High-frequency absorption in a multilayered superconducting $Bi_2Sr_2CaCu_2O_8$ single crystal with Josephson coupling between layers

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High-frequency absorption in a $Bi_2Sr_2CaCu_2O_8$ single crystal has been measured as a function of temperature and magnetic field in the ranges of 4.2 K to 100 K and up to 6 kOe, respectively, at different angles between the magnetic field and the ab-plane. We have detected a component of high-frequency absorption due to the motion of Josephson magnetic flux vortices under a magnetic field parallel to crystal layers. This absorption occurs in a magnetic field parallel to the ab-plane at temperatures ranging from the 2D–3D transition down to liquid helium temperature without notable variations in its intensity or properties. It is caused by high-frequency currents on end surfaces parallel to the c axis within the magnetic-field penetration depth λ_c. The shape of the curve of absorption versus magnetic field is defined by the size effect due to the variation of the penetration depth $\lambda_c(H)$ as a function of the magnetic flux between layers. The features of the curve of absorption versus magnetic field reflect some important properties of the superconducting material, as discussed in the paper. © *1996 American Institute of Physics.* [S1063-7761(96)02109-9]

1. INTRODUCTION

Layered superconductors and artificial structures have attracted researchers' attention for a considerable time. Starting in the 1970s, dichalcogenides of some transition metals ($NbSe_2$, TaS_2, etc.), organic superconductors, and artificial layered structures produced by successive deposition of superconducting and normal metallic (dielectric, or semiconductor) layers have been investigated. All these structures have displayed appreciable anisotropy of electromagnetic and superconducting parameters. After the discovery of high-T_c superconductors, whose electric parameters are highly anisotropic, interest in layered superconductors increased. In this context, the most remarkable and easily available material is $Bi_2Sr_2CaCu_2O_8$ (BSCCO). The anisotropy constant γ in this material varies between 100 and 1000, depending on the processing conditions.

The BSCCO crystal structure was described by Bordet *et al.* and Sastry *et al.*[1] They demonstrated that one half of the BSCCO elementary cell along the c axis ($a=30.5$ Å) contains one CuO double layer, which is responsible for the metallic and superconducting properties of the material. The space separating these layers contains a mixture of Bi_2O_3 and SrO. The critical current density along the CuO layer (ab plane of the crystal) and perpendicular to this plane differ by four to six orders of magnitude. This suggests that the layers separating CuO planes can have electric properties of any nonsuperconducting material, including a dielectric, in which case, the conductivity and superconductivity along the c axis are due to tunnelling.

A macroscopic theory of such systems was proposed by Lawrence and Doniach[2] and later developed by other authors,[3–5] and it was also applied to high-T_c cuprate superconductors. The theory was used to interpret various experimental results.[6–12] In their study of small high-T_c cuprate crystals, mostly BSCCO, Kleiner and Müller[13] measured a set of characteristics commonly used to detect Josephson coupling in a material. They demonstrated that the Lawrence–Doniach model can be applied to these materials, and their features can be interpreted by describing them as a pile of Josephson junctions.

We have measured the high-frequency (HF) absorption in BSCCO single crystals at various temperatures in external magnetic fields. The resulting curves of absorption parameters as functions of magnetic field are quite different from similar curves for YBaCuO single crystals[14] and demonstrate a strong anisotropy of the absorption. In our brief report on these measurements[15] we assumed that this difference is caused by the magnetic-flux patterning due to the Josephson coupling.

2. SAMPLES AND EXPERIMENTAL TECHNIQUES

We measured the HF absorption in $Bi_2Sr_{1.7}Ca_{1.3}Cu_2O_{8-\delta}$ single crystals at 500 to 900 MHz in a magnetic field of up to 6 kOe at temperatures ranging between 4.2 and 100 K.

We have studied $Bi_2Sr_2CaCu_2O_{8-\delta}$ and $Bi_2Sr_{1.7}Ca_{1.3}Cu_2O_{8-\delta}$ single crystals. Samples with the standard composition had a superconducting transition temperature of about 85 K. Hence the temperature range of measurements using liquid nitrogen as a coolant was insufficient. Therefore we decided to use $Bi_2Sr_{1.7}Ca_{1.3}Cu_2O_{8-\delta}$ single crystals grown by D. A. Shulyat'ev at Moscow Institute of Steel and Alloys. The transition temperature in these samples derived from the low-frequency magnetic susceptibility was 92.5 ± 2 K (transition onset), and the transition width was about 2.5 K. The transition width was defined as the temperature range in which the induction signal changed by 80% of the total signal variation due to the transition. The samples

