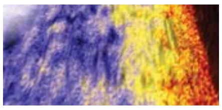


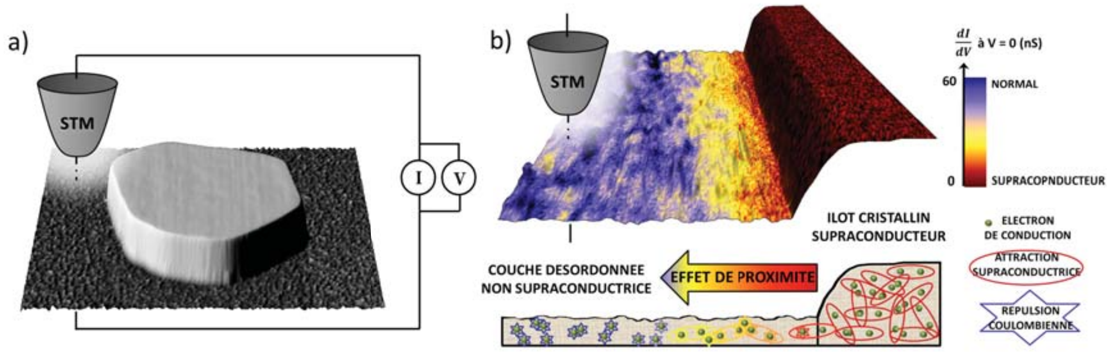
Coulomb repulsion against propagation of superconductivity: who wins ?

Superconductivity is a quantum phenomenon that results from the attraction between the conduction electrons. They mate in pairs and form Cooper pairs. But electrons also repel each other because they all carry the same electric charge, which is the Coulomb effect. A superconducting material compensates for this repulsion by forming a screen positive charge around each electron. Now arises the following question: Can a material acquire superconducting properties despite strong Coulomb interaction?

Physicists from the "Spectroscopy of new quantum states" team of the Institute of Nanosciences de Paris (INSP) have shown that the Cooper pairs propagate in a very disordered two-dimensional material.

When a superconductor is in contact with a normal non-superconducting metal, the Cooper pairs propagate over a small distance, it is the proximity effect. A part of superconducting properties is thus “transferred” in the normal range. For example, in specific designs non-dissipative currents can be induced, a superconducting signature appears in the density of electronic states and the magnetic field is expelled. However disorder increases the Coulomb repulsion. In addition, there is less positive charge available in a two-dimensional or one-dimensional material to screen this force.

With a scanning tunneling microscope, the team measured the local current-voltage characteristics at the surface nanostructures of lead deposited on a silicon substrate (Figure b). The synthesized islands are few atomic layers thick monocrystals which become superconductive at a temperature below 7 K (Figure a). Around them, the silicon surface is covered with a monolayer of amorphous lead that it remains in the normal state to study temperature 0.3 K.



a) The image measured with scanning tunneling microscope shows a crystalline lead island surrounded by the disordered layer of lead. (Dimensions: 2.1 nm x 215 nm x 215 nm). Around the image is schematically traffic tunnel current I measured in terms of the applied voltage V.
b) The current-voltage characteristic I-V is measured at the edge of the island. The color code shows that the zero voltage side of the island is superconducting (red), the disordered layer is normal (blue) away from the island and gradually becomes superconducting near the island (yellow-red). It is the proximity effect, Cooper pairs propagate in the disordered layer but the pairs are separated beyond twenty nanometers due to the Coulomb repulsion. (Dimensions: 2,1 nm x 67 nm x 20 nm.)

To model the proximity effect, the researchers INSP collaborated with Spanish theoricians, JC Cuevas, from the Department of Theoretical Physics of Condensed Matter at the Autonomous University of Madrid, and F. S. Bergeret from the Centre Materials Physics in San Sebastian. They first described the electrical current transport in the amorphous layer as the equivalent of an RC circuit, according to the existing model called "dynamic Coulomb blockade." Theoricians then combined this simple transport model with the Usadel equation, which allows calculating the proximity effect in a diffusive system. The theoretical results agree remarkably well with the experimental data with only one adjustable parameter the diffusion coefficient D. D is related to the size ξ of Cooper pairs in the amorphous layer (ξ is the effective coherence length). ξ is found to be equal to 15 nm in this disordered layer of lead, which is two times less than in the crystalline islands. More theoretical work is needed to fully treat the Usadel equations in presence of strong Coulomb interaction.

Besides the fact that the first direct measurement of the proximity effect in a highly diffusive medium brings new elements to the microscopic description of the phenomenon, it can also be a technique to explore the properties of otherwise inaccessible materials. It can be implemented to measure the diffusion coefficient of ultrathin conductive layers or determine the nature of the interface between normal and superconducting electrodes in nanoelectronic devices.

References

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