Anomalous behavior of the critical current of a grain-boundary Josephson junction in a bulk (Ba,K)BiO$_3$ bicrystal

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(Submitted 12 November 1993)
Pis'ma Zh. Eksp. Teor. Fiz. **59**, No. 3, 159–162 (10 February 1994)

The electrical transport properties of grain boundaries in bulk bicrystals of the oxide superconductor $Ba_{0.55}K_{0.45}BiO_3$ have been studied. The grain boundary in these bicrystals is a Josephson barrier. Near the transition temperature, the critical current of this barrier has a power-law temperature dependence with a critical exponent of 3/2. The critical current of a grain boundary exhibits a nonmonotonic behavior as the temperature is lowered. A possible interpretation of this behavior is discussed.

1. INTRODUCTION

Bulk bicrystals of the oxide superconductor Ba(Pb,Bi)O$_3$ were the first material in which it was demonstrated that a macroscopic plane defect of the grain-boundary type could serve as a Josephson barrier separating superconducting single-crystal blocks.[1] When, after the discovery of the high-T_c superconductors, a similar approach was taken to develop Josephson junctions in thin-film high-T_c bicrystals, the effort was rewarded with substantial progress in research on the Josephson effect on the high-T_c materials.[2-4] So far, however, there have been no reports of the fabrication and study of Josephson junctions based on bicrystals of the extremely interesting "copper-less" high-T_c superconductor $Ba_{0.55}K_{0.45}BiO_3$, with a transition temperature above 30 K.

2. EXPERIMENTAL DETAILS

The bicrystals were grown by a method based on electrochemical deposition developed in Ref. 5. The test samples consisted of a system of two single-crystal blocks, each with the cubic faceting characteristic of perfect cubic (Ba,K)BiO$_3$ crystals.[6] Laue diffraction patterns of the bicrystals recorded by the broad-beam method revealed two, shifted systems of diffraction peaks, each corresponding to a single crystal of cubic symmetry. The relative shift of the systems of peaks on the patterns was utilized to determine the solid angle of the misorientation of the single-crystal blocks. In the present study we used bicrystals in which the misorientation was more than 15° in

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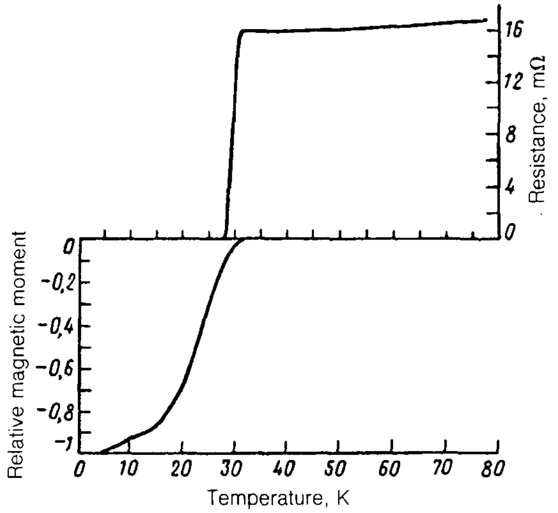

FIG. 1. Temperature dependence of the magnetic moment and resistance of grain boundaries of a $Ba_{0.55}K_{0.45}BiO_3$ bicrystal.

terms of each component. A detailed study was made of the effect of the misorientation angle and of the properties of the small-angle grain boundaries (with a misorientation of less than 15°); those results will be published later. The typical size of the single-crystal blocks in the test samples was about 1 mm. The cross-sectional area of the grain boundaries was on the order of 0.5 mm^2.

