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Small-number arrays of intrinsic Josephson junctions

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Abstract

Arrays of nanometre-thick Bi2212-intrinsic Josephson junctions (IJJ's) are studied in various geometries. The samples with only a few IJJ's allow for the intrinsic-tunnelling spectroscopy with minimum of Joule heating. The reproducible low-voltage peaks of the spectra probably stem from a superconducting gap which is half the usual size. We estimate the internal temperature in the IJJ stacks and analyze the importance of the self-heating for the macroscopic-quantum-tunnelling experiments involving IJJ's.

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1. Introduction

Intrinsic Josephson junctions (IJJ's) [1] are convenient objects for fundamental studies on high-temperature superconductors (HTS's). The intrinsic tunnelling is an integral part of many effects in HTS's and therefore is central in many experiments.

Studies on IJJ's gave new insight in the fields of Abrikosov- and Josephson-vortex physics [2–5] and in the superconducting- and pseudogap-spectroscopy where IJJ's provided information "from inside the crystal," i.e. without adverse effects from deteriorated surfaces [6,7]. Phonon excitations were seen in the intrinsic-tunnelling spectra as well [8]. Finally, recent experiments on macroscopic quantum tunnelling (MQT) have once again demonstrated that IJJ's are essential in studies on HTS's [9,10].

Self-heating from high-bias needed to reach voltages beyond the superconducting gap is now a well-understood problem in experiments on IJJ's [11–13]. The heating problem is also due to a relatively poor thermal conductivity of HTS's. Decreasing linear dimensions of mesas/stacks that are commonly used in studies IJJ's [14] was found to somewhat alleviate the heating, but since the total power is proportional to the sum-gap voltage (i.e. number of junctions N), N should be kept low also. For usual mesas the limiting case of $N = 1$ means that the single junction is in a direct contact with the normal-metal electrode and thereby can have weakened superconducting characteristics. Stacks that have superconducting electrodes should therefore be used.

In this report, we first describe a technique [15] for making thin stacks enclosing only a few IJJ's without proximity of normal-metal electrodes [16]. These samples allow for the intrinsic-tunnelling spectroscopy with a minimum of Joule heating. Then we discuss the reproducible low-voltage peaks of the intrinsic-tunnelling spectra that probably stem from a superconducting gap which is half the usual size. Finally, we self-consistently estimate the internal temperature in the IJJ stacks and analyze the importance of the self-heating for the microscopic-quantum-tunnelling experiments involving IJJ's.

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2. Samples

We use a refined flip-chip technique introduced earlier [15] to isolate and study a few IJJ's [16].

The processing starts with the fabrication of a bow-tie-shaped mesa with a micro-bridge in the centre using photolithography and Ar–ion etching. The thickness of the mesa d is about 100 nm. The (first) 40-nm-deep slit ($< d/2$) is etched into the bridge (see Fig. 1a). Then we flip the sample and glue it to another substrate, thus sandwiching the single crystal between the two substrates. Taking the substrates apart also cleaves the single crystal into two pieces, one with the mesa being upside down. We remove excess parts of the crystal that might also stick to that substrate using sticky tape. A new gold layer is then deposited and patterned to make four electrodes attached to this flipped mesa. Finally, a CaF_2 protection layer with an open window placed across the bridge is formed with a lift-off photolithography. Further Ar–ion etching incises another slit into the bridge through that window (see Fig. 1b). When the slits overlap along the c axis, a stack of IJJ's appear in the middle and becomes gradually higher with further Ar–ion etching [16] (see Figs. 1c and 2).

It is worthwhile mentioning that we use quite low energy and current of the Ar–ion beam, 230 V and 0.1 mA/cm^2, respectively, corresponding to the etching rate of about 1.5 nm/min (1 IJJ/min). It was found that even such weak beams could affect superconducting properties of the etched areas. Nonetheless, the original properties can be easily recovered by a 10-min annealing at 120 °C in air.

3. Current–voltage characteristics

Fig. 3 shows a typical current–voltage (I–V) characteristic of a stack with relatively large number of IJJ's. The characteristic is multiple-valued and hysteretic which is representative for the one-dimensional arrays of superconductor-insulator-superconductor (SIS) type of Josephson junctions. Each consecutive branch of this brush-like pattern corresponds to increasing number of IJJ's that have switched to the quasiparticle-tunnelling state.

