CNR-SPIN (Genova, Italy)

HYBRID JOSEPHSON JUNCTIONS BASED ON InSb NANOFLAGS

Dr. Matteo Carrega

Outline

- InSb nanoflags for advanced devices
- InSb nanoflag Josephson junctions
- Superconducting diode in a single Josephson junction
- SQUID based on InSb nanoflags

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Università di Genova

Quantum Technologies

New J. Phys. 20 (2018) 080201 https://doi.org/10.1088/1367-2630/aad1ea

New Journal of Physics
The open access journal at the forefront of physics

Deutsche Physikalische Gesellschaft DPG
IOP Institute of Physics
Published in partnership with: Deutsche Physikalische Gesellschaft and the Institute of Physics

ROADMAP

The quantum technologies roadmap: a European community view

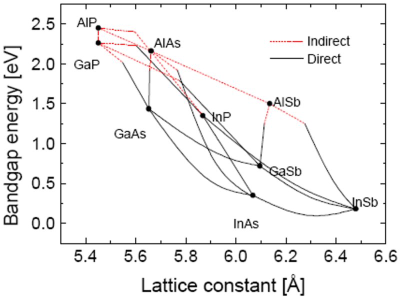
Antonio Acín[1,2], Immanuel Bloch[3,4], Harry Buhrman[5], Tommaso Calarco[6], Christopher Eichler[7], Jens Eisert[8], Daniel Esteve[9], Nicolas Gisin[10], Steffen J Glaser[11], Fedor Jelezko[6], Stefan Kuhr[12], Maciej Lewenstein[1,2], Max F Riedel[6], Piet O Schmidt[13,14], Rob Thew[10], Andreas Wallraff[7], Ian Walmsley[15] and Frank K Wilhelm[16]

Low temperature superconducting electronics

InSb semiconductor

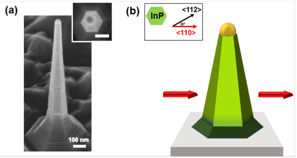
Why InSb?

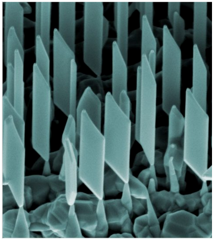
- narrow bandgap 0.23eV $\rightarrow$ mid-IR optoelectronics
- high bulk mobility $7.7 \cdot 10^4 \text{cm}^2/(\text{Vs})$ $\rightarrow$ high-speed electronic devices
- small effective mass $m = 0.018 m_e$ $\rightarrow$ low power electronic devices
- strong spin orbit interactions $E_{SOI} \sim 200\mu\text{eV}$ $g \sim 50$ $\rightarrow$ spintronics and topological devices



InSb nanoflags

InSb: challenging to grow 2D quantum wells
$\rightarrow$ novel approach: 2D nanoflags





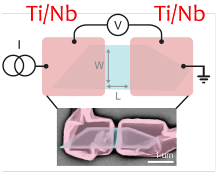
Tapered nanowires are used as stems

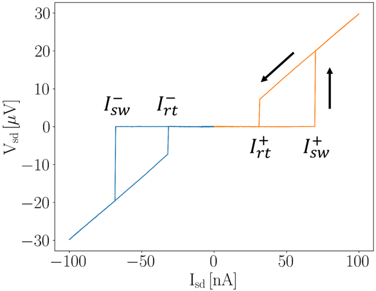
- length $\sim 2\mu$m
- width $\sim$ 700nm
- tickness $\sim$ 100nm
- defect-free structure
- mobility $\sim 29500\text{cm}^2/(\text{Vs})$
- mean free path $l_e \sim$ 500nm

