rf surface resistance of Y-Ba-Cu-O thin films

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The rf surface resistance of superconducting Y-Ba-Cu-O thin films has been measured using a stripline resonator technique. The electron-beam-evaporated films have been measured from 0.6 to 17.4 GHz and from 4.2 to 8 K. The surface resistance reaches as low as $3.9\times10^{-4}\Omega$ at the lowest frequency, and is expected to improve significantly as the film quality is optimized.

The rf surface resistance is a key property of the oxide superconductors that can provide information about the mechanisms of superconductivity as well as determine their usefulness for applications such as high-speed interconnections and wideband analog signal processing.[1] To date, measurements have been performed on bulk La-Sr-Cu-O (Ref. 2) and Y-Ba-Cu-O (Refs. 2–4) as well as La-Ba-Cu-O (Ref. 5) by placing the samples in appropriate cavities. Such measurements have focused on examining the normalized surface impedance as a function of temperature in order to evaluate the applicability of BCS theory. There is difficulty, however, in obtaining absolute values for the rf surface resistance, especially as a function of frequency, to enable a detailed assessment of the material. Furthermore, many practical applications demand thin films, which may behave differently from the bulk materials.

We present the first, to our knowledge, quantitative rf loss measurments on thin films of the new oxide superconductors. A superconducting stripline resonator technique is utilized to obtain quantitative data on thin films of high-T_c $YBa_2Cu_3O_x$.

The thin films were made[6] by electron-beam evaporating multilayers (individual layer thickness equal to 20–80 nm) of the constituent metals onto $25\times12.5\times0.63$ mm^3 yttria-stabilized zirconia (YSZ) substrates. The high-T_c phase was formed by annealing the films in oxygen at 850 °C. Typically, the midpoint of the superconducting transition, measured resistively, was 83 K with the onset at 94 K and zero resistance around 70 K. X-ray-diffraction patterns indicate that the 1-μm-thick randomly oriented polycrystalline films consist mostly of the desired high-T_c phase. In addition, the films are generally very smooth, have residual resistivities of 600 $\mu\Omega$ cm just above the transition, and critical current densities of 7×10^3 A/cm^2 at 4.2 K. Auger profile analysis reveals that while films are compositionally uniform in the direction perpendicular to the plane of the film, there is some interdiffusion at the substrate-film interface.

The rf losses are measured using a stripline resonator technique that has previously been applied to Nb, NbN, and Nb_3Sn superconductors.[7,8] The superconductive stripline structure is obtained by depositing the superconductors on three separate substrates and then mechanically clamping the substrates together [see Fig. 1(a)]. For this measurement, thin-film Nb is used for both the top ground plane and the center conductor, while the Y-Ba-Cu-O thin film is used only for the bottom ground plane. The Nb is deposited on low-loss[7] (loss tangent $\tan\delta\leq10^{-6}$) 0.41-mm-thick sapphire substrates. Note that dielectric losses in the YSZ substrate, suspected to be substantial,[9] do not come into play since the YSZ substrate lies outside the stripline structure. The 300-nm-thick Nb center conductor is patterned as shown in Fig. 1(b). Gaps (300 μm) are etched in the line to capacitively isolate the resonator section of the center conductor from both the input and output. A sine wave is applied at the input and the output is synchronously monitored using a spectrum analyzer. Resonances are observed at frequencies for which the line length is an integer multiple of half the wavelength, or $l=n\lambda/2$. In our experiments, the 50-Ω Nb stripline (center conductor width $w=150$ μm) has a length $l=8.36$ cm leading to a first resonance around 0.6 GHz. The quality factor Q is obtained by measuring the half-power points at each resonance.

In each experiment, a measurement was first made on an all-Nb resonator containing two Nb ground planes and one Nb center conductor. Next, the bottom Nb ground plane was removed, replaced with a Y-Ba-Cu-O ground

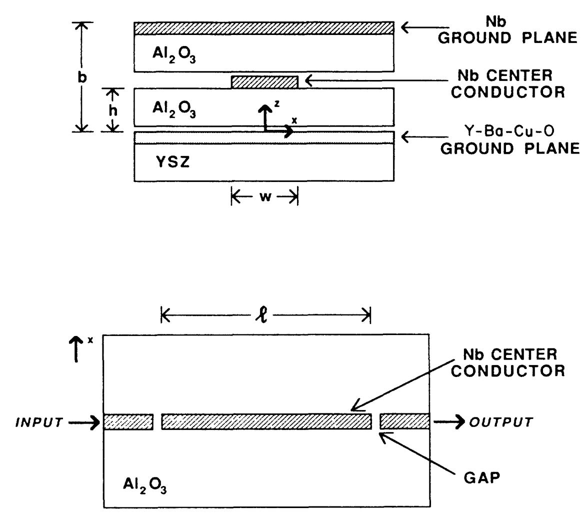

FIG. 1. (a) Cross-sectional view of stripline resonator. (b) Top view of center conductor. Actual Nb center conductor is in meander-line pattern to provide longer length.

