Program and Abstract Book
of the COST Action Meeting
“Emerging Quantum Materials Based on Superconducting Nanostructures”

2 to 3 October 2024

Contents

Aims and Scope

The International Meeting dedicated to Emerging Quantum Materials based on Superconducting nanostructures will provide an overview of the state-of-the-art achievements in the field of superconducting Nanodevices and Quantum Materials for Coherent Manipulation. It aims at bringing together specialists working in several actively developing and mutually fertilizing domains: Superconducting 3D Nanoarchitectures, Topological Superconductivity, Dimensionality and Topological Effects in Abrikosov Vortex Systems, Vortex Dynamics in Nanoengineered Superconductors, Superconducting Resonators and RF Applications, Thin Film Superconducting Hybrids. Its vigorous topical scope ranges from fundamental theoretical, numerical and experimental studies of Superconducting and Hybrid Nanostructures with emphasis on vortex physics – to design and optimization of the novel functionalized Quantum Materials for versatile applications including, but not limited to, resonators with enhanced quality factors, bolometers with ultralow noise power, integration of superconducting technologies in quantum information processing and sensing.

Importantly, the first COST Action CA21144 SuperQuMap International Meeting to be held in the Republic of Moldova will provide an unprecedented opportunity to the researchers of the East-European Countries to present and discuss their current investigations at a high-European-level scientific forum, to get acquainted with the advanced theoretical and experimental methods in the field, and to initiate novel motivating interactions with colleagues from the other COST Action Member Countries.

Meeting starts on Wednesday, October 2, 2024 at 8:30 at the Moldova State University (Strada Alexei Mateevici 60, MD2009, Chișinău, Republic of Moldova) https://usm.md/?lang=en. The meeting is organized in cooperation with https://mscmp.usm.md/.

The Meeting will cover six topics:

- Superconducting 3D Nanoarchitectures

The state of the art in the field of superconducting 3D nanoarchitectures will be represented. We will outline the vision for advancing the future research in topological superconducting nanoarchitectures and their application prospects as novel quantum materials. The non-reciprocity effects due to interplay between the inhomogeneous magnetic field and the anisotropic defects will be discussed.

- Dimensionality and Topological Effects in Abrikosov Vortex Systems

The intricate nature of Abrikosov vortices will be addressed, with a specific focus on their interaction with topological effects across various dimensions. Recent advancements in nanotechnology, vortex imaging, and simulations will play a pivotal role in comprehensively elucidating the influence of dimensionality and topology on vortex dynamics.

- Superconducting Resonators and RF Applications

We will explore recent advancements in the design and performance of superconducting resonators, emphasizing their interaction with superconducting and magnetic systems. Key topics will include innovations that improve the quality factors of resonators, the integration of superconducting technologies in quantum computing and sensing, and practical applications.

- Thin Film Superconducting Hybrids

Proximity effects between superconductor and other materials such as high spin-orbit semiconductors or ferromagnetic insulators give rise to a diverse set of non-trivial superconducting states. The fundamental aspects and the potential technological application will be discussed.

- Vortex Dynamics in Nanoengineered Superconductors

In superconducting qubits, vortices are a source of decoherence, whereas in topological qubits vortices provide a way to manipulate non-abelian anyons. We will consider materials, which are capable of detection and counting of massive and massless single particles, and superconductors that support high vortex velocities (>10 km/s) for fluxonic devices operating with single flux quanta.

- Topological superconductivity

We will address various effects of Ising and Rashba superconductivity: anisotropy, 2D and quasi-2D effects, the Ising pairing in the atomically thin $NbSe_2$, the FFLO-phase.

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N. Barišić	University of Zagreb, Zagreb, Croatia
S. I. Beril	Pridnestrovian State University, Tiraspol, Republic of Moldova
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B. Ujfalussy	HUN-REN Wigner Research Centre for Physics, Budapest, Hungary
J. Van den Vondel	KU Leuven, Leuven, Belgium

Program

Overview

	October 1	October 2	October 3	October 4
	Arrival	**Registration**	*Chair – W. Lang*	**Departure**
10:00			**Vladimir M. Fomin**	
10:30-			**Predrag Miranović**	
11:00		**Coffee break**	**Coffee break**	
11:25		**Opening**		
		Chair – V. M: Fomin	*Chair – B. Ujfalussy*	
11:30		**Vadim Geshkenbein**	**Alejandro V. Silhanek**	
12:00		**Yonathan Anahory**	**Oleksandr Dobrovolskiy**	
12:30		**Ali Gencer**	**Joris Van de Vondel**	
13:00		**Lunch**	**Lunch**	
		Chair – A. V. Silhanek	*Chair – J. Van de Vondel*	
14:00		**Neven Ž. Barišić**	**Balazs Ujfalussy**	
14:30		**Bernd Aichner**	**Vladislav Pokorný**	
15:00		**Wolfgang Lang**	**Miguel Rodríguez Martin** **Igor Bogush** **Anton Pokusinskyi**	
15:30		**Evangelia Moschopoulou**		
16:00		**Coffee break**	**Coffee break**	
		Chair – V. Pokorný	*Chair – N. Ž. Barišić*	
16:30		**Anatolie Sidorenko**	**Vyacheslav Misko**	

17:00		**Jose Antonio Moreno**	**Jose David Bermúdez-Perez** **Albina Nikolaeva** **Leonid Konopko**	
17:30		**Elena Condrea** **Stepan Beril** **Flash poster presentations:** **S. Šćepanović, V. Boian**		
18:00			**Round Table: Main Outcomes, New Research Routes and Perspectives. Closing**	
18:30		**Dinner**	**Dinner**	

Abstracts

COMMENSURABILITY EFFECTS AND LONG-TERM STABILITY OF PINNING LANDSCAPES IN COPPER-OXIDE SUPERCONDUCTORS FABRICATED BY FOCUSED HE-ION-BEAM NANOPATTERNING

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The focused beam of a helium ion microscope (HIM) is an excellent tool for creating closely spaced nanocolumns in thin films of copper-oxide superconductors [1]. Within these nanocolumns, the critical temperature T_c is reduced or entirely suppressed due to the disruption of the superconducting charge carrier pairs by scattering on numerous point defects. Most irradiation-induced displacements affect oxygen atoms while not reducing the overall oxygen content in the sample. It is widely accepted that the oxygen atoms are displaced only a few unit cells, which implies that moving back only requires minimal energy.

To optimize the conditions for creating nanostructures suitable as Abrikosov-vortex pinning arrays via focused He^+-beam irradiation (He-FIB), we have investigated the impact of various irradiation parameters on the structural and superconducting properties of $YBa_2Cu_3O_{7-\delta}$ (YBCO) thin films. An important point is the optimal number of 30 keV He^+ ions needed to irradiate a dot of the nanocolumn lattice for maintaining the crystalline framework of YBCO intact while suppressing its superconductivity. Using aberration-corrected scanning transmission electron microscopy, we identified a critical dose of approximately 13,000 ions/dot beyond which the YBCO film becomes amorphous. Conversely, lower doses do not cause any visible damage. Still, they affect the behavior of magnetic flux quanta, influencing the efficiency of the vortex pinning lattices formed by the columnar defects [1]. Moreover, we demonstrate that the He-FIB technique can also be applied to $Bi_2Sr_2CaCu_2O_{8+x}$ thin films to produce efficient pinning landscapes in this highly anisotropic superconductor.

