Anomalous Proximity Effect in the Nb-BiSb-Nb Junctions

A. Yu. Kasumov, O. V. Kononenko, V. N. Matveev, T. B. Borsenko, V. A. Tulin, E. E. Vdovin, and I. I. Khodos
Institute of Microelectronics Technology and High Purity Materials,, RAS, 142432 Chernogolovka, Moscow Region, Russia

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An anomalous proximity effect was observed in coplanar Nb-BiSb-Nb junctions. The effect consists of a considerable increase of the critical current with an increase in the distance between the superconducting electrodes. The effect is explained by the quantum character of Cooper pair transport through the normal region. Some advantages of the application of such junctions are discussed. [S0031-9007(96)01251-3]

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The proximity effect consists of a mutual influence of a contacting superconductor and a normal conductor (a metal or a semiconductor). One of the manifestations of this effect is the flowing of a superconducting current through two superconductors separated by a relatively thin layer of a normal material termed a weak link [1]. The thickness d of the layer, at which a superconducting current can still be observed, reaches 100–1000 nm [2–5]. This current is related to the penetration of Cooper pairs from the superconductor to the normal region. It was considered for a long time [2–5] that a superconducting current always decreases with an increase in the thickness of a normal layer. This viewpoint, supported by numerous experiments, seemed apparent because the number of Cooper pairs crossing the normal region should naturally decrease with an increase of this region size. However, it was suggested in [6] that this situation is not valid for all types of weak links. In that work, the transport of Cooper pairs was considered for the quantum weak link—the normal region, whose size is comparable with the de Broglie wavelength of charge carriers λ. Some years later, other works on this problem were reported [7,8].

In [6], a junction with mirror-smooth parallel interlayer boundaries is considered to behave as a Fabry-Pérot interferometer. The value of superconducting current I_c in such a junction oscillated depending on its thickness. The amplitude of the current oscillations reaches the values about 100% at a thickness of 1.5λ; at greater thickness it sharply decays. It should be emphasized that, according to the theory [6], the superconducting current I_c can appreciably increase with the distance between superconducting electrodes. Such an anomalous behavior of the critical current has not previously been observed.

In this Letter we report on the first observation of an increase in the critical current with an increase of the weak link length in coplanar Nb-BiSb-Nb junctions (Fig. 1). To the best of our knowledge, superconducting BiSb-based junctions have not yet been used; we fabricated such junctions not long ago [9], although the unique electron properties of this material have long been known [10]. One of these properties is an abnormally low effective mass of electrons m^* equal to $0.9 \times 10^{-3} m_0$ where m_0 is the mass of a free electron and, hence, a very great de Broglie wavelength $\lambda \approx 800$ nm in single crystals with 6 at. % Sb [10]. As compared with Bi single crystals, the values of m and λ in BiSb crystals change by approximately an order of magnitude; a similar tendency is observed in polycrystalline BiSb films [11].

In this work we mainly used junctions based on BiSb films containing about 6.5 at. % Sb. Junctions on the basis of bulk BiSb single crystals were also used. The films were deposited onto an oxidized Si substrate by a partially ionized beam with an accelerating voltage up to 5 kV [12]. Films deposited at a rate of 2 nm/s at an accelerating voltage of 2 kV exhibited the greatest mobility $\mu = 5 \times 10^4$ cm^2/V s and the lowest resistivity $\rho = 140\ \mu\Omega$ cm (parameters measured at 4.2 K). The structure of grain boundaries in these films was rather regular. In this work, we used such films (500 nm thick) because any deviation from the optimal deposition regime resulted in the deterioration of the electrical properties.

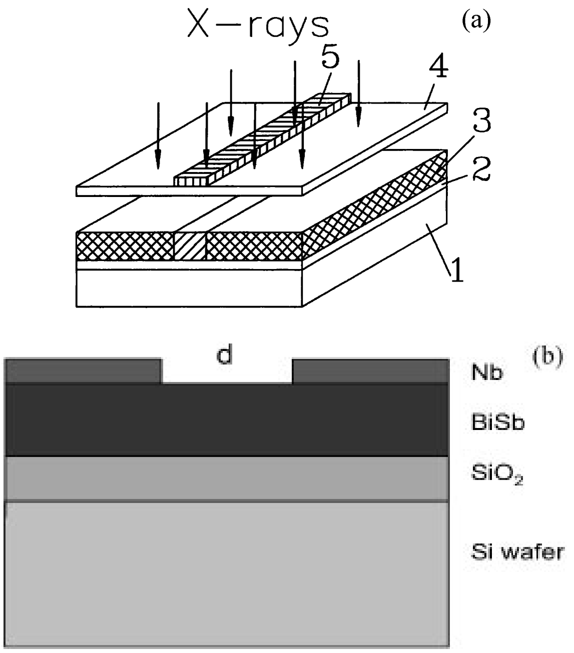

FIG. 1. The scheme of junctions fabrication. (a) X-ray lithography; (b) a schematic cross-sectional view of the junction.

