Half-integer Shapiro steps in InSb/Nb Josephson junctions

A. Iorio[1], B. Turini[1], S. Salimian[1], M. Carrega[2], L. Chirolli[1], A. Crippa[1], E. Strambini[1], V. Zannier[1], L. Sorba[1], F. Giazotto[1], and S. Heun[1]

[1] *NEST, Istituto Nanoscienze-CNR and Scuola Normale Superiore, Pisa, Italy*
[2] *CNR-SPIN, Genova, Italy*

AndQC

National Enterprise for nanoScience and nanoTechnology

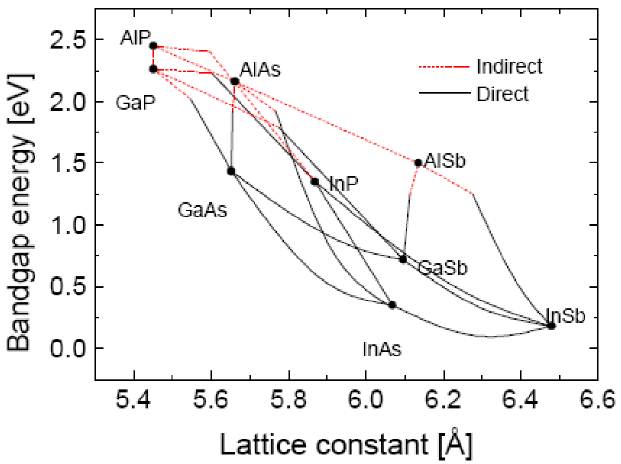
NEST

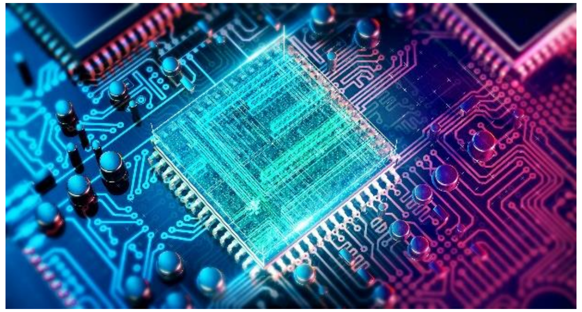
Why InSb?

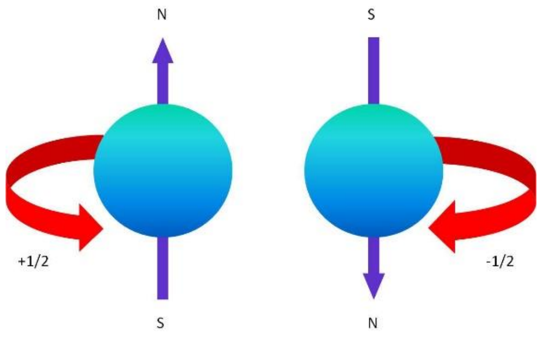
- Narrow bandgap (0.23 eV) ⟶ mid-infrared optoelectronic devices.

- High bulk electron mobility (7.7 x 10^4 $cm^2/(Vs)$), small effective mass (0.018 m_e) ⟶ high-speed and low-power electronic devices.

- Strong spin-orbit interaction ($E_{SOI} \sim 200\ \mu eV$), large Landé g-factor ($g^* \sim 50$) ⟶ spintronics and topological quantum computing.

