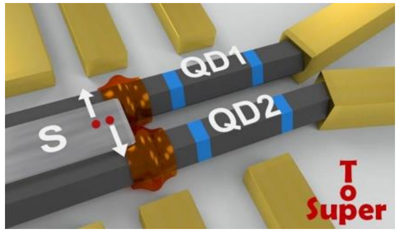
# High Mobility Free-Standing InSb Nanoflags for Quantum Technologies

Stefan Heun

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

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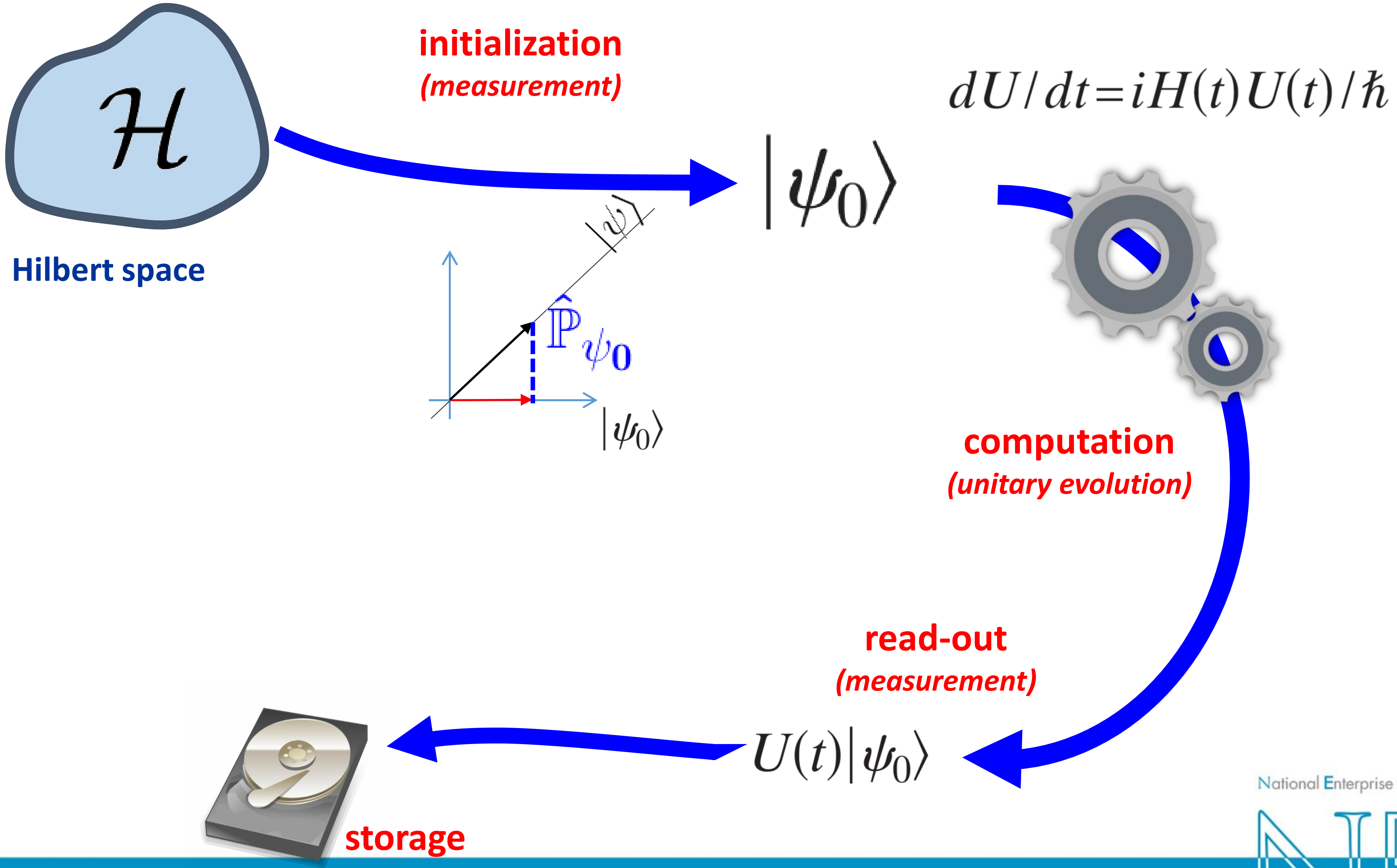
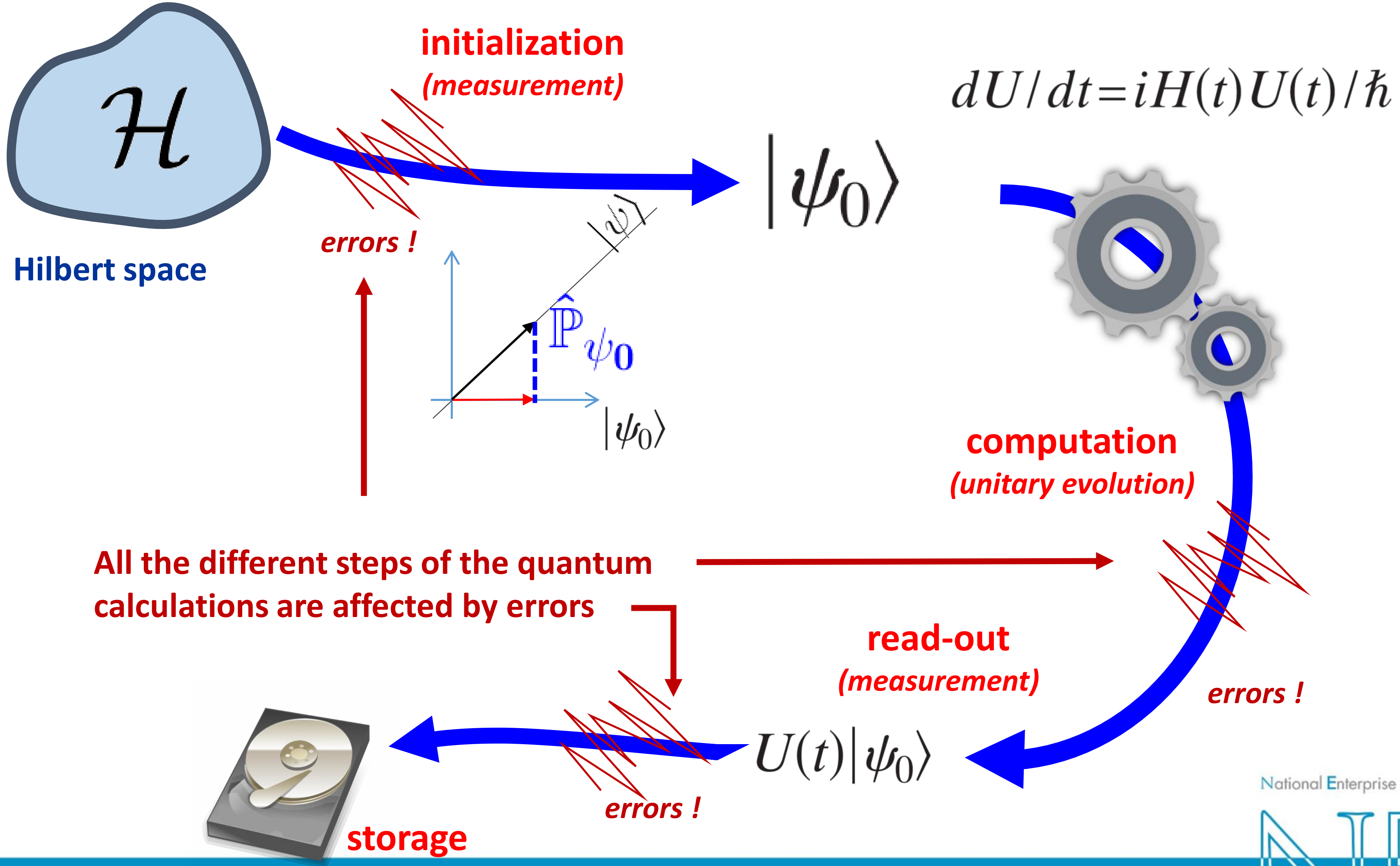
# The road to quantum computing



# The road to quantum computing



# Topological States of Matter

## New states of Matter:

NEWS | IN FOCUS

PHYSICS

# Nobel for 2D exotic matter

*Physics award goes to theorists who used topology to explain strange phenomena.*

BY ELIZABETH GIBNEY AND DAVIDE CASTELVECCHI

David Thouless, Duncan Haldane and Michael Kosterlitz have won the 2016 Nobel Prize in Physics for their theoretical explanations of strange states of matter in 2D materials, known as topological phases.

The British-born trio's work in the 1970s and 1980s laid the foundations for predicting and explaining bizarre behaviours that experimentalists discovered at the surfaces of materials, and inside extremely thin layers. These include superconductivity — the ability to conduct without resistance — and magnetism in very thin materials. At the time, these mathematical theories were quite abstract, said Haldane in an

Physics prizewinners Michael Kost

Nature 538 (2016) 18

PERSPECTIVE

PUBLISHED ONLINE: 25 OCTOBER 2017 | DOI: 10.1038/NMAT5012

nature materials

# Topological states of condensed matter

Jing Wang[1,2]* and Shou-Cheng Zhang[3]*

**Topological states of quantum matter have been investigated intensively in recent years in materials science and condensed matter physics. The field developed explosively largely because of the precise theoretical predictions, well-controlled materials processing, and novel characterization techniques. In this Perspective, we review recent progress in topological insulators, the quantum anomalous Hall effect, chiral topological superconductors, helical topological superconductors and Weyl semimetals.**

Nat. Mater. 16 (2017) 1062

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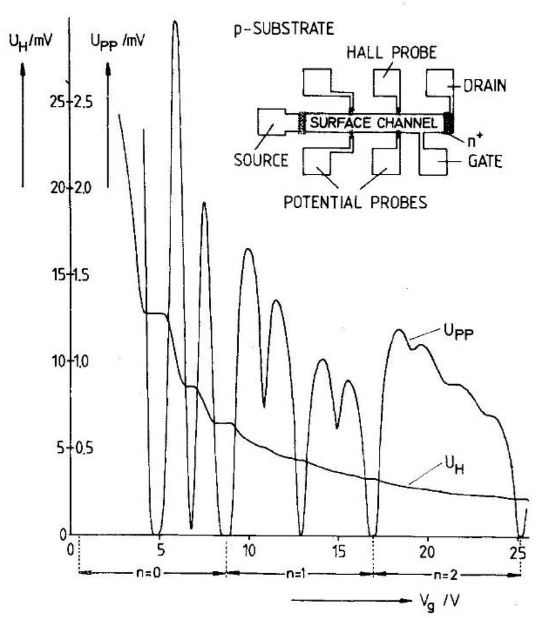
# Topological States: Quantum Hall Effect

VOLUME 45, NUMBER 6 PHYSICAL REVIEW LETTERS 11 AUGUST 1980

**New Method for High-Accuracy Determination of the Fine-Structure Constant Based on Quantized Hall Resistance**

K. v. Klitzing
*Physikalisches Institut der Universität Würzburg, D-8700 Würzburg, Federal Republic of Germany, and Hochfeld-Magnetlabor des Max-Planck-Instituts für Festkörperforschung, F-38042 Grenoble, France*




K. v. Klitzing et al., PRL 45 (1980) 494.

PHYSICAL REVIEW B VOLUME 38, NUMBER 14 15 NOVEMBER 1988-I

**Absence of backscattering in the quantum Hall effect in multiprobe conductors**

M. Büttiker
*IBM Thomas J. Watson Research Center, P.O. Box 218, Yorktown Heights, New York 10598*
(Received 21 March 1988)

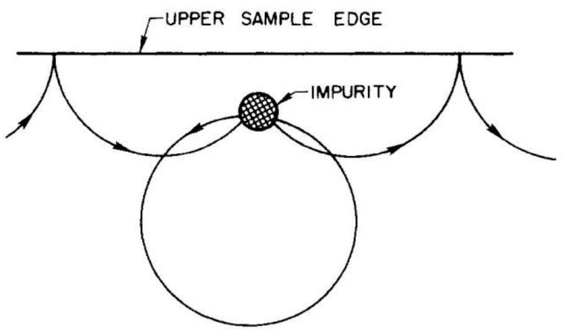



FIG. 4. Quasiclassical skipping orbits along the upper edge of the sample in presence of a localized impurity. In a high magnetic field backscattering over distances large compared to the cyclotron radius is suppressed.

M. Büttiker, PRB 38 (1988) 9375.

# Topological Quantum Computation

REVIEW

## Topological Quantum Computation—From Basic Concepts to First Experiments

Ady Stern[1]* and Netanel H. Lindner[2,3]

Quantum computation requires controlled engineering of quantum states to perform tasks that go beyond those possible with classical computers. Topological quantum computation aims to achieve this goal by using non-Abelian quantum phases of matter. Such phases allow for quantum information to be stored and manipulated in a nonlocal manner, which protects it from imperfections in the implemented protocols and from interactions with the environment. Recently, substantial progress in this field has been made on both theoretical and experimental fronts. We review the basic concepts of non-Abelian phases and their topologically protected use in quantum information processing tasks. We discuss different possible realizations of these concepts in experimentally available solid-state systems, including systems hosting Majorana fermions, their recently proposed fractional counterparts, and non-Abelian quantum Hall states.

The principal obstacles on the road to quantum computing are noise and decoherence. By noise, we mean imperfections in the execution of the operations on the qubits (quantum bits). Decoherence arises when the quantum system that encodes the qubits becomes entangled with its environment, which is a bigger, uncontrolled system. There are two approaches to tackling these barriers. One is based on complete isolation of the computer from its environment, careful elimination of noise, and protocols for quantum correction of unavoidable errors. Enormous progress has been achieved in this direction in the past few years. The other approach, which is at the root of topological quantum computation, is very different. It uses a non-Abelian state of matter (*1–10*) to encode and manipulate quantum information in a nonlocal manner. This nonlocality endows the information with immunity to the effects of noise and decoherence (*2–6*).

### Non-Abelian States of Matter

Several properties define a non-Abelian state of matter (*1*, *2*, *6–10*). It is a quantum system whose

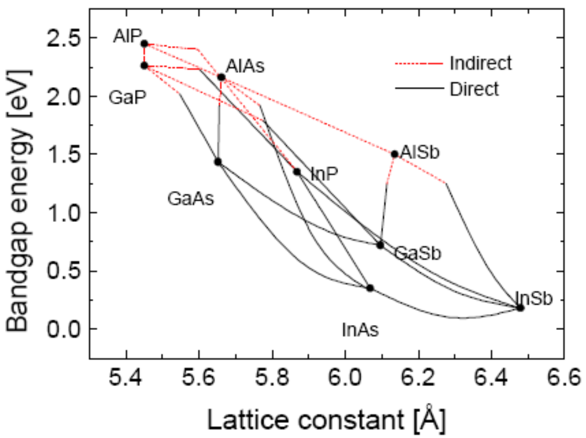
[1]Department of Condensed Matter Physics, Weizmann Institute of Science, Rehovot 76100, Israel. [2]Institute of Quantum Information and Matter, California Institute of Technology, Pasadena, CA 91125, USA. [3]Department of Physics, California Institute of Technology, Pasadena, CA 91125, USA.

