Temperature, frequency, and rf field dependence of the surface resistance of polycrystalline $YBa_2Cu_3O_{7-x}$

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The rf surface resistance of a single bulk polycrystalline $YBa_2Cu_3O_{7-x}$ sample was measured with TEM resonant cavities as a function of temperature from 4.2 to 100 K, rf field amplitude from 0 to 640 G, and frequency from 175 to 1050 MHz. The surface resistance increased monotonically with rf field amplitude, saturating at a value approximately 5% of the normal-state surface resistance. The surface resistance is strongly frequency and temperature dependent below the saturation region and weakly frequency and temperature dependent above. Low-field surface resistances as small as $\lesssim 1.1\ \mu\Omega$ (at 175 MHz) were observed at $T=4.2$ K. The superconducting state did not break down, even at the highest field achieved ($\sim$640 G).

INTRODUCTION

Several investigators have measured rf losses in polycrystalline high-T_c superconductors.[1-3] Bulk materials typically have surface resistances (R_s) much larger than those predicted by the BCS theory. These high surface resistances are thought to depend on material properties which vary from sample to sample, thereby making R_s unpredictable. Thus, it is surprising that measurements of single samples at low rf field amplitude ($B_{\rm rf}$) with microwave strip lines have yielded a quadratic frequency dependence in R_s, a result consistent with the BCS theory.[4,5] Moreover, cross comparison of various bulk ceramics has also hinted at a quadratic frequency dependence of R_s at low $B_{\rm rf}$.[6] These results indicate, at a minimum, that the measured surface resistance is related to the superconducting state.

In an earlier paper, we presented data for bulk $YBa_2Cu_3O_{7-x}$ (hereafter designated Y-Ba-Cu-O) which show a monotonic increase in R_s vs $B_{\rm rf}$ at $T=77$ K and 204 MHz.[7] We now expand these results for a different bulk Y-Ba-Cu-O sample which has a sharp superconducting transition to investigate the temperature dependence and rf field dependence of R_s at several frequencies.

EXPERIMENT

The generic apparatus for our rf measurements is pictured in Fig. 1. The resonant cavity consisted of a cylindrical copper enclosure, 10 cm in diameter and 80 cm long or 25 cm long for experiments below 600 MHz and above 600 MHz, respectively. A long, thin cylindrical sample, located inside a quartz tube, was lowered coaxially into the copper cylinder. For isothermal high-field measurements, the cavity and quartz tube were flooded with either liquid helium or liquid nitrogen. For measurements as a function of temperature, the cavity temperature was monitored using sensors at the top and bottom outer surfaces of the copper enclosure. The cryogen was boiled away, and the cavity was allowed to warm slowly enough so that the two sensors recorded the same temperature to within 0.5 K. This procedure assured a condition of approximate thermal equilibrium in the cavity.

The cavity was operated in its fundamental TEM mode in which the sample behaved as a resonant coaxial line such that its length corresponded to one half-wavelength of the rf field. Before each experiment, the background losses due to the external Q of the pickup probe, the copper cylinder, and the quartz tube were measured at 4.2 K and at the specific frequency of interest using thin, high-purity, lead wires of appropriate length and similar diameters. At 4.2 K, the power dissipation associated

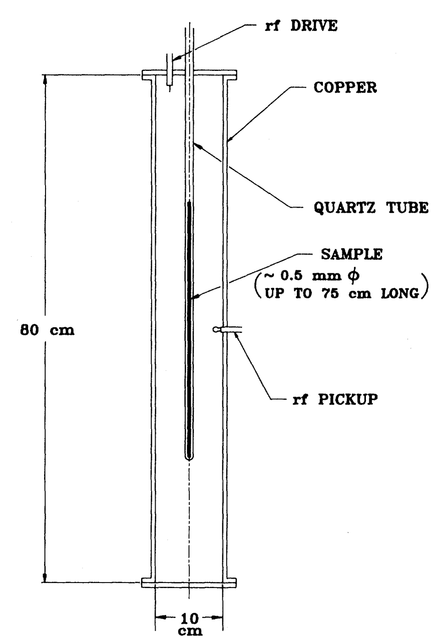

FIG. 1. Generic TEM resonant cavity for the measurement of the surface resistance of a superconducting rod. The sample acts as a half-wave resonant coaxial line. The outer conductor is made of copper. The entire cavity is filled with liquid cryogen.

with the superconducting lead wire is negligible, and the measured decay time τ_b is due only to the background. The pickup probe dominated the other losses, and so the contribution of the background was assumed to be independent of temperature. The same measurements with the lead wires were done at room temperature where the power dissipation due to the wire dominates all other loss mechanisms. The geometrical factor associated with the sample was calculated from the measured decay time τ_s(Pb) and the surface resistance of lead R_s(Pb) by $\Gamma_s = \omega \tau_s(\text{Pb}) R_s(\text{Pb})$. This geometrical factor is material independent and was found to agree, within 15%, with a simple model of a lossy, infinite coaxial transmission line.

