Surface impedance of YBaCuO single crystals in the mixed state

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The real part of the surface impedance Re Z of YBaCuO single crystals in an external magnetic field has been investigated experimentally. The behavior obtained with the external field **H** parallel to the **c** axis of the single crystal [Re $Z \propto \sqrt{H-H_{c1}}(H \gg H_{c1})$ or Re Z is a linear function of the field $(H \lesssim H_{c1})$] is consistent with the existing theoretical models for the impedance of type-II superconductors in the mixed state. The possibility of determining the lower critical field and the critical current density from the field dependence of the impedance is discussed.

1. INTRODUCTION

The dissipation of energy when an electromagnetic wave is reflected from the surface of a type-II superconductor in the mixed state is known to be determined by the dynamics of the vortex lattice.[1,2] The high-frequency (hf) currents induced by the electromagnetic wave in the surface layer interact with quantized vortex filaments of the magnetic flux, setting them in motion and thereby causing the appearance of an hf electric field in the superconductor. This hf field together with the shielding hf currents can cause the dissipation of energy.

The question of the hf response of type-II superconductors in the mixed state was first examined by Gittleman and Rosenblum.[1] They studied the motion of an individual vortex, whose properties were described by introducing a potential relief associated with pinning centers and two parameters, viz., the viscosity coefficient η and the effective mass m. One of the important results obtained in Ref. 1 was a definition of the so-called depinning frequency ω_d. When the frequency of the external magnetic field is greater than ω_d, the motion of the vortices is determined only by the viscosity, and the vortices may be considered free. The surface resistance is then determined by the properties of the "pure" superconductor and does not depend on the defects in the sample under investigation.

Gor'kov and Kopnin[2] considered the interaction of an electromagnetic wave with a type-II superconductor in the mixed state and showed that it behaves as an anisotropic medium described by Maxwell's equation with appropriate material equations. In particular, they derived an expression for the active part of the surface impedance for fields in the range $H_{c1} \ll H \ll H_{c2}$:

$$\text{Re}\, Z = \sqrt{\frac{2\pi\omega\rho_f}{\mu c^2}}. \qquad (1)$$

Here ρ_f is the flux flow resistance, $\mu = B/H$, and B is the induction in the superconductor. This formula holds provided the depth of the skin layer δ is large compared with the London penetration depth, which places an upper limit on the frequency. If the condition $\omega \gg \omega_d$ is also satisfied, expression (1) should describe the linear response of type-II superconductors in the range of magnetic fields where $\mu=$const.

Recently, Sonin, Tagantsev, and Traito[3] calculated the response of a type-II superconductor including some minor interactions that were omitted in Ref. 2. The impedance was calculated for the case in which the magnetic field is perpendicular to the surface of the sample. They showed[3] that the behavior of the impedance in weak magnetic fields $(H < H_{c1})$ is described by the expression

$$\text{Re}\, Z \propto (H - H_p),$$

where H_p is the field corresponding to the onset of penetration of magnetic flux into the superconductor with consideration of the demagnetization factor N_z:

$$H_p = H_{c1}(1 - N_z).$$

For $H > H_{c1}$ we have Re $Z \propto \sqrt{H-H_{c1}}$, which coincides with the result in Ref. 2. A transition from one law to the other occurs at H close to H_{c1}. The conclusions drawn in Ref. 3 were confirmed experimentally for a sample of a low-temperature superconductor having the specially selected composition $Pb_{0.81}In_{0.19}$ and little bulk pinning.[4]

From this standpoint, the interest in investigations of YBaCuO single crystals is due not just to the possible special features of ρ_f for this class of superconducting materials. Single crystals of YBaCuO are known to be hard type-II superconductors and are described fairly well by a critical-state model. Therefore, the bulk pinning cannot be neglected in the general case. However, this applies only to small fields, in which the induction B in the sample is nonuniform. When $H_{c1} \ll H \ll H_{c2}$ and $\omega > \omega_d$ hold, it may be expected that Re Z will be proportional to $\sqrt{B}$.

In this communication we show that the behavior of the active component of the impedance of a YBaCuO superconducting single crystal is satisfactorily described by the theoretical models already developed when H is oriented parallel to the **c** axis (perpendicularly to the most developed surface).

There is presently no thoroughly developed theory for the case in which **H** is perpendicular to the **c** axis (parallel to the surface). In this orientation a major role is played by

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the Bean–Livingston surface barrier, whose influence on the hf response has not been systematically taken into account. The Bean–Livingston barrier results in the existence of a layer near the surface that is free of vortices and partially shields the vortex system.

