TT 27: Focus Session: Unconventional Transport Phenomena in Low-Dimensional Superconducting Heterostructures

The investigation of new superconducting systems and effects is key to the development of superconducting electronics and quantum technologies. Recent studies have demonstrated that systems of low dimensionality in particular offer enormous possibilities for the realization of unconventional superconducting phases and quantum states. An effect hosted by low-dimensional superconducting systems is the supercurrent diode effect. The supercurrent diode effect was experimentally observed in 2020 and has since then been intensively investigated worldwide. The effect has been seen in a variety of low-dimensionality hybrid systems, such as two-dimensional van der Waals heterostructures, in magnetic proximity systems as well superlattices. The origin of the effect, however, is still under debate and several explanations have been proposed for its underlying mechanism including lack of inversion symmetry, spin-orbit coupling and screening effects. This Focus session will bring together the most recent developments in the field of superconducting effects in low-dimensionality systems and update the community on their physics and perspective applications, with particular attention to recent results related to the supercurrent diode effect.

Organizers: Wolfgang Belzig and Angelo Di Bernardo (Universität Konstanz)

Time: Wednesday 9:30–13:00 Location: HSZ 03

Invited Talk TT 27.1 Wed 9:30 HSZ 03

Superconducting diode effect in Rashba superlattice — •Teruo Ono — Kyoto University, Japan

The diode effect is fundamental to electronic devices and is widely used in rectifiers and AC-DC converters. However, conventional diodes have an energy loss due to finite resistance. We found the superconducting diode effect (SDE) in Nb/V/Ta superlattices with a polar structure, which is the ultimate diode effect exhibiting a superconducting state in one direction and a normal state in the other [1-3]. SDE can be considered as the nonreciprocity of the critical current for the metal-superconductor transition. We also found the reverse effect, i.e., the nonreciprocal critical magnetic field under the application of the supercurrent [4]. We also found that the polarity of the superconducting diode shows a sign reversal as a magnetic field is increased, which can be considered as the crossover and phase transitions of the finite-momentum pairing states predicted theoretically [5]. SDE in Nb/V/Ta superlattices needs an application of an external magnetic field to break the time reversal symmetry, which is a disadvantage in applications. We recently succeeded in demonstrating SDE in a zero-field by introducing ferromagnetic layers in superlattices [6]. The polarity of the SDE is controlled by the magnetization direction of the ferromagnetic layer, leading to development of novel non-volatile memories and logic circuits with ultralow power consumption.

[1] J. Magn. Soc. Japan 43, 17 (2019)
[2] Nature 584, 373 (2020)
[3] Jpn. J. Appl. Phys. 60, 060902 (2021)
[4] Appl. Phys. Express 14, 073003 (2021)
[5] Phys. Rev. Lett. 128, 037001 (2022)
[6] Nat. Nanotechnol. 17, 823 (2022)

Invited Talk TT 27.2 Wed 10:00 HSZ 03

Quasiparticle-based and Cooper-pair based superconducting diodes — •Maria Spies[1], Stefan Ilić[2], Sebastián Bergeret[2], Francesco Giazotto[1], and Elia Strambini[1] — [1]NEST, Istituto Nanoscienze-CNR and Scuola Normale Superiore, I-56127 Pisa, Italy — [2]Centro de Física de Materiales (CFM-MPC) Centro Mixto CSICUPV/ EHU, E-20018 Donostia-San Sebastián, Spain

Diodes are key elements for electronics, optics, and detection. Their evolution towards low dissipation electronics has lead to the hybridization with superconductors (S) and the realization of non-reciprocal transport of both quasiparticles and Cooper pairs. That occurs when both spatial inversion and time-reversal symmetries are broken.

Here, we review both effects comparing their efficiencies and basic principles. The quasi-particle diode is a superconducting tunnel junction with zero conductance in only one direction. The directionselective propagation of the charge has been obtained through the broken electron-hole symmetry induced by the spin selection of a ferromagnetic tunnel barrier made of a EuS thin film separating a superconducting Al and a normal metal Cu layer. It achieves a large rectification of up to 40%.

