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Physica C 368 (2002) 337–342

PHYSICA C

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Tunnel barriers for an all-high-T_c single electron tunneling transistor

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Abstract

We have studied possible implementations of high-resistance tunnel barriers for an all-$YBa_2Cu_3O_{7-\delta}$ superconducting single-electron transistor (SSET). The step-edge and biepitaxial techniques have been employed to fabricate the junctions. Both technologies appear very promising for the implementation of all-high-T_c SSET.

Keywords: High-T_c SSET; Tunnel barriers

1. Introduction

Recently there has been a great effort in searching for new physical T_c systems suitable as computational units in a quantum computer, qubits. The quantum computers based on solid-state qubits are probably the preferred choice. A large class of the proposed realizations makes use of the gapped quasiparticle-excitation spectrum of superconducting structures to suppress decoherence. One of the two implementations admitted by the charge-phase (Cooper pair–vortex) duality in Josephson devices are the phase qubits. Among them particular attention is given to the systems based on high-T_c superconductors. The suggested designs exploit the unique property of these superconductors—the d-type symmetry of the wave function. In the phase qubits the superconducting single-electron transistor (SSET) can be used to collapse the wave function into one of the two basis states, which differ by the phase, and to perform the control entanglement of states of multiple qubits [1,2]. We should emphasize that the high-T_c qubits require high-T_c based SSET, as the technology that has been well established for fabrication of their low-T_c (mainly Al) counterparts is not compatible with the high-T_c Josephson junction technology in a straightforward way.

The requirements for the operation of the SSET are small capacitance and high resistance of the tunnel junctions between the superconducting electrodes and the superconducting island. Submicrometer structures with low capacitance in HTS

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0921-4534/01/$ - see front matter
PII: S0921-4534(01)01193-5

have already been realized and it is of significant interest to study the feasibility of high resistive tunnel barriers.

Two types of HTS structures known to give high values of the normal resistance were investigated—the step-edge and the biepitaxial Josephson junctions.

2. Fabrication procedure

The samples fabrication procedure has been described in detail elsewhere [3,4] and is briefly summarized in the following. E-beam lithography was used to define in the (1 0 0) $LaAlO_3$ substrate both the step and the alignment marks for the subsequent processing stages. The pattern was transferred into the substrate by argon ion beam through a 150 nm thick carbon mask, producing steps 270–450 nm high. A YBCO film 75–145 nm thick was grown on the etched substrate by KrF eximer laser ablation at $T = 760$ °C and oxygen pressure of $P_{O_2} = 0.6$ mbar. A 20 nm thick layer of gold was deposited in situ on top of the YBCO at room temperature. The second e-beam lithography was made to fabricate 250 nm thick gold pads for electrical connections. The third e-beam lithography defined the carbon mask for the fabrication of the bridges across the step. Making use of the marks predefined in the substrate we were able to align all microbridges to the steps with accuracy better than 200 nm. The YBCO was ion beam etched through the carbon mask. Finally, the in situ gold layer covering the YBCO was removed by ion milling.

For the fabrication of the biepitaxial junctions 20–30 nm thick CeO_2 films were deposited by RF magnetron sputtering at $T = 700$ °C in mixed atmosphere of Ar and O_2 with partial pressure $P_{O_2} = P_{Ar} = 6$ Pa. The seed layers were then suitably patterned using standard photolithography and Ar ion milling etching. A 100–120 nm thick YBCO film was then deposited by inverted cylindrical magnetron sputtering at $T = 770$ °C and $P_{O_2} = P_{Ar} = 55$ Pa. Finally, microbridges with width ranging from 2 to 20 μm were fabricated by photolithography and Ar ion milling etching.

3. Experimental results and discussion

3.1. Wide step-edge Josephson junctions

It is well established that with the step-edge junction (SEJ) technology the normal resistance R_N can be tuned by several orders of magnitude by reducing the ratio between the film thickness (t) and the step height (s). We aimed at understanding how high the value of the resistance could be and how reproducible the submicrometer junctions can be made with extreme values of t/s, namely less than 0.3.

In this section we will present data from three different sets of SEJs obtained by varying the step height and the film thickness but keeping their ratio $t/s \approx 0.3$ almost constant. All measurements are done at 4.2 K. In Table 1 the characteristic parameters of 4 μm wide SEJs related to the three chips are reported. For comparison the most significant data related to the biepitaxial technology is also included.

