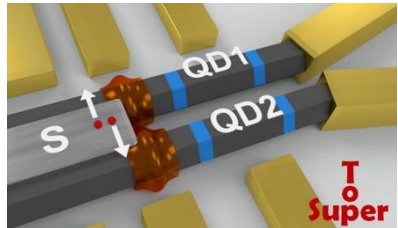


Josephson Diode Effect in High-Mobility InSb Nanoflags

Stefan Heun

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



AndQC

National Enterprise for nanoScience and nanoTechnology

NEST

Outline of the talk

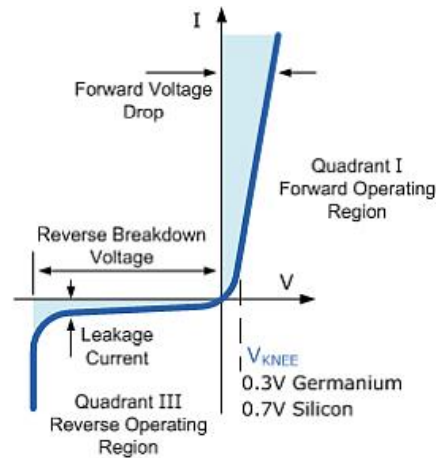
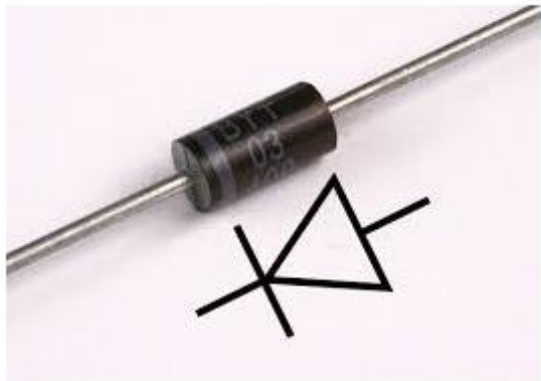
- Non-reciprocity in condensed matter systems
- InSb nanoflags for advanced devices
- Nanoflag-based Josephson junctions
- Josephson diode effect in InSb nanoflags

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

Non-reciprocal transport

Semiconductor diode with pn-junction



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

Magneto-chiral anisotropy (MCA)

- Magneto-chiral anisotropy caused by breaking of spatial-inversion and time-reversal symmetries

- $R = R_0 [1 + \gamma \hat{e}_z (\mathbf{B} \times \mathbf{I})]$

- Elusive in CM systems

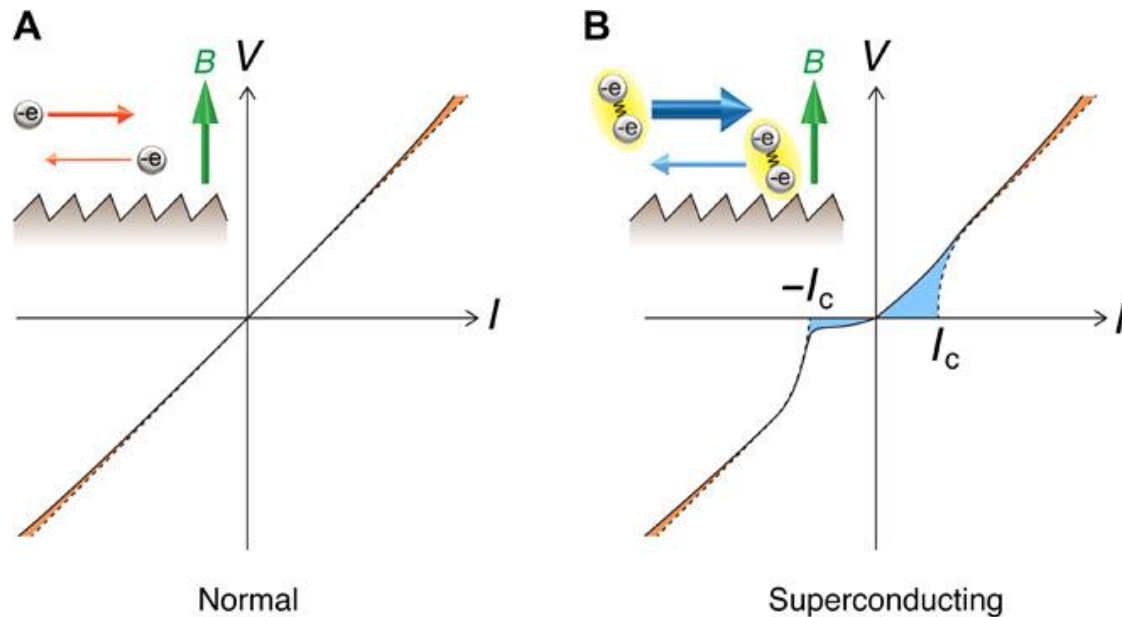
- $\gamma \sim \left(\frac{E_{SOI}}{E_F} \right) \sim 10^{-3} \text{ to } 10^{-2} \text{ T}^{-1} \text{ A}^{-1}$

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

Article

Observation of superconducting diode effect

<https://doi.org/10.1038/s41586-020-2590-4>

Received: 14 March 2020

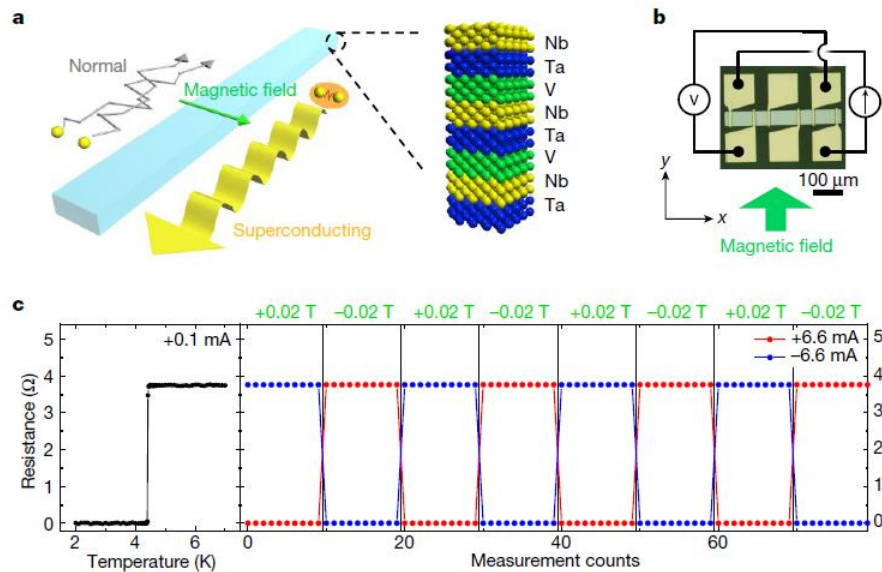
Accepted: 23 June 2020

Published online: 19 August 2020

Check for updates

Fuyuki Ando¹, Yuta Miyasaka¹, Tian Li¹, Jun Ishizuka², Tomonori Arakawa^{3,4}, Yoichi Shiota¹, Takahiro Moriyama¹, Youichi Yanase² & Teruo Ono^{1,4}✉

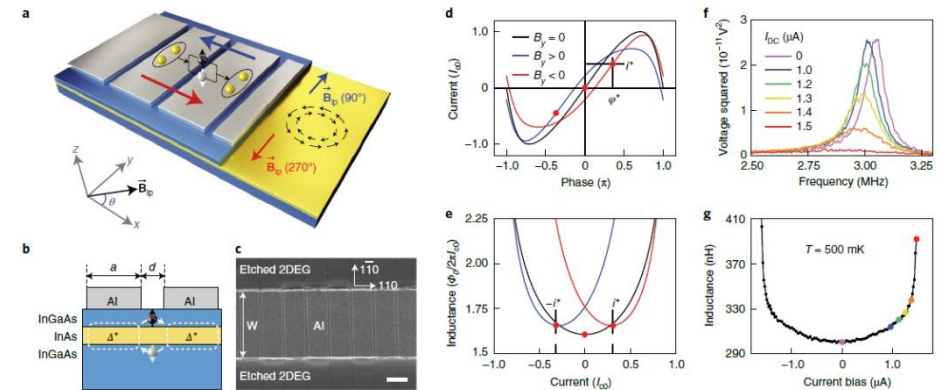
Nonlinear optical and electrical effects associated with a lack of spatial inversion symmetry allow direction-selective propagation and transport of quantum particles, such as photons¹ and electrons^{2–9}. The most common example of such nonreciprocal



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

Supercurrent rectification and magnetochiral effects in symmetric Josephson junctions

Christian Baumgartner^{1,8}, Lorenz Fuchs^{1,8}, Andreas Costa², Simon Reinhardt¹, Sergei Gronin^{3,4}, Geoffrey C. Gardner^{3,4}, Tyler Lindemann^{4,5}, Michael J. Manfra^{3,4,5,6,7}, Paulo E. Faria Junior², Denis Kochan², Jaroslav Fabian², Nicola Paradiso¹✉ and Christoph Strunk¹



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

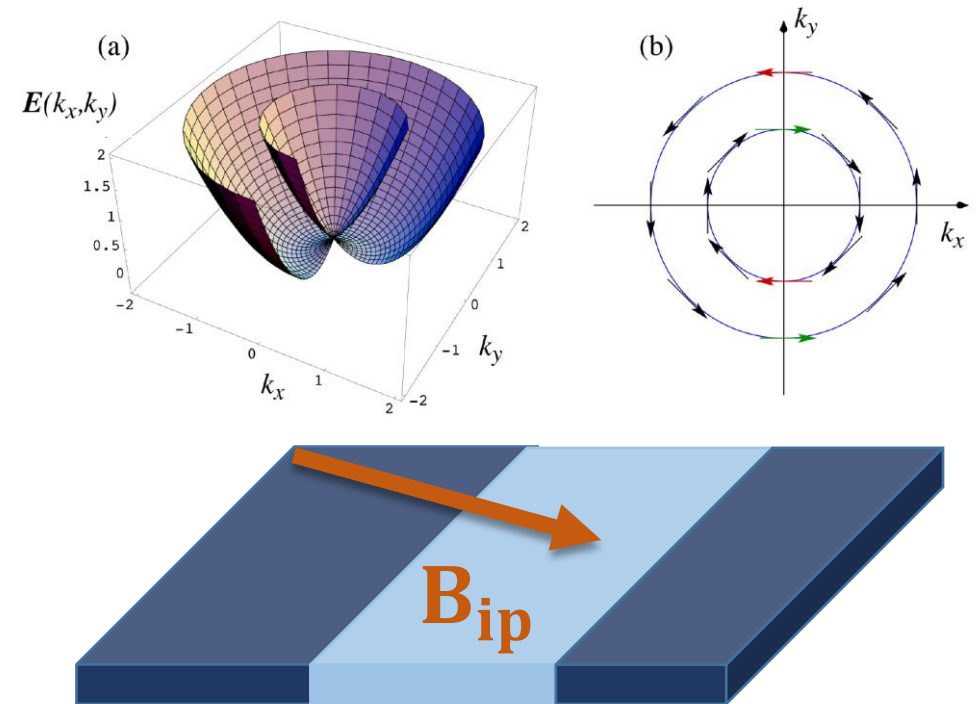
Ingredients for intrinsic SDE

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

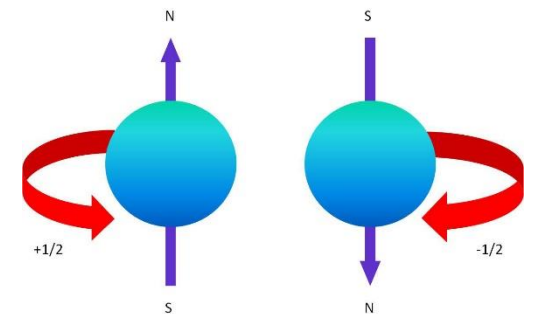
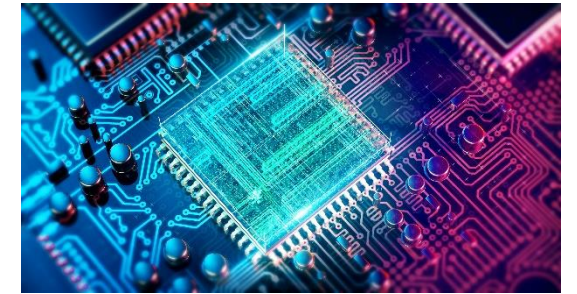
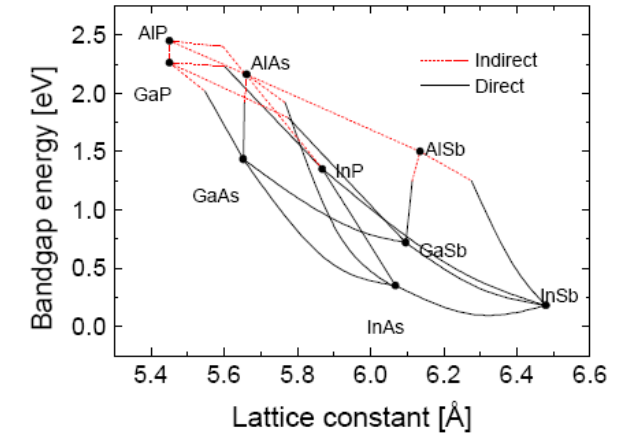


Outline of the talk

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

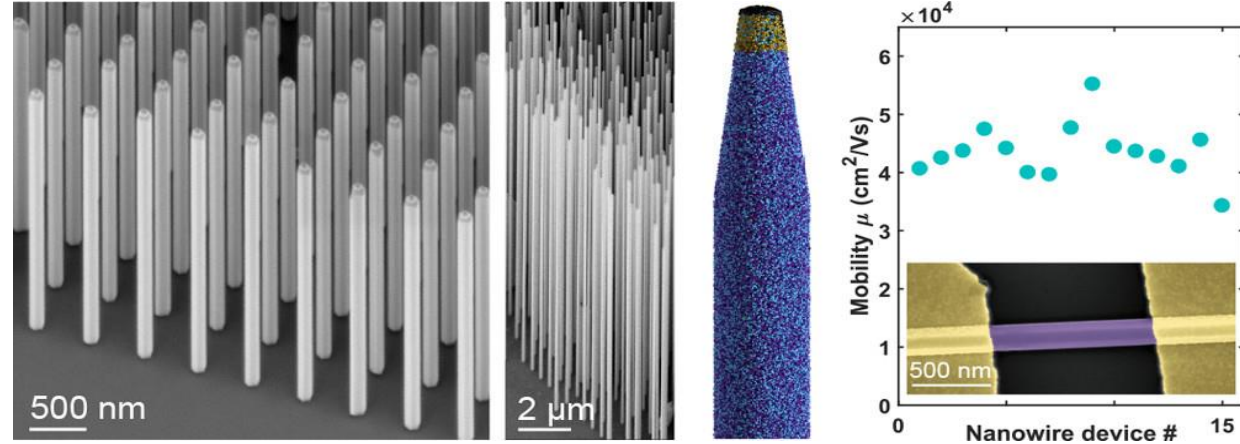
Why InSb?

- Narrow bandgap (0.23 eV) \longrightarrow mid-infrared optoelectronic devices.
- High bulk electron mobility ($7.7 \times 10^4 \text{ cm}^2/(\text{Vs})$), small effective mass ($0.018 m_e$) \longrightarrow high-speed and low-power electronic devices.
- Strong spin-orbit interaction ($E_{SOI} \sim 200 \mu\text{eV}$), large Landé g-factor ($g^* \sim 50$) \longrightarrow spintronics and topological quantum computing.



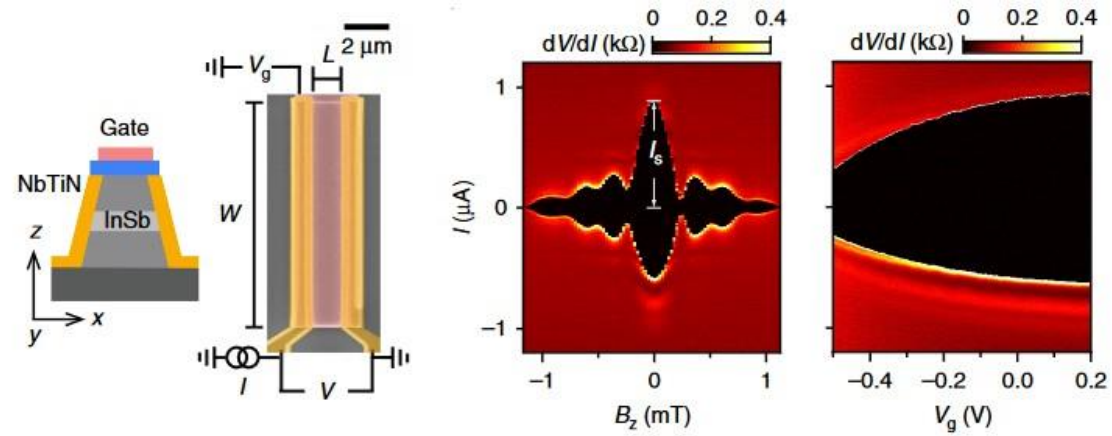
InSb nanostructures

- InSb nanowires:



Nano Lett. 2019, 19, 6, 3575–3582

- InSb quantum wells:

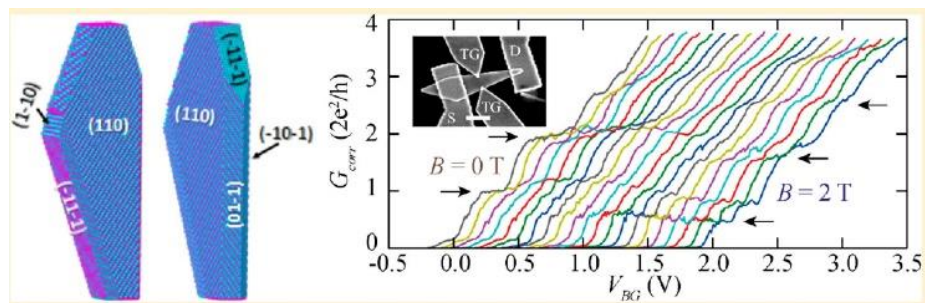


Nat Commun 10, 3764 (2019)