On the other hand, supercurrent diodes made with hybrid S/spinorbit/ S Josephson Junctions or with two-dimensional Rashba superconductors have been demonstrated to show zero resistance in only one direction. We describe the equation of the supercurrent diode effect in a generic formalism that may inspire novel devices based on helical magnetism induced in conventional superconductors.

Invited Talk TT 27.3 Wed 10:30 HSZ 03

Non-reciprocal superconductivity and the field free Josephson diode — •Mazhar Ali — TU Delft, Delft, Netherlands

Nonreciprocal transport is incredibly important in technology; for example, asymmetry in the current-voltage response in semiconductor junctions has been the cornerstone of computing technology for half a century. The diode effect is a very basic demonstration of nonreciprocity. Nonreciprocal superconductivity, however, proved elusive, and only in 2020 was the superconducting diode effect (superconducting in one direction while normal conducting in the other) discovered for the first time in a bulk alloy of V/Nb/Ta. By breaking both inversion and time reversal symmetry (using an applied magnetic field), a difference in the critical superconducting current (I) for positive vs negative voltages (V) was seen. Recently, we demonstrated a Josephson diode (JD), created in a quantum material Josephson junction (QMJJ, a junction made up of two superconductors separated by a barrier comprised of a quantum material). A diodic effect was seen without an applied magnetic field; a puzzling result for theoretical physicists but an important advance for potential technological application. Using an inversion symmetry breaking heterostructure of $NbSe_2/Nb_3Br_2/NbSe_2$, half-wave rectification of a square-wave excitation was achieved with low switching current density, high rectification ratio, and high robustness. Future directions for optimizations and novel explorations, as well as a broader impact of using other quantum materials will be discussed.

15 min. break

TT 27.4 Wed 11:15 HSZ 03

Investigating the mechanism behind the Josephson Diode Effect in $NiTe_2$/superconductor Devices — •Emily C. McFarlane[1], Jonas A. Krieger[1], Mihir Date[1], Banabir Pal[1], Procopios C. Constantinou[2], Vladimir N. Strocov[2], Stuart S. P. Parkin[1], and Niels B. M. Schröter[1] — [1]Max Planck Institute of Microstructure Physics, Halle, Germany — [2]Swiss Light Source, Paul Scherrer Institute, Villigen, Switzerland

The Josephson diode - recently realized in NiTe2/superconductor devices in the presence of an external magnetic field [1] - has many potential uses in new superconducting memory and logic devices. These $NiTe_2$/Ti/Nb devices are the first Josephson diodes where the Josephson diode effect (JDE) was concluded to arise from finite momentum Cooper pairing. However, the role of the Ti layer directly at the $NiTe_2$ interface is not yet fully understood. Ti-doped $NiTe_2$ is seen to be superconducting [2], so here we investigate the possibility of intrinsic superconductivity at the $NiTe_2$/Ti interface by investigating its electronic structure with angle-resolved photoelectron spectroscopy. In isostructural $PdTe_2$, a van Hove singularity (vHS) near the Fermi level was linked to intrinsic superconductivity [3]. We find a similar vHS in the vicinity of the Fermi level in the electronic structure of $NiTe_2$, which can be shifted in energy at the interface due to a doping effect by aluminium.

[1] B. Pal *et al.*, Nat. Phys. 18, 1228 (2022)
[2] B. S. de Lima *et al.*, Solid State Commun. 283, 27 (2018)
[3] Kyoo Kim *et al.*, Phys. Rev. B 97, 165102 (2018)

TT 27.5 Wed 11:30 HSZ 03

Reversal of the AC and DC supercurrent diode effect in ballistic Josephson junctions — Andreas Costa[1], Christian Baumgartner[1], Simon Reinhardt[1], Sergei Gronin[2], Geoffrey C. Gardner[2], Tyler Lindemann[2], Michael J. Manfra[2], Denis Kochan[1], Jaroslav Fabian[1], •Nicola Paradiso[1], and Christoph Strunk[1] — [1]University of Regensburg — [2]Purdue University