Note a monotonous decrease of the branch critical currents, as well as a decrease of the branch separation in voltage with increasing branch count number i (and the corresponding voltage V_i). In the ideal case of identical IJJ's, all the branches would be equally spaced in voltage ($V_i = \text{const} \times i$) and would have one and the same critical current I_{ci}. However, the presence of self-heating makes both I_{ci} and V_i/i to decrease.

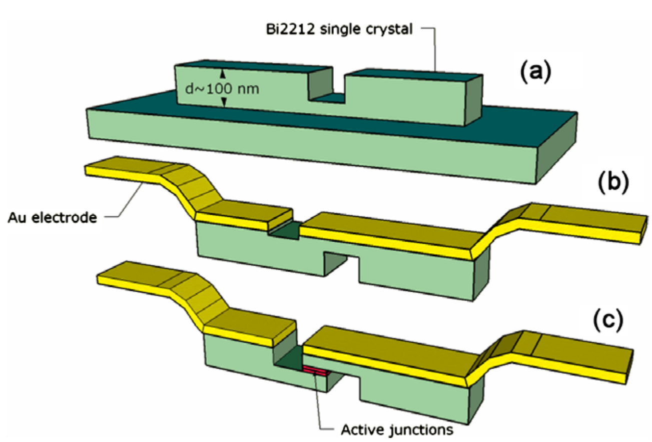

Fig. 1. Schematic sketch of a zigzag-type structure with an active stack of IJJ's in the middle of a small and thin single crystal. (a) 100-nm mesa with a slit on top of a large single crystal; (b) flipped mesa with the gold layer on top and the second slit which is being made; (c) the slits overlap in the c-axis direction and a stack of active IJJ's is formed. The relative sizes are not in scale.

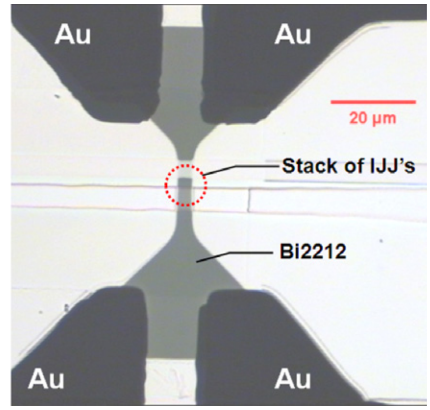

Fig. 2. A backlight image of one of our samples. The stack in the middle of the microbridge is marked by circle. Note that Bi2212 is very thin and therefore semi-transparent. Horizontal lines are edges of the CaF_2 etch mask covering everything but the middle part of the bridge. We usually make three such microbridges on a 5 × 5 mm^2 sapphire substrate.

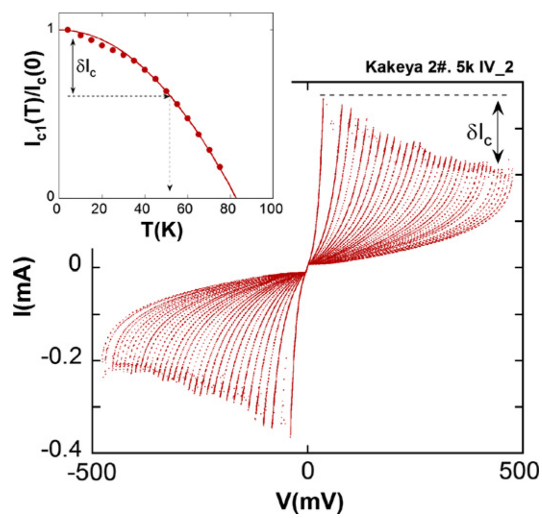

Fig. 3. The hysteretic multiple-valued current–voltage characteristics of a sample with about 35 IJJ's measured at $T = 5$ K (main panel). The inset shows the temperature dependence of the normalized critical current of the first branch. The critical currents of the following branches decrease with the count number due to increasing heat dissipation. It is this decrease δI_c that we use to estimate the internal temperature for high-voltage branches (see the inset) [17]. There is no branch corresponding to $V = 0$ because of two-probe measurements for this sample.