For example, the mobility and resistivity of the films deposited at a rate of 5 nm/s were 2×10^3 $\mathrm{cm}^2/\mathrm{V\,s}$ and 520 $\mu\Omega$ cm, respectively. The structure of grain boundaries in these films was disordered.

Junctions were fabricated by optical and x-ray lithographies [13] [Fig. 1(a)]. The positive polymer resist (e.g., PMMA) film of 1 μm thickness (3) is spun on the substrate (1) covered with a BiSb film (2). PMMA strips are fabricated by means of x-ray lithography. Cu $L\alpha$ irradiation ($\lambda = 1.33$ nm) was used as a source of x-ray beams. We have used x-ray Au masks (5) with polyimide supporting membranes (4). Au patterning was realized with the help of electron beam litography and subsequent electroplating of gold onto a conductive layer through the resist. The thickness of polyimide was varied from 2 to 4 μm and the thickness of Au film equal to 300 nm. The next step consists in the spinning of the photoresist, and open windows in it are created to form two contact pads of superconductive metal (the Nb films 100 nm thick were deposited by magnetron sputtering) connected with a narrow trench which intersects the initial polymer resist structure. After the metal has been deposited, a liftoff procedure is carried out in a solvent of the resist. The liftoff operation left two Nb contact areas, connected by a 2.5 μm wide Nb stripe with a slit in the middle, on the surface of BiSb (Fig. 1). Three batches of seven junctions with slits 0.6, 1.2, and 2.0 μm were fabricated of the same substrate. The absence of Nb short circuits was checked by scanning electron microscopy. In addition, some reference specimens where Nb stripes had no slits were fabricated; in these specimens $I_c = 7 \times 10^6$ $\mathrm{A/cm}^2$ and $H_c = 1.6$ T at 4.2 K and $\Delta I_c/I_c$ was about 10% for various specimens. The voltage was measured to an accuracy of 10 nV, which allowed the registration of a superconducting current up to 0.1 μA.

No superconducting current in the junctions with a 2.0 μm slit was observed. In other junctions, the spread of the values for critical current $\Delta I_c/I_c$ was about 10%; I_c and normal resistance $R_N \approx 1\ \Omega$ remained unchanged after several temperature cyclings at 300–4.2 K. The value of the critical current in the junctions with 1.2 μm slit was 2.5 times higher than that in the junctions with 0.6 μm slit (Fig. 2); this is the main result of this work.

The anomalous increase of the critical current with the distance between superconducting electrodes cannot be explained by theories based on the "trajectoral" (diffusional or ballistic) transport of Cooper pairs through the weak link [2–5]. All the theories of quantum transport of Cooper pairs [14], except for the theory developed in [6,7], consider the quantization of the transverse motion, which gives rise to a monotonous staircase dependence of I_c on the junction width. The geometry of the junction described in [6] differs from that used in our experiments. However, the quantum-mechanical models of the junctions are similar. In the case of [6], this is a potential well surrounded by barriers; in our work it is a potential well without barriers (the Fermi energy of electrons $E_f \approx 1$–2 meV for BiSb [10] is much smaller than $E_f \approx 5$ eV for Nb [15]); the well width is equal to d. In both cases, the resonant transparency of junctions is observed when the well width d accommodates an integral number of $\lambda/2$ [16]; it seems, for junctions with $d = 1.2$ μm, this number is 3, and resistance of these junctions must be lower than resistance of the junctions with $d = 0.6$ μm. The theoretical curve [6] describing the temperature dependence of $V_c = I_c R_N$ is fairly close to the experimental values obtained in this work (Fig. 3). However, one important divergence from the theory exists: In the experiment the difference between the values of critical currents in the junctions with $d = 1.2$ and 0.6 μm varies slightly with temperature (Fig. 3), whereas the theory predicts a considerable increase of this difference in the region of low temperatures [6]. Note that the $V_c(T)$ dependence observed in our experiments is characteristic of pure weak links with transparent boundaries [17].