Fig. 1 shows the I–V characteristics of SEJ #2. The curve is RSJ-like with 10% hysteresis and no excess current. The I–V characteristic of SEJ #3

Table 1
Fabrication parameters (film thickness (t), step height (s), and their ratio (t/s)) and properties of 4 μm wide Josephson junctions (critical current (I_c), normal resistance (R_N), and the McCumber parameter (β_c)) related to the three chips #1, 2, and 3 obtained by the step-edge technique. For comparison representative data related to a 4 μm biepitaxial junctions have also been included. All the data refer to $T = 4.2$ K

	t (nm)	h (nm)	t/s	I_c (μA)	R_N (Ω)	I_cR_N (mV)	β_c
SEJ #1	145	450	0.33	55	22	1.2	1.5
SEJ #2	120	450	0.27	13	60	0.78	2
SEJ #3	70	270	0.27	4	2000	8	5.5
NGbiep #1	100	–	–	0.1	1000	0.1	1.2

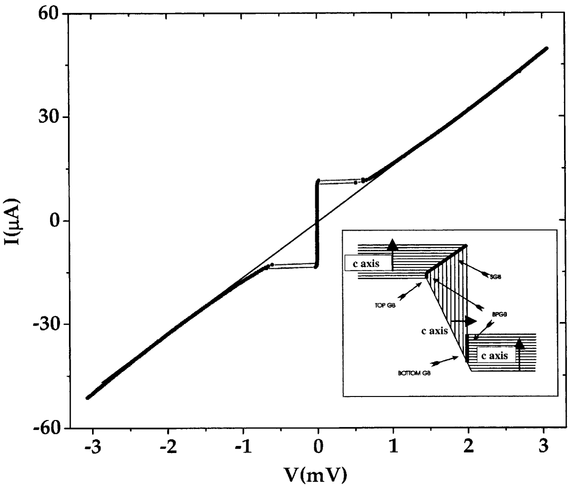

Fig. 1. I–V characteristics of SEJ #2 at $T = 4.2$ K. The dashed line is the linear fit at high bias. The inset shows the microstructure of the grain boundaries formed at the top and bottom parts of the step.

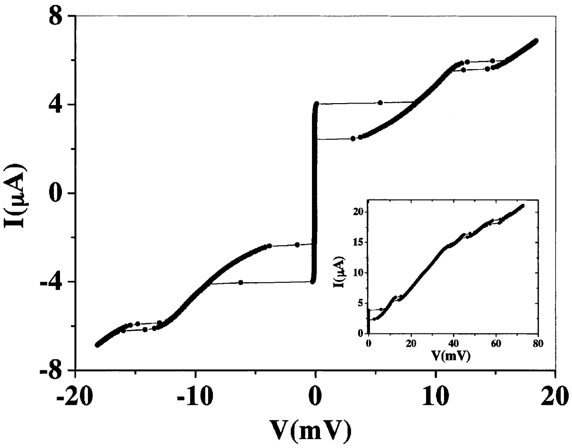

Fig. 2. I–V characteristics of SEJ #3 at $T = 4.2$ K. The inset shows the positive branch at higher voltages.

reported in Fig. 2 is quite different. The curve is RSJ-like only at low voltages with a high degree of hysteresis (almost 50%) corresponding to a value of the McCumber parameter $\beta_c = 5.5$ suggesting that tunneling is the dominant mechanism of transport. The inset shows the positive branch of the I–V characteristic at high voltages. Distinct hysteretic voltage steps of the order of 5 mV are clearly observed. Moreover the resistance of the junction increases by almost 500 Ω after each voltage step. We were able to detect more than 25 hysteretic voltage steps with similar characteristics on the voltage scale up to 600 mV. Such kind of features were also observed in SEJ #1 and #2 though the number of steps was much reduced, about 2 or 3 on the scale of 100 mV.

In order to interpret this data let us make a closer look at the microstructure of the SEJJs [5]. The grain boundary formed at the top of the junction consists of two parts: a basal plane faced grain boundary (BPGB), which nucleates on the substrate up to a thickness of 10–20 nm of the growing film and a symmetric grain boundary (SGB) on top of it. For the BPGB the interface plane is perpendicular to the substrate, while the SGB is at 45° to it. The bottom GB consists instead of an almost pure BPGB. In a previous work we have established that normally the symmetric grain boundary is responsible for the Josephson behavior of the junctions, whereas the BPGB carries a high critical current and can therefore be neglected [6].

