Towards supercurrent flow imaging by Scanning Gate Microscopy in InSb Josephson Junctions

Antonio Lombardi

Supervisors: Prof. S. Heun and Prof. L. Sorba

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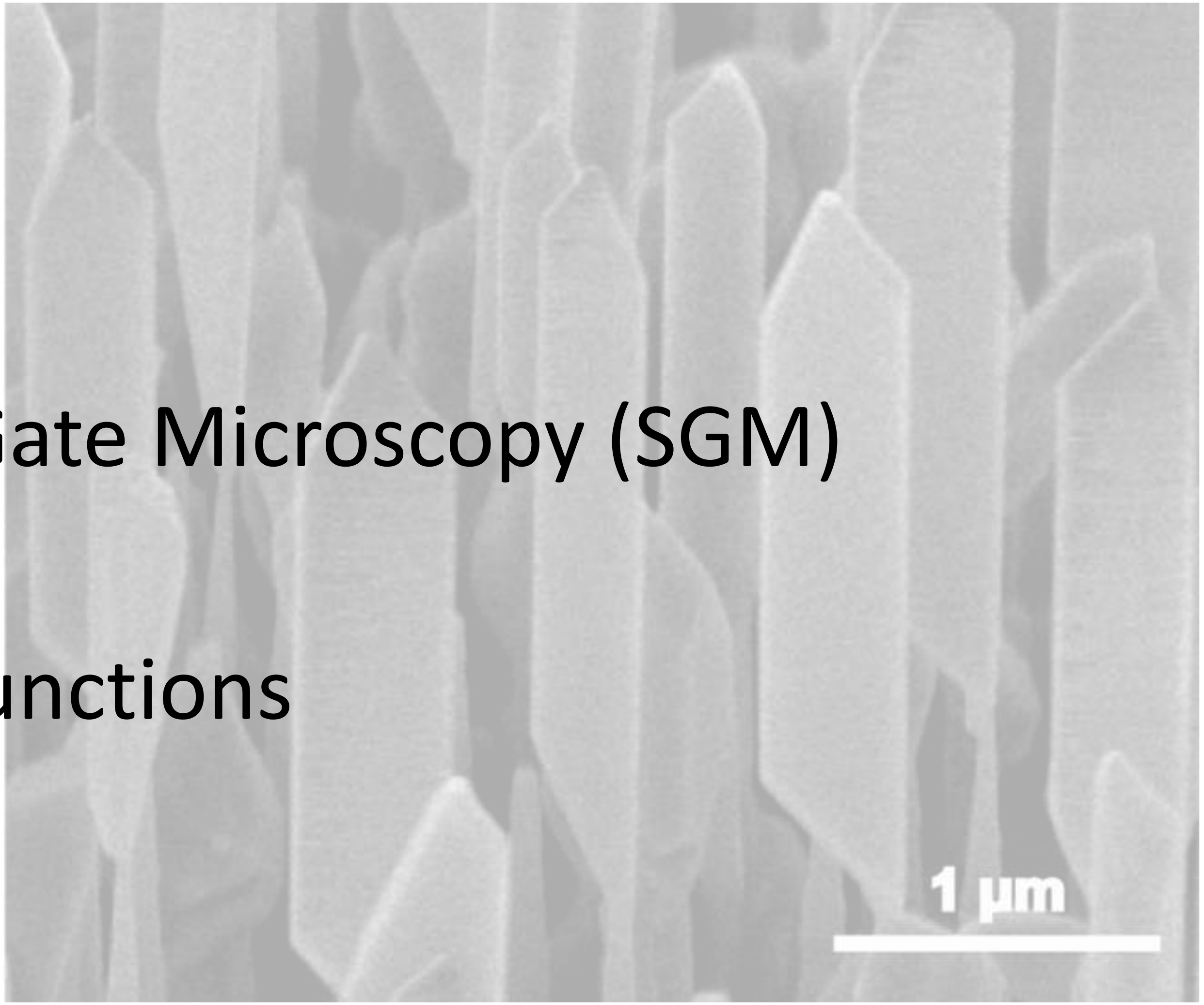
Outline

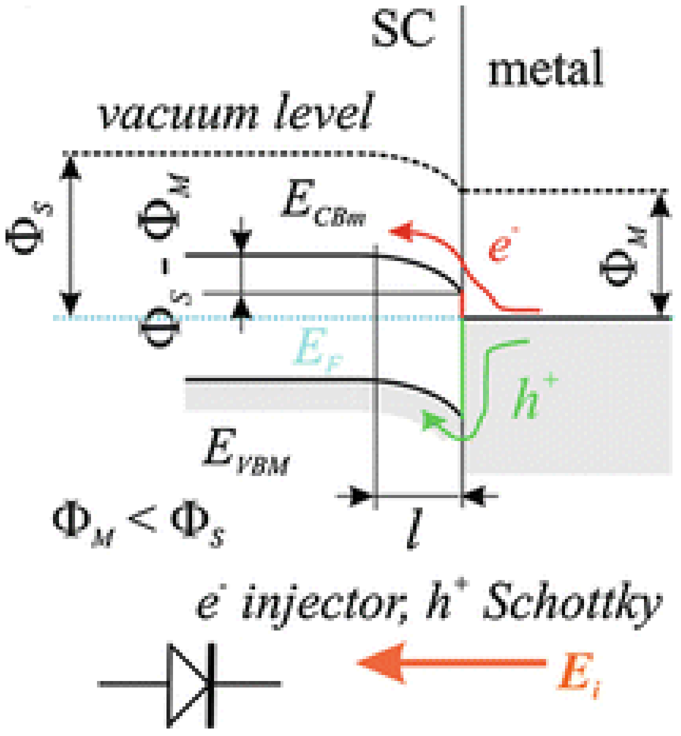


- About InSb nanoflags
- Introduction to Scanning Gate Microscopy (SGM)
- SGM of S-N-S Josephson Junctions

Why InSb?

- No Schottky barriers: ohmic contacts
- Narrow bandgap: Eg = 0.23 eV
- Low effective mass: $m^* \approx 0.018\ m_e$
- Large Landè factor: $g^* \approx 50$
- Strong spin orbit coupling: $E_{SOI} \approx 200\ \mu eV$

- Fast, low power electronic devices
- Spintronics
- Topological quantum information



From C.S.S. Kumar, "Surface Science Tools for Nanomaterials Characterization"

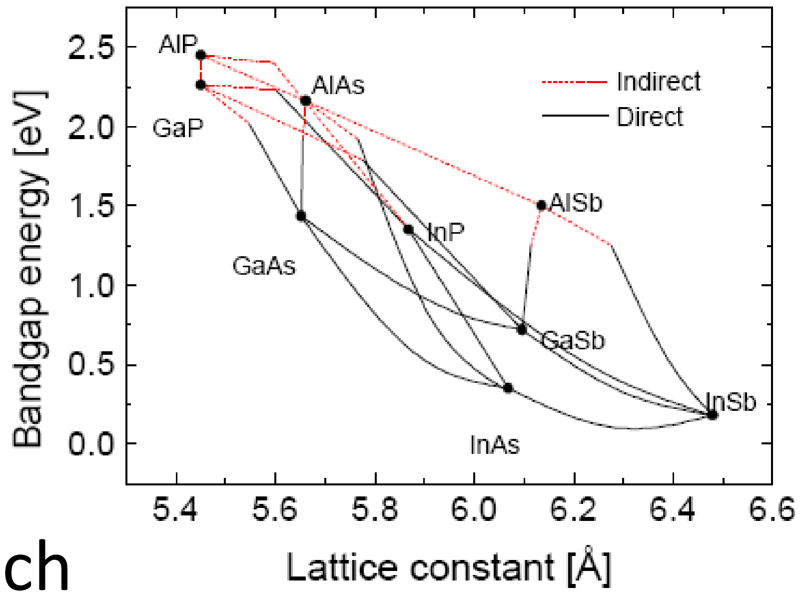
Why InSb nanoflags?

Smallest bandgap: lattice mismatch issues

InSb nanowires | InSb QWs

Lateral stress relaxation
Limited design flexibility

Scalable + flexible approach
Stacks of buffer layers needed

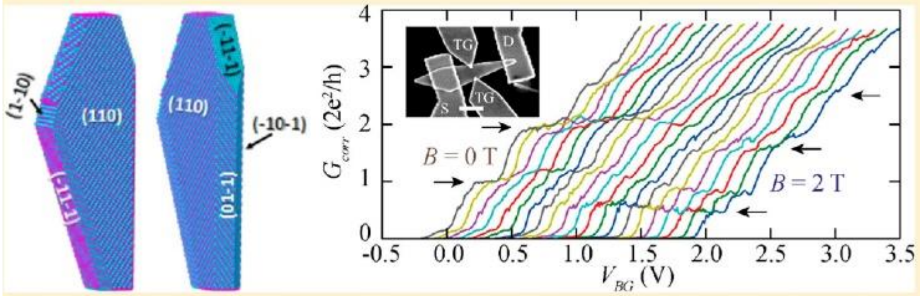


Wishlist: high quality and easy-to-grow structures with 2D geometry

Why InSb nanoflags?