Verma et al. ACS Appl. Nano Mater. 2021

InSb Josephson junctions

InSb nanoflag SNS devices



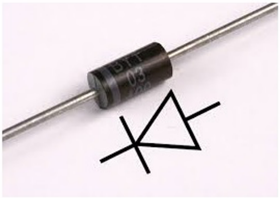


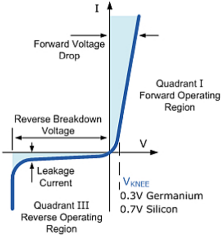
- Nb superconducting contacts $\Delta \sim 1.3$meV $\rightarrow \Delta^* \sim 250\mu$eV
- length $\sim$ 200nm and width $\sim$ 700nm
- ballistic regime $l \ll l_e$
- high transparency $\tau \sim 0.9$

Salimian APL 2021, Turini NanoLetters 2022

Diodes

The *pn* junction is at the basis of conventional electronics





Is it possible to obtain an analog for superconducting circuits?

Breaking of both time-reversal and inversion symmetry!

SDE experiments

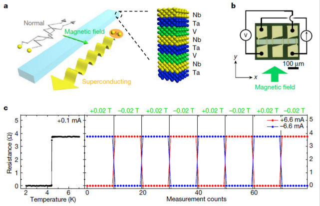
Article

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

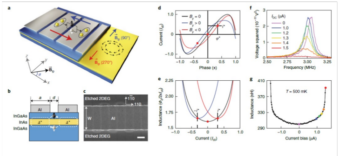


F. Ando et al., Nature 584 (2020) 373.

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

Supercurrent rectification and magnetochiral effects in symmetric Josephson junctions

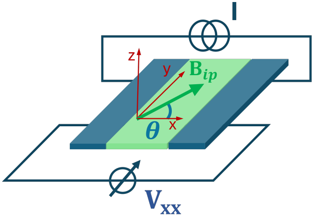
Christian Baumgartner[1,8], Lorenz Fuchs[1,8], Andreas Costa[2], Simon Reinhardt[1], Sergei Gronin[3,4], Geoffrey C. Gardner[3,4], Tyler Lindemann[4,5], Michael J. Manfra[3,4,5,6,7], Paulo E. Faria Junior[2], Denis Kochan[2], Jaroslav Fabian[2], Nicola Paradiso[1]✉ and Christoph Strunk[1]

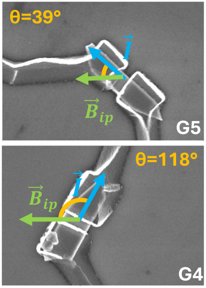


C. Baumgartner et al., Nat. Nano 17 (2022) 39.

SDE in a single Josephson junction

InSb nanoflag planar Josephson junction





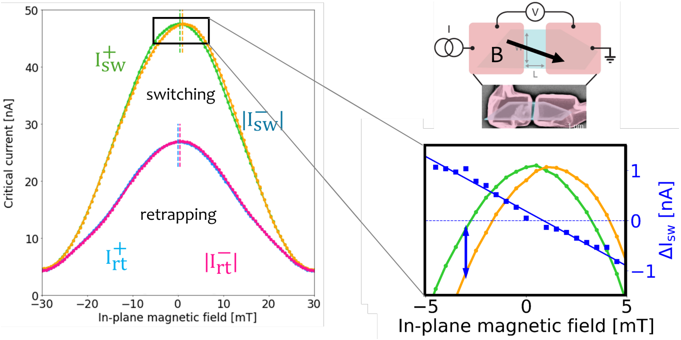
need for a planar B field

Turini et al NanoLetters 2022

Josephson diode effect

Supercurrent at 30mK

$I_{SW}^{\pm}$ switching current in opposite bias directions



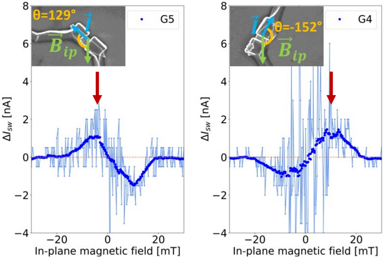
JDE is driven by magnetic field!

