Evidence for a multilayer superconductivity of BiSrCaCuO (2212) in rf absorption Author

K. V. Baginskiĭ, V. A. Berezin, S. A. Govorkov, and V. A. Tulin
Institute of Problems in Microelectronic Technology and Highly Pure Materials, Russian Academy of Sciences, 142432 Chernogolovka, Moscow Region, Russia

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The absorption of rf electromagnetic power ($f \approx 700$ MHz) in BiSrCaCuO single crystals has been studied experimentally near the superconducting transition temperature T_c in a magnetic field. In weak magnetic fields, and below T_c, an additional absorption due to the Josephson component of vortex filaments in the single crystal is found.

The high-T_c metal oxide superconductors are strongly anisotropic media in terms of electromagnetic properties. This anisotropy is attributable to the presence of one or several copper–oxygen planes—the elements (layers) primarily responsible for the electrical conductivity—in the unit cell. It is also attributable to the different interplanar conductivities for the different compounds. The BiSrCaCuO single crystals have strongly anisotropic electrical properties and have thus attracted large interest in research on layered superconducting systems.[1-3]

According to the present understanding, a vortex filament in a layered superconductor is an alternation of pointlike vortices in an individual layer (pancakes), which are coupled either by a magnetic interaction, if the magnetic field is perpendicular to the layers, or by segments of Josephson vortices in the interlayer volume, in the case of an oblique magnetic field.[4] In a parallel magnetic field, a vortex filament consists of only a Josephson component. The 2D nature of the superconductivity is linked primarily with the existence of thermally excited vortex–antivortex pairs, against whose background a (Berezinski–) Kosterlitz–Thouless phase transition occurs.[5,6]

The test samples in the experiments we are reporting here were $Bi_2Sr_{1.7}Ca_{1.3}Cu_2O_8$ single crystals with geometric dimensions on the order of $1 \times 1 \times 0.1$ mm. The c axis was parallel to the shortest dimension, which was perpendicular to the plane of the crystal.

The absorption was measured in the frequency range 600–1000 MHz. The sample was placed in a helical resonator whose diameter was approximately the same as that of the test sample. Electrical connection to the helical resonator was made with the help of coaxial cables, with the central conductor going to the end of the helix. The helix was made of copper wire. The test sample was in a vertical plane (with c axis horizontal) inside the helix. The whole assembly was housed in a nitrogen cryostat, between the pole tips of an electromagnet. By rotating the electromagnet we were able to alter the orientation of the magnetic field with respect to the ab plane of the sample, from parallel to perpendicular.

Figure 1 shows the temperature dependence of the power absorbed in the resonator with the test sample. In the temperature range 120–40 K the resistivity of copper (all

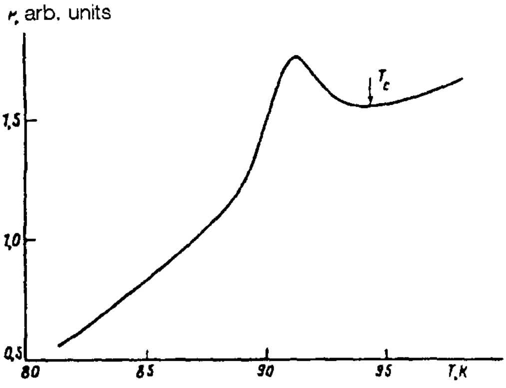

FIG. 1. Temperature dependence of the absorption of a helical copper resonator with a BiSrCaCuO single crystal in the vicinity of the superconducting transition. The arrow shows T_c.

parts of the resonator were made of copper) is a fairly strong function of the temperature. In Fig. 1 we can clearly see the related behavior; against this background we see an absorption maximum, slightly below the transition temperature T_c determined from the vanishing of the magnetic-field dependence of the absorption.

