Freestanding Oxide Membranes: science and applications

October 20-21 2025, Naples (Italy)

ABSTRACT BOOK

Joint Workshop
Financial support under PNRR, M4.C2.I1.1 MUR, funded by
the European Union – NextGenerationEU – Projects OMEGA and FOXES

Consiglio Nazionale delle Ricerche SPIN

DIPARTIMENTO DI FISICA ETTORE PANCINI

Finanziato dall'Unione europea NextGenerationEU

Ministero dell'Università e della Ricerca

Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

20 October 2025

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10.10 **Polarization Vortices in a Ferromagnetic Metal via Twistronics**
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10.30 **Unfolding the challenges to prepare single crystalline complex oxide freestanding membranes**
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10.50 **Freestanding $EuTiO_3$ Membrane – Towards Strain Induced Multiferroicity**
I. Lary, Tel Aviv University, Israel

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15.20 **Fine lattice tuning for strain-sensitive $NaNbO_3$ membranes**
O. Krymskaya, CNR-SPIN, University of Rome Tor Vergata, Italy

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Y. Chen, CNR-SPIN, Italy

12.50 **Superconducting FeSe thin films: Growth optimization for ring geometry exploration**
J. Petrovic, PSI Center for Photon Science, Paul Scherrer Institute, Switzerland

13.10 **Closing**

13.20 Lunch Break

Engineered Oxide Quasicrystals with Tunable Aperiodicity

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Quantum interfaces, essential for next-generation quantum technologies, require precise control over electronic and atomic-scale properties at material junctions. Oxide bicrystals present a novel platform for engineering such interfaces, offering tunable structural and electronic characteristics. In particular, by controlling twist angles, quantum interfaces with enhanced coherence, symmetry-breaking effects, and electronic transport properties can be obtained. In this talk, I will focus on three key aspects of obtaining oxide bicrystals with a focus on obtaining oxide quasicrystal with tunable *aperiodicity*. Using $SrTiO_3$ and $BaTiO_3$ as examples, I will showcase our group's work in achieving thin membranes and their bicrystals (with precise twist angles) with excellent control over thickness, stoichiometry, and surface termination. Additionally, I will introduce the sacrificial layer approach, which yields oxide membranes with a room-temperature dielectric constant of approximately 300. I will also discuss ways to create quasicrystalline interfaces with 8- and 12-fold symmetry combined with our experimental results. This work offers a materials science perspective on how epitaxy can enhance membrane technology, unlocking new opportunities for applications in energy storage, sensors, and nanoelectronics.

Polarization Vortices in a Ferromagnetic Metal via Twistronics

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Recent advances in moiré engineering have revealed new pathways for manipulating lattice distortions and electronic properties in low-dimensional materials. The development of methods for growing epitaxial films of complex oxides and separating them from the substrate via dissolution of a sacrificial layer allows these materials to partake in the twistronic game [1]. Here, we demonstrate that twisted-stacking can induce polarization vortices in freestanding metallic $SrRuO_3$ membranes, as shown in Fig. 1, despite the presence of free charge screening [2]. These polarization vortices are correlated with moiré-periodic flexoelectricity induced by shear strain gradients, and exhibit a pronounced dependence on the twist angle. In addition, multiferroic behavior emerges below the ferromagnetic Curie temperature of the films, whereby polarization and ferromagnetism coexist and appear to compete, showing opposite twist-angle dependencies of their respective magnitudes. Density functional theory calculations provide insights into the microscopic origin of these observations. Our findings extend the scope of topological polarization design beyond dielectric materials and into metals.

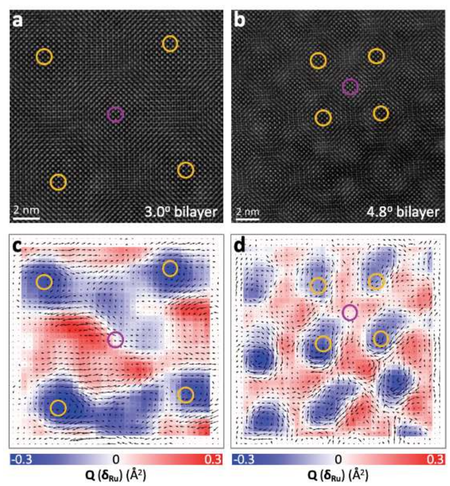

Fig. 1: Atomic-scale imaging of polar vortices in twisted-bilayer SRO membranes. a-b, Planar-view STEM-HAADF images focusing on the interface in the 3.0° and 4.8° twisted bilayers, showing Moiré patterns. c-d, Ru off-center displacement vector maps extracted from the STEM images focusing on the top layer, superimposed with their toroidal moment Q(δ_{Ru}), showing clear polarization vortices in metallic SRO.

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Unfolding the challenges to prepare single crystalline complex oxide freestanding membranes

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Single crystalline complex oxide freestanding membranes represent a transformative platform for exploring novel physical phenomena and advancing next-generation electronic device concepts. Among various fabrication approaches, the sacrificial layer method has emerged as a particularly straightforward and adaptable technique for membrane preparation. However, significant challenges persist in the precise synthesis and nanoengineering of diverse complex oxide compositions with various deposition methods.

In this work we present an investigation of chemical synthesis methods for producing high-quality, ambient-stable Ca-doped $Sr_3Al_2O_6$ (SAO) sacrificial layers to fabricate freestanding complex oxide membranes [1], including $La_{0.7}Sr_{0.3}MnO_3$ (LSMO) and $BiFeO_3/La_{0.7}Sr_{0.3}MnO_3$ (BFO/LSMO) bilayer systems. Our findings reveal that calcium incorporation in SAO plays a critical role in determining the sacrificial layer stability, influencing epitaxial growth dynamics and interface quality of the complex oxide layers [2]. Notably, direct BFO deposition on SAO produces nanocomposite arrangements, while $SrCa_2Al_2O_6$ (SC2AO) maintains the distinct layered architecture of the heterostructure. Finally, we demonstrate that the electrical transport and piezoelectric properties of the BFO/LSMO membranes, are preserved when transferred on flat arbitrary substrates. [3]

These results establish an innovative and versatile chemical synthesis platform for creating complex oxide freestanding films and bilayers that can be integrated across diverse substrate materials, potentially enabling the discovery of enhanced properties for prospective technological applications.