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

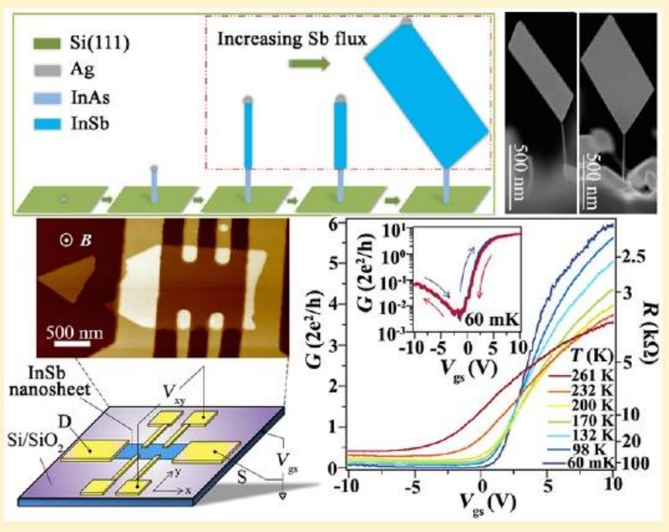
María de la Mata,† Renaud Leturcq,*,‡,§ Sébastien R. Plissard,‖ Chloé Rolland,‡ César Magén,⊥ Jordi Arbiol,*,†,# and Philippe Caroff*,‡,∇



