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COULOMB BLOCKADE ELECTROMETER WITH A HIGH-T_c ISLAND

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We report on a successful attempt to fabricate a Coulomb blockade electrometer consisting of an ultrasmall $YBa_2Cu_3O_{7-\delta}$ (YBCO) island coupled to two gold electrodes through high-resistance native surface tunnel barrier. A third electrode placed near the island was used as an electrostatic gate. Spectra typical for tunnelling into the YBCO superconductor were reproducibly measured. At temperatures below 0.5 K the low bias conductance was suppressed by the Coulomb blockade. The blockade could be periodically varied by the gate potential. An external magnetic field of up to 5 T strongly influenced the transport via the island but without any change in the period of the Coulomb oscillations.

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During the last years the discussion of the mechanisms of high-T_c superconductivity (HTS) has focused on the excitation spectrum of HTS materials. In particular, in the view of theories involving a spin-fluctuation mechanism and, as a consequence, d-wave symmetry of the superconducting wave function, an extensive search for nodes of the energy gap has taken place. The present experimental and theoretical situation is complicated [1]. Tunnelling spectroscopy has long been considered as the most reliable method to study the density of excited states. However, for HTS materials with their extremely short coherence lengths and strong anisotropy, it appeared to be very difficult to reproducibly make tunnel junctions of sufficient quality. The interpretation of results is also complicated. Mineev recently suggested [2] to attack this problem involving the methods of single electronics. The present work is the first experimental step in this direction.

The low bias conductance is suppressed by the Coulomb blockade in a Coulomb blockade electrometer. The blockade can be periodically lifted by the gate potential. When the island of the electrometer is made of a normal metal, the period ΔV_g(normal) corresponds to a change by $1e$ of the charge of the island [3], $\Delta V_g(\text{normal}) = e/C_g$ (C_g being the island-to-gate capacitance). The situation is different for a superconducting island. Under certain conditions electron transport via a small superconducting island is sensitive to the presence of a gap in the quasiparticle excitation spectrum [4]. While one has to overcome only the charging energy to make an electron tunnel onto the normal metal island, additional energy equal to the gap is required for tunnelling of every odd electron in the case of a superconducting island. Thus tunnelling of single electrons is suppressed and instead tunnelling of two electrons to form a Cooper pair on the island is favoured (parity effect). This effect was experimentally observed in S-S-S [5] and N-S-N [6] structures with conventional superconductors (LTS). It revealed itself in doubling of the period: $\Delta V_g(\text{superconducting}) = 2\Delta V_g(\text{normal})$. It was argued [2] that nodes of the gap function would impose much more severe constraints on temperature for the parity effect to be present. Therefore, the parity effect may serve as a tool to check for nodes of the order parameter. The advantage of this approach is that it is based on a very robust, purely thermodynamic effect.

In this paper we present results of an experimental study of the electron transport in an ultrasmall N-S-N tunnel structure.

The samples for the study were fabricated as follows:

A 150 nm thick $YBa_2Cu_3O_{7-\delta}$ (YBCO) film was grown *in situ* by laser ablation on a MgO substrate. To form the tunnel barriers we followed the procedure of Valles et al. described in [7].

Patterning of the structure was done by a combination of *e*-beam lithography and ion-beam milling through an amorphous carbon mask. Special precautions were taken to protect the barriers during processing. More details of the preparation routine will be reported elsewhere.

Two types of structures were produced:

1) Test structures to check for degradation of YBCO resulting from processing and to estimate the Au-YBCO contact resistance. They consisted of $W \times 0.15 \times 10\mu m^3$ YBCO bridges (width $W = 0.2$ and $1\mu m$), each with four YBCO electrodes and two Au electrodes 0.2 and $1\mu m$ wide. Measurements on the microbridges confirmed that there is only a slight deterioration of superconducting properties of the YBCO films due to processing. The T_c of a bridge stayed well above 77 K even for the most narrow ones. The four-probe resistance of the $0.2 \times 0.2\mu m^2$ Au-YBCO junctions appeared to be in the range of a few megaohms.