In a given experiment, the quantity measured was the decay time of an rf pulse sent into the cavity. The decay time deviates from an exponential behavior if the surface resistance of the sample is field dependent. In this case, a proper measure of the decay time derives from the slope of the voltage-versus-time (or pickup power-versus-time) curve at pulse turn-off. Accordingly, the decay times were usually measured from this slope at critical coupling. We have also determined the decay time $\tau(B_0)$ at field B_0 by measuring the time t_0 for the field to decay from B_0 to B_0/e. If the surface resistance has a power-law dependence on the field of the form $R_s \propto B^n$ and if the drive probe is critically coupled at field B_0, it can be shown that the actual decay time $\tau(B_0)$ is related to the measured time t_0 by

$$\tau(B_0) = t_0 \frac{n}{2} \left[\ln \left(\frac{e^n + 1}{2} \right) \right]^{-1} .$$

Even in the case of a strong power dependence, the correction factor is relatively close to unity (0.81 for $n=1$ and 0.70 for $n=2$).

The measured decay time τ_c is related to the background decay time τ_b and the sample decay time τ_s by $1/\tau_c = 1/\tau_b + 1/\tau_s$. Once the contribution of the background is removed, the surface resistance R_s is determined from the sample decay time τ_s by $R_s = \Gamma_s/\omega\tau_s$. The accuracy of the absolute measurements of R_s was limited by uncertainties in reading the decay times from the oscilloscope traces. For temperatures above T_c, accuracy was limited by the intrinsic fall time of the pulse modulator; and at low temperature it was limited by the contribution of the background.

For the field dependence of the surface resistance, the rf field level was absolutely calibrated by measuring both the input power P while critically coupled and the intrinsic decay time τ. These two numbers are related to the energy content U by $U = P\tau$. Because of the simple geometry, the energy content U can simply be related to the surface rf magnetic field at the center of the sample. The absolute accuracy on the determination of B_{rf} is approximately 10% and is due mainly to the nonuniformity of the sample cross section.

The sample was prepared from phase-pure Y-Ba-Cu-O powder which was combined with a set of organics and extruded.[8] After firing, its diameter was 0.44 mm and its starting length was 80 cm. To perform measurements at different frequencies, we simply broke the sample to get the desired length. After fabrication, low-field rf measurements were taken at $T=4.2$ and 77 K, and the sample was then stored for ten months in air inside a quartz tube.

TEMPERATURE DEPENDENCE

The sample underwent a sharp transition from the superconducting state to the normal state as the temperature was raised. This transition is pictured in Fig. 2. At both 243 and 505 MHz, there was approximately a 1000-fold increase in R_s as the temperature rose from 77 K to the critical temperature $T_c \simeq 91$ K at low field ($B_{\text{rf}} \lesssim 0.05$ G). The low-field data agreed with data taken ten months earlier ($R_s \lesssim 1.1\ \mu\Omega$ at 4.2 K and 175 MHz), indicating stability of the sample's rf properties in the presence of air.

We have attempted to fit the data to $R_s \propto e^{-A/T}$ and to $R_s \propto T^n$; however, neither of these models would fit the data at all three frequencies over an extended temperature range.

FREQUENCY DEPENDENCE

The same data, together with additional data points taken at 4.2 K, are shown in Fig. 3 where the surface resistance is shown as a function of frequency for various temperatures. The data approximately follow a quadratic frequency dependence at all temperatures through 90 K while it follows a square-root dependence at 92 K. The data at 505 MHz is systematically lower than would be expected from the measurements at 243 and 1041 MHz. This could be due to a lack of homogeneity of the original sample which was measured at 243 MHz. It was then broken in two pieces; one piece was measured at 505 MHz and the other piece was broken again and measured at 1041 MHz.