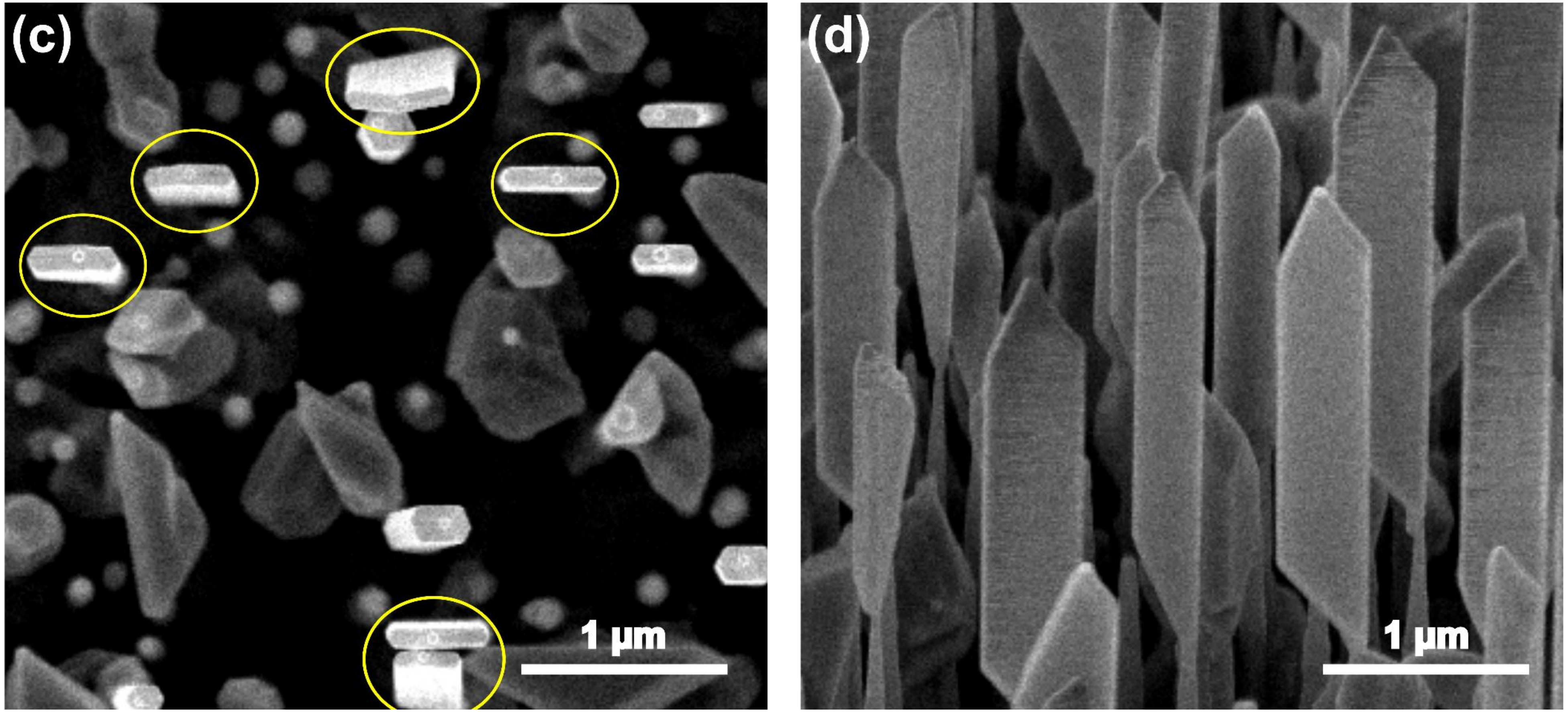






National Enterprise for nanoScience and nanoTechnology

InSb Nanoflags



Defect-free InSb zinc blende lattice

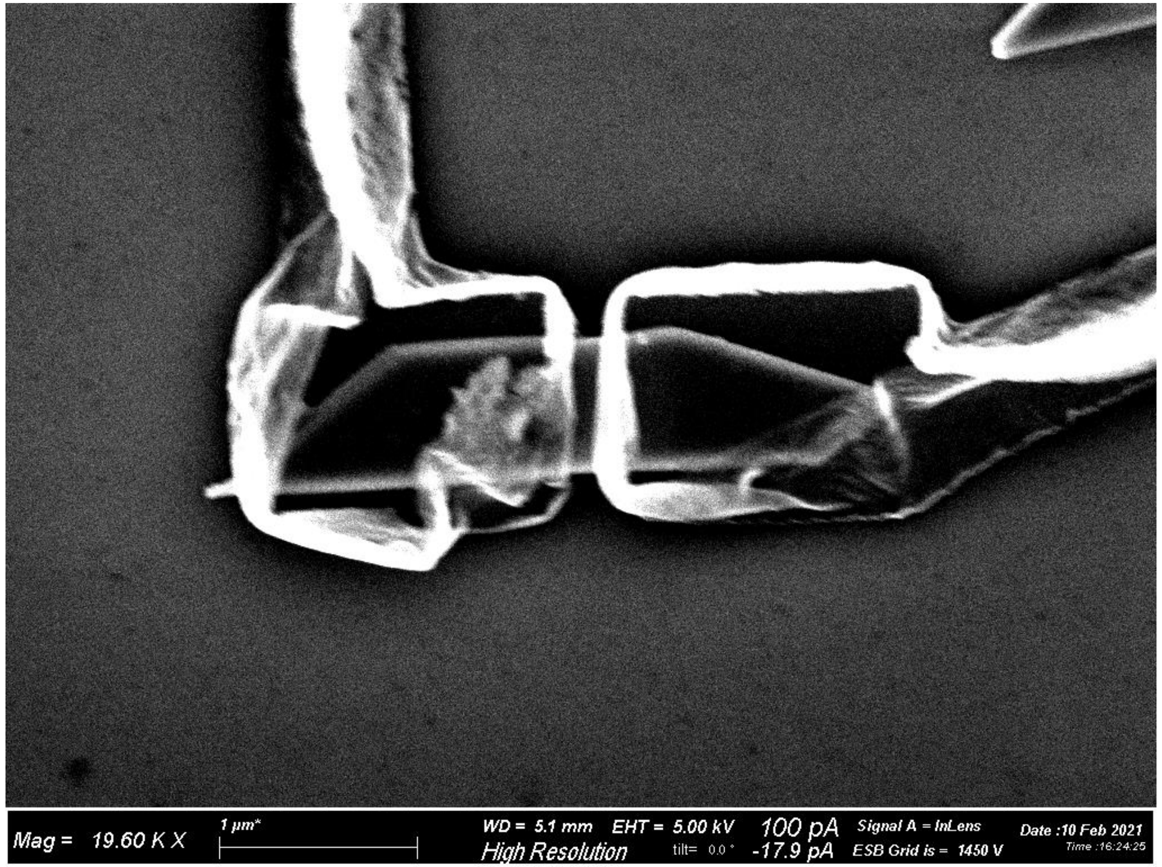
InSb nanoflags:
Length 2.8 µm
Width 470 nm
Thickness 105 nm

High mobility
29500 $cm^2/(Vs)$

I. Verma et al., ACS Applied Nano Materials 4 (2021) 5825.
S. Salimian et al., Appl. Phys. Lett. 119, 214004 (2021).
B. Turini et al., Nano Lett. 22, 8502−8508 (2022).