2. EXPERIMENTAL METHOD

The single-crystal sample of YBaCuO investigated, which was prepared by standard techniques, had the form of a rectangular plate measuring 1.5×1.0 mm^2 with a thickness of 0.1 mm. The **c** axis of the single crystal was perpendicular to the plane of the plate.

The absorbing cell used was a spiral resonator with a length of ~5 mm, which was made from copper wire with a diameter of 0.1 mm and whose resonant frequency was ~900 MHz. Communication with it was accomplished by a capacitive mechanism by placing the central conductors of coaxial cables at end surfaces of the spiral. High-frequency power was supplied to the resonator by means of one coaxial cable, and the voltage from the other cable was recorded by a detector, whose signal was supplied to a personal computer. The spiral resonator was placed in a copper tube with a diameter of 10 mm, to which the coaxial leads were attached. An external magnetic field was created by an electromagnet and monitored by a Hall sensor. The electromagnet could be rotated around the vertical axis without displacing its field from the horizontal plane. The sample was placed in the resonator at the antinode of the magnetic field. To increase the filling factor of the internal space of the absorbing cell and, therefore, the sensitivity of the experiment, the resonator had a flattened shape approximating the cross section of the sample investigated. The normal to the plane of the sample, which was parallel to the **c** axis, was oriented horizontally, so that we could shift the external magnetic field from a parallel orientation to the surface of the plate, which could be established from the impedance minimum in a field $H_{c1}<H<H_{c2}$, to a perpendicular orientation by rotating the magnet. The resonator with the sample and a heating element was placed in a Dewar vessel with gaseous helium between the poles of the electromagnet and cooled to the boiling point of liquid nitrogen. The temperature was monitored by a carbon thermometer fastened to a copper tube.

A signal proportional to the power passing through the resonator with the sample was measured in the experiments. The variation of this signal in the range of temperatures and magnetic fields investigated amounted to less than 10% of the total signal passed, which we traced during preparation for the measurements. When the variation of the signal has such an amplitude, it is proportional to the absorption in the resonator with the sample, and the sensitivity remains high. When the influence of the resonator is small and the absorption is a simple function of the real part of the impedance, the variation of the signal passing through the resonator with the sample is proportional to the variation of the real part of the impedance of the sample. Thus, we obtained the dependence of the real part of the surface impedance on the external magnetic field.

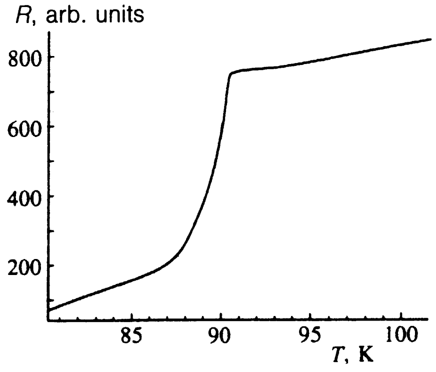

FIG. 1. Temperature dependence of the absorption of hf electromagnetic power (900 MHz) in a cell with a sample of a $YBa_2Cu_3O_{1-\delta}$ single crystal.

3. EXPERIMENTAL RESULTS AND DISCUSSION

Figure 1 presents the temperature dependence of the absorption in the cell containing a test sample. The resistivity of copper undergoes an appreciable change at a temperature near the boiling point of nitrogen; therefore, along with the signal from the sample there is a monotonic decrease in absorption as the temperature decreases due to absorption in the copper spiral. The abrupt drop in absorption in the vicinity of 90 K corresponds to the transition of the YBaCuO single crystal to the superconducting state. When the dependence of the absorption on the magnetic field is studied, there is no variation of the contribution from the absorption of the copper wire; therefore, the entire variation of the absorption upon variation of the magnetic field corresponds to absorption in the single crystal investigated.

Figure 2 presents plots of the dependence of the absorption in the sample on the strength of the external magnetic field at several temperatures. The orientation of the magnetic field during these measurements was perpendicular to the plane of the single crystal, so that the main contribution (owing to the ratio between the areas) should

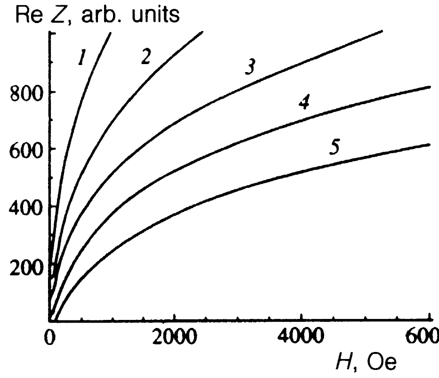

FIG. 2. Dependence of the real part of the impedance in a YBaCuO single crystal on the magnetic field parallel to the **c** axis at various temperatures near T_c: *1*) $T=88.9$ K; *2*) $T=87.4$ K; *3*) $T=86.0$ K; *4*) $T=84.7$ K; *5*) $T=81.3$ K.