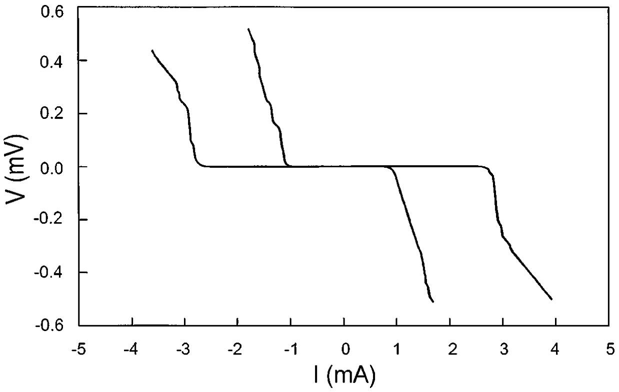

FIG. 2. I-V characteristics for the junction at 4.2 K. $I_c = 1$ mA for 0.6 μm slit junction; $I_c = 2.5$ mA for 1.2 μm slit junction.

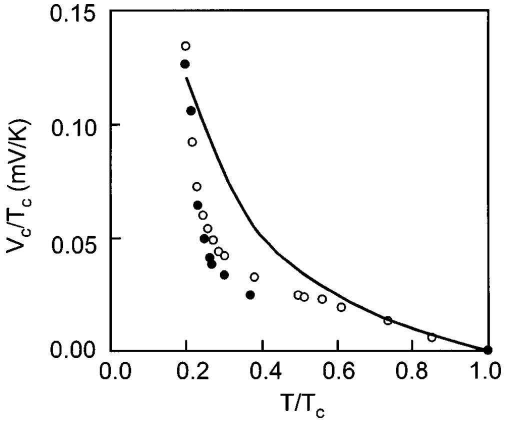

FIG. 3. Temperature dependence of the characteristic voltage $V_c(T)$ for 0.6 μm slit junction (circles) and for 1.2 μm slit junction (dots). The solid line represents the theoretical curve from [6].

A transparent boundary is a characteristic distinguishing our junctions from other junctions with semiconducting weak link [14,18–20]. In those junctions, Schottky barriers are often present on the metal (superconductor)-semiconductor boundaries. In Bi and its diluted alloys with Sb, no Schottky barriers exist on such boundaries [21,22]. Also of importance is the fact that Bi and Sb are almost insoluble in Nb [23] so that no compounds are formed on their interface. Therefore, a very high critical current density j_c must be due to the absence of Schottky barriers and a "good" interface, in addition to the quantum character of the Cooper pair transport. In the junctions with $d = 1.2\ \mu\text{m}$, this density is $10^6\ \text{A/cm}^2$ at 4.2 K (Fig. 2), which is somewhat greater than the value $0.8 \times 10^6\ \text{A/cm}^2$ obtained in [24]. However, this value was achieved at 1.4 K, and it drastically decreases at higher temperatures. The values of j_c for junctions, with semiconducting weak links reported in some other works [14,18–20], is 1–3 orders of magnitude smaller. The value of d in those works was smaller than 1 μm. To the best of our knowledge, there is only one work [25] in which a superconducting current was observed in a junction based on a semiconducting weak link with an unusually large value of $d = 1\ \mu\text{m}$. An external magnetic field slightly influenced this current, and the transition to the normal state occurred in rather strong fields about 0.2 T, which is unusual for Josephson junctions [2–5]. The behavior of the junctions we studied was also unusual. The transition to the normal state occurred in a field of 0.2 T. Shapiro steps were observed only in the junctions with $d = 1.2\ \mu\text{m}$ after irradiation by a second harmonic frequency field at a frequency of 36 GHz. The irradiation of the junctions with $d = 0.6\ \mu\text{m}$ only caused a decrease in the magnitude of j_c.

In our junctions, the magnitude of j_c depended on the mobility of electrons in BiSb and, hence, on the structural defects in the material of the weak link. In the junctions based on bulk BiSb single crystals prepared by zone melting $\mu = 6 \times 10^6\ \text{cm}^2/\text{V s}$ and $j_c \approx 3 \times 10^6\ \text{A/cm}^2$. In the junctions based on the films deposited at a rate of 5 nm/s [Fig. 4(a)], $\mu = 2 \times 10^3\ \text{cm}^2/\text{V s}$ and $j_c = 10^4\ \text{A/cm}^2$; the superconducting current was observed only in the junctions with $d = 0.6\mu$ wide, in wider slit junctions it did not occur (Table I). To our minds, the drastic decrease of j_c in these films is due to a disordered structure of the grain boundary. In the films deposited at a rate of 2 nm/s [Fig. 4(b)], the grain boundaries consist of a regular series of grain-boundary dislocations separated by a distance of about 3 nm [Fig. 4(c)]. Apparently, this regular structure of grain boundaries provides for a coherent passage of an electron wave without any appreciable reflection [26]. As a result, a slight decrease in j_c can take place in comparison with a single crystal, in spite of a considerable difference in mobility (a decrease in the mobility in the InAs-based junctions by an order of magnitude also caused only a very small decrease in j_c [27]).