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^{*‡v}

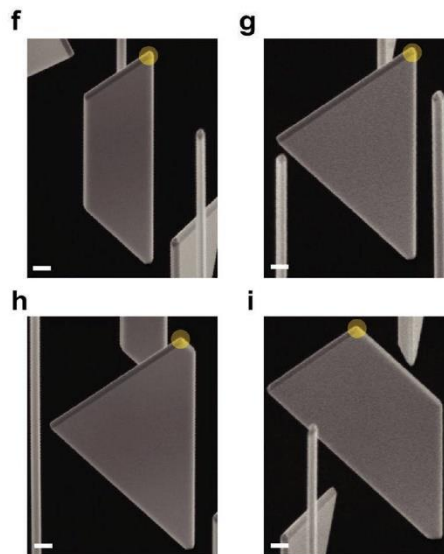


Nano Lett. 16 (2016) 825

Bottom-Up Grown 2D InSb Nanostructures

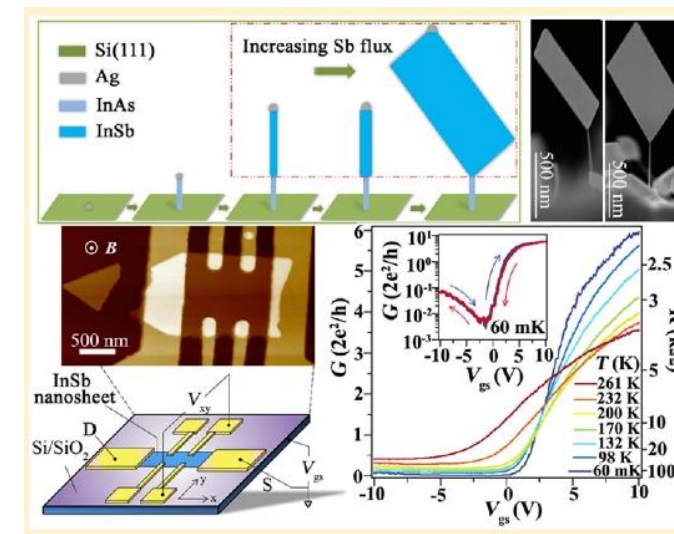
Sasa Gazibegovic,^{*} Ghada Badawy,^{*} Thijs L. J. Buckers, Philipp Leubner, Jie Shen, Folkert K. de Vries, Sebastian Koelling, Leo P. Kouwenhoven, Marcel A. Verheijen, and Erik P. A. M. Bakkers

Adv. Mater. 31 (2019) 1808181



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^{*‡}

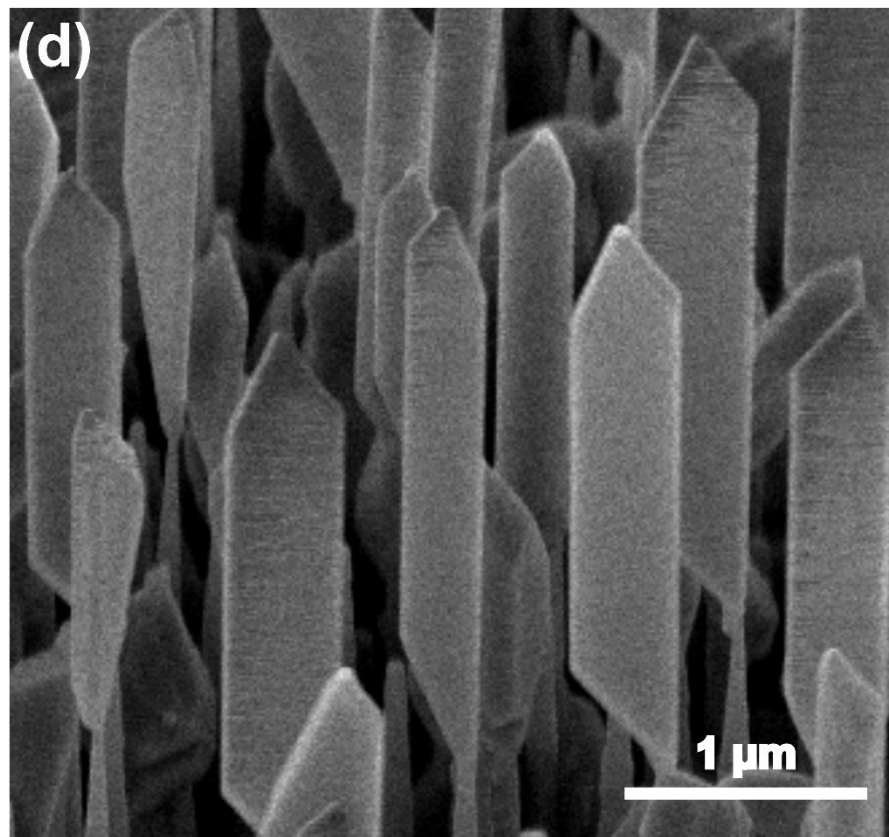
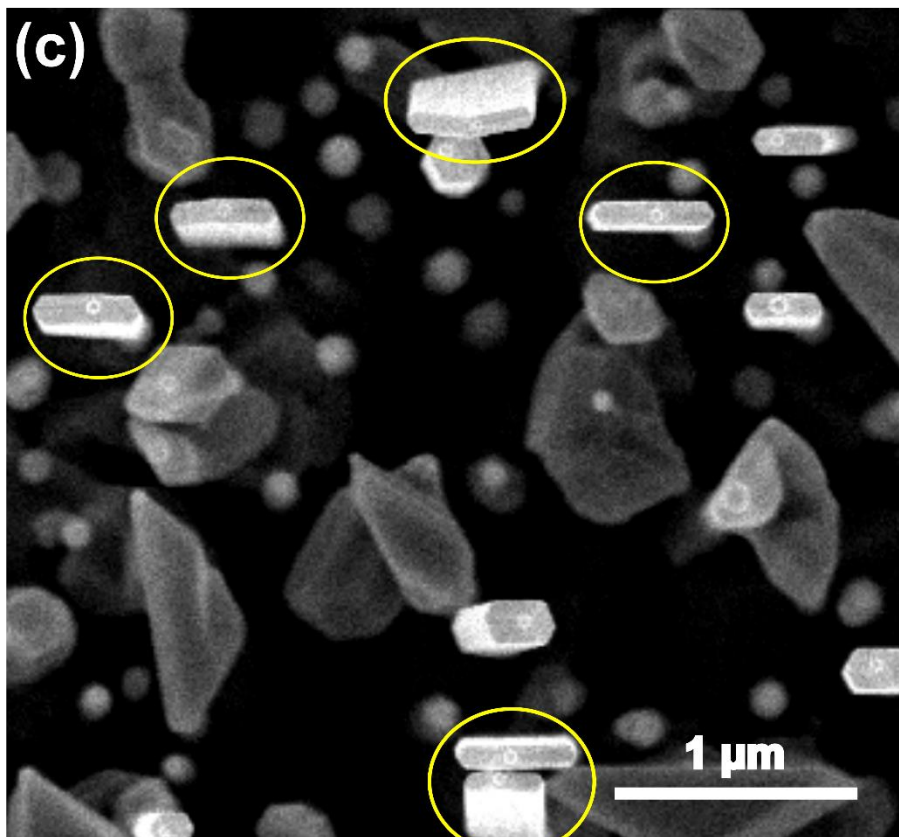


Nano Lett. 16 (2016) 834

Growth of InSb nanoflags by CBE



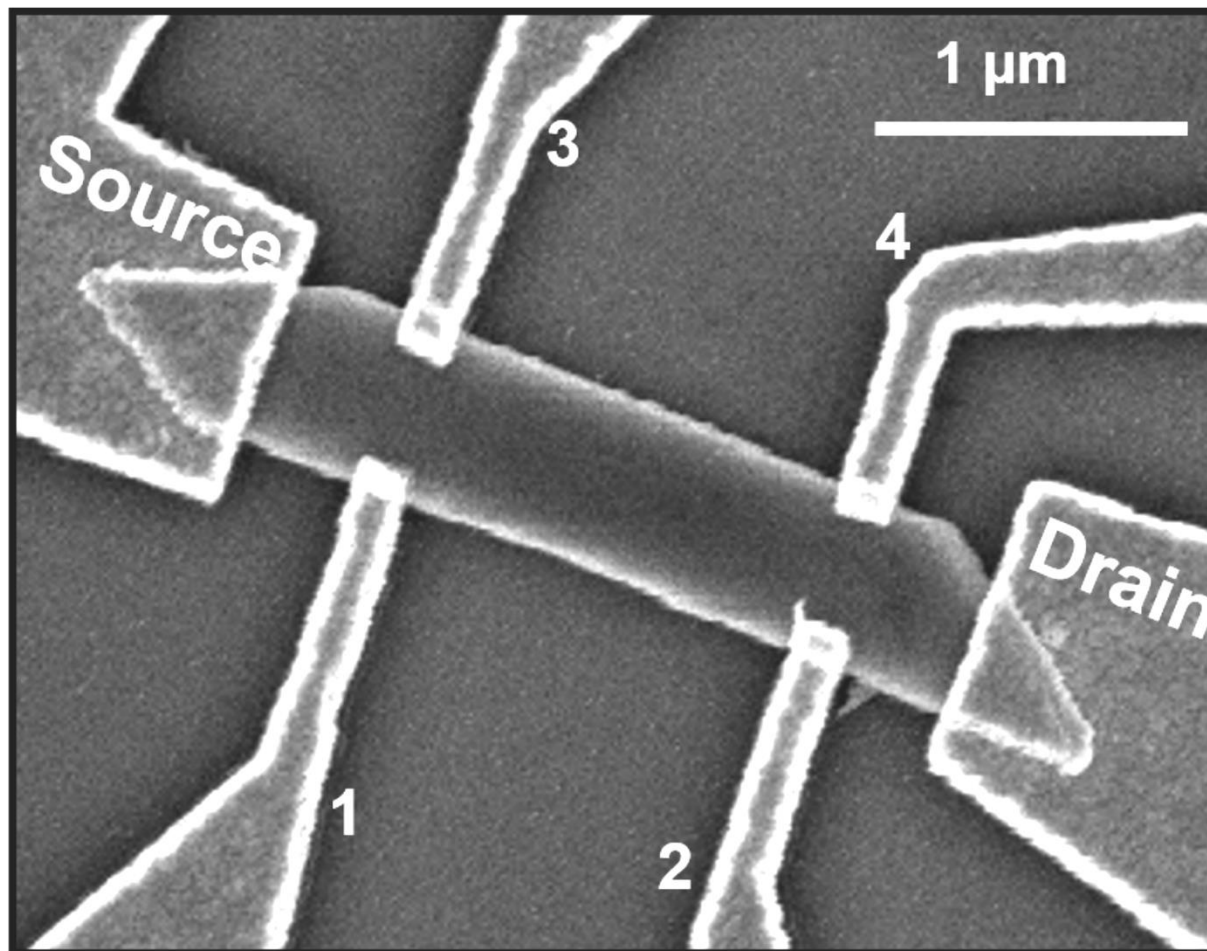
Isha Verma



Defect-free InSb
zinc blende
lattice

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

InSb Nanoflag Hall-bar device

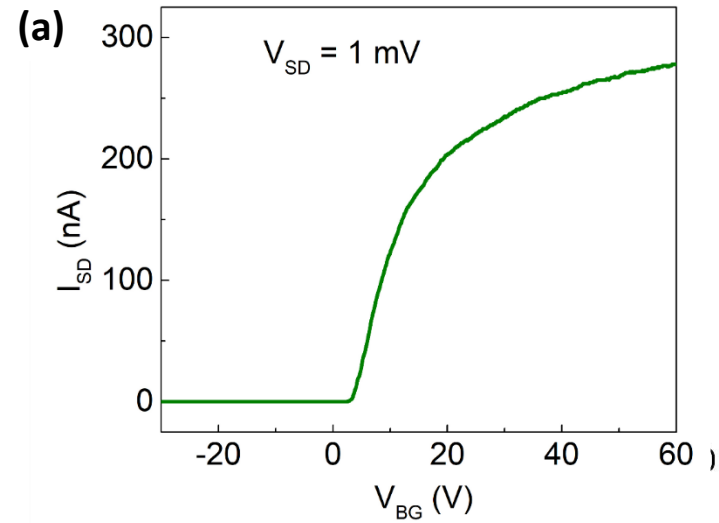


$L = 1.5 \mu\text{m}$

$W = 325 \text{ nm}$

$d = 100 \text{ nm}$

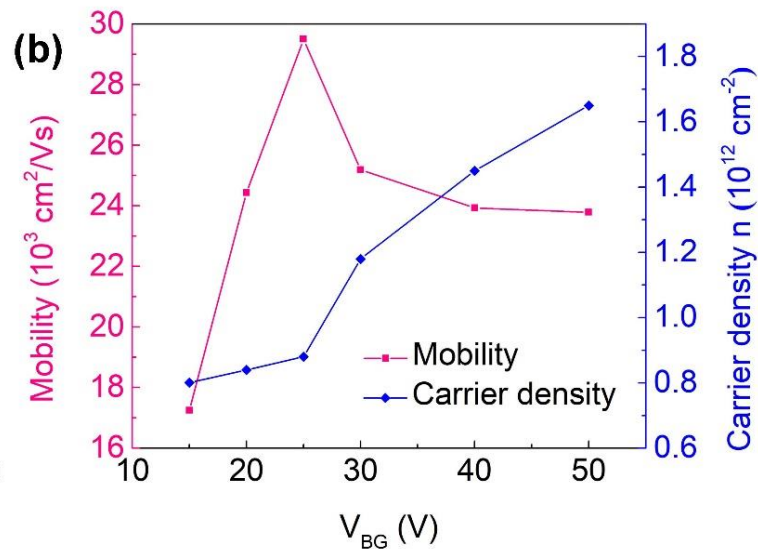
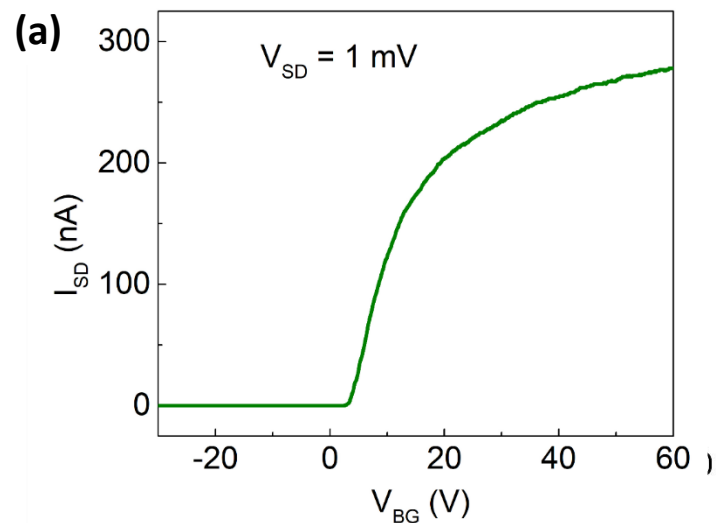
10 nm Ti/190 nm Au
Substrate: Si/SiO₂



Field-effect :

n-type conduction

$$\mu_{FE} = 2.8 \times 10^4 \text{ cm}^2/\text{Vs}$$



Field-effect :

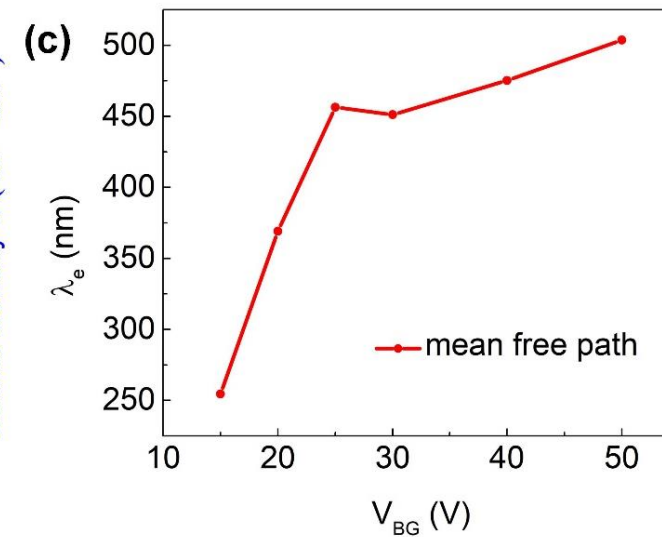
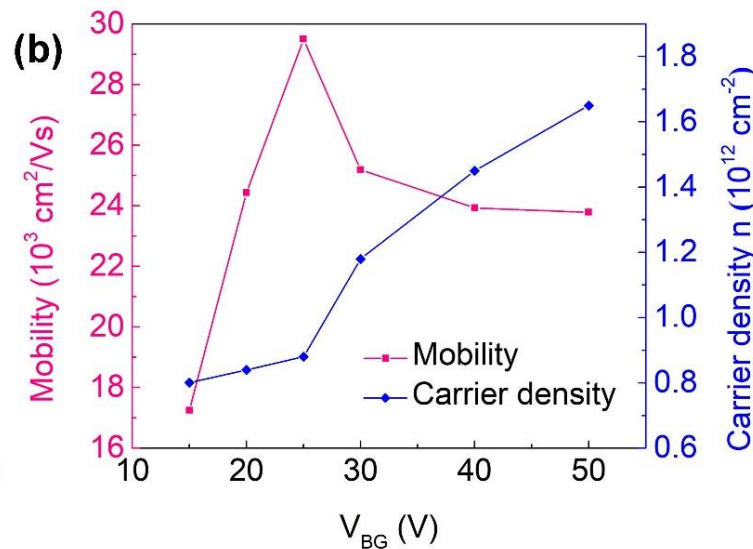
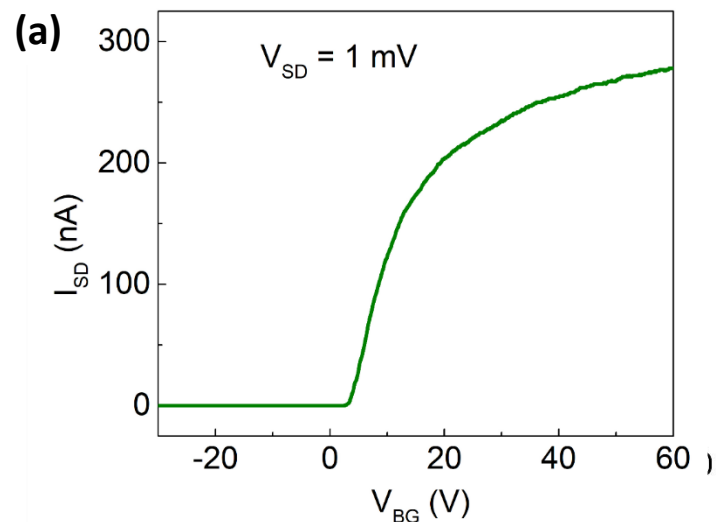
n-type conduction

$$\mu_{FE} = 2.8 \times 10^4 \text{ cm}^2/\text{Vs}$$

Hall mobility:

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

$$\text{@ } n = 8.5 \times 10^{11} \text{ cm}^{-2}$$



Field-effect :

n-type conduction

$$\mu_{FE} = 2.8 \times 10^4 \text{ cm}^2/\text{Vs}$$

Hall mobility:

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

$$\text{@ } n = 8.5 \times 10^{11} \text{ cm}^{-2}$$

Mean free path:

$$\lambda \sim 500 \text{ nm}$$

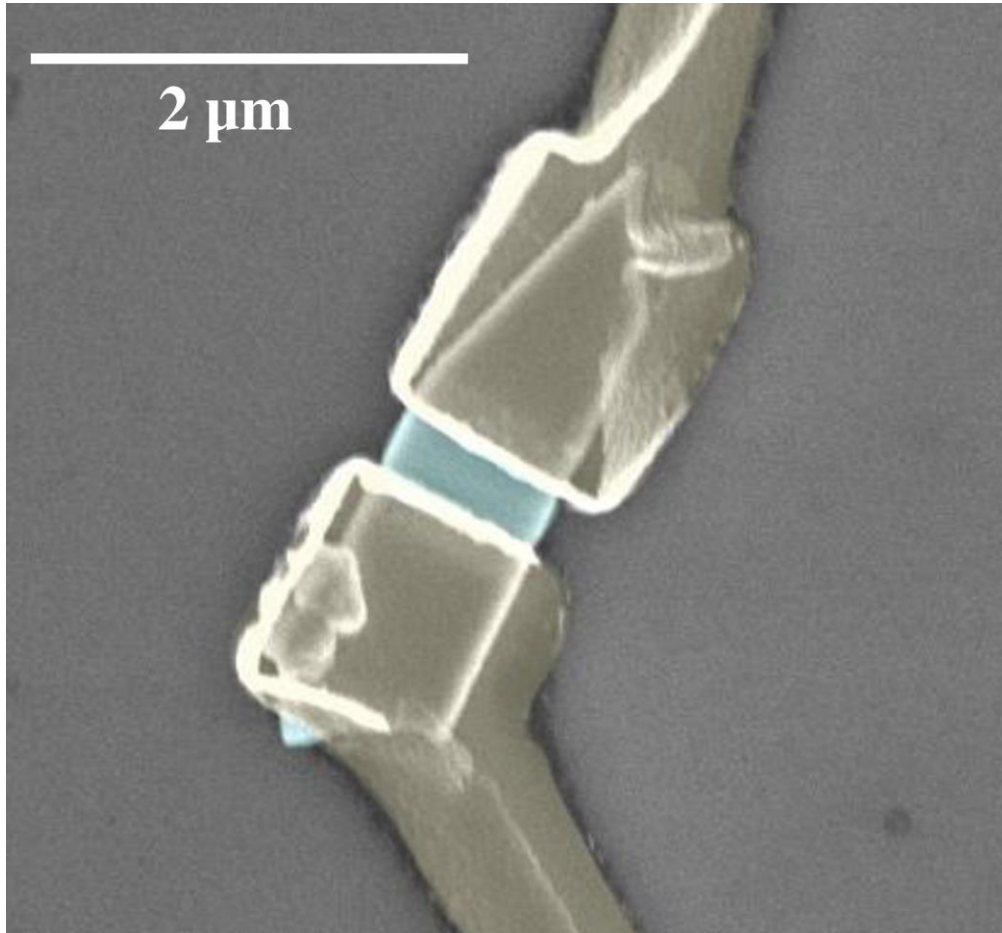
Outline of the talk

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

Nb/Ti-InSb Nanoflag-based JJs



Sedighe Salimian



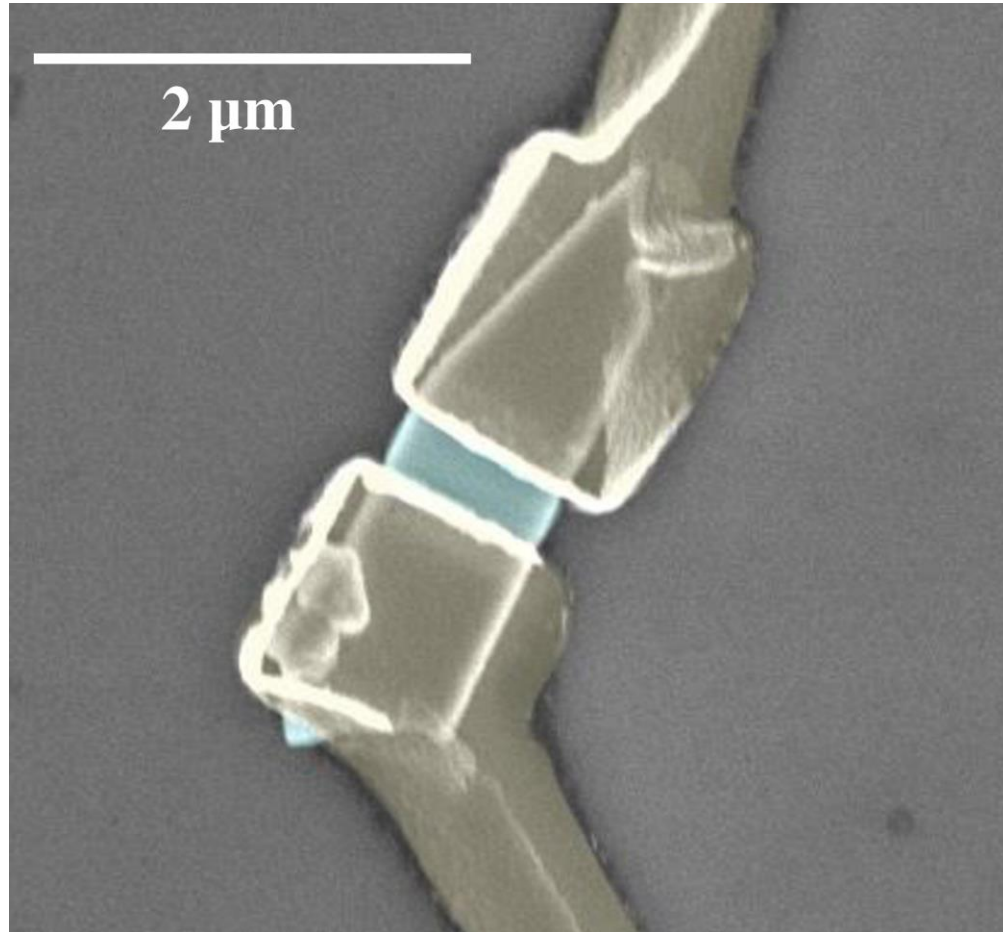
10 nm Ti/150 nm Nb
Substrate: Si/SiO₂

L = 200 nm
W = 700 nm

Nb/Ti-InSb Nanoflag-based JJs



Sedighe Salimian



10 nm Ti/150 nm Nb
Substrate: Si/SiO₂

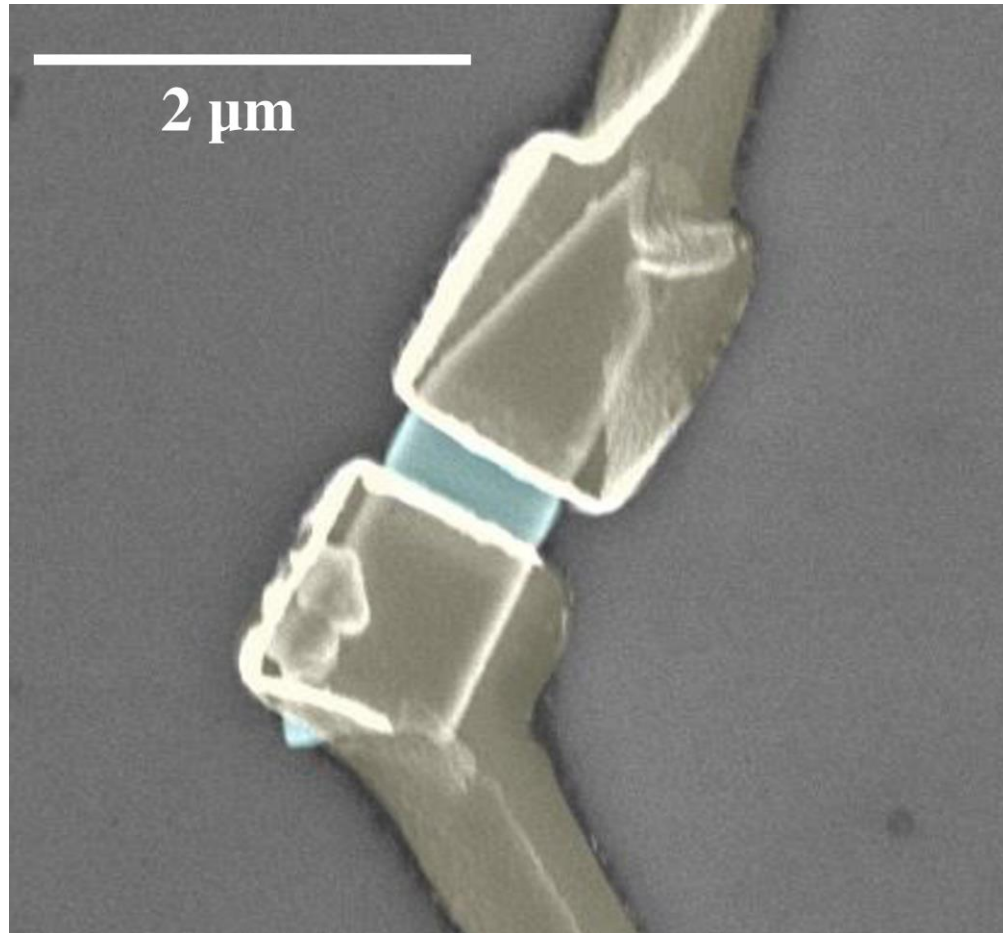
L = 200 nm
W = 700 nm

$T_c = 8.44 \text{ K} \rightarrow \Delta = 1.28 \text{ meV}$

Nb/Ti-InSb Nanoflag-based JJs



Sedighe Salimian



10 nm Ti/150 nm Nb
Substrate: Si/SiO₂

$L = 200 \text{ nm}$

$W = 700 \text{ nm}$

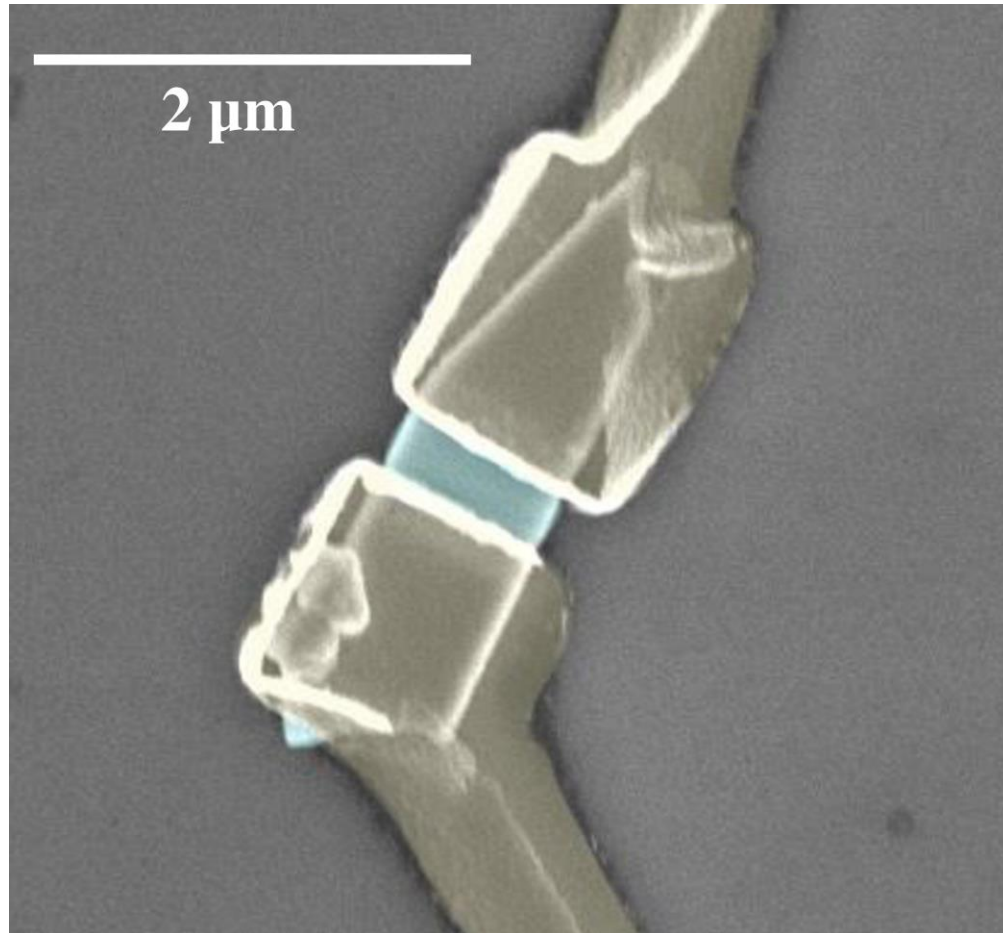
$T_c = 8.44 \text{ K} \rightarrow \Delta = 1.28 \text{ meV}$

$\lambda_e = 500 \text{ nm} \rightarrow \text{ballistic regime}$

Nb/Ti-InSb Nanoflag-based JJs



Sedighe Salimian



10 nm Ti/150 nm Nb
Substrate: Si/SiO₂

$L = 200 \text{ nm}$

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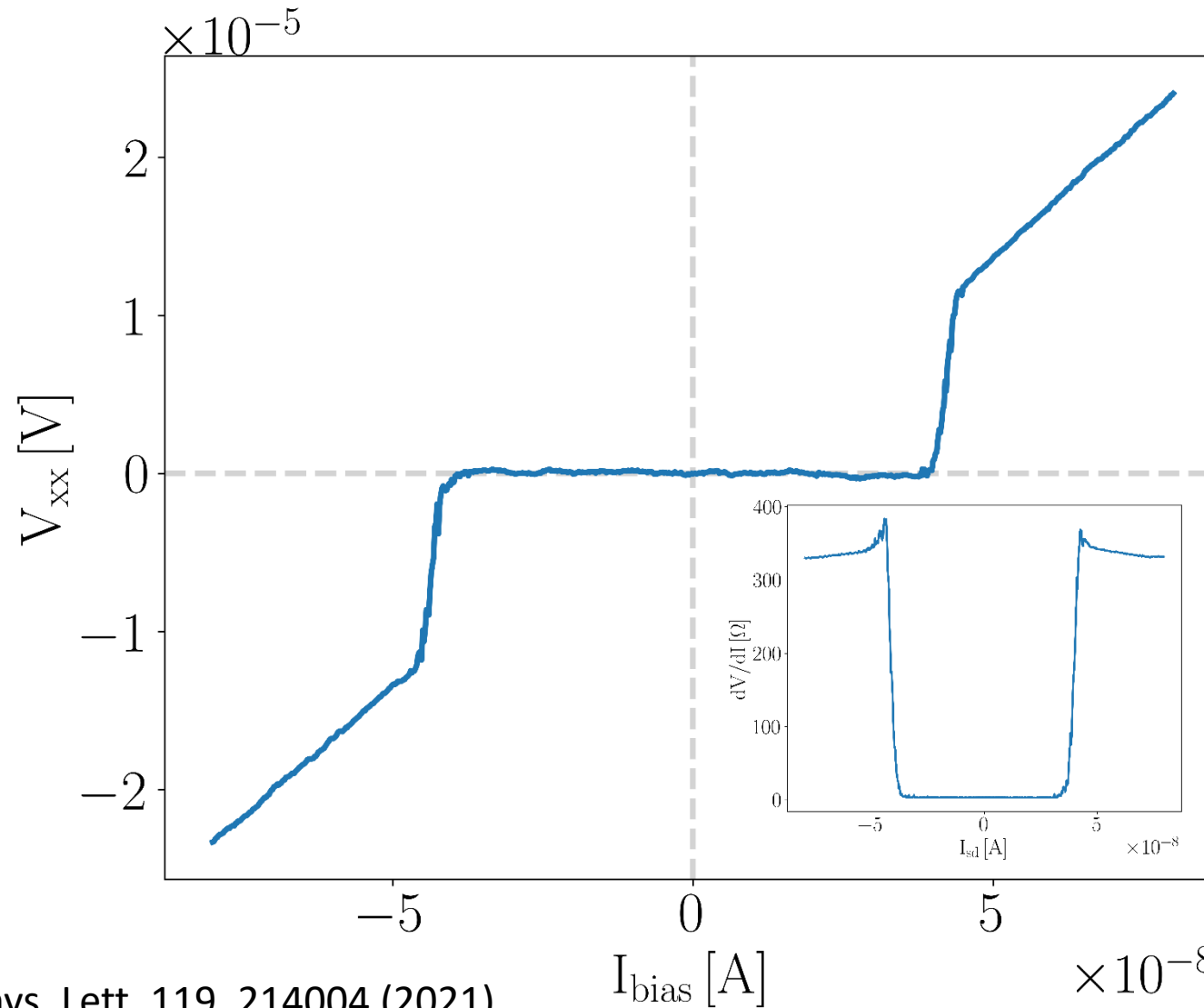
$T_c = 8.44 \text{ K} \rightarrow \Delta = 1.28 \text{ meV}$

$\lambda_e = 500 \text{ nm} \rightarrow \text{ballistic regime}$

$\xi_S = \hbar v_F / \Delta \sim 750 \text{ nm} \rightarrow \text{short junction}$

