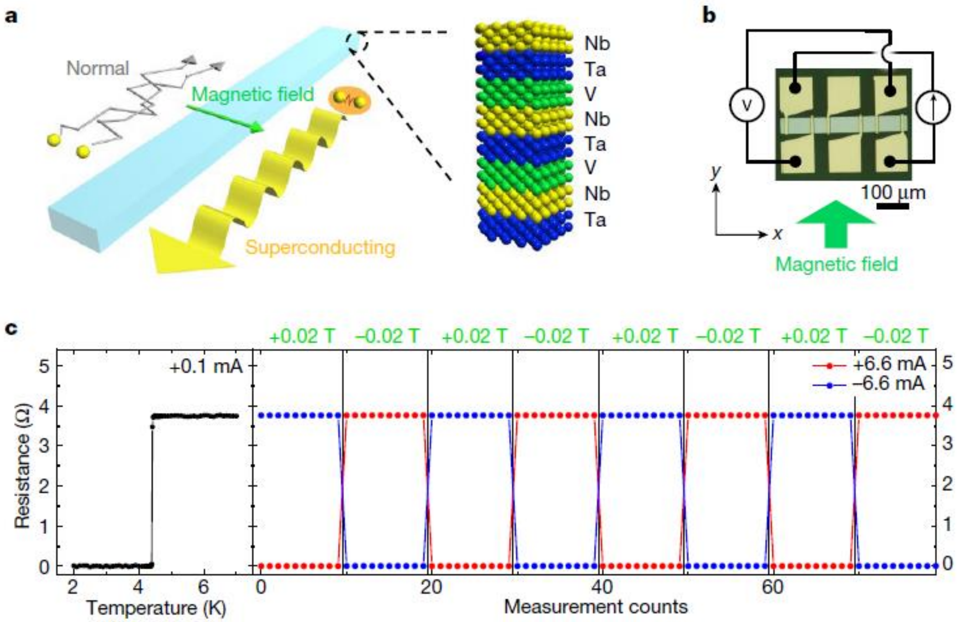
Article

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]✉

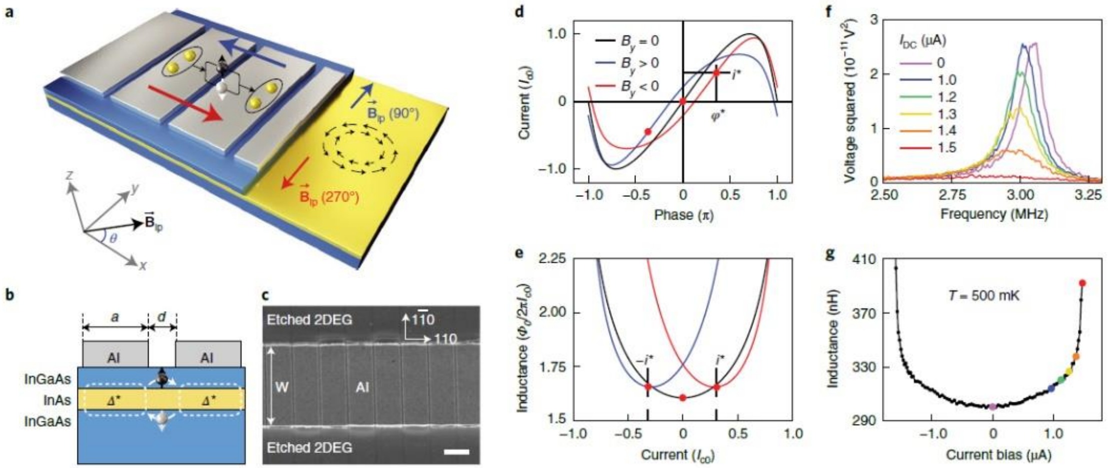
Nonlinear optical and electrical effects associated with a lack of spatial inversion symmetry allow direction-selective propagation and transport of quantum particles, such as photons[1] and electrons[2–9]. The most common example of such nonreciprocal



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

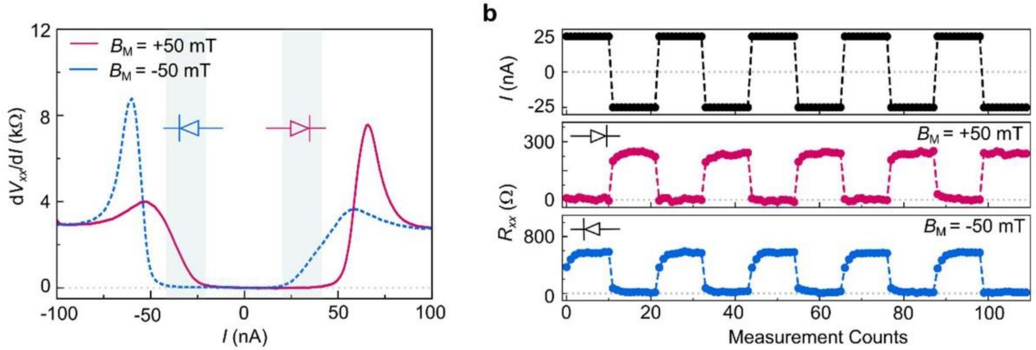
Supercurrent rectification and magnetochiral effects in symmetric Josephson junctions

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]



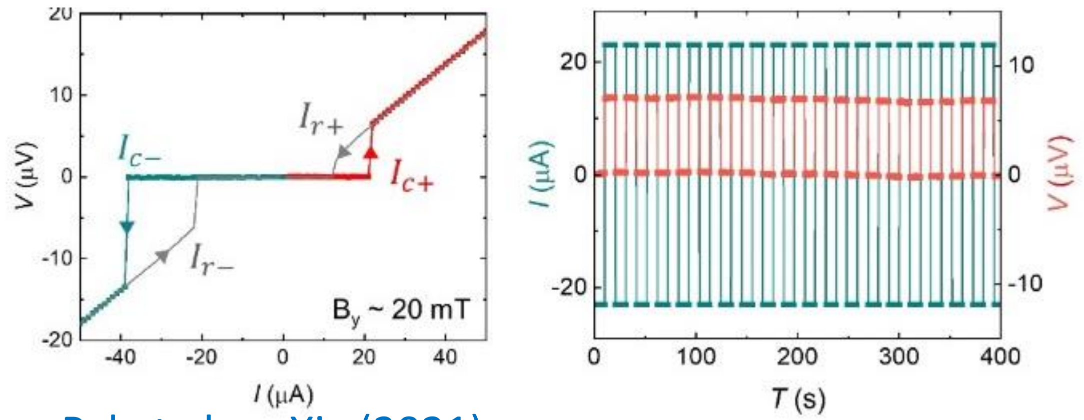
SDE in different systems

Twisted bilayer graphene



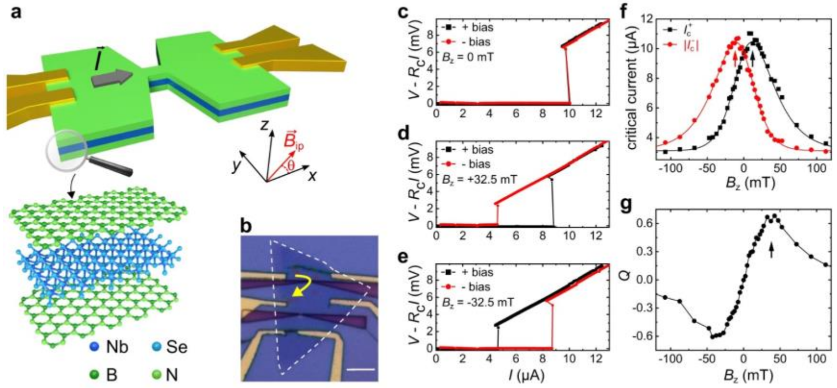
Diez-Merida et al., arXiv (2021)

Topological semimetal ($NiTe_2$)

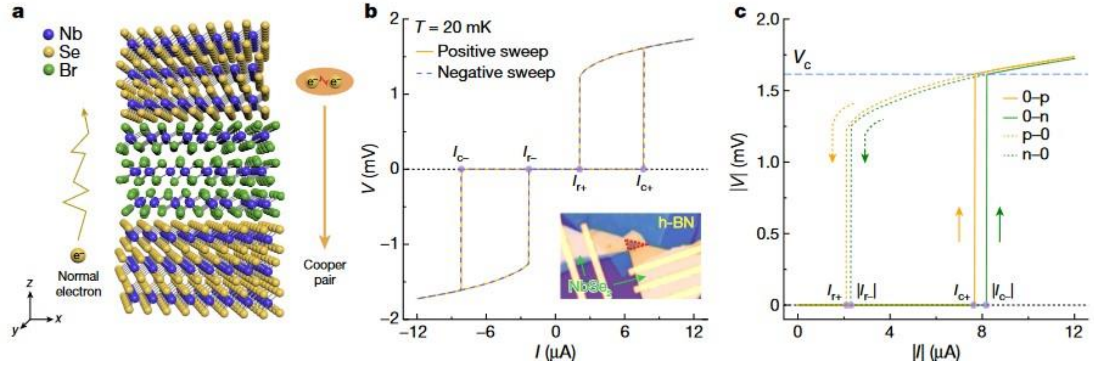


Pal et al., arXiv (2021)

Van der Waals materials



Bauriedl et al., *Nat Commun* **13**, 4266 (2022)

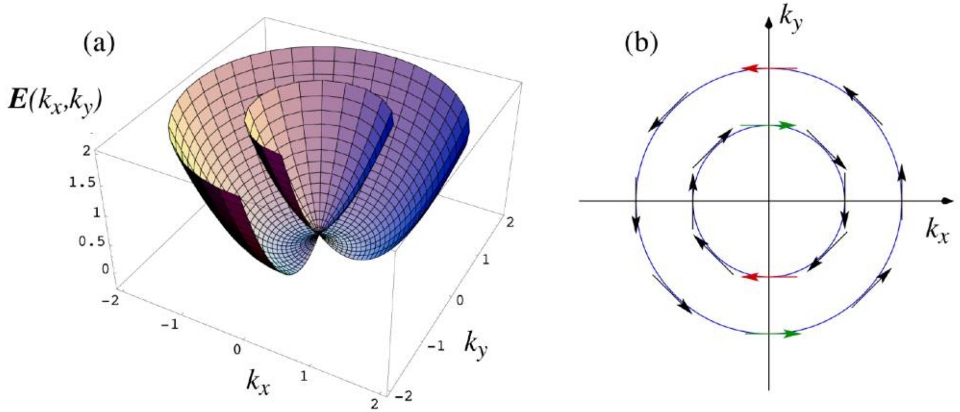


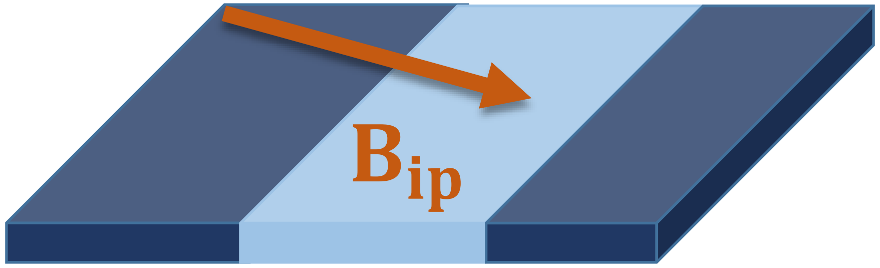
Wu et al., *Nature* **604,** 653–656 (2022)

Ingredients for intrisic SDE

SNS junction + SOI + Zeeman field

- Time-reversal breaking mechanism
- Broken inversion symmetry
- Robust superconducting phase





Ideal candidate:
strong SOI and large effective g-factor

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InSb: a convenient material

$E_G = 0.23\ eV$ → mid-IR range devices

$m^* \sim 0.018 m_e$

high-speed electronics

$\mu_{bulk} = 7.7 \times 10^4\ \mathrm{cm}^2/(\mathrm{Vs})$ →

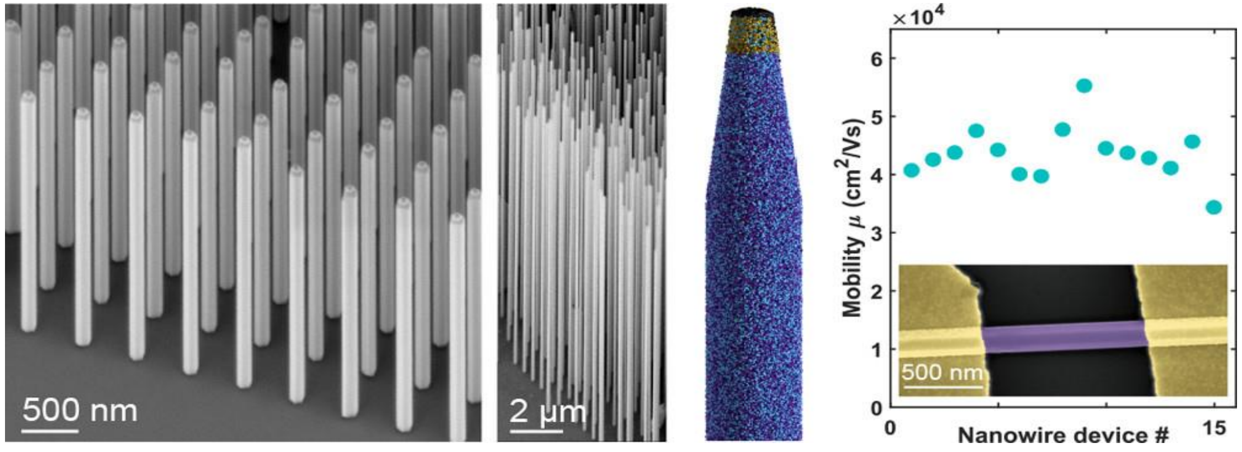
$g^*_{bulk} \sim 50$ → spintronics

not only for searching Majorana zero modes!