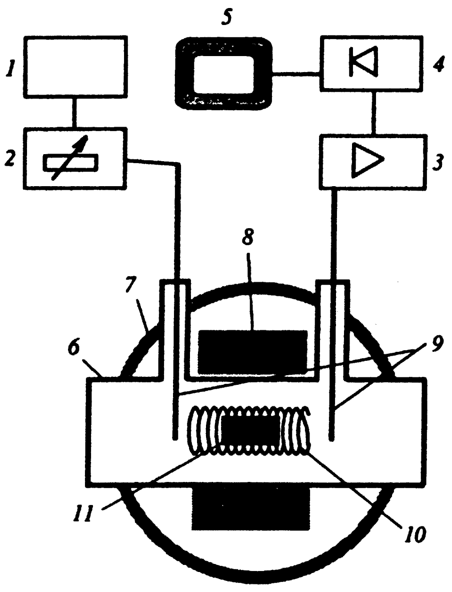

FIG. 1. Block diagram of the experimental setup: (*1*) sweep generator; (*2*) attenuator; (*3*) preamplifier; (*4*) peak detector; (*5*) personal computer; (*6*) copper tube with couplers for coaxial lines; (*7*) Helmholtz coil; (*8*) coil for demagnetizing the sample; (*9*) center conductors of coaxial lines; (*10*) helical resonator; (*11*) sample.

were split from splices. The samples used in experiments were plane-parallel wafers with good surfaces of uniform luster, which were selected using an optical microscope. The lateral dimensions of the samples ranged between 1 and 2 mm, and the thickness was about 100 μm. In our opinion, a uniformly lustrous surface indicates that a sample has been cleaved along a crystal plane perpendicular to the c axis. If the light reflectivity from the sample cleaved surface was not uniform, it was rejected. Samples selected for experiments tended to cleave into thinner pieces across their entire area. All these properties indicated that the samples were single crystals. The set of measurements given in the paper were obtained using six samples with the composition given above and properties described in this paragraph.

The power transmitted across a resonator with a sample as a function of the external parameters (temperature and magnetic field) was measured in the experiments. A block diagram of the experimental setup and a sketch of the absorption cell are shown in Fig. 1. The source of HF electromagnetic waves was a sweep generator with a sweep frequency of about 50 Hz, the sweep amplitude being larger than the width of the absorption line of the loaded resonator. The generator output could be varied between 10 μW and 100 mW. In the frequency band given above we used a helical resonator. The helix was wound with a 0.1-mm diameter copper wire. In order to increase the filling factor, the helix was flattened so as to have dimensions closer to those of the sample. In most measurements the lowest mode of the resonator had a frequency of 600 MHz.

In our experiments we used several helical resonators with resonant frequencies ranging from 250 to 1200 MHz. The shapes of experimental curves did not radically change as the frequency varied over this range. The sample, positioned between two insulating films, was inserted inside the helix. The resonator was supported inside a 10-mm copper tube by a dielectric holder. Two coaxial lines made from thin-wall stainless-steel pipes were attached to the copper tube. The pipes supported the entire structure inside a cryostat and conducted electromagnetic waves to and from the device. The coupling between the resonator and coaxial lines was capacitive, i.e., the center conductors of the coaxial lines were led to the helix ends, but had no electrical contact with them.

One coaxial line fed HF power from the sweep generator, the other conducted a signal proportional to the HF field inside the resonator. The signal was amplified by a broadband amplifier and fed to a peak detector. The detected signal proportional to the maximum HF power transmitted across the resonator as the frequency was swept was recorded by a personal computer as a function of magnetic field (derived from the signal generated by a Hall sensor) or temperature (measured by a carbon thermometer). Changes in this signal due to variations in external parameters are proportional to the HF absorption in the resonator with the sample. Usually the absorption is assumed to be proportional to the active component of the sample impedance. In our experiments this is not true, as will be shown below.

A magnetic field of up to 7 kOe was generated by an electromagnet. The magnet could be rotated about the vertical axis. When the sample plane was vertical, we could change the magnetic field orientation with respect to the sample plane (ab plane). Errors in the sample orientation determined the misalignment between the c axis and magnetic field, which was not crucial in this work. The magnetic field alignment with the sample plane was checked using HF absorption, which is very sensitive to the angle between the sample plane and magnetic field (the resulting accuracy was about 0.1°). In addition to the magnet, we used an additional coil, with the axis parallel to that of the helix and sample plane, to demagnetize the samples.

The absorption cell with the additional coil was placed inside a helium cryostat. In measurements at temperatures above 77 K its nitrogen vessel was filled with liquid nitrogen and the cryostat was filled with gaseous helium. In experiments at temperatures below that of liquid nitrogen, a small amount of liquid helium was poured into the cryostat (its level was below the cell). The temperature was scanned either by using a heater wound on an external shield of the device or owing to the gradual warming as the liquid nitrogen or helium evaporated.