The electrical transport properties of the bicrystals were studied in the regime of a given direct current, which flowed in the direction perpendicular to the grain boundaries. Comparative measurements of the resistance in the normal state and of the critical current in the superconducting state for the single-crystal blocks and the grain boundary, respectively, showed that the contribution of the grain boundary to the resistance of the bicrystal was $\leqslant 0.1\%$ and that the critical current of the single-crystal blocks was higher than that for the grain boundaries by a factor of at least 10^4. Accordingly, no further processing of the samples was carried out to create constrictions in the measurements of the critical current of the grain boundary. Pairs of measuring contacts were applied directly to the surface of each of the single-crystal blocks. In a study of the effect of a magnetic field on the transport properties, we used a test sample with a grain boundary in the form of a plane. An external field was applied in a direction parallel to this plane. The magnetic moment was measured with the help of a vibration magnetometer with a sensitivity of 10^{-5} in a measurement field of 5 Oe.

3. RESULTS AND DISCUSSION

3.1. Josephson junction in $Ba_{0.55}K_{0.45}$ BiO_3 bicrystals

Figure 1 shows the temperature dependence of the resistance of a bicrystal and that of its magnetic moment. In these measurements, the density of the measurement current (I) across the grain boundary was 0.2 A/cm^2. There is a clearly defined resistance transition with an onset temperature T_c=31.2 K and a width no greater

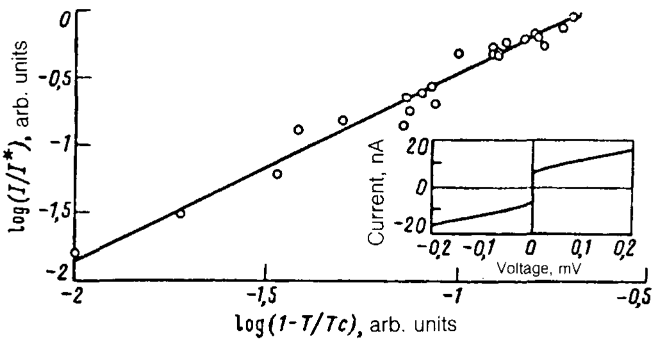

FIG. 2. Current–voltage characteristic at $T=26$ K and temperature dependence of the critical current I^* of a grain boundary of a $Ba_{0.55}K_{0.45}BiO_3$ bicrystal near the transition temperature.

than 2.7 K (as determined from the point at which the resistance has fallen below 3×10^{-6} Ω). We also see a monotonic increase in the diamagnetic response below T_c. This monotonic increase is evidence that the superconducting single-crystal blocks are of fairly high quality and that the current transport across the grain boundary is dissipation-free below 28.5 K.

Figure 2 shows a current–voltage characteristic of a $Ba_{0.55}K_{0.45}BiO_3$ bicrystal. Again, we see evidence of a dissipation-free state. The critical current (I_c) for the destruction of this state, defined on the basis of the attainment of a voltage $V=1$ μV, is shown as a function of the temperature in Fig. 2. It is extremely important to note that this critical current, which reaches 22 A/cm^2 at 13 K, is no more than 10^{-4} of the critical current of a single-crystal block, which was determined from measurements of a magnetization curve at the same temperature. The grain boundary thus leads to a significant decrease of the critical current.

The solid line in Fig. 2 is a fit of the function $(1-T/T_c^*)^\alpha$ to the experimental data, with the values $T_c^*=30$ and $\alpha=1.5\pm0.2$. We also note that an excess current is observed on the current–voltage characteristic of the grain boundary over the entire temperature range in which we observe a satisfactory agreement between the experimental data and this power law. The field dependence of the critical current is strongly modulated, with a scale value of about 0.1 Oe for the periodic variation in the current. The modulation dependence reveals that the oscillations in the critical current are irregular. It also reveals a hysteresis in the positions of the peaks as the external magnetic field is varied. A similar behavior has been observed previously for Josephson junctions at grain boundaries in $Ba(Pb,Bi)O_3$ bicrystals.[7] It was shown in that case that the periodic "diffraction" dependence of the critical current on the field for the Josephson junction was significantly complicated by the nonuniformity of the junction and by the complex magnetization of the bulk single-crystal blocks. A more detailed analysis of the field dependence found for the critical current of $Ba_{0.55}K_{0.45}BiO_3$ bicrystals will be carried out in some future papers.