One topic to be investigated is the stability of these defects over long timescales. To address this, we investigated the efficiency of pinning arrays in YBCO films over several years of storage at room temperature. The critical temperature T_c increased during an initial healing period of about three years and then showed a marginal decrease up to a total storage period of almost six years. The long-term storage in dry air did not compromise the vortex-matching signatures. This analysis suggests that room-temperature annealing reduced the defect density surrounding the columnar defect channels while maintaining robust pinning potential at their cores [2]. Our results carry significant implications for potential applications in fluxonics.

ACKNOWLEDGMENTS: The research was funded by a joint project of the Austrian Science Fund (FWF), grant I4865-N, and the German Research Foundation (DFG), grant KO 1303/16-1. It is based upon work from COST Actions CA19140 (FIT4NANO), CA21144 (SuperQuMap), and CA19108 (Hi-SCALE) supported by COST (European Cooperation in Science and Technology). B.A. acknowledges financial support from the Austrian Science Fund, grant I6079.

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[2] S. Keppert, B. Aichner, P. Rohringer, M.-A. Aurel Bodea, B. Müller, M. Karrer, R. Kleiner, E. Goldobin, D. Koelle, J. D. Pedarnig, W. Lang, Int. J. Mol. Sci., **25** (2024) 7877.

DIRECT OBSERVATION OF A SUPERCONDUCTING VORTEX DIODE

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The interplay between magnetism and superconductivity can lead to unconventional proximity and Josephson effects. A related phenomenon that has recently attracted considerable attention is the superconducting diode effect, in which a non-reciprocal critical current emerges [1–3]. Although superconducting diodes based on superconducting/ferromagnetic (S/F) bilayers were demonstrated more than a decade ago [4], the precise underlying mechanism remains unclear. While not formally linked to this effect, the Fulde-Ferrell-Larkin-Ovchinikov (FFLO) state is a plausible mechanism, due to the 2-fold rotational symmetry breaking caused by the finite center-of-mass-momentum of the Cooper pairs. Here, we directly observe, a tunable superconducting vortex diode in Nb/EuS (S/F) bilayers. Based on our nanoscale SQUID-on-tip (SOT) microscope [5,6] and supported by in-situ transport measurements, we propose a theoretical model that captures our key results. Thus, we determine the origin for the vortex diode effect, which builds a foundation for new device concepts.

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HIGH-Tc CUPRATES – STORY OF TWO ELECTRONIC SUBSYSTEMS

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The experimentally established universalities in high-T_c cuprates will be presented [1-7]. Based on them we show that the phenomenology of cuprates across the phase diagram is fully captured by the simple charge conservation relation:

$$1 + p = n_{loc} + n_{eff}$$

Here, p is the doping while n_{eff} is the carrier density and n_{loc} is the density of localized charge within a CuO_2 plaquette. The corresponding superfluid density is related to both components:

$$\rho_S = n_{eff} \cdot (O_S\, n_{loc}).$$

where all terms can be experimentally determined directly. The charge n_{loc} is responsible for all the strangeness of these compounds, which includes the pseudogap phenomenon and the superconducting glue. [7-9]

The compound-dependent constant, O_S, is fine-tuned by the local crystal structure. It arises from the *p–d–p* fluctuation by the Cu-localized holes visiting the neighboring planar–oxygen atoms and can be determined from NMR [9].

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HIGH-TEMPERATURE BIPOLARONIC SUPERCONDUCTIVITY IN MULTILAYER PERIODIC STRUCTURES

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The possibility of realizing high-temperature superconductivity (HTSC) in multilayer structures was predicted by Ginzburg [1]. In a theoretical study of HTSC in a three-layer structure of the Ginzburg sandwich type: $SrTiO_3$/FeSe (monolayer)/$SrTiO_3$, it was shown [2] that the experimentally detected HTSC in these structures [3] can be explained on the basis of a bipolaronic mechanism. The estimates of the binding energy (E_{bp}) of the bipolaron and the critical temperature (T_c) in the FeSe layer are in the range $E_{bp}{\sim}(150 \div 500)\,K$ with a maximum value of $T_c{\sim}140\,K$, i.e. bipolarons are stable quasi-particles and can exist in the structure under consideration at a temperature significantly higher than the temperature T_c of their condensation.

The theory makes it possible to simulate the material and geometric parameters of multilayer periodic structures in which critical temperatures T_c can be reached in the range of room values $T_c{\sim}300\,K$.

For the considered mechanism of HTSC occurrence, the most promising multilayer structures are multilayer structures, the layers of which, along with FeSe, CuO_2, are such layers as SrO, TiO_2, BaO and a number of others proposed in [2], [4].

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THERMOELECTRIC POWER STUDY OF 2D DICHALCOGENIDES THROUGH SCANNING THERMOPOWER MICROSCOPY ADAPTED IN A SCANNING TUNNEL MICROSCOPE

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Nanotechnology requires the use of specialized experimental techniques to investigate the physical properties of materials at the nanoscale. One such powerful technique is Scanning Tunneling Microscopy (STM), which allows the study of material surfaces at the atomic level. In STM, a sharp metal tip is positioned extremely close to the sample surface, typically of the order of angstroms. At this proximity, electrons can tunnel between the tip and the sample, generating a tunneling current [1]. This current is measured and used to produce images of the surface topography with atomic resolution, as well as to probe the local density of states through tunnel conductance.

STM can be modified to incorporate additional measurement modes, enabling the exploration of physical phenomena beyond those addressed by the conventional technique [2]. In this poster, we present a novel approach involving the development of a high-resolution Scanning Tunneling Microscope adapted as a Thermopower Microscope (STM/SThEM), which operates in a high vacuum environment and at room temperature. This innovative setup allows for the measurement of the Seebeck coefficient (S), a critical parameter in thermoelectric studies, and offers valuable insights into material properties. We demonstrate the application of this technique using our custom-built STM/SThEM microscope to study the effect of chemical doping on the thermoelectric power of the transition metal dichalcogenide WSe_2, a novel material with additional properties such as ferroelectricity and ferromagnetism [3].

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VORTEX DYNAMICS SIMULATIONS IN 3D CURVED SUPERCONDUCTOR MEMBRANES

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Superconductor 3D nanoarchitectures are a subject of extensive theoretical and experimental studies due to their potential for tuning superconducting properties by their geometry. In this regard, of special interest are effects emerging because of the extension of planar thin films into the third dimension and the impact of the 3D geometry on phenomena studied extensively for planar systems [1, 2]. In particular, vortex dynamics in superconductor films are strongly influenced by the component of the magnetic field that is normal to the film surface. When a curved thin film is exposed to a homogeneous magnetic field, the normal component of this field exhibits a complex spatial profile. Vortices tend to move along the region where the magnitude of the normal magnetic field is the largest [3]. This enables a vortex steering on curved superconducting surfaces, which can additionally be tuned by adjusting the magnitude and direction of the external magnetic field.

