Temperature-, magnetic-field-, and power-dependent microwave resistance of $YBa_2Cu_3O_{7-\delta}$

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We have measured the microwave resistance of sintered $YBa_2Cu_3O_{7-\delta}$ at 9 GHz as a function of temperature, magnetic field, and microwave power. We observe a rapid change in slope with temperature about 1 K below the onset of the superconducting transition. There is a strong magnetic field dependence only below this slope-change temperature. This behavior is similar to that seen in low-frequency resistance measurements. We also observe an increase in microwave resistance with microwave power for temperatures below the superconducting onset temperature. We estimate that the microwave currents may be large enough to give such an effect due to weak-link structures in this material. We show that the power dependence is not due to bulk sample heating, but we cannot rule out self-heating on a microscopic scale.

INTRODUCTION

The origin of the microwave losses in $YBa_2Cu_3O_{7-\delta}$ (Y-Ba-Cu-O) below the superconducting transition is of interest for both scientific and technical reasons. Recent attention has focused on the granular nature of this material. In particular, the sensitivity of the microwave losses to small magnetic fields has been attributed to the suppression of superconductivity in weak-link structures between or within superconducting grains.[1,2] Low-frequency resistance measurements have also been interpreted in terms of weak links.[3,4] These losses must be reduced if the material is to be useful in many applications. On the other hand, the granularity might be exploited to study a large system of coupled superconductors. As a probe of the material properties, a microwave measurement is a useful complement to low-frequency measurements for at least two reasons: It is a contactless measurement, and it permits the resistive behavior to be studied at temperatures below the dc zero-resistance temperature.

We have measured the microwave resistance of Y-Ba-Cu-O as a function of temperature, applied magnetic field, and microwave power. We find a rapid change in the slope of the resistance at a fairly well-defined temperature about 1 K below the superconducting onset temperature. The response to applied magnetic fields is qualitatively different above and below the slope change. Below the superconducting onset temperature, we find that the resistance increases with microwave power. We estimate that the microwave currents in our samples may be large enough to drive weak-link structures in the material normal, which would give such an effect. The power dependence is not due to bulk heating of the sample, but we cannot rule out microscopic self-heating.

EXPERIMENT

Typical polycrystalline samples were prepared by the solid-state reaction of Y_2O_3, $BaCO_3$, and CuO with relative molar amounts 1:2:3, respectively. The 99.999% purity powders were mixed, ground, and then heated in an alumina boat at 945 °C for 2 h in flowing oxygen at 1 atm. The reacted material was reground and pressed into 0.5-in-diam pellets, which were sintered at 950 °C for 8 h in oxygen, then slowly cooled. X-ray-diffraction patterns show that the samples are $YBa_2Cu_3O_{7-\delta}$ in the orthorhombic phase. The results reported here are typical of measurements on seven samples.

The samples are mounted with Apiezon N grease to a copper insert centered in one end plate of a cylindrical cavity (Fig. 1). The cavity, either copper or aluminum, resonates at 9.12 GHz in the TE_{011} mode; it is coupled to a waveguide through a circular iris. A static magnetic field uniform over the sample to better than 1% can be applied perpendicular to the cavity end plates. The microwave magnetic field is parallel to the sample surface. This field is zero at the sample center and increases roughly linearly with radius to its maximum value at the sample edge. It is larger than half its maximum value over 75% of the area of the sample. The insert and cavity tempera-

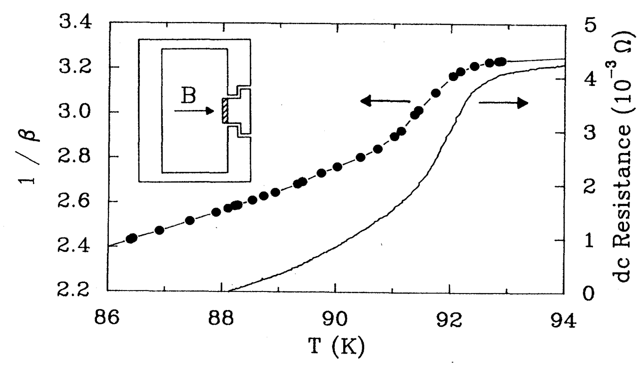

FIG. 1. The dc resistance (solid line) and the microwave resistance (filled circles) near T_c for the same sample. Changes in $1/\beta$ are proportional to changes in the real part of the sample surface impedance. The dc resistance vanishes near 88 K; the microwave resistance is still decreasing (cf. Fig. 2). Note the rapid slope change near 91 K in both curves. The inset is a cross section through the cavity axis. The sample (hatched) is attached to a thermally isolated insert in one end plate. A static magnetic field B can be applied along the cavity axis; the microwave fields are parallel to the sample surface.

tures are controlled independently with a precision of about 1 mK. The microwave power is measured[5] with a precision of 0.01%. The stray power reflected from the waveguide is less than 10^{-4} of the incident power.