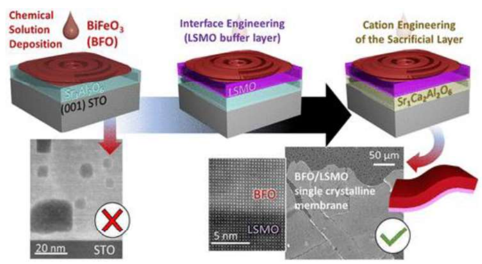

Fig. 1: The direct deposition of BFO/SAO multilayer with chemical methods results in a nanocomposite. Inserting an LSMO layer preserve the single-crystalline nature of the BFO but inhibits the membrane release. Finally, a more robust sacrificial layer composition, SC_2AO, offers an ideal building block to obtain (001)-oriented BFO/LSMO bilayer membranes.

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Freestanding $EuTiO_3$ Membrane – Towards Strain Induced Multiferroicity

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Multiferroic materials, which exhibit both ferroelectric and ferromagnetic properties, hold promise for multifunctional memory devices. However, these two order parameters rarely coexist naturally. One notable exception is europium titanate ($EuTiO_3$, ETO). In its bulk form, ETO is an antiferromagnet, but both theoretical predictions and experimental studies have shown that epitaxial strain can induce strong ferromagnetic and ferroelectric behavior [1].

A major limitation of strain engineering is the coupling between the film and its substrate, which complicates the interpretation of the material's intrinsic properties. To address this, we investigate the use of single-crystal membranes, which enable large strain while decoupling the material from substrate-induced effects.

We grow ETO thin films using pulsed laser deposition (PLD). To facilitate membrane release, we incorporate a sacrificial $Sr_3Al_2O_6$, buffer layer, which is epitaxially compatible with ETO and dissolves readily in water. To prevent undesirable reactions between europium and the aqueous environment during the release process, we add two protective $SrTiO_3$ capping layers.

Using this approach, we successfully fabricated and released ETO-based heterostructures. Reflection high-energy electron diffraction (RHEED) patterns and intensity oscillations confirm coherent, layer-by-layer growth. Transmission electron microscopy (TEM) reveals a well-defined, epitaxially grown crystalline heterostructure, consistent with the intended design. We characterize the membrane's intrinsic magnetic properties using a scanning superconducting quantum interference device (SQUID) microscope.

This work represents a significant step toward realizing strain-tunable, single-crystalline ETO membranes, opening new avenues for exploring multiferroic behavior in freestanding systems. .

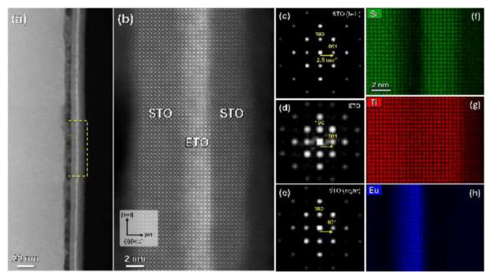

Fig 1: High-angle annular dark-field scanning transmission electron microscope images, power spectra calculated from the noted regions, and elemental maps obtained by energy-dispersive x-ray spectroscopy using net intensities of Sr L, Eu L, and Ti K characteristic x-ray photon energies, showing atomic-column resolution of the sample and the high quality of the synthesis process.

This work is funded by the Israeli Science Foundation under grant number 1711/23

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Free-standing Ferroelectric and Magnetoelectric single crystal Membranes with super-elasticity

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Ferroelectrics are usually inflexible oxides that undergo brittle deformation. We synthesized freestanding single crystalline ferroelectric BTO($BaTiO_3$), BFO($BiFeO_3$) and BTO/LSMO bi-layer membranes and with a damage-free lifting-off process. Our ferroelectric membranes can undergo a nearly 180° folding during in-situ bending test, demonstrating a super-elasticity and ultra-flexibility[1]. We found that the origin of the super-elasticity was from the dynamic evolution of ferroelectric nanodomains in BTO and phase change in BFO. High stresses modulate the energy landscape dramatically and allow the dipoles to rotate continuously. A continuous transition zone is formed to accommodate the variant strain and avoid high mismatch stress usually causing fracture. BTO/LSMO shows a self-assembled spring shape due to the lattice mismatch as free-standing in the air. Such spring can undergo up 50% of the length change upon a mechanic forced is loaded. The phenomenon should be possible in other ferroelectrics systems through domain engineering. The ultra-flexible epitaxial ferroelectric membranes could enable many magnetoelectric applications such as flexible sensors, memories and electronic skins.

1. Dong, *et al*., Science **366**, 475-479 (2019)

Complex Oxides Micromechanics

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Micro-Electro-Mechanical Systems are one of the fundamental building block of state-of-the art consumer electronics and are so far on silicon technology.

The physical properties of the oxides of transition metals are dominated by 3d and 5d orbitals, giving rise to electron correlation phenomena and a strong interplay between electronic, spin, and lattice degrees of freedom. A key properties of complex oxides is the coexistence of a large variety of electronics properties (magnetism, superconductivity, high-k dielectrics, ferroelectricity, …) and often compatible lattice structure (mainly perovskite-type). This opens the possibility to realize epitaxial heterostructures where the physics of each layer synergistically determines the behavior of the final device.

The growth of complex oxides in thin epitaxial films over oxide substrates with selected crystallographic orientations allows engineering micro&nanomechanical devices with tailored functionalities, geometries, and structural properties. This is possible thanks to advanced fabrication protocols combining surface and bulk micromachining [1] that we implemented on oxides compounds taking inspiration from standard Si-based MEMS technology,

Some of our recent results in the field of oxide nanomechanics includes nanoactuators[2], mehcanical bolometers, magnetic resonators [3], or superconduting MEMS [4].