In this talk, I will introduce a formalism we developed based on differential geometry and conformal mappings for numerical simulations of curved surfaces using a finite difference approach. Differential geometry is a powerful tool that describes spaces with curvature or curvilinear coordinates, e.g., in General Relativity. Conformal mapping transforms the initial surface into a domain of plane with the geometry being encoded in a conformal factor and an extrinsic curvature tensor. This formalism allows us to apply the finite difference method to simulations of curved films by incorporating these conformal factors and curvatures into the model equations.

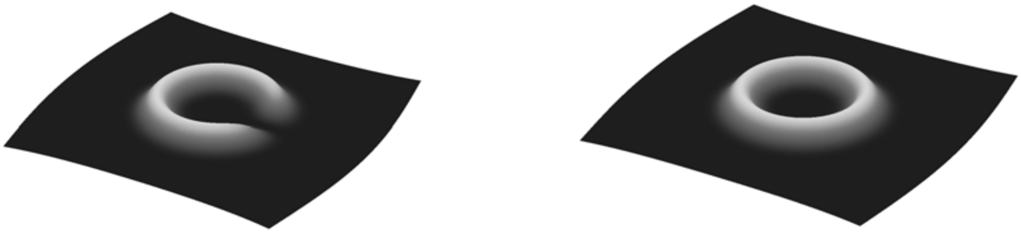

Figure 1. Examples of the considered geometries: (a) C-shaped well, (b) ring-shaped well.

I will discuss several theoretical aspects of the formalism and illustrate its application to the Schrödinger equation for a charged particle in static electric and magnetic fields. Further, the method is applied to the time-dependent Ginzburg-Landau equation for the superconducting order parameter. The considered geometries include a ring-shaped well and a C-shaped well (Fig. 1). It is demonstrated that vortices can be pinned by geometrical effects and that a vortex ratchet effect can be achieved by geometric adjustments alone. Both pinning and vortex ratchet effects can be controlled by varying the external magnetic field.

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SUPERCONDUCTING NANOSTRUCTURES FOR SPINTRONICS

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Increasing energy consumption and the necessity of the energy efficiency and the radically reduction of the power consumption level becomes a crucial parameter constraining the advance of supercomputers. The most promising solution is design and development of the non-von Neumann computers with brain-like architecture, first of all – the Artificial Neural Networks (ANN) based on superconducting elements. Superconducting ANN needs elaboration of two main elements – functional nanostrtuctures: nonlinear switch similar to the neuron, and linear connecting elements similar to synapse [1]. There are presented results of design and investigation of artificial neurons, based on superconducting spin valves, and superconducting synapses, based on layered hybrid nanostructures superconductor-ferromagnet. Are presented results of the theoretical and experimental study of the proximity effect in a stack-like superconductor/ferromagnet (S/F) superlattices with Co- ferromagnetic layers of different thicknesses and coercive fields, and Nb-superconducting layers of constant thickness equal to coherence length of niobium.

The superlattices Nb/Co demonstrate change of the superconducting order parameter in thin niobium films due to switching from the parallel to the antiparallel alignment of neighboring ferromagnetic layers. We argue that such superlattices can be used as suitable base elements for superconducting spintronics for ANN engineering [2]. Design of the ANN using that two base elements, artificial neurons and artificial synapses, allows construction of the computer with several orders of magnitude lower energy consumption in comparison with the traditional computer designed from semiconducting base elements.

ACKNOWLEDGEMENTS: The study was supported by the project of the Moldova State Program «Functional nanostructures and nanomaterials for industry and agriculture» no. 20.80009.5007.11.

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MAGNETOTRANSPORT PROPERTIES OF BISMUTH WIRES BELOW 25 K

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In this paper we report on magnetotransport measurements of single crystalline bismuth wires at high magnetic fields and low temperatures. These investigations are motivated in part by the unusual electronic properties of the semimetal bismuth that reflect its unique location in an intermediate position between good metals and semiconductors and present the fundamental and practical interest. Measurements of the magnetoresistance (MR) and magnetothermopower (Seebeck coefficient) in the range of magnetic field up o 20 T reveal a various behavior of quantum oscillations for the different values of temperatures that persist from 4.2 to 25 K. Observed Shubnikov-de Haas oscillations exhibit anomalies in their amplitude up to 15 T which deviates from the conventional Lifshitz-Kosevich behavior below the magnetic ordering temperature and around 20 K. The latter, which has so far not been observed, suggests a field- and temperature-induced electronic structure transition. Thermopower (S) of the 1.1 μm wire with high resistance residual ratio (R(300K)/R(4.2K) = 30) exhibits a non-linear temperature dependence with $\partial S/\partial T < 0$ at B = 0 (Figure 1(b)). In standard low-temperature measurements of bulk Bi crystals such behaviour is associated with the phonon drag effect that dominates the total thermopower of being the sum of diffusion (Sd) and phonon drag term (Sg) at liquid helium temperature. The phonon-drag effect ($S \propto 1/T$) has been observed in the set of Bi wires a higher crystalline perfection as compared with submicron nanowires with low resistance residual ratio (Figure 1(a)).

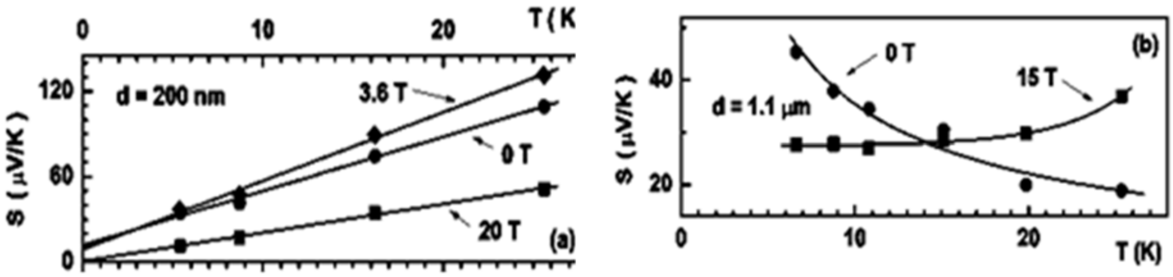

Figure 1. Dependence of the thermopower with temperature at various values of longitudinal magnetic field for the submicron nanowire (200 nm) (a) and 1.1 μm wire (b).

As shown in figure 1(b), the curves of temperature dependence S(T) have different shapes at magnetic field of B = 0 and 15 T. The observed change from $\partial S/\partial T < 0$ to $\partial S/\partial T > 0$ suggests that increasing the magnetic field enhances the relative contribution of the diffusion TEP and decreases the phonon drag contribution.

We provide a thorough analysis of the different samples, highlighting the importance of sample quality for elucidating details in the transport behavior.

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VORTEX COUNTING AND VELOCIMETRY BASED ON SLITTED SUPERCONDUCTING MICROBRIDGES

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The maximal speed $v*$ for magnetic flux quanta is determined by the energy relaxation of unpaired electrons and is thus essential for superconducting microstrip single-photon detectors (SMSPDs). However, the deduction of $v*$ from the current-voltage (*I*-*V*) curves at zero magnetic field is hindered by the unknown number of vortices, *n*, as a small number of fast-moving vortices can induce the same voltage as a large number of slow-moving ones.