2) Electrometer structures (Fig.2 insert) consisting of a YBCO island $0.2 \times 0.15 \times 1\mu m^3$ with two $0.2\mu m$ wide Au contacting electrodes and a gate electrode $2\mu m$ away from the island. Hereafter, we refer to the properties of only this type of structures.

Measurements were done in an Oxford dilution refrigerator with the base temperature less than 20 mK. The set-up for transport measurements is described in [8]. The cryostat is equipped with high frequency filters to eliminate the external noise, which may excite quasiparticles. Since the junction resistance is very high, two-probe transport measurements were sufficient.

The voltage dependence of the dynamic conductance ($G = \partial I/\partial V$ vs. V) was measured at different temperatures T while cooling the sample. At high bias G inreases linearly with the voltage down to 50 K when additional structures appear in the $G(V)$ curves. They become more pronounced as the temperature decreases. A typical voltage dependence of the dynamic conductance at the temperature $T = 30$ mK is presented in Fig.1*a*. The shapes of the curves and positions of the structures are similar to those observed in Pb–YBCO planar junctions [7,9] as well as in STM experiments [10]. This is in contrast to the results of Ponomarev et al. [11], who measured the curves of a different type in a break-junction configuration. We consider the structures which are present in the $G(V)$ curves below 50 K as an evidence of superconductivity of the island.

The minimum of the curve is displaced from zero bias and the structures on the curve are asymmetric. Our data suggest that the electrometer is not symmetric and that one of the junctions dominates. As discussed in detail by Rowell in [12]

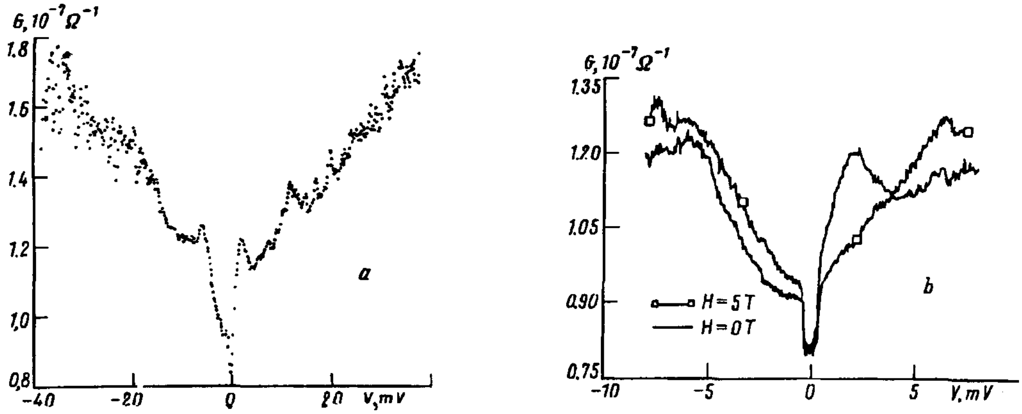

Fig.1. Dynamic conductance vs. bias voltage ($G = \partial I/\partial V$ vs. V) at $T = 30$ mK for the YBCO island connected to two Au strips

(for the example of Pb-Al) the asymmetry of a $G(V)$ curve is inherent to tunnel junctions between different materials.

The Coulomb blockade of current shows up in the $G(V)$ curves as a narrow U-shaped cusp at zero bias at temperatures below 0.5 K (Fig.1*b*, $H = 0$T). It becomes deeper (the zero bias conductance is decreasing) as the temperature goes down, and below 100 mK the blockade is well seen also in the $I-V$ curves.

A magnetic field strongly influenced the $G(V)$ dependences (Fig.1*b*, $H = 5$T) at small bias. As seen in the figure, the $G(V)$ curves become more symmetric in a field of 5 T.