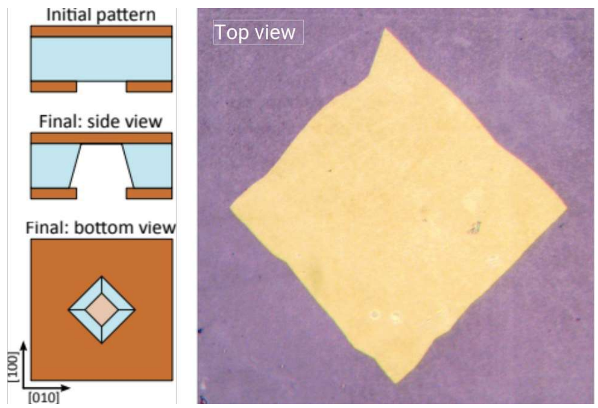

Figure 1: (left) Schematic illustration and (right) optical micrograph in reflected light of a 100 nm-thick suspended $(La,Sr)MnO_3$ membrane obtained by back-side etching of the $SrTiO_3(001)$ substrate

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Curvature-induced polar structures in oxide nanomembranes

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Structural distortions in oxide thin films can be engineered through epitaxial strain, typically applied in planar directions. However, generating controlled strain gradients often requires introducing film inhomogeneities—such as compositional variations or strain relaxation—and the films remain mechanically clamped to their substrates. Freestanding oxide membranes [1], by contrast, can be manipulated more freely: they can sustain larger strains [2], adopt three-dimensional morphologies with designed curvature, and thereby host built-in strain gradients. This opens new pathways for structural and functional design in complex oxides.

In this work, I present two examples illustrating how curvature can drive polar phenomena in oxide membranes:

• Buckling-induced strain fields: Using $BaTiO_3$ as a model tetragonal ferroelectric-ferroelastic system, I demonstrate how mechanically induced wrinkling leads to a complex strain landscape. This landscape stabilizes a two-tiered domain architecture: mesoscale a/c domain bundles aligned with wrinkle curvature, and nanoscale a_2 domains arising from local in-plane lattice misorientation [3].

• Rolling-induced polar metals: Controlled rolling of oxide membranes generates constant curvature, which can drive polar displacements even in non-ferroelectric materials. I show how microscale helical structures fabricated from $SrRuO_3$—a nominally centrosymmetric metal—exhibit anisotropic Second Harmonic Generation signal, indicative of a broken centrosymmetry in the material, potentially realizing a new form of polar metal.

I will discuss how such curvilinear architectures in oxide membranes can be harnessed to engineer novel functionalities, with potential applications in piezoelectric devices, flexible electronics, and spintronic systems.

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Ferroelectric topologies in BaTiO3 nanomembranes for light field manipulation

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Ferroelectric topological textures in oxides exhibit exotic dipole-moment configurations that would be ideal for nonlinear spatial light field manipulation. However, conventional ferroelectric polar topologies are spatially confined to the nanoscale, resulting in a significant size mismatch with laser modes. Here, we report a dome-shaped ferroelectric topology with micrometer-scale lateral dimensions, using nanometer-thick freestanding $BaTiO_3$ membranes and demonstrate its feasibility for spatial light field manipulation. The dome-shaped topology results from a radial flexoelectric field created through anisotropic lattice distortion, which in turn generates center-convergent microdomains. The interaction between the continuous curling of dipoles and light promotes the conversion of circularly polarized waves into vortex light fields through nonlinear spin-to-orbit angular momentum conversion. Further dynamic manipulation of vortex light fields can also be achieved by thermal and electrical switching of the polar topology. Our work highlights the potential for other ferroelectric polar topologies in light field manipulation.

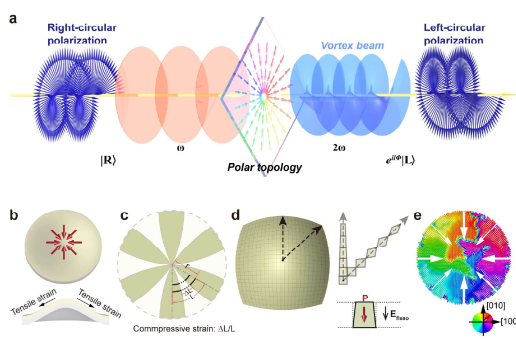

Fig. 1: Exploiting polar topology for nonlinear vortex beam generation. [1]

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$Sr_3Al_2O_6$ Sacrificial Layer for Solid Electrochemical Cells and Solid State Batteries

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The increasing interest in free-standing membranes (FSMs), coupled with the growing demand for miniaturized devices in energy storage and conversion, has led to the advancement of thin-film technologies. Indeed, FSMs are strategically important for the development of micro-electrochemical devices such as micro-Solid Oxide Fuel Cells (m-SOFCs), micro-Solid Oxide Electrochemical Cells (m-SOECs), and micro-Solid State Batteries (m-SSB). In this context, strontium aluminate $Sr_3Al_2O_6$ (SAO) has gained significant attention as a sacrificial layer in the fabrication of free-standing thin-film membranes due to its solubility in water [1-2]. For this reason, it can be used to improve the manufacturing of complex oxide thin films as free-standing membranes. One of the more attractive materials as free-standing membranes is samarium-doped ceria (SDC) and gadolinium-doped ceria (GDC) for m-SOFCs and m-SOECs [2].

Indeed, doped Ceria-based materials represent an emerging class of electrocatalysts for CO_2 reduction in SOECs due to their high stability and efficiency in converting CO_2 to CO with remarkable carbon tolerance.

Lithium manganese oxide $Li_xMn_2O_4$ (LMO), with its spinel structure, and perovskite $Li_{3x}La_{1/3-2x}TiO_3$ (LLT) are good candidates as cathode and electrolyte, respectively, for next-generation Li-ion batteries due to their high Li-ion mobility, material's low cost, and minimal toxicity [3-4].

In this work we report the growth mechanism, structural characterization, and transport properties of the SDC, LLT, and LMO onto the SAO sacrificial layer onto SrTiO3 and MgO substrates produced by Pulsed Laser Deposition (PLD) technique.

Free-standing membranes of SDC, LLT, and LMO were successfully fabricated by etching the SAO layer in water.

The ionic and electronic conductivity of the membranes was successfully characterized by Electrochemical Impedance Spectroscopy (EIS). Thus, our work demonstrates the potential of the sacrificial layer method for integrating high-quality oxide thin films into advanced device architectures.