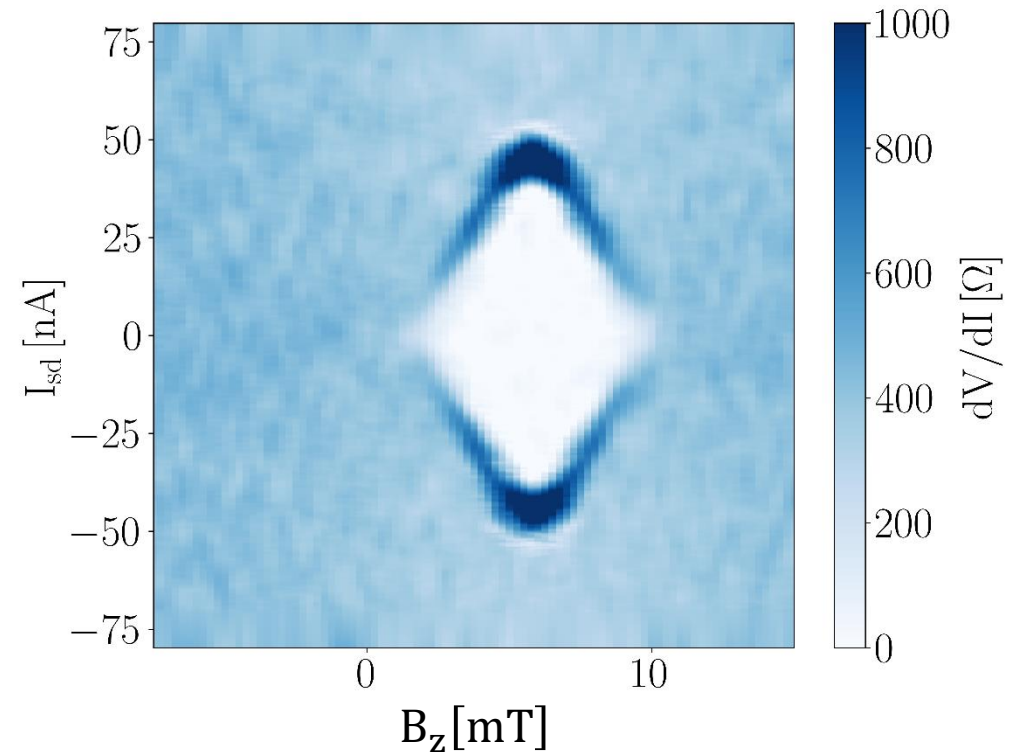
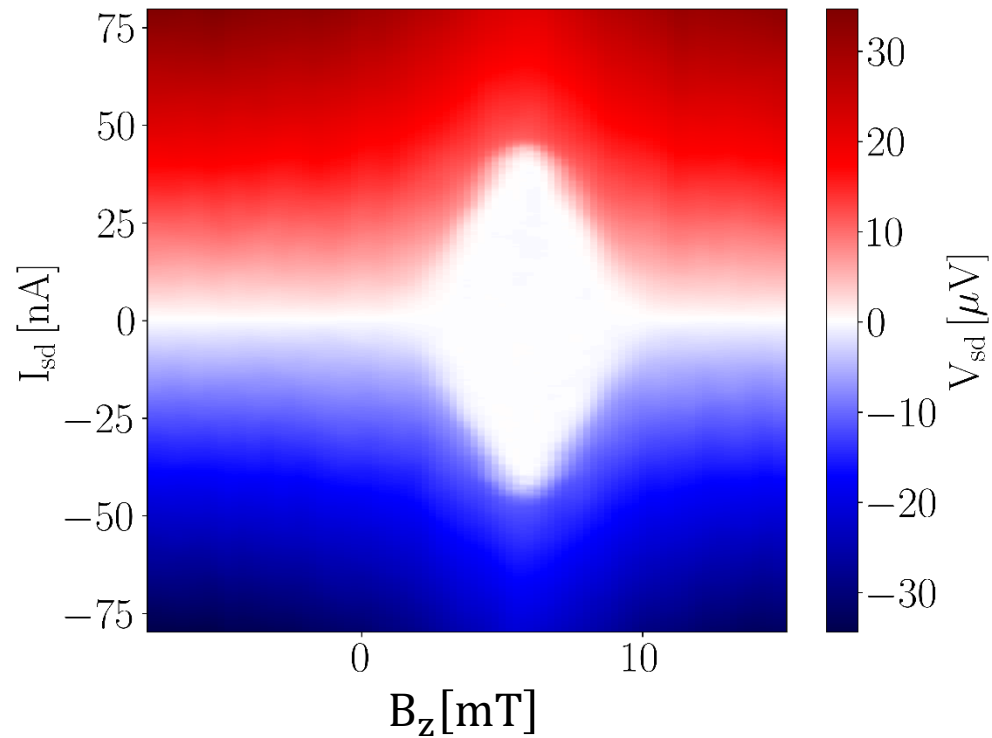
V-I shows supercurrent

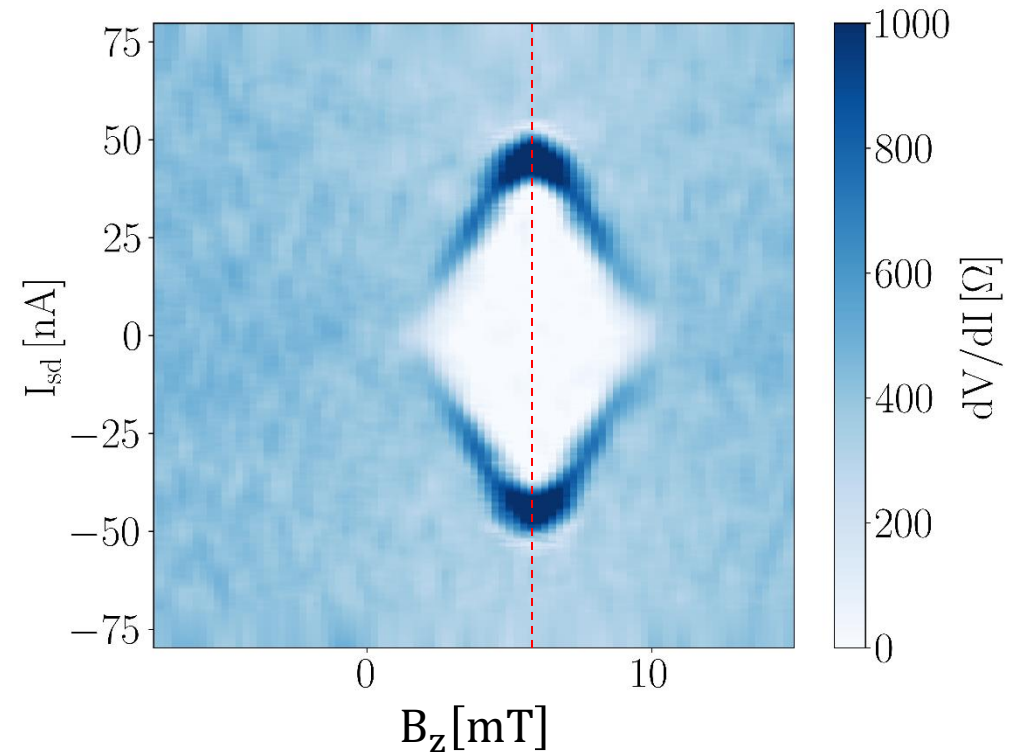
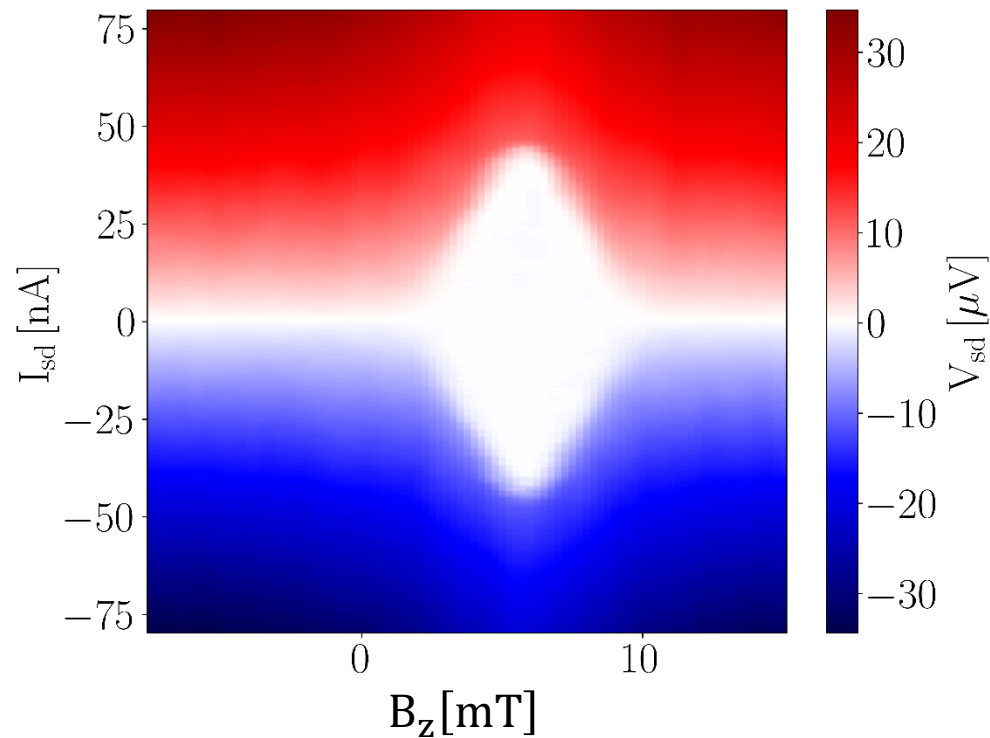
T = 250 mK



Magnetic Interference Pattern

$T = 250 \text{ mK}$



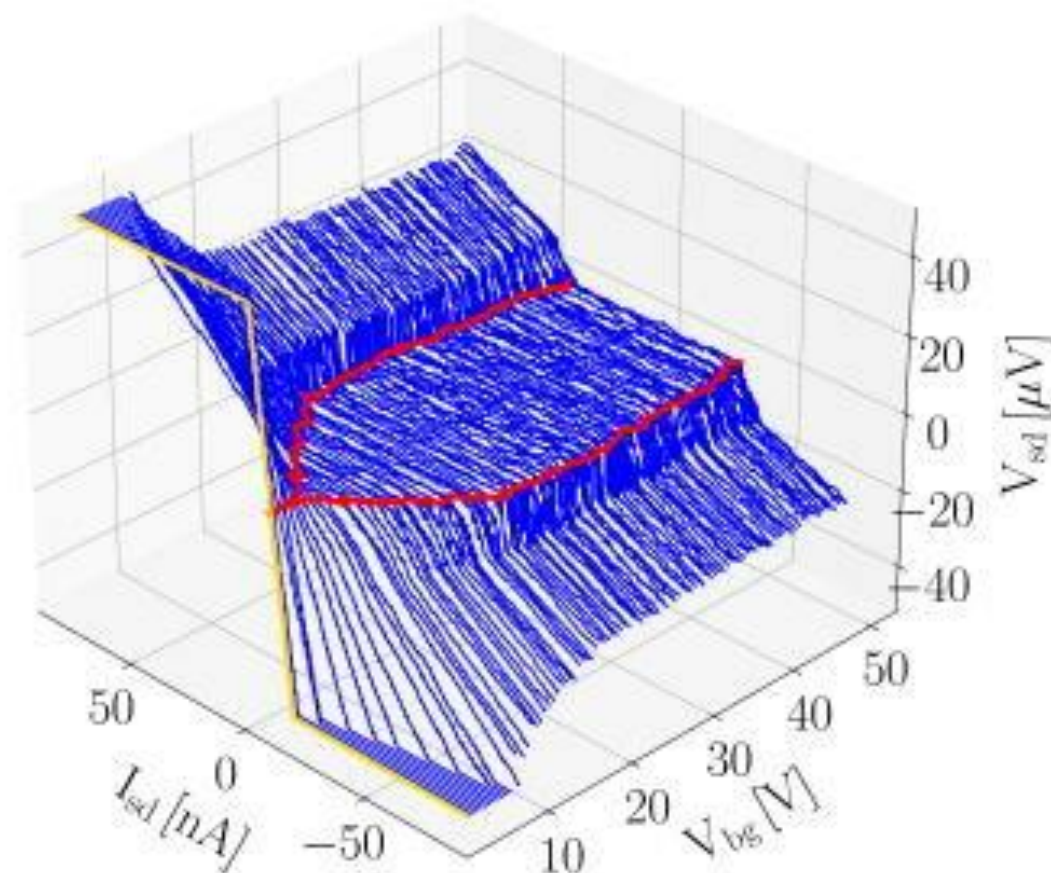
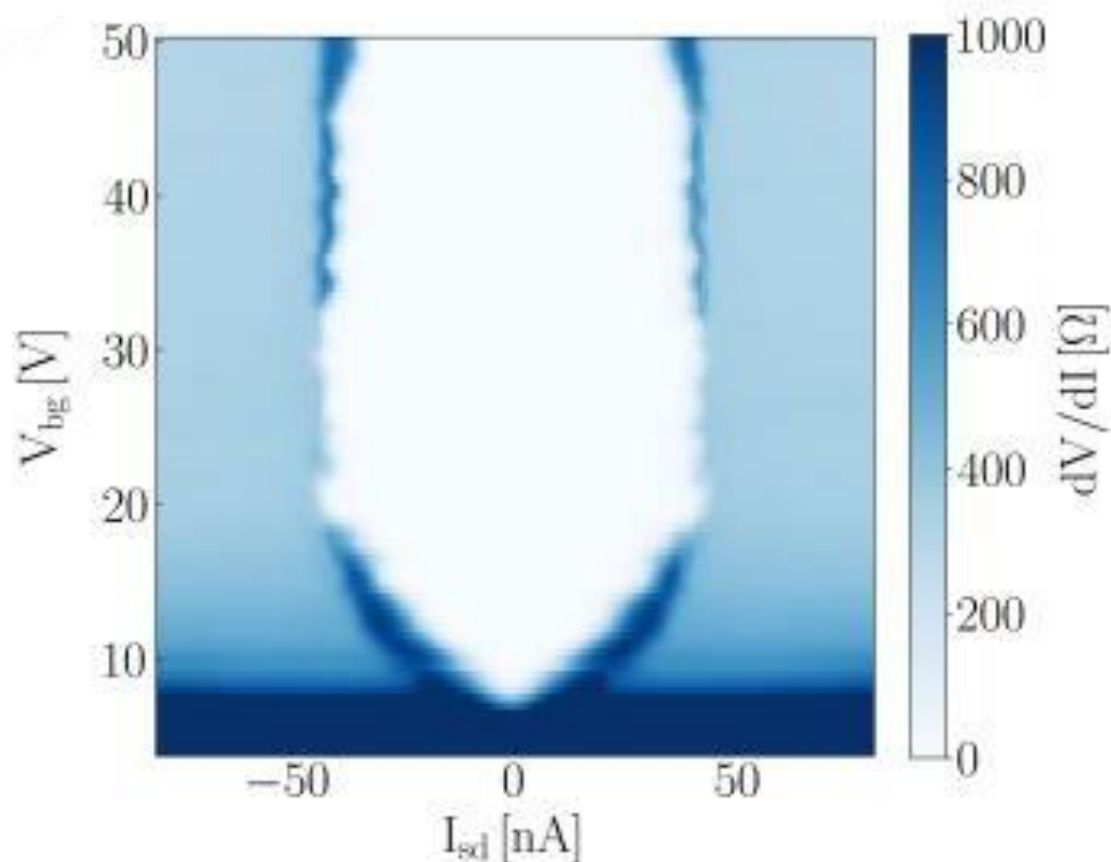


Why no sides lobes in the Fraunhofer pattern?

