CNR-SPIN (Genova, Italy)

SUPERCONDUCTING DIODE EFFECT IN HYBRID JOSEPHSON JUNCTIONS

Dr. Matteo Carrega

Outline

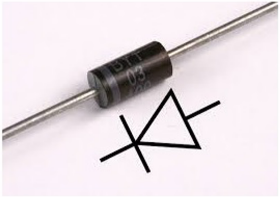
- Introduction to superconducting diode effect (SDE)
- InSb nanoflag Josephson junctions
- SDE in a single Josephson junction
- Tunable SDE in a topological Josephson junction

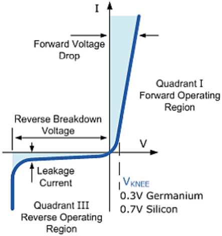
Quantum Technologies

Low temperature superconducting electronics

Diodes

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





Is it possible to obtain an analog for superconducting circuits?

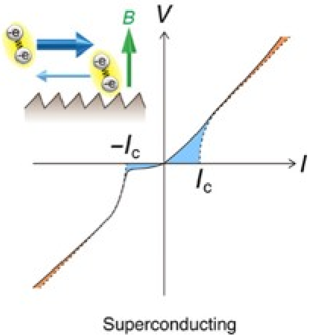
Breaking of both time-reversal and inversion symmetry!

Non reciprocal transport

Magneto-chiral anisotropy (MCA)

$$R(I) = R_0\left(1 + \gamma \hat{e}_z \mathbf{B} \cdot \mathbf{I}\right)$$

elusive mechanism in bulk semiconductor $\gamma \sim \frac{E_{SOI}}{E_F} \sim 10^{-3}$
MCA is strongly enhanced in superconductors



New energy scale $\Delta \ll E_F \rightarrow \gamma \sim 10^5$ (resistive state)

SDE experiments

Article

Observation of superconducting diode effect

https://doi.org/10.1038/s41586-020-2590-4
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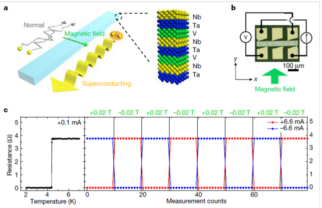
Check for updates

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

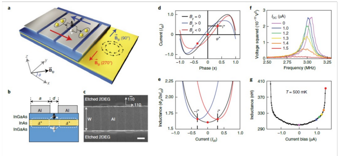


F. Ando et al., Nature 584 (2020) 373.

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.

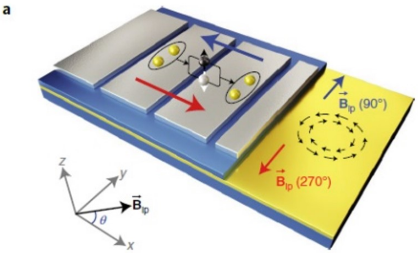
SDE in Josephson junctions

The Josephson Diode Effect

- breaking time-reversal symmetry
- breaking inversion symmetry

Hybrid semiconductor/superconductor devices

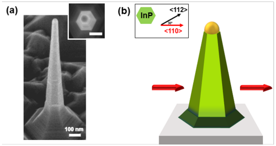
- strong spin-orbit interactions: InAs or InSb
- superconducting leads: Al or Nb

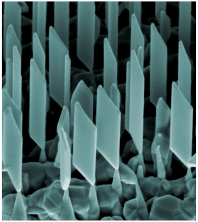


Why InSb nanoflags?

- narrow bandgap 0.23eV
- small effective mass $m = 0.018 m_e$
- strong spin orbit interactions $E_{SOI} \sim 200\mu$eV $g \sim 50$

InSb challenging to growth 2D quantum wells
novel approach: 2D nanoflags



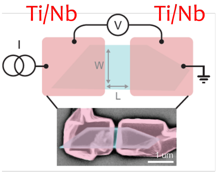


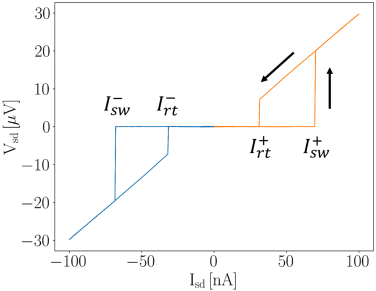
- defect-free structure
- mobility $\sim 29500 \text{cm}^2/(\text{Vs})$
- mean free path $l_e \sim 500$nm

Verma et al. ACS APPl. Nano Mater. 2021

InSb Josephson junctions

InSb nanoflag SNS devices



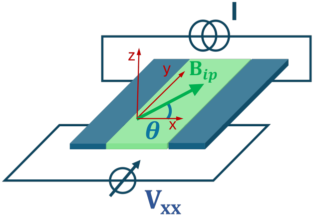


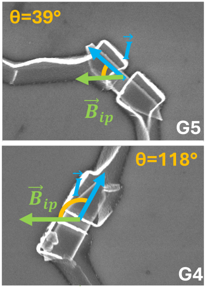
- Nb-Ti superconducting contacts $\Delta \sim 1.3$meV $\rightarrow$ $\Delta^* \sim 200\mu$eV
- length $\sim$ 200nm and width $\sim$ 700nm
- ballistic regime $l \ll l_e$
- high transparency $\tau \sim 0.9$