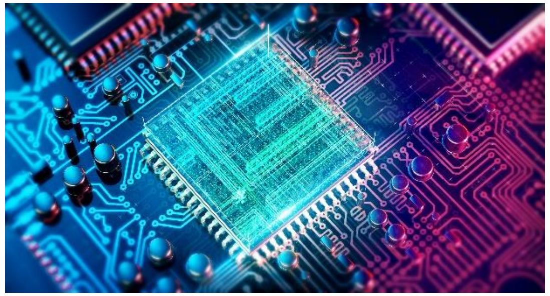
*To whom correspondence should be addressed. E-mail: adiel.stern@weizmann.ac.il

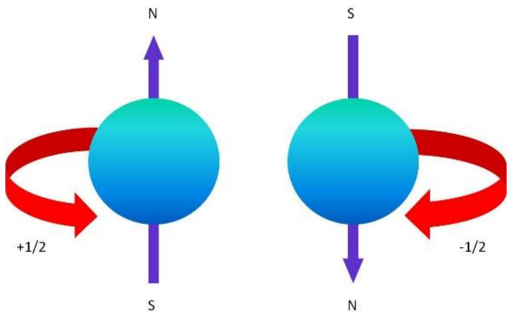
# Why InSb?

**InSb Heterostructures:**

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





# Why 2D InSb?

**Problem:**

- Nanowire morphology limits device design flexibility.

**Solution:**

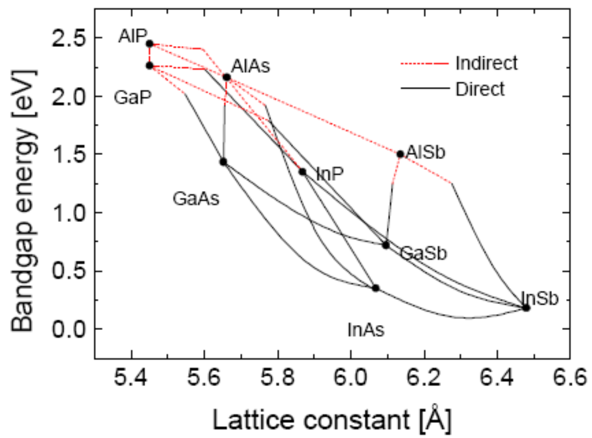
- Epitaxial growth of InSb in the form of 2D-layers.

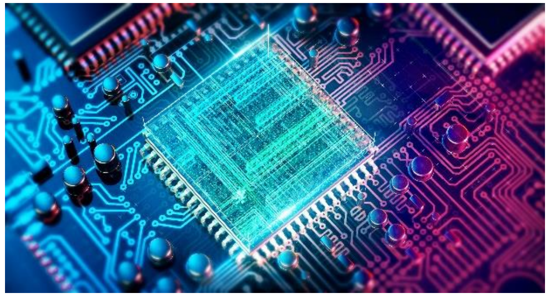
**Challenges:**

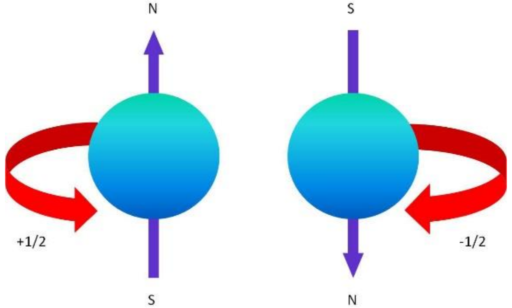
- Large lattice mismatch with common semiconductor substrates.

**Solution:**

- 2D InSb nanoflags on nanowire stem (efficient strain relaxation).



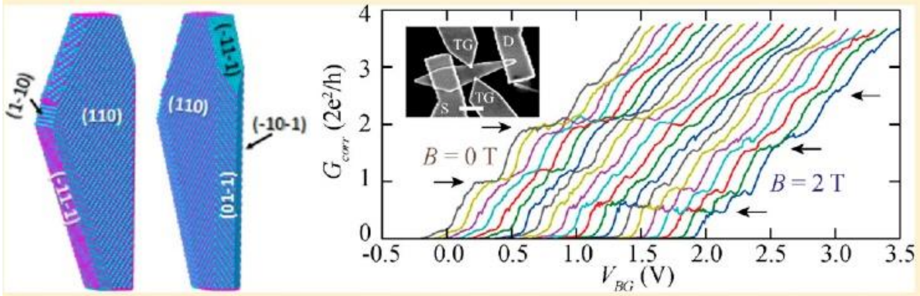





# 2D InSb nanoflags (NFs)

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

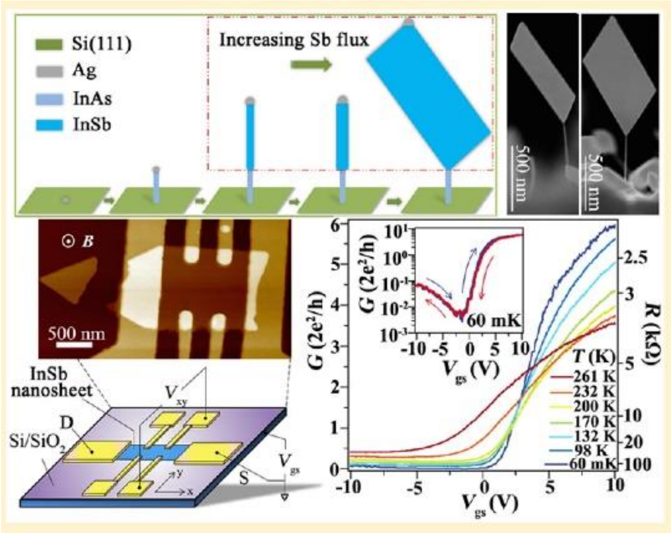
María de la Mata,[†] Renaud Leturcq,[*,‡,§] Sébastien R. Plissard,[‖] Chloé Rolland,[‡] César Magén,[⊥]
Jordi Arbiol,[*,†,#] and Philippe Caroff[*,‡,∇]



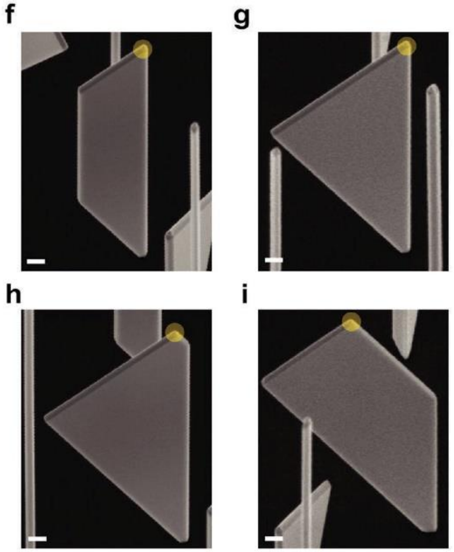

Nano Lett. 16 (2016) 825

**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**

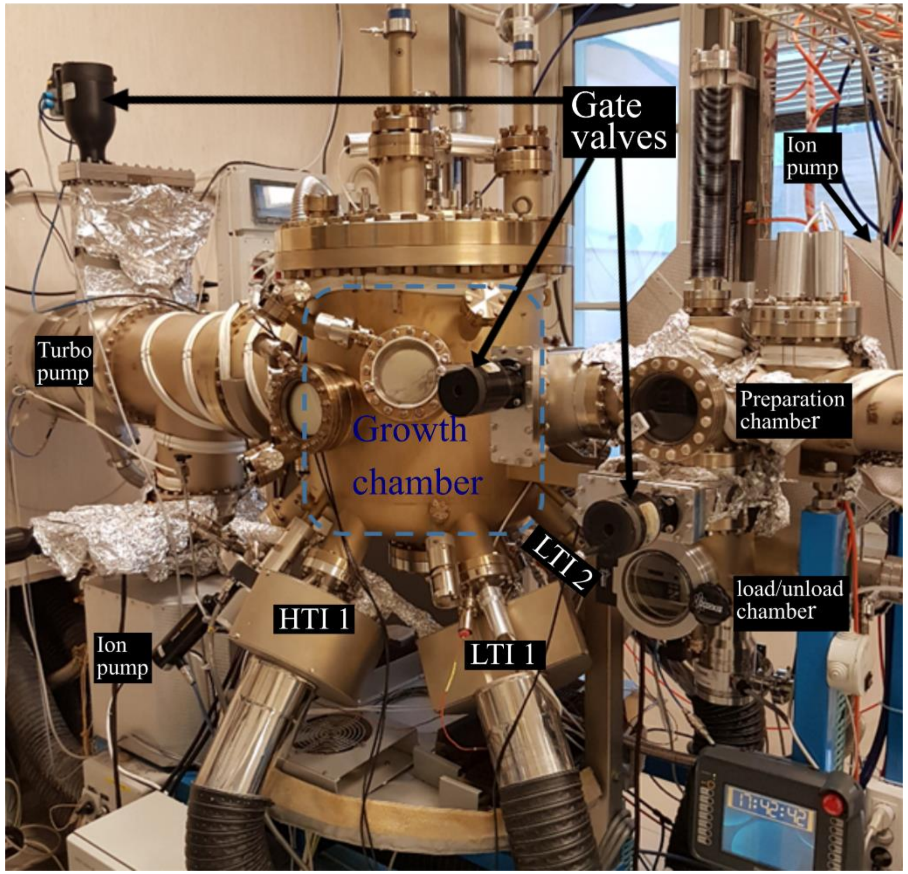
*Sasa Gazibegovic,* Ghada Badawy,* Thijs L. J. Buckers, Philipp Leubner, Jie Shen, Folkert K. de Vries, Sebastian Koelling, Leo P. Kouwenhoven, Marcel A. Verheijen, and Erik P. A. M. Bakkers*

Adv. Mater. 31 (2019) 1808181

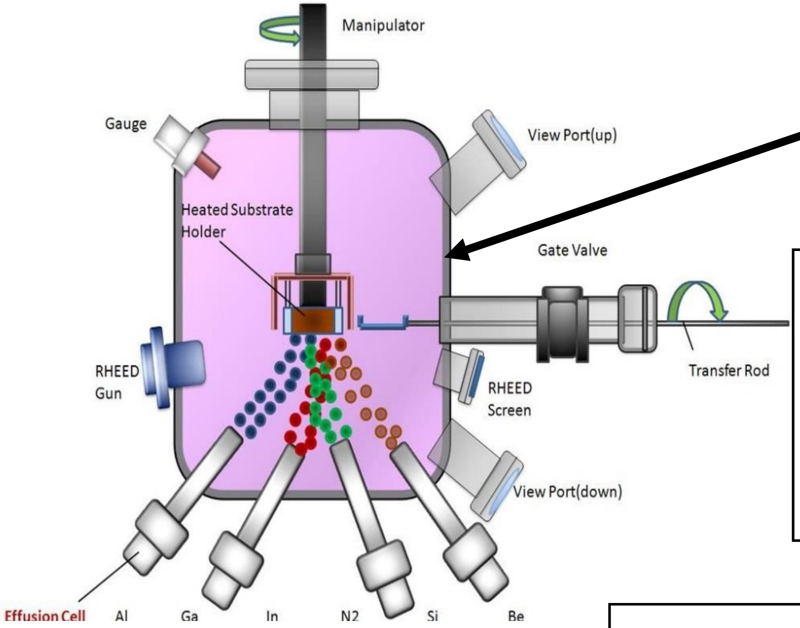
# Chemical Beam Epitaxy (CBE)