If the sample is placed inside the cell as described above, the thermal contact between the sample and copper tube on which the carbon thermometer is located is poor. In curves of sample parameters versus temperature recorded during heating and cooling, we detected a hysteresis of 1.5–2 K. If such curves were shifted along the temperature axis to get rid of the hysteresis, the relative positions of features on the curves could be reproduced to within 0.1 K. Our estimates produced a difference between the sample temperature and readings of the carbon thermometer of up to 3 K. Thus the absolute measurements of temperature in this work were accurate to within 3 K, whereas the relative positions of features of one

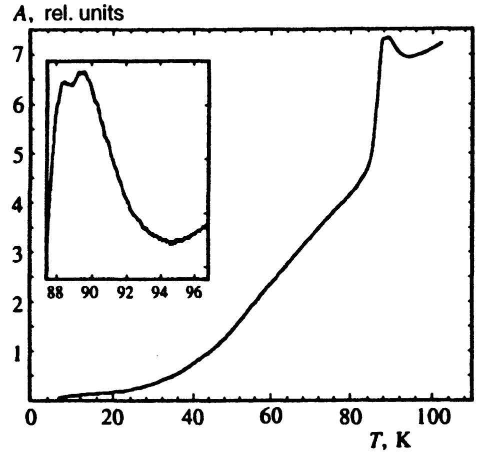

FIG. 2. Absorption intensity in the resonator with the sample versus temperature at a frequency of 600 MHz. The insert shows the absorption maximum on an enlarged scale.

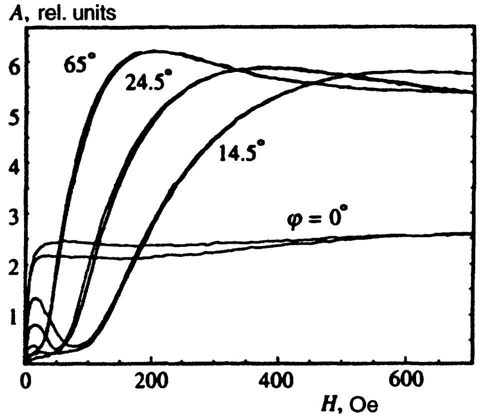

FIG. 3. Intensity of HF absorption in the sample versus magnetic field. The parameter labeling the curves is the angle between the magnetic field and sample plane (*ab* plane); $T=80$ K.

curve could be determined to a much higher degree of confidence (to within less than 0.1 K).

Since superconductors are strong diamagnetics, they are subject to a force in a magnetic field. If the sample is free to move, it can be repositioned by this force. Since the sample is in the resonator, this shift will lead to a spurious signal. In order to avoid this, we immobilized the sample, helical resonator, and their supports with vacuum grease. After hardening at low temperatures, the grease fixed the positions of the sample and cell components without changing the parameters of the absorption cell over the experimental ranges of temperature and magnetic field.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1. General characteristics of absorption in BSCCO

HF absorption in the superconductors is controlled by the parameters of carriers in BSCCO (condensate and normal excitations), i.e., basic characteristics of superconductors. In the mixed state, magnetic flux vortices contribute to HF absorption. Therefore accurate measurements of the absorption are of great importance in studies of superconductivity.

Figure 2 shows the HF absorption in the helical resonator with the BSCCO sample plotted against temperature. We use the term "resonator with the sample" because the copper resistivity changes appreciably with temperature above 30 K, and the resonator conductor and surrounding components are made of copper. Although this dependence may obscure the effects of interest, features on the curve of the sample absorption are clearly seen around the critical temperature—specifically, steps in the absorption intensity in the superconducting and normal states and a peak at a temperature slightly below T_c.

The insert shows the absorption maximum on an enlarged scale. It has a clear doublet structure. The doublet structure was only detected in two samples, whereas in most samples the peak was not split. Although the accuracy of absorption plotted in Fig. 2 is fairly high, we cannot as yet propose a correct procedure for subtracting the change in the absorption due to the changing copper resistivity. Therefore we will not discuss the HF absorption as a function of temperature, except the features seen around T_c.

Figure 3 shows the HF absorption in the sample versus magnetic field. In this case we use the term "absorption in the sample" because the Q-factor of the empty resonator is constant with magnetic field. In comparison with the typical impedance behavior of type II superconductors versus magnetic field,[16,17] our plots look somewhat peculiar because of their nonmonotonic shape. If the magnetic field is not parallel to the *ab* plane (the curves corresponding to $\varphi=65°$, 24.5°, and 14.5° in Fig. 3), the absorption has a maximum at a relatively high magnetic field, and its angular dependence can be accounted for if we assume that it is determined only by the field component perpendicular to the *ab* plane. If plotted against $H_0 \sin \varphi$, where H_0 is the external magnetic field and φ is the angle between its direction and the *ab* plane, the curves recorded at $\varphi=65°$, 24.5°, and 14.5° coincide with each other (with the exception of the feature at low magnetic fields). If the magnetic field is parallel to the *ab*-plane (the curve corresponding to $\varphi=0$ in Fig. 3), the shape of the absorption curve is radically different from those recorded in an inclined field. This curve shows an absorption maximum at low magnetic field (in this sample at $H_{max} \sim 25$ Oe). The low-field peaks in the curves recorded at $\varphi=65°$, 24.5°, and 14.5° in Fig. 3 reflect the shape of the absorption curve at $\varphi=0$.

It follows from the theory that the real part of the superconductor surface impedance varies monotonically with temperature between T_c and $T \rightarrow 0$.[18] The absorption maximum in metals usually results from a change in the sample opacity to some HF magnetic-field component.