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Fine lattice tuning for strain-sensitive $NaNbO_3$ membranes

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$NaNbO_3$ (NNO) is a complex oxide known for its sensitive piezoelectric, optical, and photocatalytic responses. At room temperature, NNO remains indecisive between ferroelectric and antiferroelectric states, differing only slightly in energy. In epitaxial thin films, even modest strain, below 1%, can shift this subtle balance, altering its functional behavior. Recent studies suggest that membranes thinner than 40 nm prefer ferroelectric order, while thicker films likely maintain mixed and switchable states.

This delicate equilibrium can be finely tuned by selective doping. We introduced about 25% Ca^{2+} on the A-site, probably stabilizing reversible electric-field-driven switching, and 12.5% Mn^{4+} on the B-site to lower the optical bandgap and enhance visible-light absorption. Such co-doped composition ($Na_{0.75}Ca_{0.25}Nb_{0.875}Mn_{0.125}O_3$) can be particularly promising for optical devices, sensitive piezoelectric sensors, and perhaps for improved photocatalytic water splitting.

To further explore and possibly amplify these NNO properties, we propose studying them in freestanding membrane form. Considering the material's extreme strain sensitivity, we precisely tuned the lattice parameter of a $Sr_3Al_2O_6$-based sacrificial layer to match NNO. Partial substitution of Sr by Ca finely reduces the lattice parameter from ~16 Å to about 15.8 Å, ideally matching the NNO pseudocubic cell (3.88–3.95 Å). Small additions of Na^+ significantly speed water dissolution, while trace Cu^{2+} seems to stabilize the sacrificial layer during membrane growth under optimal conditions for NNO deposition. Such gentle, lattice-matched membrane release might allow precise control over piezoelectric, photocatalytic, and optical responses, perhaps opening pathways toward flexible electronics, micro-capacitors, nonlinear optics, and piezo-photocatalytic systems.

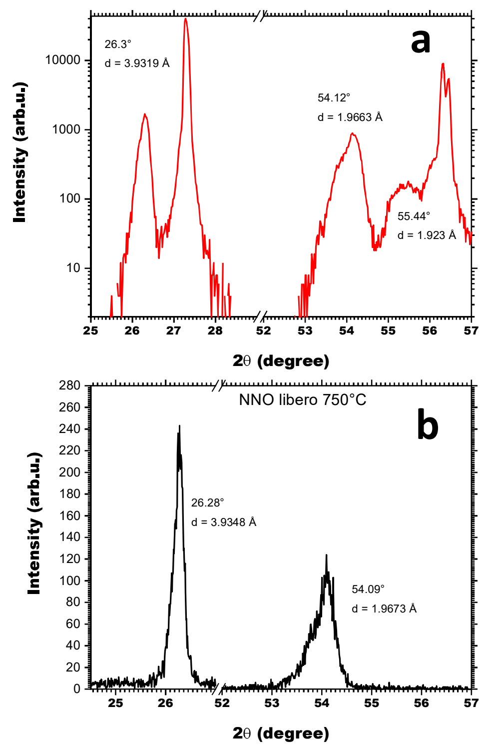

Fig. 1 XRD study for NNO 100 nm films deposited at 750°C and oxygen pressure 1 mbar over the 20 nm sacrificial Ca-doped SAO layer: a) on NGO (110) substrates, b) released freestanding membrane.

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Band-gap and spin texture engineering in bismuth calchogenhalides van der Waals double layers

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Two-dimensional (2D) heterostructures [1-2] are among the most interesting classes of van der Waals (vdW) materials due to their intrinsically tunable properties emerging thanks to a wide range of fundamental degrees of freedom such has stacking, stoichiometry, twisting, and so on.

Materials exhibiting strong spin–orbit coupling (SOC) are highly sought after for the development of next-generation spintronic devices, where electron spin can be manipulated without the need for external magnetic fields.

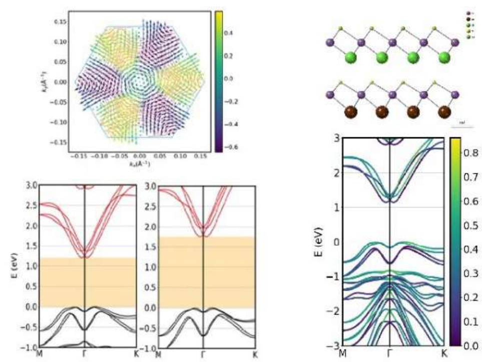
Spin control in spin-textured band materials [3,8] or Rashba effect [9] arising in materials where SOC is accompanied with the lack of spatial inversion symmetry are fundamental phenomena that are being widely explored in the context of 2D vdW heterostructures.

The interplay between the interlayer interaction (driven by vdW forces), SOC [10-11], twisting between different layers, in-plane or out-of-plane strain [3-7] give rise to a large number of exotic behaviors.

Promising candidates in this context are 2D *Bismuth*-based ternary compounds in which the presence of the heavy *Bi* atom plays a central role in enhancing SOC and have attracted considerable attention due to their large Rashba spin splitting [2] which allows their use in spintronic applications. [10-11]

This family of materials belongs to a class known as "Janus" materials, characterized by an intrinsic asymmetry between the top and bottom peripheral layers and this breaking of spatial symmetry can enhance or induce the Rashba effect.[8-9,12]

Furthermore, the intrinsic asymmetry of the "Janus" structure generates a built-in electric field within each monolayer and drives charge separation along the stacking direction, condition that can enable the emergence of new kind of phenomena.



In this work, we explore by first principles calculations (within Density Functional Theory framework, even with hybrid exchange-correlation functionals) the electronic properties of vdW bilayers of bismuth chalcogen halides: BiXY (X = S, Se, Te and Y = Cl, Br, I), with the main focus on the band gap and Rashba coefficients tunability. Spin texture patterns tunability by considering all different combinations of chalcogens and halogens and different kinds of stacking of the two layers, will also be discussed.

Finally, we will also discuss the effects of an applied external electric field along the stacking direction and/or the presence of "in plane" / "out of plane" (hydrostatic) uniaxial and biaxial strain applied on the BiXY bilayers and the effect of the relative twisting between the layers in order to obtain some hints about the existence of possible "magic angles" that enables the emergence of new quantum phases and phenomena.