## 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

# People Involved

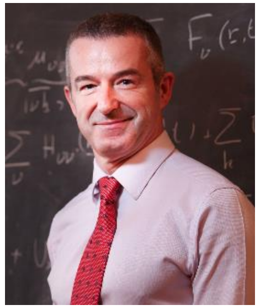
## *Growth activity*

*Isha Verma*

*Valentina Zannier*

*Daniele Ercolani*

*Lucia Sorba*



*Fabio Beltram*

## *Devices & Transport*

*Sedighe Salimian*

## *Theory*

*Matteo Carrega*

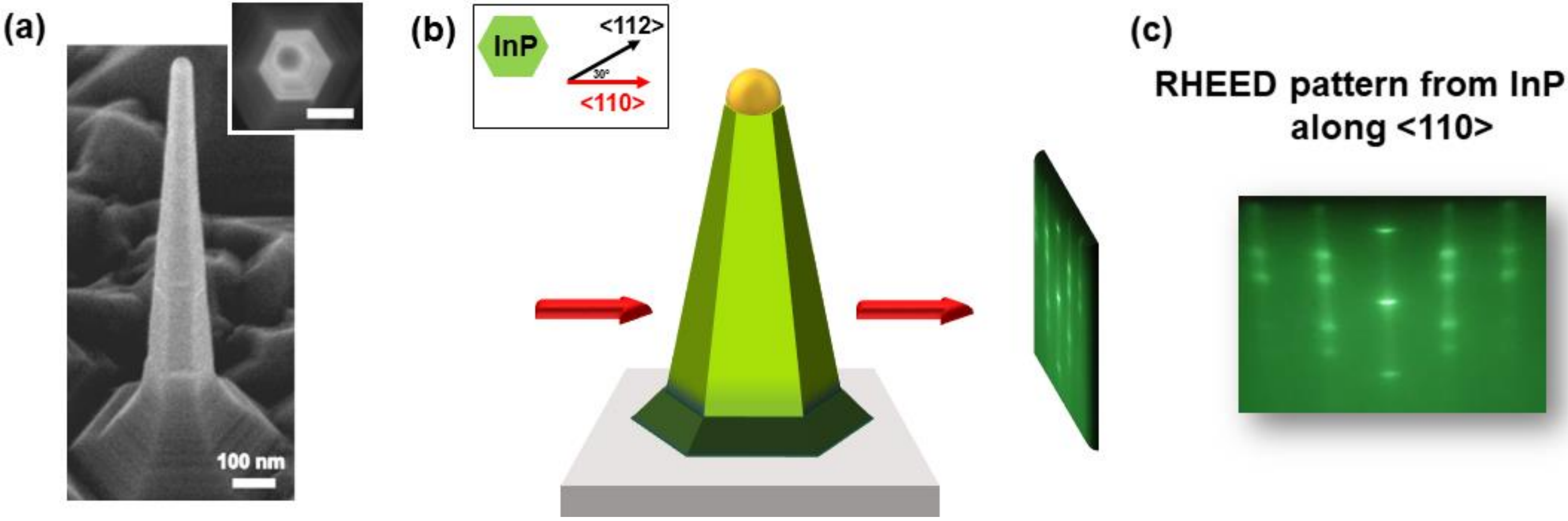
## *TEM Characterization*

*Francesca Rossi*

## *Numerical Simulations*

*Michal P. Nowak*

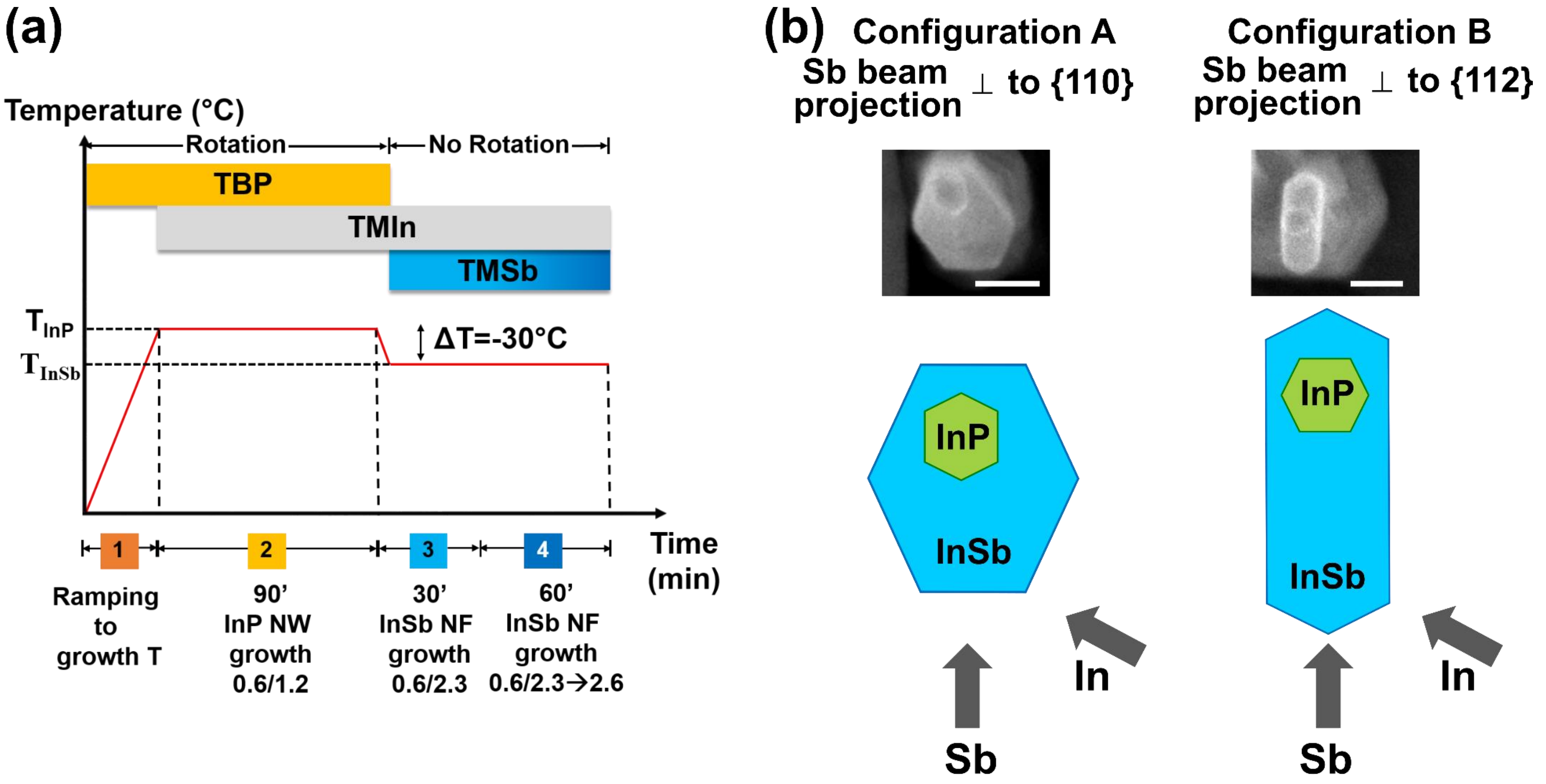
# Alignment of InP NWs for growth of InSb NFs




InP NW grown on InP(111)B

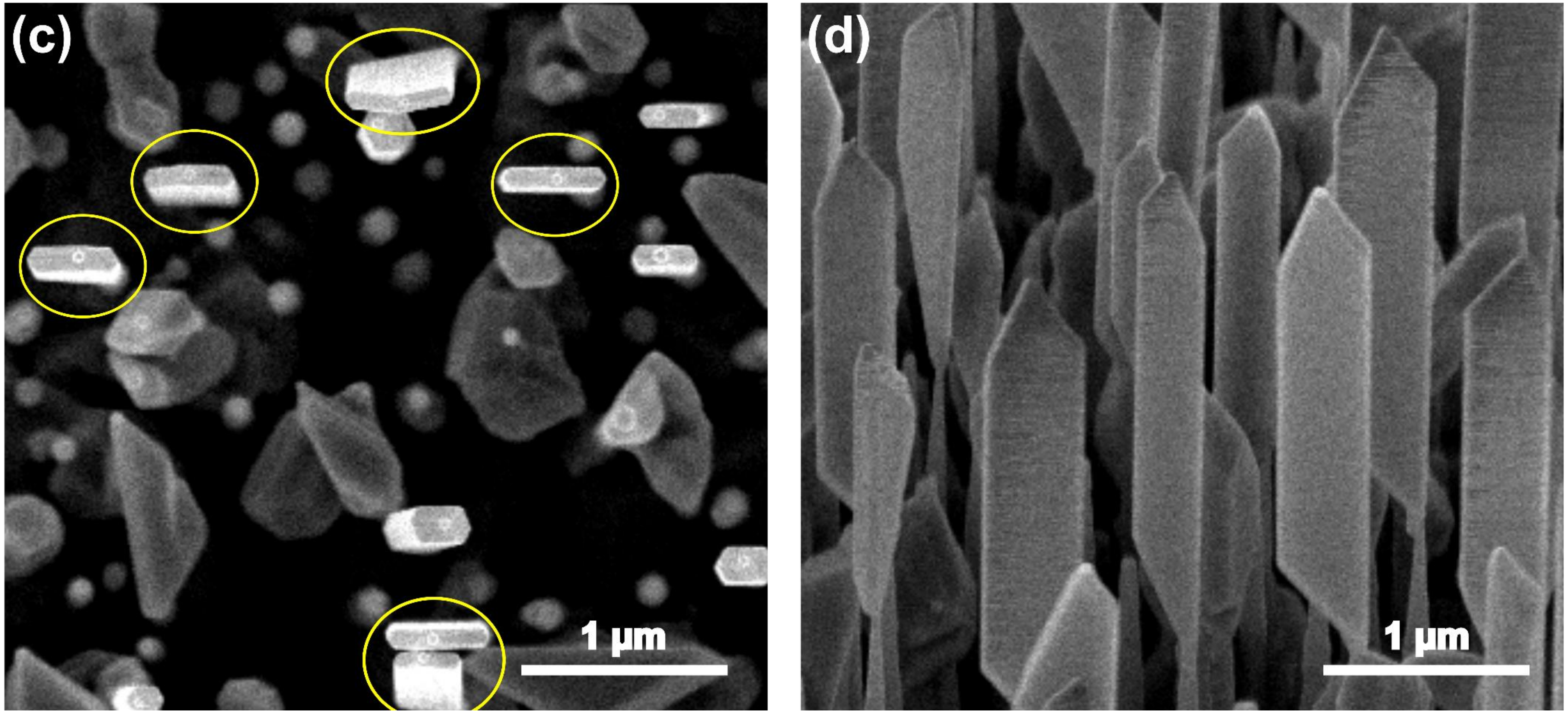
I. Verma et al., ACS Applied Nano Materials 4 (2021) 5825.

# Growth of InSb nanoflags




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

# Growth of InSb nanoflags

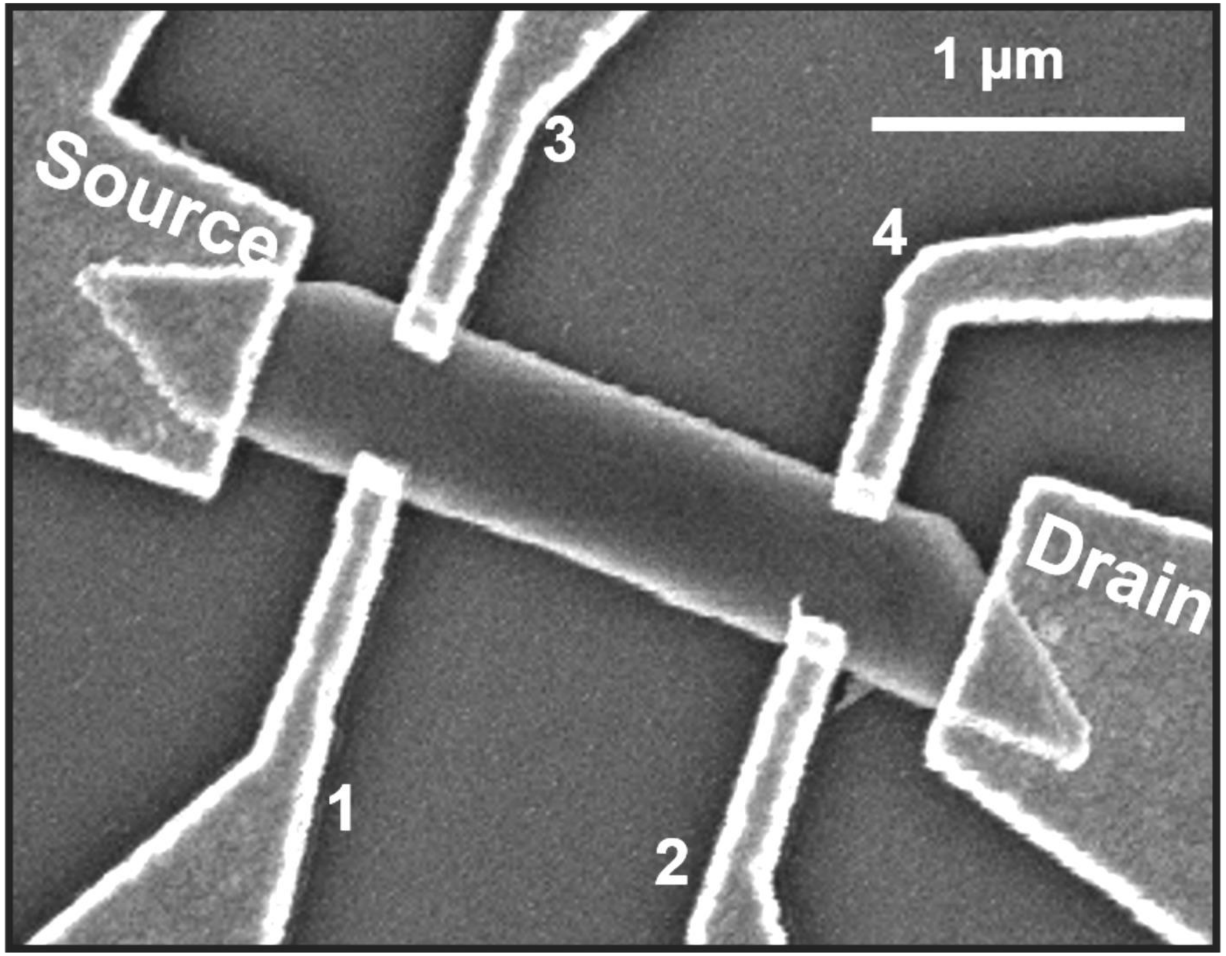



Defect-free InSb zinc blende lattice

**InSb nanoflags:**
Length 2.8 μm
Width 470 nm
Thickness 105 nm

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

# SEM of InSb NF 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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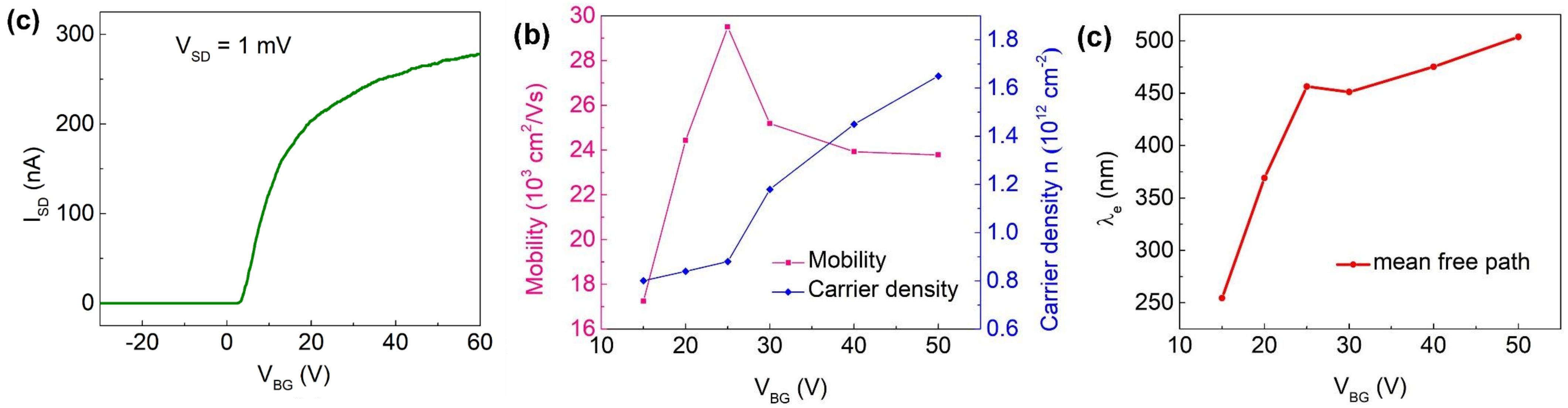
# InSb Electron Mobility

