Tunable superconductivity in an array of metal dots decorating graphene

Nanoscale hybrid systems form an emerging family of devices whose particularity is to combine two materials of different nature (such as a molecule coupled to a metal, a semiconductor coupled to a superconductor, etc..). The heterogeneous association gives rise to synergies and provides new functionalities not present in either material alone. We focus here on a hybrid platform provided by graphene, an effectively two-dimensional, atomically-thin carbon sheet, decorated on its top surface with an array of tiny disks or nanoparticles of a superconducting metal such as tin or lead. This kind of device provides an experimental platform for studying quantum phase transitions in 2-Dimensional superconductors.

Superconductivity does not occur spontaneously in graphene (or, at least, no sign of intrinsic superconductivity has been detected so far). However, in our hybrid system (Fig. 1), because electronic charges in the graphene travel directly on its surface, they can easily "catch" some superconducting character by their coupling to superconducting dots adsorbed on top. That is, the correlations between pairs of electrons that produce superconductivity in the metal can "bleed" into the non-superconducting material over a given distance. This is an example of a fundamental phenomenon called the "proximity-effect".

It happens that graphene provides an ideal material for studying novel aspects of the proximity effect, this for three reasons: 1. The intrinsically low electronic density of graphene is not high enough to deplete the superconductivity in a system of tiny dots. 2. the exposed and relatively inert 2D electron gas on the graphene surface can be easily coupled to a 2D array of decorating dots ; there is efficient interfacial coupling and no strong potential barrier at the metal/graphene interface. 3. Last but not least, the strength of the resulting superconducting correlations in the graphene sheet can be tuned over a wide range by varying the "doping" (i.e. the density of graphene free-carrier charges) with a voltage *V* applied on a backgate electrode that generates a perpendicular electrostatic field (Fig. 1).

Thus, the graphene layer can play the role of a *variable resistance* 2D metal. Above a given threshold of the graphene's doping, the superconducting correlations from a superconducting dot can be transmitted far enough across the graphene to connect with the correlations emerging from neighbouring dots. This gives rise, by percolation, to a global superconducting state extending over the entire hybrid system. Thanks to the versatility of the hybrid platform, various parameters such as the order and symmetry of the metal dot array, its density, the nature of the materials and the structural quality of the underlying graphene can be studied over a large range.

High dot density can be achieved by a self-assembly method ("dewetting" of a thin film of metals such as Sn or Pb). This yields a two-dimensional, random array of metal-graphene-metal Josephson junctions. At the other extreme, by electron beam lithography we have got a metal density coverage as low as 3% for ordered triangular arrays of Sn dots with diameters a few hundred nm (see Fig.1), leading to a controllable superconducting state.

Interesting cases are obtained using disorder to modify the way superconductivity disappears in the hybrid system. Disorder in graphene can be produced in various ways. We first used slightly oxidized graphene where structural defects induce a regime of strong electronic localization at low temperatures, giving rise to a superconducting-to-insulating transition controllable by a gate voltage (see Fig. 2). More directly, in further experiments using low defect-density graphene, tuning the density of electrons with the backgate could effectively tune the degree of disorder more finely, just by changing the effective sheet resistance. When the coupling between dots becomes very small, quantum fluctuations in the superconducting phase of each island start to occur, giving rise to a metallic rather than an insulating state in this case. The system loses its superconductivity but residual superconducting correlations give the new metallic state some remarkable specific properties such as non-linearities.

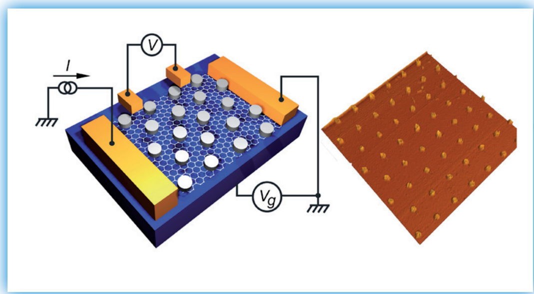

Fig. 1. ***At left*** *: Principle of a graphene transistor with tin disks (not to scale) decorating a graphene plane; the electrical properties are measured with four gold electrodes.* ***At right:*** *Atomic Force Microscope (AFM) micrograph of the central, active part of the device showing the triangular array of Sn dots.*

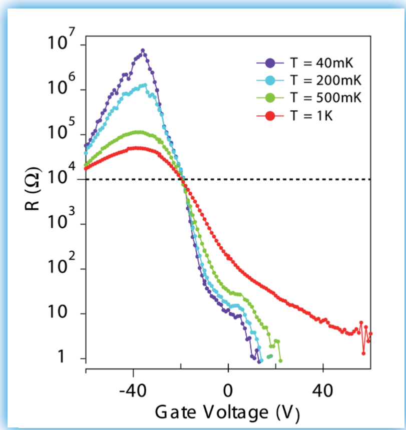

Fig. 2: Effect of varying the perpendicular electric field for various temperatures showing 7 orders of magnitude of resistance tuning at the lowest temperature. The large dynamic contribution of the conductance within the graphene layer enables us to observe a temperature-dependent transition from superconductor (at positive gate voltage V) to insulator at negative V.

In collaboration with theoreticians from Landau Institute, Moscow, we have demonstrated the existence of this "exotic" metallic phase which replaces the superconducting state at a critical level of disorder in the graphene. We could explore the quantum phase transition that exists between these two states. Our experimental results shed light on the process involved in suppression of superconductivity by disorder in a 2D system. The detailed behaviour of the quantum phase transition reveals a specific percolative regime and a universal resistivity predicted by the theory of percolation in 2D.

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FURTHER READING

Collapse of superconductivity in a hybrid tin-graphene Josephson junction array
Zheng Han, A. Allain, H. Arjmandi-Tash, K. Tikhonov, M. Feigel'man, B. Sacépé and V. Bouchiat
Nature Physics 10, 380 (2014).

Electrical control of the superconducting-to-insulating transition in graphene–metal hybrids
A. Allain, Zheng Han and V. Bouchiat
Nature Materials 11, 590, (2012).