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Ultrafast electron diffraction for the dynamical investigation of thin layered samples at REGAE

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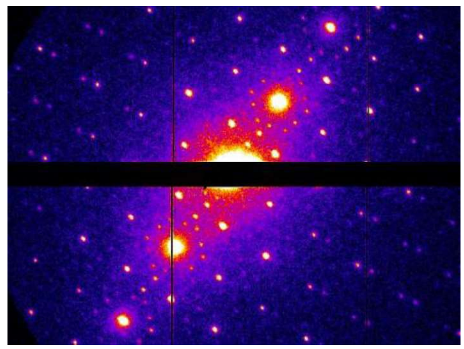
Ultrafast electron diffraction (UED) allows studying dynamical processes with femtosecond time resolution at the atomic scale [1]. Due to their strong interaction with matter, electrons are particularly suited for the investigation of very thin samples. For such UED experiments DESY in Hamburg has built and is operating the REGAE facility

REGAE is based on a RF-operated linear accelerator which generates short electron pulses with energies of 2 MeV – 5 MeV and a duration of less than 20 fs.

For electron diffraction experiments from solid samples REGAE is equipped with a high-precision crystallography goniometer. Diffraction patterns are recorded with a Jungfrau 1M detector, capable of direct electron detection and single shot experiments [2].

In a first demonstration experiment we were able to solve and refine the structure of the layer silicate muscovite and the in-commensurate structure of the quantum material tantalum disulfide (TaS_2) at great level of detail and with high quality [2].

For time resolved diffraction experi-ments REGAE is equipped with a pump laser system providing wavelengths of 800 nm and 400 nm. The system is currently upgraded with a NOPA to provide a larger pump wavelengths range and a cryo-cooler for diffraction experiments at temperatures down to 10 K.



Diffraction pattern of a 30 nm thick TaS_2 sample recorded with 3.5 MeV electrons at REGAE.

More recently we have conducted diffraction experiments of $LiMnO_4$ oxide membranes grown by PLD [3]. The results highlight the great potential of UED for dynamical and operando studies of Li-ion battery electrodes and their charging dynamics in presence of light excitation.

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Complex Oxide Membranes as Platforms for the Growth of Freestanding Heterostructures

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Freestanding complex oxide membranes offer a powerful platform for exploring low-dimensional quantum phases, strain-tunable functionalities, and novel heterostructure geometries. However, fabricating high-quality freestanding films remains challenging, particularly for solvent-sensitive transition metal oxides (TMOs) such as VO_2, $SrIrO_3$, YBCO, and others, where conventional water-based or wet-etch lift-off techniques often compromise structural and electronic integrity [1].

In this talk, I will present a strategy to overcome these limitations based on the vector substrate concept [2, 3]. This approach employs ultrathin single-crystalline $SrTiO_3$ (STO) membranes, transferred onto mismatched host substrates (e.g., sapphire, silicon), as epitaxial templates. These STO membranes maintain excellent crystallinity and enable the growth of functional TMOs in symmetry and orientation configurations otherwise inaccessible via conventional epitaxy. In particular, advanced spectroscopic techniques such as ARPES have demonstrated the successful growth of electronically functional oxide films, including TiO_2, $SrVO_3$, $SrNbO_3$, and even chalcogenides like FeSe, on these vector substrates [3]. These results confirm that full electronic functionality can be preserved in freestanding geometries.

$SrTiO_3$ (STO) membranes can efficiently serve as a versatile, solvent-free platform for the fabrication of freestanding complex oxide heterostructures. Importantly, they enable the direct application of well-established growth procedures developed for conventional STO substrates, allowing seamless adaptation of existing material recipes. This approach opens also new opportunities to investigate previously observed emergent phenomena at STO/TMOs interfaces.

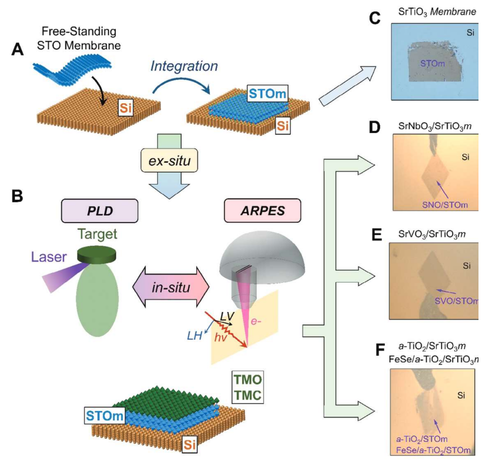

Fig 1. Workflow of the in situ study of PLD-grown complex oxide membranes using ARPES [3]. A) Integration of a freestanding $SrTiO_3$ membrane (STOm) onto a Si wafer. B) Growth of complex oxides on the Si-integrated STOm and subsequent in situ ARPES measurements. C–F) Photographs of the STO membrane and the resulting heteroepitaxial films.

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Spalled freestanding oxides micro-membranes: advantages, challenges and perspectives

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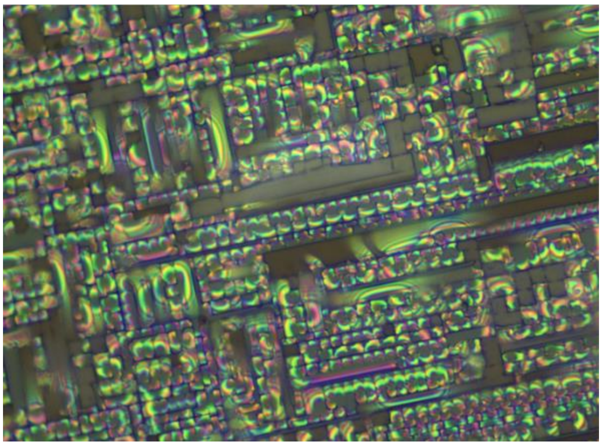
The discovery of the water-soluble $Sr_3Al_2O_6$ sacrificial layer, a simpler alternative to HF-removable oxides, has represented a major breakthrough in the field of freestanding oxide membranes. This advancement opened unprecedented opportunities for exploring complex phase diagrams and accessing otherwise unreachable states of matter, as freestanding oxide membranes exhibit flexibility and structural tunability far superior to that of bulk materials and conventional epitaxial films.

As an alternative to this approach, a novel fabrication method has been developed at CNR-SPIN Naples, based on strain engineering in PLD-grown samples. This technique enables the realization of freestanding epitaxial bilayer membranes by spalling part of the underlying single-crystal substrate along with the grown film. The resulting membranes retain high-quality epitaxial film/substrate interfaces and are obtained in large numbers (~10^5 per PLD growth), with lateral sizes of a few microns [1,2,3].

