Field-induced variations of the microwave surface impedance of $YBa_2Cu_3O_7$ crystals near T_c

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The microwave surface impedance Z_s of a $YBa_2Cu_3O_7$ single crystal is investigated as a function of the magnetic field H_0 at different temperatures close to T_c. It is shown that Z_s depends on H_0 for applied fields higher as well as lower than H_{c1}. A model is discussed in which the field dependence of Z_s below H_{c1} is ascribed to the field-induced variations, within the penetration depth, of the partial concentrations of both normal and condensate electrons. The field dependence of Z_s above H_{c1} is explained using the Coffey and Clem model. [S0163-1829(97)04733-4]

The study of the effect of a dc magnetic field on the microwave (mw) response of high-T_c superconductors is of interest for understanding the mechanisms responsible for microwave energy losses. Investigation is commonly performed by measuring the power absorption with standard EPR spectrometers[1–6] or, alternatively, the surface impedance.[7–9] Results reported in the literature have been obtained in both ceramic[1,2] and single-crystal[3–9] high-T_c superconductors. Measurements in ceramic samples are mainly performed at low applied fields, where microwave currents flowing through Josephson junctions play an important role. On the contrary, measurements in single crystals are generally performed in the mixed state, where dissipation is ascribed to fluxon dynamics.

Here we report experimental data on the field-induced variations of the mw surface impedance Z_s of a $YBa_2Cu_3O_7$(YBCO) single crystal. Measurements have been performed at different values of the temperature close to T_c. We have found that Z_s depends on the applied field even when the sample is in the full Meissner state. Furthermore, the surface impedance versus applied field curves exhibit an abrupt slope variation at relatively low fields. We have elaborated a phenomenological model which accounts well for the experimental results.

Experiments have been performed on a YBCO single crystal of approximate dimensions $2\times1.5\times0.2\ \mathrm{mm}^3$ with the c axis parallel to the shortest edge. The sample is located inside a rectangular cavity, resonating at 6 GHz and tuned in the TE_{102} mode, in a region in which the magnetic field $H(\omega)$ is of maximal intensity. The input power is of the order of 0.1 mW. The output signals are detected by a superheterodyne receiver. Measurements refer to the amplitude of the wave transmitted by the cavity as a function of the applied field H_0; at $H_0=0$ the wave amplitude is reduced to zero through interference with a reference signal. Since we do not make use of automatic frequency control of the mw oscillator, the output signal is influenced by both the resistive and the reactive components of the surface impedance Z_s. Indeed, when the input power to the cavity is fixed at a constant level, the detected signal is proportional to the field-induced changes of Z_s:

$$\Delta Z_s(H_0,T)=|Z_s(H_0,T)-Z_s(0,T)|.$$

All measurements have been performed in the zero-field-cooled sample with both the static magnetic field $\mathbf{H}_0$ and the microwave field $\mathbf{H}(\omega)$ parallel to the crystal c axis. We remark that, in all the range of temperatures in which we are interested, no hysteresis has been observed at increasing or decreasing fields, independently of the cooling conditions, i.e., all signals fall above the irreversibility line.

The sample had been previously characterized through measurements of the nonlinear microwave response near T_c;[10] its critical temperature is $T_c=(92.2\pm0.1)$ K. Furthermore, in a range of temperatures of about three degrees below T_c, the temperature dependence of the upper critical field H_{c2} is well described by: $H_{c2}(T)=H_{c2}(0)[1-(T/T_c)^2]$, with $H_{c2}(0)=(260\pm4)$ kOe.

Figure 1 shows ΔZ_s as a function of H_0in the YBCO sample with the crystal c axis parallel to both fields $\mathbf{H}(\omega)$ and $\mathbf{H}_0$, at two different values of the temperature: $T=91.6$ K (●), $T=89.9$ K (■). In both cases, the signal increases at increasing H_0 and approaches a constant value when H_0 tends to $H_{c2}(T)$.