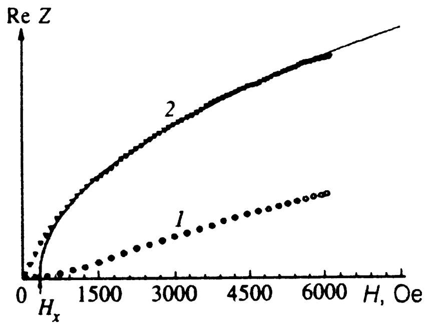

FIG. 3. Field dependence of the real part of the impedance: *1*) external field perpendicular to the **c** axis of the single crystal; *2*) field parallel to the **c** axis. The solid line is an extrapolated curve obtained from the expression Re $Z(H)=\alpha(H-H_x)$, where $H_x=320$ Oe.

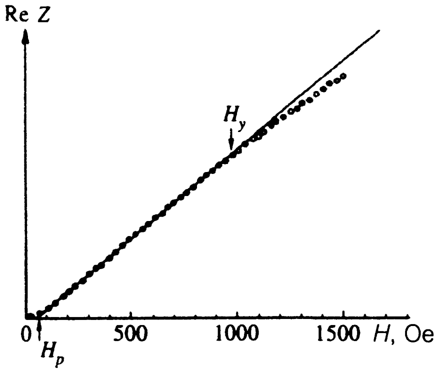

FIG. 4. Initial portion of the field dependence of the real part of the impedance. The solid is an extrapolated curve obtained from the expression Re $Z(H)=\beta(H-H_p)$, where $H_p=60$ Oe.

be made by the planes that are perpendicular to the **c** axis. The vortex lines in these measurements were perpendicular to the surface, as in theoretical treatments.

The behavior of the impedance is nearly unchanged over the entire temperature range investigated from T_c to 80 K, except where the impedance varies abruptly in the vicinity of the actual transition. The plateau near zero field disappears there, indicating that the critical field for entry of the magnetic flux into the sample vanishes.

Let us now turn to a detailed treatment of the dependence of the absorption on the magnetic field at 80 K. This temperature is stable for our setup and can be maintained indefinitely when there is a regular supply of nitrogen.

Figure 3 presents plots of the field dependence of the real part of the surface impedance of the single crystal at $T=80$ K for the parallel and perpendicular geometries. The plots obtained exhibit anisotropy with Re $Z(\mathbf{H}\| \mathbf{c})/$ Re $Z(\mathbf{H}\perp \mathbf{c})\approx 3$. According to the theory in Ref. 3, the field dependence of the surface impedance in fields in the range $H_{c1}\ll H\ll H_{c2}$ was quantitatively approximated for $\mathbf{H}\|$ **c** by means of the expression Re $Z(H)=\alpha\sqrt{H-H_x}$ (see Fig. 3), where α is a scale factor and H_x is an adjustment parameter. The experimental values of Re $Z(H)$ in fields greater than 1.1 kOe (Fig. 3) were chosen for the approximation. It is seen from Fig. 3 that the experiment is accurately described by the theory when $H_x=320$ Oe.

To study the behavior of the impedance in weak fields, the initial portion of the variation of Re Z was traced in greater detail for the case of a field parallel to the **c** axis of the single crystal (Fig. 4). It is seen from the figure that the dependence is nearly linear at fields equal to 150–850 Oe, as in the case of weak bulk pinning.[4] Therefore, we extrapolated the experimental data using the dependence Re $Z=\beta(H-H_p)$ for the values of the magnetic field just cited (see Fig. 4). Here β is a scale factor, and H_p is an adjustment parameter with the value $H_p=60$ Oe.

Thus, as expected on the basis of Ref. 3 (see Introduction), in the range $H_{c1}\ll H\ll H_{c2}$ the real part of the surface impedance is accurately described by a square-root dependence on the external magnetic field. To account for the observed linear field dependence of Re Z in weak fields, the form of $B(H)$ must be utilized. As calculations in the framework of the Bean model and experiments involving measurements of the magnetic moment $M(H)$ for YBaCuO single crystals[5,6] showed, $B(H)$ is proportional to H^2 in weak fields. Taking into account that Re $Z \propto \sqrt{B}$, we obtain Re $Z\propto H$.