A measurement of the standing-wave ratio in the waveguide shows that cavity is undercoupled.[6] The sample resistivity is computed as follows:[7] For an undercoupled cavity ($\beta < 1$) one has

$$1/\beta = (1+\sqrt{p})/(1-\sqrt{p}) = \gamma_s R_s + \gamma_c R_c \, .$$

Here β is the ratio of the cavity Q to the coupling Q, and $p = P_r/P_i$ is the ratio of the power reflected from the cavity and the incident power. The γ's are constants which depend only on the dimensions of the cavity and sample.[8] R_s and R_c are the real parts of the surface impedance of the sample and cavity, respectively. For a cavity without a sample, there is no measurable change in p with temperature, magnetic field, or microwave power, so that $\Delta(1/\beta) = \gamma_s \Delta R_s$.

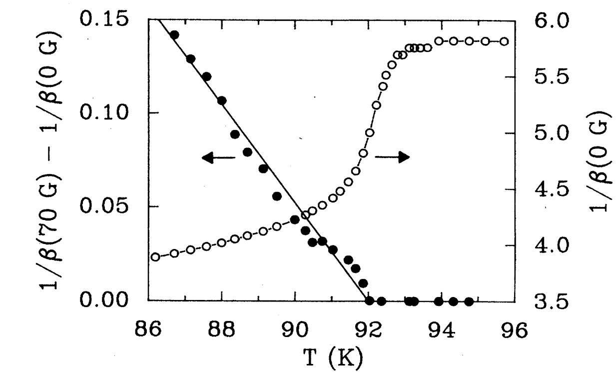

FIG. 3. The difference in the microwave resistance in 70 and 0 G for a second sample (filled circles). The difference vanishes approximately linearly with an intercept of (92.0 ± 0.3) K (solid line). Also shown is the microwave resistance in 0 G (open circles). The change in slope here is also near 92 K.

MAGNETIC FIELD DEPENDENCE

Figure 1 shows the microwave and dc resistances for the same sample near T_c. Above T_c both decrease approximately linearly with T (not shown); the sample dc resistivity is about 10^{-4} Ω cm at 95 K. Both drop rapidly at T_c, then decrease more slowly. The dc resistance is zero below about 88 K. There is no feature at this temperature in the microwave resistance, which is decreasing even at 10 K. There is a change in slope in the microwave resistance at about 91 K, which becomes more prominent when a magnetic field B is applied to the sample (Fig. 2). The dc resistance behaves similarly (see, for example, Fig. 1 of Ref. 3).

The behavior of the microwave resistance in an applied magnetic field allows one to distinguish three temperature regions. Above T_c we observe no B dependence. Just below T_c the effect of the magnetic field is quite small; it can be accounted for by a shift in T_c of 0.053 K kG^{-1}, which is consistent with measurements of dH_{c2}/dT in single-crystal samples.[9] At lower temperatures, however, the response to the magnetic field is qualitatively different.

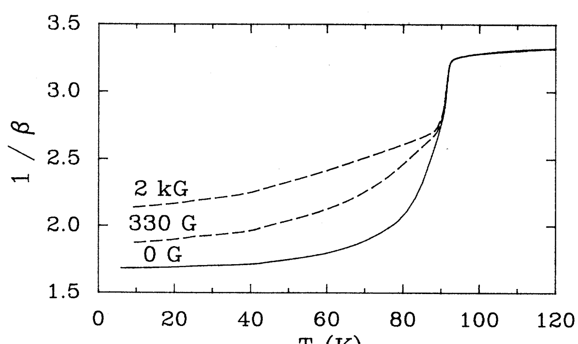

FIG. 2. The microwave resistance in various magnetic fields (same sample as Fig. 1). The change in slope near 91 K is larger with an applied field. The sample was cooled in zero field before each sweep.