Nb-InSb Nanoflag-based JJs

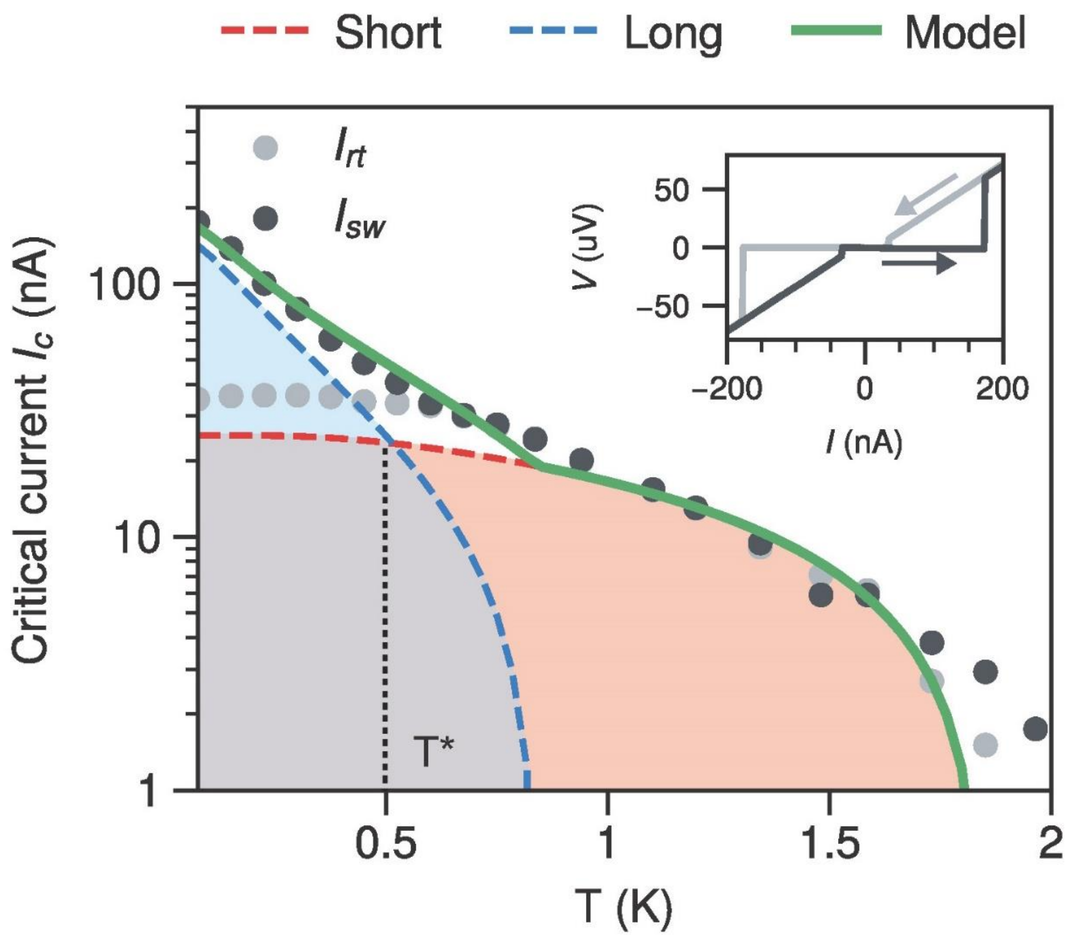
- InSb nanoflag (3.35 µm x 650 nm, 100 nm-thick)
- 150 nm-thick Nb contacts
- Channel length L = 80 nm
- Mean free path 500 nm



Chip SC 18 device I6 1-3

A. Iorio et al., Phys. Rev. Research, in press; arXiv:2303.05951.

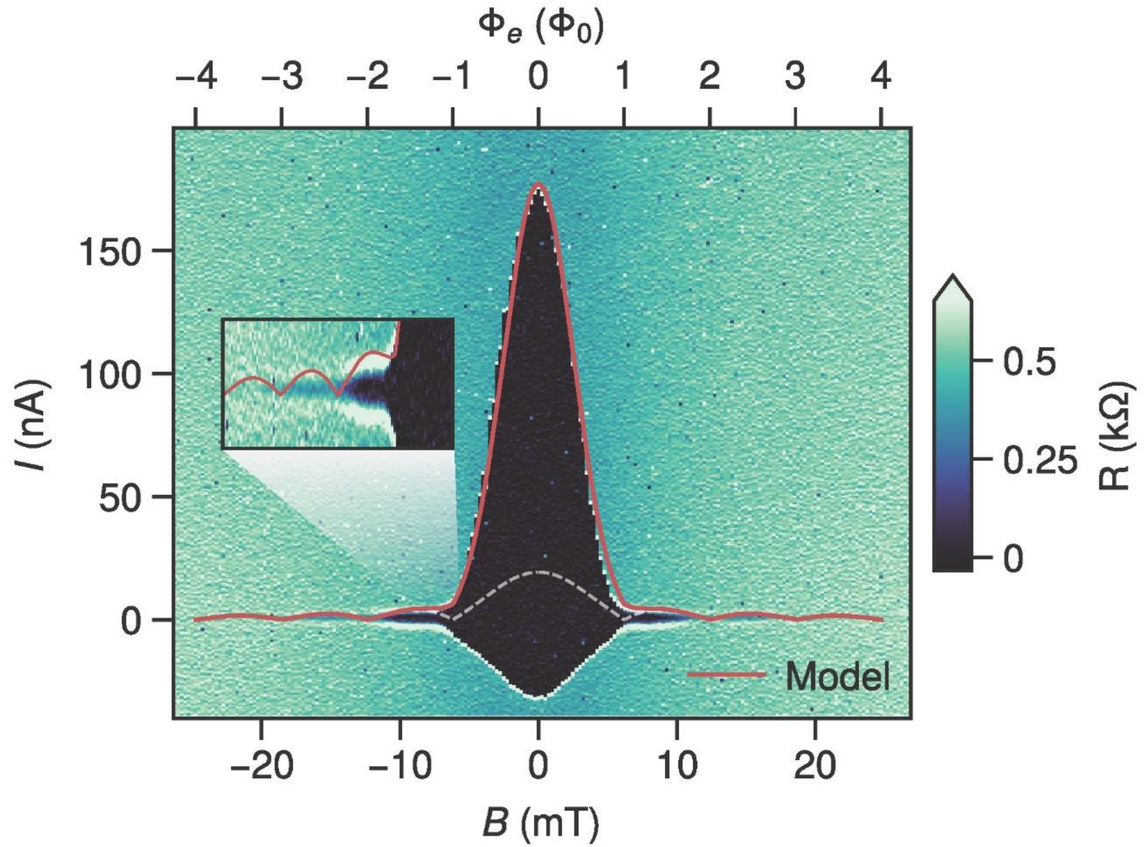
T-dependence of critical current



- I_{sw} = 170 nA
- I_{rt} = 30 nA
- T > T*: I_{sw} follows predictions for short junction model (τ = 0.93, $\Delta^* = 280\ \mu eV$)
- T < T*: exponential increase in I_{sw} with decreasing T (long junction)
- Fit: E_{Th} = 20 µeV, path length 3.5 µm