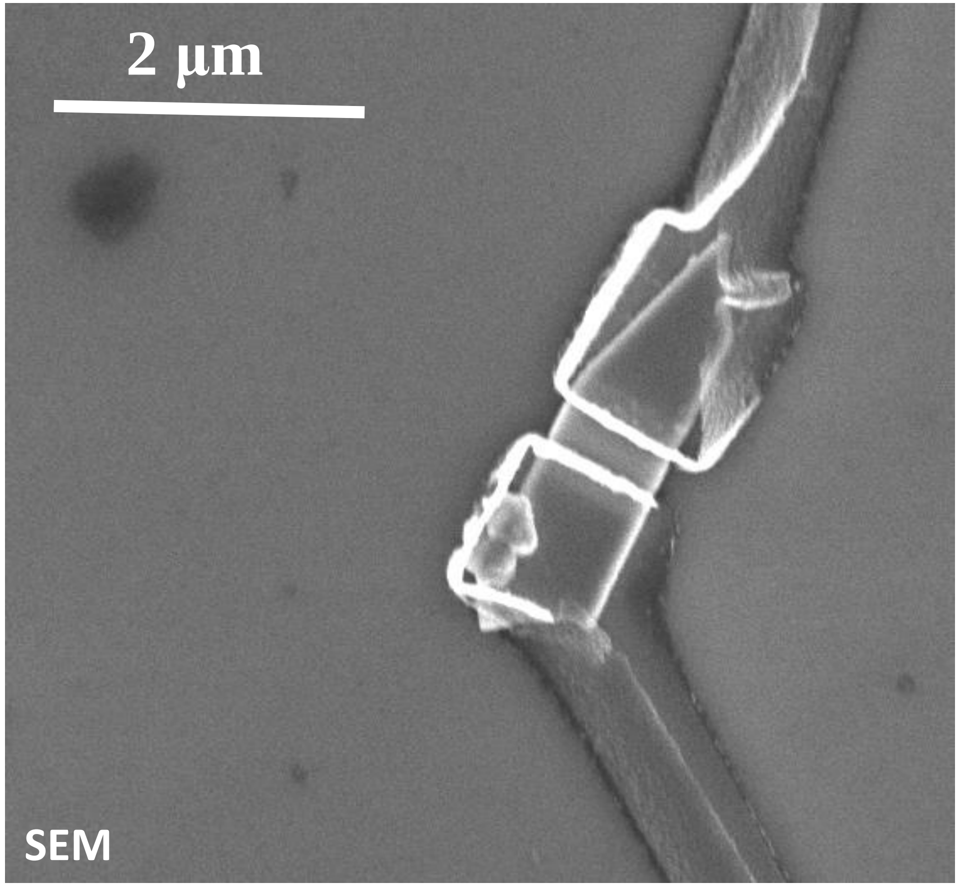



Field-effect mobility 28000 cm$^2$/Vs
Nanoflags are n-type

Hall mobility: 29500 cm$^2$/Vs @ 4.2 K
At n = 8.5 x $10^{11}$ cm$^{-2}$
Mean free path $\lambda_e \sim$ 500 nm

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

# Nb/Ti-InSb Nanoflag-based JJs



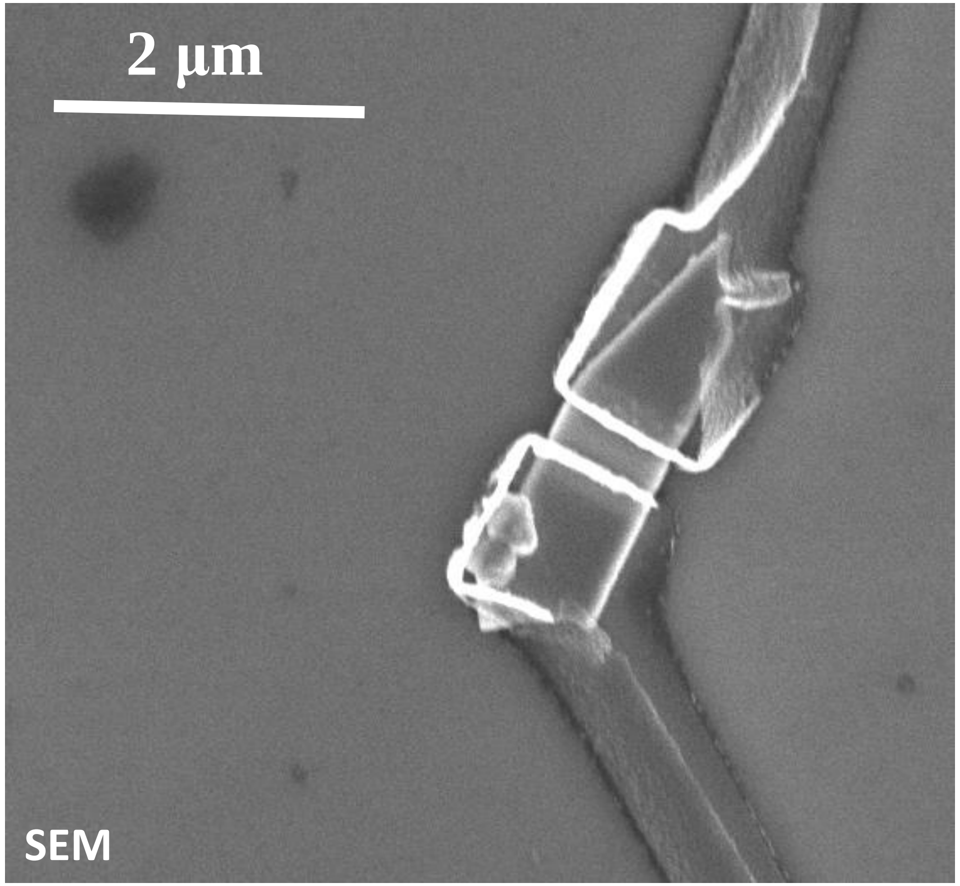

10 nm Ti/150 nm Nb
Substrate: $Si/SiO_2$

L = 200 nm
W = 700 nm
d = 100 nm

Ballistic regime! Mean free path $\lambda_e$ > length L of the junction, $\lambda_e > L$.

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

# Nb/Ti-InSb Nanoflag-based JJs




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

L = 200 nm
W = 700 nm
d = 100 nm

$T_c$ = 8.44 K
$\Delta = 1.76\ k_B T_c$ = 1.28 meV

Ballistic regime! Mean free path $\lambda_e$ > length L of the junction, $\lambda_e > L$.

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

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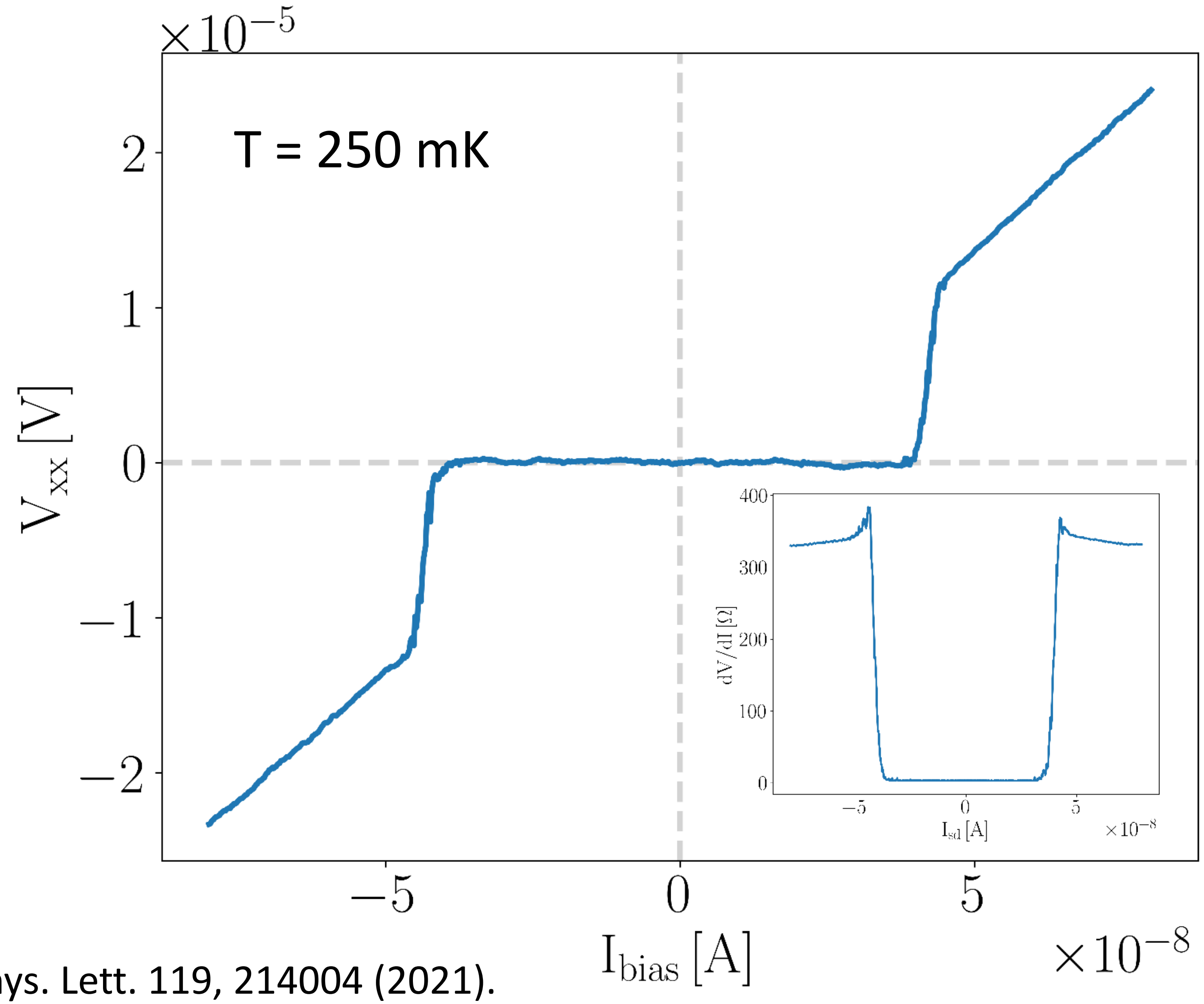
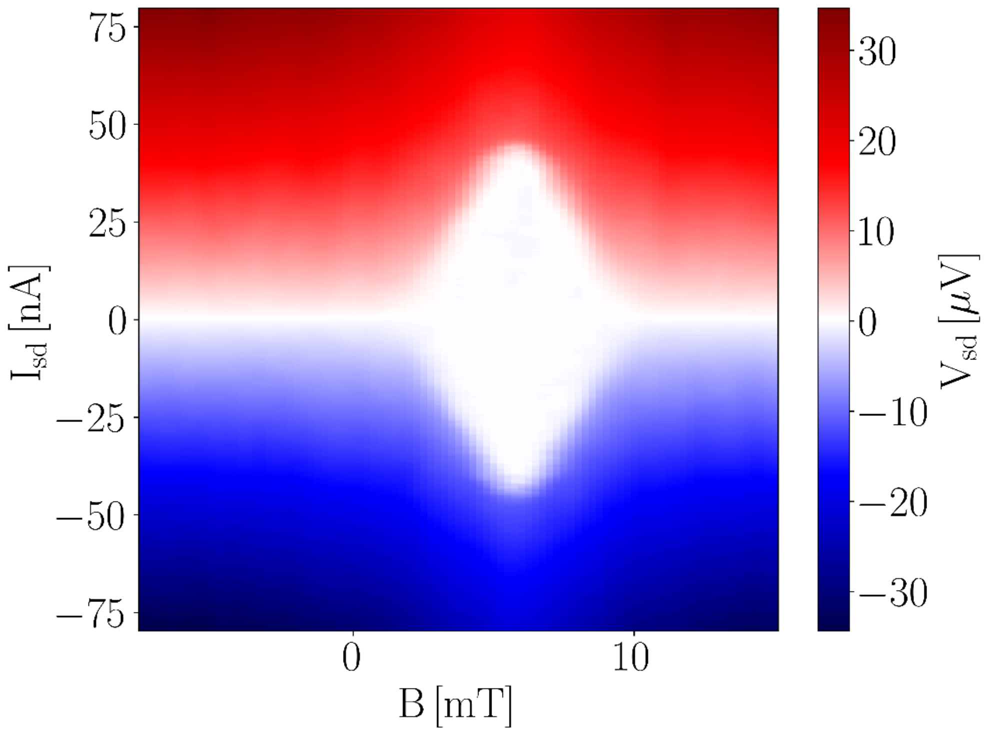
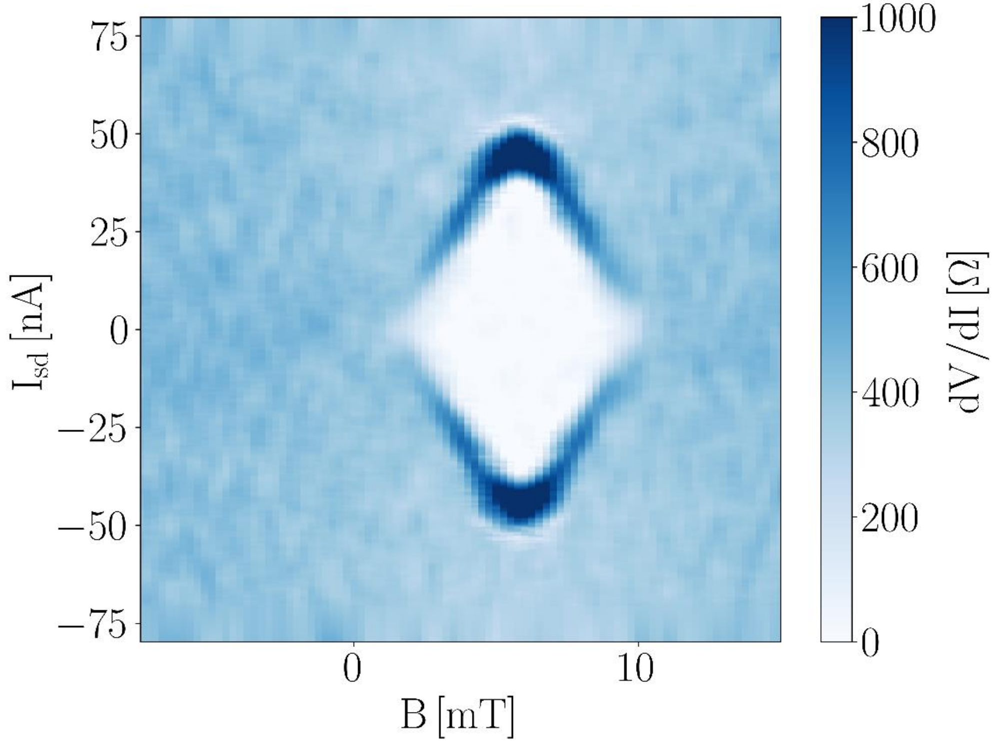
# V-I shows supercurrent