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*,†

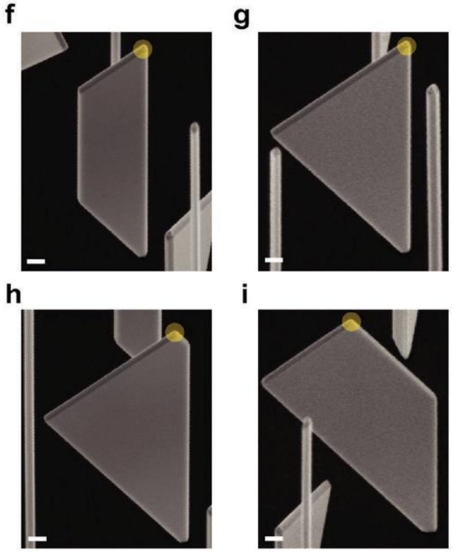


Nano Lett. 16 (2016) 834

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

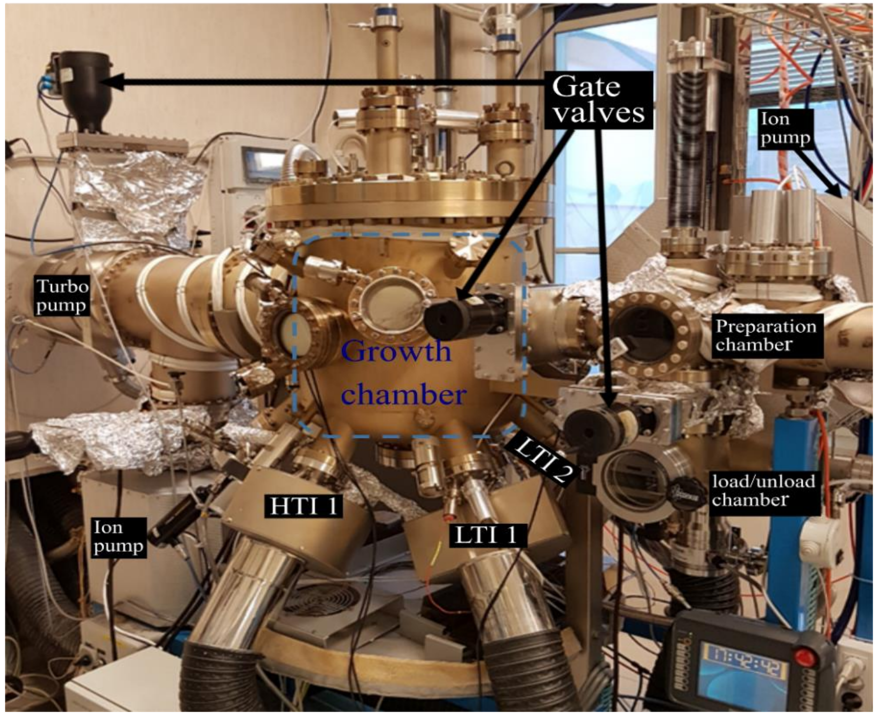


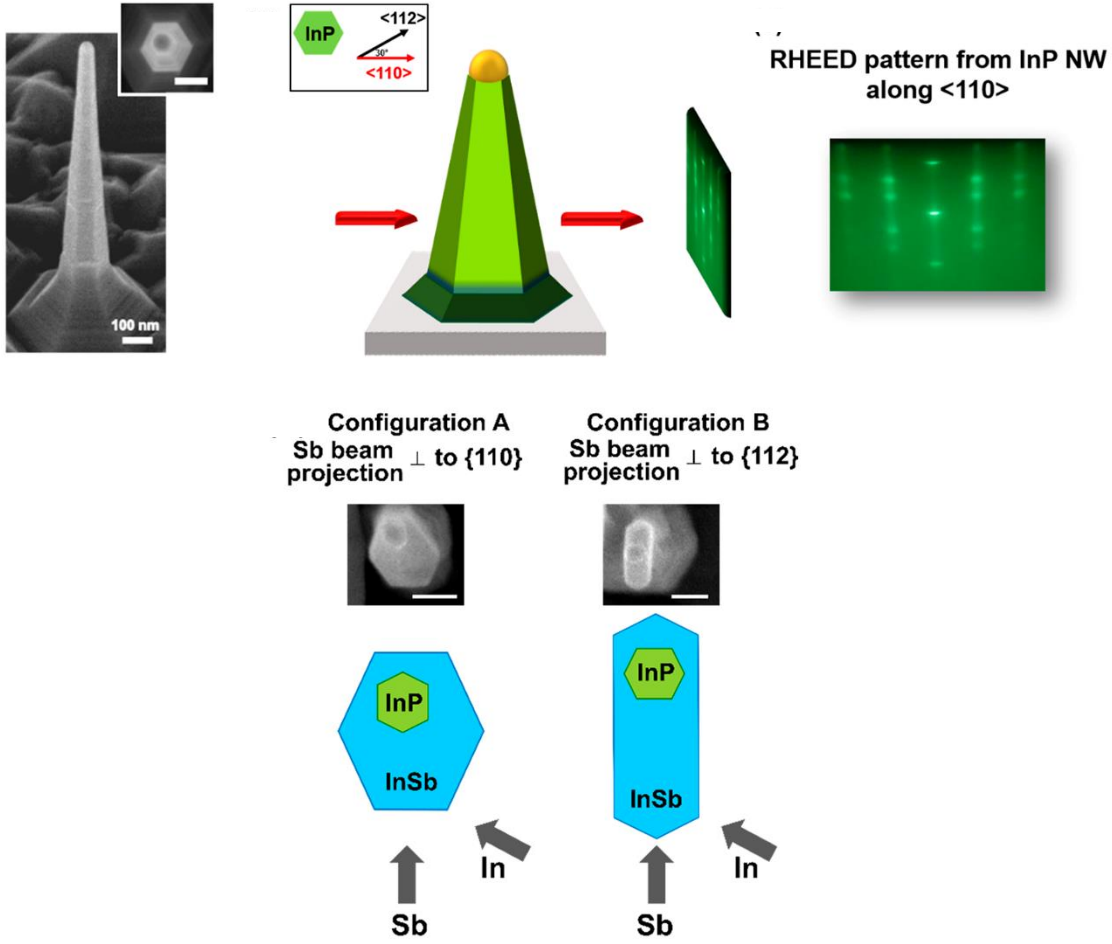
InSb NanoFlags growth procedure

Prof. Sorba's group @NEST

CBE system at NEST lab

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





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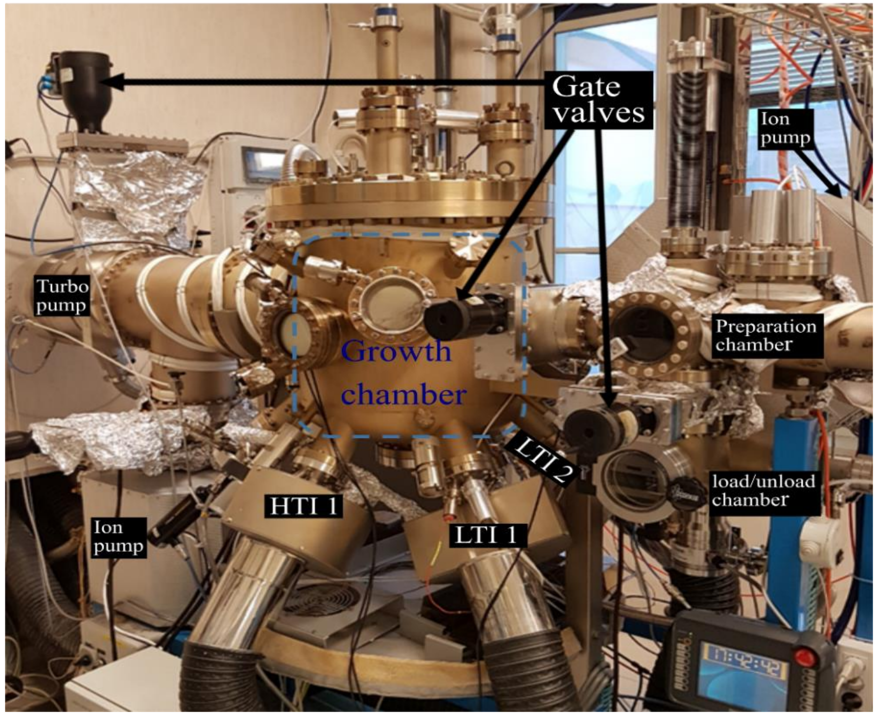
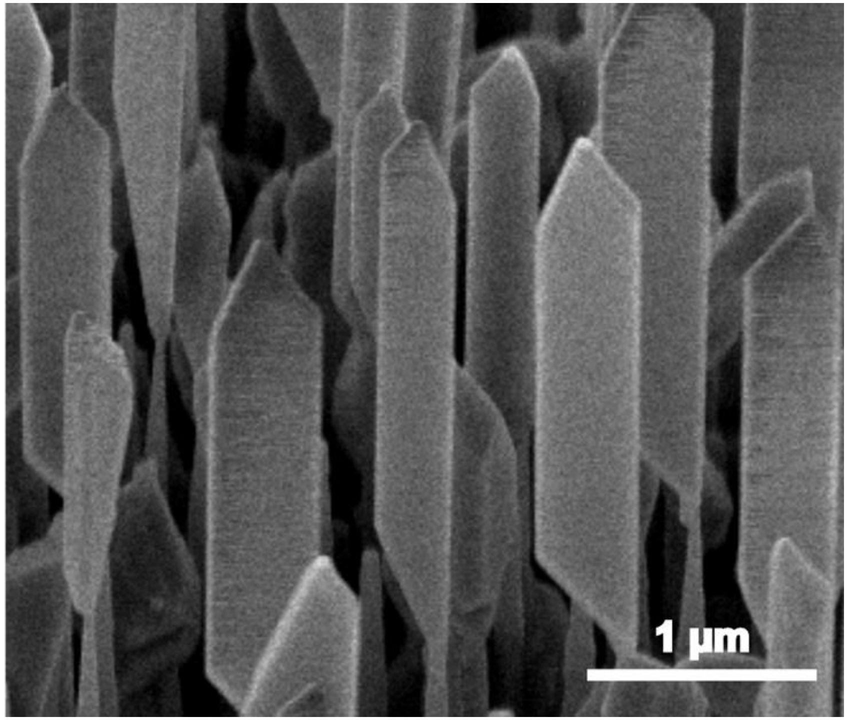


I. Verma et al., ACS Appl. Nano Mater. 2021, 4, 5825-5833

L ≈ 3 μm; W ≈ 500 nm; d ≈ 100 nm



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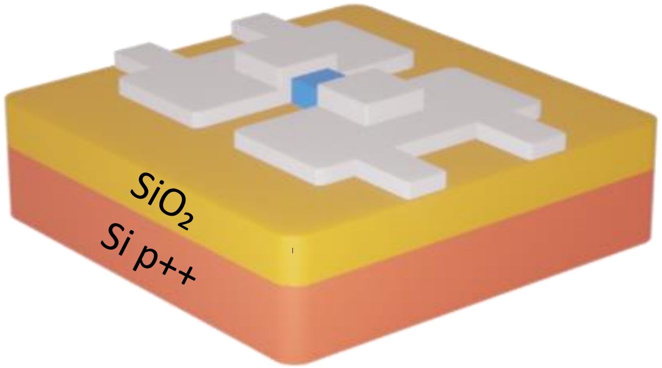
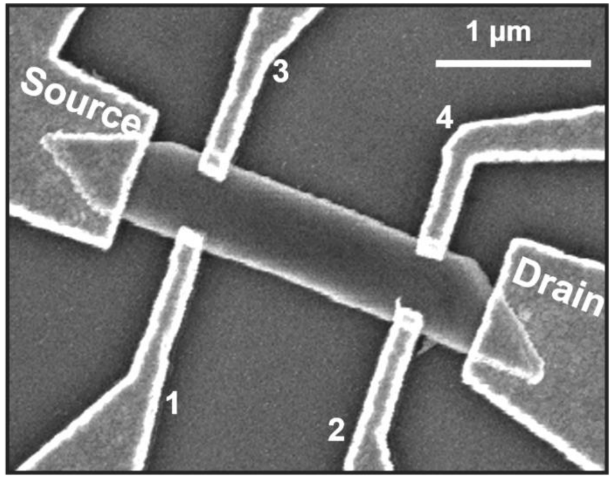
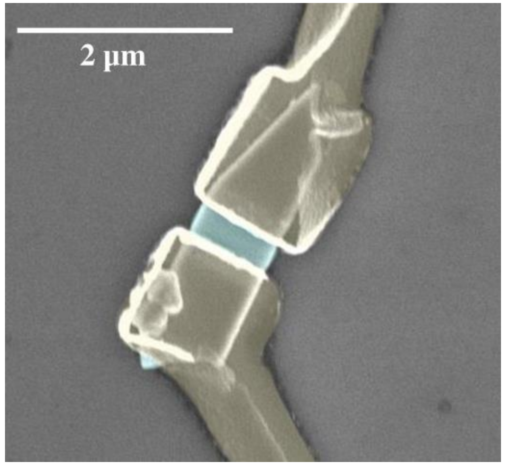
Nanoflag-based device nanofabrication

- Random dry transfer on pre-patterned Si(100) p++ substrate with 280 nm SiO_2 as dielectric
- Selected nanoflags position determined by SEM
- Leads patterning by Electron Beam Litography
- Surface passivation: 1 min in 1:9 $(NH_4)_2S_x$ at 40°C
- Metal deposition by thermal evaporation (Ti/Au) or sputtering (Ti/Nb)