Here, we describe the fabrication method, highlighting the role of PLD parameters in governing membrane formation. We demonstrate its application to $SrTiO_3$-based bi- and trilayer membranes (as $LaAlO_3/LaSrMnO_3/SrTiO_3$, shown in Figure) as well as to oxide films on ruthenate substrates.



Optical image of an as-grown spalled $LaAlO_3/LaSrMnO_3/SrTiO_3$ sample, showing square-shaped membranes of approximately 3 µm in size (iridescent area) and the exposed $SrTiO_3$ substrate following membrane detachment (dark green area).

Furthermore, we illustrate their relatively straightforward integration on Si via van der Waals stacking, focusing on the case of $LaAlO_3/SrTiO_3$ freestanding spalled membranes.

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Micromanipulation and characterization of freestanding oxide hetero-membranes grown by RHEED-PLD method

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Oxide heterostructures provide a versatile and promising platform for exploring novel electronic phases and developing groundbreaking device architectures. By employing a method rooted in pure strain engineering and leveraging Pulsed Laser Deposition (PLD) assisted by Reflection High-Energy Electron Diffraction (RHEED), we have demonstrated the fabrication of freestanding $LaAlO_3/SrTiO_3$ (LAO/STO) micro-membranes. These membranes exhibit electronic properties that closely mirror those of their bulk heterostructure counterparts, confirming the viability of our approach.

Building on this advancement, we extended the same fabrication technique to create freestanding $LaAlO_3/Sr_2RuO_4$ (LAO/SRO) hetero-membranes, to probe strain-dependent superconductivity in SRO. In this configuration, the LAO layer is deposited via RHEED-assisted PLD, while the substrate consists of a SRO single-crystal grown using the floating zone method. To characterize the structural and morphological features of these membranes, we carried out detailed analyses using optical microscopy and scanning electron microscopy (SEM), focusing on membrane formation, chemical composition, and crystallographic orientation.

Examples of membrane manipulation and transfer onto marked Si substrates using micromanipulators in the field-emission scanning electron microscope are presented. Additionally, preliminary electrical transport measurements at room temperature are discussed.

These findings open new possibilities for integrating oxide functionality into semiconductor electronics.

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Geometric and Strain Effects on the Electronic Properties of (111) LAO/STO Interfaces

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The (111)-oriented interfaces of perovskite oxides, such as $LaAlO_3/SrTiO_3$ (LAO/STO), provide a unique platform to engineer two-dimensional electron systems with strong spin-orbit coupling, multiband character, and tunable symmetry breaking. In this seminar, we explore how the hexagonal symmetry of the (111) interface and strain affect the low-energy electronic structure and topological properties of the confined electron gas.

Using a tight-binding model that incorporates spin-orbit coupling, trigonal crystal field effects, and electronic confinement self-consistently, we demonstrate [1-2] that both geometry and strain are key to controlling topological transitions and Berry curvature features. Specifically, the application of compressive trigonal strain can drive the system through a topological phase transition by tuning the location and gap of symmetry-protected Dirac cones in the Brillouin zone. The resulting phase supports quantum spin Hall behavior with nontrivial spin and orbital momentum textures.

Moreover, we predict that Berry curvature hotspots emerge naturally in this setting and can be indirectly probed through a gate-tunable anomalous Hall effect under an in-plane magnetic field. These findings provide guidance for future experiments aiming to harness symmetry-breaking fields and strain engineering to manipulate transport and topological responses in (111) oxide heterostructures.

We suggest that LAO/STO membranes grown along the (111) direction, possibly in freestanding form, are promising candidates for realizing gate-tunable topological phases and for probing fundamental Berry-phase-related transport phenomena in oxide systems.

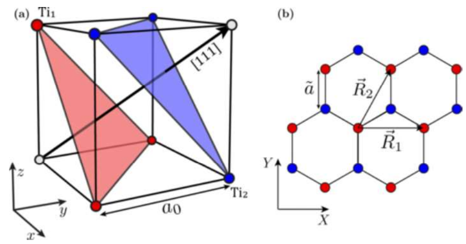

Fig. 1: (a) Schematic representation of Ti atoms in STO lattice. The red and blue dots represent two different nonequivalent atoms belonging to the two different planes depicted in the figure. (b) Projection on the (111) plane of the Ti atoms.

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Charge and spin transport properties of STO-based nanostructures in normal and superconductive phases

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We have computed the spin-Hall conductance in a multiband model describing the two-dimensional electron gas formed at a LaAlO3/SrTiO3 interface in the presence of a finite concentration of impurities [1]. Combining linear response theory with a systematic calculation of the impurity contributions to the self-energy, as well as to the vertex corrections of the relevant diagrams, we recover the full spin-Hall vs sheet-conductance dependence of LaAlO3/SrTiO3 as reported in Trier *et al.* [Nano Lett. **20**, 395 (2020)], finding a very good agreement with the experimental data below and above the Lifshitz transition. In particular, we demonstrate that the multiband electronic structure leads to only a partial, instead of a complete, screening of the spin-Hall conductance, which decreases with increasing the carrier density. Our method can be generalized to other two-dimensional systems characterized by a broken inversion symmetry and multiband physics.

We have analyzed a single and a double quantum dot coupled to two fermionic leads, a representative model for describing transport in nanostructures, applicable to systems with strong local electron-electron interactions. We solved the Lindblad equation to analyze the system's steady state and dynamics. Subsequently, we have used numerical techniques based on matrix product states to simulate the entire system, including the fermionic leads, avoiding Markovian and weak coupling approximations. inadequate in some regimes of small bias and strong electronic correlations, incorrectly predicting the absence of current. Moreover, we have introduced a magnetic field to explore joint effects with those due to spin-orbit coupling,

We have studied the superconducting properties of multiband two-dimensional transition metal oxide superconductors by analyzing not only the role played by conventional singlet pairings, but also by the triplet order parameters, favored by the spin-orbit couplings present in these materials [3]. In particular, we have focused on the two-dimensional electron gas at the (001) interface between band insulators LaAlO3 and SrTiO3, where the low electron densities and the sizable spin-orbit couplings affect the superconducting features.