When the ratio t/s is extremely reduced, the film on the step becomes naturally oxygen depleted, in contrast to the usual case. Oxygen out-diffusion, which predominantly occurs along the a–b planes, is facilitated by the reduced film thickness (23 nm for SEJ #3) and the orientation of the film on the step. Also, for the latter reason, BPGB is less affected than SGB. In this situation, the weakest link for the Josephson transport is the intrinsic tunneling in between the a–b planes in the step region, first observed by Rapp et al. [7] in artificially oxygen depleted YBCO films. The possibility of c-axis tunneling in our samples is strongly supported by the observation of the semiconducting behavior of the temperature dependence of resistivity close to the transition temperature (of the order of 50 K). The regular voltage steps then correspond to the serial switching of intrinsic junctions into the resistive state. The high value of the I_cR_n product about 8 mV is in fact comparable with the voltage steps observed at higher bias. For SEJ #1 and #2 a thicker YBCO film on the step (40–50 nm) presents less oxygen vacancies. Both the SGB and intrinsic c-axis junctions act as weak links. In both samples, the I_cR_n value is in the usual range for SEJs (compare Table 1), while the hysteretic voltage steps are again of the order of 5 mV.

3.2. Submicrometer step-edge Josephson junctions

The transport properties of the submicrometer-wide SEJs were studied at the temperatures below 100 mK in the dilution refrigerator on two samples #1 and #2.

At 20 mK two 0.3 μm junctions on samples #1 and #2 showed I–V curves with a critical current of 10 and 1 nA and a normal resistance of the order of 10 and 60 kΩ respectively. In the following we will refer to them as sub #1 and #2. Fig. 3a shows the I–V characteristic of sub #2 in current bias mode. An interesting feature is the presence of regular steps up to a voltage of about 100 μV. Importantly, the steps were observed in the same voltage range and with close periodicity on sub #1, while the current scale was different by a factor of 10. The picture becomes more dramatic, when the measurements are performed in the voltage bias regime (Fig. 3b), and it becomes evident that the periodic features correspond to current peaks.

A magnetic field of up to 5 T does not change the position of the current peaks on the I–V curves, while suppressing the critical current roughly by half (see Fig. 3a and b). The upper limit of the range, where the peaks are present, gradually moves down wiping out the peaks at the higher voltages as the magnetic field is increased. The temperature up to 90 mK does not influence the position of the peaks, their voltage range or the critical current. Data for higher temperatures would be important for the understanding of the transport mechanisms in these structures.

The current peaks on the I–V curves definitely point to some resonant modes in the structure, possibly suggesting that the tunneling current is probing a spectrum of discrete energy levels. The nature of these levels is not exactly known. We can suggest a scenario based on the predictions of Ingerman et al. [8]. The authors have analyzed coherent multiple Andreev reflections (MAR) and current resonances in long ballistic SNS junctions and obtained a picture strikingly similar to that observed in our experiment. In the framework of the MAR scenario the spacing between the Andreev bound states at the surface of the superconductor S is determined solely by the transverse size of the normal region N. The current peaks correspond to the bias eV equal to the difference in energy between two bound states. Therefore the position of these double resonances is determined by geometry and is independent of the gap. The upper voltage limit for such a process is however 2Δ, which in our experiment we attribute to the peak at 170 μV in zero magnetic field.

The major problem with this scenario stands in the fact that the junction has to be ballistic on the length scale $\hbar v_F/eV$, while the YBCO junctions are known to have a very short mean-free path. Taking the table value of 10^7 cm/s for the Fermi velocity and 33 μV for the voltage position of the resonant peaks we arrive at the unrealistic length of the order of a few microns. However, as we have

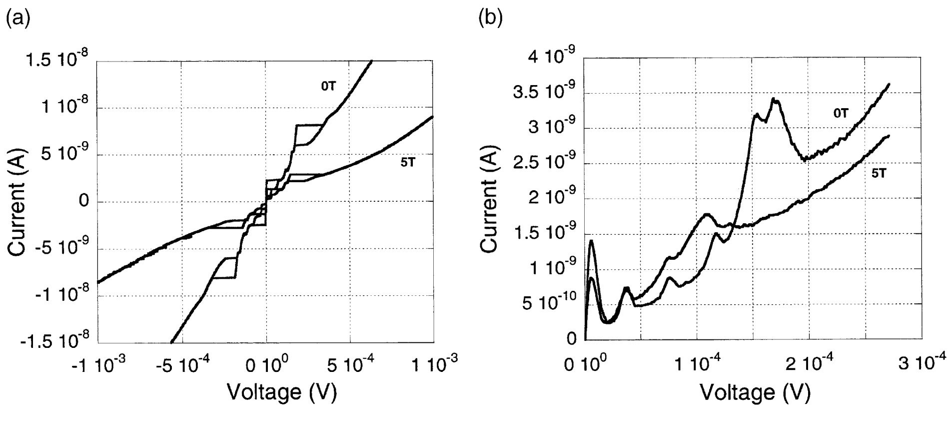

Fig. 3. I–V characteristics of sub #2 at $H = 0$ and 5 T in current bias mode (a) and voltage bias mode (b).

shown above tunneling takes place in the *c*-direction of the film grown on the substrate step. Then the length in question is the thickness of the film on the step surface, about 20 nm. This length corresponds to a significantly smaller Fermi velocity of 10^4 cm/s, which can be justified by the oxygen depletion and anisotropy.