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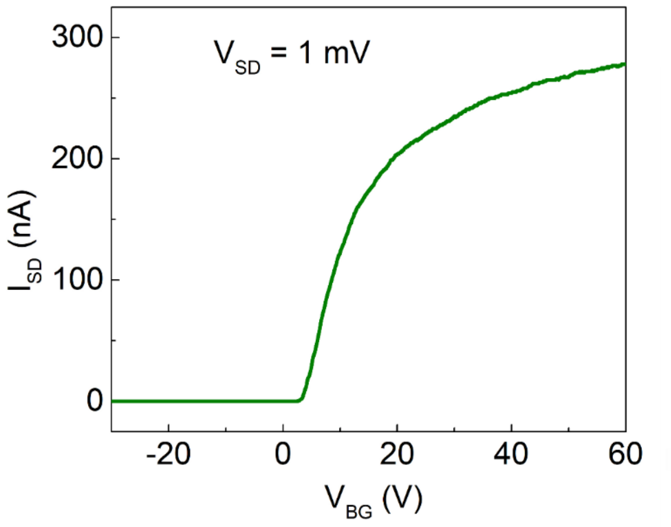
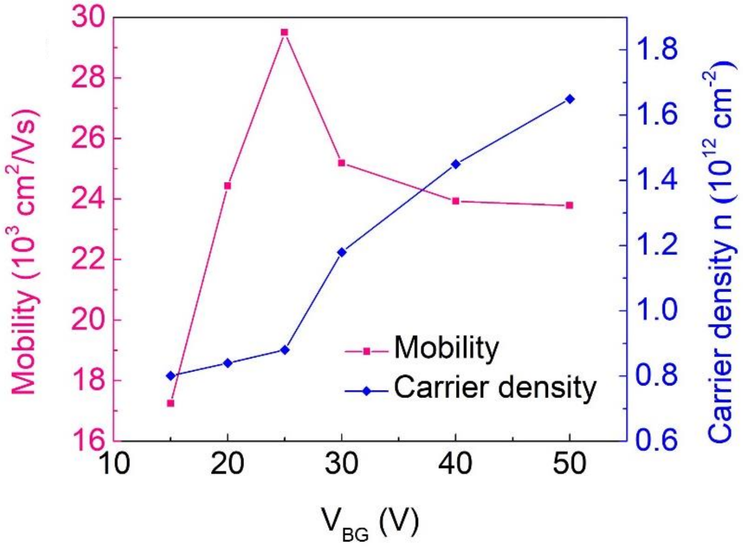
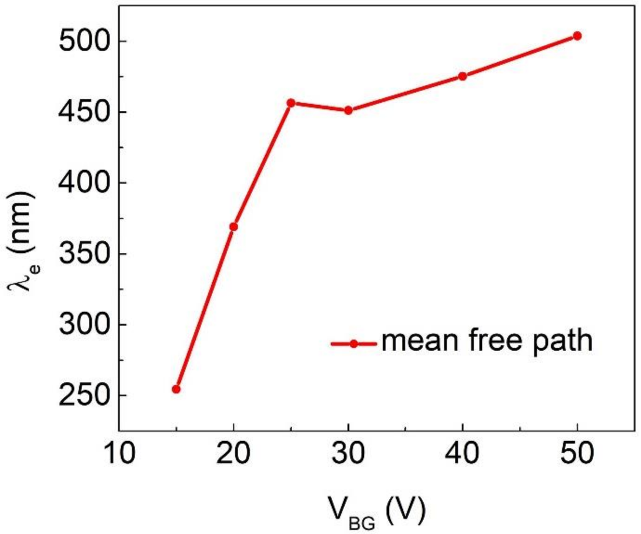
Nanoflag-based device performance

4.2 K measurements

I. Verma et al., ACS Appl. Nano Mater. 2021, 4, 5825-5833







Field-effect :

n-type conduction

$\mu_{FE} = 2.8 \times 10^4$ cm²/Vs

Hall mobility:

$\mu_H = 2.95 \times 10^4$ cm²/Vs

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

Mean free path:

$\lambda \sim 500$ nm

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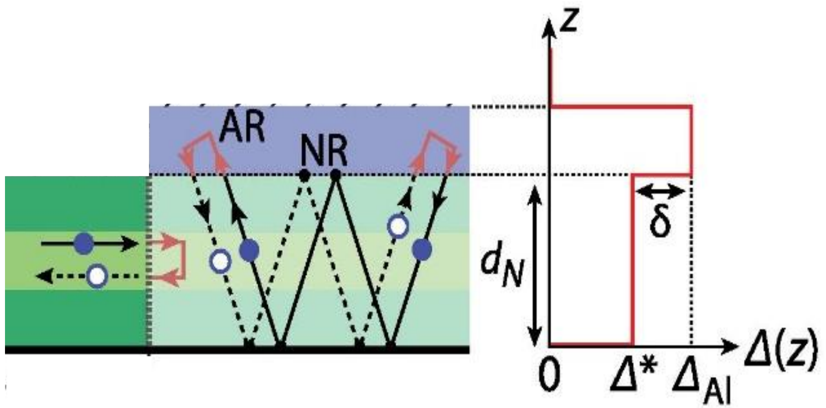
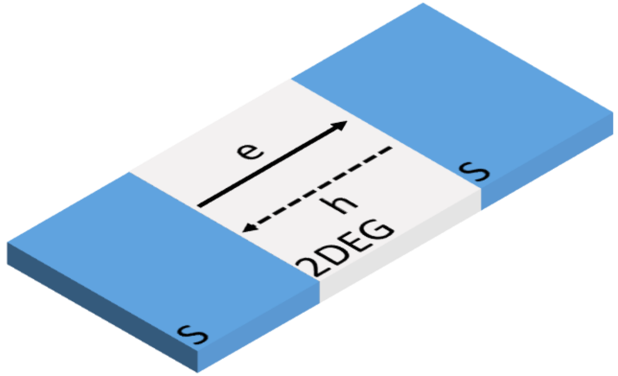
Superconductor-Semiconductor hybrids

- Proximity effect: superconducting pairing in the semiconductor
- Electrostatic control of the charge carrier occupation in the semiconductor region (Field Effect)



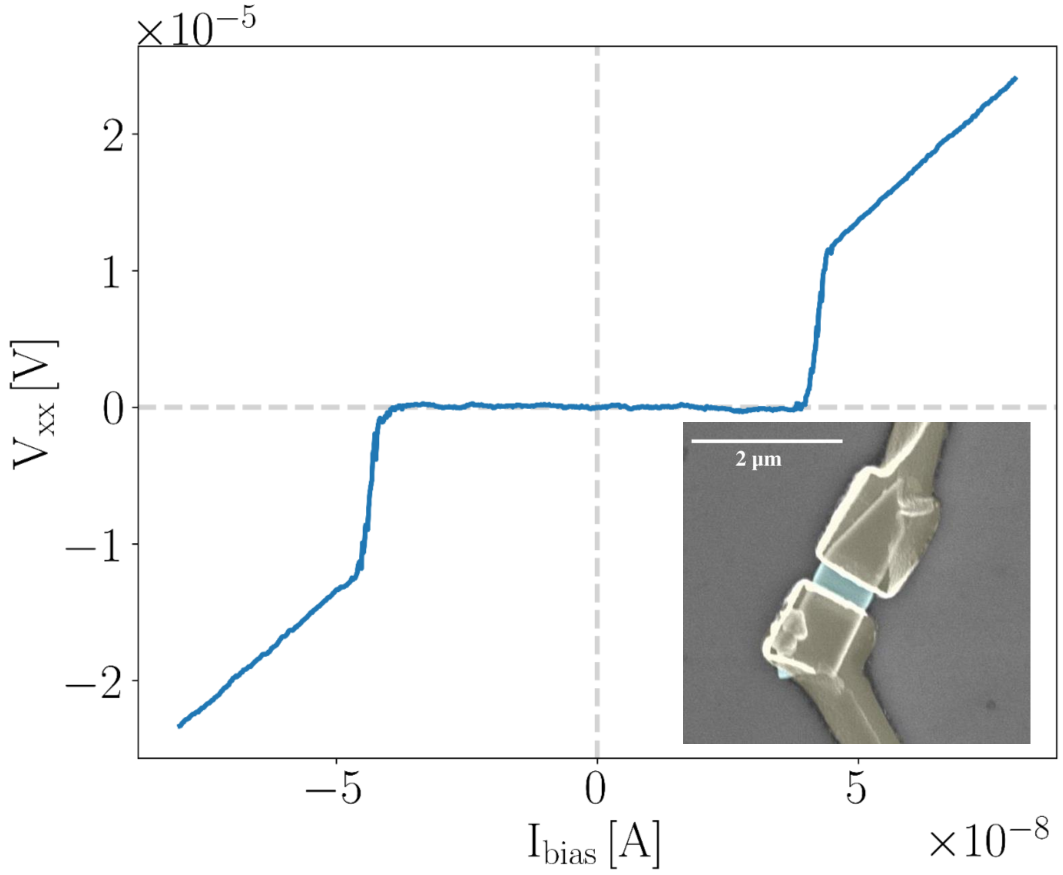
Phys Rev Appl 7, 034029 (2017)