The first electrodynamic explanation of this type of maximum in superconductors was proposed for absorption in aluminum thin films near T_c.[19] It runs as follows. In the case of full penetration of the magnetic field, the sample properties are similar to those of a poor dielectric, and its absorption grows with decreasing impedance. If the HF magnetic field is screened owing to metallic conductivity, the absorption drops with the impedance. An absorption maximum usually occurs when the penetration depth equals the typical

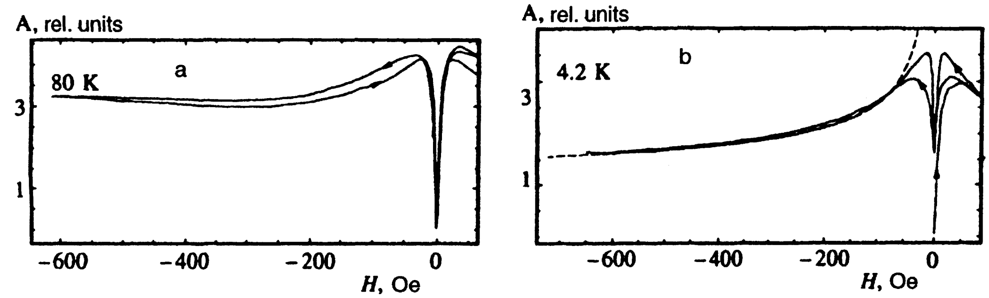

FIG. 4. Intensity of HF absorption in the BSCCO single crystal versus magnetic field: (a) at a temperature of 80 K; (b) at 4.2 K. The dashed line is the fit ($\propto H^{-0.5}$).

sample size. The behavior of this absorption maximum is quite complicated and requires a dedicated study, so here we give only a brief description. When the sample width is about 1 mm and its thickness less than 100 μm, the skin depth in the normal state is expected to be larger than the sample dimensions. In the superconducting state, the London penetration depths λ_i should be much smaller than these dimensions. Under these conditions, a maximum will be observed slightly below the critical temperature, when λ_i equals the appropriate dimension of the sample. The subscript i refers to the anisotropy of the sample's electrical properties.

In a magnetic field aligned with the c axis, the sample transfers to the mixed state, and its impedance (and the magnetic field penetration depth) increases with the magnetic field to its normal value at H_{c2}. In this case, the sample impedance again takes a value at some magnetic field for which λ_i equals the appropriate sample dimension, and a maximum is observed in the absorption as a function of magnetic field. An analytic formula for the absorption maximum, if it existed, could be used to derive a parameter proportional to the impedance, which is important in comparing the experimental data with theory.

3.2. Absorption in a parallel magnetic field

*Experimental results.*We demonstrated in the previous section that the behavior of HF absorption in a magnetic field parallel to the ab plane is radically different from that in an inclined magnetic field. We now discuss this absorption in detail.

Figure 4 shows the BSCCO absorption versus magnetic field at two temperatures, 4.2 K and 80 K. The curves demonstrate the following differences between the two temperatures so different with respect to T_c. The additional absorption at low magnetic fields shows little change (the amplitude at the maximum at 4.2 K is approximately the same). The absorption component monotonically rising with the field is absent in the measurements at 4.2 K. The absorption minimum at $H=0$ and $T=4.2$ K strongly depends on the sample history, whereas at 80 K this dependence is weaker. The lowest point in the low-temperature curve corresponds to the absorption detected after cooling the sample. During the first sweep of the magnetic field, the first increase in absorption occurs at a finite field (3.5 Oe at 4.2 K, which is close to the penetration threshold of magnetic field parallel to the ab axis measured in BSCCO by Zavaritskiĭ *et al.*[20]), and the absorption grows slower than during subsequent sweeps. Furthermore, the absorption at $H=0$ in sequential sweeps is notably larger than during the first sweep, as shown in Fig. 4, especially at 4.2 K. The character of the hysteresis at the two temperatures is also different: at 4.2 K, absorption at the maximum is higher when the magnetic field drops, whereas at 80 K it is higher when the field rises.

In our opinion, absorption in the configuration with the magnetic field parallel to the ab plane and at low temperatures contains one component only. It increases with magnetic field, has a broad maximum centered at about 30 Oe, and then drops monotonically. The dropping high-field section can be fit well by the function $A \propto H^{-0.5}$ (dashed line in Fig. 4). There is a narrow minimum at $H=0$ with a very narrow parabolic section over an interval of about 1 Oe. If we ignore this parabolic part, the absorption measurements can be approximated by the function $A \propto H^n$, where $n \leqslant 1$. At a temperature of 80 K, there is a second component in the absorption that increases at high magnetic fields. This component is probably due to HF absorption by normal electrons due to the kinetic inductance of superconducting electrons, that exists around T_c. In this case, the external magnetic field reduces the order parameter, and absorption increases.

