1.3.4 Quantum Hall effect in hybrid Josephson junctions

Quantum transport in two-dimensional electron systems was investigated at low temperatures and in high magnetic fields. Weak localization and the quantum Hall effect were studied in various material systems. Recently we also studied proximity effect in hybrid semiconductor-superconductor Josephson junctions, a powerful platform where intriguing topological properties can be investigated. Our findings demonstrate the potential of these hybrid devices to investigate the coexistence of superconductivity and quantum Hall effect and constitute the first step in the development of new device architectures hosting topological states of matter.

The study of two-dimensional (2D) electron systems represents a milestone in building solid-state nanodevices for applications in quantum technology. Starting from conventional semiconducting heterostructures, based on III-V compounds, an increasing number of novel 2D materials is investigated, both to explore fundamental physics and to develop new applications with potential impact on the future market. Mechanical exfoliation indeed allows for the fabrication of monolayer-thin devices ranging from a single 2D layer, like graphene and its van der Waals relatives, to multilayer systems with different and tunable properties while changing the number of layers. Although in all these systems electrons are confined in two spatial dimensions, very different properties can be observed, depending on the specific material and its band structure. Indeed, while in semiconducting heterostructures charge carriers behave as conventional electrons with parabolic bands, in graphene they obey a linear dispersion relation resembling the physics of relativistic Dirac fermions. Another emerging layered material, black phosphorus (bP), shares some aspects with graphene in the 2D monolayer configuration, but with important differences, that pave the way to new devices and potential applications. These differences stem from the peculiar and anisotropic shape of the bP band structure, which affects both its electronic and optical properties.

Low-temperature measurements allow investigating a large variety of quantum phenomena in these materials. For instance, quantum Hall physics emerges in the presence of a strong perpendicular magnetic field, with the formation of Landau levels (LLs) and the simultaneous coexistence of insulating bulk and metallic one-dimensional channels. The precise structure of LLs is influenced by the nature of the material hosting the 2D electron system, and the topologically protected edge states, chirally propagating along the border of the sample, inherit peculiar features.

Work at NEST aims at addressing the physics of novel 2D materials with special emphasis on new and intriguing quantum properties. To this end, we use state-of-the-art fabrication techniques and low-temperature magneto-transport measurements in combination with advanced microscopy techniques, such as scanning probe and scanning gate microscopy (SGM). These activities are supported by theoretical predictions and proper modelling of experimental data, and benefit from national and international collaborations. SGM represents a unique tool combining both high lateral resolution and quantum transport techniques, which allowed e.g. to unequivocally detect localized charged structures and their position with respect to quantum point contacts (QPCs) properly patterned on the sample. This resulted in the unambiguous detection of the 0.7 anomaly, directly observed from SGM maps [1].

Moreover, by low-temperature magneto-transport experiments, weak localization was recently observed in graphene [2,3] and bP [4], in excellent agreement with theoretical predictions, from which characteristic scattering lengths could be inferred. The temperature dependence of the phase coherence length in bP decreases weaker than expected for two dimensions, with a power law closer to what expected for quasi-onedimensional systems like nanowires or carbon nanotubes. This peculiar character can be ascribed to the highly anisotropic nature of the puckered honeycomb crystal structure of bP [4,5]. We have as well observed the effects of the highly anisotropic structure of bP in the high-field longitudinal magnetoresistance, complemented by polarized Raman spectroscopy measurements [6].

Research also focused on innovative 2D materials and their combinations. We have reported the first experimental study of graphene transferred on β-Si_3N_4(0001) and provided a comprehensive quantitative understanding of the physics of ultrathin Si_3N_4 as a gate dielectric for graphene-based devices [7]. Furthermore, quantum transport data in single-crystal CVD graphene samples showed more than 12 flat and discernible half-integer quantum Hall plateaus on both the electron and hole sides of the Dirac point [3]. We have also reported on a buried split-gate architecture with this material. The control of the edge trajectories in these graphene-based devices is demonstrated by the observation of various fractional quantum resistances, as a result of a controllable inter-edge scattering [8]. These ideas have very recently found an application in quantum metrology as a programmable resistance standard based on a cascaded quantum Hall bisection scheme [9].

This architecture results particularly useful and unique in view of direct imaging via SGM, since graphene constitutes the topmost layer of the device [8,10]. As shown in Fig. 1, we found evidence of the backscattering of quantum Hall edge channels in a narrow graphene Hall bar, induced by the gating effect of the conducting tip of the SGM [10]. We demonstrated full control over the edge channels and were able, because of the spatial variation of the tip potential, to separate copropagating edge channels in the Hall bar, creating junctions between regions of different charge carrier density, that have not been observed before in devices based on top or split gates.