Turini et al, Nanoletters 2022

Supercurrent asymmetry

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

in-plane B_{ip} field dependence

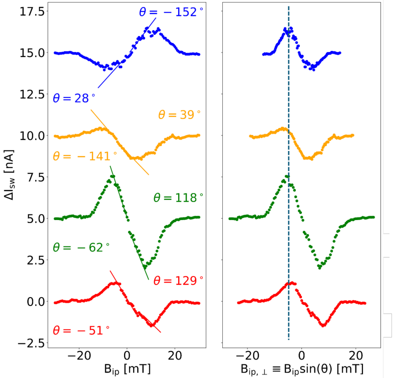


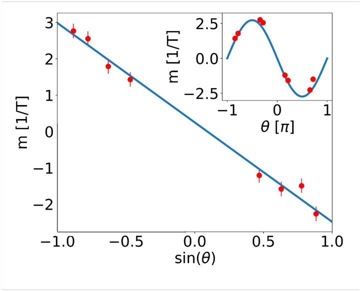
- anti-symmetric in B
- linear behaviour around $B = 0$
- rounded maxima
- suppression above $\sim$ 20mT

Turini et al, NanoLetters 2022

Angle dependence

JDE depends on the planar angle $\theta \rightarrow$ Rashba SOI





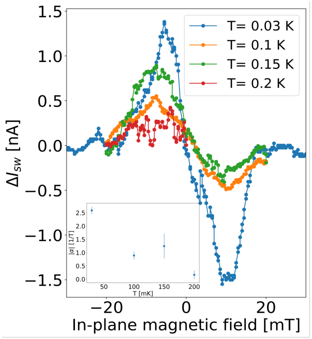
$$\eta = \frac{\Delta I_{SW}}{I_{SW}^{+} + |I_{SW}^{-}|} = mB_{ip}$$

linear coefficient $m \propto \sin(\theta)$

Turini et al, NanoLetters 2022

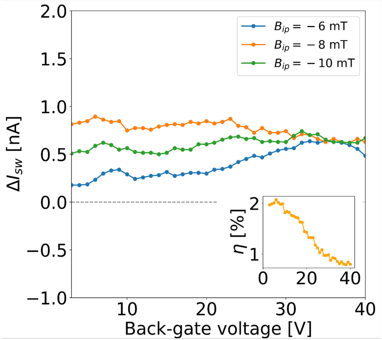
Extrinsic parameters

JDE temperature dependence



JDE gate-voltage dependence

$\eta = \Delta I_{SW}/(I_C^+ + I_C^-)$

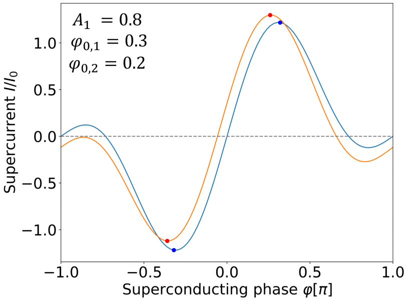


Turini et al, NanoLetters 2022

JDE interpretation

- ballistic and short junction regime
- dominant Rashba SOI
- finite momentum pairing $q = g\mu_B B/v_F$
- high transparency $\tau \rightarrow$ skewed CPR

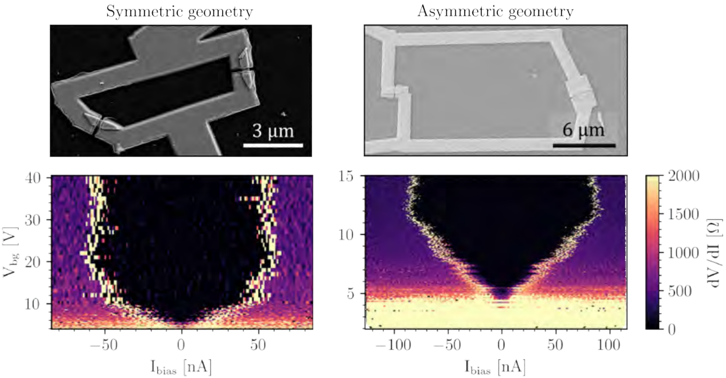
$$I = I_0 \sum_n c_n \sin(n\phi)$$



SQUID based on InSb nanoflags

How to inspect the CPR content?