Figure 2 shows ΔZ_s as a function of H_0 in an enlarged scale at low fields. All the curves have been obtained with

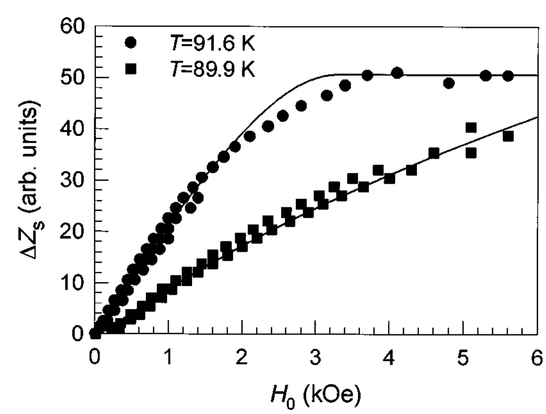

FIG. 1. Variation of the microwave surface impedance, ΔZ_s, as a function of the external magnetic field H_0 in a YBCO sample; crystal c axis parallel to both $\mathbf{H}_0$ and $\mathbf{H}(\omega)$. Symbols are the experimental points. The continuous lines are expected curves using the Coffey and Clem model (Ref. 14) and parameters $\lambda_0/\delta_0=8.3\times10^{-2}$ and $\lambda_0=1400$ Å. Input microwave power ~0.01 mW.

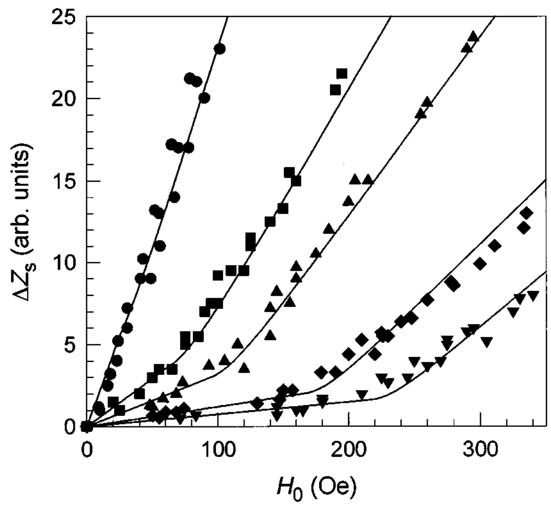

FIG. 2. ΔZ_s as a function of H_0 in a YBCO crystal sample with $c \| \mathbf{H}_0 \| \mathbf{H}(\omega)$. $T=91.5$ K (●), $T=90.4$ K (■), $T=89.4$ K (▲), $T=87.2$ K (◆), and $T=85.5$ K (▼). The continuous lines are expected curves using our model, discussed in the text, with $\alpha_0=2\times10^{-5}$ Oe^{-1}, λ_0/δ_0, and δ_0 having the same values as those of Fig. 1, respectively. Input microwave power ~1 mW.

the same field geometry as that of Fig. 1, $c \| \mathbf{H}(\omega) \| \mathbf{H}_0$, at different values of the temperature: $T=91.5$ K (●), $T=90.4$ K (■), $T=89.4$ K (▲), $T=87.2$ K (◆), and $T=85.5$ K (▼). To improve the resolution, measurements of Fig. 2 have been performed using an input power level higher than that of Fig. 1. Each ΔZ_s vs H_0 curve exhibits an ''elbow'' at a particular value of the dc magnetic field, which we call H^*. Except very near the elbow, the experimental points relative to a fixed temperature fall along two straight lines of different slopes intersecting at H^*; on increasing the temperature H^* decreases and both slopes increase. From Fig. 2 one can see that ΔZ_s varies with the applied field even at low fields, when the sample is for sure in the full Meissner state. To our knowledge, this finding had not yet been discussed. Later on we afford evidence that H^* is the lowest field at which fluxons are present over the whole sample. It is worth noting that, below H^*, the closer to T_c the temperature, the higher is the slope of the ΔZ_s vs H_0 curve. This is suggestive of the fact that the influence of H_0 on Z_s is temperature dependent, being the highest for T very close to T_c and undetectably small below ~80 K.

In Fig. 3 is shown H^* as a function of the temperature. Each value of H^* has been determined by the intersection of the two straight lines fitting the ΔZ_s vs H_0 measurements at a fixed temperature. H^* data has been fitted by the law expected for the temperature dependence of the lower critical field, $H_{c1}(T)=H_{c1}(0)[1-(T/T_c)^4]$. The continuous line of the figure corresponds to the best fit obtained with $H_{c1}(0)=840$ Oe; this value is consistent with the ones reported for YBCO single crystals.[11]

In the field geometry in which all measurements have been performed, the value of the magnetic field at which fluxons start penetrating the sample is expected to be smaller than H_{c1}, because of demagnetization effects. However, for temperatures close to T_c the penetration field at the sample edge is higher than the one obtained from the measured pen-