In my talk I will introduce an approach for the quantitative determination of *n* and $v*$. The idea is based on the Aslamazov and Larkin prediction of kinks in the *I*-*V* curves of wide and short superconducting constrictions when the number of fluxons crossing the constriction is increased by one. We realized such conditions in wide MoSi thin strips with slits milled by a focused ion beam and revealed quantum effects in a macroscopic system [1]. By observing kinks in the *I*-*V* curves with increase of the transport current, we evidenced a crossover from a single- to multifluxon dynamics and deduced $v*$ of about 12 km/s. Our experimental observations are augmented with numerical modeling results, which reveal a transition from a vortex chain over a vortex jet to a vortex river with increase of *n* and *v*. Overall, our findings are essential for the development of one-dimensional and two-dimensional few-fluxon devices and provide a demanded approach for the deduction of maximal vortex velocities at the SMSPD operation conditions.

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SUPERCONDUCTOR 3D NANOARCHITECTURES

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Superconductor 3D nanoarchitectures are a subject of a vigorous theoretical and experimental studies [1] as a playground for novel fascinating fundamental superconducting properties and their highly prospective applications in nanoelectronics and optoelectronics, quantum optics and quantum information processing [2]. In 3D superconductor nanoarchitectures, a topological transition between the vortex and phase-slip regimes determines the magnetic-field–voltage and current–voltage characteristics revealing a nontrivial topology of superconducting screening currents. An abrupt switch-on of the transport current triggers the transition from the vortex- to phase-slip-regime in superconductor open nanotubes [3]. Various dynamic topological transitions in superconductor open nanotubes take place under a combined dc+ac transport current [4]. Relying upon the time-dependent Ginzburg-Landau equation, it is found that vortex chains, vortex jets, and phase-slip regimes occur in superconductor open nanotubes due to the inhomogeneity of the normal magnetic field component. Distinct from planar thin films, the vortex jets are constrained within the half-tubes and correlate strongly between them. At lower magnetic fields, vortices follow the same path within the half-tubes, forming single vortex chains. At higher magnetic fields, the vortex trajectories undergo multifurcations, giving rise to patterns composed of vortex jets consisting of a few vortex chains. Due to a stronger confinement of single vortex chains in tubes of small radii, jumps in the average voltage and frequency of microwave generation are unveiled, which occur when the number of fluxons moving in the half-tubes increases by one [5]. The peaks in the induced voltage and jumps in the microwave generation frequency as a function of the applied magnetic field are predicted for nanotubes of rather small radii pointing to the decisive role of the interaction of vortices in the both half-tubes for the correlated vortex dynamics. Effective steering of vortex chains and jets is realized by tilting the magnetic field in the plane perpendicular to the nanotube axis, with a jet-to-chain transition unseen for planar constrictions [6]. In addition to prospects for the tuning of GHz-frequency spectra and the steering of vortices as information bits, the discussed findings lay the foundation for on-demand tuning of vortex arrangements in superconductor 3D nanoarchitectures in tilted magnetic fields. By introducing a lattice of asymmetric pinning sites along the preferred vortex paths, a non-reciprocal flux transport exhibits a vortex ratchet effect, which is twice stronger than in the respective planar membranes. It is attributed to the inhomogeneous-field-induced vortex channeling through the areas containing the asymmetric pinning sites [7].

ACKNOWLEDGEMENTS: I am grateful to I. A. Bogush, R. Córdoba, R. H. de Bragança, O. V. Dobrovolskiy, and R. O. Rezaev for fruitful collaborations.

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RECENT ADVANCES IN HIGH PERFORMANCE MgB_2 WIRES FOR PRACTICAL APPLICATIONS

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MgB_2 is widely recognized as a promising superconductor for practical applications at temperatures around 20 K, offering advantages in cryogenic cooling and cost-effectiveness. In the context of wire production, two primary methods are employed: Powder-In-Tube (PIT) and Internal Mg Diffusion (IMD). These methods yield high-density MgB_2 phases with improved grain connectivity, resulting in high transport critical current density (Jc).

IMD-processed wires have gained prominence in MgB_2 research, particularly due to efforts aimed at enhancing structural uniformity and maximizing the filling factor of IMD-MgB_2 wires. Türkiye, with its abundant and high-purity boron resources, has successfully produced amorphous boron powders crucial for MgB_2 wire fabrication. While PIT has been the dominant method over the past two decades, recent trends favor the production of IMD-MgB_2 wires.

In this presentation, we share our latest findings on developing high-performance MgB_2 long wires using an advanced IMD approach for high-magnetic-field applications. Our objective is to enhance the critical current carrying capacity of IMD-processed wires by incorporating C-coated amorphous boron powders and low-temperature activators such as Cu or Sn. This strategy aims to create MgB_2 wires with higher Technology Readiness Levels (TRL), making them more suitable for potential large-scale applications.

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ENHANCEMENT OF FLUX PINNING BY CREEP, - NONMONOTONIC RELAXATION OF CAMPBELL PENETRATION DEPTH

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In the traditional view of magnetic flux creep in type-II superconductors, all relevant observables relax monotonically, as the vortex density gradient decays with time. Here, we propose a revised model where vortices, initially freed from shallow pinning sites by thermal fluctuations, are re-trapped by deeper sites with larger average curvature [1]. This process dominates in the initial stages of relaxation and can be observed by measuring the Campbell response, which probes the linear response of the vortices inside the pinning wells. Direct experimental measurements confirm the predicted non-monotonic behavior, validating this new, general picture of the vortex creep mechanism [2].

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QUANTUM OSCILLATIONS AT THE TOPOLOGICAL INSULATOR MICROWIRE/TOPOLOGICAL SUPERCONDUCTOR INTERFACE

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In this work, the magnetoresistance (MR) of topological insulator (TI) single-crystal $Bi_{0.83}Sb_{0.17}$ and polycrystalline Bi_2Te_2Se glass-coated microwires in contact with In_2Bi superconducting (SC) leads was investigated. To study the TI/SC interface, the glass-coated microwire was connected to copper leads on one side using In_2Bi superconducting alloy (T_c=5.6 K) and on the other side using gallium. Gallium has superconductivity at temperatures below 1 K, so it was a normal metal in our measurements. The topologically nontrivial 3D superconductor In_2Bi has proximity-induced superconductivity of topological surface states. The *h/2e* oscillations of magnetoresistance in longitudinal and transverse magnetic fields (up to 1 T) at the TI/SC interface were observed at different temperatures (4.2 K–1.5 K) [1,2] (see Fig. 1). To explain the observed oscillations, we used magnetic flux quantization, which requires a multiply connected geometry where flux can penetrate into normal regions surrounded by a superconductor. The effective width Δr of the closed superconducting area of the TI/SC interface was determined to be 15 nm based on the analysis of FFT spectra and the beats of the MR oscillations for two different directions (longitudinal and transverse) of the magnetic field.