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

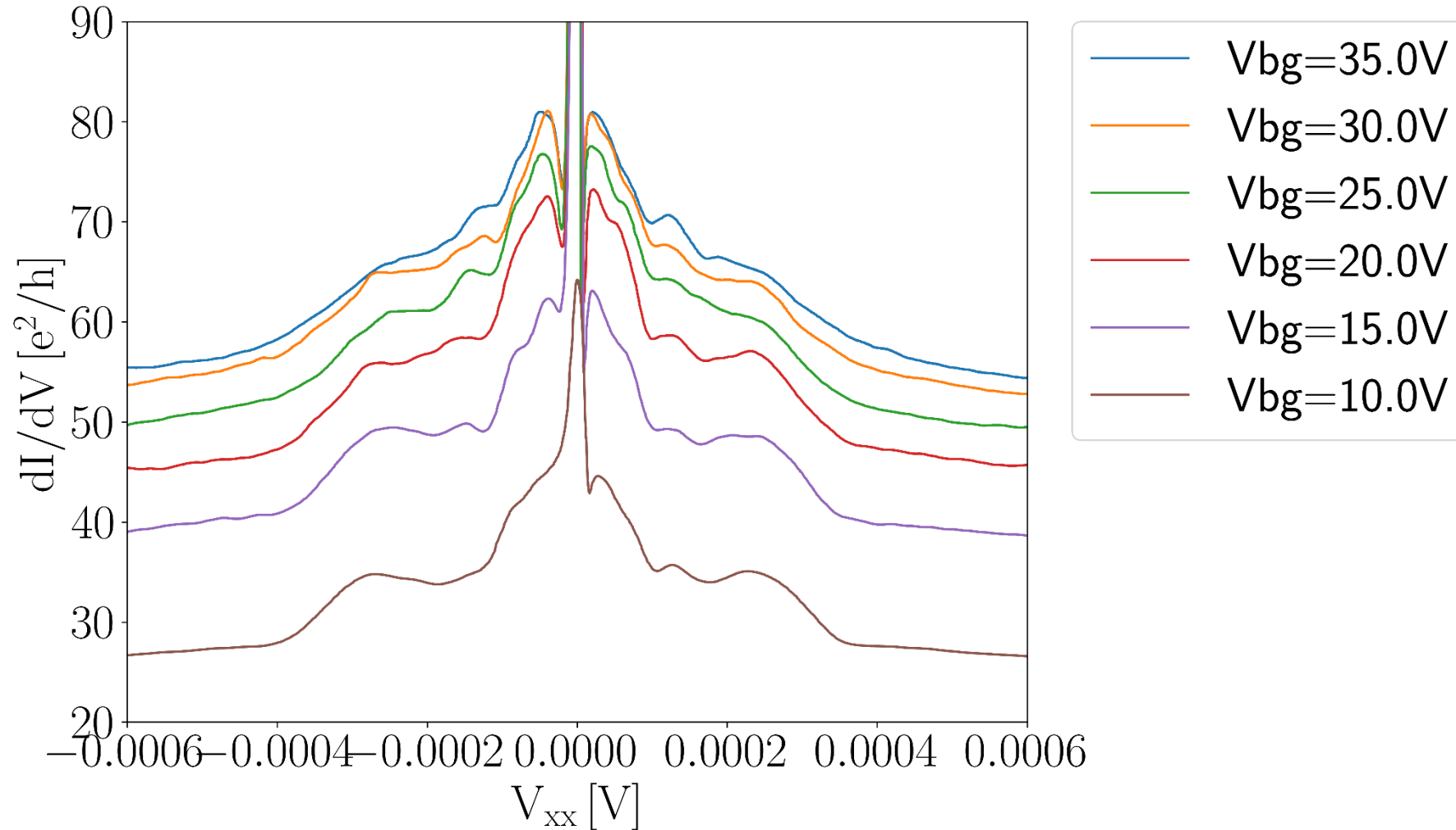
Gate-controlled supercurrent

$T = 250 \text{ mK}$



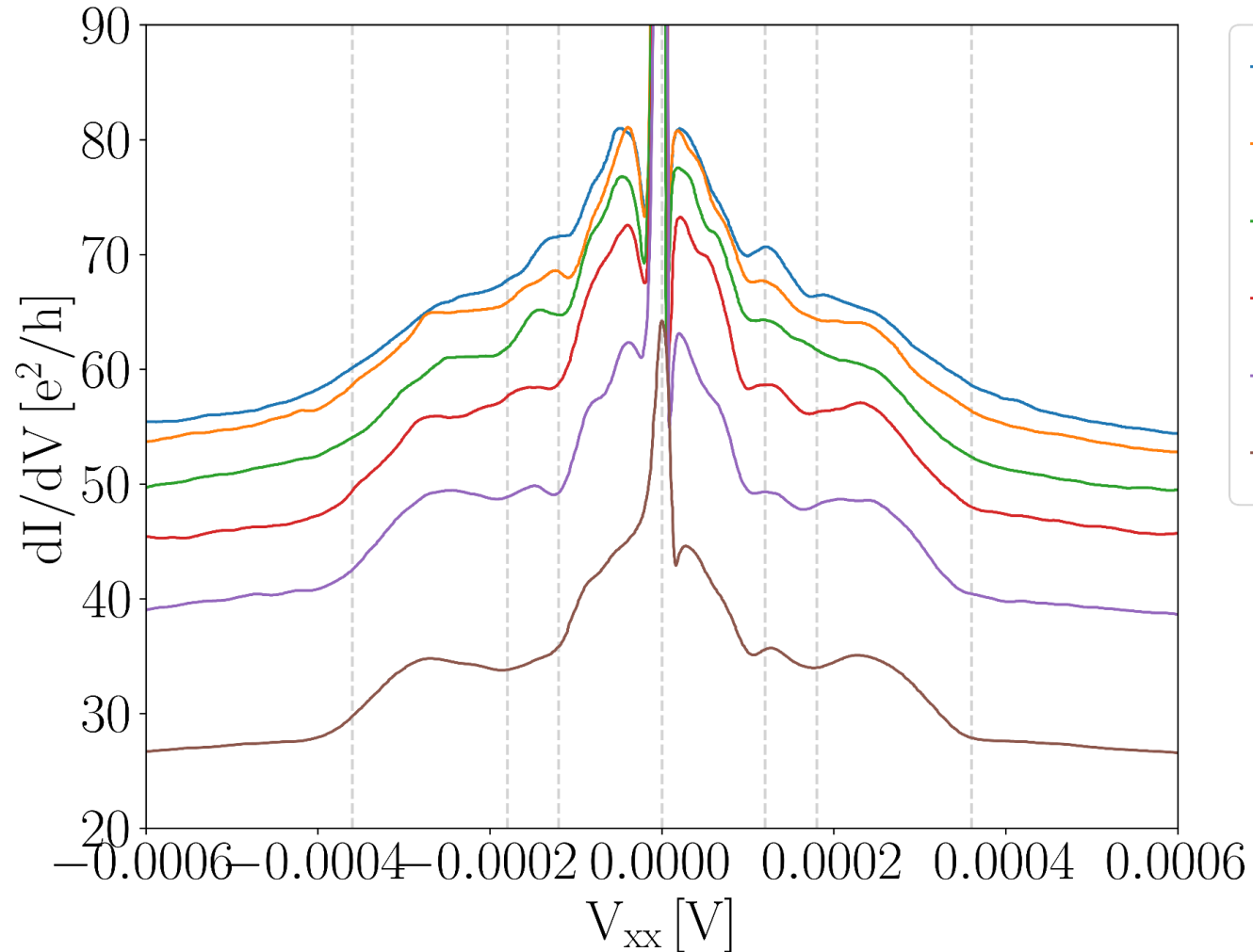
Multiple Andreev Reflections

$T = 250 \text{ mK}$



Multiple Andreev Reflections

$T = 250 \text{ mK}$



- $V_{bg}=35.0\text{V}$
- $V_{bg}=30.0\text{V}$
- $V_{bg}=25.0\text{V}$
- $V_{bg}=20.0\text{V}$
- $V_{bg}=15.0\text{V}$
- $V_{bg}=10.0\text{V}$

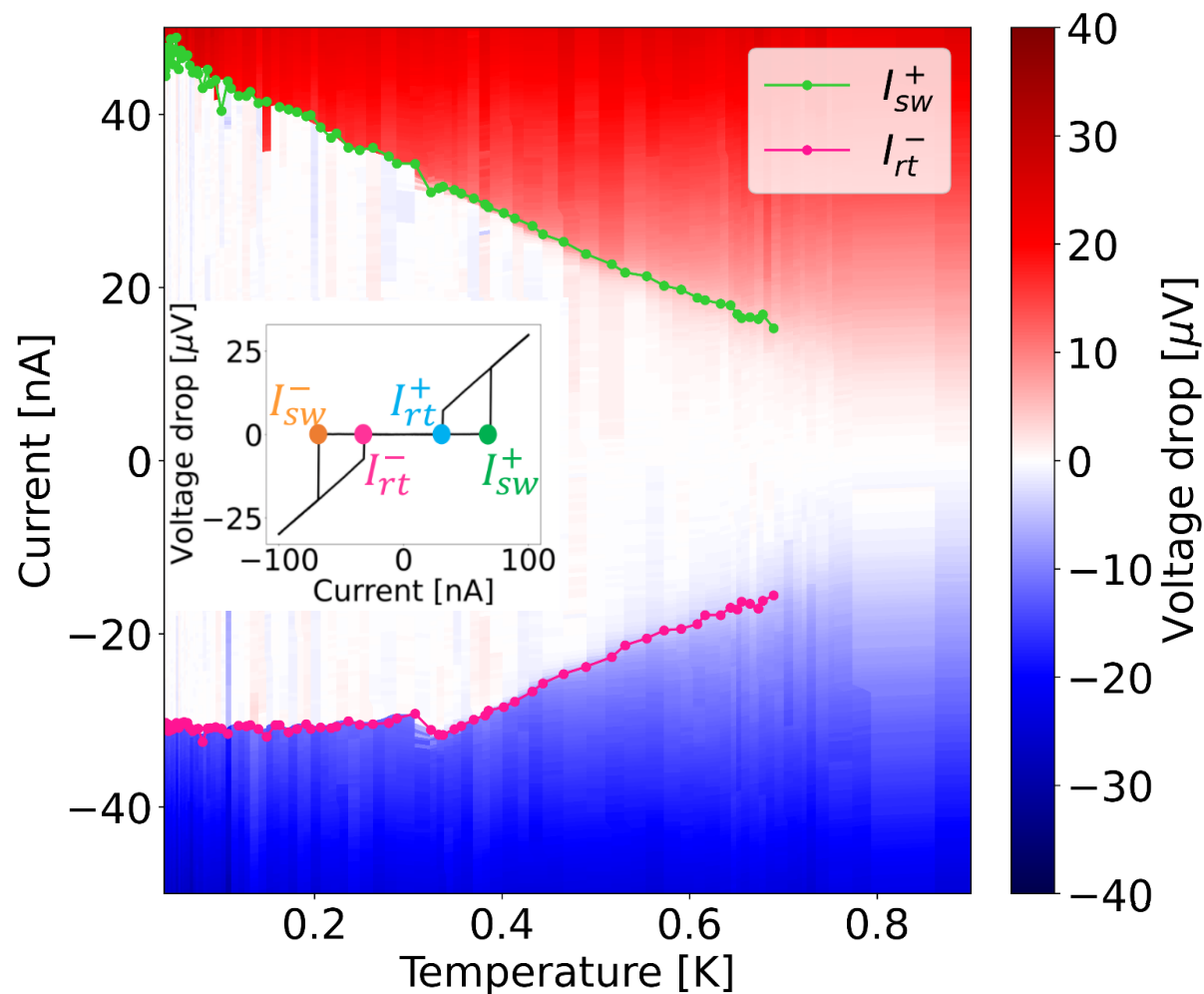


Michal P. Nowak

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

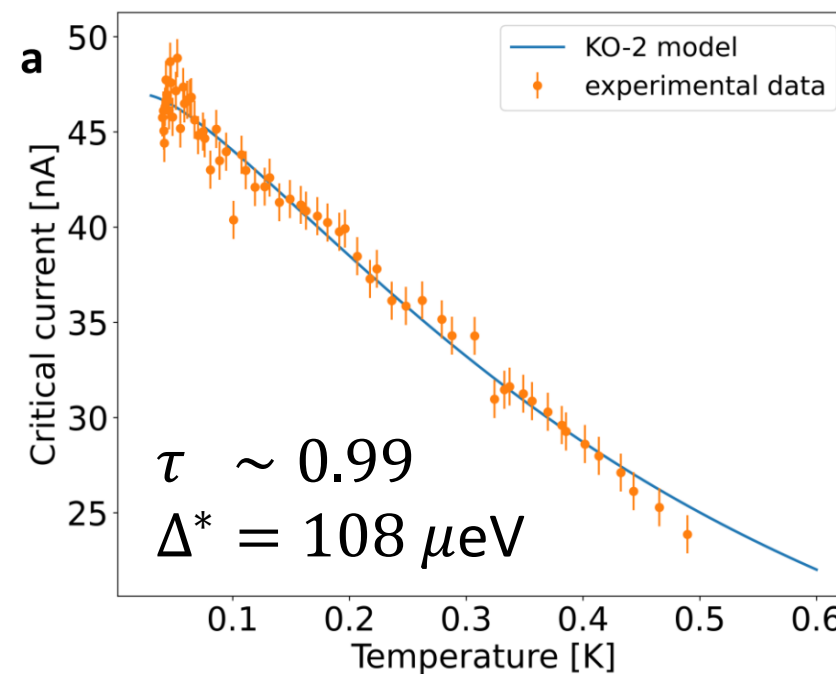
$$\Delta^* \sim 160 \mu\text{eV}$$

transparency $\tau = 0.94$



KO-2 model:

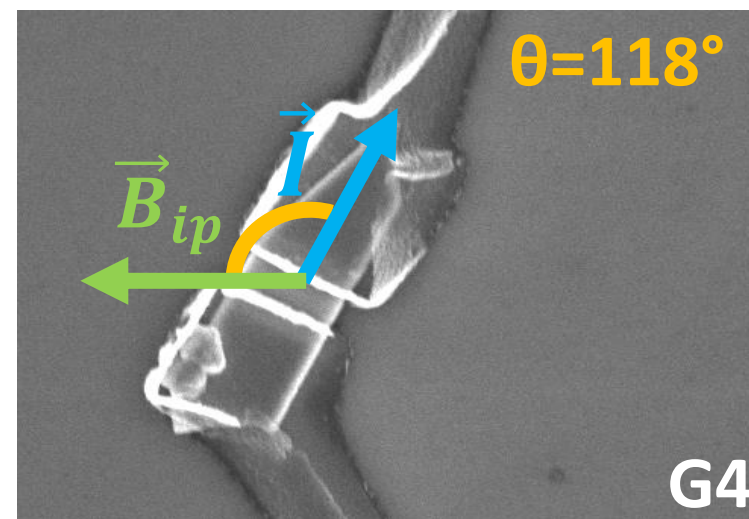
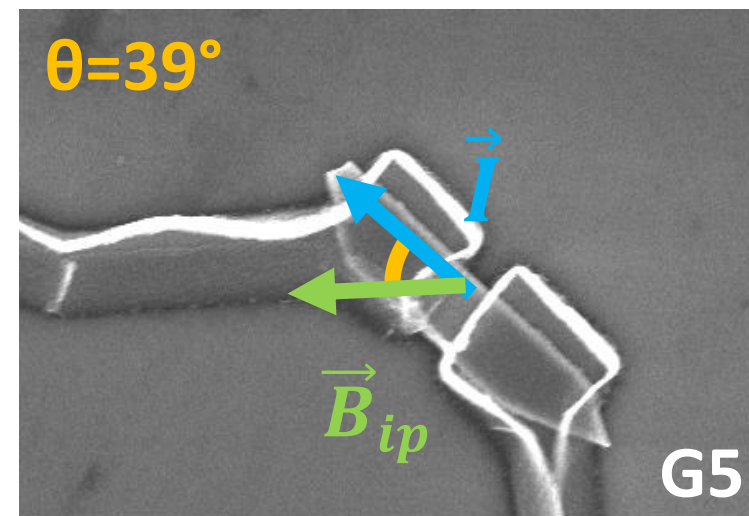
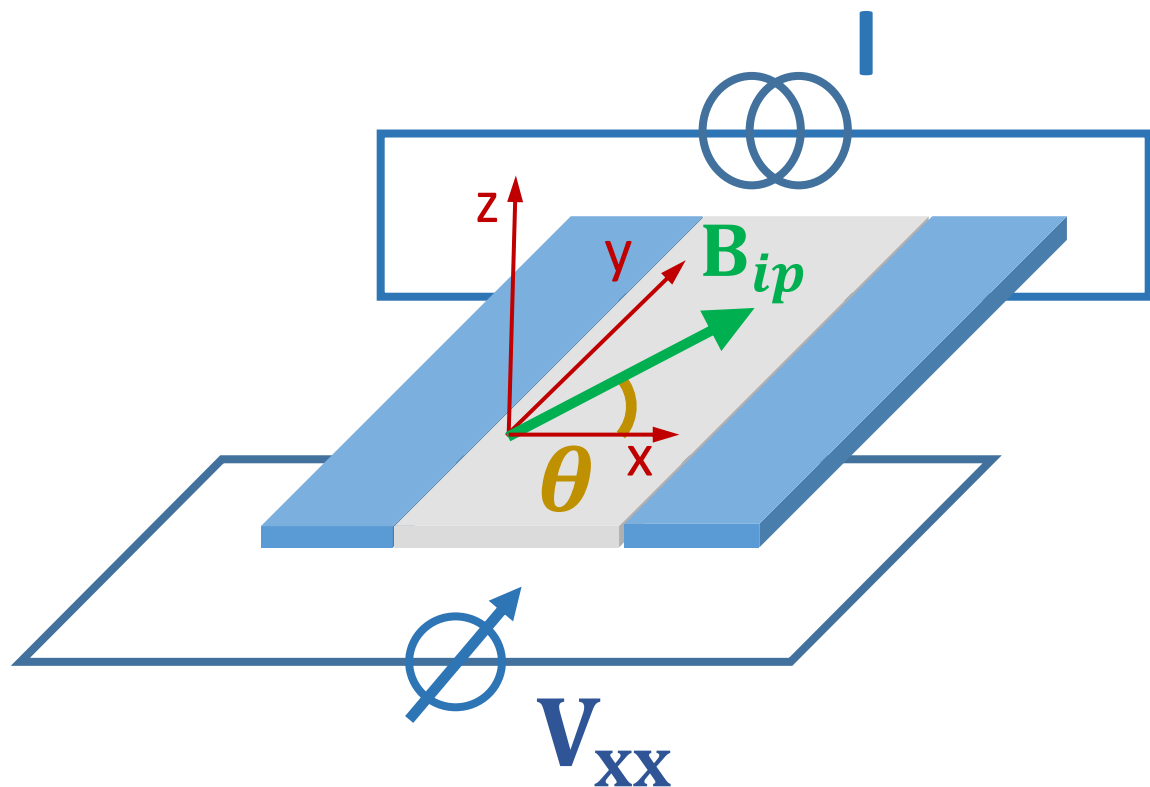
$$I(\varphi) = I_0 f(\varphi) = I_0 \frac{\bar{\tau} \sin \varphi \tanh \left[\frac{\Delta^*}{2k_B T} \sqrt{1 - \bar{\tau} \sin^2 \left(\frac{\varphi}{2} \right)} \right]}{2 \sqrt{1 - \bar{\tau} \sin^2 \left(\frac{\varphi}{2} \right)}}$$



Outline of the talk

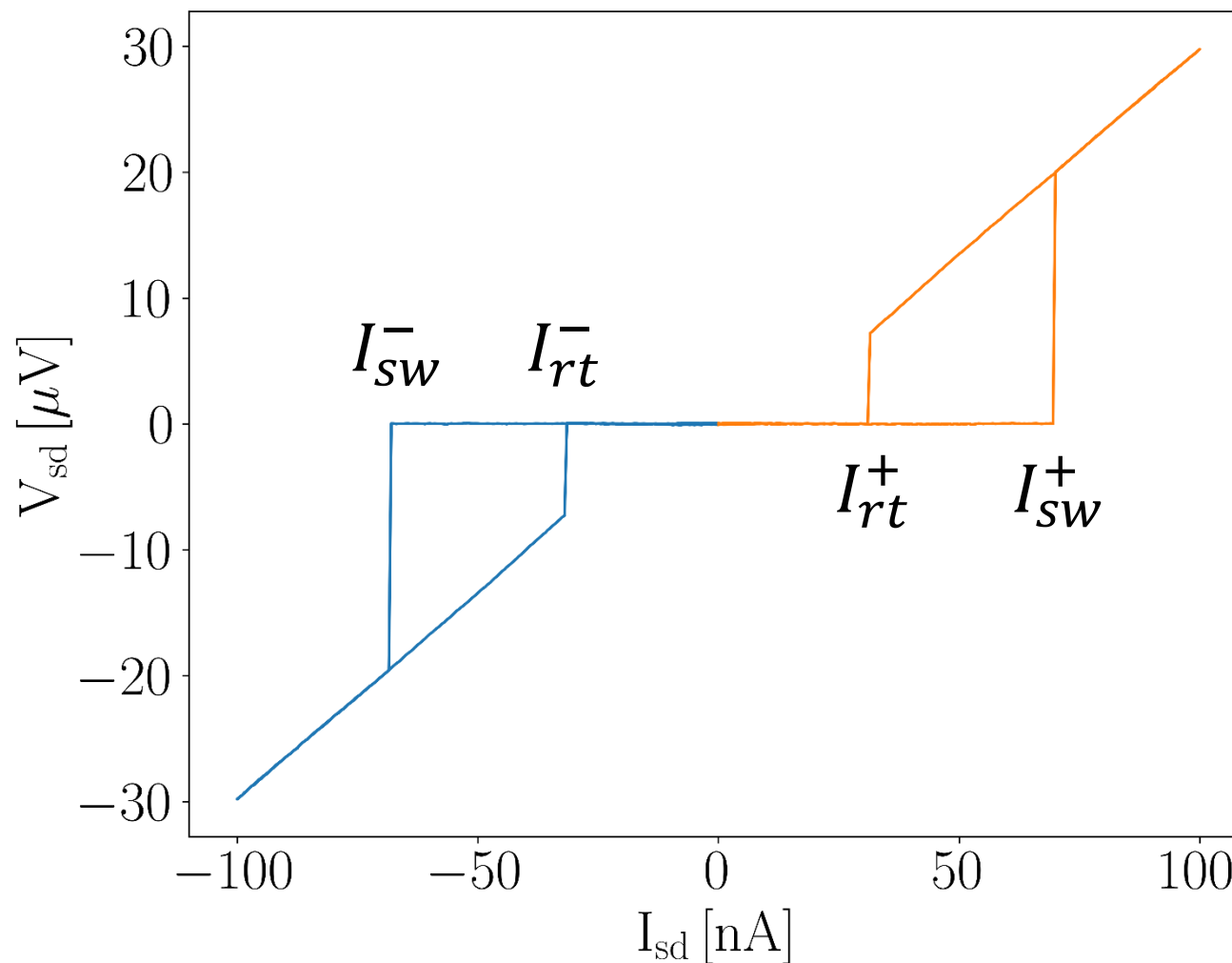
- Non-reciprocity in condensed matter systems
- InSb nanoflags for advanced devices
- Nanoflag-based Josephson junctions
- **Josephson diode effect in InSb nanoflags**