Figure 3 shows the difference between the resistance in 70 and 0 G as a function of T for a second sample. The difference goes to zero linearly at (92 ± 0.3) K, approximately the temperature of the slope change in zero field and below T_c. For comparison, the microwave resistance in zero field for this sample is also shown in Fig. 3.

Measurements made at fixed temperature confirm this behavior (Fig. 4). For $B \leq 500$ G, there is no measurable change with B in the microwave resistance for $T = 100$ K (above T_c) nor for $T = 92.4$ K [below T_c but above the slope change (cf. Fig. 3)]. (The B dependence described

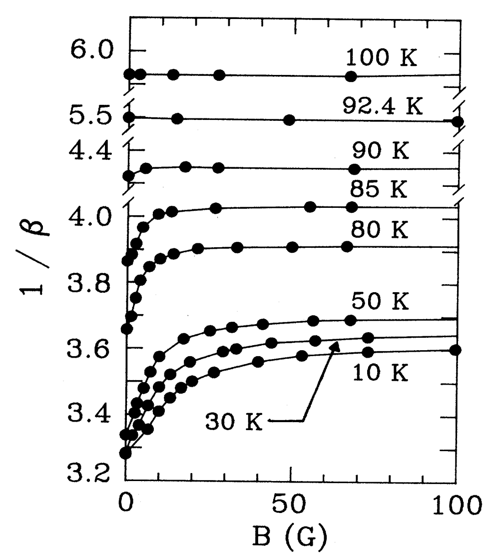

FIG. 4. The microwave resistance as a function of the magnetic field B at various T. The lines connect data points. There is no measurable B dependence at $T = 100$ K, which lies above T_c, nor at $T = 92.4$ K, which lies between T_c and the slope change temperature (see Fig. 3). For $T \leq 90$ K, the resistance increases rapidly at small fields, then approximately linearly and more slowly for $100 \lesssim B \lesssim 500$ G (not shown for clarity). Data taken with B increasing; there is substantial hysteresis.

above for this temperature region is below our experimental resolution for $B < 500$ G.) For $T \leq 90$ K (below the slope change), however, the resistance increases rapidly with B then slows to an approximately linear increase. The linear behavior has been attributed to dissipative flux line motion.[2,10] The slopes in this high-field linear region ($100 < B < 500$ G, not shown for clarity) for the data in Fig. 4 are 0.050, 0.025, 0.025, 0.035, 0.050, and 0.110 kG^{-1} ($\pm 10\%$) for $T = 10$, 30, 50, 80, 85, and 90 K, respectively. The high-field slope increases with increasing temperature, with the exception of the 10-K data. The width of the region of rapidly varying slope at low field increases with decreasing temperature, however, so the 10-K data may not have reached its limiting high-field behavior by 500 G.

These results are qualitatively similar to low-frequency resistance measurements and can be interpreted in the same way.[3] The initial drop in resistance can be attributed to the superconducting transition of individual grains, which have the small sensitivity to magnetic fields observed for single-crystal samples. As the temperature is lowered, the sample resistivity is quickly dominated by another mechanism with a slower temperature dependence and a much higher magnetic field sensitivity. This crossover gives the change in slope just below T_c and accounts for the magnetic field results. Unlike the low-frequency resistance, however, the microwave resistance does not drop to zero when a percolating superconducting path through the sample is established. The reason is that the surface current at each point in the cavity is proportional to the local microwave magnetic field. Because of the fixed field pattern in the cavity, the entire sample (within an electromagnetic penetration depth of the surface) contributes to the microwave losses.

Two other groups have reported distinct changes in the microwave response with temperature for polycrystalline and single-crystal samples. Glarum, Marshall, and Schneemeyer[2] find that, for polycrystalline samples, rapidly varying features in the microwave absorption for $B < 10$ G disappear near T_c, leaving behavior similar to which they observe for single crystals. They attribute this change in behavior to the uncoupling near T_c of individual grains in polycrystalline samples. With single crystals, Dulčić, Crepeau, and Freed[11] find qualitatively different behavior in three temperature regions below T_c, with boundaries at about 50 and 80 K. They attribute the change in behavior at 80 K to the expulsion of magnetic flux from twin boundaries.