InSb nanostructures

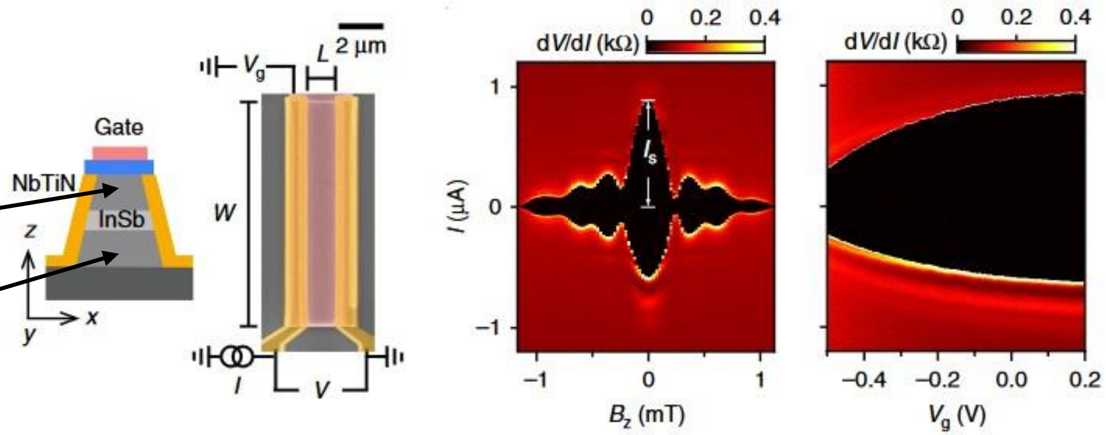
- InSb nanowires:

Nano Lett. 2019, 19, 6, 3575–3582



- InSb quantum wells:

Thick buffer layers are required due to lattice mismatch

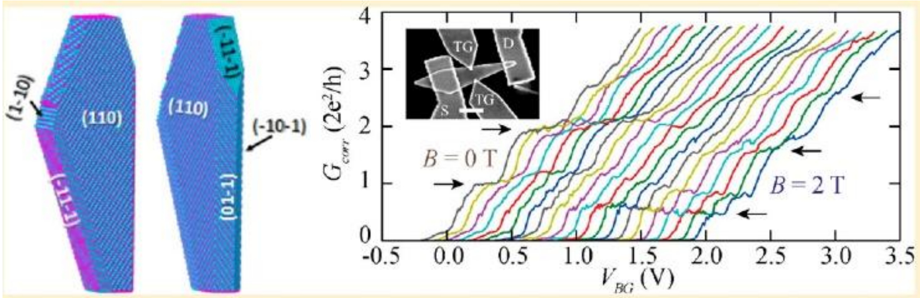


Nat Commun **10,** 3764 (2019)

A novel approach: 2D nanoflags

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

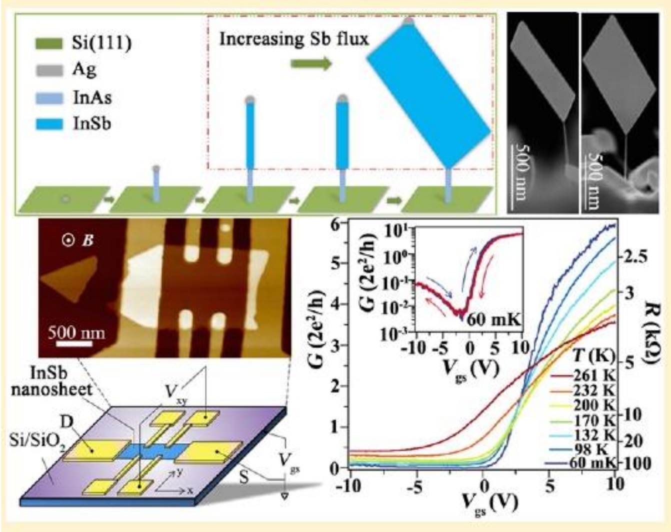
María de la Mata,[†] Renaud Leturcq,[*,‡,§] Sébastien R. Plissard,[∥] Chloé Rolland,[‡] César Magén,[⊥] Jordi Arbiol,[*,†,#] and Philippe Caroff[*,‡,∇]



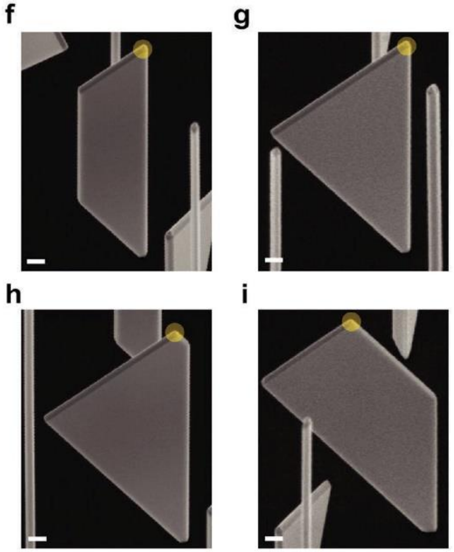
Nano Lett. 16 (2016) 825

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



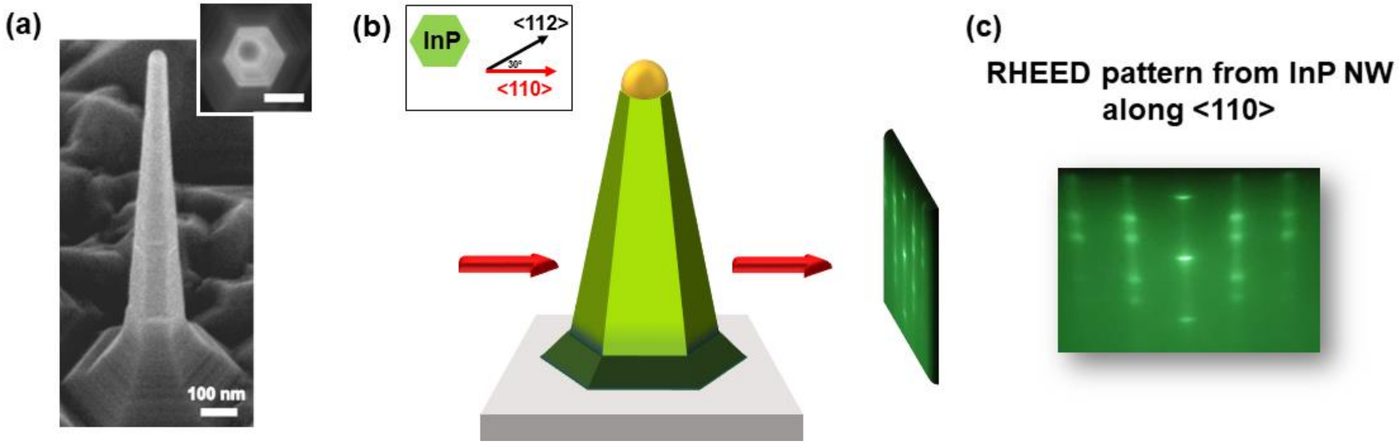
Bottom-Up Grown 2D InSb Nanostructures

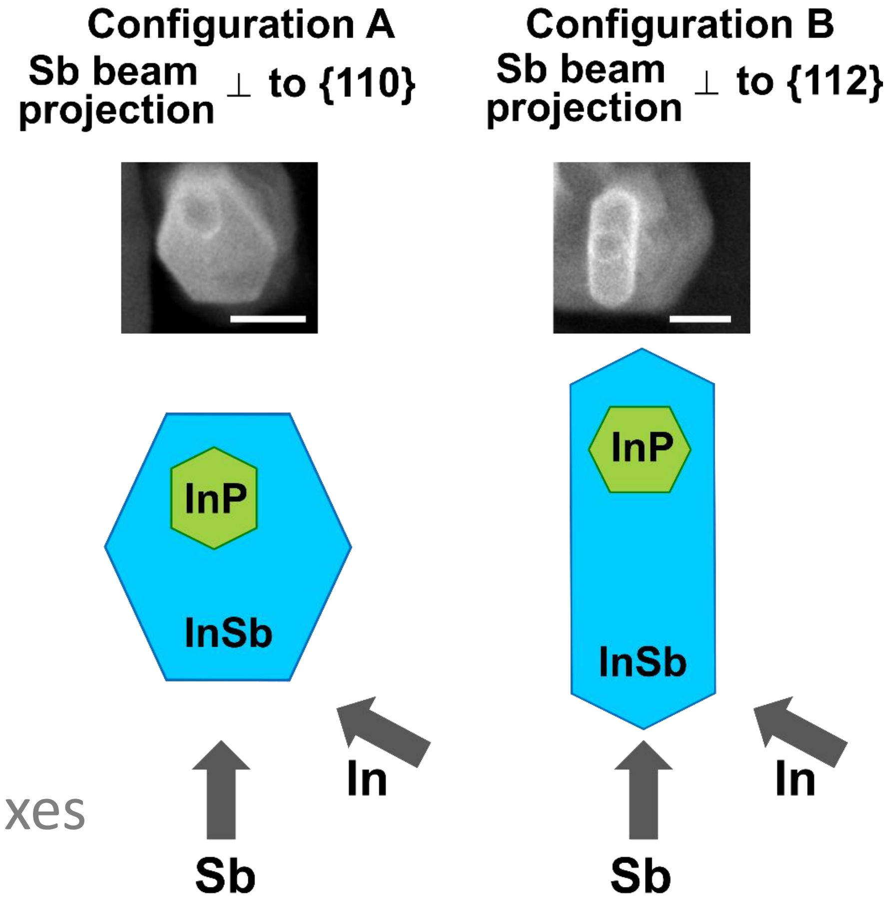
Sasa Gazibegovic, Ghada Badawy,* Thijs L. J. Buckers, Philipp Leubner, Jie Shen, Folkert K. de Vries, Sebastian Koelling, Leo P. Kouwenhoven, Marcel A. Verheijen, and Erik P. A. M. Bakkers*

Adv. Mater. 31 (2019) 1808181

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

tapered InP nanowires are used as *stems*



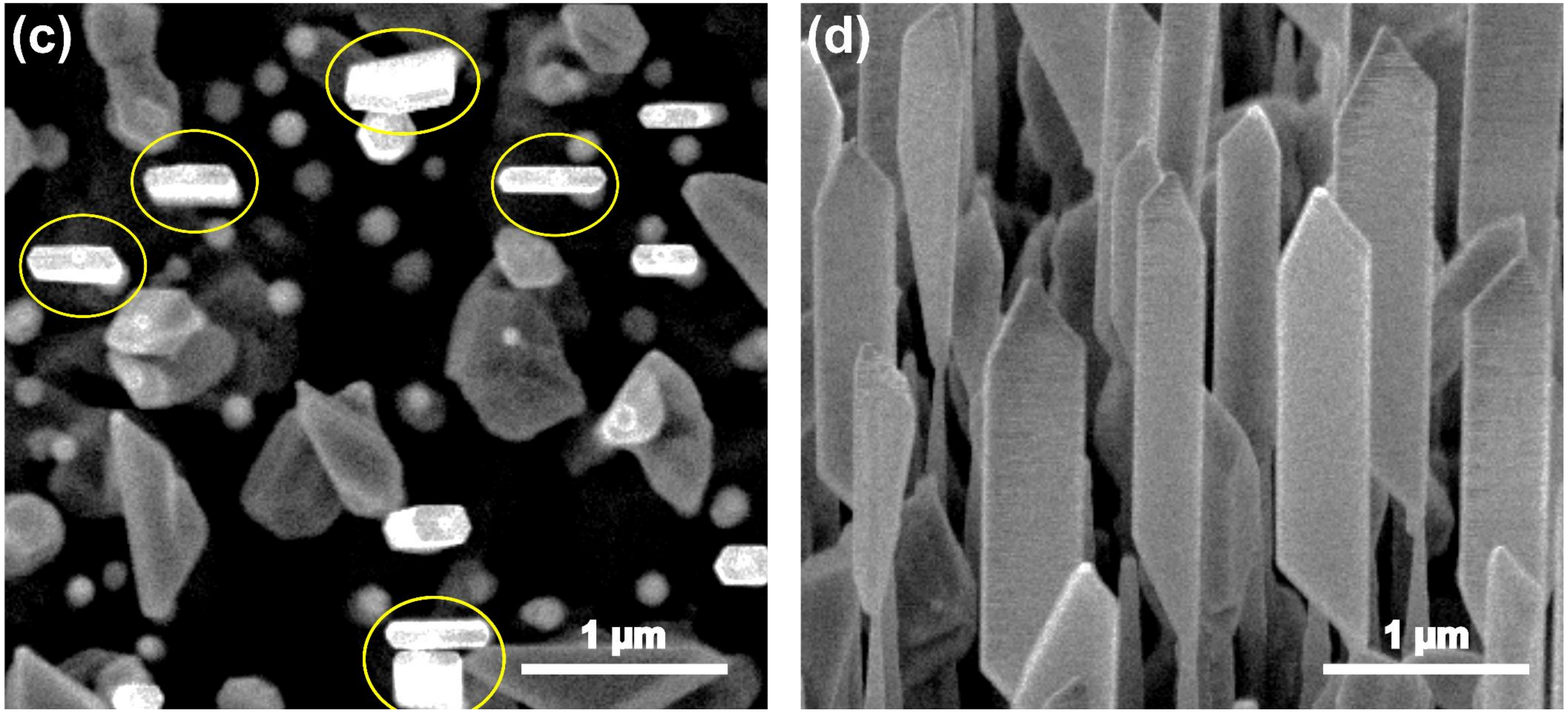


the 2D shape is obtained with directional fluxes

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

Growth of InSb nanoflags via CBE

Isha Verma



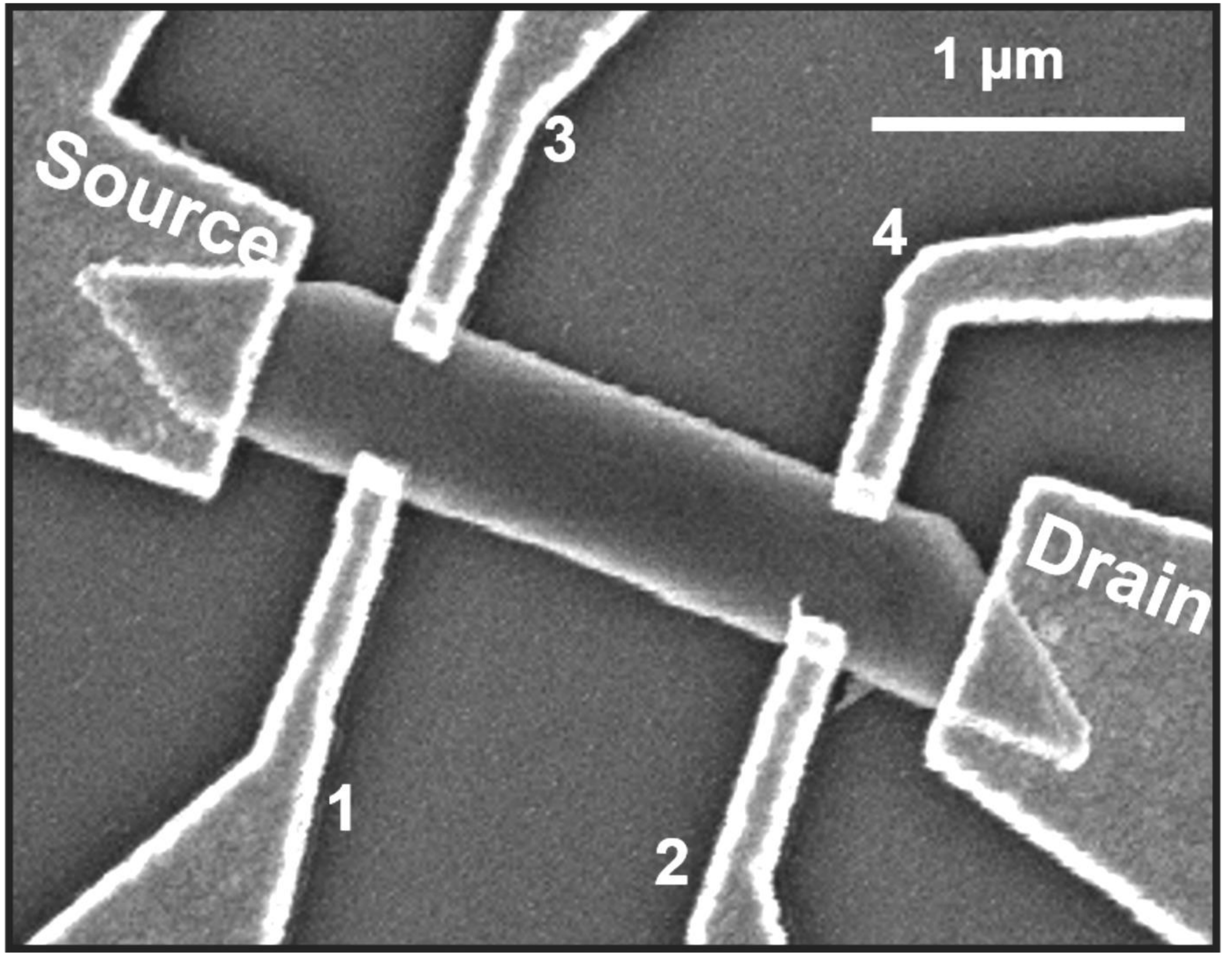
- ZB lattice
- defect-free crystal

Nanoflags:

- ❑ $t \sim 100$ nm
- ❑ W ~ 500 nm
- ❑ $L \sim 2\ \mu$m

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

Nanoflag in Hall bar geometry



Sample geometry:

- ❑ $t \sim 100$ nm
- ❑ $W \sim 325$ nm
- ❑ $L \sim 1.5\ \mu$m

Leads:

Ti/Au 10/190 nm

Substrate:

Si/SiO_2

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

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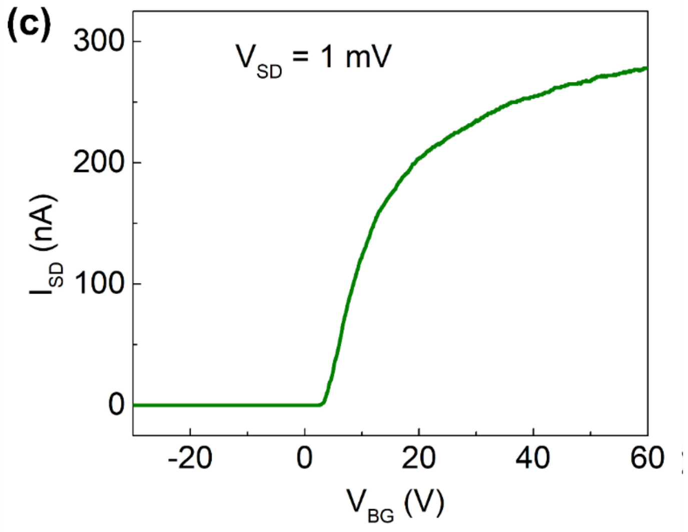
InSb NF characterization @ T= 4.2 K



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

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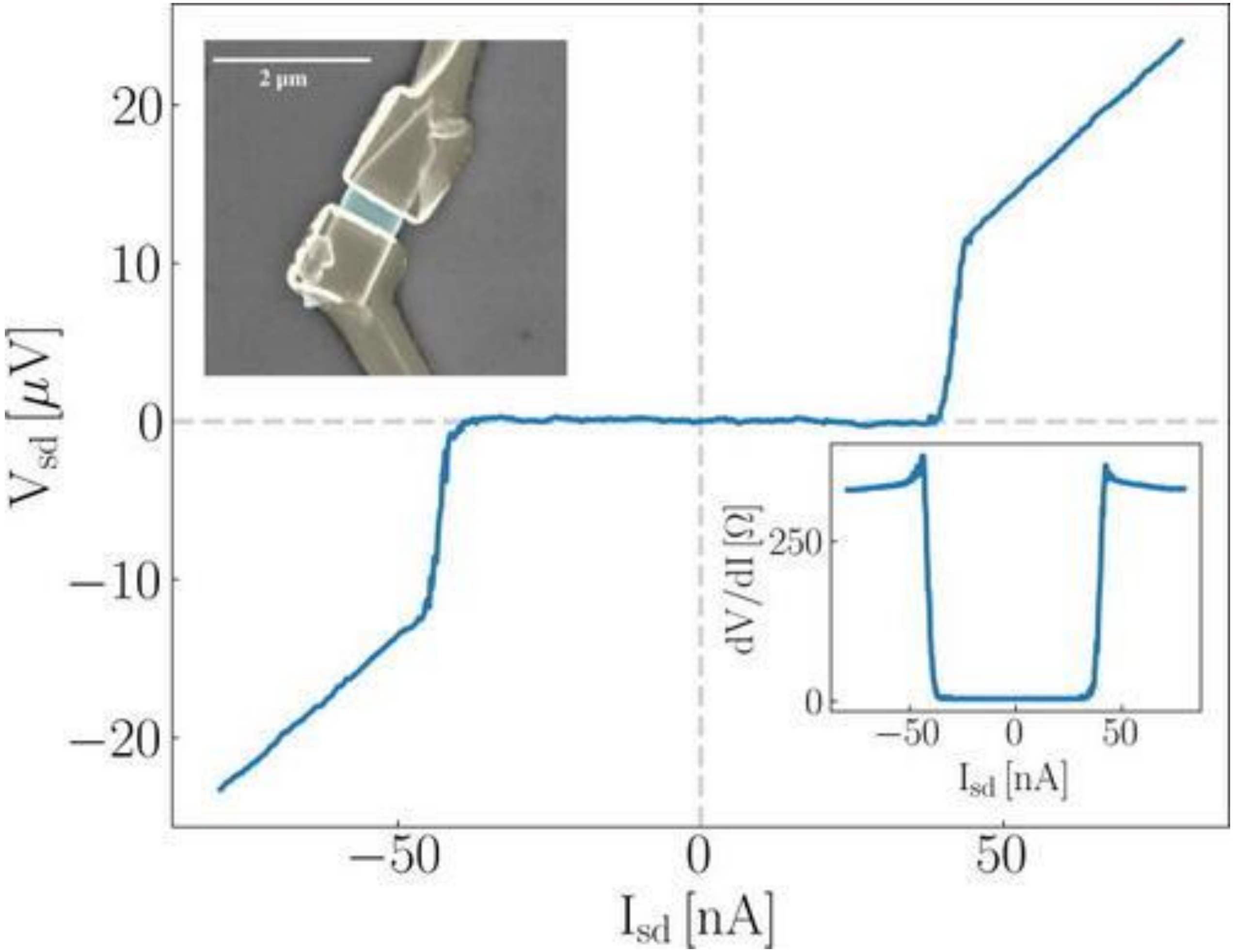
NF-based Josephson junction

Sedighe Salimian



Deposition of superconducting leads

150/10 nm Nb/Ti

↓

Super-normal-super junction

$T_c = 8.44\ K \ \Rightarrow \Delta = 1.28$ meV

- $\lambda_{MFP} = 500$ nm
- $L = 200$ nm
- $\xi_{SC} = \hbar v_F/\Delta \sim 750$ nm

BALLISTIC REGIME (λ_{MFP}, L)

SHORT JUNCTION (L, ξ_{SC})

T= 250 mK

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

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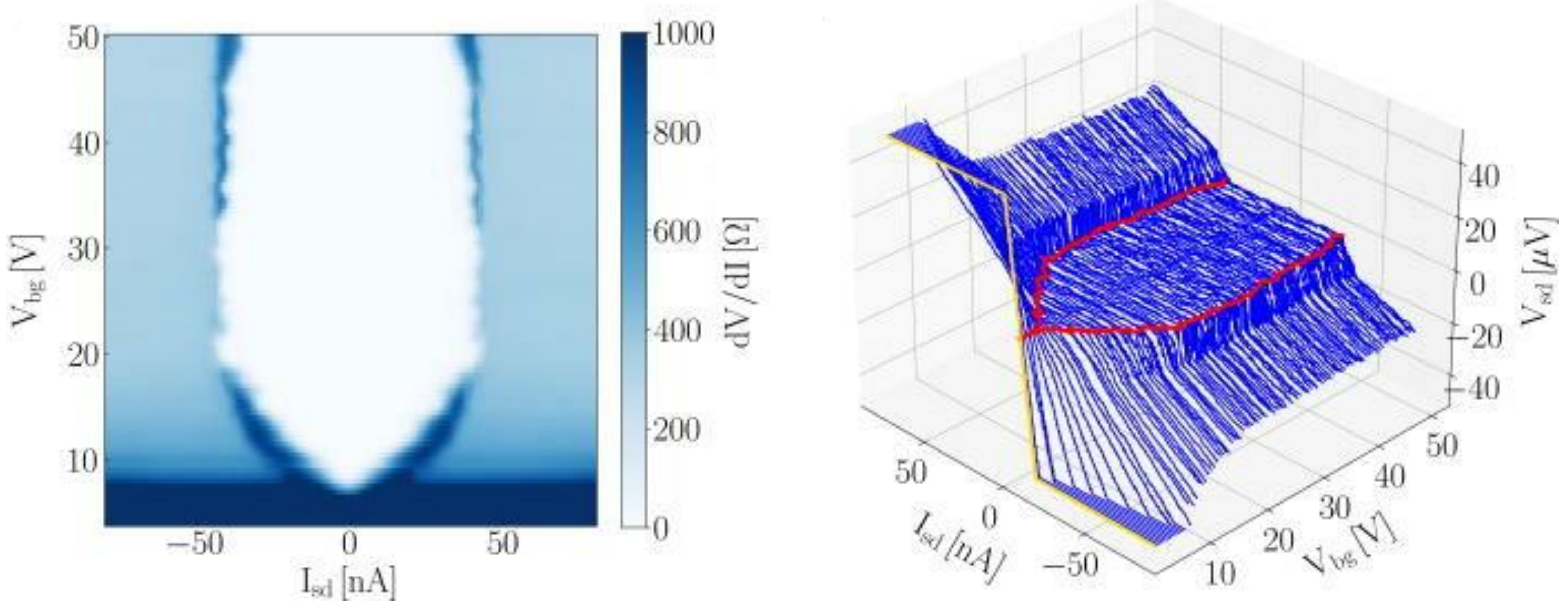
Gate-controlled supercurrent

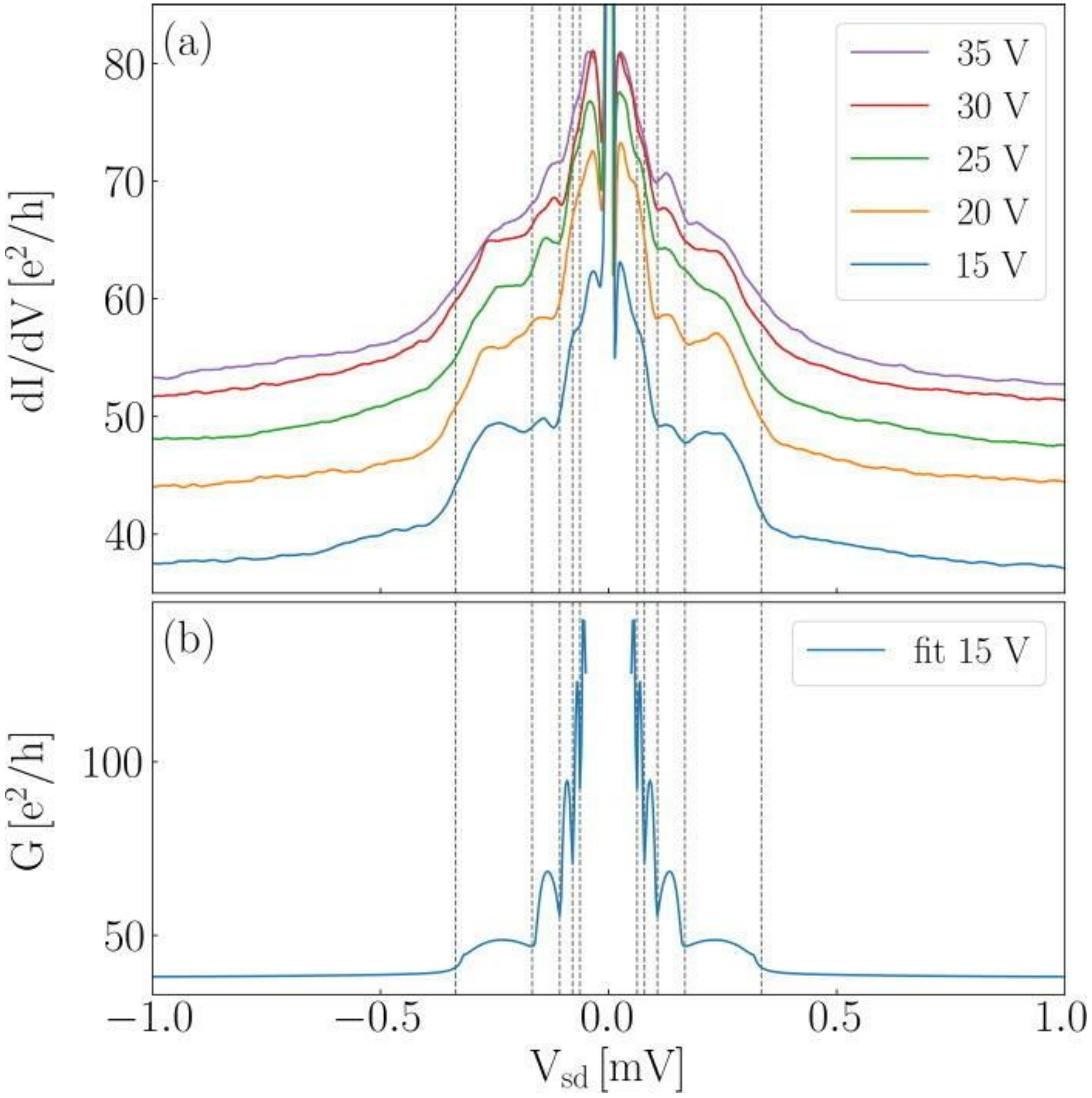


S. Salimian et al., *Appl. Phys. Lett.* **119**, 214004 (2021)

T= 250 mK

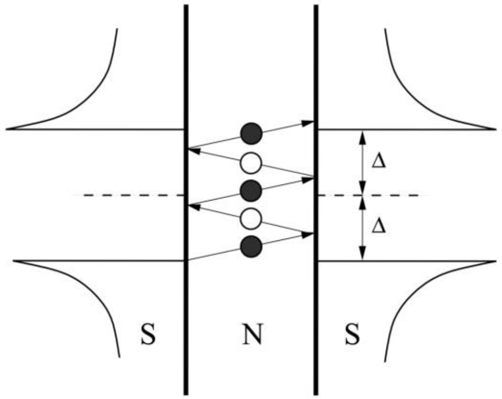
Multiple Andreev reflections

Michal P. Nowak



Matching condition for

$$neV_n = 2\Delta^*$$



The model: Best fit:

- M families of modes: i=1,..,M — 1
- N_i transport modes — 40 (V_{BG})
- τ_i transmission coefficient — 0.94
- Δ^* =superconducting gap — 160 μeV