In studying the temperature dependence of the absorption amplitude at low magnetic fields, we performed the following measurements. When the sample was slowly cooled (or heated), the electromagnet was fed with a slowly changing ramp current such that the field around the sample varied between $+40$ Oe and -40 Oe (the field was scanned through the maxima at both positive and negative fields). The resulting curves are shown in Fig. 5a and b. It is clear that the lower envelope of the curve corresponds to the minimum absorption at zero magnetic field, and the upper envelope to the maximum absorption in the scanning range of magnetic field.

The curve of maximum HF absorption in magnetic field versus temperature around T_c (Fig. 5a) shows three temperatures at which the character of absorption changes. At the temperature indicated by arrow A, the nonmonotonic dependence of the absorption versus magnetic field discussed above disappears. Above the point B, the field derivative of the absorbed power, dA/dH, drops sharply, although a weak dependence can be detected when the field is scanned over a wide range. At temperatures above point C, the absorption is independent of the field.

Experimental measurements over a wide temperature range (Fig. 5b) have demonstrated that the field-dependent absorption in a parallel magnetic field depends weakly on the

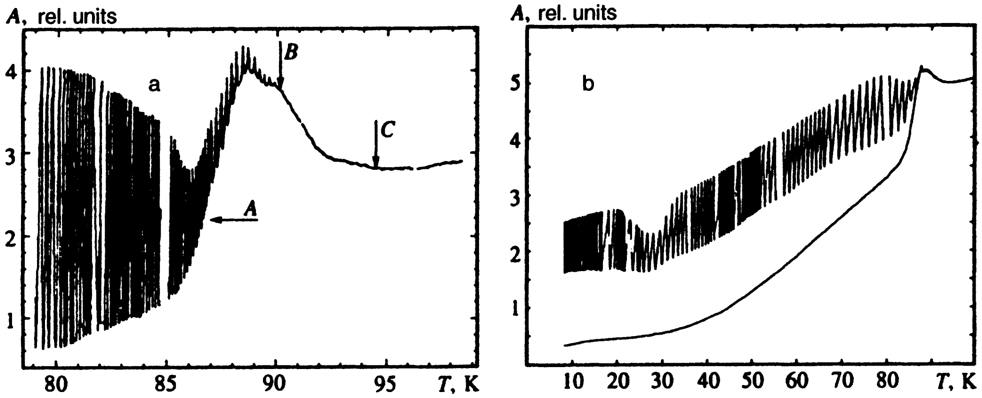

FIG. 5. Field-dependent absorption in the sample recorded under periodically varying magnetic field versus temperature: (a) near T_c; (b) over a wider temperature range. The arrows indicate characteristic temperatures.

temperature over a wide range from 4.2 to 80 K. In our samples, the field-dependent absorption disappears at temperatures above 88.5 K, i.e., 3 K below the superconducting transition (91.5 K), which is determined by the position of point B. These temperatures can be accurately determined by extrapolating to zero the amplitude of field-dependent absorption (point A) and noting when sharp changes in the absorption disappear (point B). Below T_B the sample has HF properties of a superconductor (the absorption strongly depends on the magnetic field). The temperature at point C corresponds to the onset of a fast change in the HF impedance with decreasing temperature around the superconducting transition point. Figure 5b also shows the absorption at zero magnetic field plotted against the temperature.

It can be seen in Fig. 5b that there is a notable change in the field-dependent absorption around 25 K without a radical change in its character. This can be tentatively ascribed to a phase transition in the structure of magnetic vortices and supercurrents in the sample at this temperature. The position of this feature in the $T-H$ plane is close to the line of irreversibility discussed by de la Cruz *et al.*[21] and Zeldov *et al.*,[22] (T* region in these publications). Furthermore, Duran *et al.*,[23] and Gupta *et al.*,[24] who studied damping of a rigid pendulum with an attached BSCCO sample, detected maxima of the damping decrement around this temperature. The processes taking place in the system of Josephson vortices at this temperature deserve further investigation.

Figure 6 shows curves similar to those in Fig. 5a recorded at different frequencies. They indicate that the curve of absorption measured at the higher frequency has no maximum near T_c, whereas maxima in the plots against field can be seen at both frequencies. This is an indication that the origins of these maxima are different. Figure 6 also indicates that the aforementioned change in the character of the hysteresis occurs at about 80 K.

The sizable difference between the absorption at zero magnetic field and at the minimum near $H=0$ recorded in repeated scans of magnetic field indicates that a magnetic flux is frozen into the sample, which may result from pinning of magnetic vortices or a surface barrier to their motion. In order to distinguish between these two possibilities, we have measured the absorption during repeated scans of a weak magnetic field. The magnetic field was varied at a frequency of 2 Hz with an amplitude of 20 Oe. Sampling was started after seven periods of field oscillation, when the signal amplitude had settled. The resulting curves were averaged over 100 measurements.

The recorded curves are given in Fig. 7. The difference between the shapes of the curves of absorption versus magnetic field at lower and higher dc magnetic fields (labeled curves) is obvious. The typical curves are those corresponding to $H=0$ and $H=53$ Oe; the rest demonstrate a transition between extreme cases. At low magnetic fields the curves show a narrow absorption minimum after the field rate changes sign. The difference between the curves in Figs. 7 and 4 is that the amplitude of magnetic field oscillations is smaller than the separation between absorption maxima, whereas in Fig. 4 it is larger. If the turning point of the magnetic field scan is between H_{max} and $-H_{max}$, the features in the curves in Fig. 7 can be seen.