The increase in absorption with an applied magnetic field has been widely attributed to the suppression of weak-link superconductivity.[1,2] The maximum current which a Josephson junction can support without dissipation—the critical current I_c—is a function of T and B, given by

$$I_c = I_0(T)\sin(B/B_0)/(B/B_0) ,$$

with $B_0 = (\Phi_0/2d\lambda_L)$, where Φ_0 is the flux quantum, d is the junction width, and $\lambda_L(T)$ is the London penetration depth. A given junction will become dissipative as the magnetic field pushes I_c below the measuring current I. For a sample with a distribution of junction sizes, the oscillatory behavior with B will be averaged out, so one would expect an increase in absorption with B up to some field which reflects a typical junction size and little field dependence above.[3,12] The prefactor I_0 increases as $T \rightarrow 0$ (as does λ_L^{-1}) so that larger applied fields are required at lower temperatures to suppress superconductivity in the junctions. This behavior can be seen in Fig. 4.

POWER DEPENDENCE

If the weak-link model is correct, the junctions should be driven normal at sufficiently large measuring currents, so that one would expect the sample resistance to increase at sufficiently large measuring currents. Nonlinear current-voltage characteristics have been reported in low-frequency measurements.[3,4] In cavity measurements at higher frequencies, four groups have reported on the dependence of the resistance on the local microwave magnetic field (which is proportional to the surface current). Wijeratne *et al.*,[13] at 80 GHz, find a microwave power dependence only at high power (100 mW in a waveguide transmission measurement), where they attribute it to sample heating. Zahopoulos, Kennedy, and Sridhar[14] report a large increase in resistance at 8 GHz and 4.2 K for a microwave field of 4.6 G; because the effect depended upon the microwave power pulse length, they also attributed this to sample heating. Hein *et al.*,[15] measured the Q of a cavity containing a Y-Ba-Cu-O sample at 3 GHz and 4.2 K as a function of the microwave magnetic field H at the sample. Replotted as microwave resistance ($\propto 1/Q$), their data increase approximately linearly with H for $H < 6$ G; above 6 G, the resistance increases much more rapidly up to their measurement limit of about 9 G. They attribute their results to heating of individual grains. Delayen *et al.*,[16] on the other hand, find an effect which is independent of microwave power pulse length or repetition rate. If their data at 204 MHz and 77 K are replotted on a linear scale, one observes an approximate linear increase in the resistance for $H < 2$ G. Above 2 G, the resistance at first increases more rapidly, then slows to another approximately linear region for $40 < H < 160$ G. The overall shape of this curve is remarkably similar to the curves for $T \leq 80$ K shown in Fig. 4, which give the shift in resistance with a *static* magnetic field.

One difficulty with interpreting these measurements is determining whether an observed shift with microwave power level is due to a change in temperature of the sample or a change in microwave magnetic field at the sample. Three of the groups used direct cooling of the sample surface (with helium gas[14,15] or liquid nitrogen[16]) to minimize temperature changes. We have taken a different approach. We use very thin samples to minimize the temperature difference between the sample surface and the end-plate insert to which the sample is mounted. We measure the shift in resistance with power as a function of temperature and the shift in resistance with temperature. The ratio of the shift with power and the shift with temperature at any given temperature is the effective thermal conductance required if the power dependence is an artifact of sample heating.

Figure 5 shows the results for a sample ground down to a thickness of 0.013 in. Below T_c we observe an approximately linear increase in $1/\beta$ (proportional to the sample microwave resistance) with microwave power absorbed by the sample P_s over the range 1–100% of the maximum power available. (This linear behavior in *power* is not inconsistent with the linear behavior in *field* at low fields in the data of Hein and Delayen because of the limited range of our measurements.) P_s was determined by measuring the heater power required to keep the end-plate insert temperature constant when the microwave power is turned off. The largest P_s obtained was about 8 mW at 95 K. (P_s depends upon the sample resistance as well as the incident microwave power.)

Figure 5 gives the slope $\partial(1/\beta)/\partial P_s$ at various T near T_c. The change in $1/\beta$ for this sample over 10–100 K is 2.65. Note that 92 K, where the effect is largest, is *above* the temperature of the slope change for this sample (see Fig. 3). Also shown is the temperature derivative of the microwave resistance $\partial(1/\beta)/\partial T$. The rough correlation with the power derivative suggests sample heating as the origin of the power dependence. The ratio of the two derivatives gives an effective thermal resistance of about 400 K W^{-1} at 80 K, 250 K W^{-1} at 85 K, and 100 K W^{-1} at 90 and 92 K, with uncertainties of about 20%. The *largest* thermal resistivity for sintered Y-Ba-Cu-O reported[17,18] is less than 2 m K W^{-1} over this temperature range. This implies a thermal resistance for our sample of less than 5 K W^{-1}, which is too small by a factor of 20–80 to account for the power dependence.[19] This estimate is probably quite conservative, since the conductivity should be a strong function of sample porosity;[17] the measured density of our sample is 80% of the theoretical value, nearly twice the density of the sample for which the above thermal conductivity was reported. Furthermore, the thermal resistivity of Y-Ba-Cu-O *increases* with T in this range; our data would require the opposite behavior.