Thus, the field dependence of the impedance has three special points, viz., H_p and H_x, which give the adjustment parameters of the approximations (Figs. 3 and 4), and H_y, which is the point where the deviation of Re $Z(H)$ from linearity begins, i.e., the field corresponding to the change from a linear dependence to a square-root dependence or the crossover field (Fig. 4). The field H_p, which is actually the field corresponding to the beginning of the increase in the impedance, may be interpreted as the beginning of magnetic field penetration into the sample. Then the lower critical field can be evaluated for a defect-free sample from the penetration field with the aid of the relation[5]

$$H_{c1}=H_p/(1-N_z).$$

This method is similar to the method of determining H_{c1} from the deviation of the measured dependence of $M(H)$ from linearity, where M is the magnetic moment. However, due to the significant error in the determination of the demagnetization factor for real single crystals, the results obtained are not sufficiently reliable. If, nonetheless, the demagnetization factor is estimated from the dimensions of the sample, and the experimental value $H_p\approx 60$ Oe is utilized, the value obtained $H_{c1}=360$ Oe is in satisfactory agreement with $H_x=320$ Oe.

To overcome these difficulties V. V. Moshchalkov *et al.*[6,7] proposed a method for extrapolating the quadratic component of the dependence of $M(H)$ to zero to determine the linear contribution of the Meissner currents. In our experiments this procedure is similar to extrapolating the square-root dependence of Re Z to zero. We note that here the extrapolation is performed from the region where $B(H)$ is linear. In fact, the jump in the field on the surface of the sample is determined from the variation of Re Z in fields in the range $H_{c1}\ll H\ll H_{c2}$, and then $H_x=H_{c1}$ (Fig. 3).

We interpret H_y (Fig. 4) as the field for "complete" penetration. This means that a vortex lattice forms throughout the sample. This corresponds to the maximum of the magnetic moment on the $M(H)$ curves. Then the critical current density j_c can be determined from H_y. We obtain $j_c \approx 4\times10^4$ A/cm^2 using the relationship between H_y and j_c and the expression from Ref. 8 for a thin disk

$$H_y = \frac{j_c t}{2} \ln \frac{D+\sqrt{D^2+t^2}}{t},$$

where D is the diameter of the disk and t is its thickness.

The estimate just given is fairly rough. This is attributable to the shape of the sample and the error in the determination of H_y (Fig. 4). However, we would like to focus attention on the possibility of determining j_c from field dependence of the impedance.

Let us briefly comment on the value of the working frequency, which was about 900 MHz in the present experiment. The main reason for using this frequency that we can measure the response of samples in the frequency range from 200 to 1200 MHz with high sensitivity. To increase the filling factor for small samples, it is convenient to work in the upper part of this range. The proposed estimates of the depinning frequency of YBaCuO lie in the range extending upward from 1000 MHz. Our measurements on epitaxial YBaCuO films with a large critical current showed that the depinning frequency $\omega_d > 1000$ MHz, and the possibility of observing variation of the absorption at such values is associated with thermal depinning of the vortices near the critical temperature. As was pointed out in the introduction, the dynamics of the vortex lattice can be explained phenomenologically by using effective parameters that describe the behavior of a vortex in a superconducting material, such as the potential relief, the effective mass, and the viscosity. The potential relief is determined by various defects, which are effective vortex-pinning centers, and, when their concentration is not very large, by the interaction of free vortices with pinned vortices and with one another (so-called collective pinning). The depth and profile of the individual potential wells will be different for different kinds of defects and for different distances from the pinning centers for free vortices (at constant concentration).

This differentiation of the pinning centers should be especially evident in high-T_c superconductors owing to the broad range of thermal energies in the superconducting state. The depinning frequency ω_d will be different for vortices immobilized on different pinning centers and at different distances from the pinning centers. The vortices satisfying $\omega_d < \omega_0$ (the working frequency) will contribute to the absorption at all temperatures below T_c. In addition, if the thermal energy is greater than the pinning energy, the thermally depinned vortices will also make a contribution to the absorption. If the depinning frequency is greater than the working frequency, the vortices whose pinning energy is smaller than the thermal energy will make a contribution to the absorption when the temperature is lowered. Then the hf absorption can serve as a tool for the thermal spectroscopy of pinning centers.

Thus, the field dependence of the real part of the surface impedance of YBaCuO single crystals has been investigated experimentally in this work. It has been shown that the results obtained are described fairly reliably by generally accepted electrodynamic models of type-II superconductors in the mixed state. A method for determining the lower critical field and the critical current density from the field dependence of Re Z has been proposed.

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