- Electrostatic control of supercurrent flow



InSb nanoflag Josephson Junction

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



Temperature: 300 mK

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

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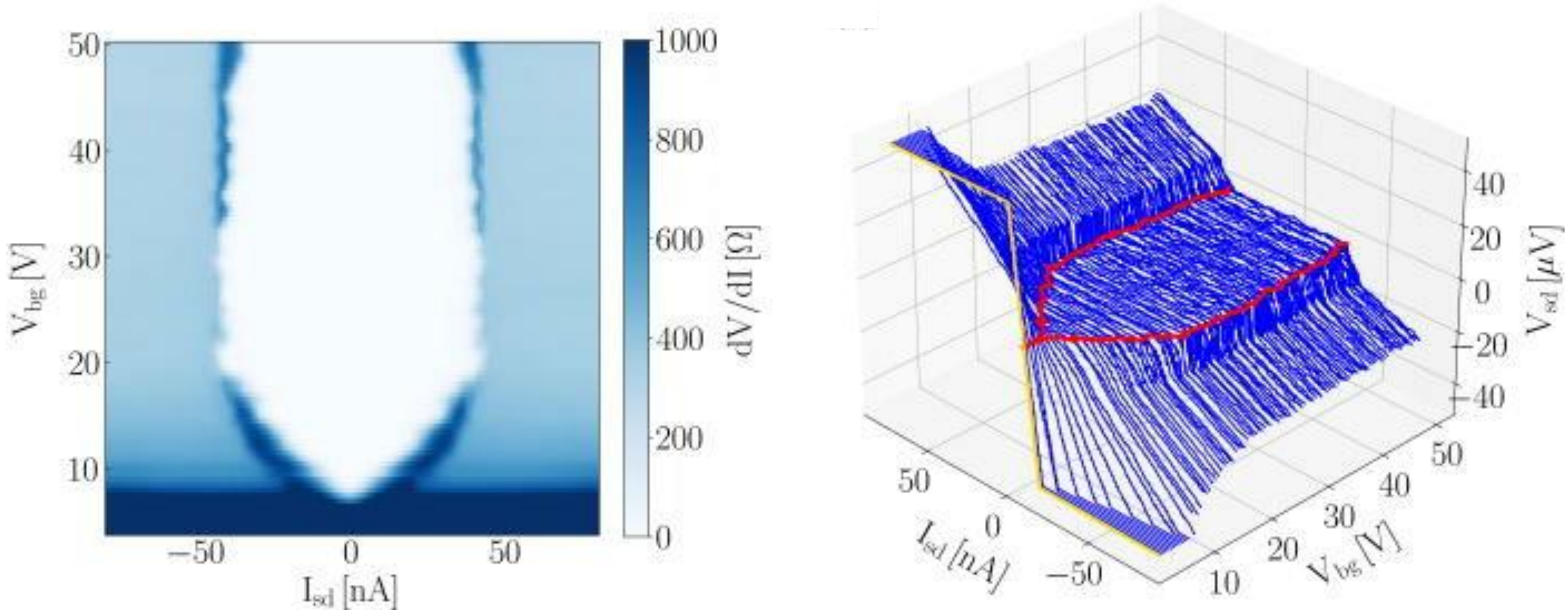
Gate tunable supercurrent: JoFET

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



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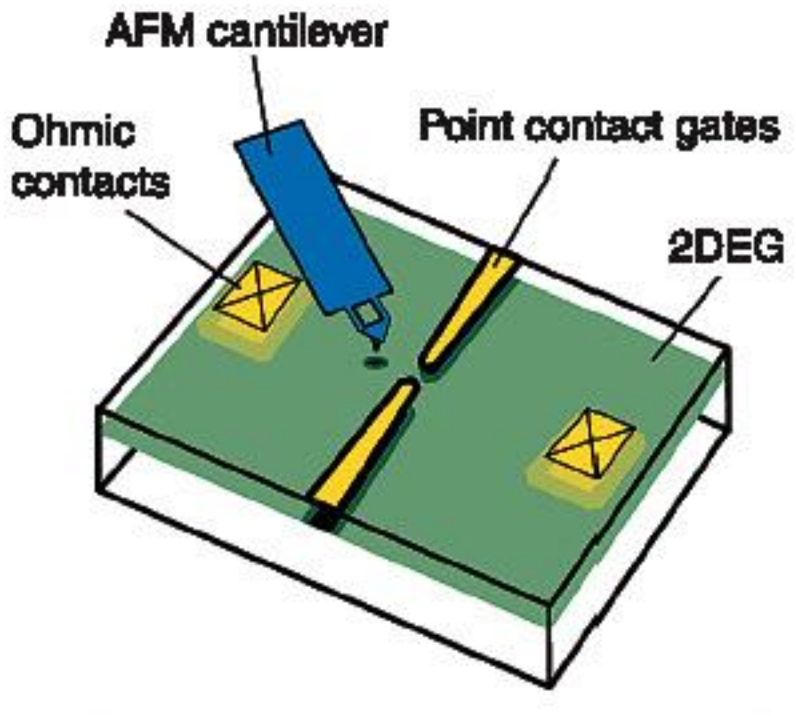
What is SGM?

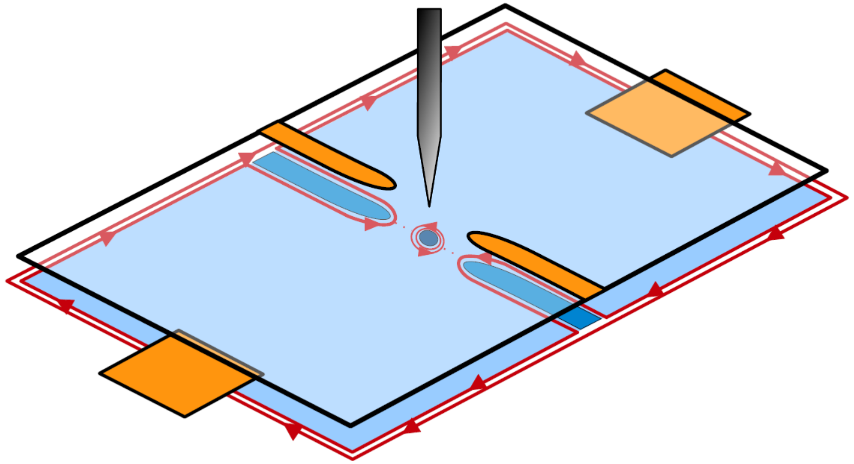
- Scanning Probe Microscopies: STM, AFM,…
- Study of local properties of nanostrucures
- AFM -> Topography
- What about probing electrical properties?
- Let’s polarize an AFM tip!
- Local gating: movable scattering center
- Conductance vs. tip position map

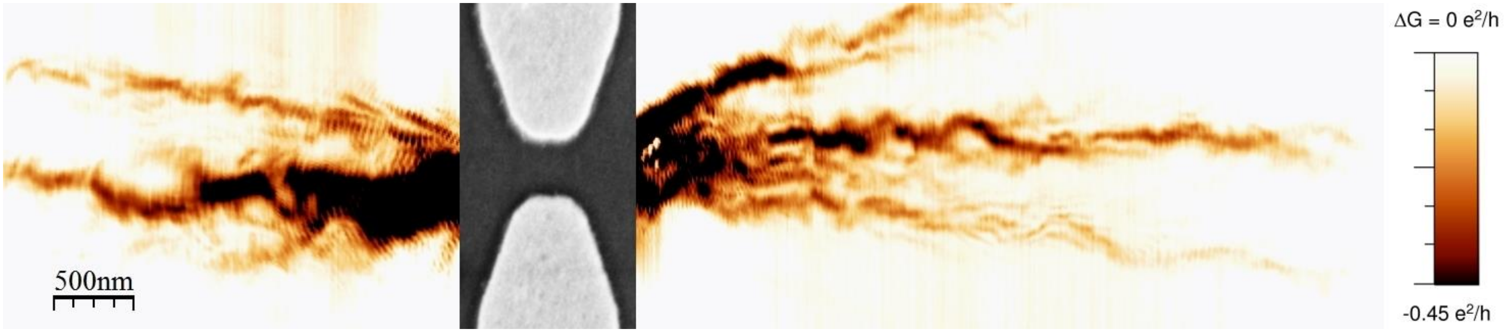


M. A. Topinka et al.: Science **289** (2000) 2323.

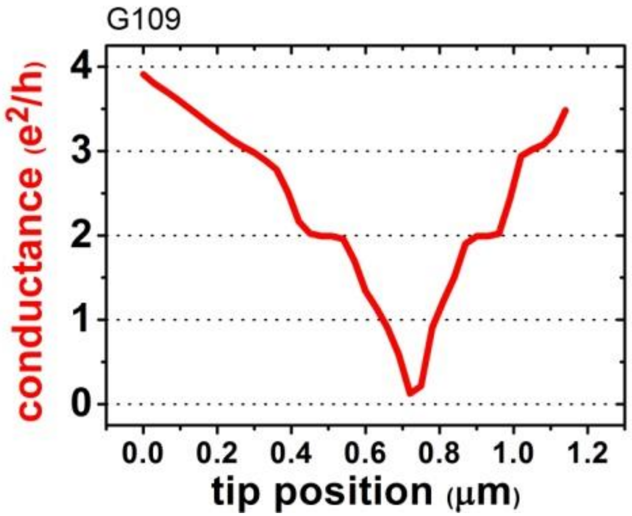
Previously @NEST...