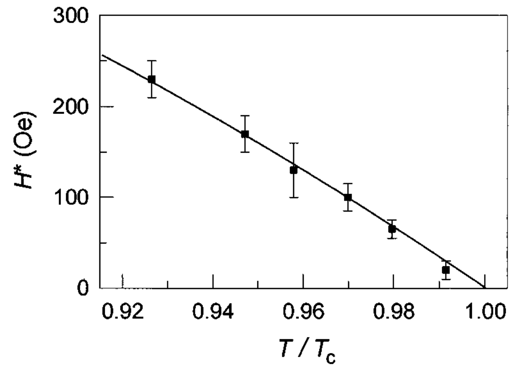

FIG. 3. H^* as a function of the temperature. Symbols are the values of H^* deduced from ΔZ_s vs H_0measurements, as described in the text. Continuous line is a plot of $H_{c1}(T)=H_{c1}(0)[1-(T/T_c)^4]$, with $H_{c1}(0)=840$ Oe.

etration field scaled by the standard elliptical demagnetization factor.[12] This is due to geometrical-barrier effects.[12,13] We suggest that the effective penetration field over the whole sample be H^*.

Microwave losses induced by dc magnetic fields in single crystal high-T_c superconductors have been investigated by several authors.[3–8] Different models have been put forward; in all of them the presence of fluxons is essential to account for the magnetic-field dependence of the surface impedance. In particular, Coffey and Clem[14] (CC) have developed a comprehensive theory for the electromagnetic response of type-II superconductors in the mixed state, taking into account flux-creep, flux-flow, and pinning effects in the two-fluid model of superconductivity. Their theory applies for $H_0>2H_{c1}$, when the static magnetic field inside the crystal can be supposed as generated by a uniform density of fluxons n_0; in this case $H_0\approx B_0=n_0\phi_0$.The mw field inside the sample is characterized by a complex penetration depth, $\tilde{\lambda}$, which is influenced by the fluxon motion and the very presence of vortices which bring along normal material in their cores. In the linear approximation ($H_{\mathrm{mw}}\ll H_0$) the following expression of $\tilde{\lambda}$ has been obtained:[14]

$$\tilde{\lambda}^2=\frac{\lambda^2+i\delta_v^2/2}{1-2i\lambda^2/\delta^2}, \tag{1}$$

where λ is the London penetration depth, δ is the normal fluid skin depth, and δ_v is the complex effective skin depth arising from the vortex motion.

Both λ and δ depend on the magnetic field as

$$\lambda=\lambda_0\{(1-w_0)[1-B_0/B_{c2}(T)]\}^{-1/2} \tag{2}$$

and

$$\delta=\delta_0\{1-(1-w_0)[1-B_0/B_{c2}(T)]\}^{-1/2}, \tag{3}$$

where $\lambda_0=(mc^2/4\pi ne^2)$ is the London penetration depth at $T=0$ K, $\delta_0=(c^2/2\pi\omega\sigma_0)^{1/2}$is the normal metal skin depth at $T=T_c$, w_0 and $(1-w_0)$ are the fractions of normal and superconducting electrons at $H_0=0$, with $w_0=(T/T_c)^4$.

At microwave frequencies and for temperatures close to T_c one may assume that vortices are in the flux-flow regime.[5,8] In this case δ_v is given by

$$\delta_v = \frac{2B_0\phi_0}{4\pi\eta\omega}, \tag{4}$$

where $\eta = \phi_0 B_{c2}(T)\sigma_0/c^2$ is the viscous drag coefficient of the fluxon motion.

In the London local limit[15] the surface impedance is given by

$$Z_s = R_s + iX_s = i\omega\tilde{\lambda}; \tag{5}$$

so, in the CC model, the field dependence of Z_s arises from changes of the complex penetration depth induced by the very presence of fluxons and their motion.

The continuous lines of Fig. 1 are plots of $\Delta Z_s = |Z_s(H_0) - Z_s(0)|$ as a function of H_0, after Eq. (5). We have used $\lambda_0/\delta_0 = 8.3\times 10^{-2}$; this value is the one used for the fitting of the temperature dependence of third-harmonic signals in a similar sample of YBCO single crystals.[16] Here λ_0 has been used as a parameter, the best fit being obtained with $\lambda_0 = 1400$ Å. As is evident from Fig. 1, the CC model accounts quite well for the experimental data at relatively high magnetic fields, $H_0 > 2H_{c1}$.