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

# Fraunhofer Pattern




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

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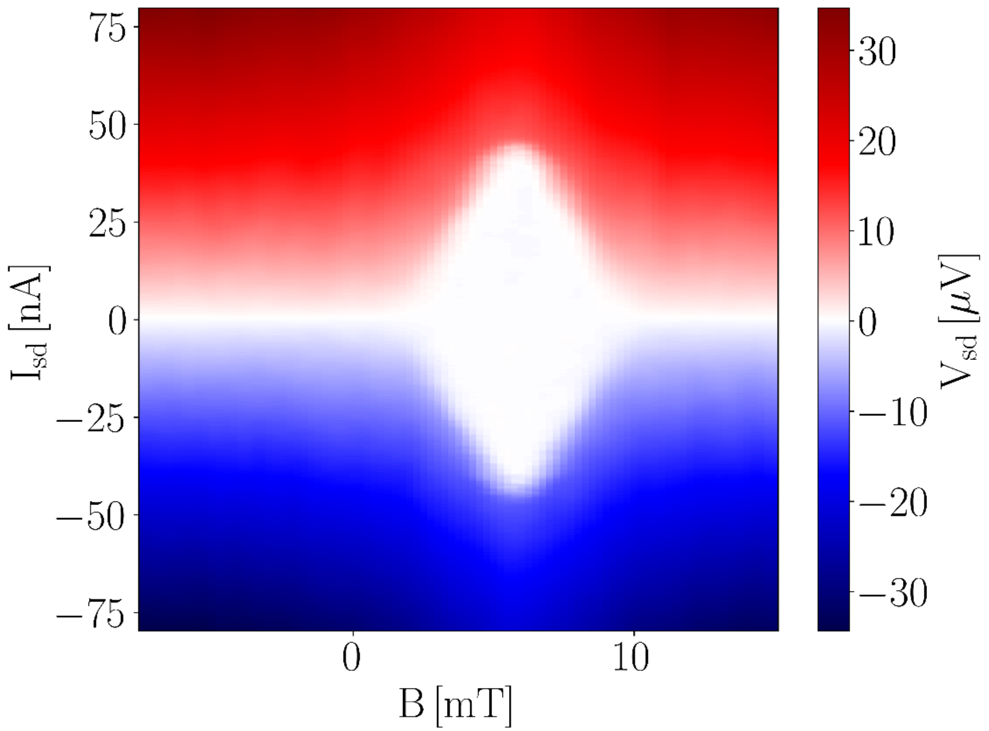
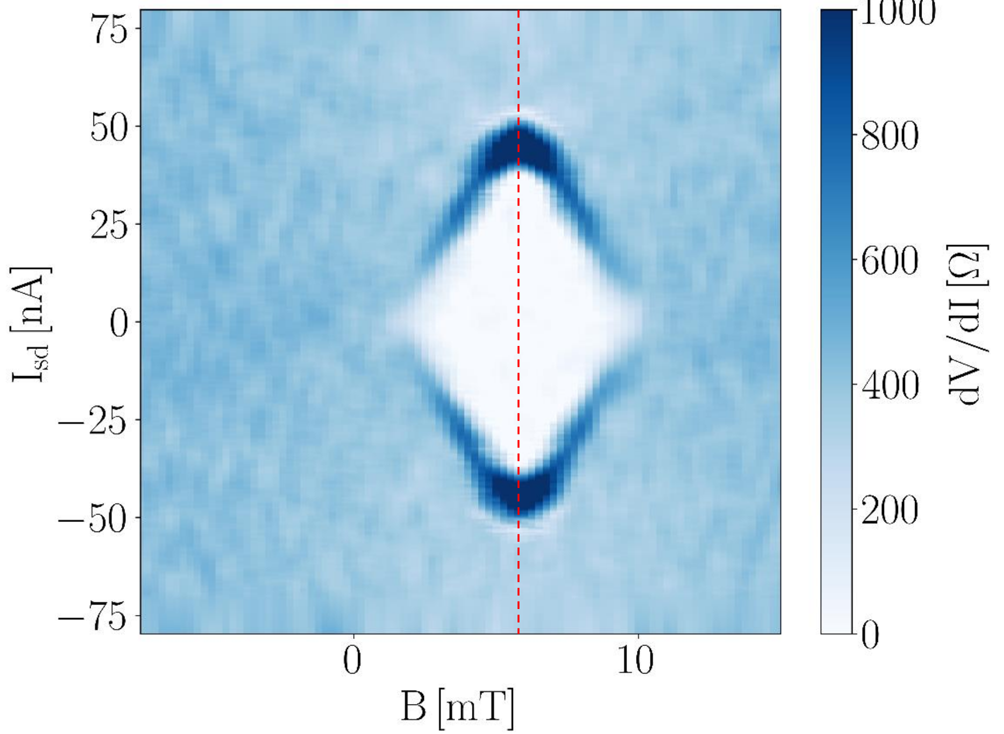
# Fraunhofer Pattern

Small offset of 6 mT
(residual magnetization in cryostat)




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

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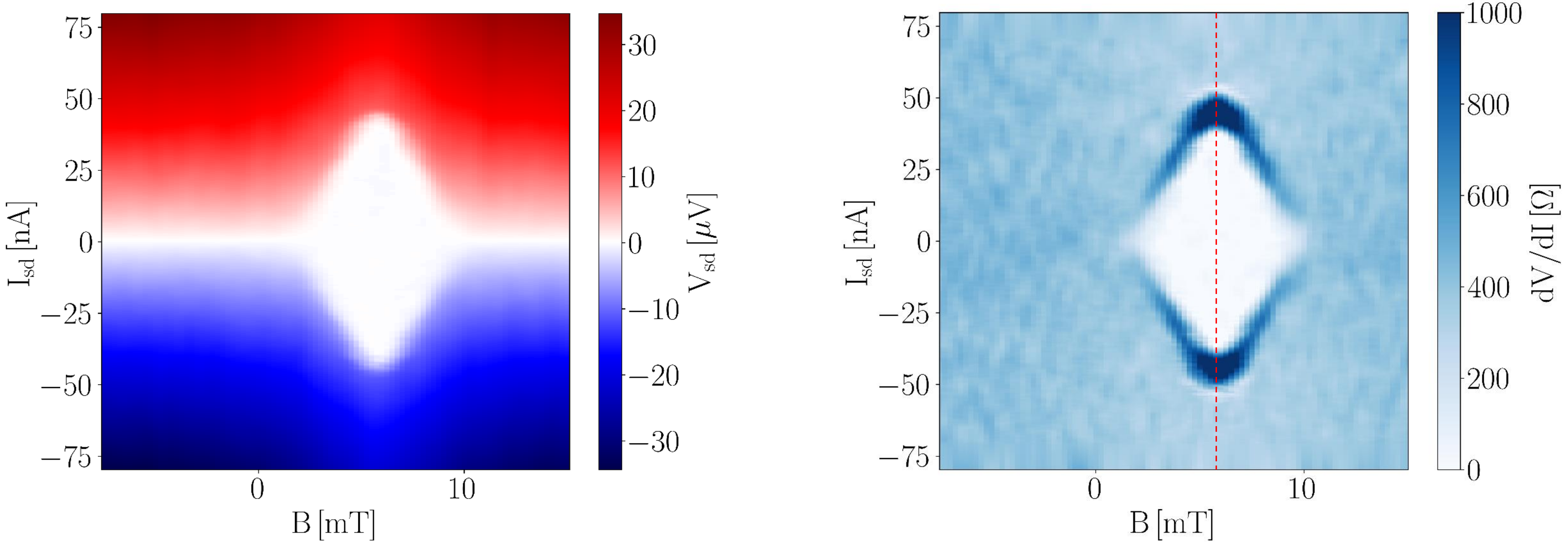


Why no sides lobes in the Fraunhofer pattern?

- 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).

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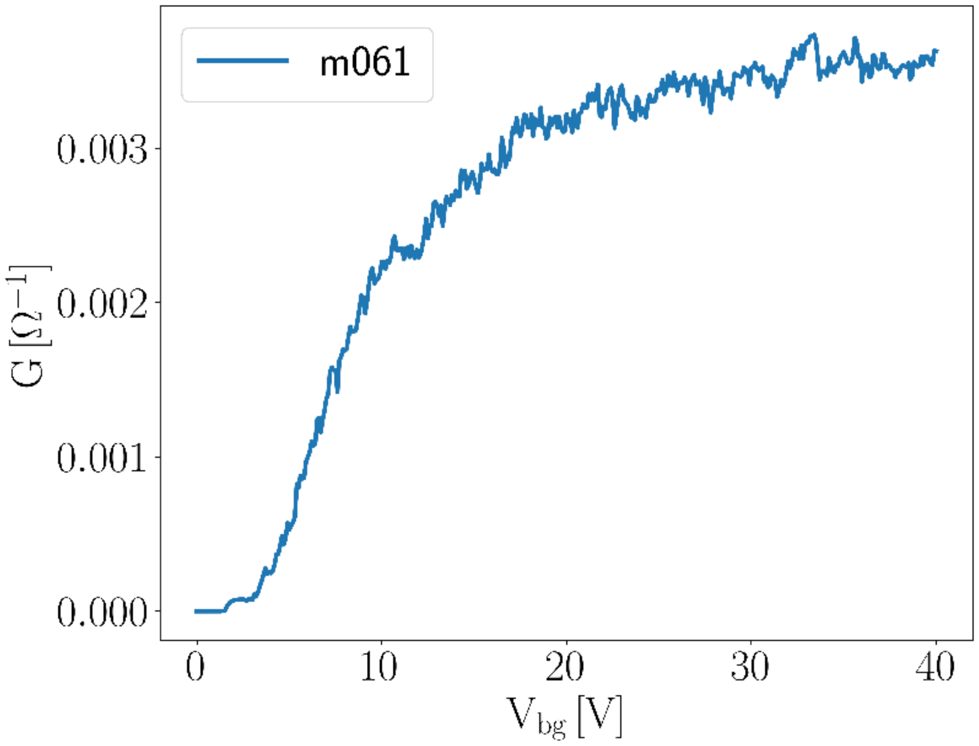
# Gate-tunable Supercurrent

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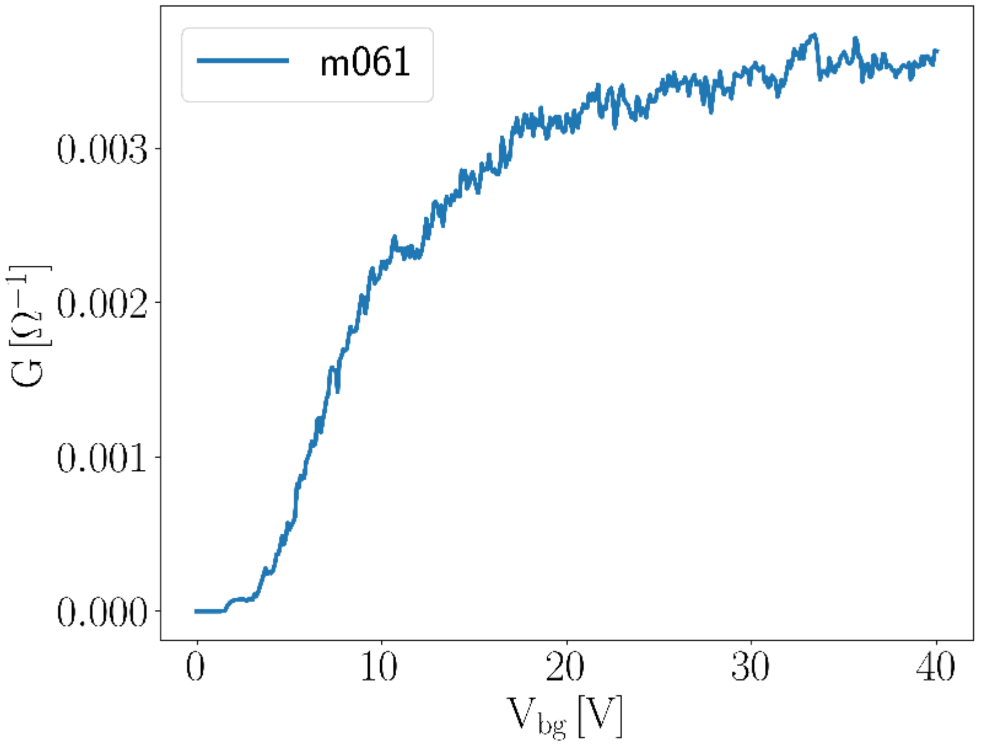