T= 250 mK

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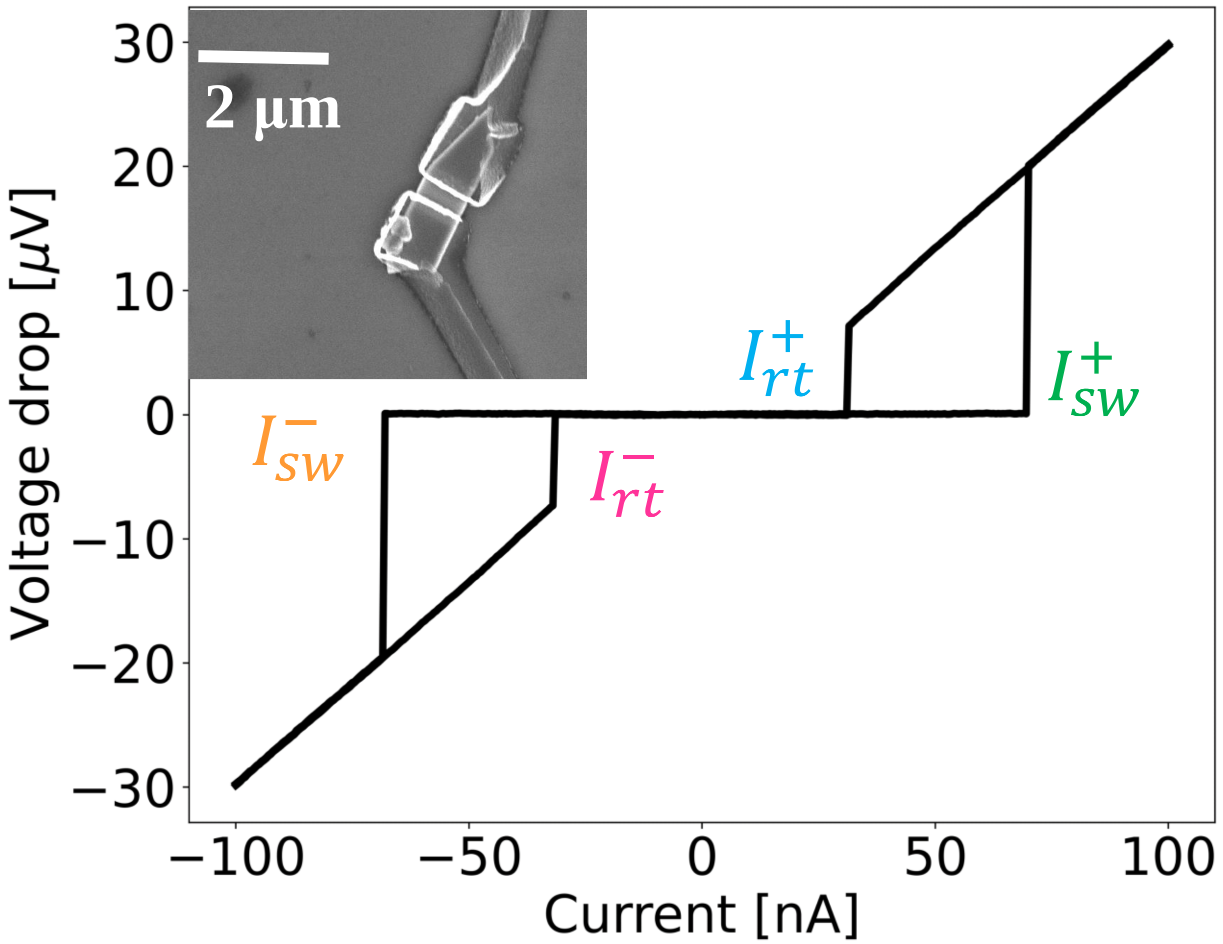
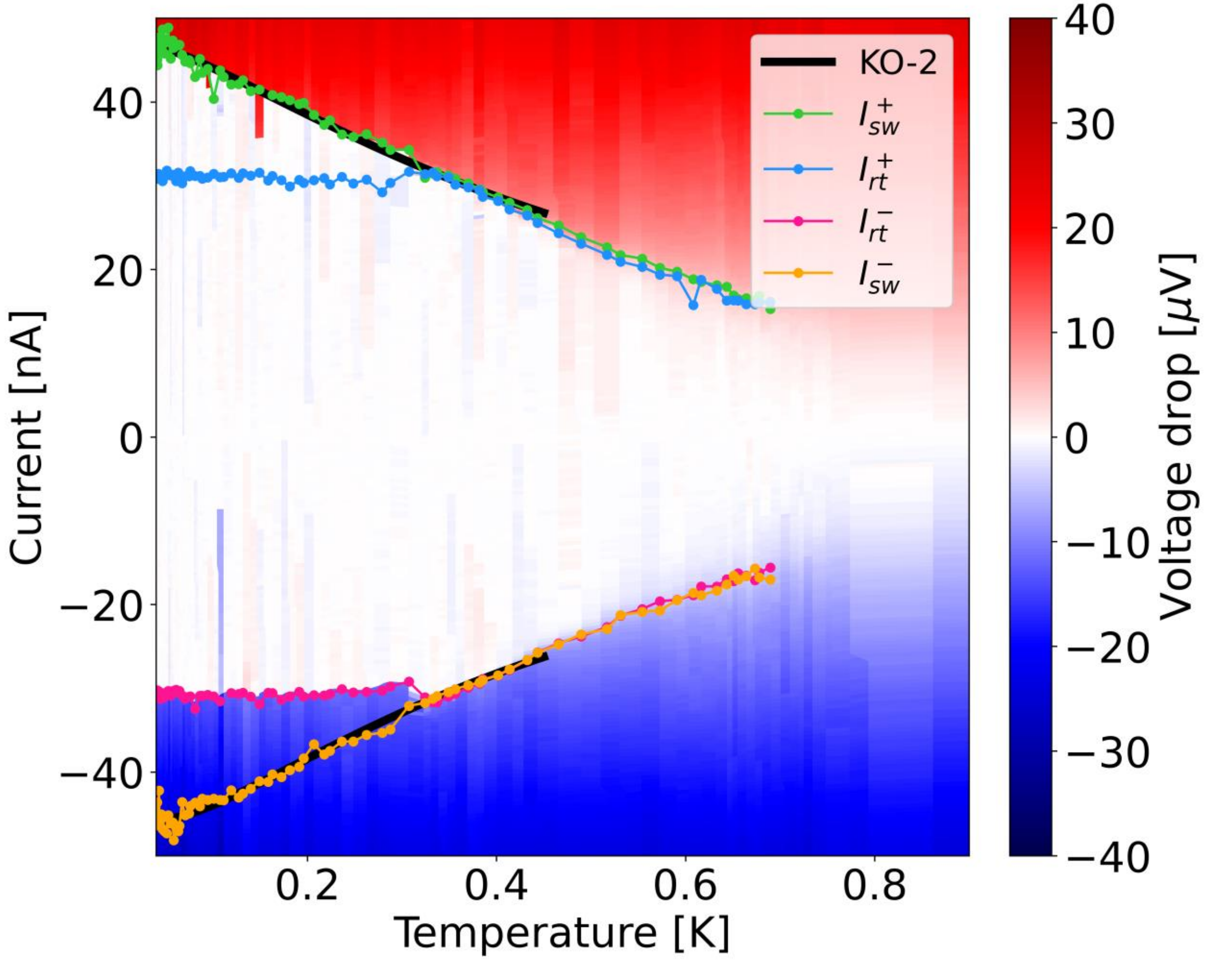
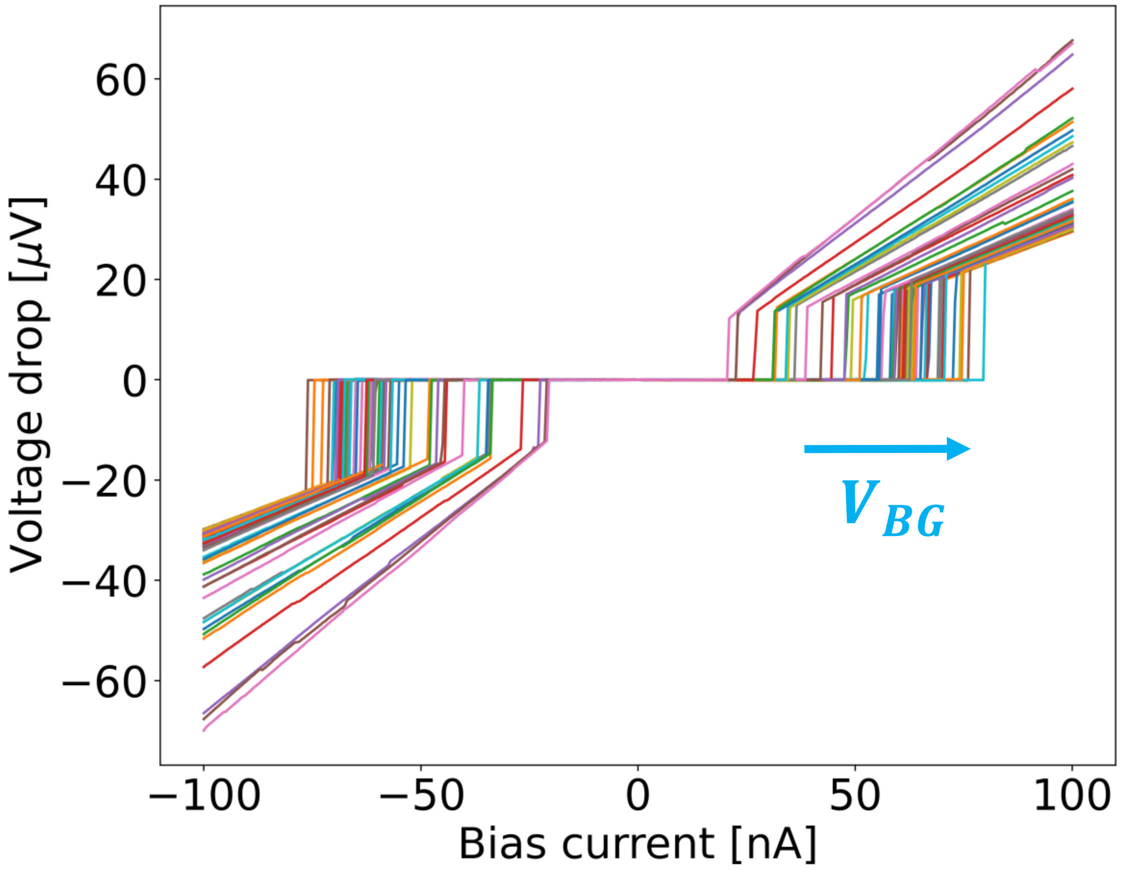
IV characteristics vs. temperature