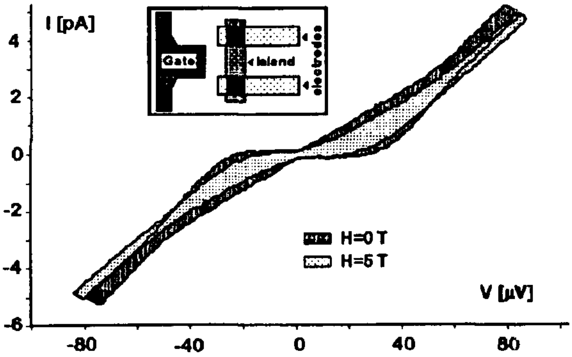

Fig.2. The envelopes of two sets of $I-V$ curves taken at $H = 0$ and $H = 5$T. Each curve in a set corresponds to a different gate potential. $T = 30$mK. The insert shows the layout of the sample

Varying the potential of the gate electrode, we were able to lift the blockade periodically going all the way to a linear $I-V$ curve and back to complete blockade (Fig.2). The maximum offset voltage V_{off} was about 30 μV, corresponding to a total capacitance C_Σ of the island to the electrodes of about 5 fF [3].

The $I-V$ curves are also influenced by a magnetic field. Fig.2 illustrates that the amplitude of oscillations of the $I-V$ curves by the gate potential is noticeably suppressed by a magnetic field. Furthermore, under the magnetic field the $I-V$ curves remain non-linear around zero bias even when the blockade is completely lifted by the appropriate gate potential.

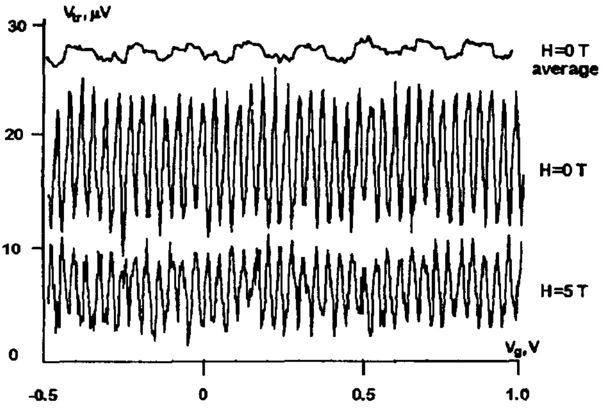

Fig.3. The dependence on the gate potential of the transport voltage (V_{tr} vs. V_g) of the current biased junction at $H = 0$ and $H = 5$T. The result of averaging the former curve over its main period is also shown

To study the influence of external fields on transport in more details we biased the double-junction by a certain current and traced the transport voltage versus the gate potential. Fig.3 shows that V_{tr} oscillates as a function of V_g. The period ΔV_g of the oscillation is not affected by a magnetic field of up to 5T, but evidently the amplitude is. The phase of the oscillation is the opposite for the two curves in Fig.3, however, the phase shift was not studied systematically.

In order to analyse the periodicity of the $V_{tr}(V_g)$ oscillation we used a Fast Fourier Transform (FFT) algorithm. A Fourier power spectrum was obtained for each bias. It revealed an unexpectedly rich structure. All Fourier components behave in the same way when bias is changing. This observation makes improbable that the observed complicated spectrum is due to tunnelling via some uncontrolled particles.

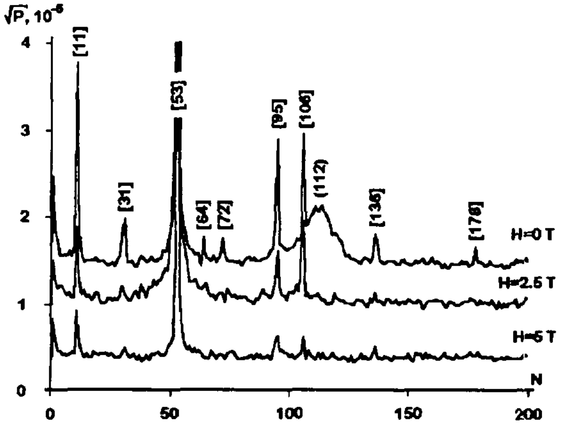

Fig.4. The square-root of the averaged Fourier power spectra (P) at $H = 0$, 2.5 and 5T. The scale (N) on the X-axis corresponds to the number of periods in a 2V gate sweep. The magnitudes of the main peaks at $N = 53$ for each magnetic field are $2.2 \cdot 10^{-5}$, $1.6 \cdot 10^{-5}$ and $0.91 \cdot 10^{-5}$ correspondingly. The exact positions of the broad bump and the most significant peaks are marked. The curves are displaced by $5 \cdot 10^{-7}$ from each other for the sake of clarity