A. Iorio et al., Phys. Rev. Research, in press; arXiv:2303.05951.

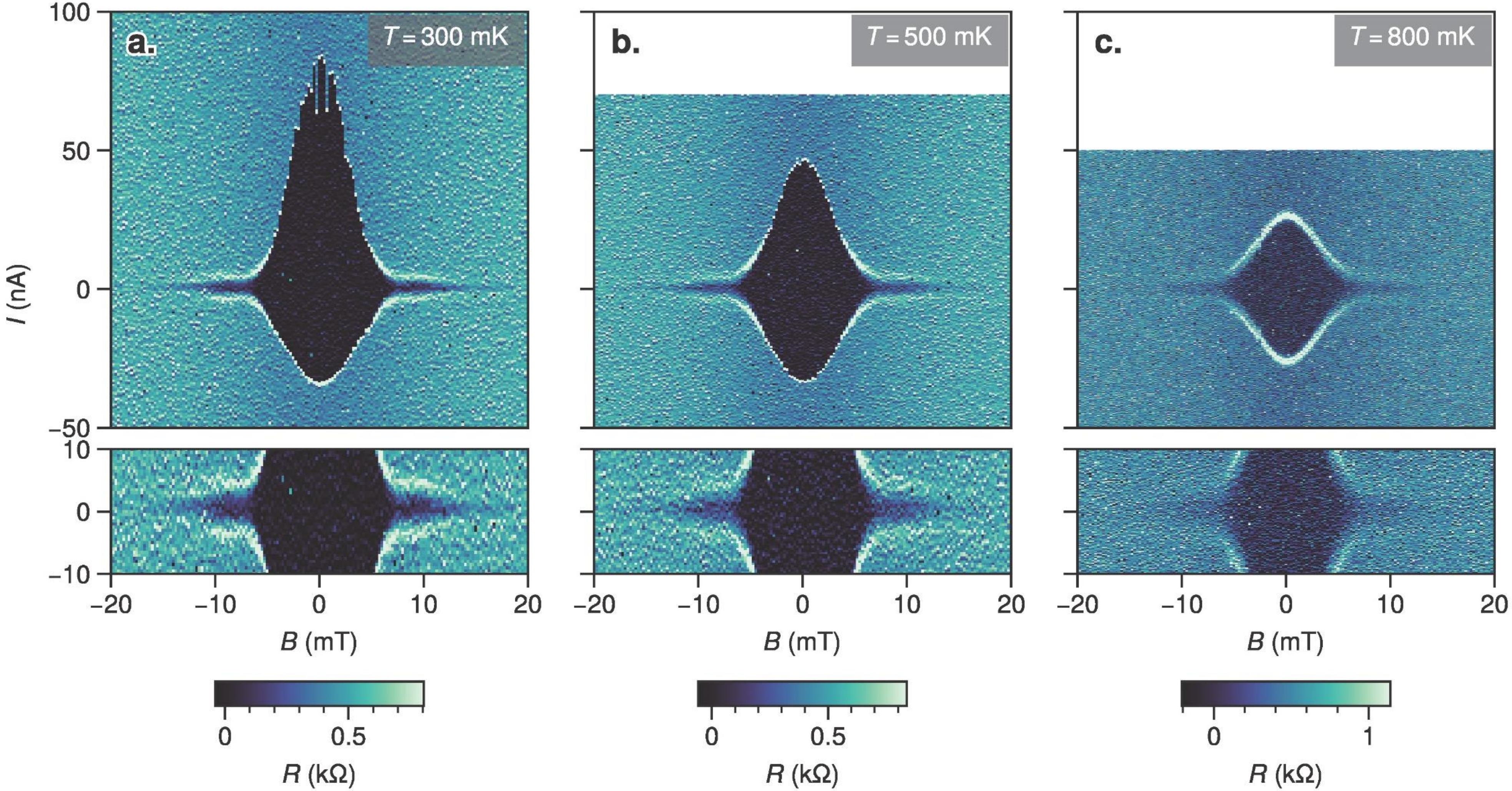
Magneto-transport



- Unconventional Fraunhofer pattern
- Well described by superposition of
  - Conventional Fraunhofer pattern (short junction)
  - Monotonic quasi-Gaussian decay (long junction)

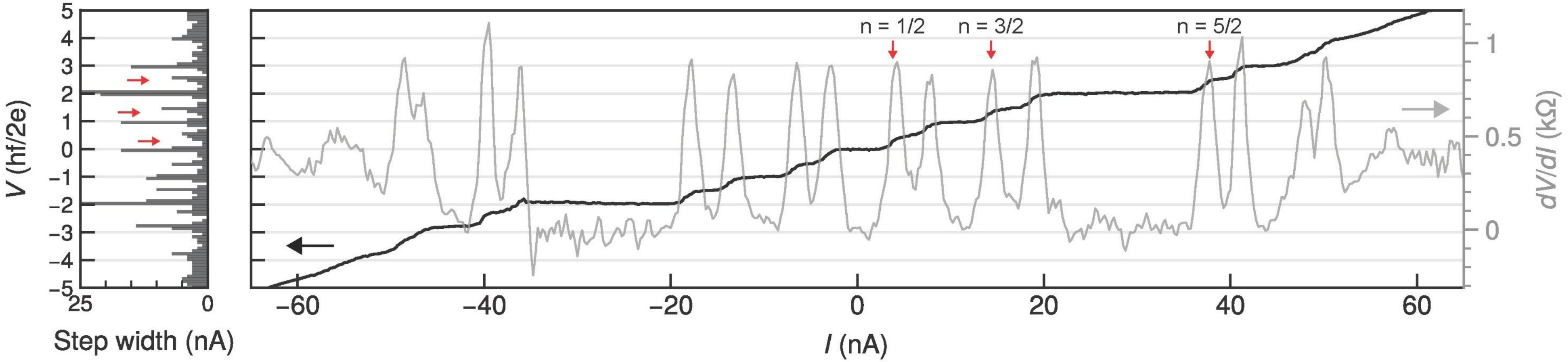
A. Iorio et al., Phys. Rev. Research, in press; arXiv:2303.05951.