Figure 2 shows the behavior of the absorption as a function of the magnetic field. In these measurements the magnetic field made an angle of 12° with the plane of the crystal. In this figure we see two absorption maxima: one at a magnetic field of about 1.5 kOe and one at about 20 Oe. The scale of the larger maximum corresponds to the scale of the change in absorption at the maximum on the temperature dependence. The position of this larger maximum along the magnetic-field scale as the orientation is varied is governed by the size of the projection of the field onto the c axis of the crystal. The second maximum is considerably smaller. It is shown in larger scale in the inset in Fig. 2. We see that this maximum consists of some additional absorption in weak magnetic fields, and that some or all of this absorption is absent at a zero magnetic field. The absorption increases as the magnetic field is raised from $H=0$, goes through a maximum, and then is suppressed by the field as the latter is raised further. We estimated the amplitude of this absorption from the depth of the minimum in a zero field. We see a hysteresis in the

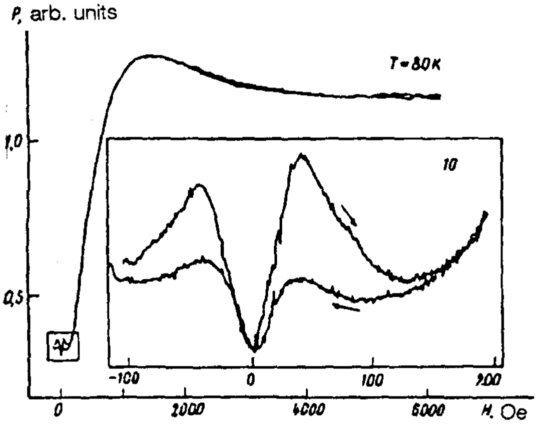

FIG. 2. Magnetic-field dependence of the absorption of rf power by a BiSrCaCuO single crystal. The inset shows the rf absoprtion in a larger scale versus the magnetic field in the region of weak magnetic fields. The arrows show the direction in which the field was swept.

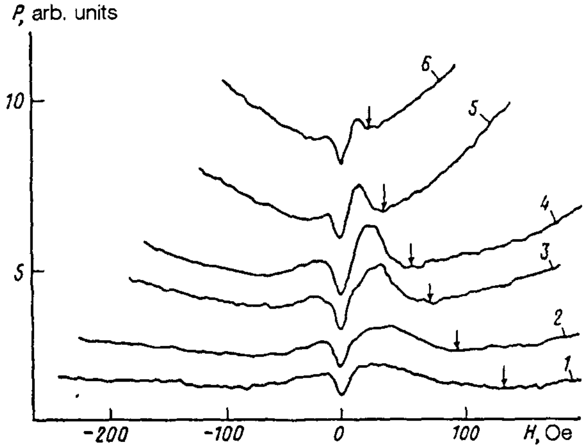

FIG. 3. Absorption of rf power versus the magnetic field at various temperatures. 1—$T = 79.8$ K; 2—84.7; 3—87.8; 4—88.3; 5—90.6; 6—91.2 K. The arrows show relative minima of the absorption.

absorption as the direction of the field sweep is reversed. This absorption arises after the transition to a superconducting state. Its maximum amplitude is observed at $T = 88$ K (with $T_c = 94.5$ K). As the temperature is lowered further, the amplitude decreases slowly. A study of this absorption for various orientations of the magnetic field with respect to the Cu–O planes showed that it was at a maximum when the field was parallel to the *ab* planes, and that it fell off with a deviation from this parallel arrangement, reaching a minimum amplitude when H was parallel to the c axis (in our geometry it was not possible to align H exactly parallel to the c axis).

Figure 3 shows several curves of the field dependence of the absorption for various temperatures for the case in which H was parallel to the *ab* plane. (These recordings were made in a common direction, from left to right.) The arrows in this figure mark relative minima of the absorption. We are arbitrarily adopting the abscissa as the boundary field for the suppression of the additional absorption. We see that this field increases monotonically as the temperature is lowered from T_c.