- Mapping of coherent electron flow across a QPC
- Tomography of Integer Quantum Hall edge states





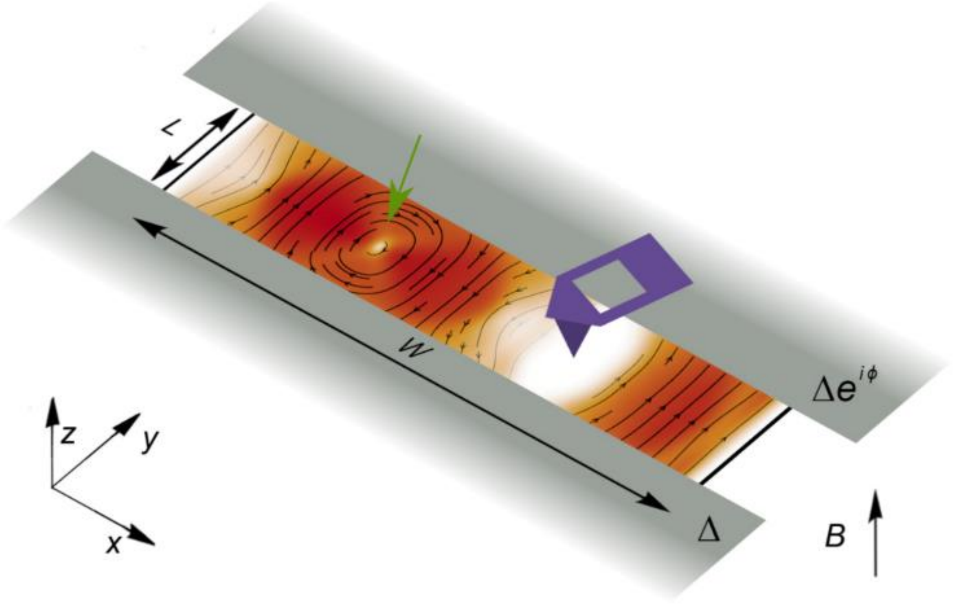
N. Paradiso et al., Physica E **42** (2010) 1038.



Supercurrent flow imaging

K.Kaperek et al., PHYSICAL REVIEW B 106, 035432 (2022)

- The polarized tip locally depletes the junction…
- …effectively blocking possible electron trajectories
- The junction’s critical current depends on the tip position



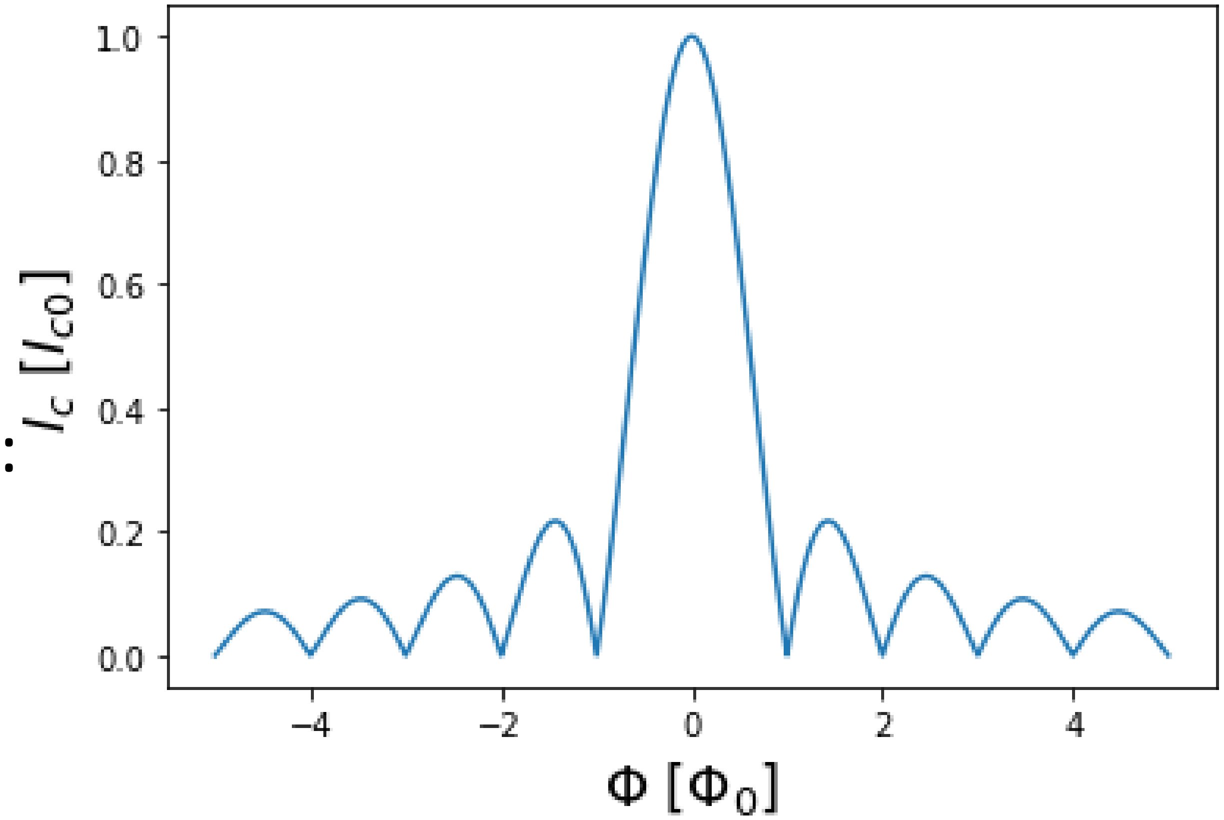
Fraunhofer pattern

Superconducting quantum interference inside of the junction

Critical current depends on the applied magnetic field

For short rectangular tunnel junctions: standard Fraunhofer pattern

$$I_c(\Phi) = I_{c0} \left| \frac{\sin\left(\frac{\pi\Phi}{\Phi_0}\right)}{\frac{\pi\Phi}{\Phi_0}} \right|$$



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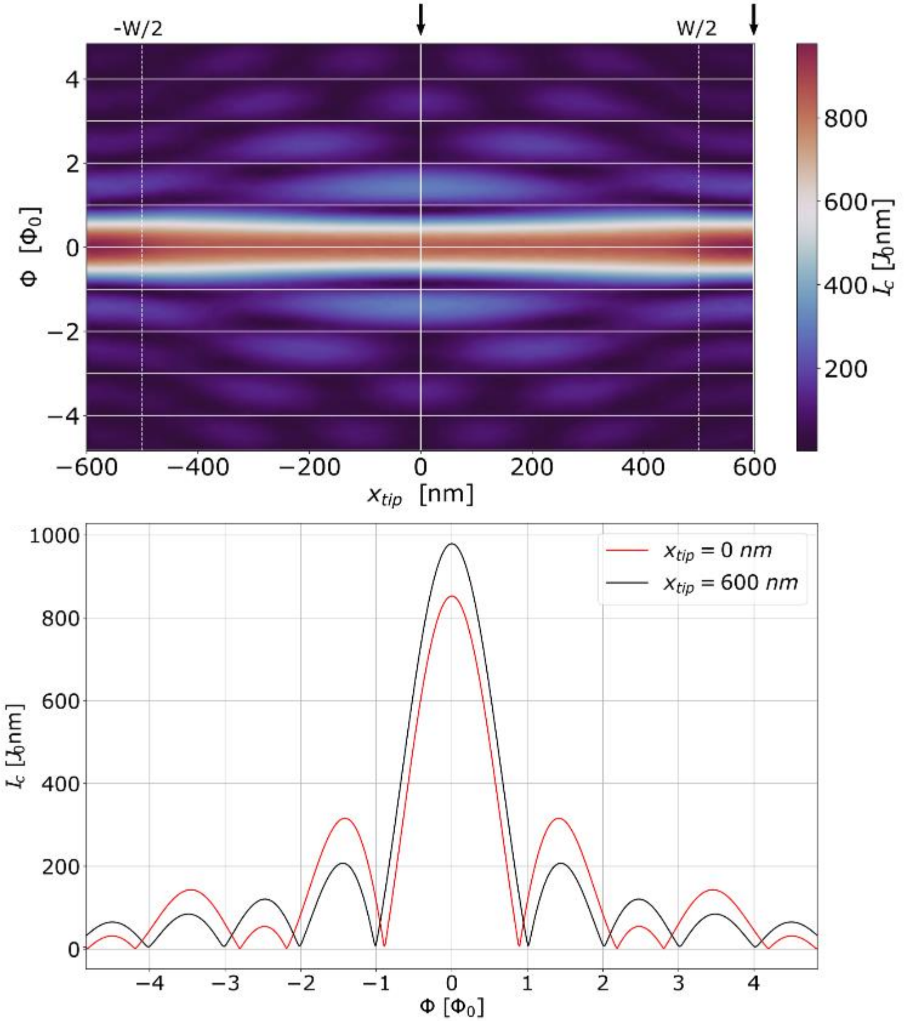
The effect of local gating

Let’s position the SGM tip in the geometrical centre of the juction

Even-odd effect with respect to the unperturbed Fraunhofer pattern

Influence on the positions of Fraunhofer minima

Can we use this to map supercurrent vortexes?