Finally, we have extended the calculation of the charge and spin transport properties of single and double quantum dots to the case of superconducting leads.

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Quantum Transport and Devices based on LAO/STO freestanding micro-membranes

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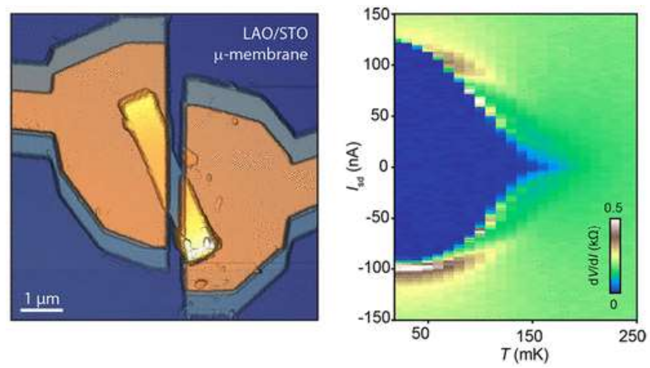

The development of methods for producing free-standing oxide membranes has opened new possibilities for controlling material properties, integrating oxides with other material platforms, and exploiting their functional properties in devices. In this presentation, I will focus on how free-standing geometries expand the possibilities for mesoscopic quantum electronic devices, a field traditionally dominated by conventional semiconductor platforms such as silicon, germanium, or III–V heterostructures.

The canonical oxide 2DEG at the LAO/STO interface exhibits unique properties, including strong spin–orbit interaction and an intrinsic, gate-tunable superconducting phase. I will discuss how free-standing geometries enable new approaches to realizing mesoscopic oxide devices. The focus will be on the platform of spalled LAO/STO micro-membranes [1], with an emphasis on their superconducting properties [2], offering new insights into the microscopic structure of the superconducting phase. Furthermore, we have achieved local electrostatic gate control of micro-membranes and quantum dot devices which exhibit evidence of effective attractive interactions at low temperatures.

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Freestanding single-crystal superconducting electron-doped cuprate membrane

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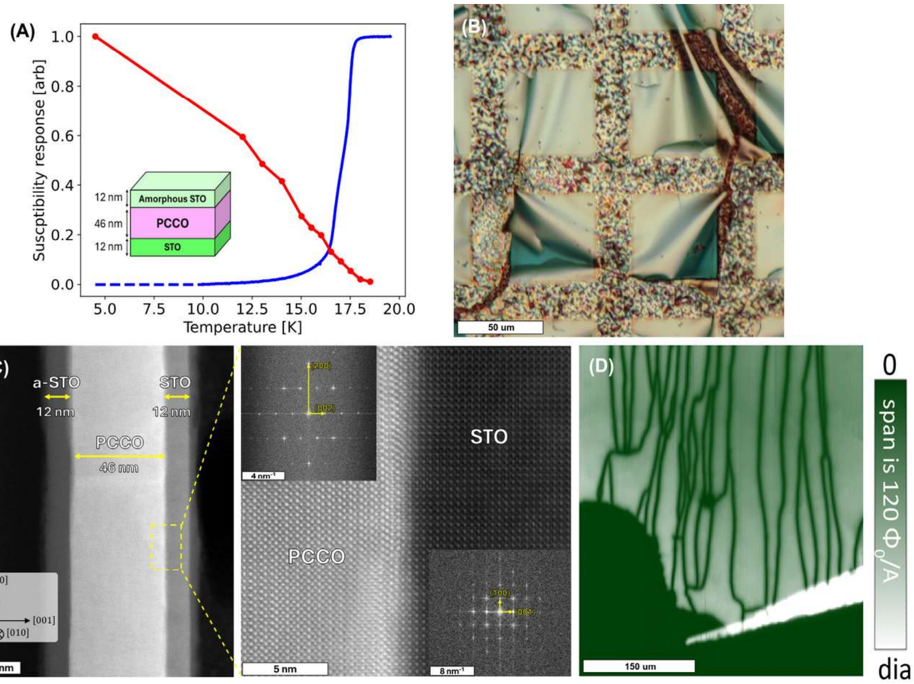

Thin films of cuprate superconductors are easier to control in terms of doping as compared to bulk samples. However, they require specific substrates to facilitate epitaxial growth. These substrates are often incompatible with materials used in electronic applications.

Furthermore, it is challenging to separate the substrate's properties from the material of interest. Here, we demonstrate the fabrication of an electron-doped cuprate membrane.

We show that the membrane has a coherent crystal structure. Furthermore, the superconducting properties of the membrane post-liftoff closely resemble those of the thin films pre-lift-off, as revealed by a scanning superconducting quantum interference device (SQUID) microscope. Future experiments involving strained cuprate membranes will be discussed.

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Theory of charge-to-spin conversion under quantum confinement

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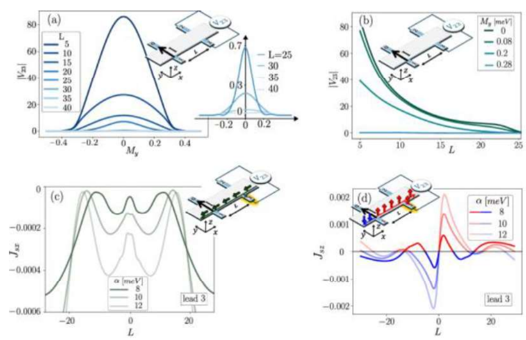
The interplay between spin and charge degrees of freedom in low-dimensional systems is a cornerstone of modern spintronics, where achieving all-electrical control of spin currents is a major goal. Spin-orbit interactions provide a promising mechanism for such control, yet understanding how spin and charge transport emerge from microscopic principles remains a fundamental challenge. Here we develop a spin-dependent scattering matrix approach to describe spin and charge transport in a multiterminal system in the presence of Rashba spin-orbit interaction. Our framework generalizes the Büttiker formalism [1] by offering explicit real-space expressions for spin and charge current densities, along with the corresponding linear response function. It simultaneously captures the effects of quantum confinement, the response to external magnetic fields, and the intrinsic properties of the electronic bands, offering a comprehensive description of the spin-charge interconversion mechanisms.