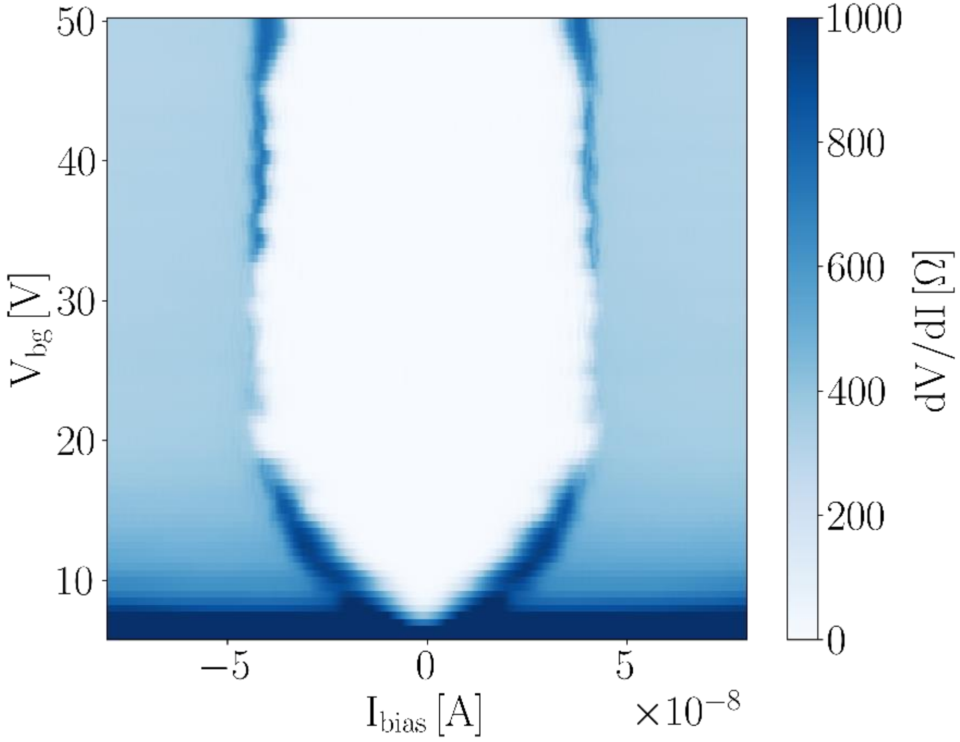


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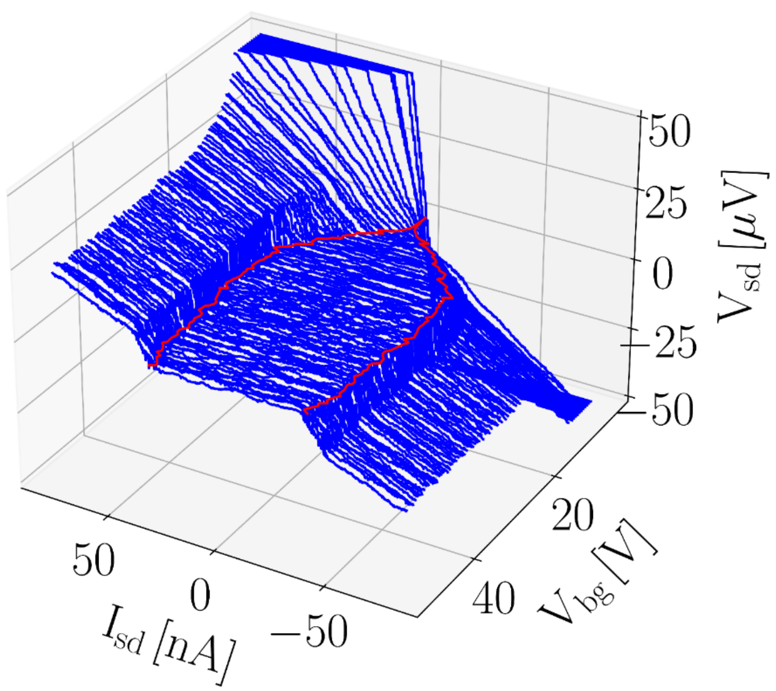
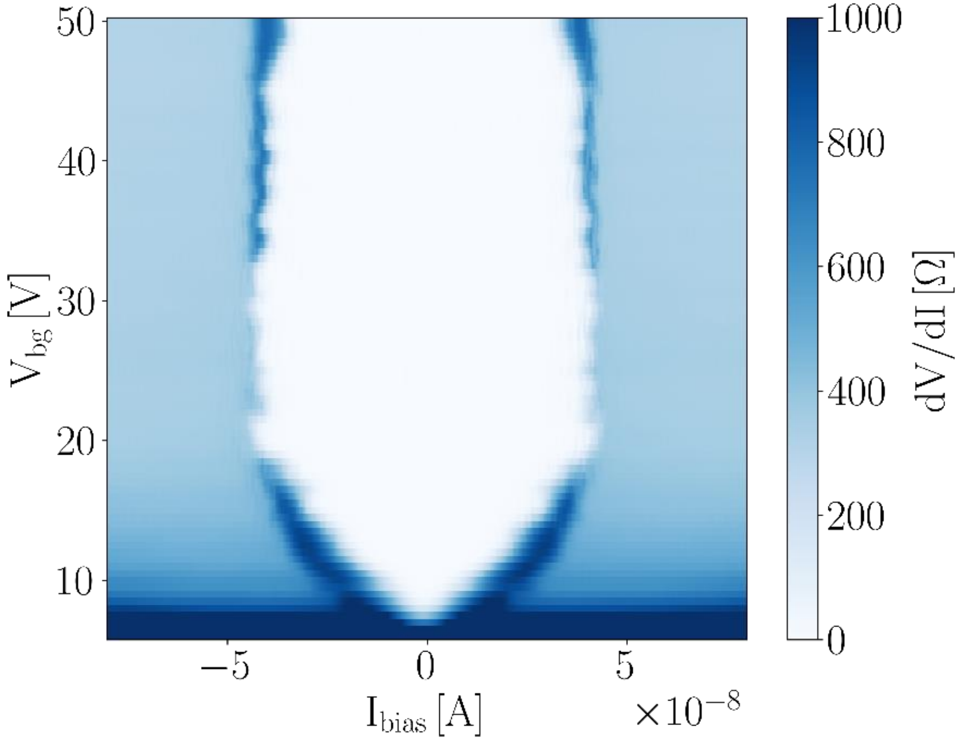
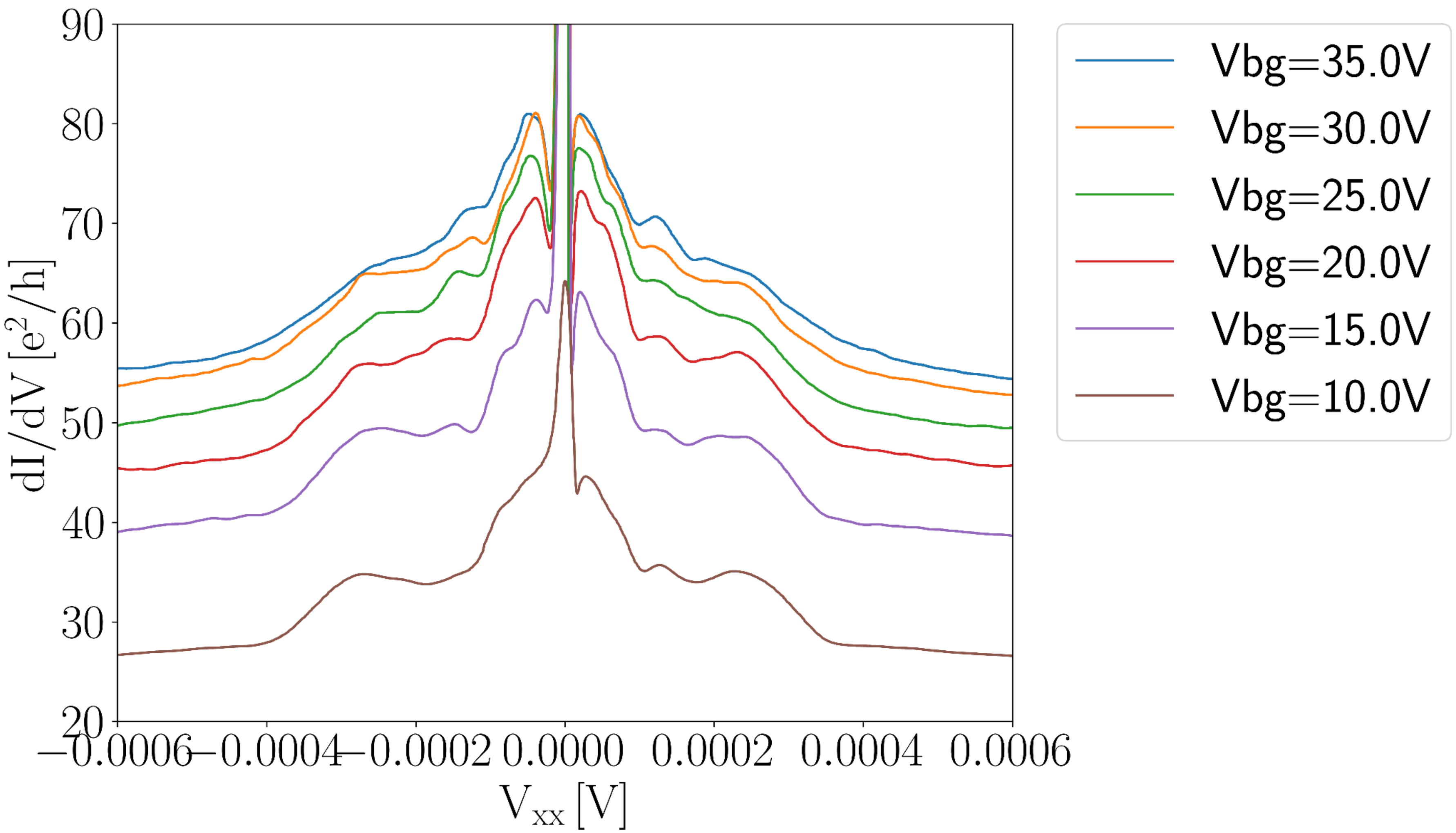



S. Salimian et al., Appl. Phys. Lett. 119, 214004 (2021).

# Multiple Andreev Reflections (MARs)




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

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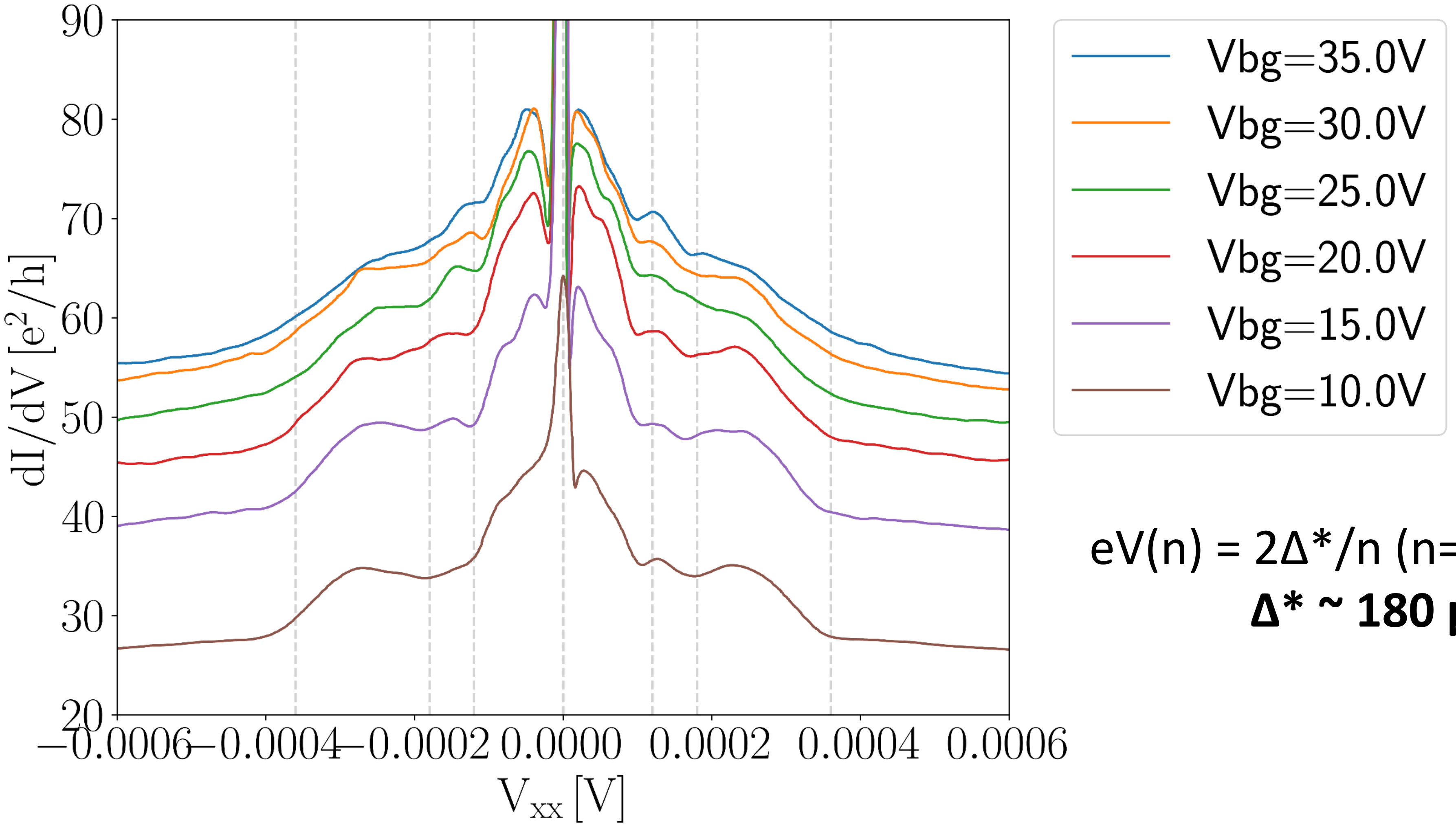


$eV(n) = 2\Delta^*/n$ (n=1, 2, 3 . . .)