Figure 8 illustrates the sensitivity of the observed absorption to the magnetic field when the field is parallel to the *ab* plane. The absorption curves for three angles between the field vector and sample plane are shown. The sample orientation with respect to its holder is known to within 5°. The effect of small deviations of magnetic field on the absorption-curve shape indicates that even an angle of 0.1° between the sample plane and magnetic field is significant. Owing to the symmetry about zero angle, we can assert that the upper curve in Fig. 8 corresponds to the magnetic field in the sample plane.

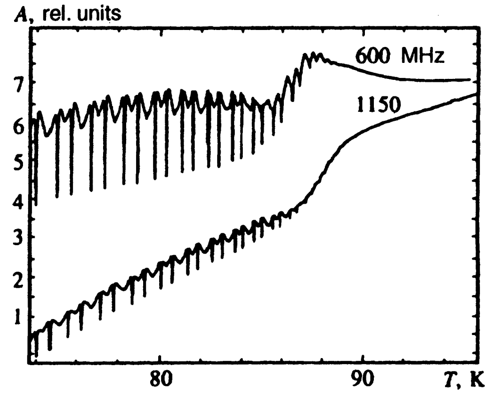

FIG. 6. High-frequency absorption in the BSCCO crystal versus temperature recorded at two frequencies in a periodically varying magnetic field.

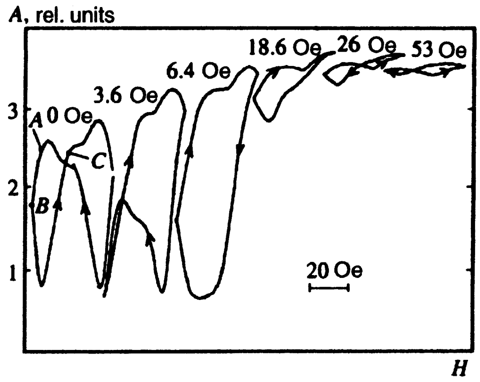

FIG. 7. HF absorption in the BSCCO sample in a periodically varying weak magnetic field. Labels indicate the dc magnetic field. Letters at the curve corresponding to $H=0$ label characteristic points on the curve (see Sec. 3.2), $T=80$ K.

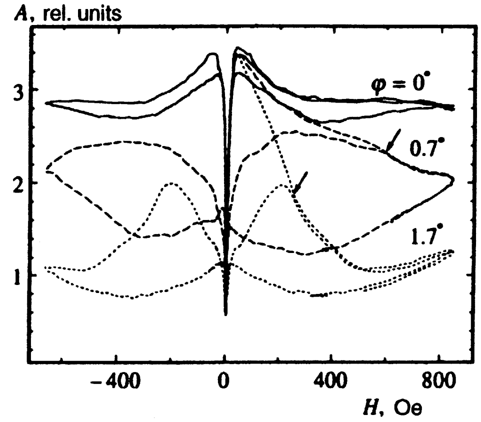

FIG. 8. HF absorption versus magnetic field at small angles between the magnetic field and the ab plane of the BSCCO crystal. The arrows indicate the direction of the field scan. The angles of deviation from the symmetrical orientation label the curves, $T=80$ K. The points beyond which the absorption curves of demagnetized samples coincide with those of magnetized samples (shown by arrows on the curves corresponding to $\varphi=0.7$ and 1.7°) correspond to the normal magnetic-field component H_{c1}^*.

Prior to each of these measurements, we demagnetized the sample. To this end, the external field was set low (± 10 Oe), and a periodic magnetic field with a gradually dropping amplitude was generated by the additional coil. The initial amplitude was 40 Oe, its frequency 2 Hz, the total decay time was 50 s, the amplitude versus time being an approximately linear function. After demagnetization, the absorption at a given field was maximum (if $H \neq 0$), which corresponded to the maximum mobility of vortices. Then a ramp current was fed to the electromagnet. The absorption increased with the field and had a maximum at about 30 Oe.

The rising section of the curve around $H=0$ did not change at small angles between the field and sample plane, as seen in Fig. 8. Beyond the absorption maximum, the curve shapes are different at different angles.

In a magnetic field whose absolute value is higher than a certain number depending on the angle, the absorption curves have shapes typical of the given angle, which is shown in Fig. 8. We interpret this behavior in terms of generation of two-dimensional vortices normal to the ab plane when the normal field component is higher than H_{c1}^* (i.e., the first critical field with due account of the demagnetization factor). These vortices fix Josephson vortices, split them into small sections, reduce their mobility, and hence reduce HF absorption. It follows from these measurements that at 80 K the first critical field is about 150 Oe. Two-dimensional vortices trapped in the sample are eliminated in the process of demagnetization. We have presented these data to demonstrate the exquisite sensitivity of the absorption curves to magnetic field orientation. The HF absorption is linear, i.e., the absorption rate is independent of the HF magnetic field amplitude.