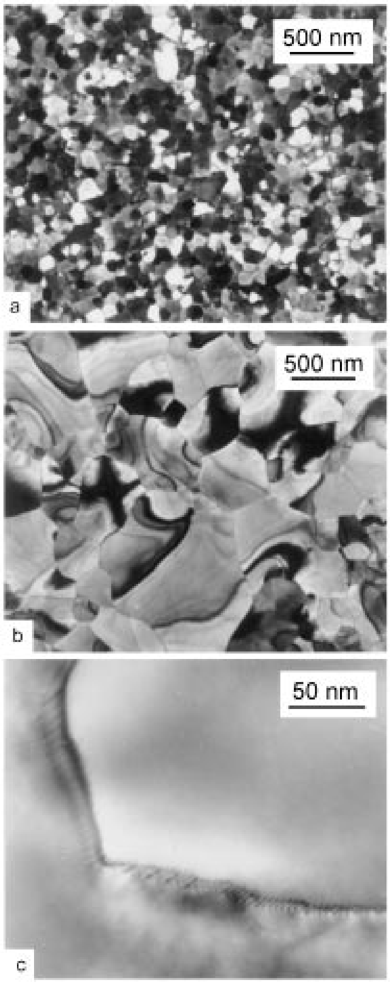

FIG. 4. TEM images of the BiSb films deposited on the SiO_2/Si_3N_4 membranes at the rates 5 nm/s (a) and 2 nm/s (b); (c) dislocation structure of the grain boundary of the BiSb films deposited at the rate of 2 nm/s.

Regrettably, we cannot make a more accurate comparison of j_c values in films and single crystals because the roughness of the single crystal surface does not allow us to use conventional lithography techniques for the preparation of junctions. The junctions were cut out with a focused laser beam, and this technique did not permit the fabrication of junctions with d less than 1 μm. Nevertheless, at $d \geq 2\ \mu\text{m}$, the superconducting current disappears as in the case of films. The uneven edges of the laser cut cause some spread in the j_c values for different junctions based on single crystals. Single crystals of two compositions were used with a Sb content of 6.5% and 10%. It was found that the magnitude of j_c is, on average, three times smaller in the junctions based on single-crystals with 10 at.% Sb. We could achieve a reproducibility of the parameters only for the film-based junctions. In other works [14,18–20], the problem of reproducibility for the junctions with semiconducting weak links important for practical application has not even been raised.

Using quantum weak links could help solve the problem of irreproducibility of the junction parameters I_c first of all. In conventional junctions $I_c \sim \exp(-d/\xi_n)$, where ξ_n is the coherence length in the normal region, therefore even a slight change in d causes appreciable changes in I_c. In quantum weak links, changes in the junction size by $\leq 0.1\lambda$ should not strongly influence I_c [6–8]. We fabricated a chain of 1200 BiSb-based junctions connected in sequence. The chain switched synchronously to the normal state, giving rise to a voltage of about 1 V. These chains were stable to temperature cycling from 300 to 4.2 K and degraded only when heated above 200 °C.

In conclusion, we would like to discuss whether such an effect is possible in other superconductor-normal-superconductor (SNS) junctions, i.e., is it really anomalous? From the theoretical point of view [6], the effect must be observed in any SNS junctions if the distance between the superconducting electrodes is approximately equal to λ and the pulses of electrons differ in the S and N electrodes. The wavelength is less than 1 nm in usual metals, and it is very difficult to fabricate the SNS junctions with such a thin N layer. The fabrication of suitable SNS junctions on the basis of semimetals, degenerate semiconductors, and heterostructures is obviously more real. We are planning an investigation of this effect in the Bi nanobridges ($\lambda = 100$ nm) whose fabrication technology has already been developed [28,29].

In summary, we observed an anomalous proximity effect which consists of the enhancement of superconductivity in the junction normal region as the distance between the superconducting electrodes increases. The effect is accounted for by the quantum character of the weak link. The advantages of quantum weak links as compared to conventional weak links are discussed from the viewpoint of their practical application.

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