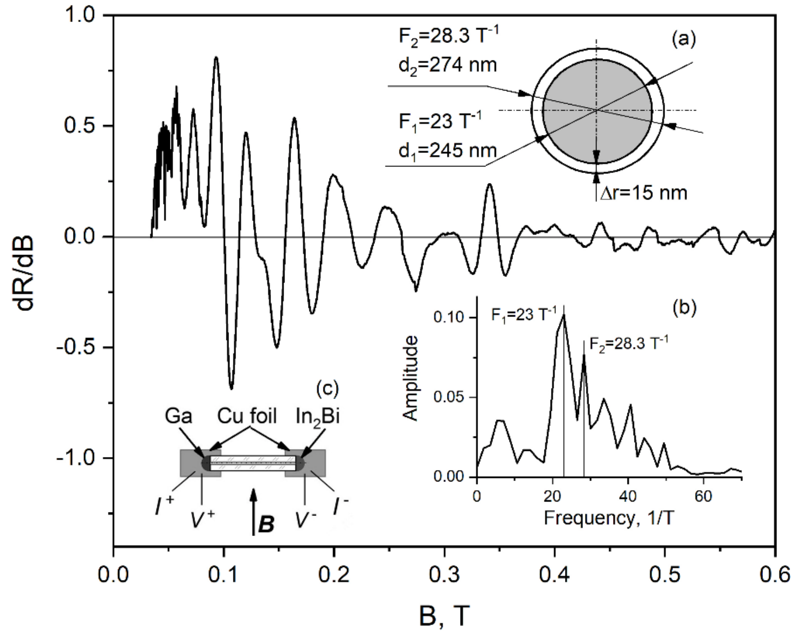

Figure1. Magnetic field dependence of the derivative of transverse MR for the $Bi_{0.83}Sb_{0.17}$ glass-coated microwire, D = 19 µm, d = 1.7 µm measured at 1.5 K (monotonic part is subtracted); Insert (a): The TI-SC contact area, for example, is presented in the form of a circle; Insert (b): FFT of the oscillating part of the derivative of transverse MR; Insert (c): Sketch of microwire mounting.

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VORTEX MATTER IN COPPER-OXIDE SUPERCONDUCTORS WITH PERIODIC DEFECTS

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The talk will focus on understanding how strategically placed topological defects affect the arrangement of Abrikosov vortices in a superconductor. This involves creating a precise potential landscape that can pin the vortices in place. It is crucial to ensure that these vortices are magnetically coupled, and hence, their separation should not exceed the London penetration depth at the desired operating temperature. The latter should be significantly lower than the superconductor's critical temperature T_c to minimize the impact of thermodynamic fluctuations. Achieving nanoscale resolution is particularly challenging in copper-oxide superconductors due to their complex atomic structure and susceptibility to environmental influences. Traditional lithographic methods are limited in this context, but these challenges can be overcome using a focused beam from a helium ion microscope (He-FIB). The 30 keV He^+ ion beam is employed to create various arrays of defect columns in thin films of $YBa_2Cu_3O_{7-\delta}$ (YBCO). These nanocolumns suppress T_c due to pair-breaking caused by numerous point defects, making them effective pinning sites for Abrikosov vortices.

The distinctive layout of our pinning landscapes leads to several noteworthy phenomena. The interaction between vortex pinning at artificial regular and intrinsic irregular sites results in the creation of an ordered Bose glass of vortices [1,2]. A periodic pinning pattern with voids allows us to study the competition between pinning and elastic forces that seek to restore the genuine hexagonal vortex arrangement [3]. In ultradense hexagonal pinning landscapes, we observe reentrant zero resistance at an applied magnetic field of 3.8 T, accompanied by a pronounced peak in the pinning force density of the vortex ensemble caused by commensurability effects. When the vortex density aligns with the precisely known density of defect columns, we can determine the pinning force exerted on an individual vortex by an artificial defect. We will also discuss how this pinning force varies with temperature in the context of Ginzburg-Landau theory.

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SUPERFLUIDITY ON NON-TRIVIAL GEOMETRIES IN A MAGNETIC FIELD AND FINITE TEMPERATURES IN THE CONTEXT OF THE BOSE-HUBBARD MODEL

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Quantum materials exhibit unique properties that make them suitable for the development of new technologies as well as for the improvement of existing devices. Many of these applications exploit the superconducting capabilities of the materials, allowing further development of a wide range of areas, such as metrology or quantum computation. It is well known that there exists a very close relationship between superconductivity and superfluidity, so advancements in the study of superfluid systems can be translated into an improvement of the understanding of superconductivity.

In this work we study the properties of the Bose-Hubbard model, which exhibits a superfluid phase, making use of the quantum rotor approach, which carefully includes the spatial correlations. This allows us to investigate a complicated form of the system: three-dimensional lattice under a uniform synthetic magnetic field with reduced dimensionality, i.e. with finite thickness in the direction perpendicular to the field. This opens up new possibilities, e.g. to analyze the correlations between strongly interacting bosons under the influence of a magnetic field in terms of the distance to the system's edge, visualizing effects of non-trivial topology of the band structure, or discovering parallels between finite and infinite systems in certain conditions. Furthermore, we are able to improve the accuracy on the account of the thermal fluctuations, which allows us to properly describe the state of the system at non-zero temperature. These elements allow for a better understanding of the Bose-Hubbard model, in particular, of its superfluid phase, which can in turn be related to superconductivity.

ATTRACTIVE VORTEX-VORTEX INTERACTION IN LOW-κ SUPERCONDUCTORS

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Type II superconductors whose Ginzburg-Landau parameter is close to the limiting value of $1/\sqrt{2}$ experience unusual thermodynamic properties when transitioning from the Meissner state to the mixed state [1]. It is believed that the reason for such behavior is the attractive interaction between the vortices. In order to investigate more deeply the nature of the interaction between vortices in low-κ superconductors, a generalized London model was developed that is valid in low magnetic fields. However, the attractive inter-vortex force is shown to be elusive within the simple picture of pairwise inter-vortex interactions. That's why we started a numerical investigation of the stability of the hexagonal vortex lattice, a structure that is most stable when the inter-vortex interaction is repulsive. It is shown that equilibrium vortex lattice structure undergoes structural phase transition from hexagonal one in high magnetic field to vortex chains in low fields. Structural transformation of vortex lattice is macroscopic manifestation of attractive vortex-vortex interaction in low-k superconductors.

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ENHANCED MAGNETIC FLUX PINNING AND CRITICAL CURRENT IN SUPERCONDUCTORS WITH NON-PERIODIC PINNING ARRAYS

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Non-periodic arrays of pinning sites (APS) are generally thought to be inefficient in magnetic flux pinning, since these APS are incommensurate with periodic vortex lattice whose deformations lead to an increase in the elastic energy. However, pinning properties of a superconductor can be even improved by using these APS. We demonstrate enhanced pinning in quasiperiodic (QP) and hyperbolic-tessellation (HT) APS.