Recent experiments [1,2] have demonstrated that the supercurrent diode effect (SDE), –i.e., a nonreciprocal supercurrent– can be obtained by applying a Zeeman field in the presence of spin-orbit coupling. The effect consists in a finite difference ΔI_c between positive I_c^+ and negative $|I_c^-|$ critical current (DC SDE), and an asymmetry in the Josephson inductance as a function of current (AC SDE). In this work, we show that, at high in-plane fields, the AC and DC SDE both change sign. Based on a minimal and analytical model, we clearly identify the origin of this sign change in terms of a 0-π-like transition –an effect predicted in the literature [3] but so far never experimentally observed. Thanks to our inductance measurements we can directly link the AC SDE reversal to the modification of the CPR induced by the Zeeman field. Our results illustrate the power of the Josephson inductance as a probe of phase transitions in unconventional superconductors.

[1] Ando *et al.*, Nature **584**, 373 (2020)
[2] Baumgartner *et al.*, Nature Nano. **17**, 39, (2022)
[3] Yokoyama *et al.*, Phys. Rev. B **89**, 195407 (2014)

TT 27.6 Wed 11:45 HSZ 03

Theoretical study of the supercurrent diode effect in 2DEG Josephson junctions — •Andreas Costa[1], Denis Kochan[1,2], and Jaroslav Fabian[1] — [1]University of Regensburg, Germany — [2]Slovak Academy of Sciences, Slovakia

Superconducting junctions exhibit fascinating physical phenomena, making them promising building blocks for quantum computing. The competition between the two fundamental spin interactions—ferromagnetic exchange and spin-orbit interaction (SOI)—and superconductivity has already been demonstrated to substantially modify the spectroscopic and transport signatures of these junctions, and potentially results in topological superconductivity.

In this talk, we will focus on 2DEG-based S-N-S Josephson junctions that combine intrinsic SOI with proximity-induced superconductivity originating, e.g., from top Al islands. We will demonstrate that turning the nonsuperconducting (N) weak link additionally ferromagnetic—e.g., through a magnetic field—can imprint a strong direction dependence on the current-phase relation, which finally rises a substantial difference between positive and negative critical currents, and thereby a pronounced supercurrent diode effect. Motivated by pioneering experimental studies [1–3], we will elaborate on powerful theoretical approaches—such as numerical tight-binding simulations [2, 3] and analytical studies of the Andreev spectrum—to characterize and understand the features of this Josephson supercurrent diode effect.

[1] Phys. Rev. Lett. 126, 037001 (2021)
[2] Nat. Nanotechnol. 17, 39 (2022)
[3] J. Phys. Condens. Matter 34, 154005 (2022)

TT 27.7 Wed 12:00 HSZ 03

Plasmons and dynamical screening in layered superconducting heterostructures — •Yann in 't Veld[1], Mikhail Katsnelson[1], Andrew Millis[2,3], and Malte Rösner[1] — [1]Radboud University, Nijmegen, the Netherlands — [2]Flatiron Institute, New York, USA — [3]Columbia University, New York, USA

Layered metals host low-energetic plasmonic and phononic excitations, which both strongly couple to electrons. At the same time these excitations hybridize with each other, which can be tuned by the surrounding material, resulting in a complex interplay of different bosons. Here we investigate how this interplay affects superconductivity in layered materials and how it is affected by the substrate material. To this end we use a one-loop theory which consistently treats phonons, plasmons, their mutual interaction and environmental screening on the same footing. We find two regimes with large transition temperatures, controlled by the substrate screening. One is mediated by conventional phonon pairing, which shows a significantly reduced transition temperature due to consistent screening. The other regime is dominated by the unconventional electron-plasmon interaction, where we find strong effects of normal-state renormalization on the superconducting state. These results show how crucial a consistent treatment of all pairing and screening channels is for low-dimensional superconductivity.

