Quantum supercurrent transistors in carbon nanotubes
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Recommended with a commentary by Benjamin Huard, Stanford University

The conductance quantization in passage through ballistic narrow constrictions (of dimensions smaller than the phase coherence length) between two metallic reservoirs in their normal state is a well studied problem both theoretically and experimentally. By contrast, a dissipationless supercurrent can flow due to the Josephson effect for similar constrictions linking two superconducting reservoirs. However, if the length of the constriction is smaller than the superconducting coherence length ξ, the critical current is predicted to be quantized [1, 2]. In this situation, one can think of the supercurrent as being carried by the Andreev bound states, whose number increase with the transverse dimensions of the constriction. This point of view has been useful in understanding several experiments performed using a variety of linking conductors: tunnel junctions, diffusive metal wire [3], 2D electron gas [4], atomic contacts [5, 6] and more.

Jarillo-Herrero *et al.* investigate a system where the link is a metallic carbon nanotube (CNT). The CNT is less than 0.5 μm long which is smaller than the superconducting coherence length $\xi \simeq 3$ μm. The electronic states in the CNT are well separated in energy as proven by the Coulomb diamonds (conductance as a function of gate voltage and bias voltage) observed at 4 K, when the Al electrodes are in their normal state. In the superconducting state, a supercurrent can flow only if the gap between the Fermi level in the leads and the closest level in the CNT is not too big. As this energy separation can be tuned by applying a gate voltage V_g to the CNT, Jarillo-Herrero *et al.* were able to tune and measure the critical current as a function of V_g (see Fig. 2a in the paper). This setup thus provides an elegant way of testing successfully the predictions regarding the mesoscopic Josephson effect.

The authors also observed sharp features in the conductance at bias voltages $V_n = \frac{2\Delta}{en}$ where n is an integer and Δ is the superconducting gap of the aluminum. These features are the signature of multiple Andreev reflections (MAR) in the linking conductor, and are not affected by the applied gate voltage (see Fig.S4 in the supplementary information of their paper).

In order to explain quantitatively the measurement of the critical current as a function of gate voltage, one has to understand what is actually being measured. At any gate voltage V_g, the supercurrent flowing through the CNT is a function $f_{V_g}(\delta)$ of the difference δ between the phases of the two superconducting electrodes. When a constant supercurrent I flows through the CNT, the system adapts so that the phase δ is a solution of $f_{V_g}(\delta) = I$. Naively then, one would expect that the critical current I_C is the maximum of the function $f_{V_g}(\delta)$. Using the tunneling rates between the electrodes and the CNT obtained by measuring the Coulomb diamonds in the normal state, one can predict the value of I_C as a function of gate voltage using the concept of Andreev bound states for the geometry considered. However, as the temperature is finite, the phase δ oscillates, and only its average value satisfies the above equation. Therefore, the measured switching current corresponds to the smallest current at which the fluctuating phase δ spends a non negligible amount of time near the maximum of f_{V_g}. It can thus be much lower than I_C depending on how the phase fluctuates. More quantitatively, in the case of low dissipation in the environment of the linking conductor, the measured critical current has been proven to be proportional to $I_C^{3/2}$ [7].

The letter shows a good agreement between the measured critical current as a function of gate voltage and the prediction for $I_C(V_g)$ when taking into account the phase oscillations. In the end, the dependence of supercurrent on V_g is described nicely using only one fit parameter (a global factor due to the unknown fluctuations of δ).

The experiment also verifies that I_C can be tuned by the resistance R_N in the normal state, just as in the 'bulk' Josephson effect. Similar behavior has been observed in atomic contacts where the tuning parameter is the transmission of the contact instead of V_g [8]. The product $I_C R_N$ depends on the type of conductor linking the two superconducting electrodes.

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