Periodic APS are efficient for matching flux, resulting in a narrow peak in the critical current J_c. We found that a five-fold Penrose-tiling APS provided a broad maximum in $J_c(\Phi)$ [1], as verified in experiments with APS of antidots [2] and magnetic dots [3]. We demonstrated theoretically and experimentally [4, 5] that QP APS can enhance J_c in the important range above the matching flux. Thus, QP APS could be useful for applications demanding high J_c over a broad range of fields.

HT APS are characterized by a gradient density of pinning sites. Vortex matter in this device can coexist in three different phases: in a liquid phase, in a viscous liquid phase, and in a solid phase [6]. The penetration of magnetic flux in HT APS is strongly inhomogeneous, in contrast to the conventional Bean model. The magnetization of this device displays a remarkable hysteresis. Due to the enhanced asymmetry of the surface barrier for vortex entry and exit, HT APS could be used as a “capacitor” to store magnetic flux. The enhanced pinning efficiency of graded APS was demonstrated [7] by magnetization and MOI measurements in superconducting a-$Mo_{79}Ge_{21}$ thin films with antidots.

Recently, using the focused beam of a helium ion microscope, ultradense kagomé-like patterns have been fabricated in thin films of the cuprate superconductor $YBa_2Cu_3O_{7-\delta}$ [8]. In these kagomé-like patterns, the voids lead to magnetic caging of vortices, resulting in unconventional commensurability effects that manifest themselves as peaks in the critical current and minima in the resistance versus applied magnetic field up to ~0.4 T. These findings open the way for a controlled manipulation of vortices in cuprate superconductors by artificial sub-100 nm pinning landscapes.

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CROSSOVER FROM ISOLATED YSR STATES TO GAPLESS SUPERCONDUCTIVITY IN 2H-NBSE$_{2-X}$S$_X$ AT THE ATOMIC SCALE

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Anderson's theorem states that the superconducting gap of s-wave superconductors remains fully open even in presence of a large amount of non-magnetic impurities. A single isolated magnetic impurity leads to in-gap states, called Yu-Shiba-Rusinov (YSR) states. These states produce local density of states oscillations and have been extensively studied in pure 2H-NbSe$_2$ with a small number of magnetic impurities[1,2]. Here we study 2H-NbSe$_{2-x}$S$_x$ with highly diluted Fe impurities (0.02 at.%) and find that gapless superconductivity sets in over large areas[3]. The characteristic electron-hole asymmetry of the density of states of isolated YSR states is lost in the gapless regime. YSR oscillations exhibit wavevectors which differ from the ones found in pure 2H-NbSe$_2$, unveiling features in the electronic band structure such as the van Hove anomaly along the Γ-M direction. We show through density functional calculations that substitutional Se-S disorder leads to a band structure with enhanced quasi two-dimensional character. However, at the same time, the charge density wave of pure 2H-NbSe$_2$ is destroyed by in-plane disorder, leading to in-plane isotropic vortex cores in the gapless regime. Our experiments show that electronic correlations and disorder produce gapless superconductivity even with minute amounts of magnetic impurities.

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INTRINCIC VERSUS EXTRINCIC STRAIN DEPENDENCE OF SUPERCONDUCTIVITY IN THE QUASI-2D SUPERCONDUCTOR $CeIrIn_5$

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The selective control of the structure and physical properties of correlated electron materials at local, nano- and micro-length scales forms the basis of quantum nanodevices. The most investigated control parameters and the associated phase transitions that they drive are temperature, pressure, magnetic field and doping. Strain is only recently being explored as an extrinsic tuning parameter of the properties of quantum materials, mainly in conjunction of reduced dimensionality via the growth of thin films. Yet, intrinsic strain (inherent to the structure of a quantum material), is equally important to the understanding and control of the physical properties of the material and to the establishment of coherence at the ground state.

We will present here the intrinsic strain dependence of the structure and superconductivity of the quasi 2D superconductor $CeIrIn_5$. The evolution of the strain and the associated structural parameters as a function of temperature down to 300 mK (i.e. below its bulk superconducting transition) is clearly associated with the zero-resistance superconducting state at 1.2 K and the bulk superconductivity at 400 mK. We will compare our results with those obtained for thin films where the structure and superconductivity of $CeIrIn_5$ are controlled by extrinsic strain.

ESTIMATION OF CARRIER DENSITY IN Te-DOPED BISMUTH MICROWIRES

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In this report a new approach to characterizing the carrier density *n* in Te-doped Bi micro-wires is described. Carrier density is a fundamental parameter for determining the electrical transport properties of micro- and nanowires to optimize their performance for different applications, such as thermoelectrics. Measurements of the Hall effect, which is basically a 2D phenomenon, may be inapplicable for microwires and the Shubnicov–de Haas (SdH) oscillations for highly doped microwires. To determine the carrier density *n* of different Te-doped Bi microwires, we used measurements of Seebeck coefficient α(*n*) at 300 K at relative resistance $R_{300}/R_{4.2}(n)$. Glass-insulated Bi-Te microwires were prepared by liquid-phase casting by the Ulitovsky method [1]. The samples had a strictly cylindrical shape, the (1011) orientation along the wire axis, a diameter of >0.2 μm, and a length of a few tens of meters.

(a) (b)

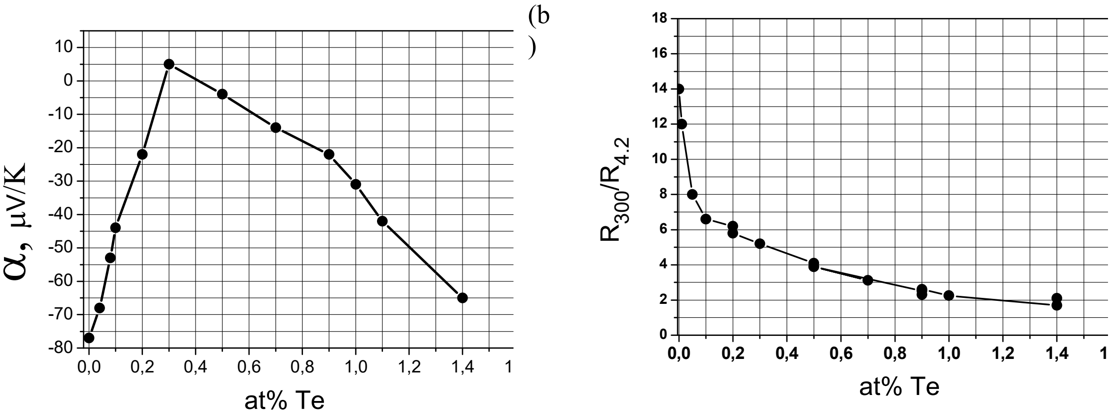

Figure 1. (a) Concentration dependences of coefficient Seebeck α(n) at 300 K and (b) - $R_{300}/R_{4.2}$ (n) of Bi-Te wires.

From (SdH) oscillations(to 0,4 at %Te) it was estimated Te concentration (in cm^{-3}) at 4.2K. At concentration- 0.3 at %Te there is a sign change thermopover which is a reference point and corresponds Lifshits's to topological transition [2].- to occurrence T- zone of conductivity at alloying. The results offer practical to optimize these parameters during preparation micro-wires for different applications.