TT 27.8 Wed 12:15 HSZ 03

Investigation of Nb gate-controlled superconducting nanoscale devices. — •Leon Ruf, Elke Scheer, and Angelo Di Bernardo — 78464 Konstanz, Konstanz Germany

The electrical conductance in nanoscale devices can be modulated by an applied electric field (EF). In semiconductors the charge density is low, and the EF can penetrate deeply. However, in superconductors the charge carrier density is high and the external EF decays exponentially over a short distance. In 2018, it was reported [1] that the superconducting state can be partially and fully suppressed in gated nano constrictions by a strong applied EF which they attribute to an EF induced perturbation of the superconducting state. Since then, the observations were controversially discussed attributing them to an EF effect [1], high-energy quasiparticle injection [2], low-energy-mediated phonon excitation [3] or hot-spot generation [4]. Here, we are studying Nb gated Dayem bridges. Our observations show reversible full suppression of the supercurrent for Nb devices made by lift off, not for geometrically comparable etched devices. We discuss our observations in the light of the suggested mechanisms [1-4].

[1] G. De Simoni *et al.*, Nat. Nanotechnol. 13, 802 (2018)
[2] L. D. Alegria *et al.*, Nat. Nanotechnol. 16, 404 (2021)
[3] M. F. Ritter *et al.*, Nat. Electron. 5, 71 (2022)
[4] J. Basset *et al.*, Phys. Rev. Res. 3, 043169 (2021)

TT 27.9 Wed 12:30 HSZ 03

Gate-controlled switching in non-centrosymmetric superconducting devices — •Jennifer Koch, Leon Ruf, Elke Scheer, and Angelo Di Bernardo — Universität Konstanz, Konstanz, Germany

Gate-controlled superconducting devices have become of great interest for the development of energy-efficient hybrid superconductor/semiconductor computing architectures. The idea behind this technology stems from the recent discovery that superconducting devices can be controlled electrically with the application of a gate voltage [1-3].

We investigate gate-controlled switching devices made of the non-centrosymmetric superconductor $Nb_{0.18}Re_{0.82}$ for different gate-to-wire distances. This material promises a low switching voltage due to its disordered structure and should therefore be more suitable for the realization of devices compatible with CMOS transistors.

[1] G. De Simoni et al., Nature Nanotech. 13, 802 (2018)
[2] F. Paolucci et al., Nano Lett. 18, 4195 (2018)
[3] F. Paolucci et al., Phys. Rev. Applied 11, 024061 (2019)

TT 27.10 Wed 12:45 HSZ 03

Microscopic theory of gate-voltage mediated surface pair breaking and its impact on a superconducting wire — •Subrata Chakraborty, Danilo Nikolic, and Wolfgang Belzig — Fachbereich Physik, Universität Konstanz, D-78457 Konstanz, Germany

Gate-induced supercurrent suppression in a superconducting nanobridge is a hot topic for research in present days. Recent experiments find supercurrent suppression in this nano-bridge for high gate electric fields [1-3]. The microscopic understanding of this effect is not clear till now. According to many experimental findings, there are three distinct tentative mechanisms, which could be responsible for this event, at high gate fields. In our work, we theoretically investigate the role of gate-mediated surface pair breaking on the supercurrent suppression. We show that in presence of a small concentration of magnetic impurities on the surface of the bridge, large gate-fields result in strong spin-flip scattering at the surface. Using microscopic modelling based on the quasiclassical Usadel equation we present the full phase diagram of the wire, that shows a supercurrent suppression very similar to some experiment. We speculate, that our generic theoretical predictions based on this microscopic effect can be tested experimentally by modifying the surface.

[1] G. De Simoni *et al.*, Nat. Nanotechnol.**13**, 802 (2018)
[2] I. Golokolenov *et al.*, Nat. Commun. **12**, 2747 (2021)
[3] L. D. Alegria *et al.*, Nat. Nanotechnol. **16**, 404 (2021)