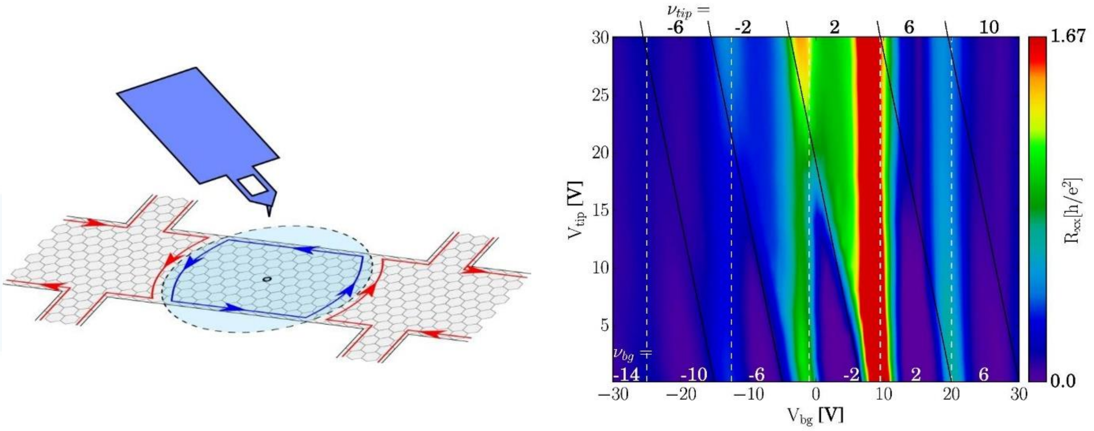

Figure 1. (a) A schematic representation of the SGM setup. By applying a voltage to the metallic tip, we can locally gate a region of choice. (b) A 2D map, showing the value of longitudinal resistance R_{xx} as a function of back-gate voltage V_{bg} and tip voltage V_{tip}. The data were collected at T = 4.2 K and B = 8 Tesla. The filling factors ν_{bg} and the filling factors underneath the SGM tip ν_{tip} are indicated. From Ref. [10].

Recent experimental and theoretical activities focused on hybrid semiconductor/superconductor systems, aiming at the emergence of new states of matter, exploiting the induced superconducting correlations in the 2D electron system thanks to the so-called proximity effect. Hybrid Josephson junctions formed by a high-quality InAs quantum-well placed between two Nb contacts have been thus realized and investigated, see Fig. 2(a). Transport measurements revealed critical temperature up to 8.1 K and high critical field, of the order of 3 Tesla. Modulation of supercurrent amplitude is achieved by side gates. Well-developed quantum Hall plateaus have been observed for magnetic fields below 3 Tesla, see Fig. 2(b), allowing for the coexistence of topological edge states and superconductivity [11,12].

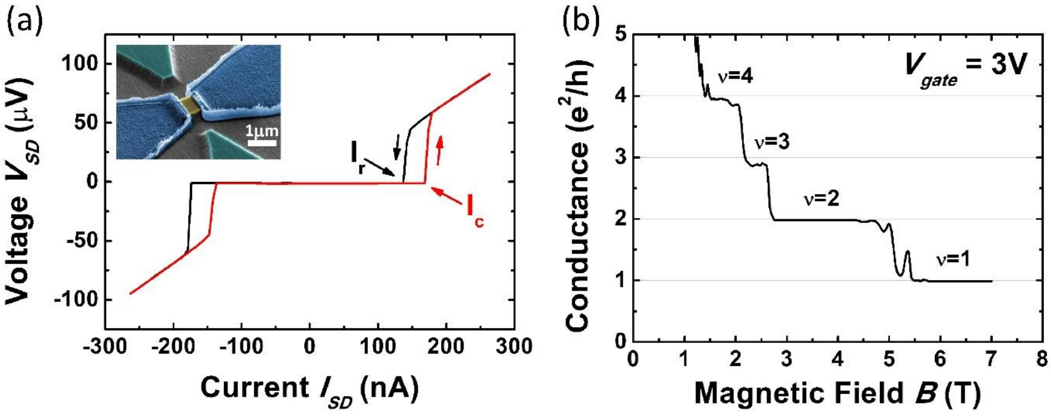

Figure 2. (a) Source-drain voltage V_{SD} vs. source-drain current I_{SD} of an InAs-based Josephson junction. The black (red) arrow shows the direction of the black (red) sweep. The inset shows a false color SEM image of the device. The mesa is yellow, side gates are green, Nb is blue. (b) Conductance (in units of e^2/h) as a function of magnetic field, showing well-developed quantum Hall plateaus already at 1.5 Tesla. From Ref. [11].

We have also fabricated and investigated a hybrid trenched Josephson junction where the width, area, and supercurrent of the two arms of a SQUID-like geometry can be independently controlled with high precision. We have demonstrated a wide tunability of interference patterns by electrostatic means, from a superconducting quantum interference device with narrow arms to a Fraunhofer pattern in an extended Josephson junction [13]. In order to study similar effects in novel two-dimensional semiconductors, such as graphene or bP, many challenges have to be faced, especially for bP, since this material is very sensitive to air, with makes the device fabrication crucial. We studied possible stabilization mechanisms of bP [14], as well as local doping strategies, and we focused our attention on the optimization of the Ohmic contacts between metals and bP [15], since the interface transparency is crucial for Cooper pair injection. Currently we are studying some prototypical superconductor/bP devices (see Fig. 3).

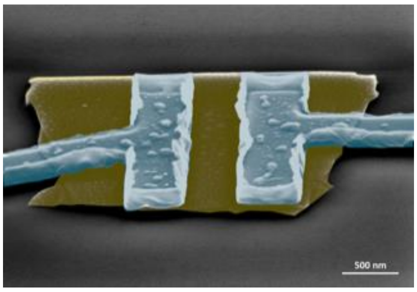

Figure 3. Tilted false color SEM image of a black phosphorus Josephson junction with Ti/Nb contacts. The black phosphorus flake is marked in yellow and the Ti/Nb contacts in blue.

These results pave the way for new device architectures with potential applications in the field of quantum computation and information. Indeed, the coexistence of quantum Hall physics and superconductivity is one of the key ingredients for the emergence of new topological states of matter, like Majorana fermions or even more exotic parafermions. The latter are predicted to form and localize at the interface between a superconductor and fractional quantum Hall edge states. Their possible realization and detection will constitute an unprecedented breakthrough, paving the way for the first development of topologically protected quantum computation architectures. The great flexibility offered by SGM, combined with low-temperature quantum transport measurements, represents a unique playground able to directly image and detect such exotic quasiparticles.

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