Design of the experiment

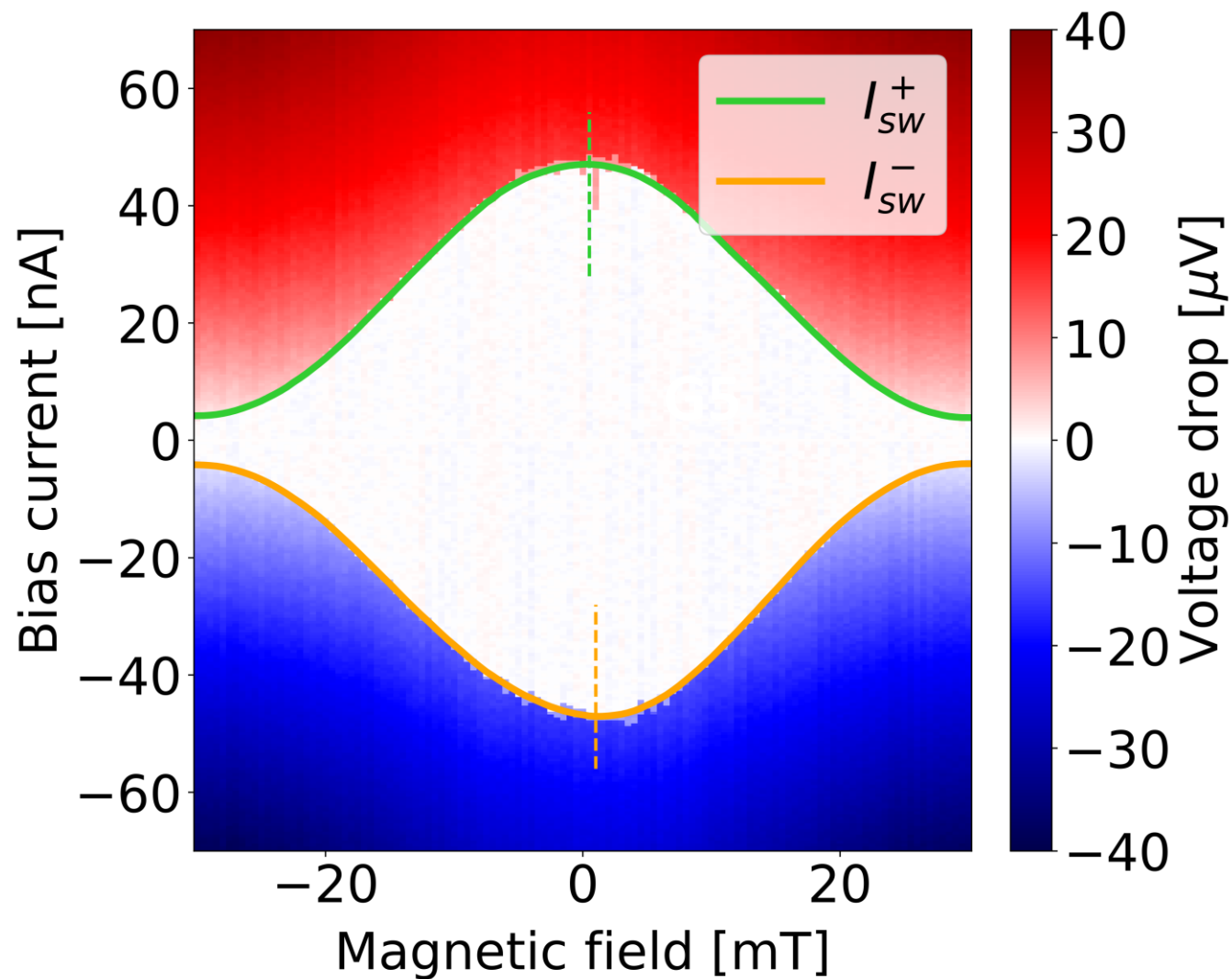
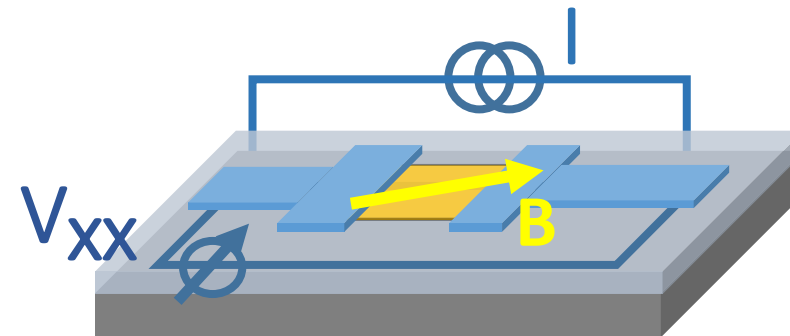


Supercurrent at 30 mK

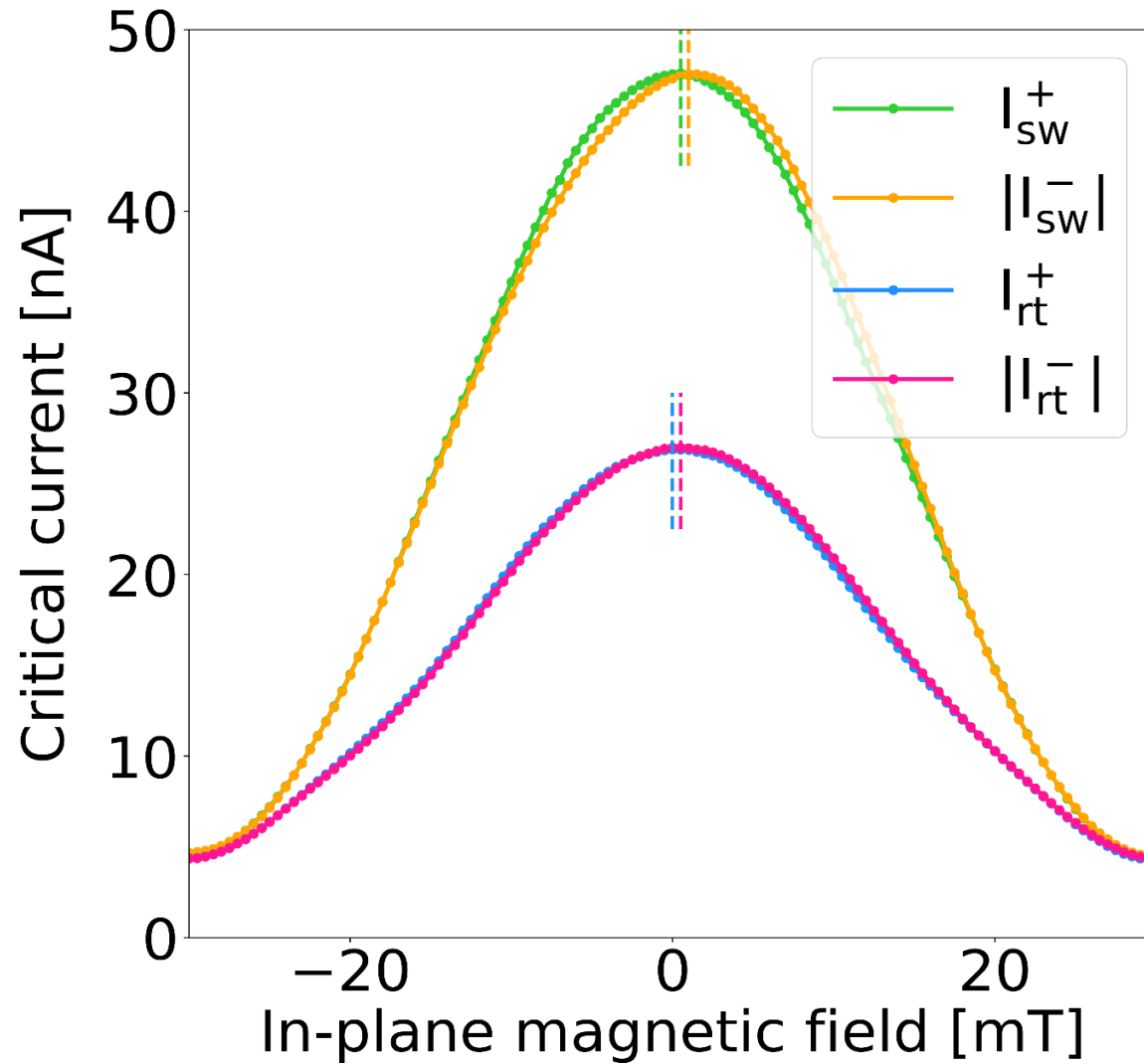
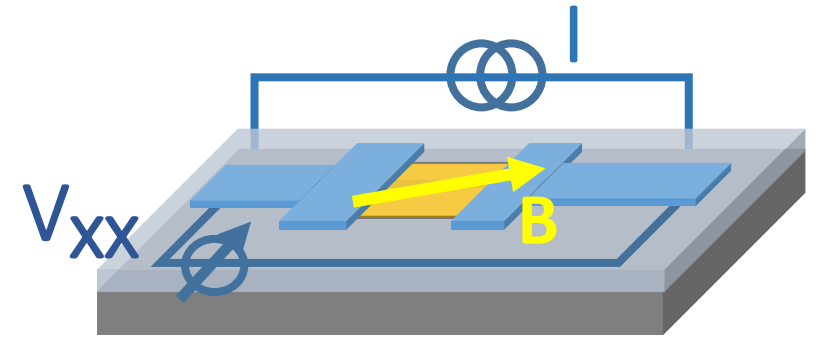
Device G4
 B = 0 mT
 $V_{bg} = 40$ V
 T = 30 mK



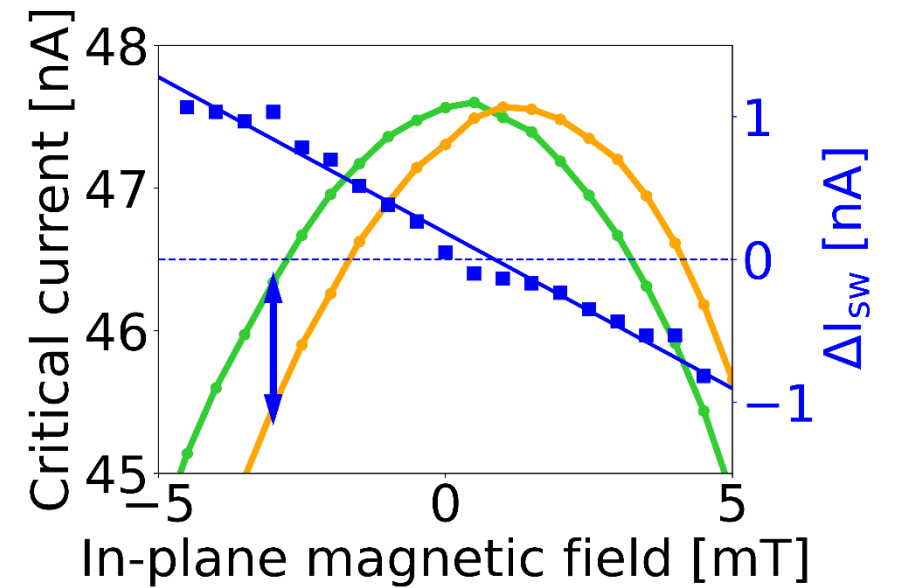
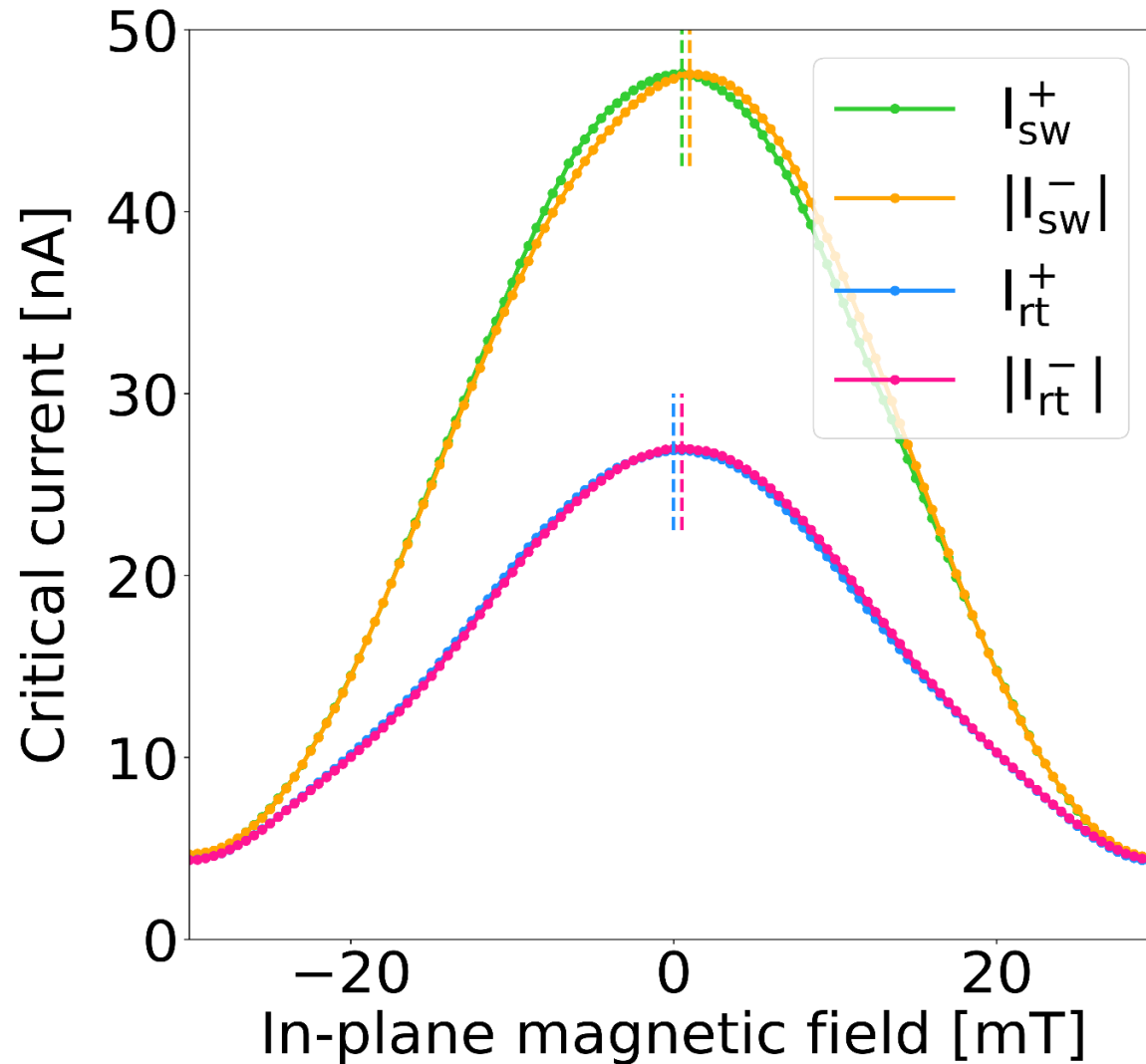
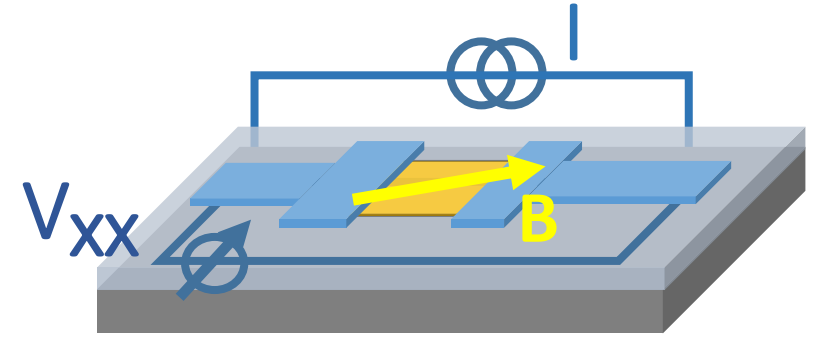
Magnetic field-driven JDE