Discussion of experimental results. BSCCO single crystals studied in this work are multilayered structures containing Cu–O high-conductivity (superconducting) layers separated by Bi_2O_3, SrO, CaO layers with poor conductivity. Presently the mechanism of conductance across separating layers is not known, but various experimental data can be interpreted if we assume that the coupling between conducting layers is due to the Josephson effect. In the mixed state, such superconductors contain complex magnetic vortices. They are composed of two-dimensional magnetic-flux vortices in Cu–O layers connected to each other either by sections of Josephson vortices or by magnetic lines of force. The configuration in the case of parallel magnetic field is determined by the average tilt angle of a vortex with respect to the Cu–O plane.

The HF absorption spectra in BSCCO single crystals in a magnetic field parallel to the ab plane are different from those detected in YBaCuO and isotropic low-temperature superconductors of the second kind, such as PbIn and Nb.[16,17,25] Their features, such as high susceptibility to the magnetic field orientation and a weak-field maximum, indicate that the absorption is related to the Josephson component of a vortex parallel to the Cu–O layers (ab plane). A magnetic field deviation from the ab plane of about one degree (the emergence of two-dimensional vortices in the Cu–O layers) results in a notable drop in the absorption maximum amplitude and changes its shape. In this case, Josephson vortices are divided into sections whose ends are fixed by two-dimensional vortices in Cu–O layers, which should lead to a drop in the absorption intensity. The temperature dependence demonstrates that absorption sets in at a temperature about 3 K lower than T_c (i.e., 88.5 K), it saturates at about 80 K and persists at temperatures down to that of liquid helium. At temperatures slightly lower than T_c the coherence length ξ_c becomes comparable to the separation between superconducting layers (15 Å), thus a transition from the two-dimensional to three-dimensional state occurs in Cu–O layers. As a result, Josephson vortices becomes possible, and the absorption due to these vortices is detected in our experiments. At 80 K, the coherence length becomes comparable to the superconducting layer thickness (3 Å), and the absorption intensity is constant at lower temperatures.[26]

We now discuss the localization of absorption in the samples. In our experiments, a sample is placed in an HF magnetic field parallel to the ab plane. The induced current is closed on the sample surface and flows both in the ab

plane and along the c axis on the side surfaces. The superconducting parameters of BSCCO are highly anisotropic; in particular $\lambda_c/\lambda_{ab}=\gamma$ may be up to 1000 depending on the fabrication and processing technique. Given that the sample lateral dimensions are a factor of about twenty larger than its thickness, the volume containing the current along the c axis (proportional to $\lambda_c D$, where D is the sample thickness) is much larger than the volume containing the current along the ab plane (proportional to $\lambda_{ab}L$, where L is the sample lateral dimension).

The electrodynamics of type II superconductors in the mixed state at frequencies $\hbar\omega \ll \Delta$ was theoretically studied by Gor'kov and Kopnin.[27] They showed that in this case a superconductor behaves like an anisotropic material described by the Maxwell equations with corresponding material parameters. Their basic parameters are the resistivity to magnetic flux drift, ρ_f, and permeability μ. Driven by an induced HF current parallel to the ab plane, the Josephson vortices should travel along the c axis. A current along the c axis drives them in the ab plane. Since BSCCO single crystals have a layered structure, the mobility of Josephson vortices along the c axis is controlled by high-energy barriers to their motion in the superconducting Cu–O layers.

Their motion is much easier in the Cu–O planes than across them. Josephson vortices can move parallel to the c axis if a two-dimensional vortex traveling along a layer parallel to the ab plane migrates by one Cu–O layer, but this motion can be impeded by other factors, such as macroscopic dimensions of the sample and strong pinning of two-dimensional vortices. In our opinion, it allows us to neglect absorption due to HF currents in the ab plane.

This suggests that absorption related to the existence of magnetic flux parallel to the layers is due to HF magnetic field penetrating a lateral surface to a depth λ_c. For samples prepared by various techniques, this penetration depth is about 100 μm. This value is derived from measurements of the critical current density j_{c0} using the relation

$$\lambda_{c0}=(\Phi_0/2\pi s j_{c0})^{0.5}.$$

If an external magnetic field parallel to the ab plane penetrates between the superconducting layers in the form of Josephson vortices, the critical current decays according to the well-known averaged Fraunhofer function:[28]

$$I_c(H)=\frac{I_{c0}|\sin x|}{x}\sim\frac{I_{c0}}{x},\quad x=\frac{\pi H}{H_0},\quad H_0=\frac{\Phi_0}{\mu_0\lambda_{c0}s}.$$

The drop in the critical current density leads to a larger penetration depth of the HF magnetic field. After substituting it into the expression for λ_{c0}, we obtain

$$\lambda_c(H)\sim H^{0.5},\quad H\gg H_{\mathrm{pen}},$$

where H_{pen} is the field due to Josephson vortex penetration of the sample.