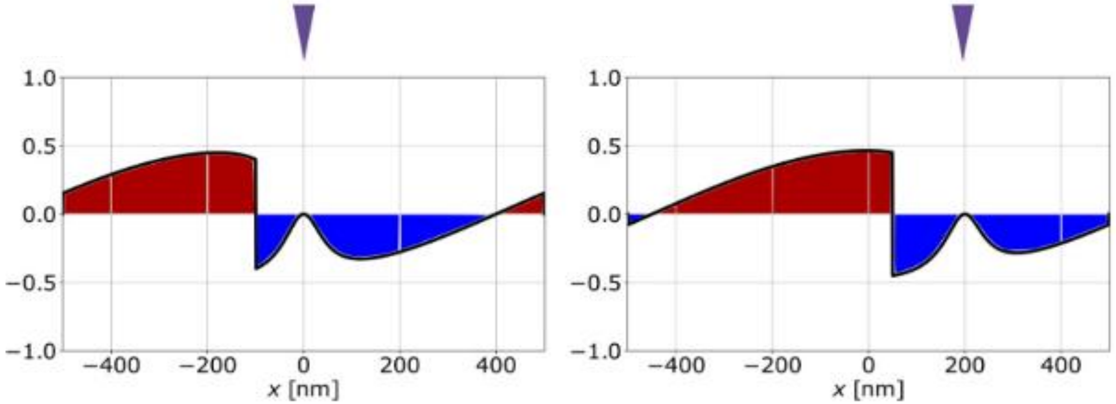


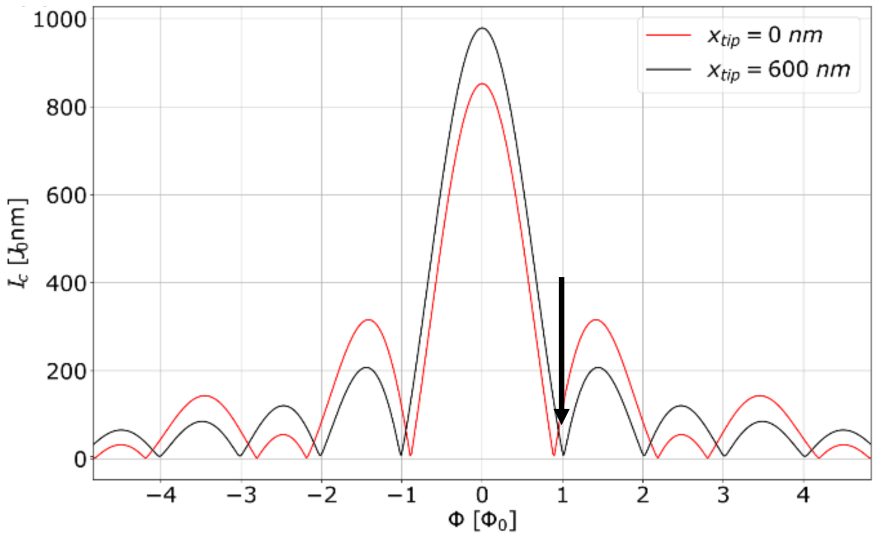
The effect of local gating

Can we use this to map supercurrent vortexes?

Critical condition is reached when the phase difference maximizes the current

It's not guaranteed that the phase difference across the junction is independent from the tip position





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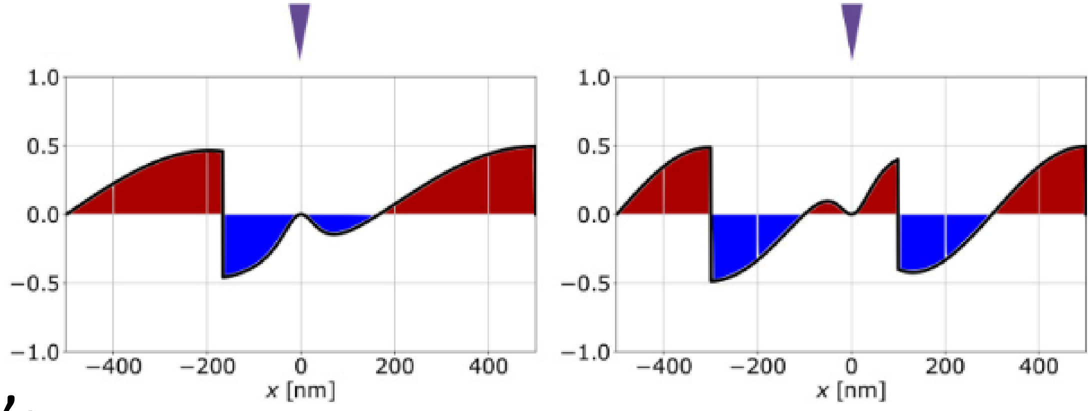
Superconducting phase-locking

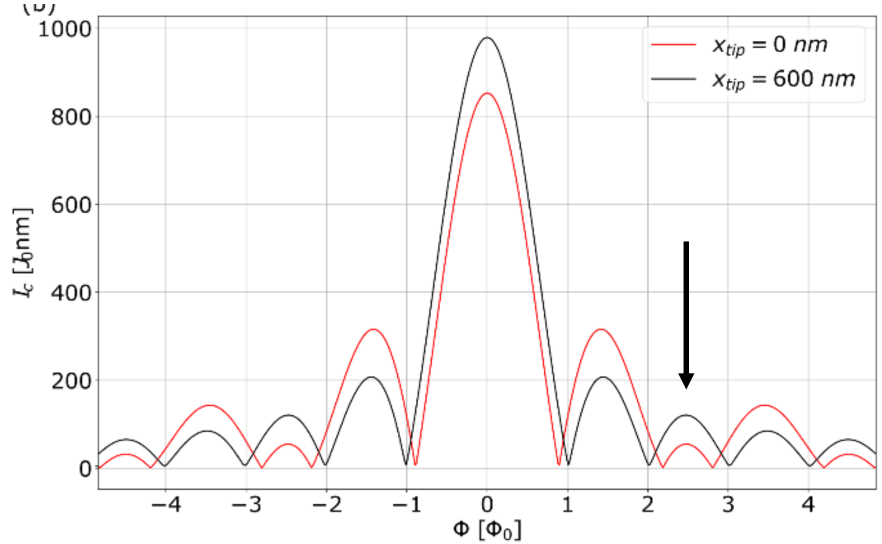
Close to Fraunhofer maxima, the superconducting phase is locked

In fact, any perturbation in the phase difference would decrease the junction's supercurrent…

…regardless of the position of the tip

We can map the supercurrent distribution





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Superconducting phase-locking