Salimian et al APL 2021, Turini NanoLetters 2022

Experiment design

InSb nanoflag planar Josephson junction





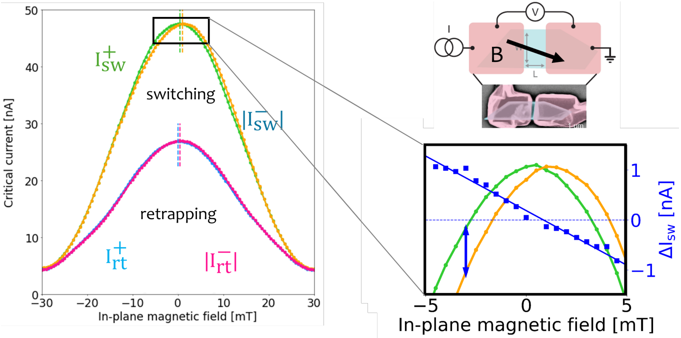
need for a planar B field

Turini et al NanoLetters 2022

Josephson diode effect

Supercurrent at 30mK

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



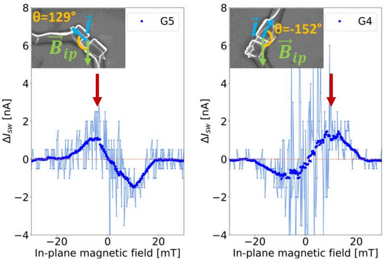
JDE is driven by magnetic field!

Turini et al, Nanoletters 2022

Supercurrent asymmetry

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

in-plane B_{ip} field dependence

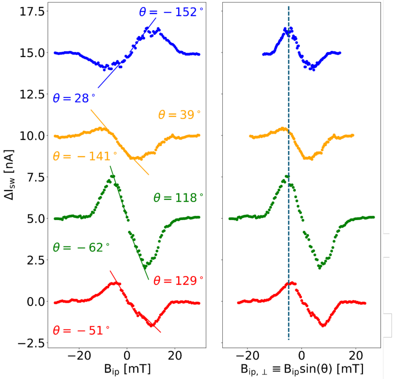


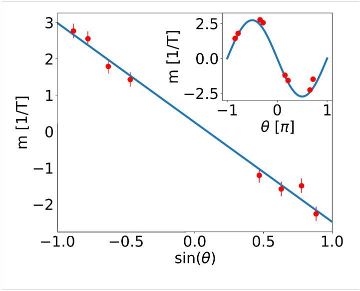
- anti-symmetric in B
- linear behaviour around $B = 0$
- rounded maxima
- suppression above $\sim$ 20mT

Turini et al, NanoLetters 2022

Angle dependence

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





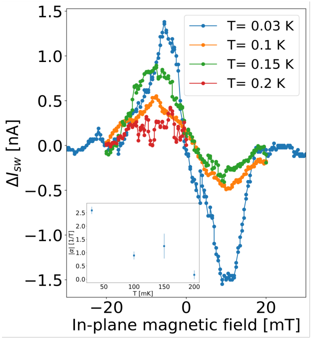
$$\eta = \frac{\Delta I_{SW}}{I_{SW}^{+} + |I_{SW}^{-}|} = mB_{ip}$$

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

Turini et al, NanoLetters 2022

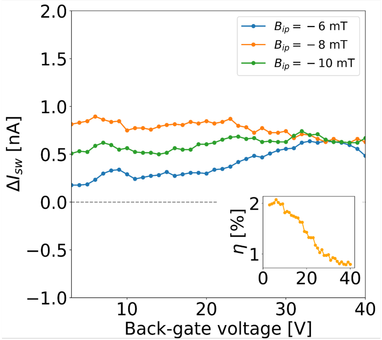
Extrinsic parameters

JDE temperature dependence



JDE gate-voltage dependence

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

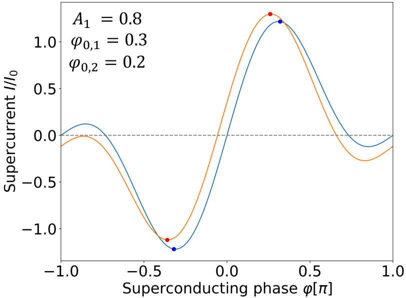


Turini et al, NanoLetters 2022

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

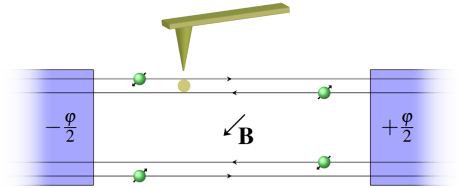
$$I = I_0 \sum_n c_n \sin(n\phi)$$



Turini et al, NanoLetters 2022

Other SNS systems

Superconducting diode effect
in a topological Josephson junction?