Using this result, we can interpret the shape of the absorption curve in a parallel magnetic field. At low magnetic fields and small concentrations of the Josephson vortices, their concentration and penetration depth increase with the magnetic field intensity, thereby increasing HF absorption. When the penetration depth becomes larger than the sample dimension, the total current induced in the sample drops, which leads to a decrease in absorption. The absorption peak is determined by the relation

$$\lambda_c(H_{\max})\approx b(\sim 1\ \mathrm{mm}),$$

where b is the sample dimension perpendicular to the HF magnetic field. The parameters of the function $\lambda_c(H)$ can be estimated using this relation. Thus the absorption that we observed in a parallel magnetic field is determined by the size effect, owing to the variation in the penetration depth λ_c resulting from an increase in the concentration of Josephson magnetic vortices.

The absorption discussed in this paper provides new tools for studying superconducting properties of anisotropic materials. The temperature dependence of the absorption (Fig. 5) yields the temperature at which the order parameter is nonzero in a macroscopic volume comparable to that of the sample (T_c), the temperature at which Josephson vortices are generated in a layered superconducting structure (2D–3D transport), and at which the structure of magnetic vortices undergoes a phase transition (minimum absorption at $T=25$ K). The notable change in the absorption taking place at a temperature above T_c derived from our data can be ascribed to the fluctuation of conductivity. Experiments in a tilted magnetic field yield information about the interaction between Josephson vortices and two-dimensional vortices in superconducting layers.

Let us dwell on the measurements in a periodic magnetic field (Fig. 7). In our opinion, they provide evidence that there is a surface barrier to the Josephson vortices. Unfortunately, we detected this effect only in freshly fabricated samples, so we cannot claim that it is a common feature of all BSCCO single crystals. Let us consider the state of the system starting at point A (Fig. 7), where the surface barrier is overcome and a change in the magnetic field leads to a flow of vortices across the sample surface. Where the magnetic field changes sign (point B), the difference between the external and internal magnetic fields decreases and a surface barrier is formed and, as a result, vortices are ejected from the field penetration range. Therefore the absorption drops and has a minimum at $H_{\mathrm{ext}}=H_{\mathrm{int}}$, when the surface barrier has the maximum height and the number of vortices in the penetration range is the largest. A further decrease in the field intensity diminishes the barrier height owing to the difference $H_{\mathrm{ext}}-H_{\mathrm{int}}$ of the opposite sign; at point C the barrier height is zero, and the vortices easily penetrate (or leave) across the surface. The difference between the magnetic fields $H_{\mathrm{B}}-H_{\mathrm{C}}$ corresponds to double the field eliminating the barrier. If the magnetic field penetration depth is larger than the sample dimension, the field nonuniformity on the surface and the resulting barrier disappear, which is demonstrated by the curve recorded at 53 Oe in Fig. 7. This indirectly confirms our interpretation of the signal shape in a parallel field.

In some sense, having selected at random the magnetic-field frequency and sample dimensions, we could detect a specific HF absorption resulting from two size effects. The typical resistivities of BSCCO in the normal state are $\rho_c\sim 1-10\ \Omega\cdot$cm and $\rho_{ab}\sim 10^{-3}\Omega\cdot$cm; the corresponding skin depths are $\delta_c\sim 10$ mm $\delta_{ab}\sim 10^{-1}$ mm at a frequency of about 1000 MHz. After the transition to the superconducting state, we expect size effects due to both components of the penetration depth. When the magnetic field is not aligned with the ab plane or zero (the absorption versus temperature is recorded), the main contribution comes from the size effect due to λ_{ab} (see, Figs. 2 and 3). When the magnetic field aligned with the ab plane is varied, the change in the absorption is controlled by the concentration of the Josephson vortices and the variation in $\lambda_c(H)$. Whereas the size effect due to λ_{ab} is sensitive to frequency (Fig. 6), the size effect due to $\lambda_c(H)$ should be observed at all frequencies $\omega \ll \Delta$. The curve similar to that in Fig. 4 was recorded by Mansky *et al.*,[29] who studied the low-frequency susceptibility of the highly anisotropic superconductor $(BEDT\text{-}TTF)_2Cu(NCS)_2$ in a magnetic field (curves of χ'' in Fig. 6, Ref. 29).

4. CONCLUSION

We have studied HF absorption in the layered high-T_c superconductor BiSrCaCuO over a wide range of temperature and magnetic field at frequencies of 300 to 1200 MHz. We have detected HF absorption in a magnetic field parallel to the crystal ab plane. The absorption relates to the motion of Josephson vortices in the multilayered crystal, driven by HF currents. The absorption as a function of magnetic field is controlled by variations in the London penetration depth λ_c with magnetic field, and the size effect.

Measurements of the absorption amplitude in a parallel magnetic field with variable external parameters allow us to detect some important processes in studies of superconductivity, such as emergence of the order parameter and its variation, the 2D–3D transition in a multilayered superconducting structure, changes in the structure of the Josephson vortices, and its dynamics.

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