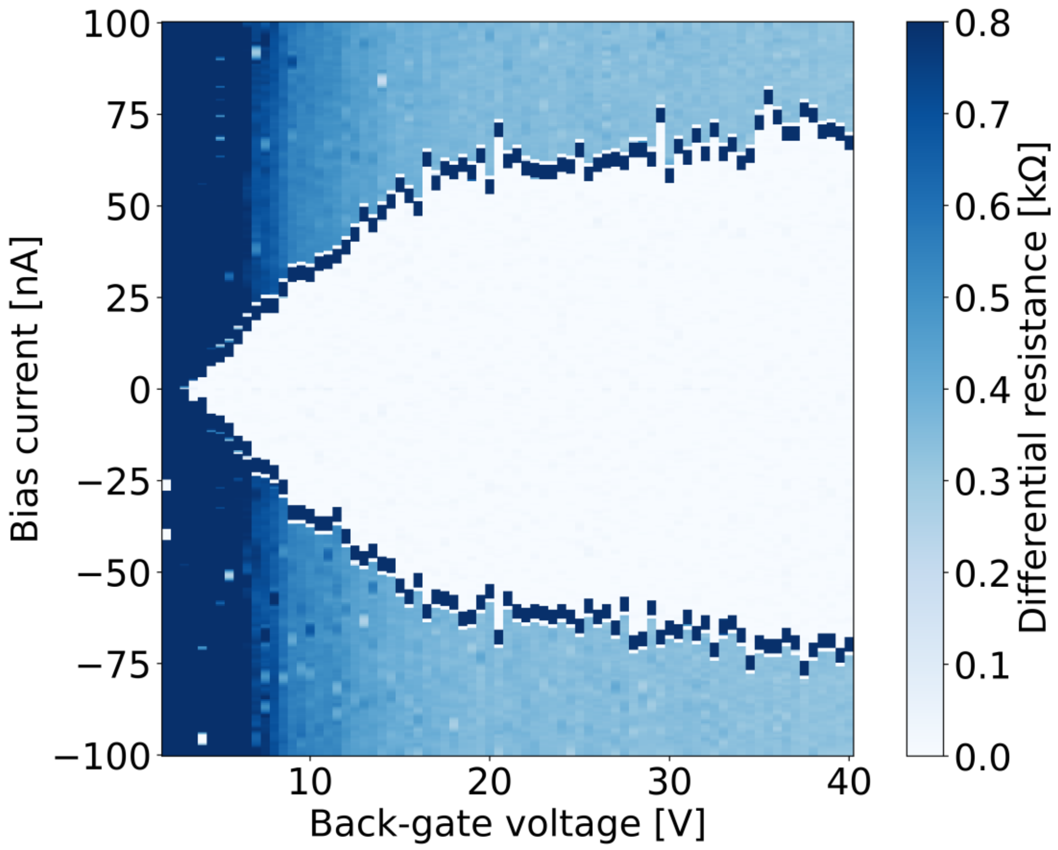




Josephson-FET

T= 30 mK





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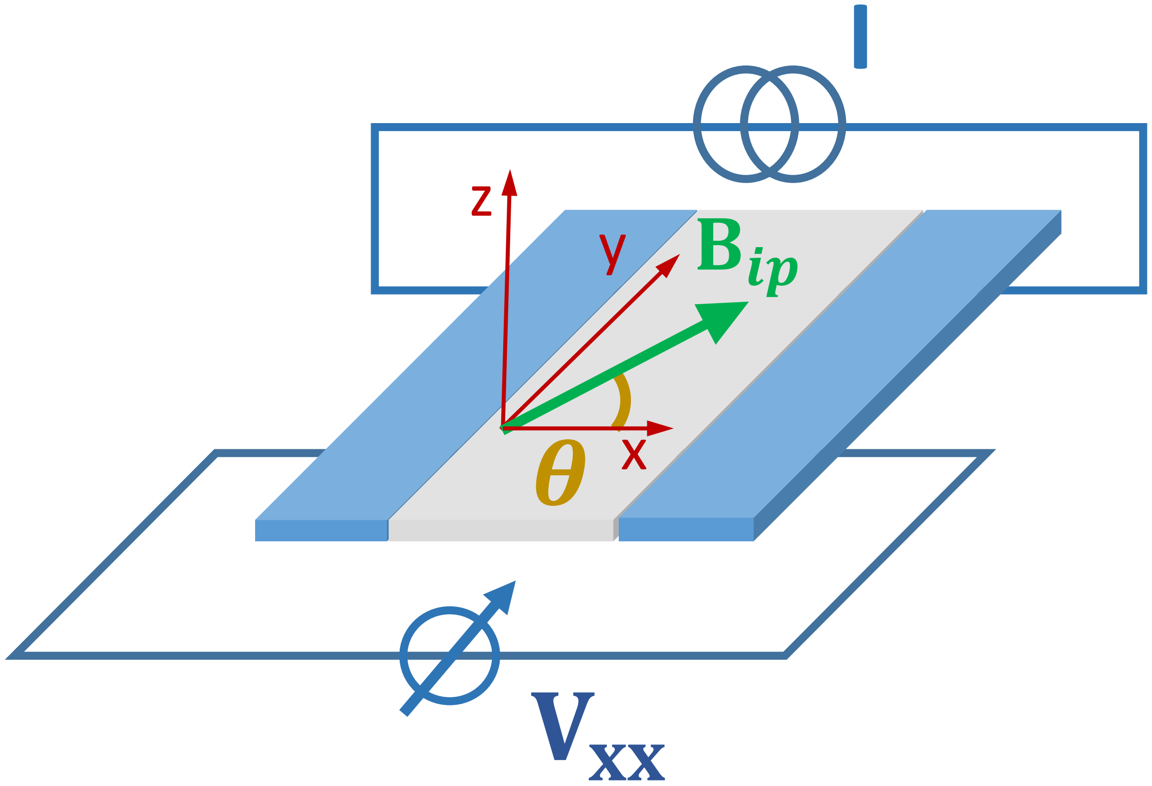
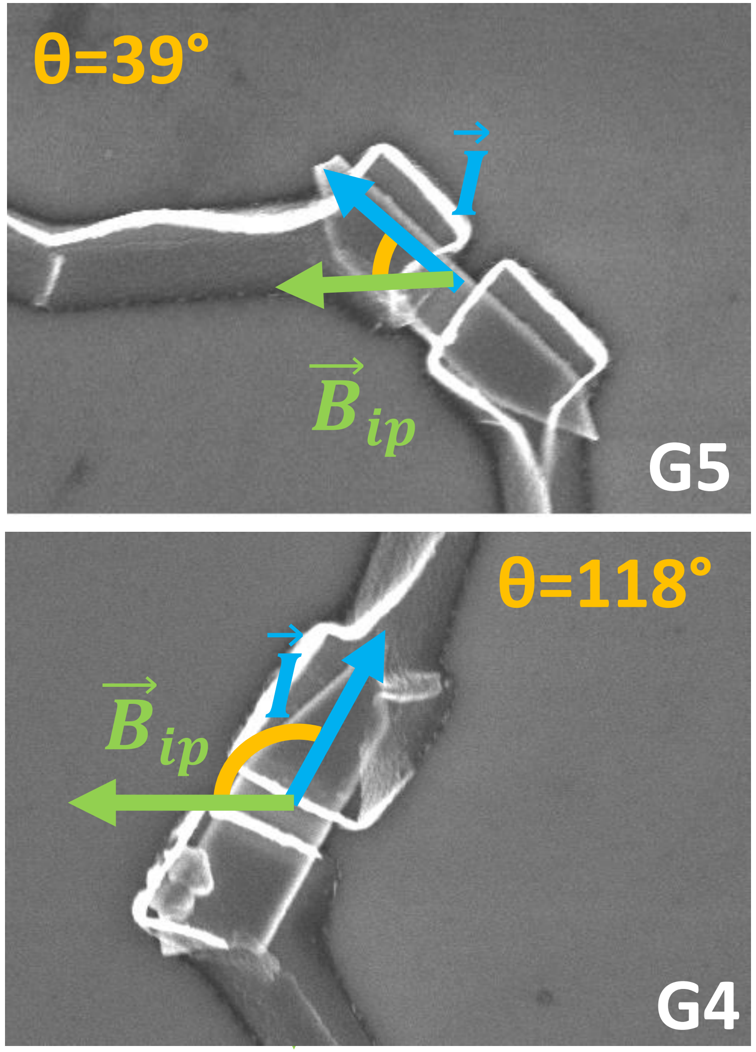
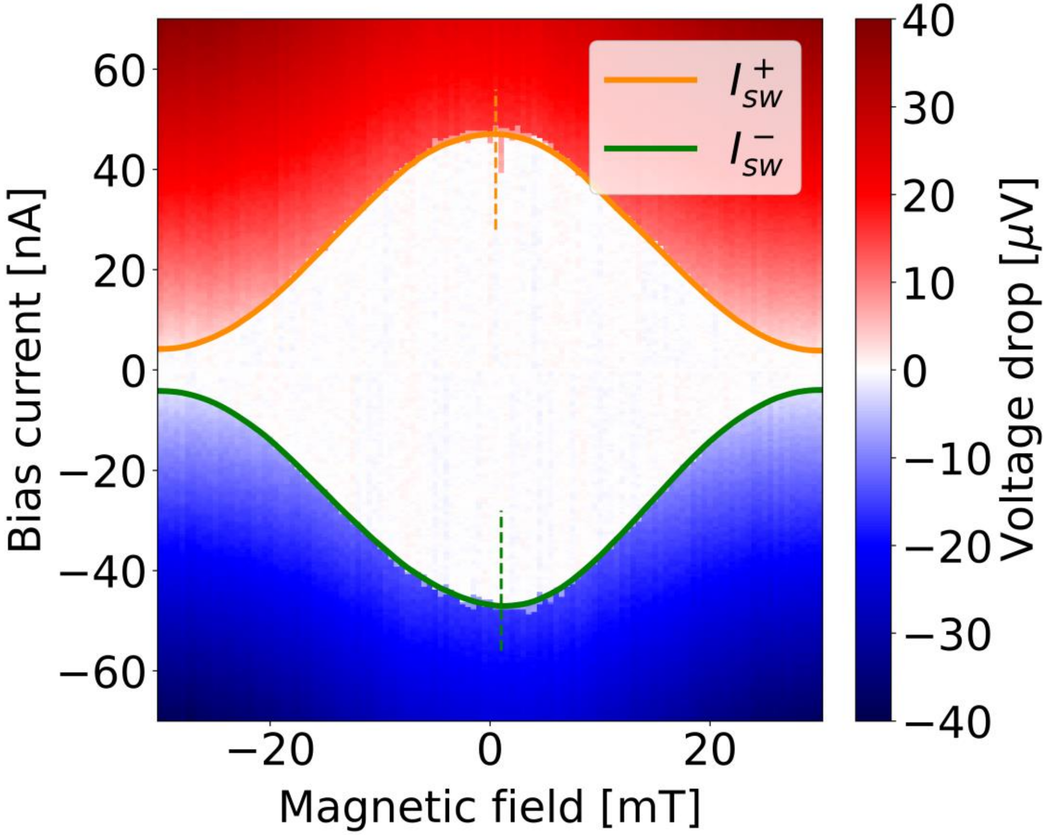
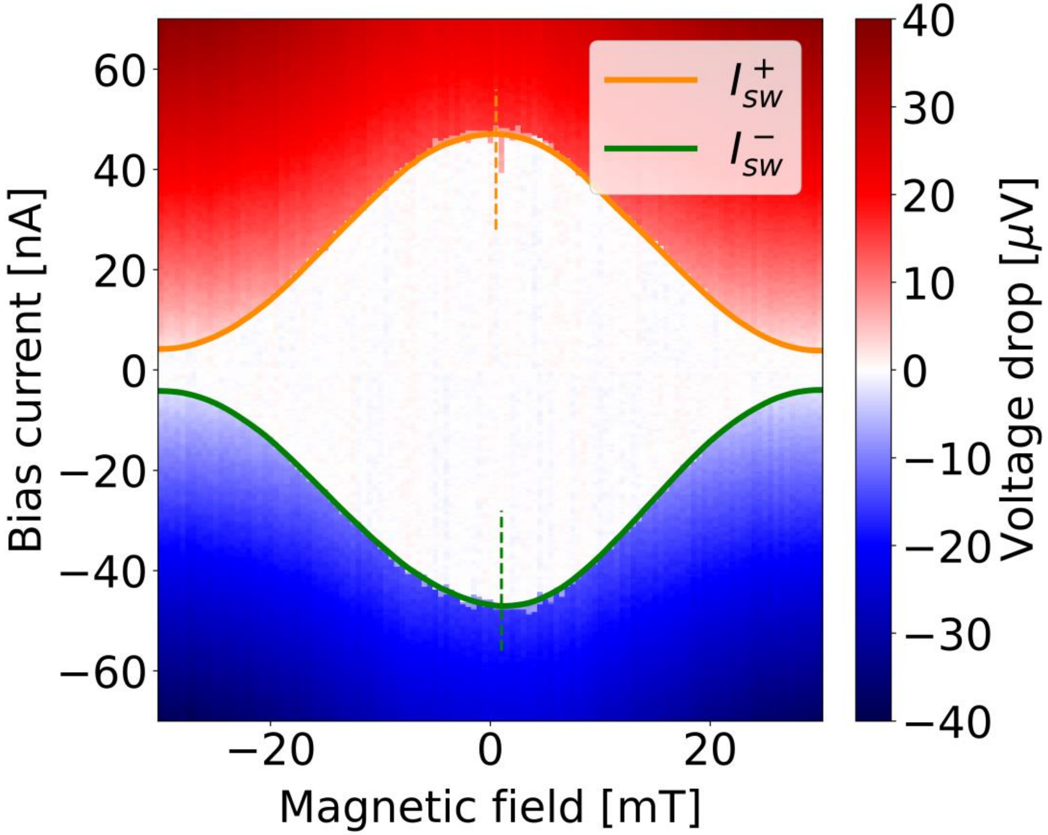
Design of the experiment



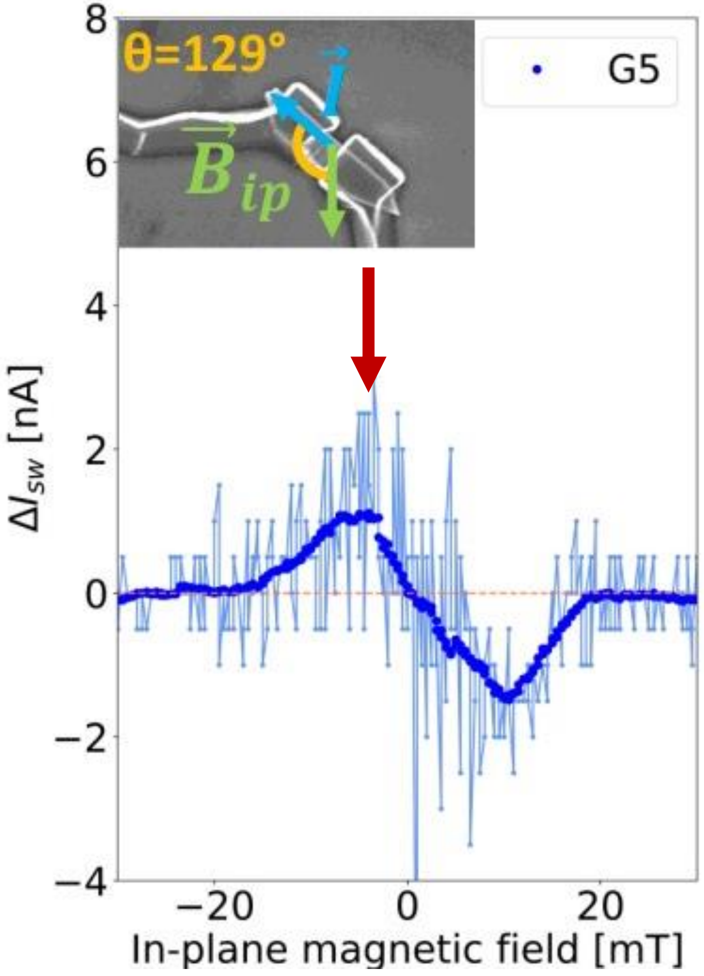


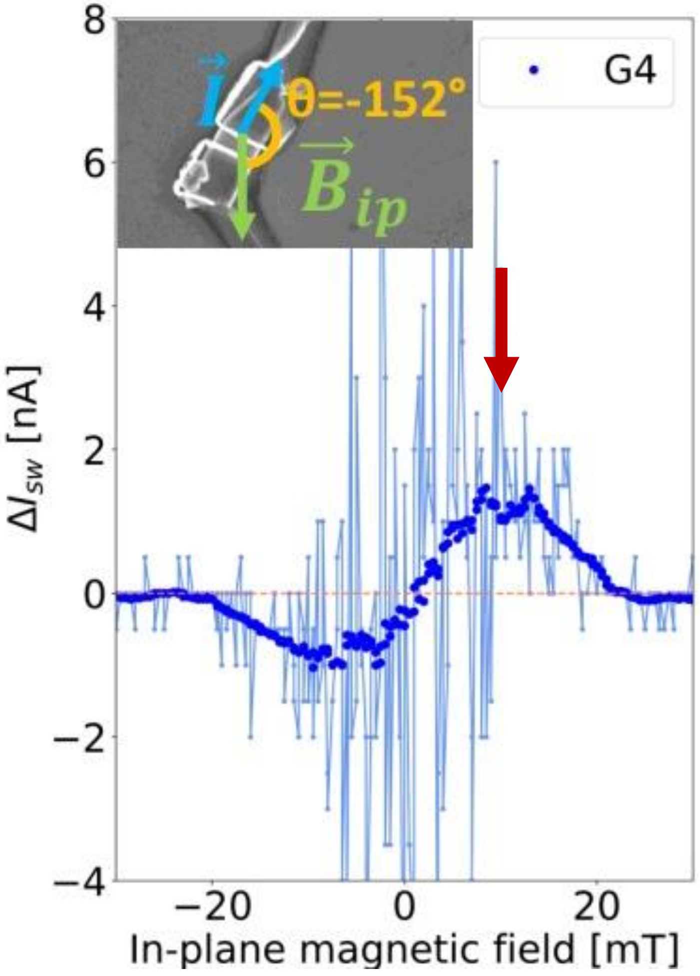
In-plane magnetic field effect





Switching current asymmetry

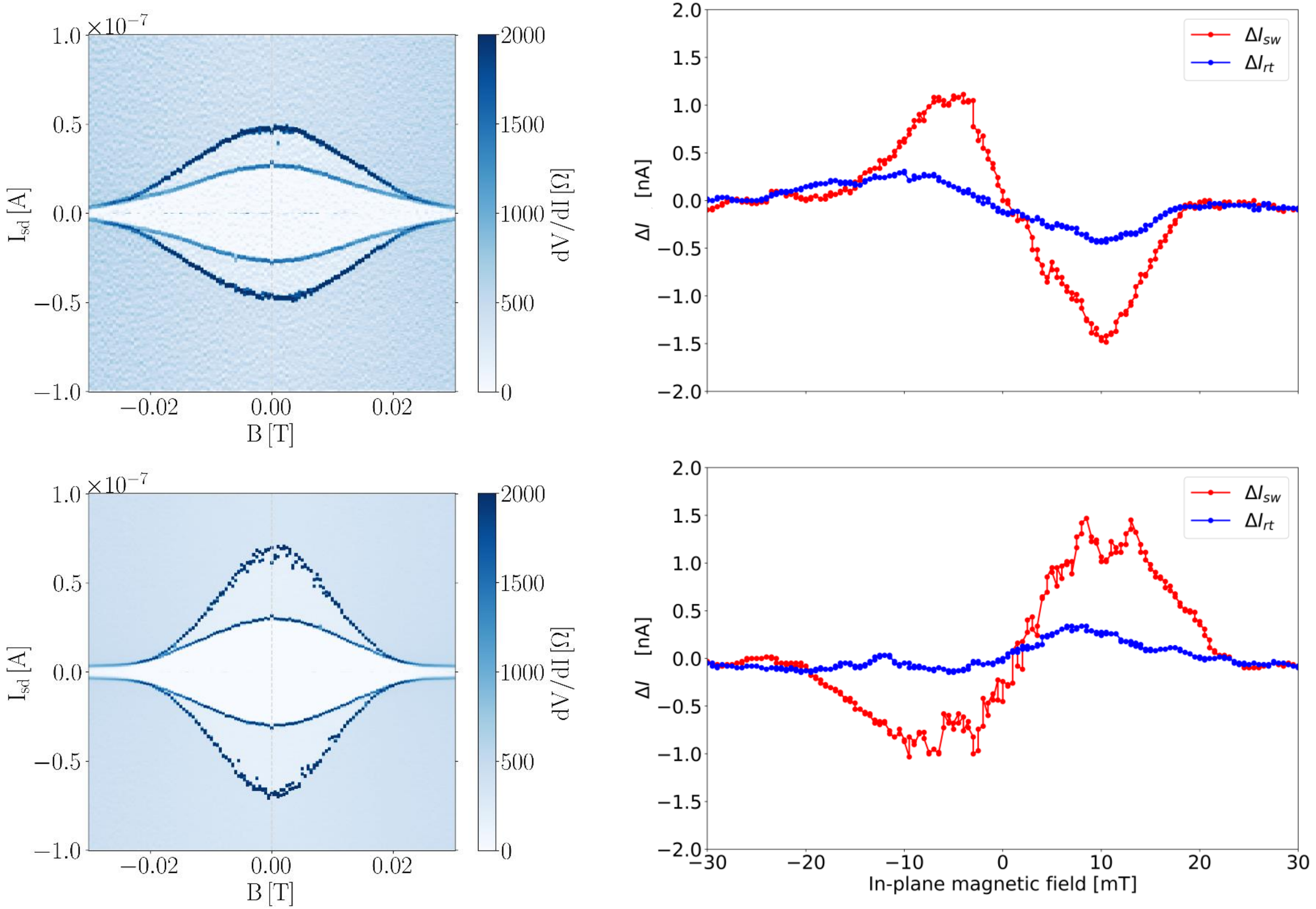




Main features:

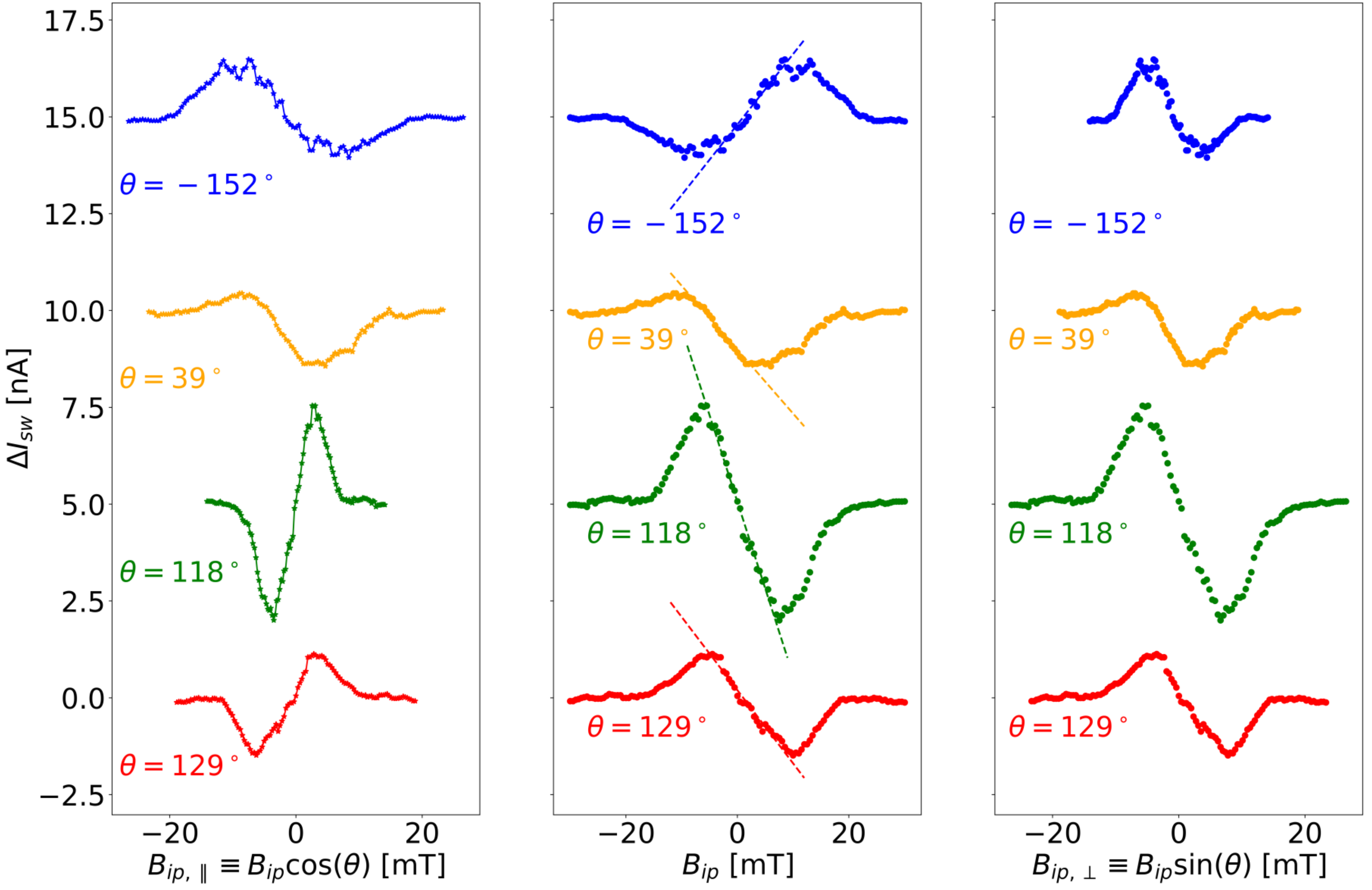
- antysimmetric behavior
- linear around $B = 0$
- rounded maximum
- suppression at $\mathrm{B} \gtrsim 20$ mT
- θ-dependent polarity

Retrapping current asymmetry



Different magnitude: remappable on T-dependence

Dependence on the angle

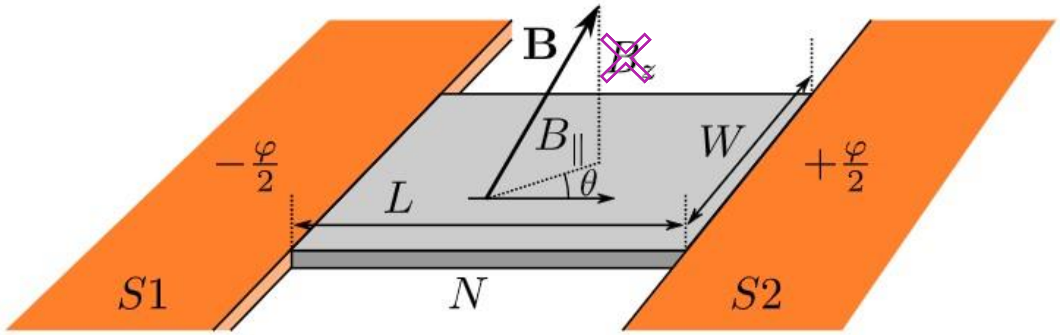


An educated guess:

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

Symmetry-breaking mechanism

How to break the equivalence $I_c^+ = I_c^-$?



$$H = H_0 + H_{SOI(\alpha,\beta)} + H_Z + H_S$$

α: Rashba SOI
β: Dresselhaus SOI

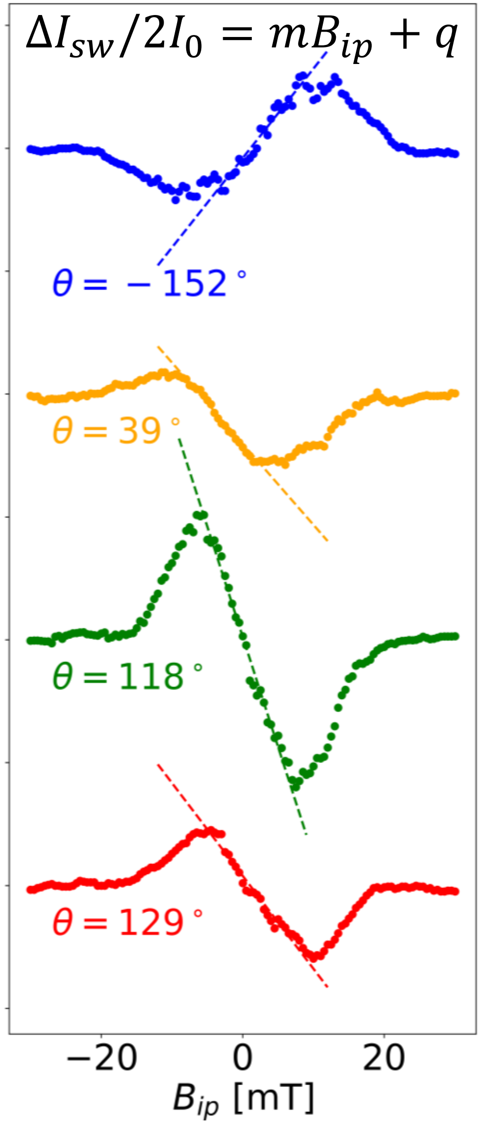
$U H(\varphi) U^\dagger = H(-\varphi)$			
U	Broken by		
$\mathcal{P}_y\mathcal{P}_x$	α, β, V_x, V_y	✖	✖
$\sigma_z\mathcal{P}_y\mathcal{P}_x$	B_x, B_y, V_x, V_y	✖	✖
$\sigma_x\mathcal{P}_y T$	B_x, α, V_y	✖	✖
$\sigma_y\mathcal{P}_y T$	B_y, β, V_y	✖	✖

$\alpha + B_{ip,\perp}$

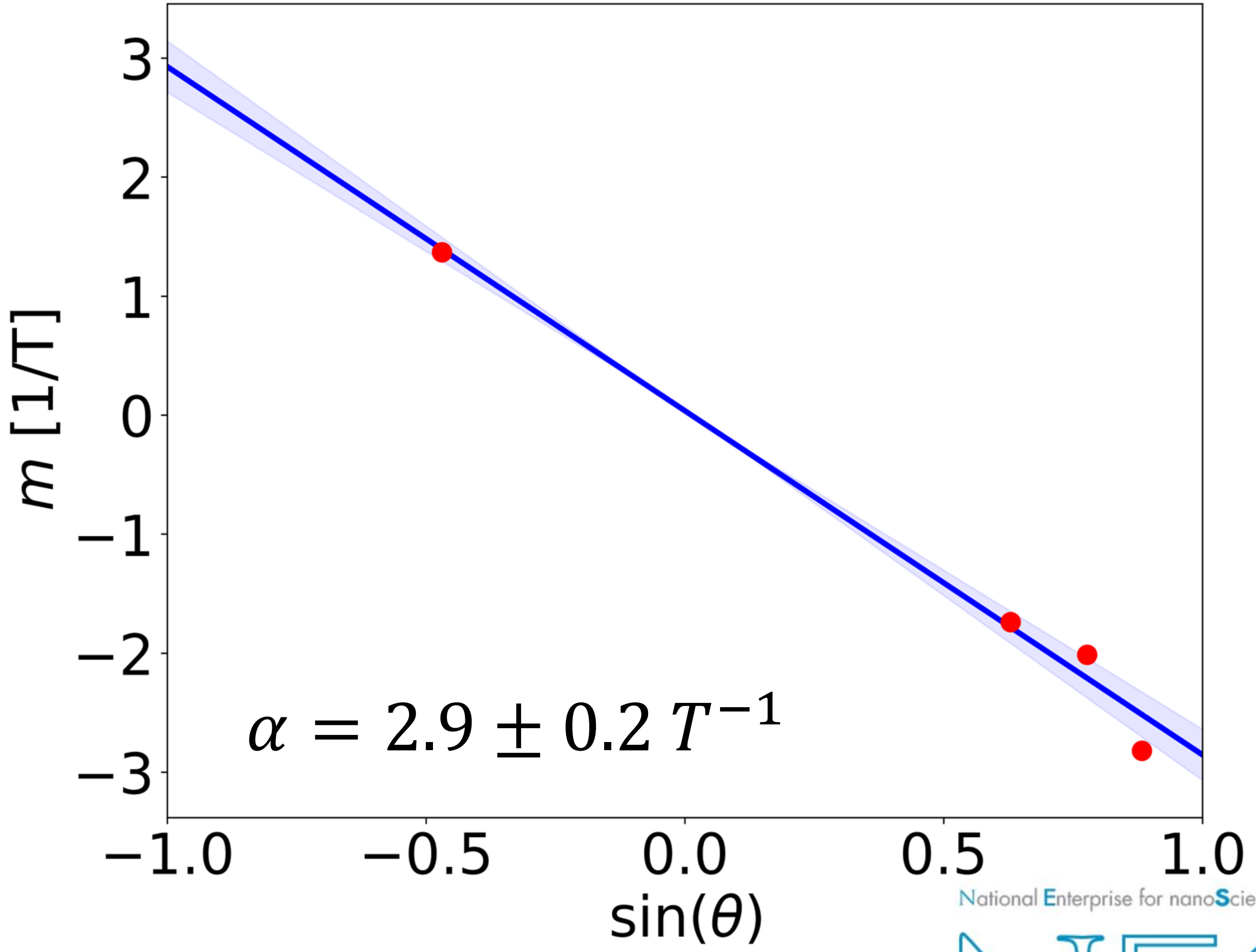
$\beta + B_{ip,\parallel}$

Rasmussen et al., *Physical Review B, 93*(15) (2016)

Dominant Rashba-type SOI



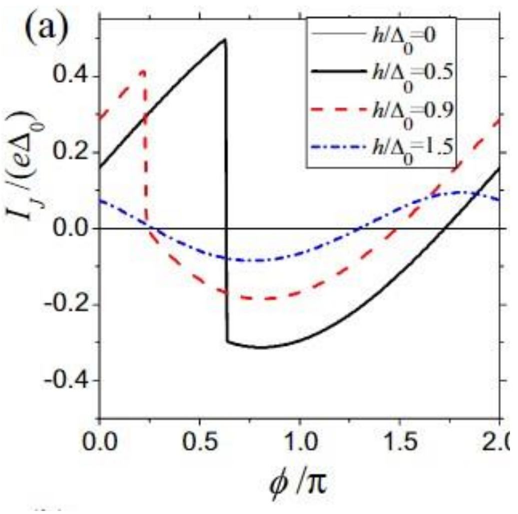
$m = \alpha \sin(\theta) + \beta \Rightarrow \eta \propto B_{ip,\perp}$