T-dependence of magnetoresistance



A. Iorio et al., Phys. Rev. Research, in press; arXiv:2303.05951.

Shapiro steps

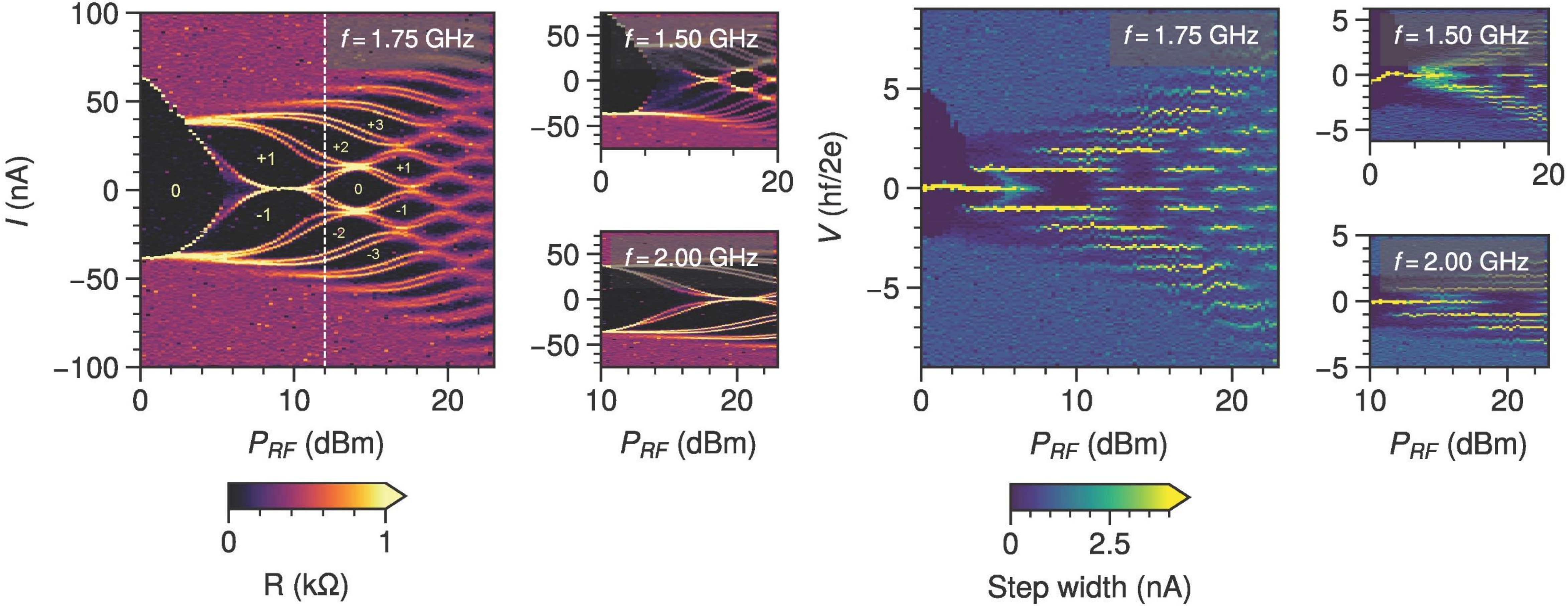


$V_n = nhf / 2e$

(f = 1.75 GHz, P_{rf} = 12 dBm)

