High-power, pulsed-microwave measurements of critical currents in thin films of Y-Ba-Cu-O and Nb

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The microwave (16.5-GHz) surface resistance of superconducting Y-Ba-Cu-O and Nb thin films is observed to increase with increasing applied microwave power. At higher powers, Nb films have been driven normal. These effects are attributed to high induced-current densities, approaching the critical values. From these measurements, values for the product λJ_c have been derived, and for Nb we have obtained the temperature dependence of this quantity. By using known values of λ, the values of J_c at microwave frequencies have been obtained.

Measurements of the microwave surface resistance[1] R_s and the complex conductivity[2] of Y-Ba-Cu-O have been reported previously.[3] More recently there has been considerable interest in the microwave field dependence of R_s in the high-temperature oxide superconductors, and several cw microwave studies have been reported.[4] In this paper we report[5] pulsed-power measurements, at 16.4 GHz, of the field dependence of the surface resistances of thin superconducting films of Y-Ba-Cu-O and Nb. Measurements were made at several temperatures below T_c. A great advantage of pulsed measurements is the ease with which average power effects, such as heating of the sample and its environment, are reduced. Our experiments utilized 10-μsec pulses at a repetition rate of 20 pulses per minute, giving a duty cycle $\simeq 3\times10^{-6}$. These values are well below those at which any heating effects (either pulsed or average) were noticeable, even at our highest power, 800 W. Thus our highest average power is about 2.4 mW, which is 3–5 orders of magnitude smaller than utilized in the referenced cw experiments.

The cw measurements[4] were oriented towards the power handling capacity of high-temperature superconductors for use in various applications to microwave circuits. Therefore they were concerned with obtaining absolute magnitudes of R_s at high microwave fields. Similarly, earlier[6] high-pulse-power studies on Nb were concerned with the transient behavior of superconducting cavities for application to particle accelerators. Our purpose in undertaking these experiments was to determine the magnitude and temperature dependence of the critical current density J_c for the high-temperature oxide superconductors at microwave frequencies and to compare them with lower-frequency data. To this end, we were not interested in evaluating the magnitude of R_s itself, but only its field dependence. From our data, approximate values of λJ_c (London penetration depth $\times$ the critical current) can be determined, and for the Nb sample we have obtained the temperature dependence of that quantity. Approximate values of the J_c at 16.5 GHz for high-quality, epitaxial films of Y-Ba-Cu-O have been obtained and are compared with low-frequency (dc) data on the same films. The Nb measurements were begun originally only to evaluate the efficacy of the technique. However, a search of the literature has not found any previous microwave data with which to compare these results, and so we are reporting them as well.

High-quality, high-J_c epitaxial Y-Ba-Cu-O films[7] were grown by laser ablation on single-crystal $SrTiO_3$ substrates [(100) orientation, 0.085 cm thick] which were previously cut into circular disks to fit into the microwave cavity resonator as described below. Disk diameters were 1.3 and 2.0 cm. Ring-shaped samples were also studied. In general, the results discussed below were independent of these variations in geometry. The films had low-frequency critical currents of about 5×10^6 A/cm^2 at 80 K and were typically about 1 micrometer thick. The Nb samples were grown on oxidized silicon wafers (0.035 cm thick) by electron beam deposition to about 230 nm thickness and typically had a dc critical current density[8] of about 6×10^6 A/cm^2 at 4 K. These substrates were also cut into disks to fit into the cavity. Y-Ba-Cu-O films were also grown on other types of substrates, such as MgO, Y-stabilized zirconia, and $LaGaO_3$. In general the higher normal-state resistivity and lower critical current of these samples prevented systematic studies at high powers. Sample deterioration in the form of electrical breakdown was often observed.

The experiment consisted in measuring the voltage-reflection coefficient Γ and Q of a circular cylindrical cavity resonator containing the thin film samples. The cavity was operated in the TE_{011} mode. All other modes were effectively suppressed, in the usual manner, by maintaining a gap (backed by a choke joint to prevent leakage) between the cylinder and one end wall. The cavity was filled with Styrofoam and the cold parts of the assembly, including waveguides, were immersed in the He exchange gas. The unloaded, empty cavity Q at 10 K was $\simeq 33\,000$. It is possible to obtain higher Q values, but in a pulsed experiment it is necessary that the cavity response time Q/ω be considerably shorter than the pulse length.[9] The circular samples were fitted into a depression centered on one end wall having a depth equal to the sample thickness. Except for the depression, this is the same geometry utilized in Ref. 1. As noted here, the purely azimuthal nature of the surface current configuration which obtains in this cavity has the distinct advantage that currents do not cross the Cu-sample boundaries. This is important in high-power measurements because high voltage points are avoided.

Rectangular input pulses were obtained from a switched traveling-wave-tube amplifier (TWTA). The power output was maintained constant and precision attenuators were used to vary the power incident on the cavity, P_i, and the reflected power, P_r, at the detector. Figure 1 shows the shape of the reflected pulses when the carrier frequency was at resonance at two different power levels. While the whole pulse is shown in these figures, the time scale was also expanded to obtain additional points in the transient region with data points taken every 5 ns. These data were stored digitally for later analysis. Since the risetime of the input pulses was short compared with the response time of the cavity, the power reflection coefficient P_r/P_i $(=\Gamma^2)$ was determined from the ratio of the flat part of the pulse (after the initial transient has died out and before the final transient) to the peak of the initial transient. The loaded Q, Q_L, was measured from the decay of the final transient whose shape is given by $\exp(-\omega t/Q_L)$.