We apply this approach both to a Hall bar geometry [2], finding agreement with experimental results at oxide interfaces [3], and to a quantum dot with Rashba spin–orbit coupling, where we uncover the interplay between spin currents and mesoscopic interference.

Fig. 1: Results for the Hall bar geometry. (a) Nonlocal voltage, $|V_{23}|$, as a function of the external magnetic field applied along y, M_y. The blue gradient corresponds to increasing lead spacings L. (b) Vertical slices from panel (a) illustrating the exponential decay of $|V_{23}|$, when the lead spacing is increased. (c) x-polarized spin current, computed using Eqs. 2, 3 of Ref [2] for $\vec{M}=0$. The inset illustrates the generation of the x-polarized spin current via the Edelstein effect. (d) Computed z-polarized spin current, also obtained from Eqs. 2, 3 of Ref. [2] for $\vec{M}=0$. The inset illustrates the generation of the z-polarized spin current via the spin-Hall effect. The source and drain leads are positioned at the center of the system, while the measuring probes are placed either to the left or right. The results in panel (a) and (b) reproduce qualitatively the experimental data of Ref. [3]



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Dirac-like fermions anomalous magneto-transport in a spin-polarized oxide two-dimensional electron system

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In two-dimensional electron systems (2DESs) the breaking of the inversion, time-reversal and bulk crystal-field symmetries is interlaced with the effects of spin-orbit coupling (SOC) triggering exotic quantum phenomena. By engineering a spin-polarized oxide 2DES with Rashba-like SOC and hexagonal band warping, here we present the first report of an anomalous quantum correction to the magnetoconductance by Dirac-like fermions experiencing competing weak anti-localization and weak localization back-scattering (Fig. 1(a) and ref. [1]), with a phenomenology analogous to that of gapped topological insulators [2]. The results were obtained on the 2DES formed at the epitaxially grown interfaces between (111) $LaAlO_3$, $EuTiO_3$, and $SrTiO_3$ single crystal, characterized by a trigonal crystal field splitting and ferromagnetism induced by Eu and Ti ions magnetic ordering [3]. The anomalous magnetoconductance disappears at the magnetic critical temperature [4], showing a direct link with the ferromagnetic order. The data are explained theoretically in a single band scenario as the combined effects of the Rashba-SOC, of the band-warping induced by the 2DES trigonal symmetry, and of the magnetic gap opening at spin-orbit induced Dirac-like point, giving rise to a non-trivial Berry phase (fig. 1(b, c)). These findings open perspectives for the engineering of novel spin-polarized functional 2DES holding promises in spin-orbitronics and topological electronics.

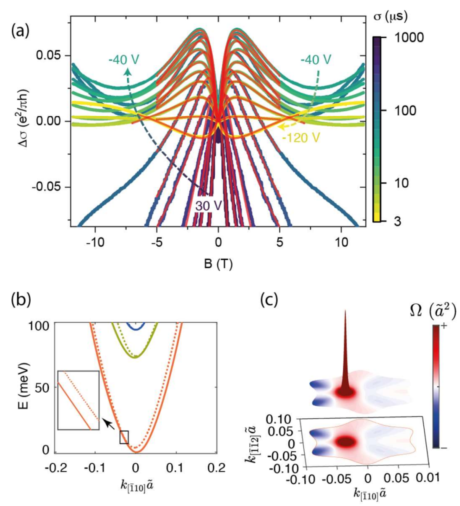

Figure 1. (a) Gate dependence of the anomalous magnetoconductance. (b) Electronic band structure in presence of in-plane magnetization. (c) The corresponding non-trivial Berry curvature with a hot-spot at the avoided crossing point.

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Superconducting FeSe thin films: Growth optimization for ring geometry exploration

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Iron selenide (FeSe) has emerged as one of the most fascinating quantum materials due to its simple crystal structure and rich phase diagram, which hosts nematicity, superconductivity and potentially topological states. Despite its relatively low superconducting transition temperature (T_c ≈ 8 K) in the bulk form, FeSe displays dramatically enhanced superconductivity when reduced to ultrathin dimensions and placed in specific interfacial environments. A striking example is the case of monolayer FeSe grown on $SrTiO_3$ (STO), where the T_c exceeds 60 K, placing it among the highest-T_c systems outside of the cuprate family [1,2]. This enhancement is widely attributed to interface effects such as charge transfer, cross-interface electron–phonon coupling, and epitaxial strain. Even more intriguingly, recent studies have shown that relatively thicker FeSe films can also exhibit significantly enhanced T_c under optimized growth conditions [3]. This suggests that growth engineering can induce robust high-T_c superconductivity in FeSe over a broader range of thicknesses than initially believed.

To enhance the superconducting T_c, thick FeSe thin films were grown on (STO) substrates using pulsed laser deposition (PLD), with particular attention paid to fine-tuning both the deposition and post-annealing parameters. When these conditions were carefully optimized, superconducting transitions around 23 K were achieved significantly higher than the 8 K observed in bulk FeSe.

Building on the standard film optimization, growth is now being extended to ring-shaped STO substrates. Unlike conventional geometries, the ring introduces a closed-loop topology that renders the superconducting phase inherently sensitive to magnetic flux threading the central aperture. This configuration enables the study of flux quantization, vortex dynamics, and phase coherence

In parallel, FeSe films are also being grown on STO membranes [4], which serve as flexible, freestanding substrates. These membrane-based systems enable advanced sample shaping and mechanical manipulation, allowing for strain engineering, backside illumination, and transmission-based spectroscopies. Such designs are expected to significantly expand the experimental capabilities for investigating superconductivity in highly tunable environments.

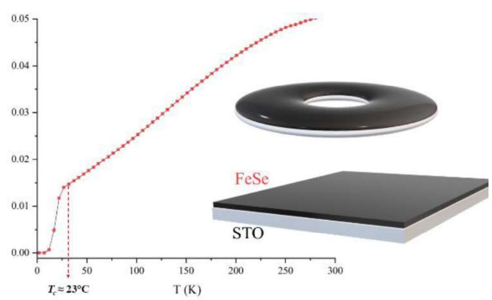

Fig. 1: FeSe thin films on STO substrates. Planar growth yields superconductivity up to 23 K; ring geometries enable flux and phase coherence studies.

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