**$\Delta^* \sim 180$ μeV**

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

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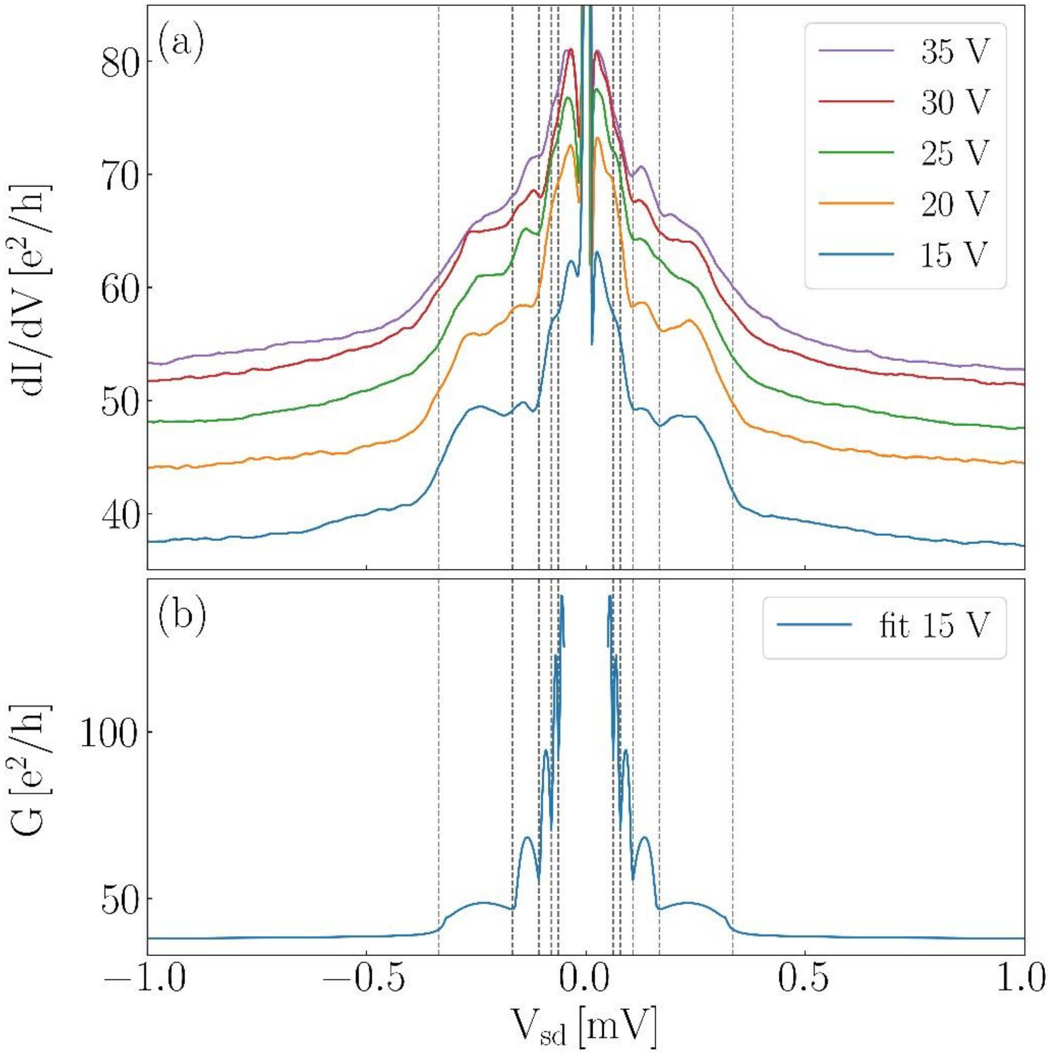
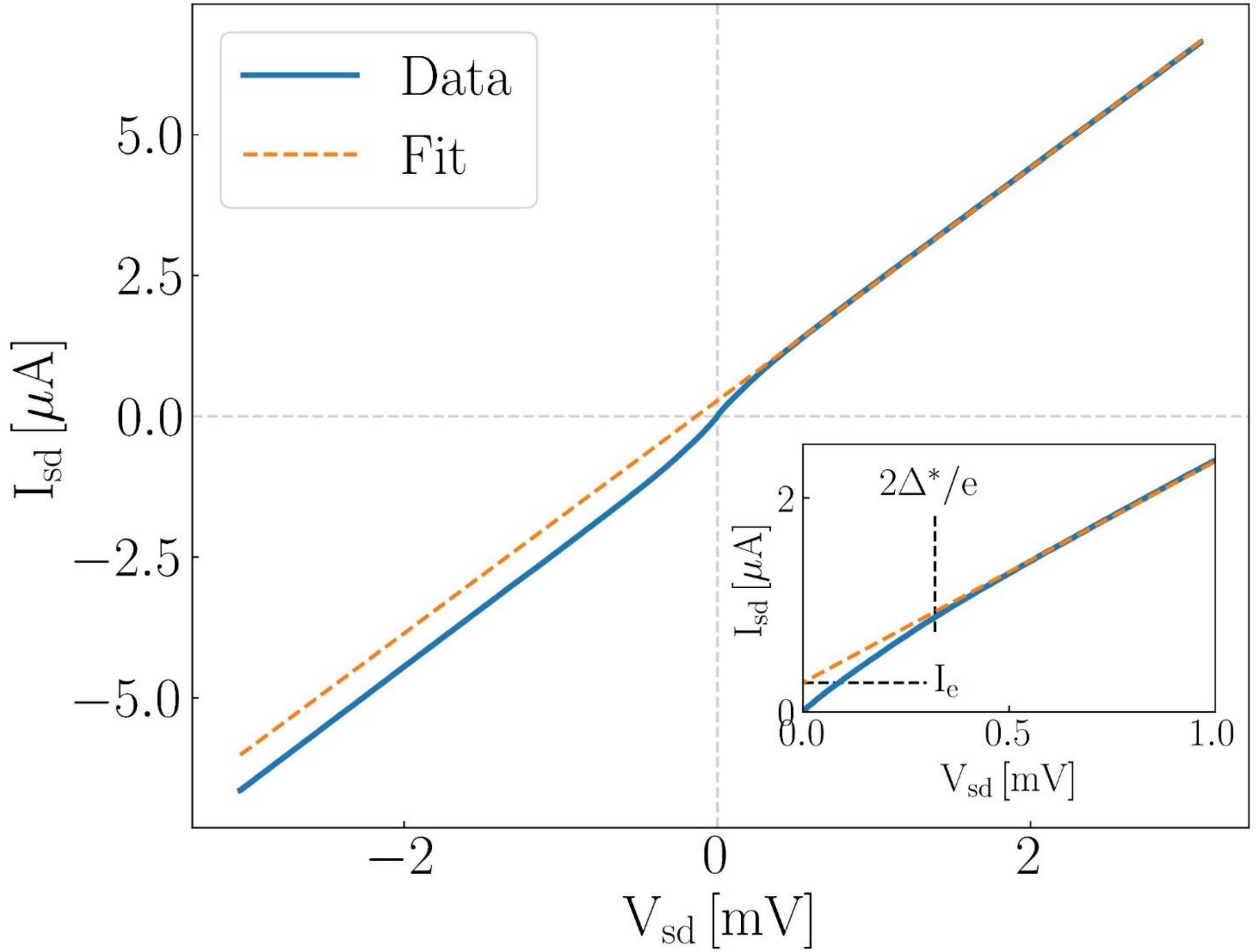
# Multiple Andreev Reflections (MARs)




- Simple scattering model of fully coherent transport.
- Best fit with 40 modes of transparency *Tr* = 0.94.
- Induced gap $\Delta^*$ = 160 μeV.
- Consistently, *Tr* and $\Delta^*$ do not change with back gate voltage,
- BUT the number of modes does: it increases from 30 to 50 for $V_{bg}$ from 10 V to 30 V.

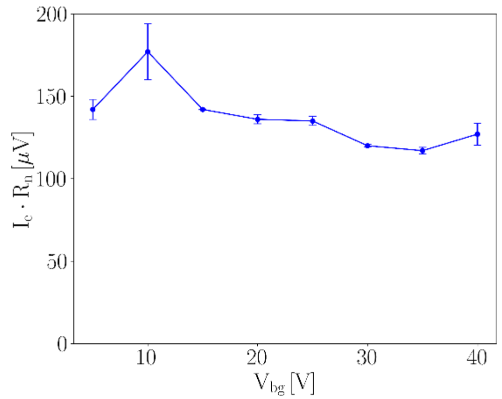
S. Salimian et al., Appl. Phys. Lett. 119, 214004 (2021).

# Excess Current




$V_{bg}$ = 40 V

$I_e$ = 265 ± 12 nA
$R_n$ = 481 ± 3 Ω
$I_eR_n$ = 127 ± 7 μV

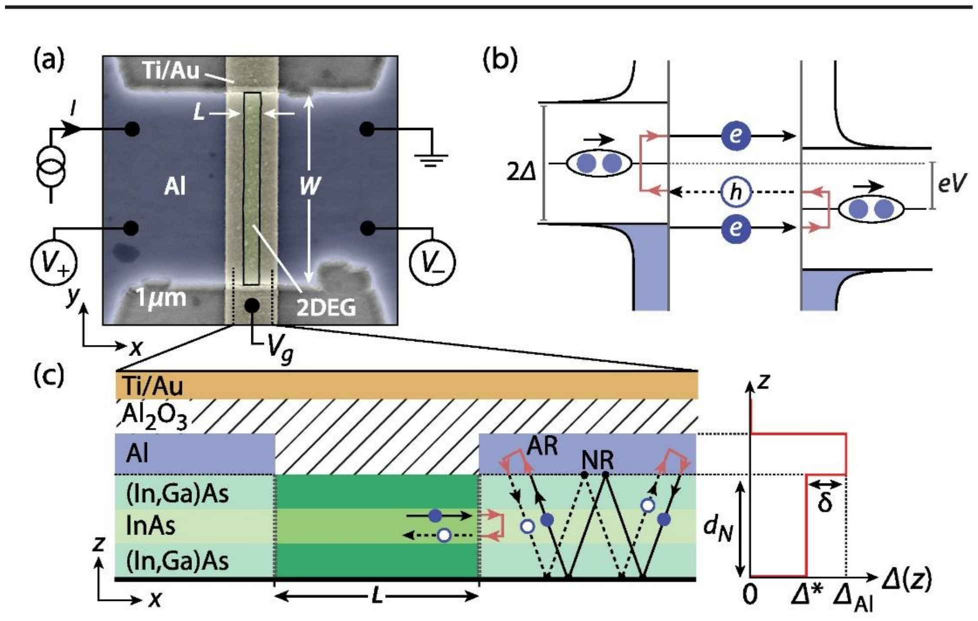



S. Salimian et al., Appl. Phys. Lett. 119, 214004 (2021).

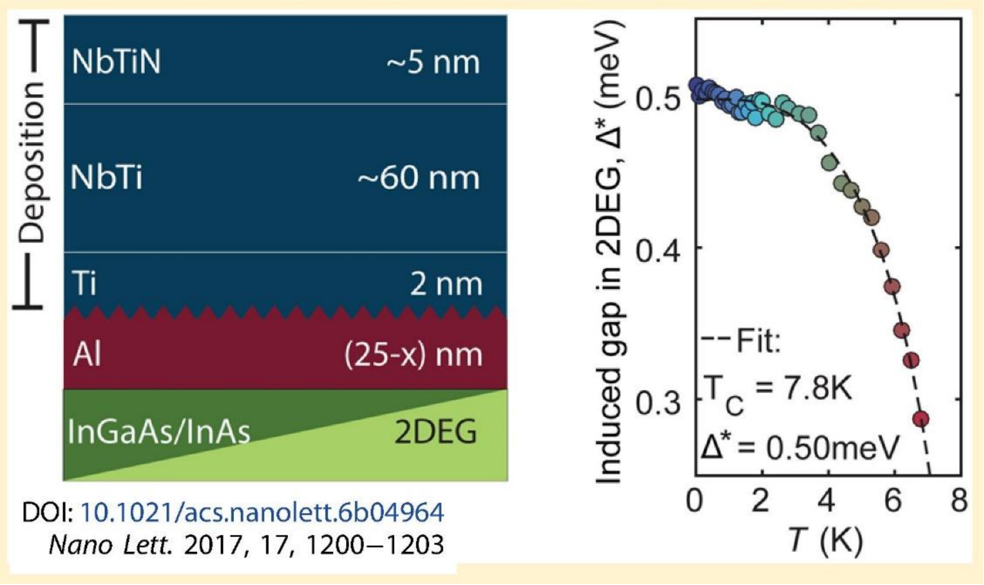
# Discussion

## Induced Gap in Semiconductor

PHYS. REV. APPLIED **7**, 034029 (2017)




## Transfer of proximity via another superconductor




## The role of Ti ?

Bulk Ti (CRC Handbook): $T_c$ = 0.5 K

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

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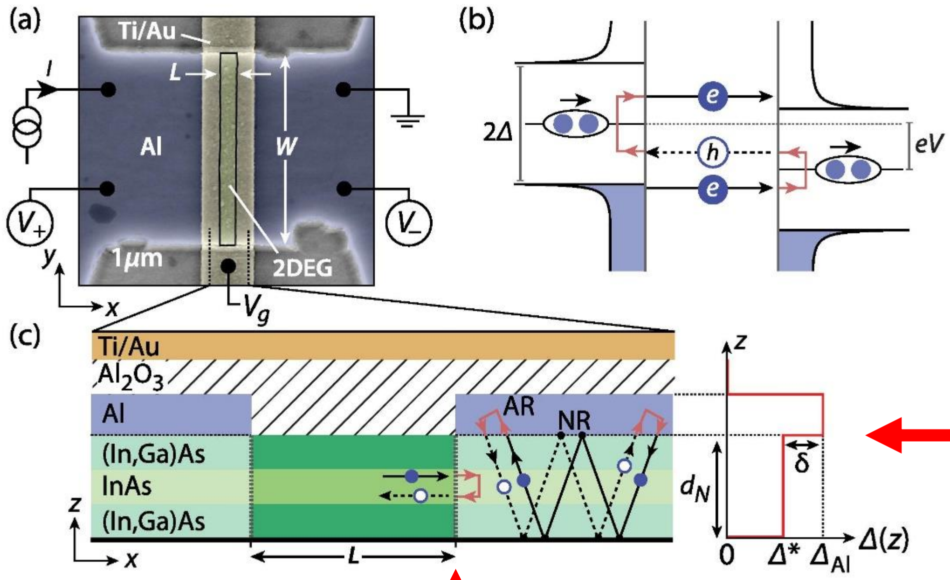
# Discussion

## Induced Gap in Semiconductor

PHYS. REV. APPLIED **7**, 034029 (2017)




Why $\Delta^* < \Delta$?

Aminov et al., PRB 53 (1996) 365:

$$\Delta^* = \frac{\Delta}{1 + \gamma_B \sqrt{\Delta^2 - {\Delta^*}^2}/(\pi k_B T_c)}$$

$\gamma_B$ measures the interface transparency.
$\gamma_B = 0$ for perfectly transparent interfaces.
Large $\gamma_B$ means small transparency.

Here: $\gamma_B \approx 10$.

*Tr* = 0.94,
consistent with $I_e R_n \approx \Delta^*/e$.