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ENGINEERING QUANTUM STATES IN RADICAL MOLECULES ON SUPERCONDUCTING SURFACES

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Engineering quantum states in metal-free organic molecules is challenging due to their complex nature and inherent limitations. We investigated the properties of molecular assemblies engineered from a radical molecule tetrabromo-tetraazapyrene on a Pb(111) superconducting surface. We used scanning tunneling microscopy and spectroscopy in combination with theoretical calculations based on density functional theory and the numerically exact solution of the superconducting Anderson impurity model to study the behavior of the Yu-Shiba-Rusinov (YSR) states. Tunneling spectra show that YSR states lie close to the Fermi energy in isolated molecules. A quantum phase transition from singlet to doublet ground state can be induced by the change in the scanning tip distance. Additionally, we show that the presence of a second molecule allows us to tune the energy of the YSR state by changing the relative distance and can induce splitting of the YSR state for certain relative orientations. Constructing odd- and even-numbered molecular chains gives evidence of a periodic arrangement of charged and neutral molecules along the chains. Furthermore, the charge state of a tetramer chain can be manipulated by external electric fields induced by the presence of the scanning tip, opening the possibility to store information in these structures. Together, we show that the different molecular assemblies can be utilized as highly tunable building blocks for superconducting molecular quantum technologies.

FRACTIONAL VORTICES AND FLUX-FLOW INSTABILITIES IN TWO-BAND SUPERCONDUCTORS

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Multiband superconductors entail rich physics associated with the coexistence of different order parameters and competing interactions. Therein, the dynamics of vortices is of special interest as novel approaches to fluxon steering can be elaborated via tuning intensity and type of pinning sites, vortex structure, and the intervortex interaction. In particular, it was predicted theoretically [1] and proved experimentally [2] that fractional components of a composite vortex in two-band superconductors can exist separately as vortices with different parameters (e.g. magnetic penetration depth, coherence length) associated with the respective superconducting condensates. Usually, the fractional components of composite vortices tend to combine in the form of a composite vortex with full magnetic flux quantum, which can be explained by an interband attraction between two vortices from the different condensates [3,4]. A moving composite vortex behaves as a single-band Abrikosov vortex with effective parameters of the two-band system, which is why experimental observations of the two-band vortex nature in resistive measurements are challenging. However, the possibility for a moving two-band vortex to dissociate into vortices of two fractional components, due to the disparity of the vortex viscosity and flux of the vortex in the different bands [3], allows for emerging features in the current-voltage (I-V) curve of the superconductor.

In my talk, I will present the results of our theoretical studies of possible mechanisms for the dissociation of composite vortices in two-band superconductors under the action of a strong rf current in the presence of strong pinning sites [5]. The problem is considered on the basis of a nonlinear dynamic equation for a single composite vortex interacting with a single pinning potential trough. For the case of a rather strong pinning, we predict that a resistive branch in the I-V curve will occur due to the depinning of a more mobile vortex fractional component, while a less mobile fractional vortex component remains pinned. By contrast, for the case of a weak pinning, the depinning of composite vortices is followed by a dissociation of a composite vortex into a slow-moving vortex component whose velocity can even drop to zero and a fast-moving fractional component, giving rise to instability jumps in the I-V curves. Fractional instabilities observed recently experimentally for superconductor 2D films and 3D nanoarchitectures will be commented within the framework of the considered model.

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EDGE MAGNETISM IN ARMCHAIR GRAPHENE NANORIBBONS

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Interest in magnetically active graphene nanoribbons stem from the fact that they have great potential for applications in topological spintronic devices. However, due to their high reactivity, the edges are passivated during the synthesis process which leads to quenching of these magnetic states. Using scanning tunneling microscopy and spectroscopy, we find that magnetism can be revived through post annealing process, where unpassivated atoms are located near the termini. Namely, a pair of intense Kondo resonances emerges at each end of zigzag terminus, of as-grown 7 atom-wide-armchair GNR on Au (111), revealing the many-body screening effects of local magnetic moments. Although the Kondo resonance originates from a missing local orbital, it extends to a distance of 2.5 nm along the side of GNR. In contrast, the signal intensity sharply drops towards the bulk of the ribbon indicating no appreciable interactions with extended π state electrons. From the temperature dependence of the half width at half maximum we determine, a Kondo temperature of 68 K. The results are complemented by density functional theory (DFT) calculations which suggest a possible coupling between Kondo states despite screening effects of substrate electrons. These findings highlight a possibility of inducing magnetic ordering in passivated GNR by de-hydrogenation of atoms at the peripheries of zigzag termini.

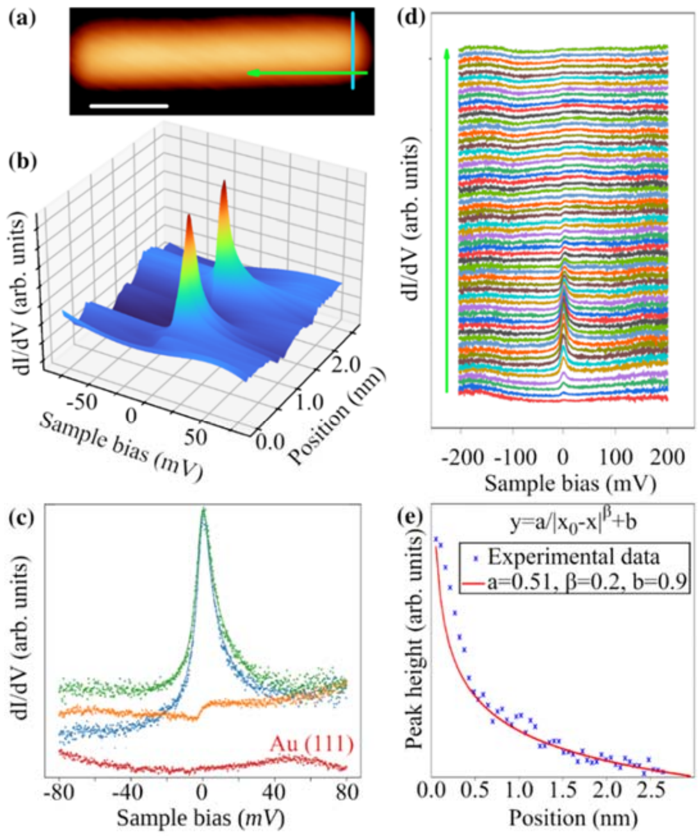

Figure 1. Spatial variations of Kondo resonances on 7-AGNR

SUPERCONDUCTING ARTIFICIAL NEURAL NETWORKS

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The need of radical reduction of energy consumption is becoming a decisive parameter limiting the development of new supercomputers. Recently it was started a very rapidly development of novel research direction: design of non-von Neumann computers with a brain-like architecture or artificial neural networks - superconducting ANNs. That requires the development of base elements of neural network - a nonlinear switching neurons and linear elements synapses, changing connection strength or "weight" of neurons in ANN [1].

The results of the design and research of artificial superconducting ANNs, based on superconducting spin valves and superconducting synapses constructed from layered superconductor-ferromagnetic hybrid nanostructures are presented.