The change in the surface resistance, ΔR_s, is proportional to the change in the unloaded Q, $1/Q_0$ [see, e.g., Eq. (2) of Ref. 1]:

$$\Delta R_s \propto \Delta \left[\frac{1}{Q_0} \right] = 1/Q_0(P,T) - 1/Q_0(0,0) \ . \tag{1}$$

Here, (0,0) indicates sufficiently low (P,T) such that $1/Q_0$ is independent of P and T. We have chosen to present our data in terms of $\Delta(1/Q_0)$ because it involves measured quantities only. Both $Q_0(P,T)$ and Q_x, the external circuit Q, can be evaluated from Γ and Q_L, since

$$\Gamma = |(\beta-1)/(\beta+1)| \ , \tag{2}$$

where $\beta = Q_x/Q_0$ is the coupling coefficient, and

$$1/Q_L = 1/Q_x + 1/Q_0 \ . \tag{3}$$

In practice $1/Q_L$ need be measured only once in any given run or set of runs in which the mechanical coupling, and hence Q_x, is held constant. The cavity fields were evaluated from

$$H_0^2 \int_c F(r) d\mathbf{r} = \frac{Q_0 P_c}{\mu\omega} \ , \tag{4}$$

where $F(\mathbf{r})$ is the normalized spatial dependence of the magnetic field, H_0 is the peak value, $P_c = P_1(1-\Gamma^2)$ is the power into the cavity, and the integral is over the volume of the cavity. The field, at the surface of the sample, H_s, is then evaluated from the known value of F at the surface. The current at the sample surface, J_s, is evaluated from the solution to the combined Maxwell and London equations in the sample,

$$J_s = H_s/\lambda \ . \tag{5}$$

Figure 2 shows $\Delta(1/Q_0)$ for one of the Y-Ba-Cu-O samples, plotted as a function of H_s. Figure 3 shows a similar plot for the Nb film. There was no observable power dependence of the empty cavity Q, Q_c. The data have not been corrected for temperature dependence of Q_c which was slight over the range of temperatures used; the maximum variation in $\Delta(1/Q_c)$ was about 10^{-5} for Fig. 2, and for Fig. 3 it was about 10^{-7}. The highest field corresponds to $P_i = 800$ W for all the curves, but the field values corresponding to a given P_i vary with Q and so are

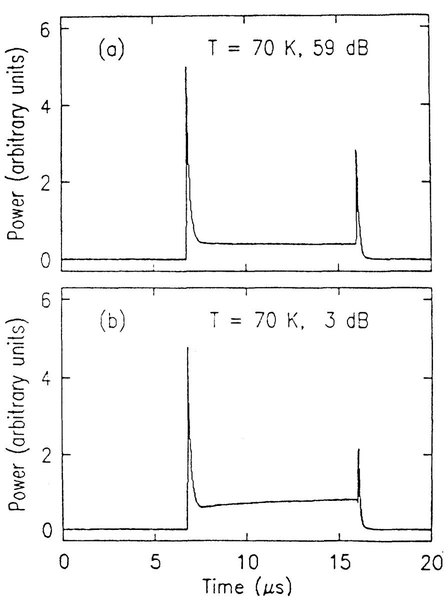

FIG. 1. Reflected pulse wave forms as measured at the crystal detector for two different power levels.

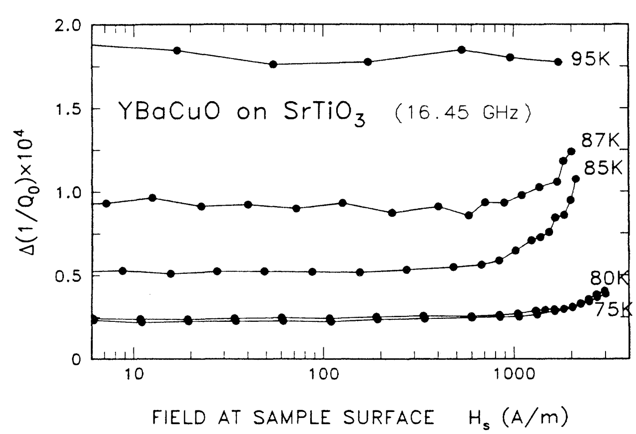

FIG. 2. $\Delta(1/Q_0)$ vs H_s at various temperatures for Y-Ba-Cu-O film referenced to Q(0, 10 K). These temperature dependences were chosen for clarity out of data taken over the entire temperature range of 10–100 K.