Another interesting point within the same scenario is the origin of the double-gap feature at 170 μV in zero field. This can be attributed to either the bulk subdominant s-wave gap or the d-wave gap severely suppressed by disorder.

As can be seen, the Josephson coupling is not completely suppressed even in the most resistive junctions and even in the magnetic field of 5 T, which emphasizes the necessity of alternative techniques for junction fabrication.

3.3. Wide biepitaxial Josephson junctions

The biepitaxial technique has been employed to obtain grain boundaries combining high resistive interface, such as those characterized by a misalignment of the *c*-axis, and low values of the critical current density J_c like 45° [0 0 1] tilt grain boundary, where a Cooper pair tunnels into a node of the superconducting $d_{x^2-y^2}$ gap in one electrode of the junction [9]. With this technique the grain boundaries are obtained at the interface between a (1 0 3) $YBa_2Cu_3O_{7-\delta}$ film grown on a (1 1 0) $SrTiO_3$ substrate and a *c*-axis film deposited on a (1 1 0) CeO_2 seed layer. The *a* and *b* axes of the (0 0 1) YBCO grown on the CeOs are rotated by 45° with respect to the two in-plane direction of the $SrTiO_3$ substrate. By changing the angle ϑ between the edge of the CeO_2 and the [0 0 1] in-plane direction we were able to obtain grain boundaries with J_c and R_N values varying by two orders of magnitude.

In Fig. 4 it is shown the *I–V* characteristic of a 4 μm junction NGbiep #3 obtained with the biepitaxial technique, by patterning the CeO_2 edge at an angle $\vartheta = 79°$ with respect to the [0 0 1] direction of the $SrTiO_3$ substrate. In this configuration the Cooper pair tunneling is almost in the node of the order parameter in one electrode of the junction (that is defined in the YBCO film grown on the seed layer). We note that the value of the Josephson current is extremely, more than 100

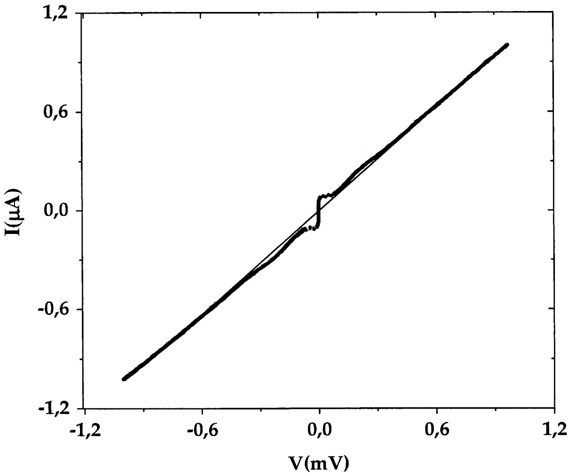

Fig. 4. *I–V* characteristic of NGbiep #3 at $T = 4.2$ K. The straight line is the linear fit at high bias.

times, reduced compared to that for SEJ #3. The value of R_N instead is comparable with the highest value we have got with the step-edge technique. This kind of grain boundaries therefore combines a highly resistive interface with low J_c values. Measurements on the submicron biepitaxial junctions at millikelvin temperatures are under way.

4. Conclusions

We have studied possible implementations of high-resistance tunnel barriers for an all-$YBa_2Cu_3O_{7-\delta}$ SSET. The step-edge and biepitaxial techniques have been employed to fabricate the junctions. We have been able to tune, by several orders of magnitude, the resistance of the SEJs by reducing the ratio between the film thickness (t) and the step height (s). With extreme values of the ratio t/s the junction properties appear to be dominated by the intrinsic tunneling. Resistance values higher than 30 kΩ have been obtained in 0.3 μm wide junctions. At very low temperatures below 100 mK *I–V* characteristic of submicron junctions obtained in the voltage bias mode showed pronounced current peaks probably related to the presence of localized Andreev levels at energies less than the superconducting gap Δ.

Different grain boundaries based on a combination of (0 0 1) 45° tilt and (1 0 0) 45° tilt or twist have been implemented by the biepitaxial technique. We have been able to get resistance value of the order of 1 kΩ in 4 μm wide junctions. Both technologies appear very promising for the implementation of all-high-T_c SSET.

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