The set of the spectra was averaged to reduce the noise and to emphasise the most significant features. Fig.4 shows the square-root of the averaged Fourier power spectra. The peak at $N = 53$, corresponding to the period ΔV_g of about 38 mV, is well pronounced for all the biases. All other peaks are much weaker and only one of them at twice the main frequency ($N = 106$) is possible to attribute to unharmonicity of the signal. The nature of the other peaks is not understood yet. It may be connected with strong correlations between electrons of the island.

The broad bump around $N = 112$ is not a side-effect of averaging, it is present on spectra for particular biases as well. We also ascertained that other frequencies are not an artefact of the FFT: e.g., the upper curve in Fig.3 was obtained by averaging the experimental dependence ($H = 0$) over its main period. The result is a slow, periodic function of V_g with the frequency corresponding to the left-most peak ($N = 11$) in Fig.4. The frequencies of some peaks are in simple arithmetic relations intrinsic to mixing in non-linear systems.

The most remarkable effect is the influence of the magnetic field on the transport. Fig.4 illustrates how the amplitudes of the FFT peaks are suppressed when the magnetic field is increased in accordance with figures 2 and 3. Note that the broad bump around $N = 112$ completely disappears already in a magnetic field of 2.5T in contrast to the narrow peaks.

We can not conclude if the main period corresponds to $1e$ or $2e$. The only way to distinguish them would be to observe the cross-over from one to the other in magnetic field. Unfortunately, it was not observed.

A magnetic field of a few Tesla should not affect single-electron oscillations. Besides, it is very low compared to the upper critical field of an HTS material. One could think therefore that even if the observed periodicity is $2e$, the cross-over to $1e$ can not be reached. Note, however, that a field of 5T creates roughly 500 vortices penetrating the island. The excitation spectrum in a vortex core is close to the one of the normal state. Thus, in principle, the vortices can provide states for quasiparticle relaxation making the cross-over possible. In our case, the field may be insufficient or the relaxation is slow. Up to now there is no theory to account for this.

Considering the opposite case of $1e$ periodicity, we can suggest three potential reasons for violation of the parity effect in our case:

1. The layer adjacent to the tunnel barrier is normal. However, the phase diagram of YBCO has a very sharp boundary between the insulating and superconducting phases of this material, which makes this possibility less probable. Ponomarev et al. [11] suggested that deterioration of YBCO layers adjacent to a tunnel barrier leads to an $S - S' - I - S' - S$ type of structures and smeared $I - V$ curves. We believe that even a layer with a reduced T_c becomes superconducting at the ultra-low temperatures of our experiments.

2. Alternatively, the spin-flip scattering on defects adjacent to the tunnel barrier can provide quasiparticle states in the gap, poisoning the parity effect. The spin-flip process was discussed by Valles et al. [7] as a potential cause of the finite zero-bias conductance always observed in YBCO tunnelling spectra. If this is the case, a magnetic field could suppress the spin-flip process [12].

3. Finally, it may be considered as an evidence for nodes of the superconducting order parameter in YBCO.

In conclusion, we have developed a technique to produce small islands of YBCO film and to make ultrasmall contacts to such islands. The islands remain superconducting at high temperatures after processing. The produced structures reveal the properties of ultrasmall tunnel junctions, where the YBCO surface layer acts as an insulator. At biases higher than a few mV, the dynamic conductance is basically linear on voltage. However, several pronounced peaks are observed, and they are affected by a strong magnetic field. Features typical to the Coulomb blockade of current were observed at low temperatures. The blockade could be periodically lifted under the external electric field. The period of the $V_{tr}(V_g)$

oscillations was not affected by a magnetic field of up to 5T, whereas their amplitude went down as the magnetic field was increased. No parity effect was distinguished. Further experiments, including a study of $LTS - HTS - LTS$ structures are under way.

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