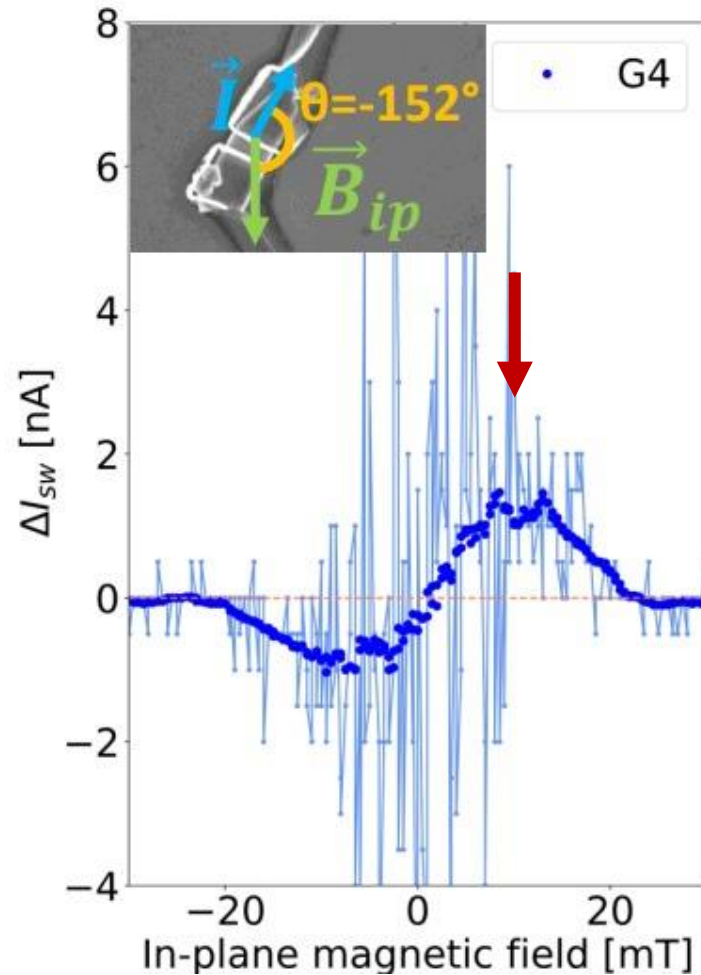
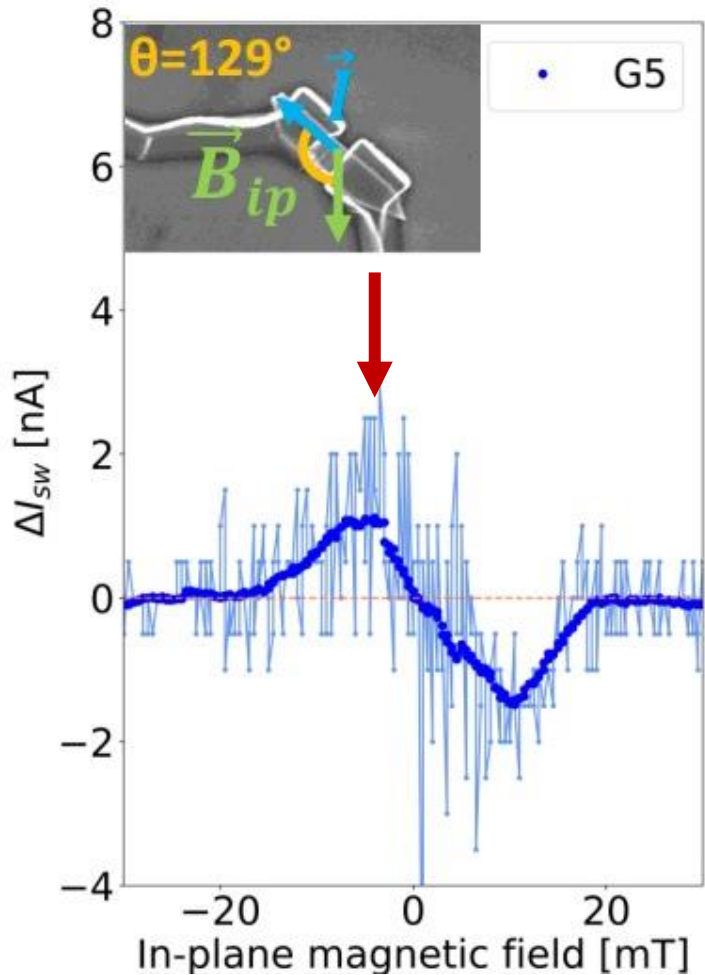
Magnetic field-driven JDE



Magnetic field-driven JDE



Switching current asymmetry

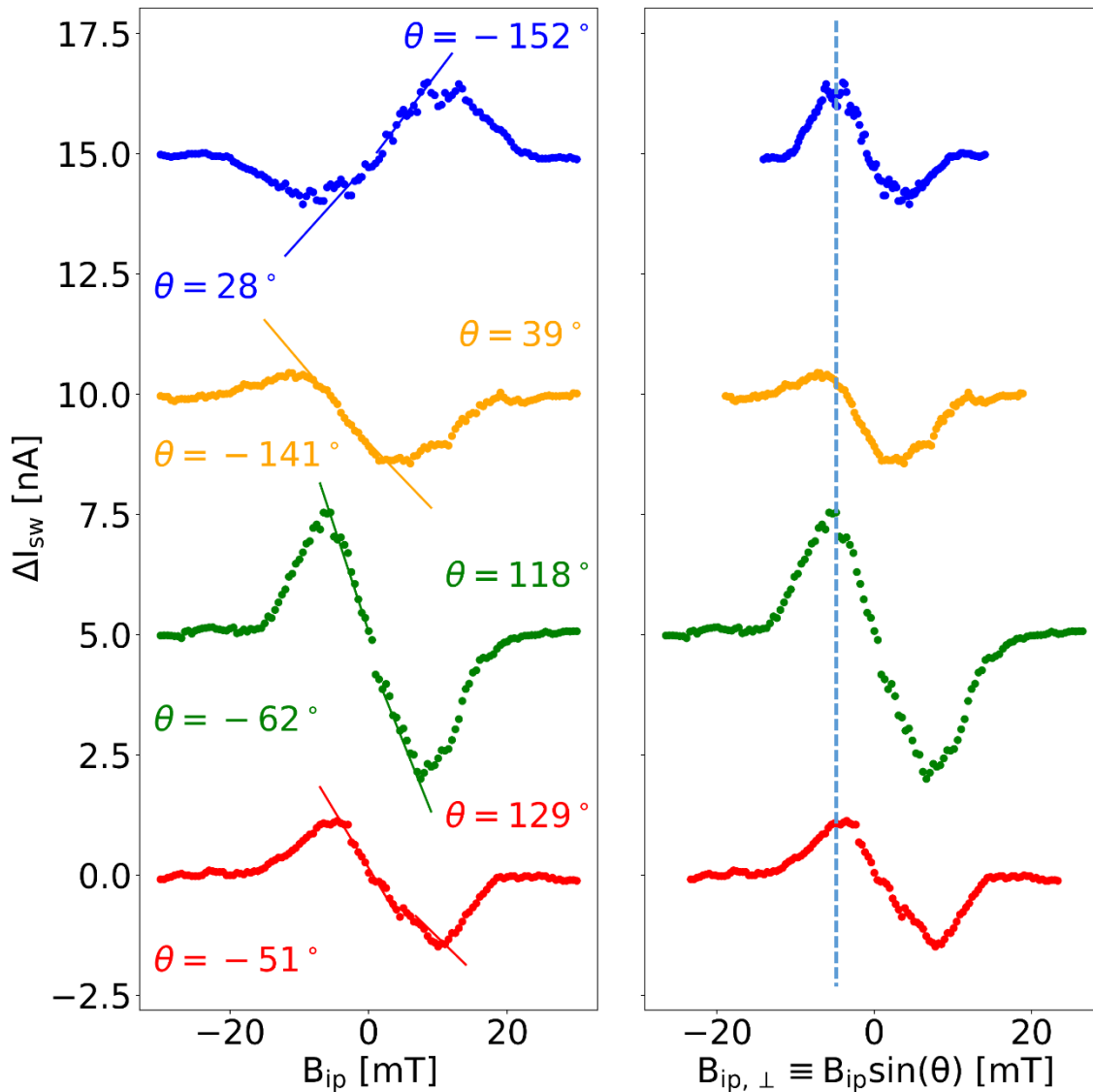
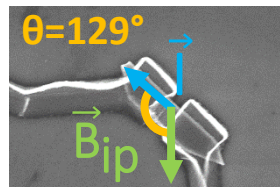
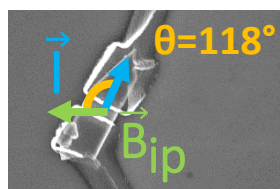
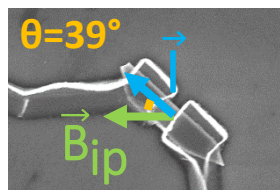
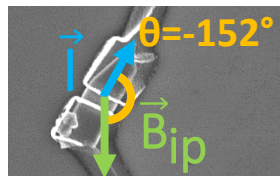


$$\Delta I_{sw} = I_{sw}^+ - |I_{sw}^-|$$

Main features:

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

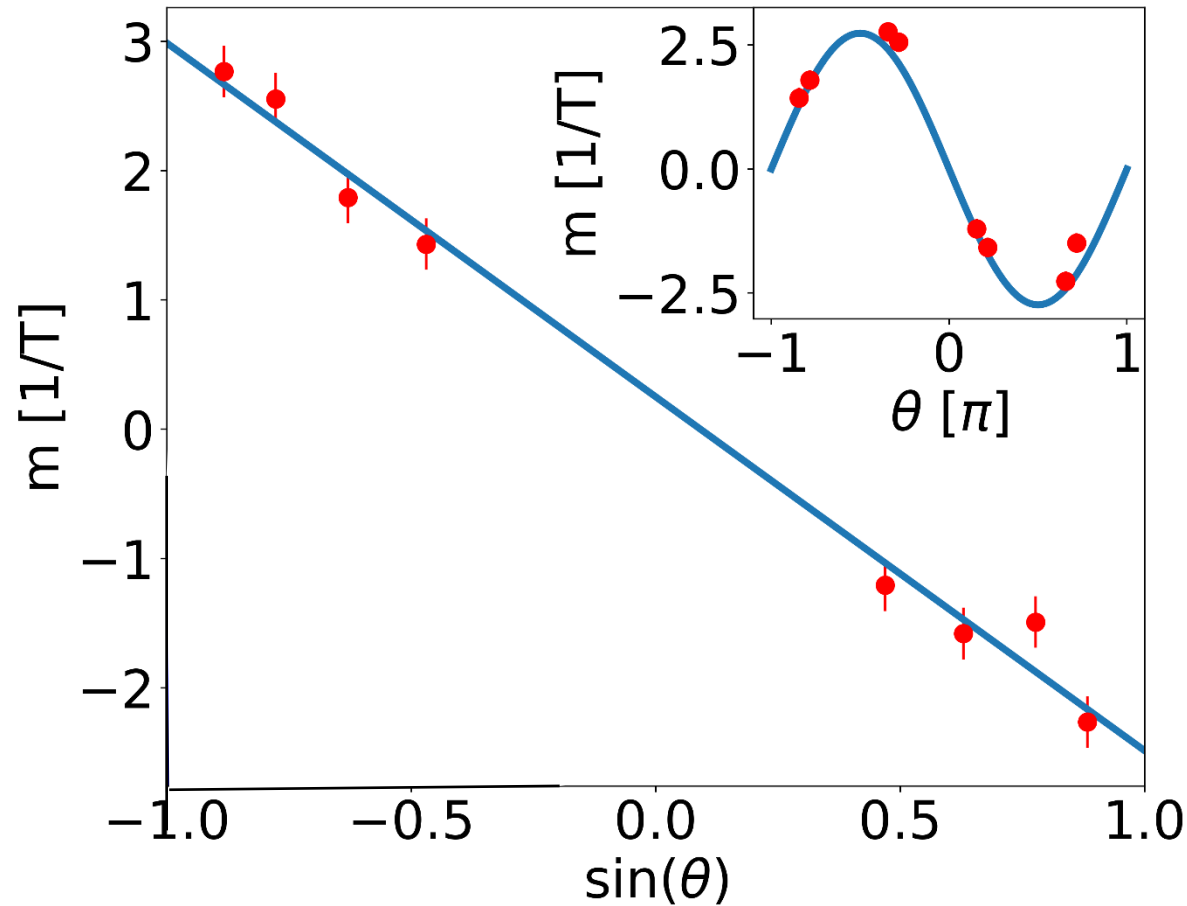
Dependence on the angle



$$\Delta I_{SW} \propto |\mathbf{B} \times \mathbf{I}|$$

**Dominant Rashba
spin-orbit coupling**

Field-driven JDE

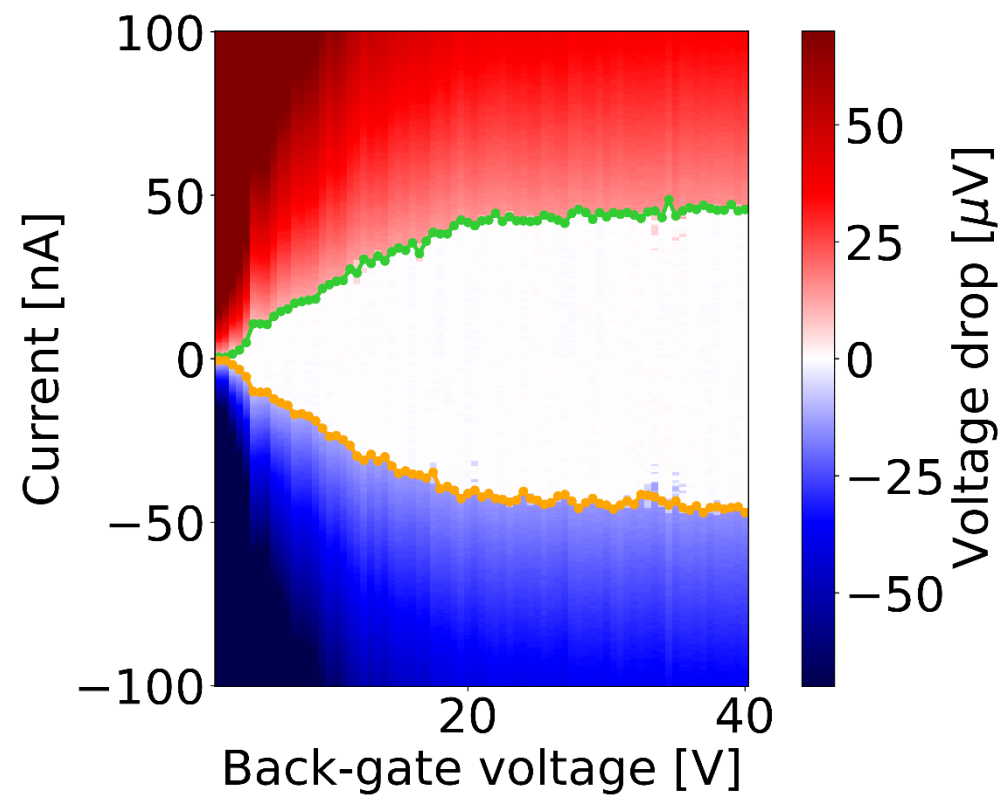
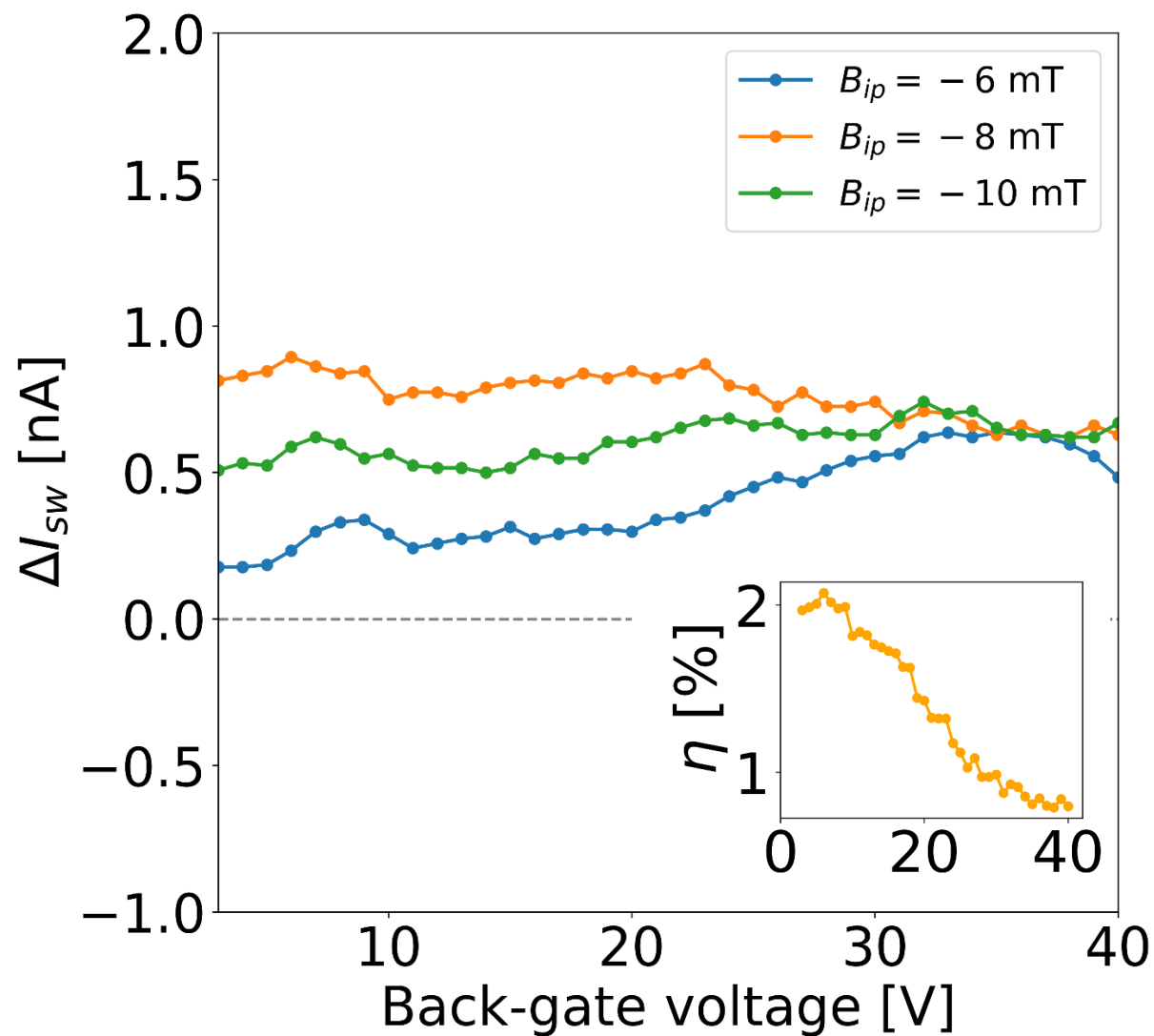


Diode rectification coefficient η
in the SO-dominated regime:

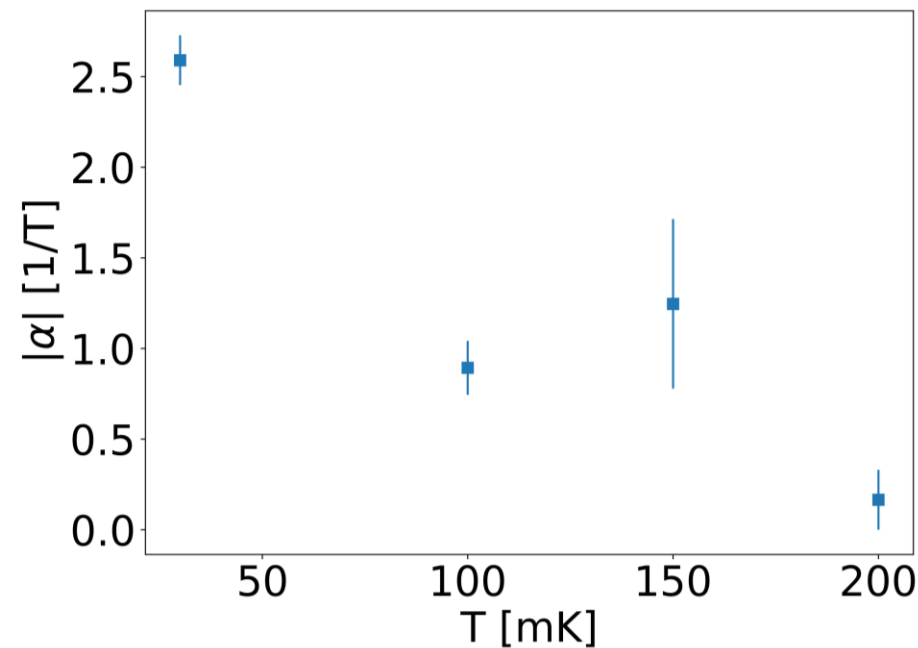
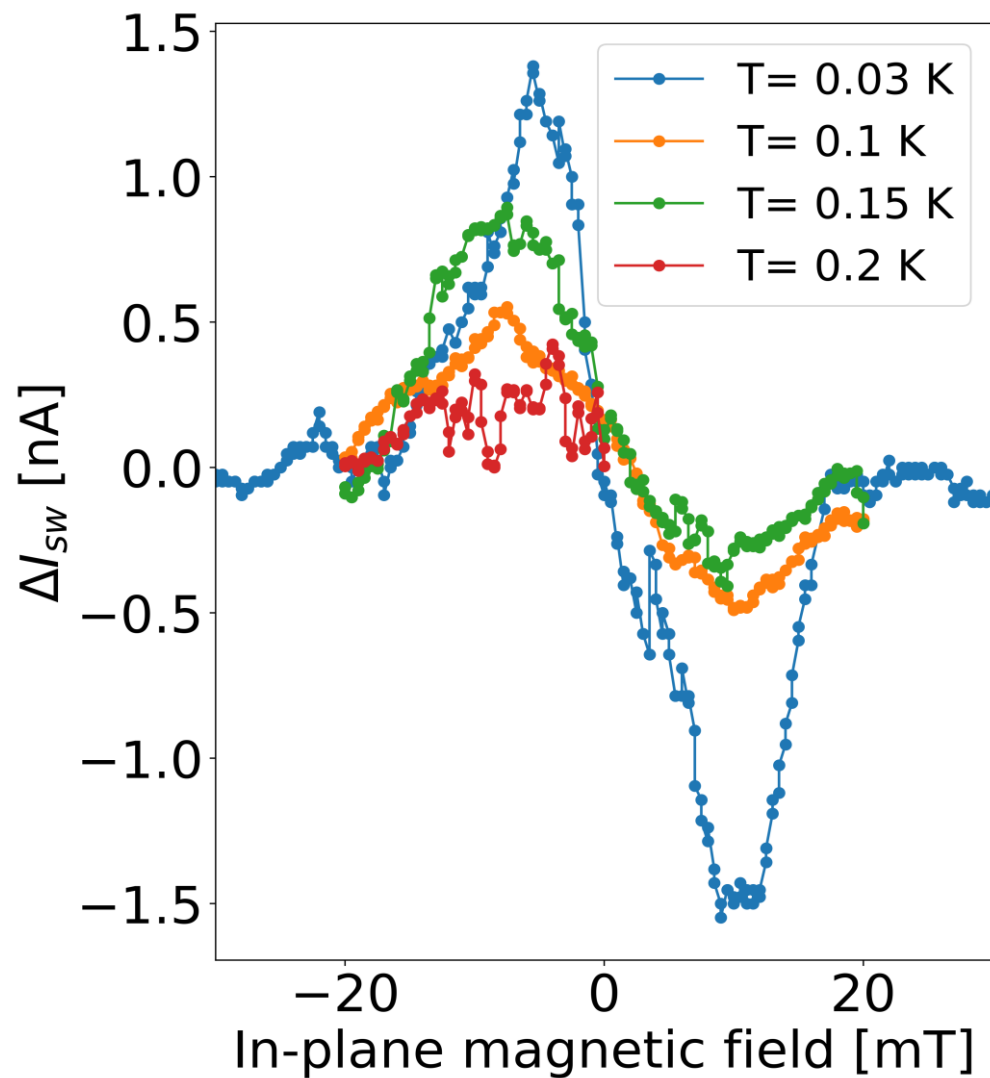
$$\eta = \frac{\Delta I_c}{I_c^+ + |I_c^-|} = \frac{2g^* \mu_B}{\pi \Delta^*} B \equiv \alpha B.$$

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

Back-gate dependence



Temperature dependence



Outlook: gate-controlled SOI

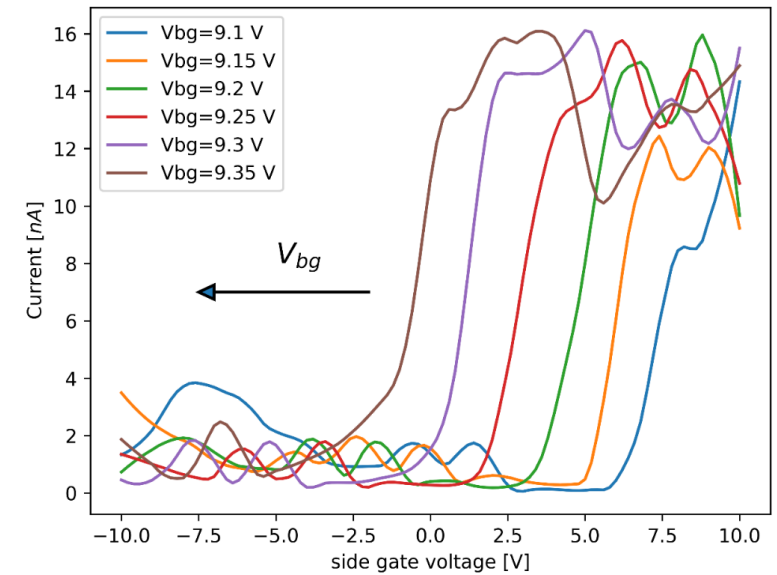
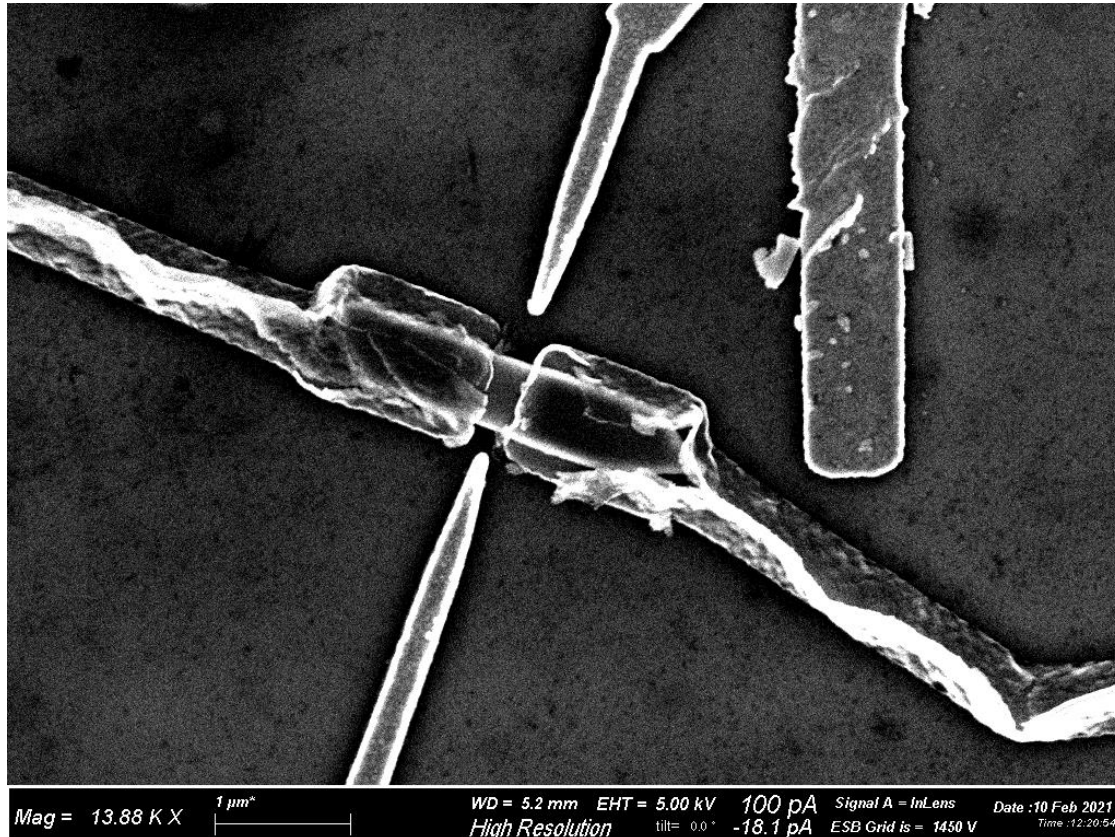
Idea: tune the effective geometry and the SO coupling with side gates



Bianca Turini



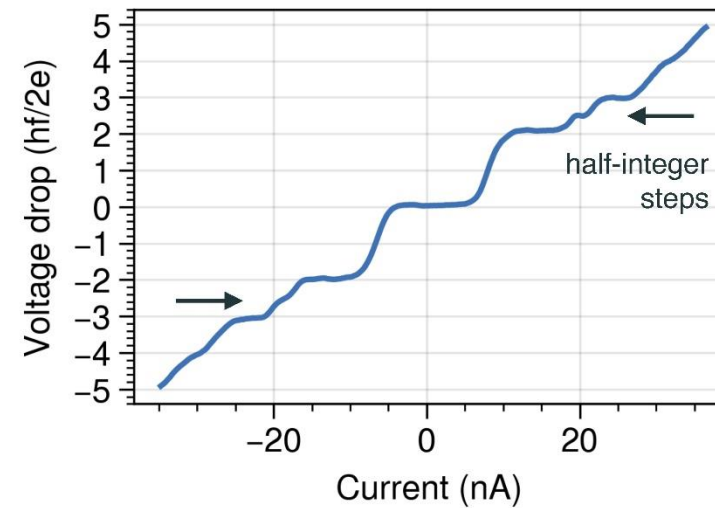
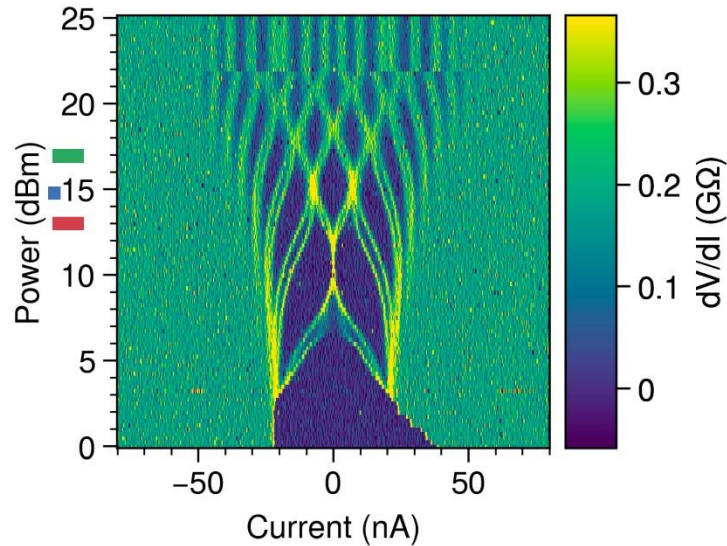
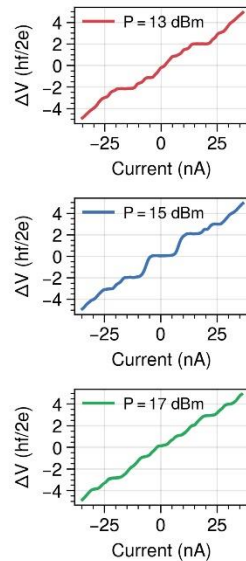
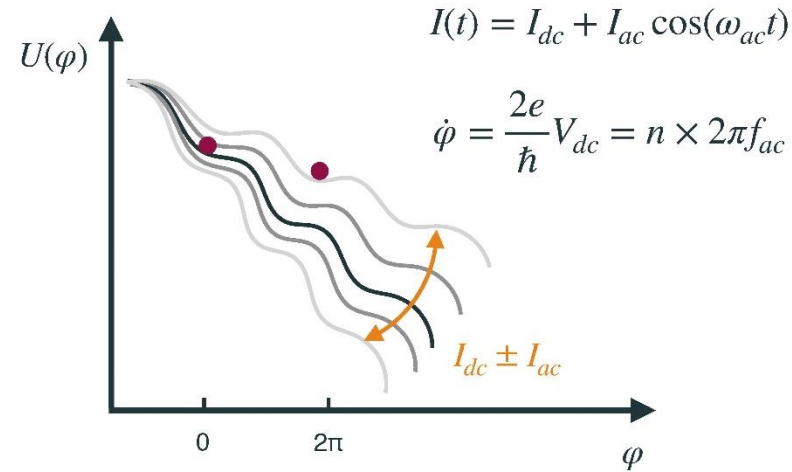
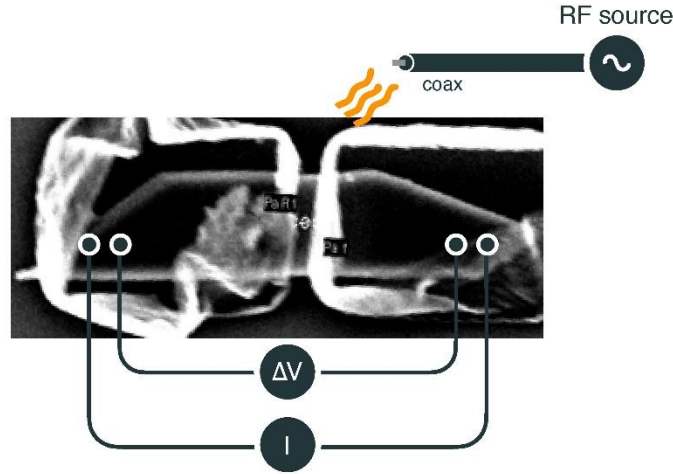
Federico Paolucci



Outlook: Shapiro steps in InSb nanoflags

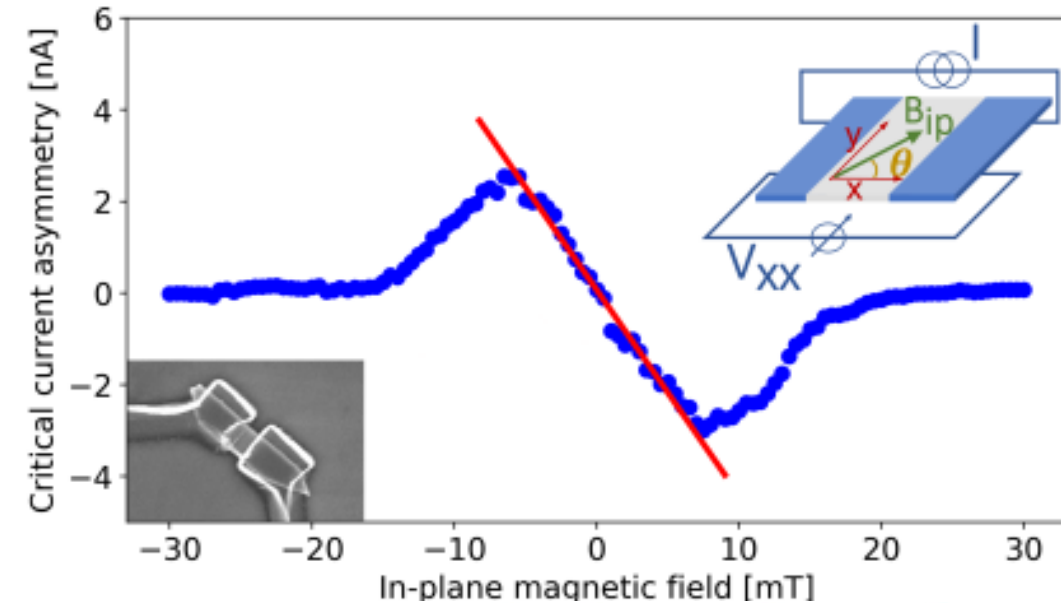
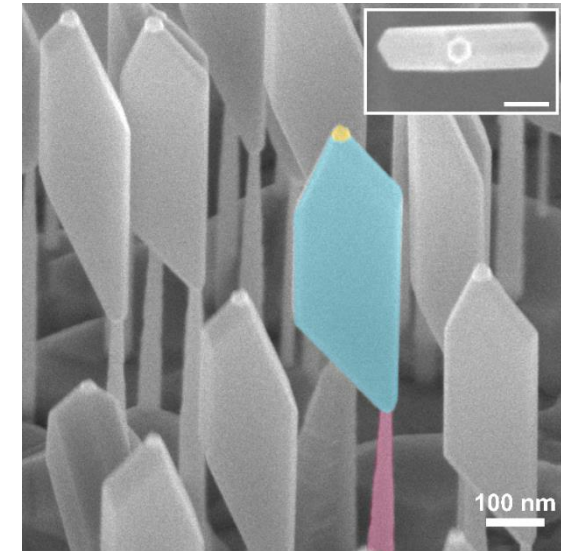


Andrea Iorio



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



People Involved

Growth activity



Valentina Zannier



Lucia Sorba



Sedighe Salimian



Matteo Carrega

Devices

Theory

Acknowledgments:



AndQC



SUPERTED

Transport



Bianca Turini



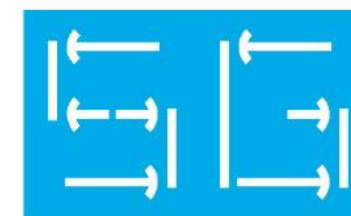
Andrea Iorio



Elia Strambini



Francesco Giazotto



SUPER GATE



Thank you for your attention!