SQUID with different geometries



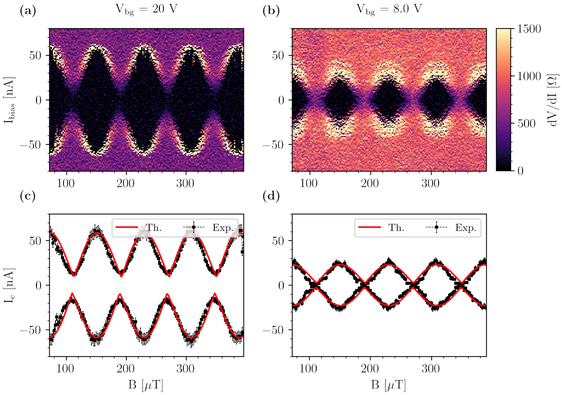
$A_{geo}^{sym} = 13.6\mu m^2$ $\quad$ $A_{geo}^{asym} = 118\mu m^2$

Chieppa et al, ArXiv 2025

SQUID response

$$I_{C,\,\mathrm{SQUID}} = \mathrm{Max}_{\varphi}\left[I_1(\varphi) + I_2\left(\varphi - 2\pi\frac{\Phi}{\Phi_0}\right)\right]$$

Interference patterns in the symmetric geometry



High transparency τ at high V_{bg}

Chieppa et al, ArXiv (2025)

Numerical simulations

Effective two band model for InSb

$$\mathcal{H}(\vec{k}) = \left(\frac{\hbar^2 \vec{k}^2}{2m^*} - \mu \right) \sigma_0 - \alpha_R k_y \sigma_x + \alpha_R k_x \sigma_y + \frac{g \mu_B}{2} B \sigma_z$$

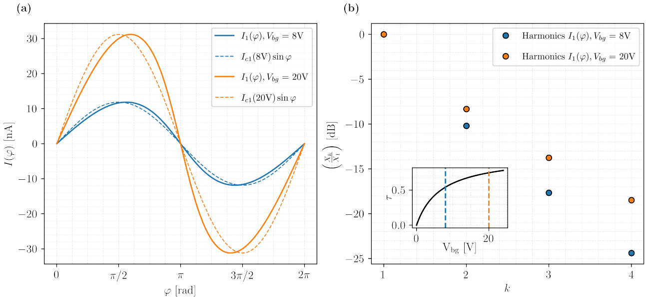
- Bogoliubov-de Gennes formalism with Δ induced SC gap

- Tight-binding simulation
- SQUID geometry with two parallel Josephson junctions
- Recursive Green function method

Chieppa et al, ArXiv (2025)

Skewed CPR

CPR of a single junction with different V_{bg}
Major skewness at high back-gate



JJ transparency modulated with V_{bg}

$$\tau = \frac{1}{1 + z^2(V_{bg})}$$

Chieppa et al, ArXiv (2025)

Conclusions

- InSb nanoflag based Josephson junction
- Josephson diode effect
- SQUID based on InSb nanoflags
- High harmonic contents and skewed CPRs

B. Turini et al, NanoLetters **22**, 8502 (2022)

A. Chieppa et al., ArXiv:2504.**** (2025)

Collaborations and projects

- **CNR-NANO**: S. Heun, L. Sorba, F. Giazotto, E. Strambini, V. Zannier, I. Verma, A. Crippa, S. Salimian, A. Iorio, B. Turini, A. Chieppa
- **Univ. Genova**: M. Sassetti, N. Traverso Ziani, S. Traverso, S. Fracassi

Project PRIN 2022 (MUR, Italy): "Topoflags"