Layered Nb/Co heterostructures demonstrate a change of the superconducting order parameter in thin niobium films due to switch from parallel to antiparallel magnetic ordering of adjacent ferromagnetic layers. Such heterostructures can be used as base elements of superconducting ANN [2,3]. Computer designed on superconducting ANN using these two basic elements - artificial neurons and artificial synapses, makes it possible to reduce for several orders of magnitude the power consumption compared to the existing computers built on semiconducting elements.

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MAGNETIC LIGHTNING IN SUPERCONDUCTING FILMS

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Magnetic flux lines in superconductors are topologically protected quantum objects which can be deformed when moving at very high velocities. These extreme conditions can be transitorily realised when superconductors undergo a thermomagnetic instability, for which the sample geometry and topology also come into play [1]. In this work, we explore the complex pattern of magnetic field penetration and identify its impact on the resonance frequency of NbTiN and Nb superconducting resonators by combining magneto-optical imaging (Figure 1) and high-frequency measurements [2]. We will also discuss the possibility of improving the performance of superconducting films by introducing periodic surface structures employing a femtosecond UV laser irradiation [3].

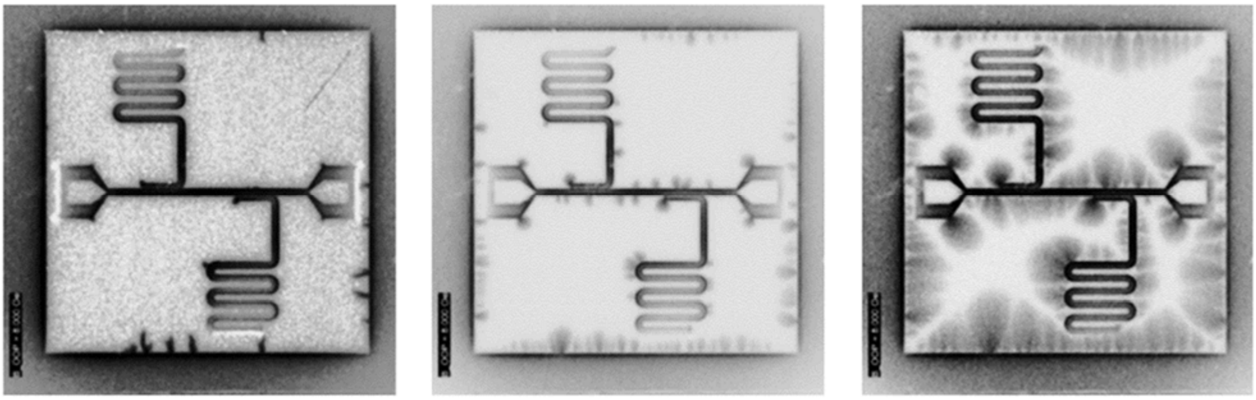

Figure 1. Magneto-optical image of a planar NbTiN superconducting resonator at three different temperatures (lowest to the left, highest to the right) after applying an out-of-plane magnetic field in zero-field-cooling conditions.

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QUANTUM SIZE EFFECTS ON ANDREEV TRANSPORT IN JOSEPHSON JUNCTIONS

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In this talk we discuss the experiments in epitaxial Nb(110)/Au(111)/Nb(110) trilayers, where the critical current density, the superconducting coherence length, and the superconducting transition temperature all show an oscillating behavior as a function of the Au-layer thickness. Such behavior cannot be understood based on simple models of the Josephson Effect, therefore we apply the first principles-based microscopic theory of inhomogeneous relativistic superconductivity to understand both the fundamentals and the specifics of the underlying physical mechanism of this behavior. We study the effects of spin-orbit coupling, and the effect of confinement and show that they induce a complex structure of Andreev states in the superconducting state which in turn modifies the quasi-particle spectrum and the Josephson supercurrent. Our study reveals the coexistence of two superconducting phases in the gold layers, the usual intraband s-wave phase and an additional Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) phase stemming from interband pairing (without magnetic field). The results indicate the rich interplay between quantum size and proximity effects which suggests the possibility of modifying superconducting transport properties by exploiting thickness-dependent quantum size effects.

NON-INVASIVE PROBING OF SUPERCONDUCTING NANOSTRUCTURES

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Understanding the dynamics of phase slips, topological fluctuations of the superconducting order parameter, in superconducting loops is very important for the development of future nanodevices. These loops show tremendous potential as building blocks for superconducting qubits [1], could be used for memory devices with topological protection [2], and determine the observed critical current profile in Superconducting Quantum Interference Devices (SQUIDs). Understanding these phase slips necessitates the capability to probe the number of flux quanta and determine the kinetic inductance associated with the Cooper pair density in such structures. Here we utilize a niobium resonator as a non-invasive probe capable of exploring the superconducting properties of an aluminum loop positioned close to the resonator. By locally applying a magnetic field, adjusting the temperature, and modifying the loop dimensions using focused ion beam milling, we induce changes in the kinetic inductance of the loop, which are directly manifested in the resonance frequency [3]. This approach highlights the promise of our proof-of-principle spectroscopy device as a tool for exploring the local Cooper pair density within inductively coupled superconducting nanostructures. Moreover, it provides an effective platform for manipulating and detecting phase slips, offering insights into the dynamics of these quantum phenomena.

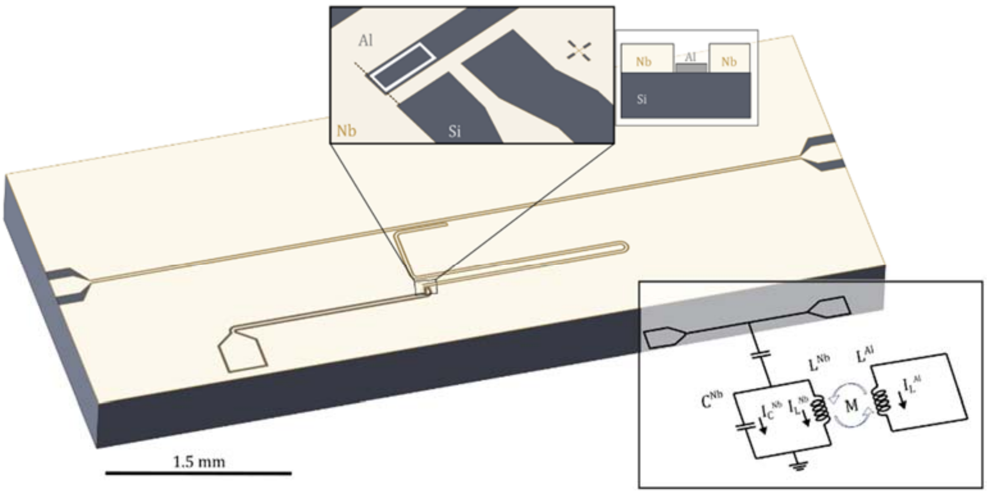

Figure 1. Schematic representation of the device, comprised of a λ/4 resonator capacitively coupled to the central feedline. The circuit diagram representation of the resonator-loop system is provided in the bottom inset.

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