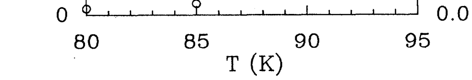

FIG. 5. The rate of change of the microwave resistance with total power absorbed by the sample P_s (filled circles). The point at 92 K lies below T_c and above the slope change temperature (see Fig. 4). There is no measurable power dependence for $T > T_c$. Also shown is the rate of change of resistance with T (open circles). The ratio of the data is the effective thermal resistance if the power dependence is due to sample heating. This thermal resistance is too large to be due to bulk sample heating. Error bars are much smaller than symbol size except where shown.

We can also rule out the possibility of a significant thermal gradient across the sample-insert boundary. We measured the thermal resistance of a joint similar to that used to mount the samples. A copper block with the same diameter as our samples was attached to a copper thermal stage with Apiezon N grease. The thermal resistance of this joint was 4.3 K W^{-1} at 10 K and 1.1 K W^{-1} at 90 K, with an estimated uncertainty of 5%. (Assuming a grease layer thickness of 0.001 in., this gives a thermal conductivity of 0.18 W m^{-1}K^{-1} at 90 K, in good agreement with the reported[20] value of 0.15 W m^{-1}K^{-1} for Apeizon N grease at 100 K.) Again this thermal resistance is too small to account for the observed power dependence.

Although these estimates show that the observed power dependence is not due to a macroscopic temperature difference between the sample surface and the insert thermometer, it is difficult to rule out the possibility of self-heating of the sample on the microscopic scale. In fact, the conclusion that weak links dominate the microwave resistance at low temperatures implies that the power absorption is not uniformly distributed throughout the sample, and therefore, there may be significant temperature gradients over microscopic distances. Of course, the observed power dependence may be an intrinsic effect. One argument against this is that we observe the largest power dependence above the slope change. If the slope change marks the temperature below which weak links dominate the losses, one might expect, in analogy with a low-frequency measurement,[3] a larger power dependence below this temperature. The situation is not completely clear cut, however, since the low-frequency measurements are also vulnerable to self-heating,[21] and this may be aggravated by percolation effects. Another possibility is that a small intrinsic increase in resistance with microwave magnetic field is masked, because of local heating, by a large increase in resistance with (local) temperature.

The maximum microwave field at the sample in our measurements is about 0.3 G, which implies a surface current of about 0.2 A cm^{-1} [1 G=(10/4π) A cm^{-1}]. Dividing this by the electromagnetic penetration depth gives an estimate for the current density near the sample surface. For a uniform superconductor (i.e., one without grain boundaries), the appropriate length scale for electromagnetic penetration is $\lambda_L(T)$ in the local limit, $\xi_0 \ll \lambda_L$, where ξ_0 is the coherence length.[22] Muon relaxation measurements[23] give $\lambda_L(0) \cong (0.14\text{–}0.17)$ μm and good agreement with the empirical form $\lambda_L(T) = \lambda_L(0)[1-(T/T_c)^4]^{-1/2}$. Assuming a penetration depth of about 0.2 μm, we obtain a maximum current density for our measurements of about 5×10^3 A cm^{-2}. The measured[24] dc critical current densities for single grain boundaries vary over the range of about $(1\text{–}50)\times10^3$ A cm^{-2}, so that the surface currents for our measurements are at the low end of the range needed to produce an observable effect.

CONCLUSIONS

Our measurements support the idea that the low-temperature microwave losses in Y-Ba-Cu-O are due to weak links and suggest that this mechanism becomes dominant at a fairly well-defined temperature just below the superconducting onset temperature. We observe a power dependence in the microwave resistance, which may be due to weak-link structures. We have ruled out bulk and joint heating effects as an explanation for this power dependence, but cannot eliminate the possibility of self-heating on a microscopic scale.

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