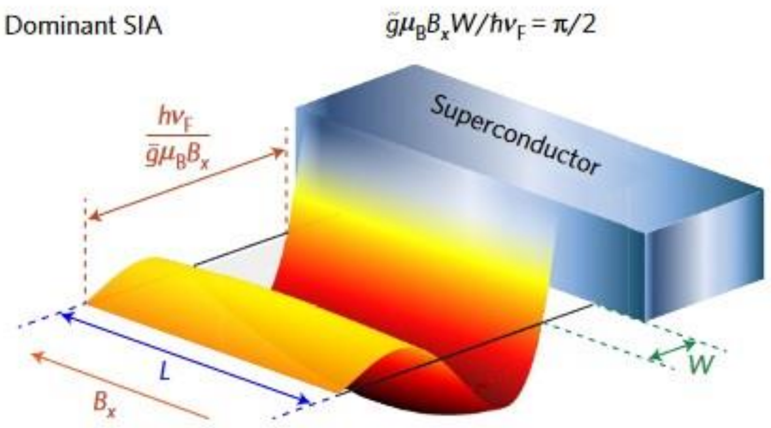
Finite momentum superconductivity

Strong RSOC + s-wave SC + $B_{ip,\perp}$: $qv_F = g^* \mu_B B_{ip,\perp}$

anomalous phase shift



spatial modulation of Δ^*



Josephson diode effect in ballistic junctions

$$\eta \equiv \frac{I_c^+ - |I_c^-|}{I_c^+ + |I_c^-|} = \frac{2qv_F}{\pi\Delta^*}$$

α_{th}(InSb NF) $\sim 8.5\, T^{-1}$

Dolcini et al., *PRB 92*(3) (2015)
Hart et al., *Nature Physics*, *13*(1), 87–93(2017)
Davydova et al., *Sci. Adv* (Vol. 8) (2022)

The CPR point of view

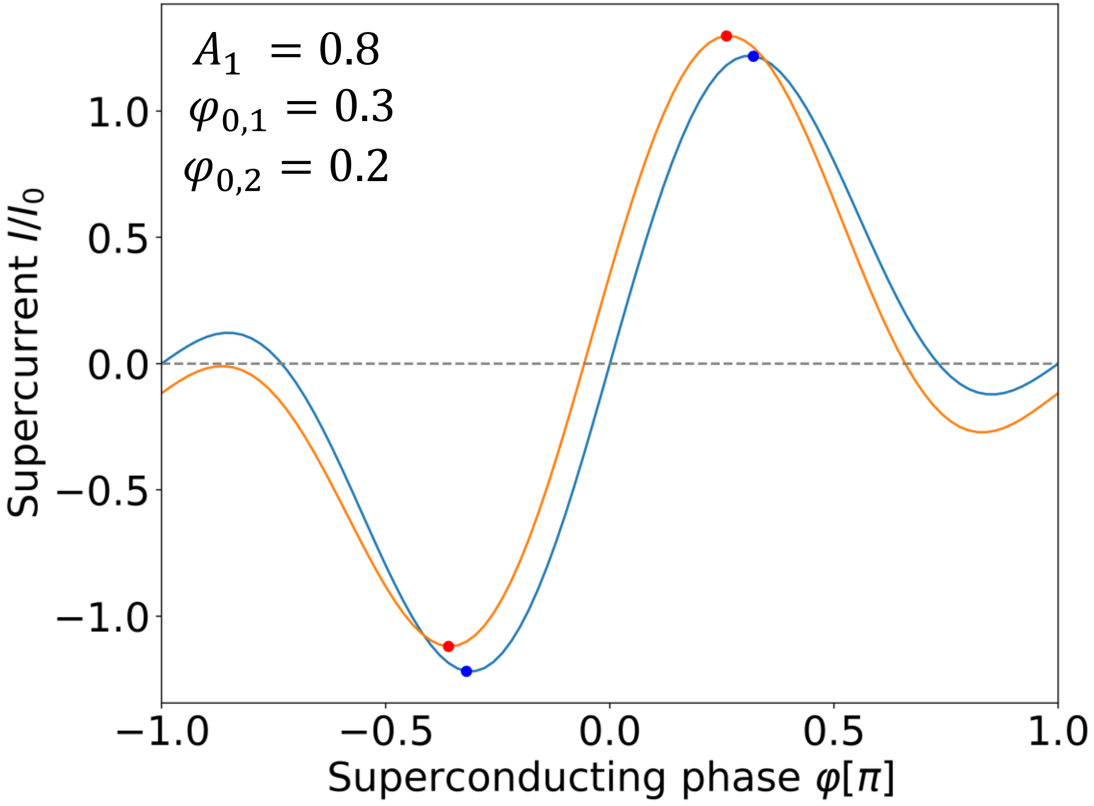
Josephson diode effect : ballistic junctions + anomalous CPR

➢ Skewed CPR

$$I = I_0 \sum_n c_n \sin(n\varphi)$$

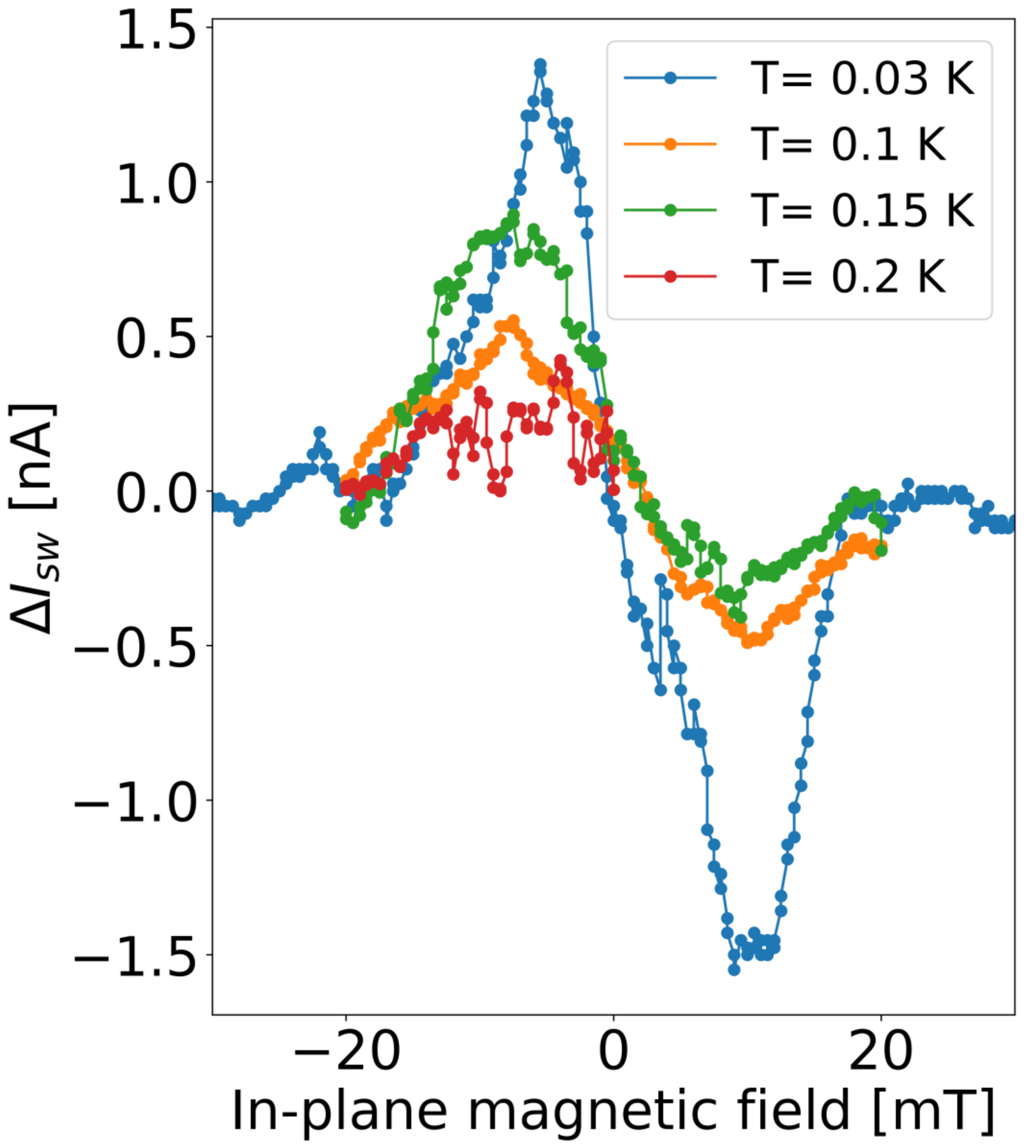
➢ Anomalous phase shift

$$I = I_0 \sum_n c_n \sin(n\varphi + \varphi_{0,n})$$



Baumgartner et al., *Nature Nanotechnology*, *17*(1), 39–44 (2022)

Dependence on the temperature



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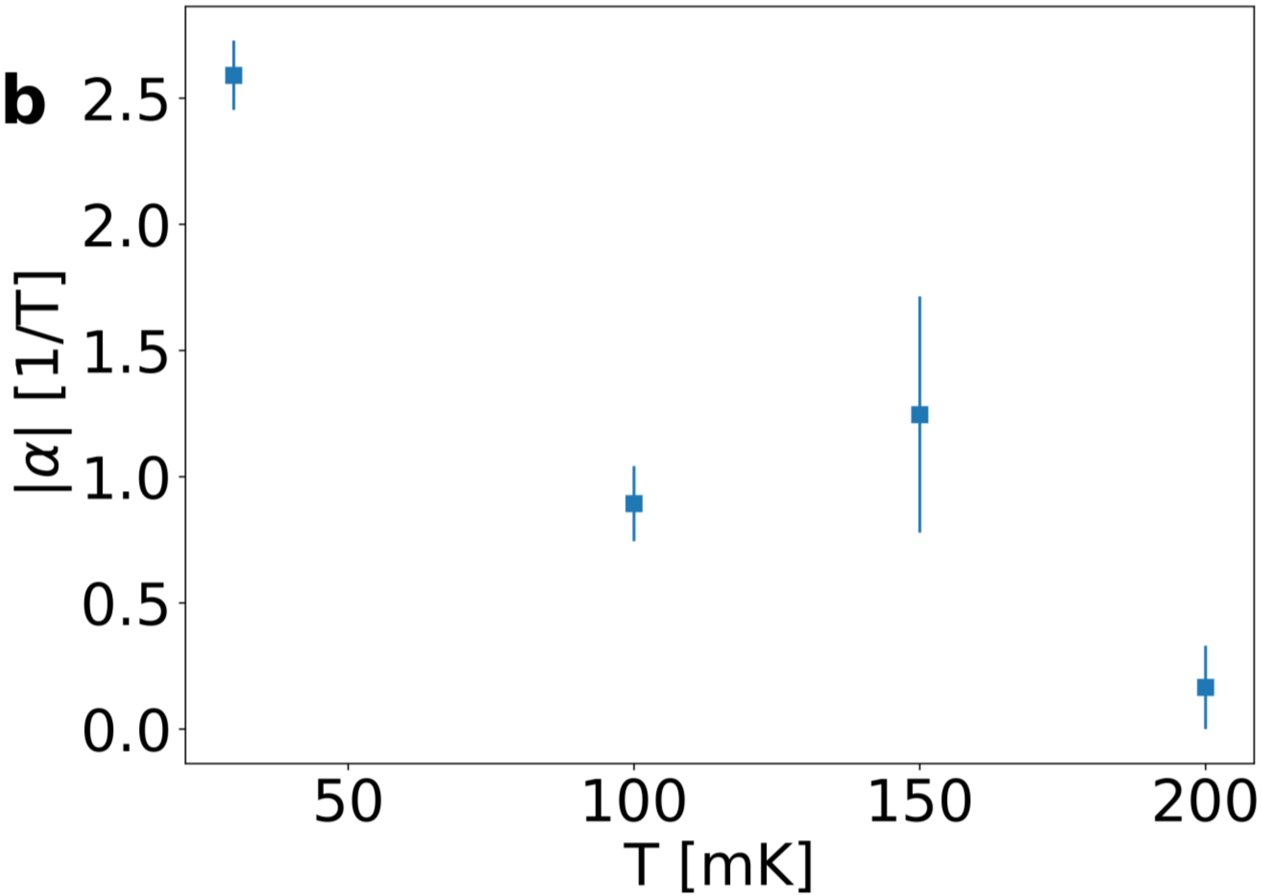
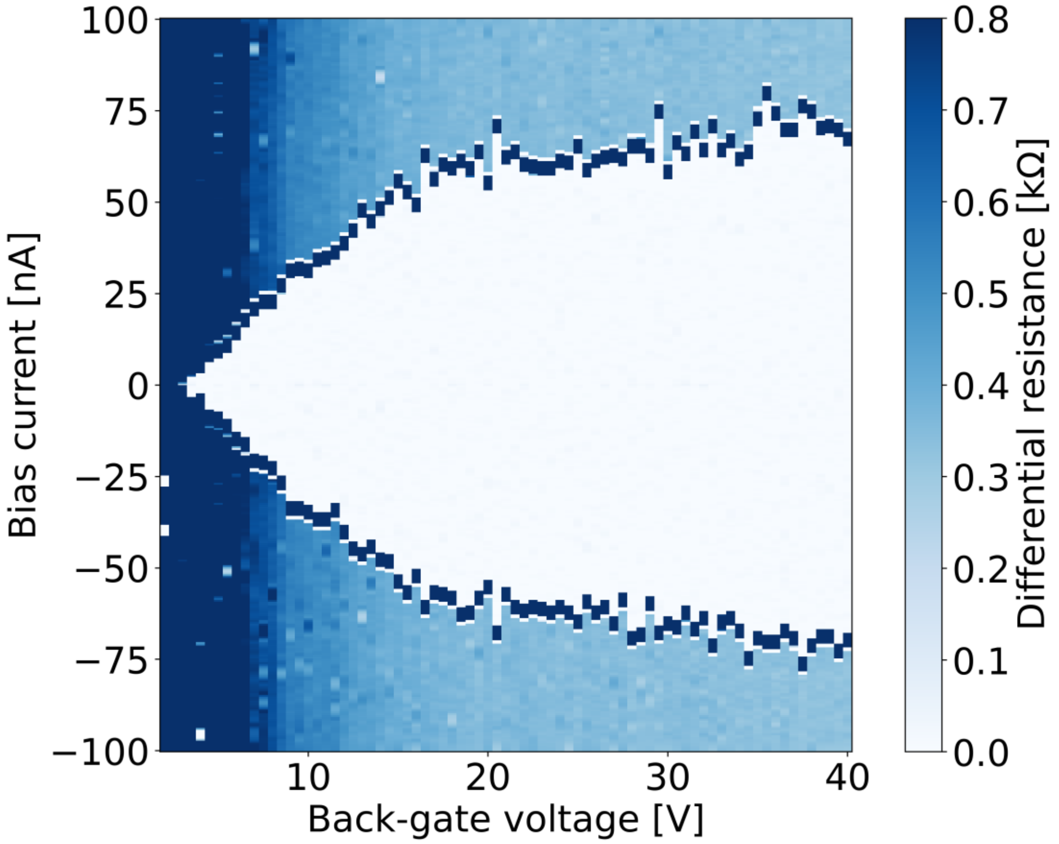
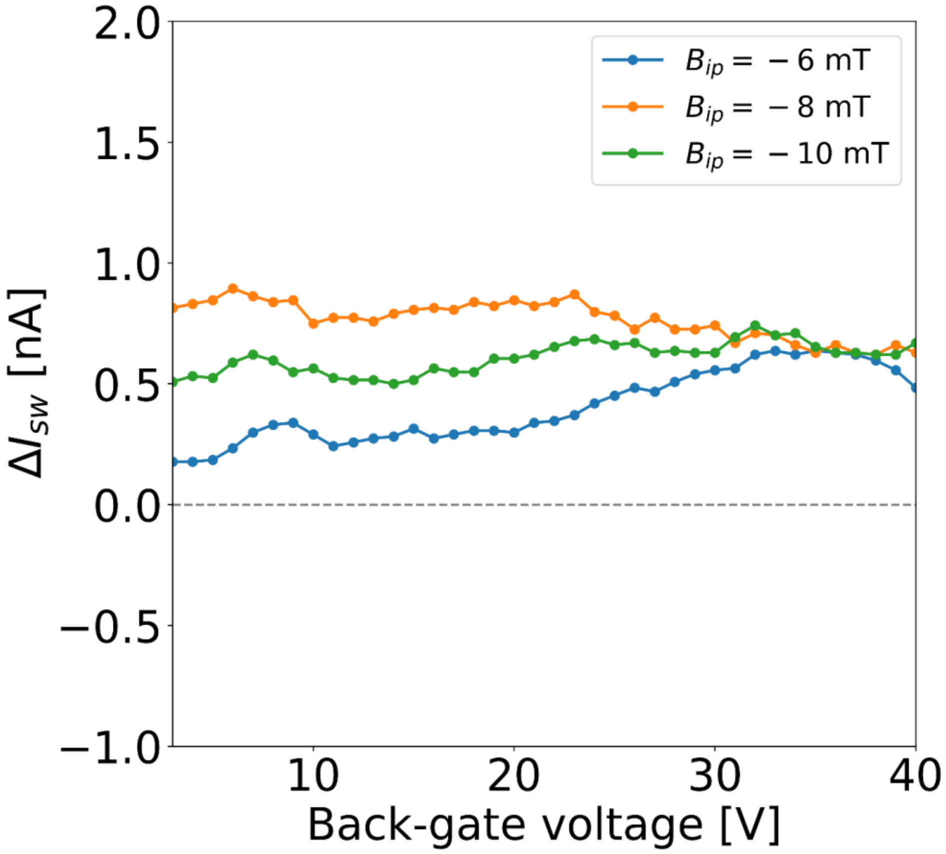
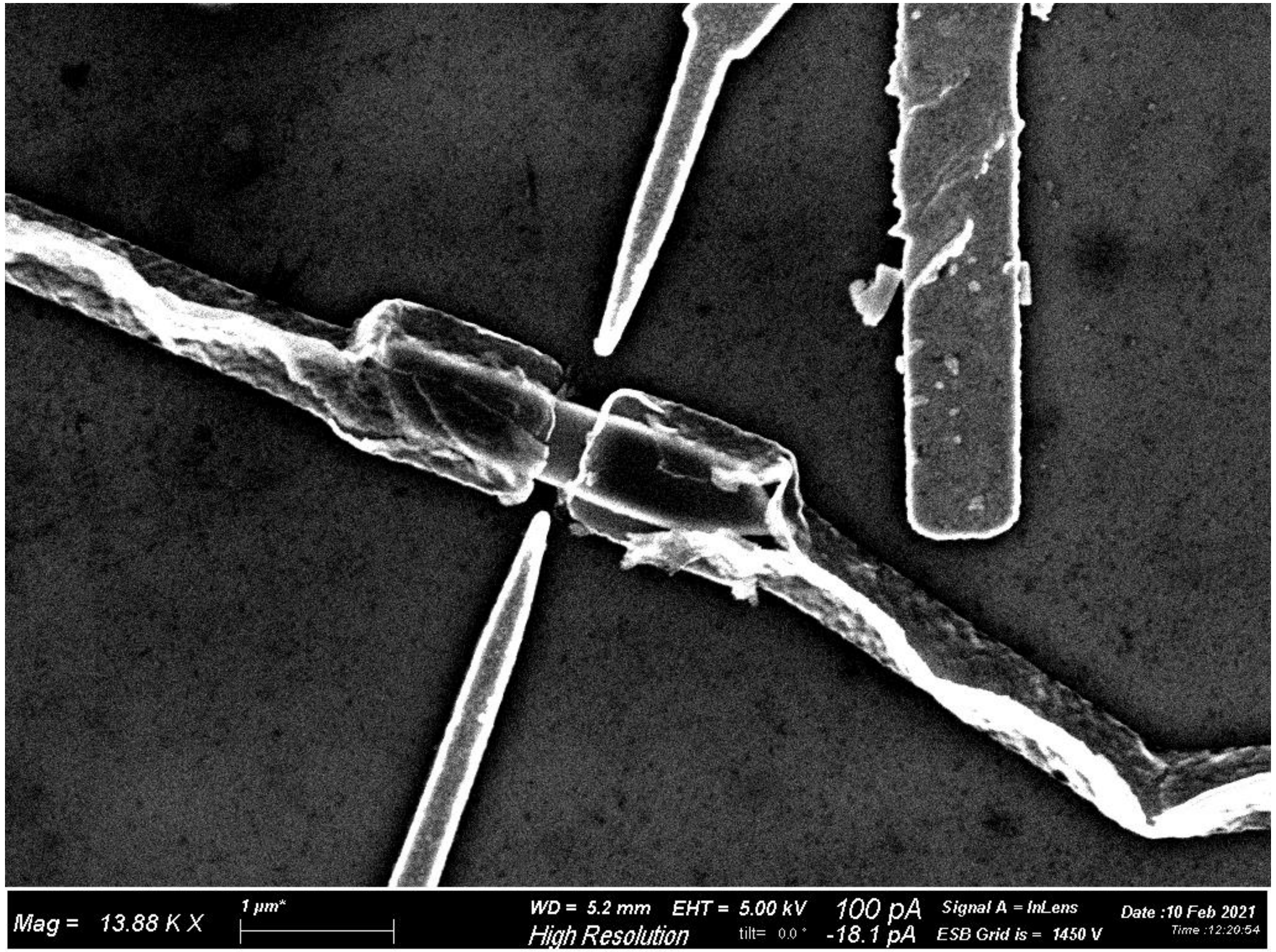