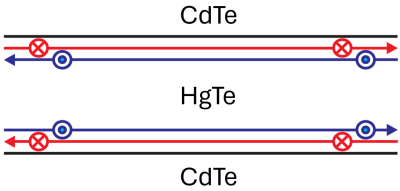
topological insulator in the normal region

Fracassi et al, APL 2024

Topological insulators

2D topological insulators: quantum spin-Hall effect

- insulating bulk
- counterpropagating metallic edge states
- spin-momentum locking
- topological protection



example: HgTe/CdTe heterostructures

Topological JJ

Topological Josephson junction in presence of B_z field

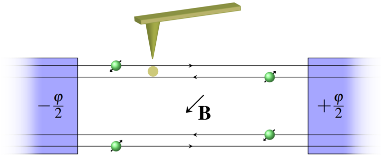
$$I_+(\phi) = I_-(-\phi)$$

On a single helical edge:

- Anomalous Josephson effect $I_\pm(\phi = 0) \neq 0$
- Supercurrent rectification $\mathrm{Max}_\phi[I_\pm] \neq |\mathrm{Min}_\phi[I_\pm]|$

NO SDE for the whole system $I(\phi = I_+(\phi) + I_-(\phi)$

Locally perturbed topological JJ



Dolcini et al, PRB 2015, Fracassi et al APL 2024

Model

SNS topological junction with a tip
Non-homogeneous system → Bogoliubov De Gennes

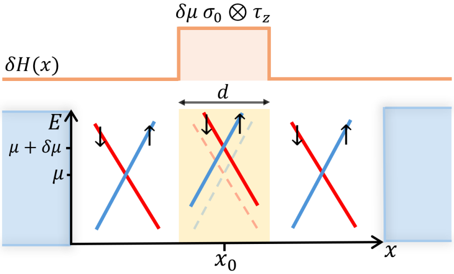
$$H = H_{edge} + H_{sc} + H_{tip}$$

- Scattering matrix formalism
- calculation of free energy
- observable: equilibrium supercurrent

$$I = -\frac{2e}{\beta}\frac{\partial}{\partial\varphi}\Re\sum_{m\geq 0}\log\det[\mathbf{1} - \mathcal{S}_A\,\mathcal{P}_{\delta H\to\Sigma}\,\mathcal{S}_{\delta H}\,\mathcal{P}_{\Sigma\to\delta H}]\big|_{E=i\omega_m}$$

Results I

Electrostatic tip $\rightarrow \Delta\mu$ variation

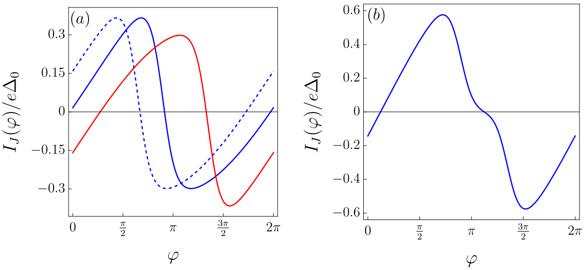


- supercurrent insensitive to chemical potential variation
- robustness to electrostatic disorder
- NO supercurrent rectification $\rightarrow$ NO SDE

Fracassi et al, APL 2024

Results II

Magnetic tip along B_z axis

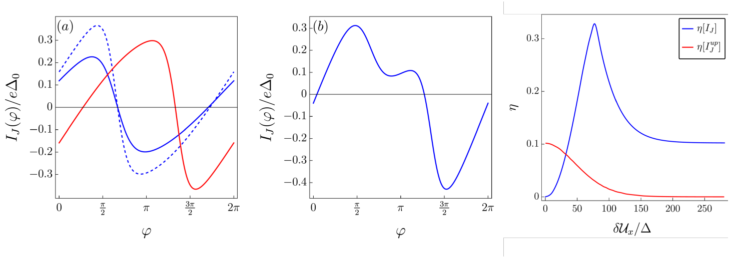


- Anomalous Josephson effect
- Tunable phase shift in the CPR
- still NO superconducting diode effect

Fracassi et al, APL 2024

Results III

Magnetic tip along B_x axis



- anomalous Josephson effect
- tunable SDE!
- sizeable rectification coefficient η

Conclusions

- Superconducting diode effect
- InSb nanoflag based Josephson junction
- Topological Josephson junction with local perturbations

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

S. Fracassi et al, Appl. Phys. Lett. **124**, 242601 (2024)

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, L. Chirolli
- **Univ. Genova**: M. Sassetti, N. Traverso Ziani, S. Traverso, S. Fracassi

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