On the basis of this set of experimental results on the transport properties of the grain boundaries, and working by analogy with $Ba(Pb,Bi)O_3$ bicrystals, we can sug-

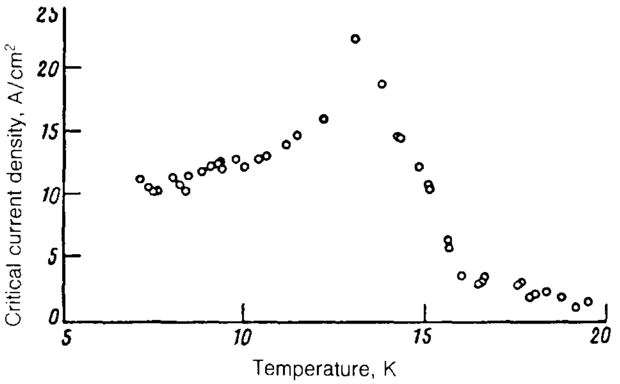

FIG. 3. Temperature dependence of the current density of a grain boundary of a $Ba_{0.55}K_{0.45}BiO_3$ bicrystal.

gest that there is a Josephson junction in the bulk $(Ba,K)BiO_3$ bicrystals. The formation of the Josephson barrier is associated with the presence of the grain boundary.

3.2. Anomalous behavior of the critical current of the grain boundary

Figure 3 shows results of measurements of the temperature dependence of the critical current I^* at temperatures down to 7 K. This behavior is nonmonotonic as the temperature is lowered. There is a clearly expressed peak in the critical current of the grain boundary near 13 K. The maximum observed critical current density is 22 A/cm^2. The characteristic voltage of the junctions, as calculated from the maximum value of the critical current, does not exceed $I_c R_N \leqslant 2$ mV. This behavior is qualitatively reminiscent of the behavior of the critical current of a grain-boundary Josephson junction in $Ba(Pb,Bi)O_3$ bicrystals.[7] The anomalous behavior of the critical current in bicrystals of this related superconductor has been linked with semiconducting properties of the grain-boundary barrier in $Ba(Pb,Bi)O_3$ bicrystals. It has been explained at a qualitative level in a theory of Josephson junctions with a semiconducting barrier.[8] The same factors explain the recent observation of an anomalous behavior of the critical current in thin-film $YBa_2Cu_3O_7$ bicrystals.[9] The bulk $Ba_{0.55}K_{0.45}BiO_3$ bicrystals studied in the present experiments are thus the third known class of Josephson junctions in bicrystals for which the grain-boundary critical current exhibits an anomalous behavior. It can thus be suggested that an anomalous behavior of the grain-boundary critical current is a universal effect, possibly associated with a manifestation of semiconducting properties of Josephson barriers at grain boundaries in these materials. Further research is planned to carry out a more detailed study of the nature of this anomalous behavior and of the conditions under which it is manifested.

4. CONCLUSION

A Josephson barrier forms at a grain boundary in bulk superconducting $Ba_{0.55}K_{0.45}BiO_3$ bicrystals. Near the transition temperature, the critical current of this barrier exhibits a power-law behavior with a critical exponent $\alpha = 3/2$, with an excess current. In other words, this barrier exhibits properties of a barrier with a direct conductivity. Josephson junctions in the bicrystals studied exhibit a significant nonuniformity in the spatial distribution of the critical current and low values of J_c, no higher than 22 A/cm^2. The critical current of a Josephson junction in $Ba_{0.55}K_{0.45}BiO_3$ bicrystals exhibits an anomalous behavior as the temperature is lowered. This behavior, which has also been seen in bicrystals of the oxide superconductors $Ba(Pb,Bi)O_3$ and $YBa_2Cu_3O_7$, may be due to semiconducting properties of the Josephson barrier at grain boundaries in these materials.

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Translated by D. Parsons