Effect of the back-gate

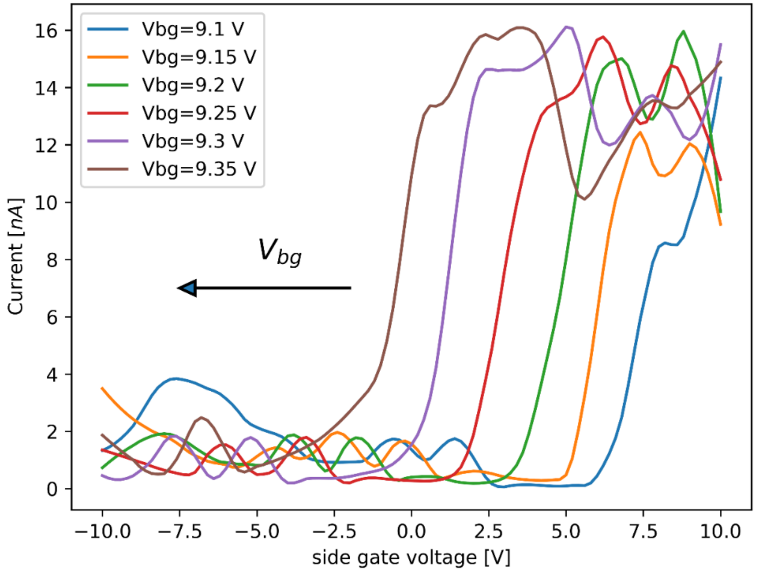




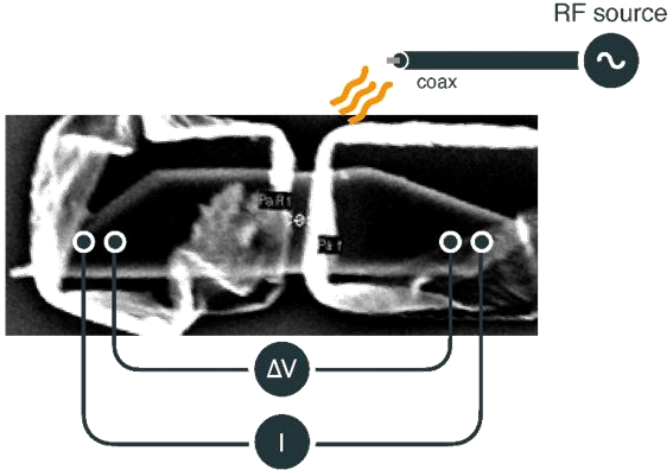
Outlook: gate-controlled SOI

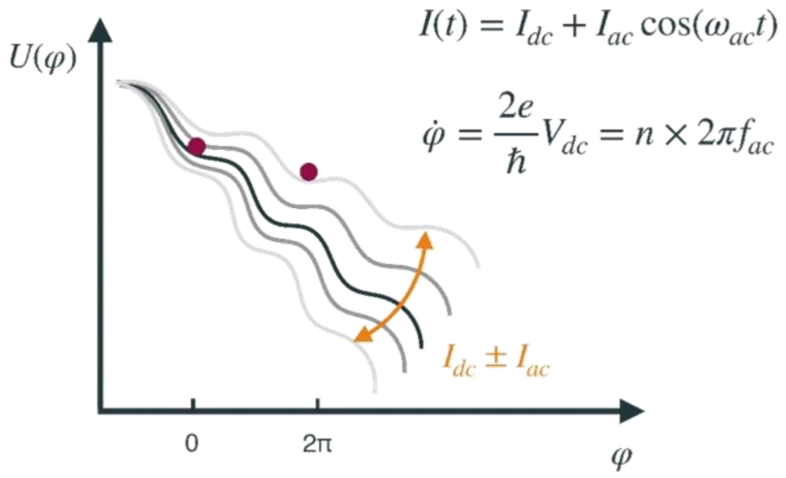


The idea: to tune the effective geometry and the SO coupling with side gates



Outlook: Shapiro steps





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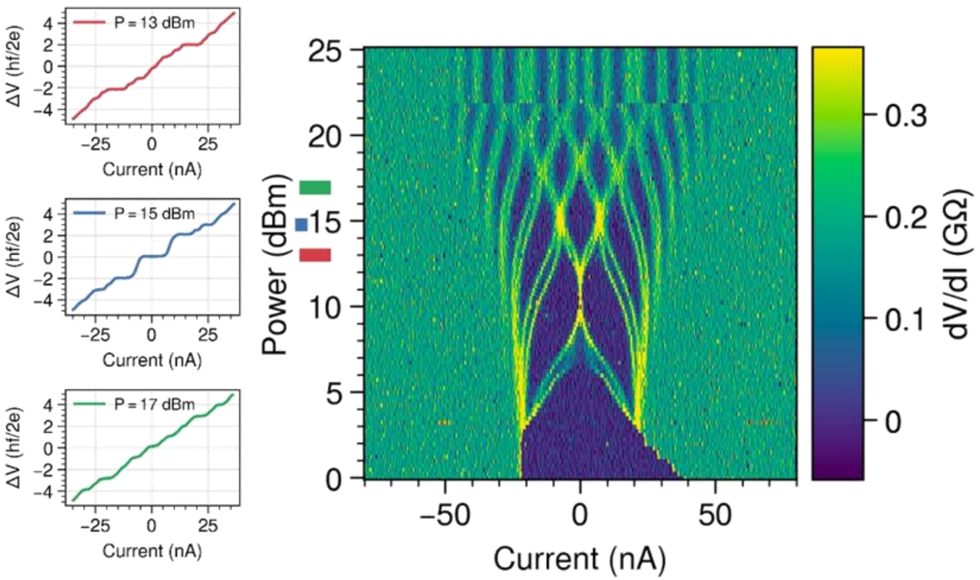
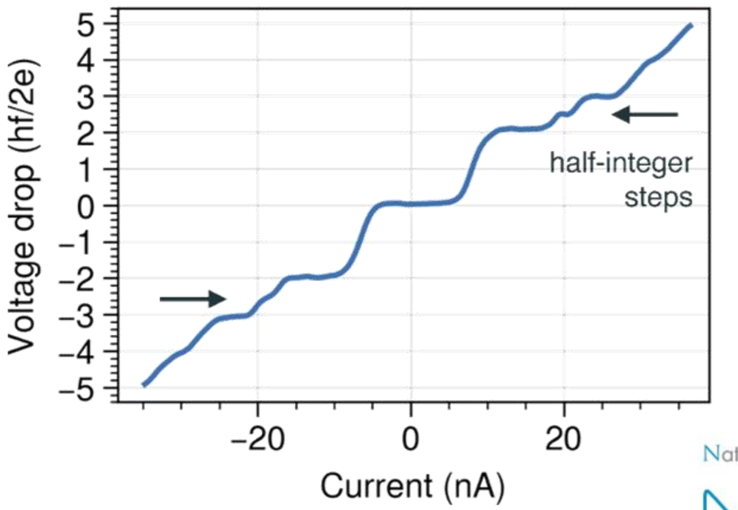
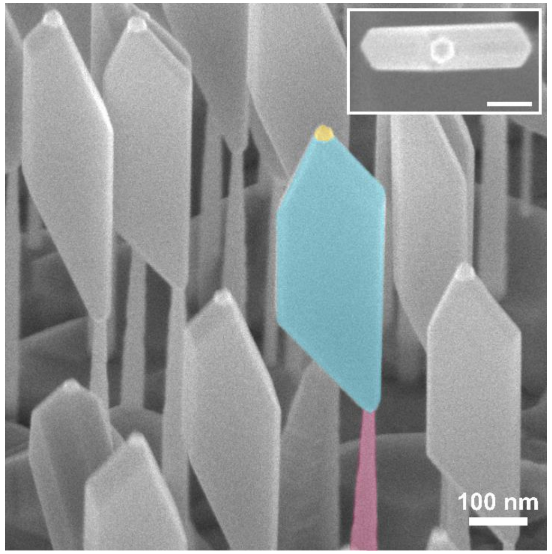
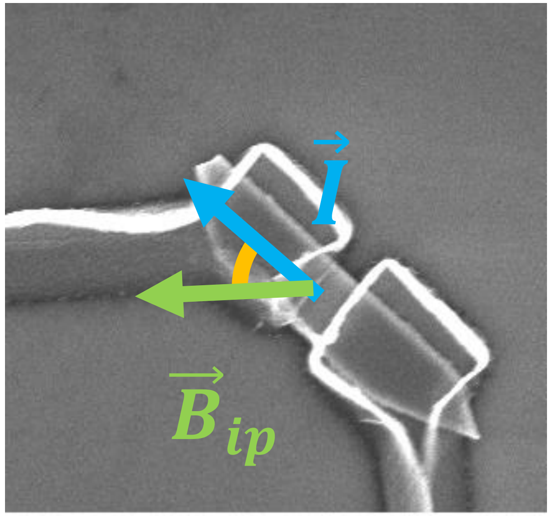




Summary

- Free-standing InSb nanoflags via CBE:
  - defect-free quasi-2D ZB structures
  - high-mobility devices
- InSb nanoflag-based Josephson junction:
  - high-trasparency of the interfaces
  - ballistic transport
  - gate-controlled supercurrent
- Josephson diode effect:
  - magnetic field-driven rectification
  - analysis of SOC in the system
  - evidence of finite-momentum superconductivity





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SUPER GATE

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