A maximum similar to the maximum in the absorption on the temperature dependence (Fig. 1) and a reflection of this maximum on the field dependence were observed in some thin aluminum films near T_c in Ref. 7, in the frequency range 30–1000 MHz. It was shown there that the maximum stemmed from a change in the nature of the rf absorption as a result of a change in the transmission of the film with respect to the normal component of the rf field. Although the impedance of the film varied monotonically, an absorption maximum was observed near T_c, in a region in which the impedance varied rapidly. Manifestations of this effect are a maximum in the absorption on the temperature dependence (Fig. 1) and a maximum in the absorption in strong fields (Fig. 2). The layered structure of the BiSrCaCuO (2212) single crystals is therefore manifested indirectly as a deep penetration of the rf magnetic field directed at right angles to the layers.

The additional absorption in weak fields is considerably more interesting (Fig. 3). The structure of a vortex system in a layered superconductor can change as the magnetic field is strengthened. On the one hand, coupled pairs (the KT phase) are suppressed by the magnetic field. However, the existence of the additional absorption over a broad temperature range refutes the possibility that this absorption is associated with vortex rings. On the other hand, the small value of the critical current parallel to the c axis implies that the interlayer superconductivity is weak, and that the structure of the Josephson vortex may break down in comparatively weak magnetic fields. The angular dependence of the intensity of the additional absorption in this case is governed by the length of the segments of Josephson vortices, which decreases with increasing angular deviation of the field from the ab plane. Unfortunately, the uncertainty regarding the position of the boundary for the existence of the additional absorption and the strong field-induced change in the basic absorption as a result of a significant deviation of the field from the ab plane rule out an in-depth study of the angular dependence of the field which suppresses the additional absorption. We believe that this field is the second critical field for the interlayer superconductivity.

The experimental results determine two boundary values of the magnetic field. First, there is $H_c^1 \approx 10$ Oe, below which the absorption curve is reversible. Second, there is $H_c^2 \approx 200$ Oe, above which there is no additional absorption, and the characteristic hysteresis disappears. The field H_c^1 determines the region in which the first row of vortices forms. In the case of a penetration of the magnetic field which is uniform along the c axis, the field H_c^1 yields an estimate of the size of a vortex in the ab plane, perpendicular to the magnetic field:

$$d = \Phi_0 / H_c^1 s,$$

where Φ_0 is the flux quantum, and s is the period of the Cu–O layers along the c axis. In our case, an estimate yields $d \approx 1$ mm at $T = 80$ K. This result corresponds to the size of the sample.

As the field is raised above H_c^1, the vortices in the volume between layers increase in density, and the vortex structure disappears at H_c^2. The field H_c^2 can therefore be used to estimate the minimum size of a vortex (the size of the vortex core):

$$d_{\min} = \Phi_0 / H_c^2 s \approx 50 \mu\text{m}.$$

From this size we find a rough estimate of the Josephson critical current density:

$$I_J \approx c\Phi_0 / 4\pi d_{\min} ds \approx 3 \times 10^3 \text{A/cm}^2.$$

Working from the behavior of the superconductor as a function of the magnetic field and the orientation, we conclude that the additional absorption in BiSrCaCuO single crystals in weak magnetic fields is due to the Josephson component of the flux vortices, which is a consequence of the layered nature of the superconducting properties of this material.

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[1] S. Martin *et al.*, Phys. Rev. Lett. **60**, 2194 (1988).
[2] T. T. M. Palestra *et al.*, Phys. Rev. B **38**, 5102 (1988).

[3] S. Martin *et al.*, Appl. Phys. Lett **54**, 72 (1989).
[4] V. L. Berezniski, Zh. Eksp. Teor. Fiz. **59**, 907 (1970) [Sov. Phys. JETP **32**, 493 (1970)].
[5] T. M. Kosterlitz and D. J. Thouless, J. Phys. C **6**, 1181 (1973).
[6] J. R. Clem, Phys. Rev. B **43**, 7837 (1991).
[7] S. A. Govorkov *et al.*, Zh. Eksp. Teor. Fiz. **89**, 1704 (1985) [Sov. Phys. JETP **62**, 983 (1985)].

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