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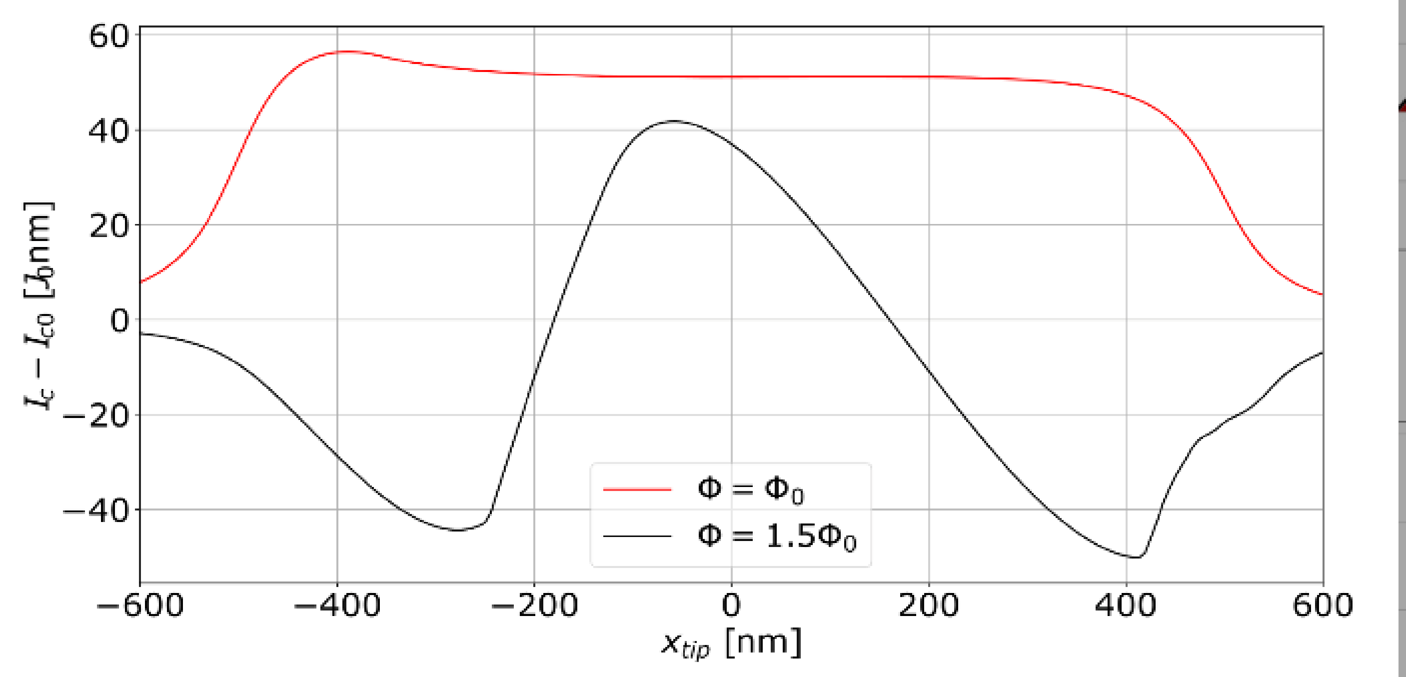

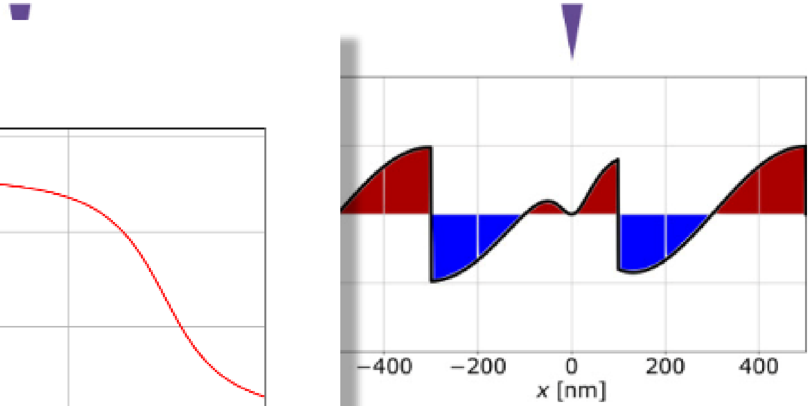

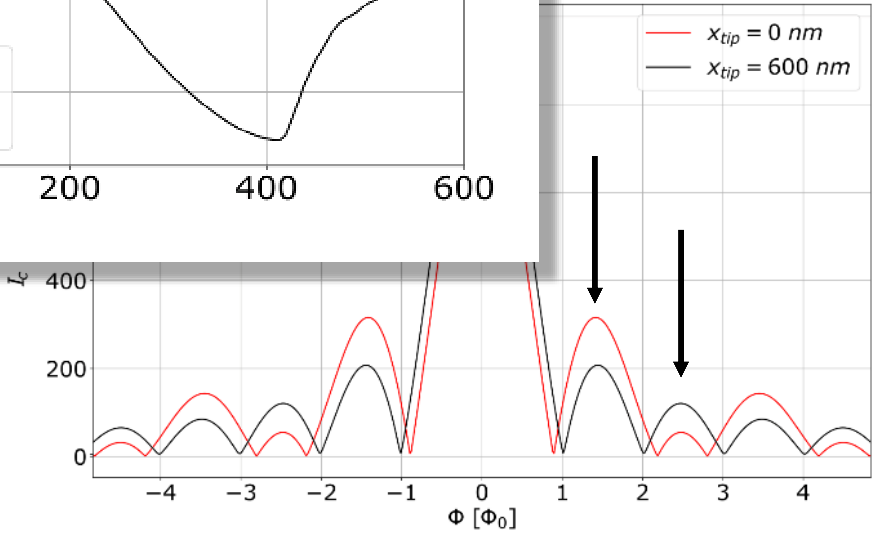

We can map the supercurrent distribution

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Conclusions

- InSb nanoflags are a promising platform for **Josephson devices**
- SGM is predicted to allow us imaging **supercurrent flow** in Josephson junctions

What are we waiting for?

- High quality Nb leads
- New sputtering machine calibration

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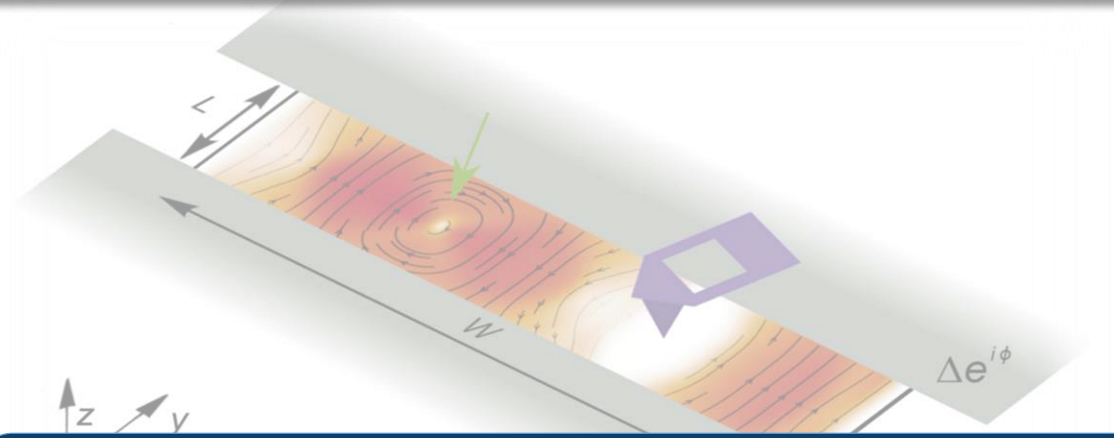
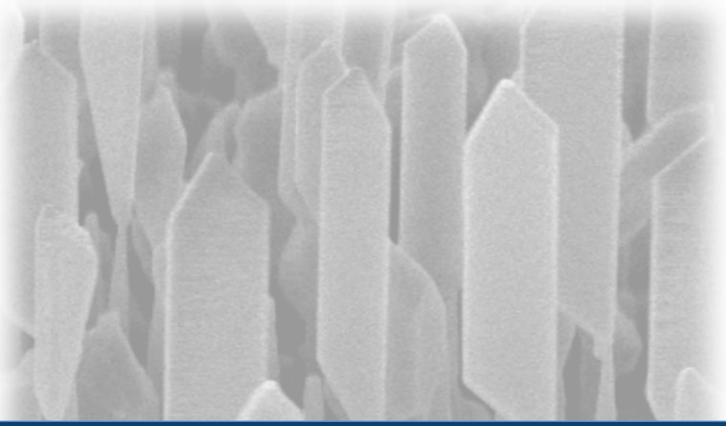
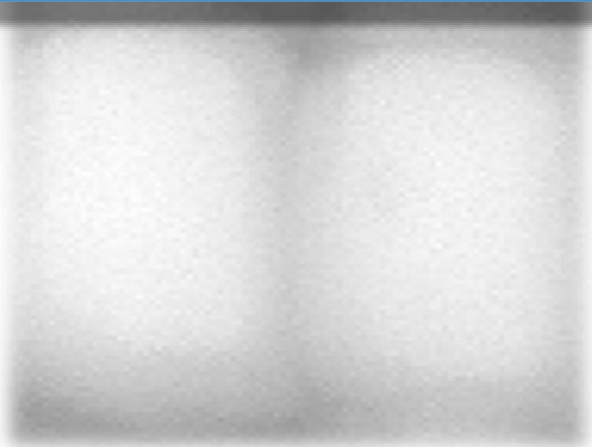




Thank you for your time!



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