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

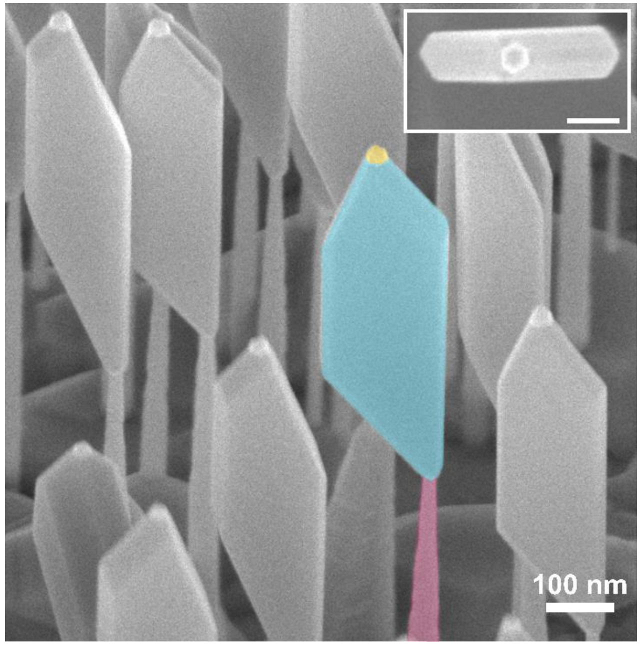
# Summary

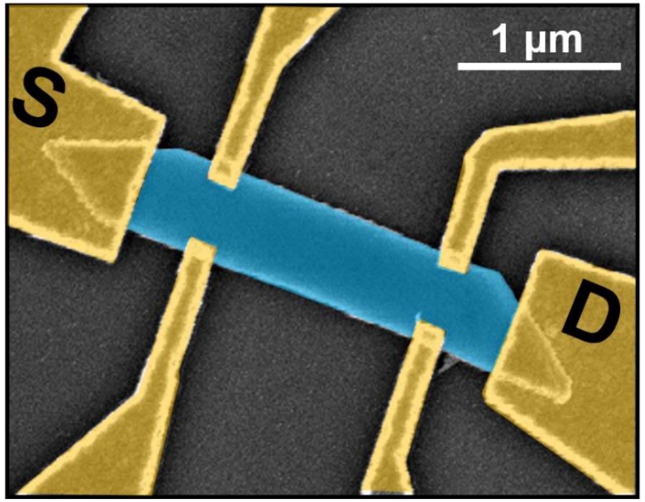
- Free-standing 2D InSb nanoflags on InP stems
- Length 2.8 µm, Width 470 nm, Thickness 105 nm
- Defect-free zinc blende crystal structure

- High electron mobility 29,500 $cm^2/Vs$
- Mean free path $\lambda_e$ ~ 500 nm

- Josephson junctions realized with Nb/Ti contacts
- 50 nA supercurrent & Multiple Andreev Reflections

- Towards topological superconductivity …

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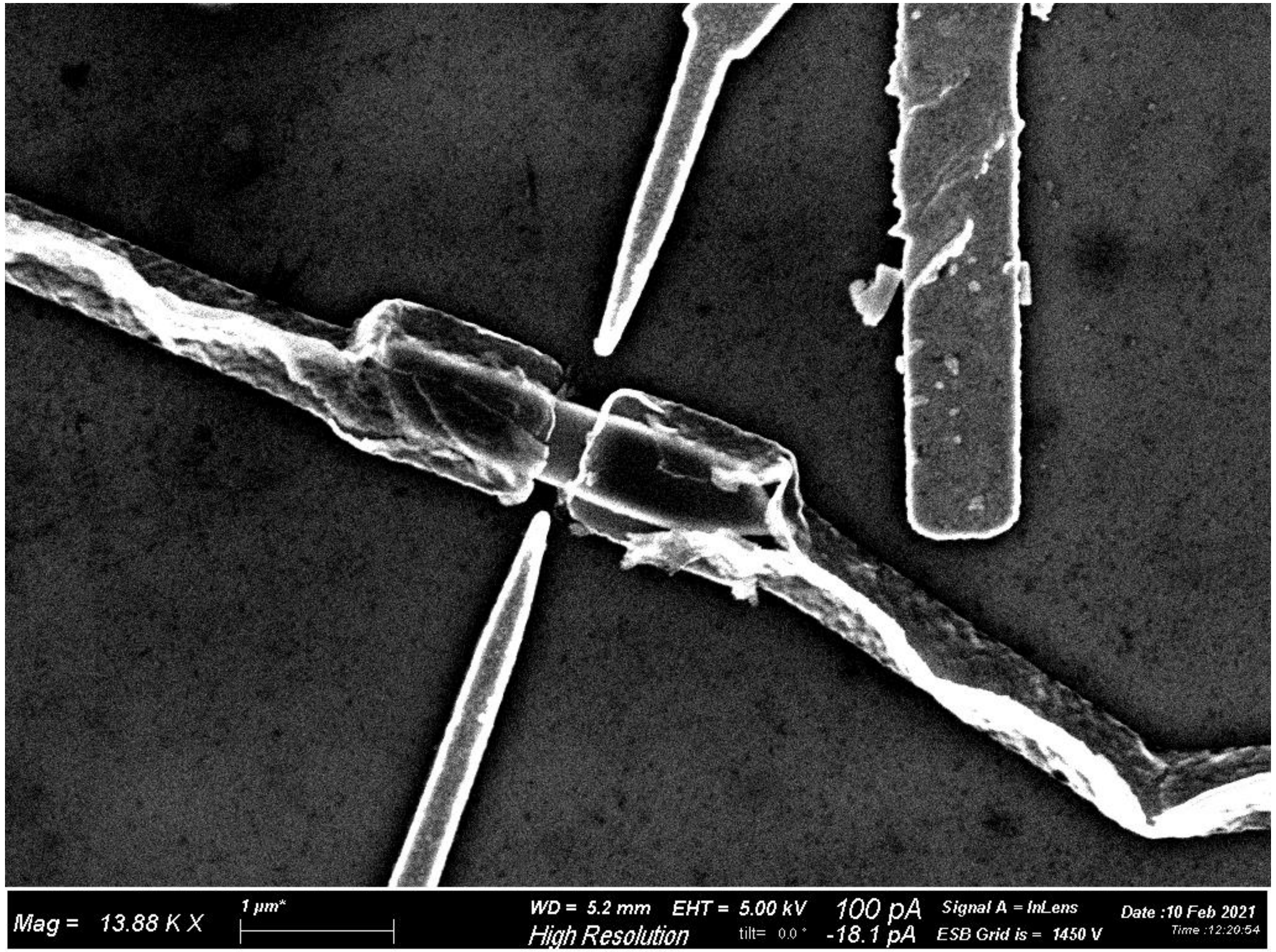
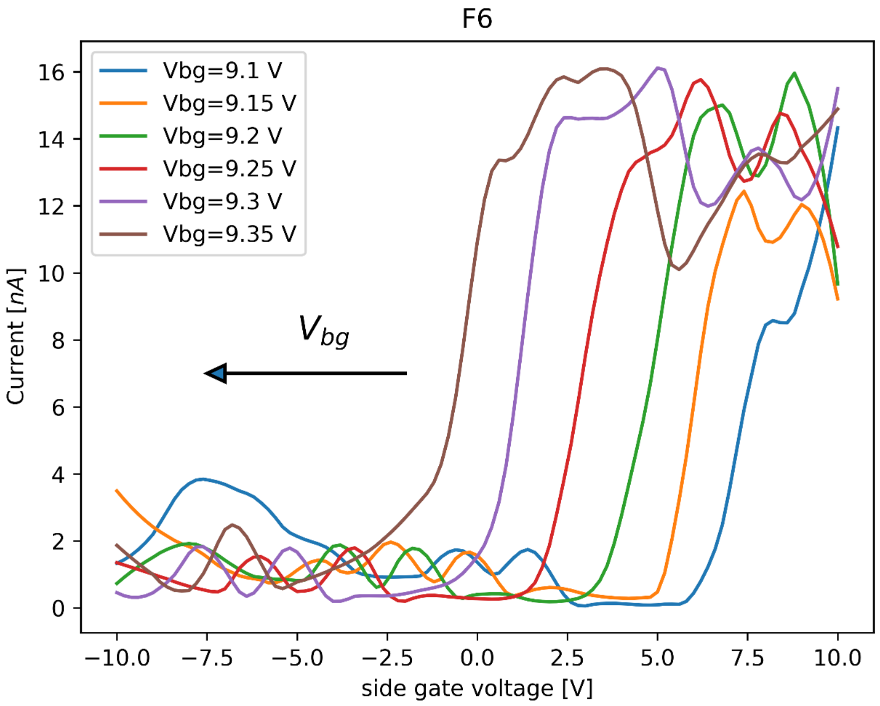
# Outlook: JJs with side gates



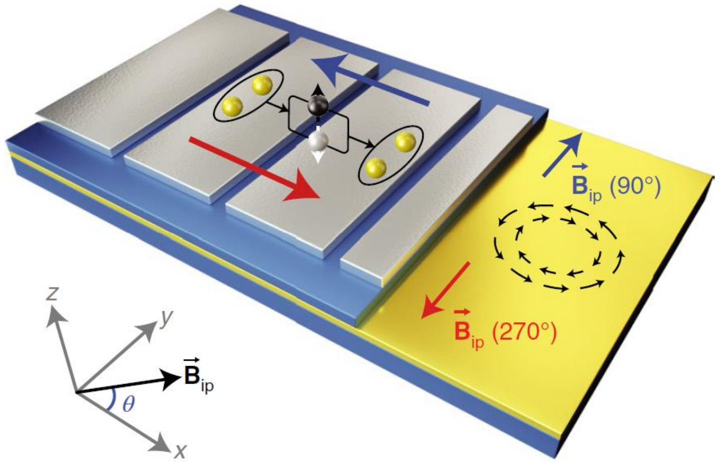

Bianca Turini

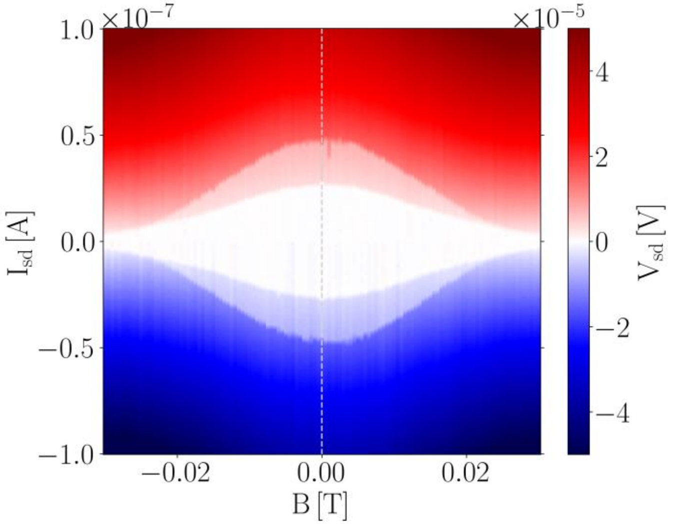
Federico Paolucci

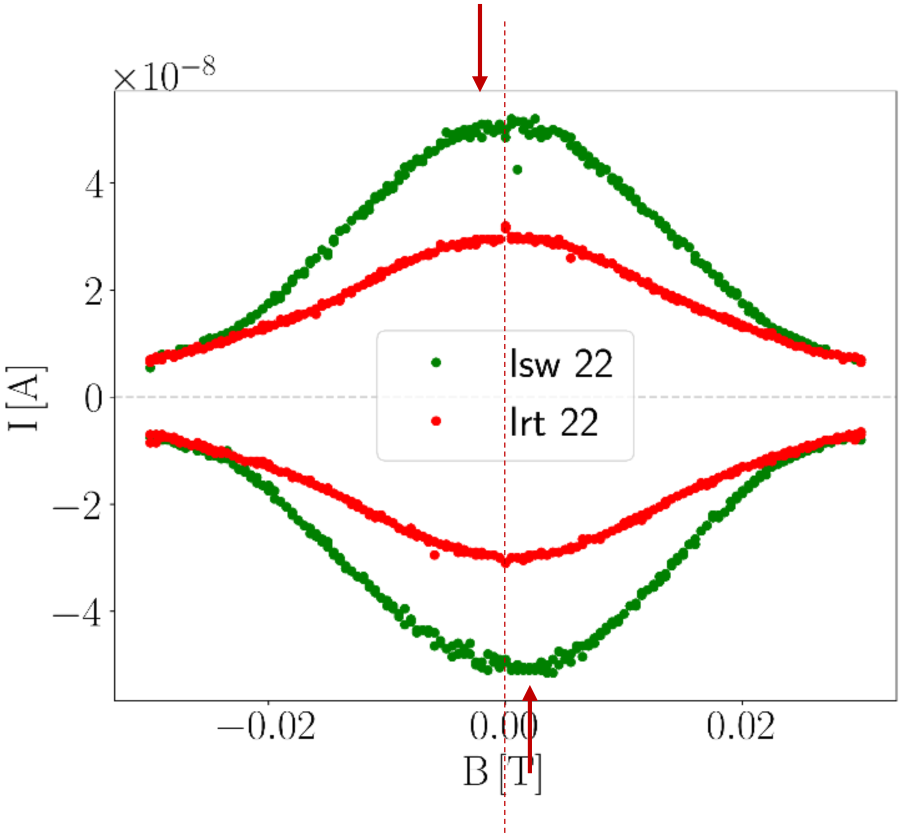


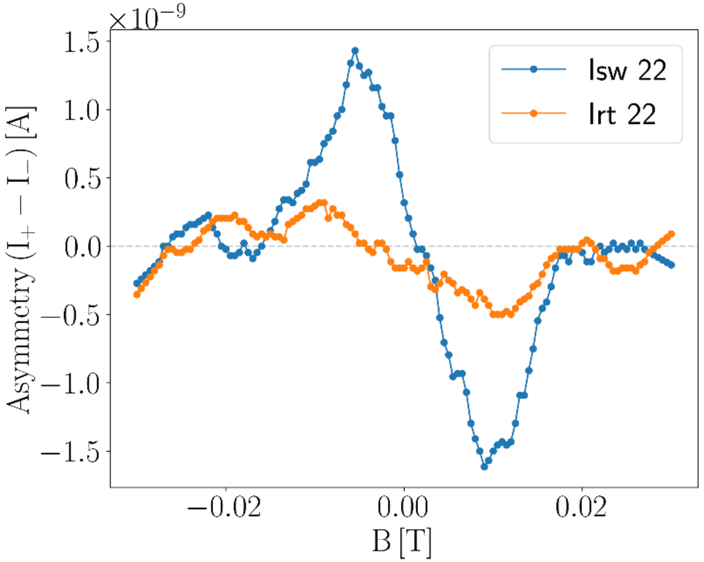
# Outlook: SC diode

Bianca Turini Elia Strambini Francesco Giazotto

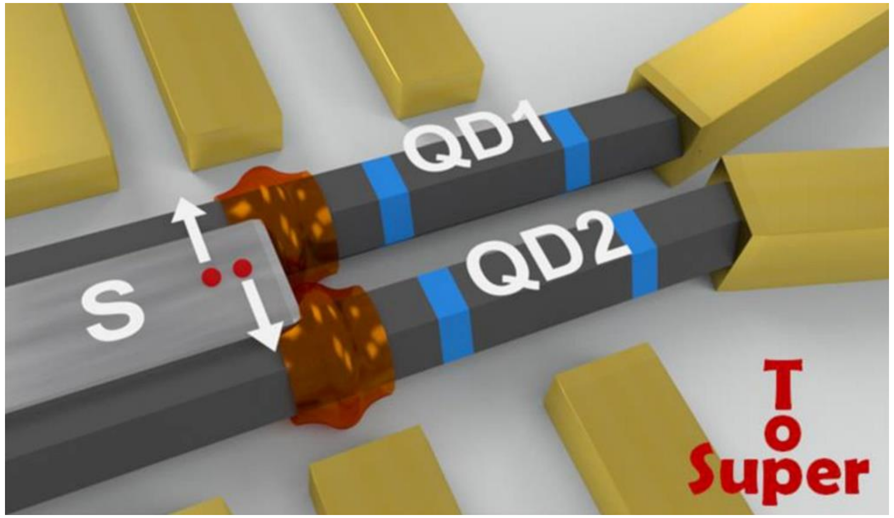


# Acknowledgements




AndQC

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# Thank you for your attention!

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