A. Iorio et al., Phys. Rev. Research, in press; arXiv:2303.05951.

Shapiro steps

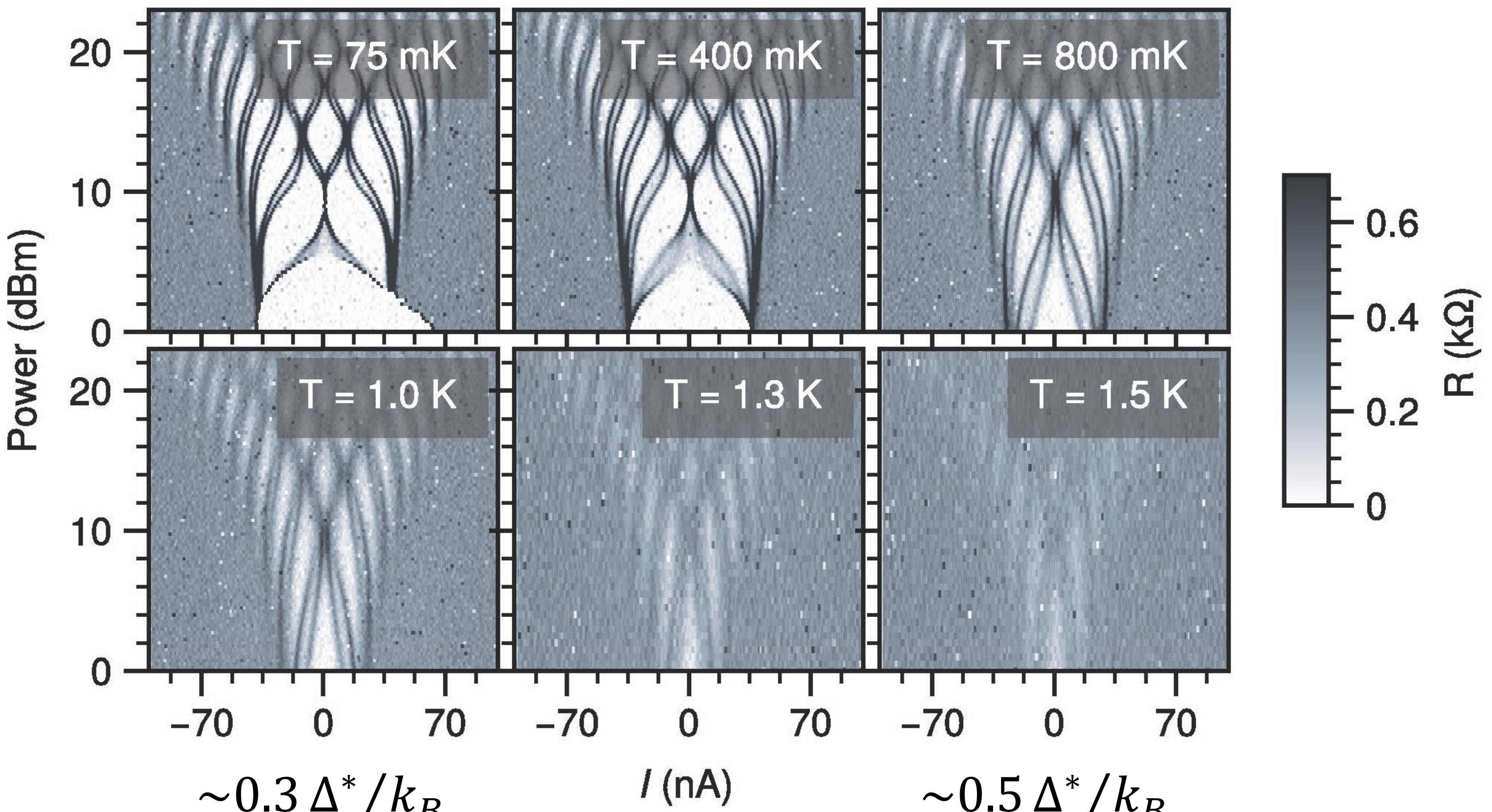


A. Iorio et al., Phys. Rev. Research, in press; arXiv:2303.05951.

National Enterprise for nanoScience and nanoTechnology
NEST

Temperature-dependence of Shapiro steps

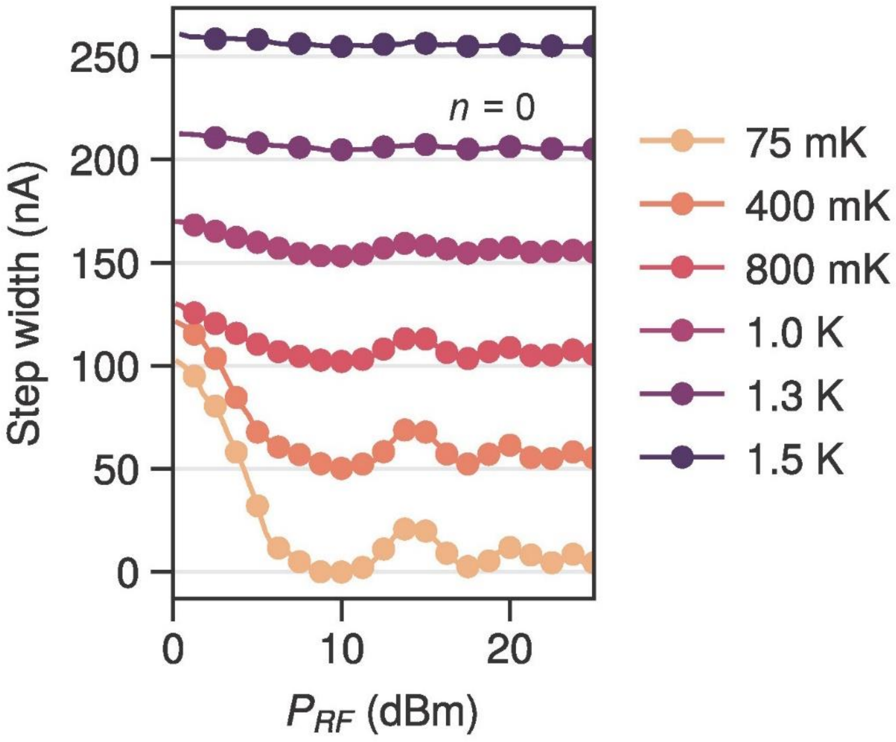
$\sim 0.02\,\Delta^*/k_B$



$\sim 0.3\,\Delta^*/k_B$ $\sim 0.5\,\Delta^*/k_B$

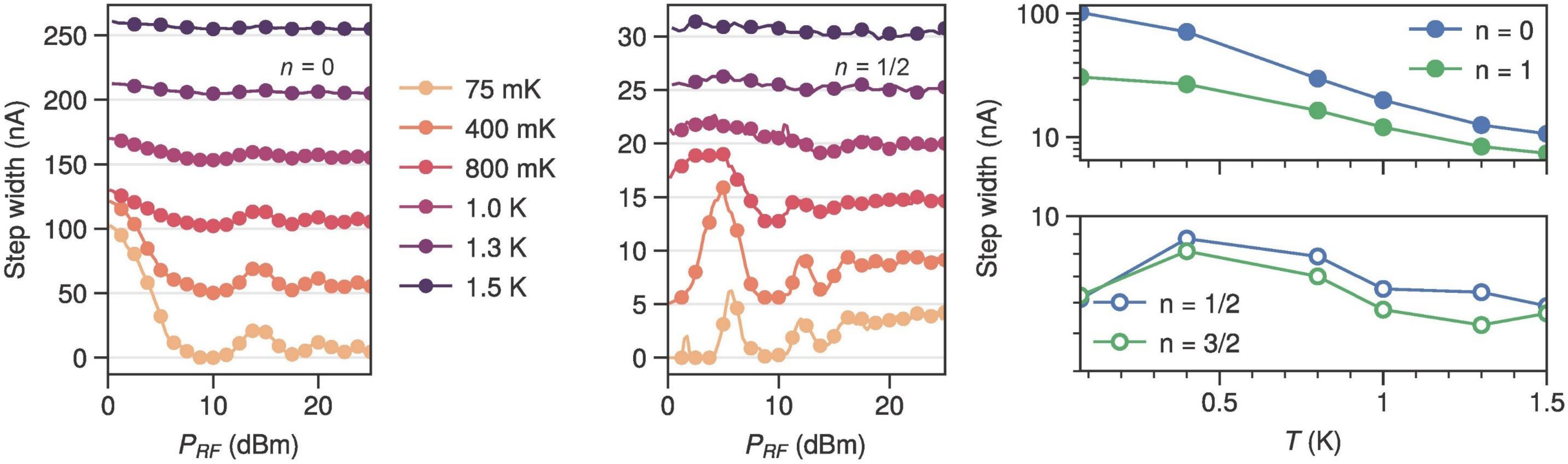
A. Iorio et al., Phys. Rev. Research, in press; arXiv:2303.05951.