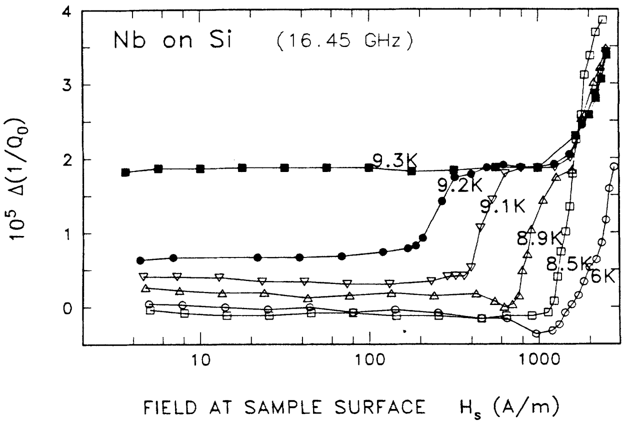

FIG. 3. $\Delta(1/Q_0)$ vs H_s at various temperatures for Nb film referenced to $Q(0, 6\ \mathrm{K})$. The temperatures shown were selected for clarity from data taken over the entire temperature range of 6–10 K.

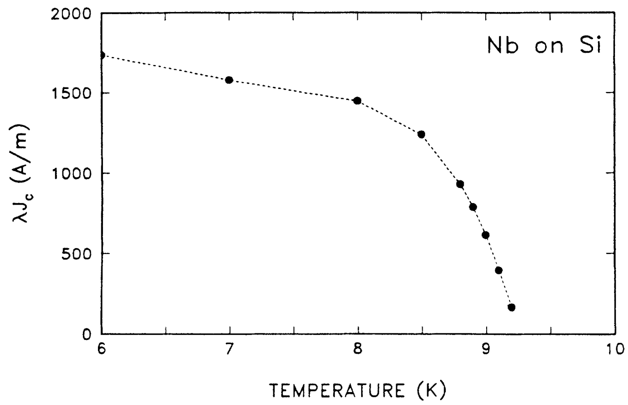

FIG. 4. Product of the penetration depth λ and the critical current J_c as a function of temperature for niobium films.

not the same for the different runs. In both figures there is a threshold value of H_s beyond which the resistance increases with increasing field. This behavior is attributed to J_s, increasing with H_s, eventually approaching the critical value J_c. The effect is clearer in the Nb data, which show a sharper increase in resistance at high fields and temperatures. It is most clearly seen in the 8.9-, 9.1-, and 9.2-K curves for which the fields become large enough to drive the sample normal. The resistance at 9.3 K is normal at all fields. Also for these temperatures, a second resistance increase is evident at $H_s \simeq 1200$ A/m. This effect seems to occur only in the normal state, as evidenced by the fact that at lower temperatures (e.g., 6 K) the resistance remains below the normal value at fields higher than 1200 A/m. The effect does not occur in the empty Cu cavity or with the Y-Ba-Cu-O present as for Fig. 2. Thus there is some nonlinearity in the normal resistivity of Nb on the oxidized Si substrate. While we do not understand the origin of this behavior, it is not important for purposes of this paper.

The sharp increase in resistance of Nb as J_c is approached enables us to calculate the product λJ_c. For each value of T, we find the value of H_s at which $\Delta(1/Q_0)$ reaches 10% of the difference between its low-power and the normal-state (9.3 K) values (i.e., 10% of the maximum change for that temperature) and enter this value into Eq. (5) to find an approximate value of $J_c(T)$. The results are shown in Fig. 4. 10% is, of course, an arbitrary choice and other fractions would produce slightly different values of λJ_c. However, we have ascertained that the shape of the curve changes little. The curve extrapolates to give $T_c = 9.25$ K at $J_c = 0$. At 6 K, using a penetration depth[10] $\lambda \simeq 90$ nm, we obtain $J_c(6\ \mathrm{K}) = 1.9 \times 10^6\ \mathrm{A/cm^2}$, in approximate agreement with dc measurements.[8,11]

Much greater pulsed power would be needed to obtain similar results on the T dependence of J_c for the Y-Ba-Cu-O films. From the 85-K data of Fig. 2 and using the 10% criterion as above, we find $\lambda J_c(85\ \mathrm{K}) = 1200$ A/m. Using a penetration depth[12] of about 140 nm, $J_c(85\ \mathrm{K}) \simeq 8.5 \times 10^5\ \mathrm{A/cm^2}$. Using the same criteria at 80 K yields a J_c of about $1.4 \times 10^6\ \mathrm{A/cm^2}$. This is in reasonable agreement with dc measurements of critical currents in these films. The more abrupt change in the surface resistance as shown in Fig. 3 for the low-T_c, Nb films is typical of superconductors which make the transition to the normal state through pair breaking accompanied by a sudden penetration of the magnetic field. The more gradual increase as seen in the Y-Ba-Cu-O films is most likely due to flux motion and field penetration at the low values of H_{c1} as has been observed at lower frequencies.[13] The data appear to indicate that J_c is not severely diminished at high frequencies and that the mechanism limiting the critical current in these high-J_c films of Y-Ba-Cu-O may still be effective up to 16.5 GHz. Our recent results on the temperature dependence[14] of the surface resistance tend to support this conclusion. They show an activated decrease in the resistance with decreasing temperature with energies of about 0.015 eV, which is in the range of energies observed at lower temperatures.[15]

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