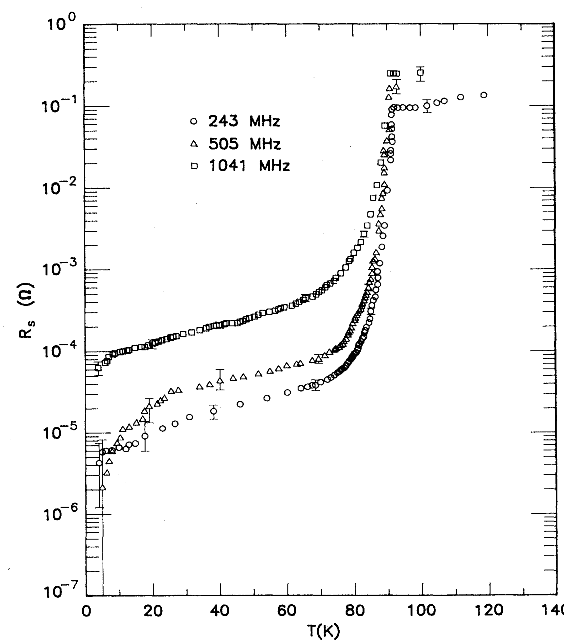

FIG. 2. Surface resistance of the bulk polycrystalline Y-Ba-Cu-O sample vs temperature at three frequencies and at low field ($B_{\text{rf}} \lesssim 0.05$ G).

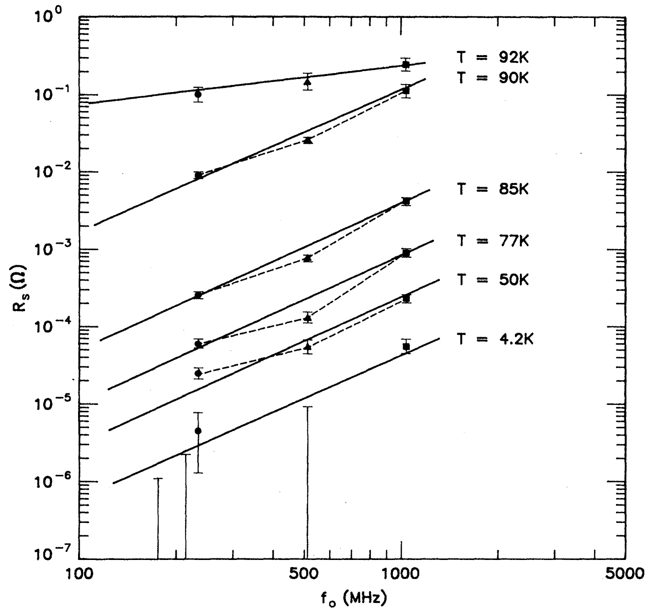

FIG. 3. Surface resistance vs frequency at low field amplitude ($B_{rf} \lesssim 0.05$ G). Some of the points have been interpolated from the data of Fig. 2. The solid lines are provided as visual aids and correspond to a quadratic frequency dependence except at $T=92$ K, where the line shows an $f^{1/2}$ dependence.

rf FIELD DEPENDENCE

The dependence of the surface resistance on the rf field at the center of the sample was measured at 4.2 and 77 K with the sample immersed in liquid helium and liquid nitrogen, and the results are shown in Fig. 4. The difference in frequency between the two temperatures is due to the different dielectric constants of liquid helium and nitrogen.

The surface resistance increased monotonically as the rf field amplitude B_{rf} was increased. Figure 4 reflects this behavior, showing that R_s increases from its zero-field value, passes through a transition region characterized by a strong B_{rf} dependence, and saturates at a value roughly 5% of the normal-state surface resistance just above T_c. The highest values of B_{rf} that we could achieve were limited either by the amplifiers available or by breakdown of the cryogen due to high electric fields at the ends of the sample. The sample stayed superconducting out to the highest field achieved, $B_{rf} \simeq 640$ G (at 77 K and 190 MHz). The "turning points" which bound the "transition regions" of Fig. 4 depend strongly on both temperature and frequency. In the transition regions, $R_s \propto B_{rf}^n$, where $1 \lesssim n \lesssim 2$, and the surface resistance is strongly dependent on both the temperature and frequency. The frequency dependence of R_s in the transition regions is approximately quadratic, as seen in Fig. 5. In the high-field region, on the other hand, R_s shows only a weak dependence on both temperature and frequency.

We can probably rule out an explanation based on heating to explain this behavior since the decay times measured were independent of pulse length and repetition rate. Furthermore, in the transition regions, the same surface resistance is measured at 220 MHz as at 1050 MHz, but at fields which are 1 order of magnitude higher so that the heat deposited in the sample per unit area is 2 orders of magnitude higher.

Interestingly, the rf behavior of our sample is qualitatively consistent with the observed microwave absorption of high-T_c materials in an applied dc magnetic field,[9-11] with the exception that we do not see hysteresis in the rf absorption. The authors of the referenced papers interpret their dc field-dependent data principally in terms of weak Josephson links.