Temperature-dependence of Shapiro steps



A. Iorio et al., Phys. Rev. Research, in press; arXiv:2303.05951.

Temperature-dependence of Shapiro steps



A. Iorio et al., Phys. Rev. Research, in press; arXiv:2303.05951.

Half-integer Shapiro steps (equilibrium)

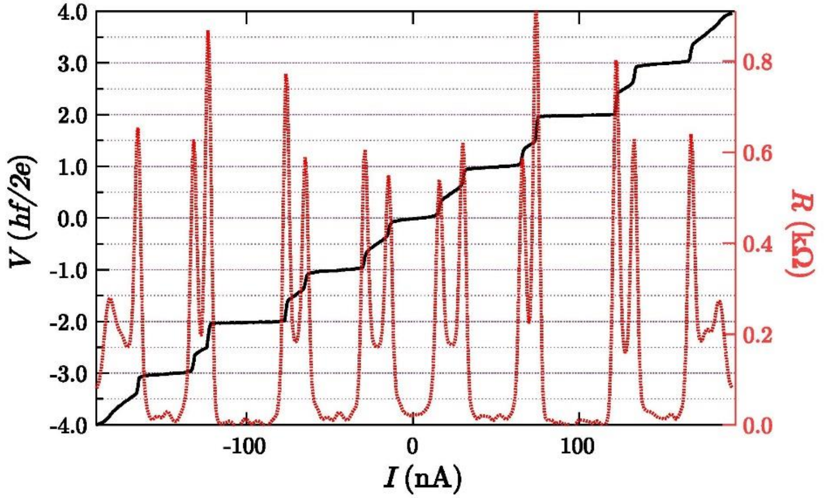
- Observed in (among others)
  - Junctions incorporating ferromagnetic layers
  - More complex circuit networks, such as junction arrays or SQUIDs
  - Non-sinusoidal CPR in highly transparent SNS

PHYSICAL REVIEW RESEARCH **2**, 033435 (2020)

Evidence of half-integer Shapiro steps originated from nonsinusoidal current phase relation in a short ballistic InAs nanowire Josephson junction

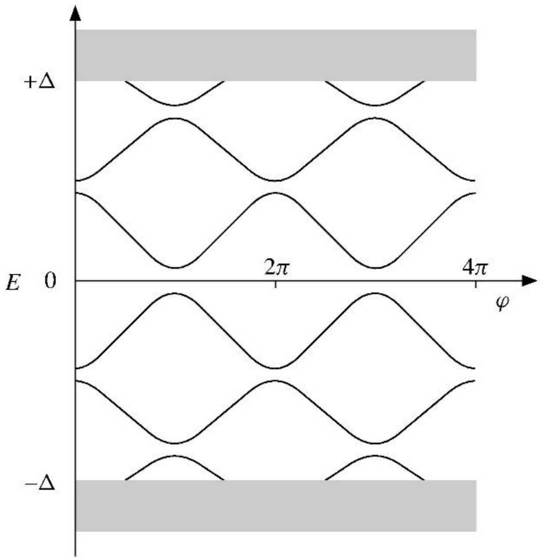
Kento Ueda,[1,*] Sadashige Matsuo,[2,3,†] Hiroshi Kamata,[4] Yosuke Sato,[1] Yuusuke Takeshige,[1] Kan Li,[5] Lars Samuelson,[6] Hongqi Xu,[5,6,7,‡] and Seigo Tarucha[3,§]

We report on half-integer Shapiro steps observed in a gate-tunable short ballistic InAs nanowire Josephson junction. We observed the Shapiro steps of the short ballistic InAs nanowire Josephson junction and found the half-integer steps in addition to the conventional integer steps. In this Josephson junction device the junction transmission can be varied with gate voltage. From measurements of the gate voltage and temperature dependences of the Shapiro steps, the origin of half-integer steps is assigned to the skewness of the current phase relation in the short ballistic Josephson junctions. These results will contribute to establish and control the superconductivity physics in the short ballistic semiconductor nanowires.

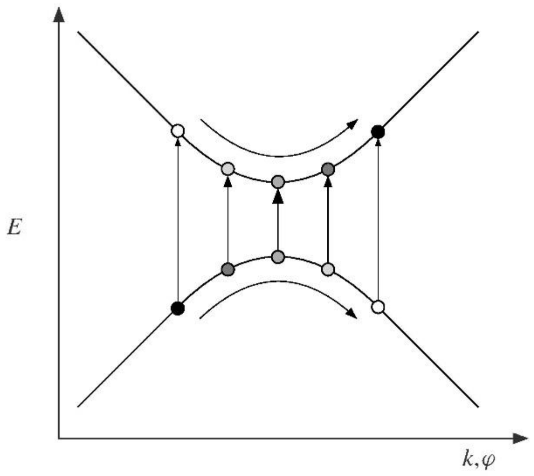


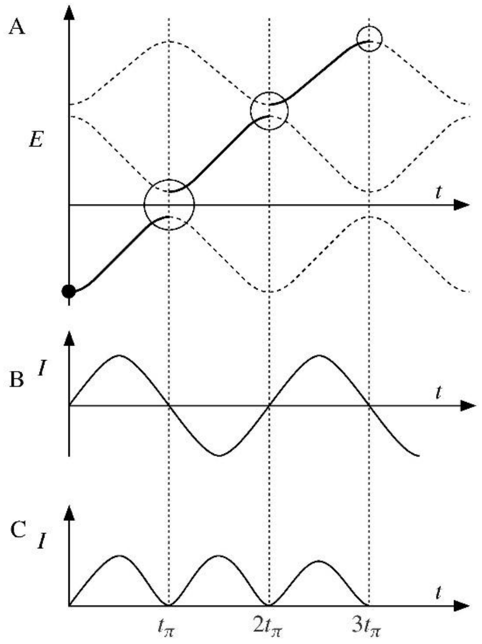
Half-integer Shapiro steps (non-equilibrium)