The experimental data at low fields, $H_0 < H^*$, cannot be explained by anyone of the models discussed in the literature, including the CC model. The surface impedance depends on H_0 even when $H_0 \leqslant H_{c1}$ and no fluxons are present inside the crystal. To account for this finding we consider processes which take place near the sample surface in a layer of thickness of the order of λ. It is well known that a magnetic field smaller than H_{c1} decays exponentially inside a superconductor within λ. It has been shown that, at temperatures close to T_c, a mw field of few Oe decaying inside a YBCO crystal modulates to a detectable extent the partial concentrations of both the normal and the condensate fluids, giving rise to nonlinear emission.[16] We assume that the dc magnetic field which decays in the surface layers perturbs in a similar way the electron concentrations: on increasing H_0 the normal fluid density increases and that of the condensate decreases. Since all measurements reported in the present paper have been performed using microwave magnetic-field intensities of the order of a few mOe, we neglect the perturbation due to the mw field and we set

$$w(H_0) = w_0(1 + \alpha_0 H_0'), \tag{6}$$

where α_0 is a phenomenological parameter and H_0' is that part of the applied field which decays in the surface layers.

Since the magnetic field decreases exponentially inside the superconductor, the perturbation term decreases as well. However, we consider the perturbation to be uniform so that α_0 accounts for an average coupling between H_0 and the electron fluids within the penetration length of the field.

We wish to emphasize that the perturbation term in Eq. (6) can only be efficient at temperatures close to T_c, when the energy gap is not large and the penetration depth is of maximal extent. This term increases linearly with H_0 as far as H_0 is equal to the penetration field H^*, when the whole superconductor goes into the mixed state. On further increasing H_0 above H^*, the perturbation mechanism becomes less and less efficient because of the decreasing magnetization.

We have calculated the surface impedance [Eq. (5)] by using the expression of $\tilde{\lambda}$ expected from the CC model [Eq. (1)], with w_0 of Eqs. (2) and (3) replaced by $w(H_0)$ of Eq. (6). Calculations have been carried out numerically in the following approximation: H_0' of Eq. (6) is set equal to H_0 for $H_0 \leqslant H^*(T)$; H_0' takes on values linearly decreasing from $H^*(T)$ to zero for $H^*(T) \leqslant H_0 \leqslant H_{c2}(T)$. In order to generalize the model for fields lower as well as higher than the penetration field, we have substituted B_0 in Eqs. (2) and (3) with $H_0 - H_0'$.

The continuous lines of Fig. 2 are expected results from our model. We have used for λ_0 and λ_0/δ_0 the same values as those used in the fitting of the data reported in Fig. 1. The only parameter we have now adjusted is α_0; the best fitting has been obtained using $\alpha_0 = 2\times 10^{-5}$ Oe^{-1}. The model accounts satisfactorily for the experimental results. In particular, it accounts for both the field dependence of the surface impedance in the Meissner state and the slope variation observed in the ΔZ_s vs H_0 curves at low fields. Separate calculations of the resistive R_s and the reactive X_s components of Z_s lead to the conclusion that at low fields both R_s and X_s contribute to the field-induced changes of Z_s, while at high fields R_s plays the most important role.

In conclusion, we have shown that the low-field variation of the surface impedance of YBCO crystals can be explained as due to the perturbation of the partial concentrations of both normal and condensate fluids induced by the applied field within the surface layer of thickness λ. This mechanism is the only one responsible for the field-induced variations of ΔZ_s at low fields, up to H^*. It is also effective to a lesser extent above H^*, when fluxons are present throughout the sample. However, in the mixed state ΔZ_s increases at a rate even greater than at low fields since new dissipation mechanisms come into play. These are the ones considered in the CC model,[14] arising from the presence of fluxons inside the crystal and their motion.

The $H^*(T)$ values which we have inferred from ΔZ_s measurements are consistent with the values of the penetration field predicted by Zeldov *et al.*[12] They have pointed out that, for a sample of rectangular cross section of width $2W$ and thickness d exposed to dc fields parallel to the shortest edge, the effective penetration field is $H_p \sim H_{c1}(d/W)^{1/2}$, smaller than H_{c1}. However, at temperatures near T_c, when pinning effects are negligible, the Meissner currents drive the entering vortices to the center of the sample with the result that vortices are only present near the edge at applied fields significantly greater than H_p.[12] Therefore, the field at which fluxons come into play in the growing up process of the microwave surface impedance is also expected to be greater than H_p. Demagnetization and geometrical-barrier effects may offset each other. We suggest that the values of $H^*(T)$ are those at which vortices are present over the whole sample. As expected, the measured values of $H^*(T)$ are close to $H_{c1}(T)$. Measurements of the microwave surface impedance at low fields may afford a convenient way for determining geometrical barriers in high-T_c superconductors.

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