Recent measurements of the anisotropic lower dc critical fields H_{c1} in single-crystal Y-Ba-Cu-O have indicated that 180 G $\lesssim H_{c1}(T=0) \lesssim 530$ G depending on the orientation of H_{c1} relative to the c axis of the crystal, and that H_{c1} is lower at nonzero temperatures, decreasing linearly

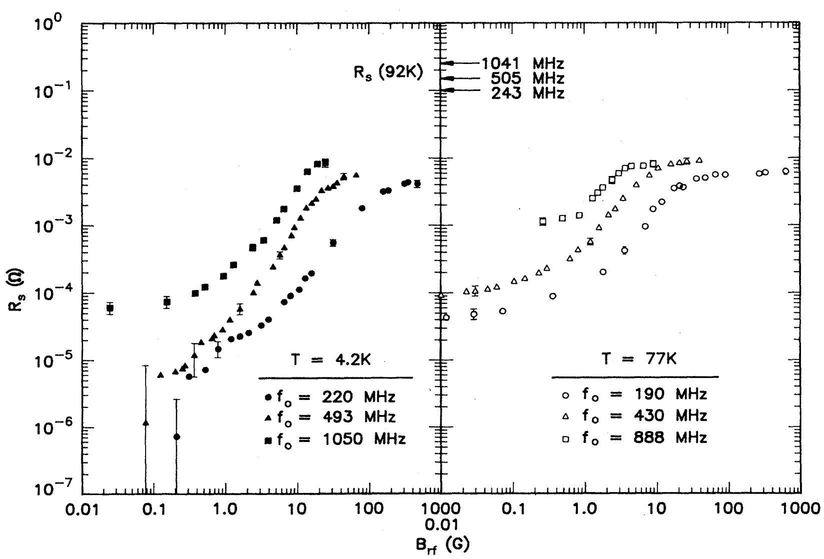

FIG. 4. Surface resistance vs rf field amplitude at $T=4.2$ K and $T=77$ K.

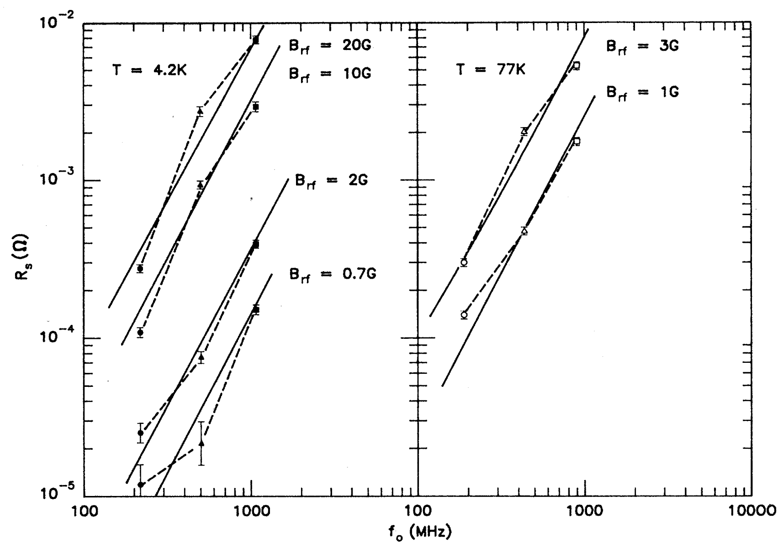

FIG. 5. Surface resistance vs frequency at selected field amplitudes. Some of the points have been interpolated from the data of Fig. 4. The solid lines are provided as visual aids and correspond to a quadratic frequency dependence.

from $T=\frac{1}{2}T_c$ to zero at $T=T_c$.[12] Figure 4 includes data at peak rf field amplitudes which are higher than these values.

Rubin *et al.*[13] report an "apparent breakdown of the superconducting state" at 93 G in a single crystal of Y-Ba-Cu-O. Since we have achieved substantially higher rf fields, it is likely that the breakdown observed in the single crystal is a thermal instability due to insufficient cooling and not a fundamental breakdown of the superconducting state. They also report a surface resistance which is nearly independent of the rf field. However, it seems that the data refer to upper bounds and, although it is clear that the surface resistance of single crystals can be lower than polycrystals, the rf field dependence of the surface resistance of single crystals is still an open question.

SUMMARY

We have measured the rf surface resistance of a bulk polycrystalline Y-Ba-Cu-O sample which has a sharp transition between the normal state and the superconducting state and which has stable rf properties when stored in air. We have found an approximately quadratic frequency dependence of the rf surface resistance at low rf field amplitudes. As the rf field amplitude is increased, the surface resistance increases monotonically while retaining an approximately quadratic frequency dependence. As the field is increased further, the surface resistance eventually saturates at an rf field amplitude which depends on both frequency and temperature. The saturation value of R_s is weakly dependent on both frequency and temperature.

ACKNOWLEDGMENTS

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