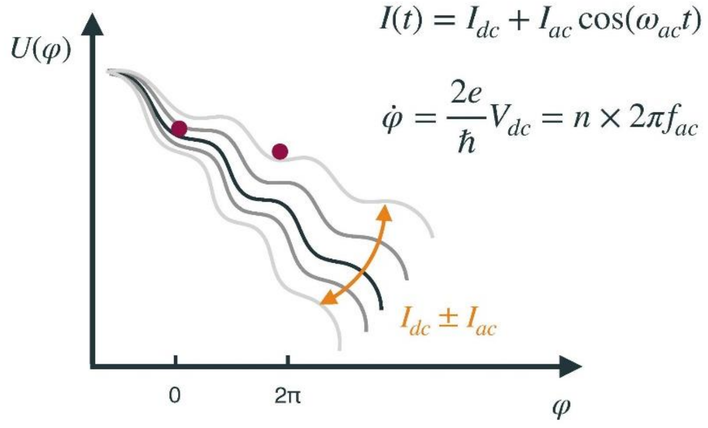
- Non-equilibrium occupation probability of Andreev Bound States
  - Strong 2φ-periodic oscillations at twice the Josephson frequency
  - Giving rise to half-integer Shapiro-steps



Schematic Andreev Bands





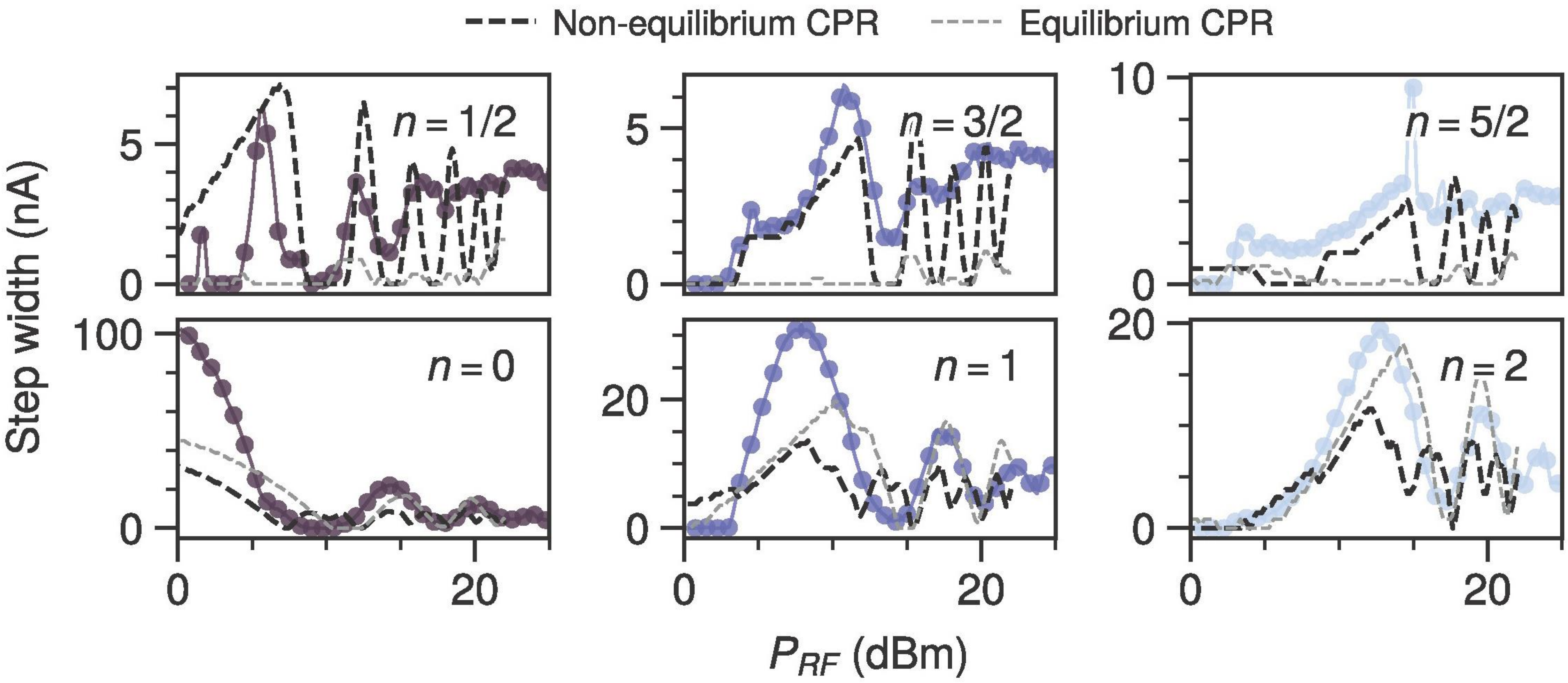


H. Kroemer, Superlattices and Microstructures 25 (1999) 877.

Josephson frequency $\omega_J = \frac{d\varphi}{dt} = \frac{2eV}{\hbar}$

$$I = \frac{2e}{\hbar} \cdot \frac{dE}{d\varphi}$$

Comparison with RCSJ Simulations



A. Iorio et al., Phys. Rev. Research, in press; arXiv:2303.05951.

Conclusions

- The high transparency of the Nb-InSb interfaces allows the investigation of unexplored transport regimes (with parallel short and long conducting channels).
- Under microwave irradiation, non-equilibrium supercurrents are excited at twice the Josephson frequency, which results in half-integer Shapiro-steps.