plane, and the measurement repeated. Substantial effort was expended in minimizing exposure of the Y-Ba-Cu-O film to air moisture. Lastly, the bottom Nb ground plane was replaced in the package and the original measurement was rerun to verify that the stripline geometry had not changed throughout the measurements.

The measured quality factor Q can be expressed as

$$Q^{-1}=Q_c^{-1}+Q_d^{-1}+Q_L^{-1}, \tag{1}$$

where Q_c is the quality factor associated with losses in the conductors, Q_d is the quality factor associated with losses in the dielectric, and Q_L is associated with the loading of the resonator by the external measurement circuit. The resonator is weakly coupled to the external circuit by means of the gaps in the center conductor; consequently, $Q_L \gg Q$ and can be ignored. Also, the dielectric losses in our sapphire substrates have been previously measured[7] to be much smaller than the Nb conductor losses in the frequency range of interest, yielding $Q_d \gg Q_c$. Essentially, the losses are then entirely due to the conductors, so we have $Q \approx Q_c$.

The surface resistance of the Y-Ba-Cu-O ground plane can be obtained from the measured Q by noting for a transmission line resonator[10]

$$Q=\pi f/\alpha_c v_p, \tag{2}$$

where α_c (Np/m) is the attenuation constant for the line, v_p is the phase velocity, and f is the resonant frequency. The stripline geometry used is essentially a TEM structure and so $v_p = c/\epsilon_r^{1/2}$ where ϵ_r is the relative dielectric constant of the substrate. For an anisotropic medium such as sapphire, ϵ_r is taken as a weighted average over the different directions.

Relating the attenuation constant of a superconducting stripline to the surface resistance of the superconductors requires a detailed knowledge of the distribution of currents in the central conductor and in the ground planes. To date, the problem has not been solved in closed form. We proceed by observing that in all of our measurements, the quality factors measured for the resonators containing a Y-Ba-Cu-O ground plane were significantly smaller than those obtained with an all-Nb stripline. To a good first approximation, we can then consider all the losses associated with the measured Q as stemming from the power dissipated in the Y-Ba-Cu-O. Now, we need only to know the current distribution, $J_g(x)$, in the ground plane. The surface resistance, R_s, is related to the attenuation constant by[11]

$$\alpha_c=\frac{1}{2Z_0}\int_{-\infty}^{+\infty}\frac{R_s\,|J_g(x)|^2}{I^2}\,dx, \tag{3}$$

where the integral reflects the power loss in the ground plane per unit length in the direction of the power transmission. Here, Z_0 is the characteristic impedance of the line, I is the total current, and the geometry is as shown in Fig. 1(a). The current distribution, $J_g(x)$, can be calculated numerically using an image method.[12] Alternatively, Eq. (3) can be more simply evaluated using an incremental inductance method first suggested by Wheeler.[13] In our case, the two methods produce solutions that agree to within 1%. The second method is described here.

To calculate $J_g(x)$ we assume perfect conductors, a valid assumption since the losses are small. Equating the magnetic field energy, $(\mu_0/2)\int|H|^2dV$, with the energy defined in terms of the inductance, $\frac{1}{2}LI^2$, and noticing that H next to the ground plane is parallel to the surface and equal to the current density per unit length in the ground plane, $J_g(x)$, we find

$$I^2(\partial L/\partial h)=\mu_0\int_{-\infty}^{+\infty}|J_g(x)|^2dx, \tag{4}$$

where $\partial L/\partial h$ is the partial derivative of the line inductance with respect to a shift in the ground plane. Substituting Eq. (4) into Eq. (3) and noting that for a TEM propagating wave $Z_0=v_pL$,

$$\alpha_c=\frac{\sqrt{\epsilon_r\epsilon_0}}{2\sqrt{\mu_0}Z_0}\frac{\partial Z_0}{\partial h}R_s. \tag{5}$$

This can be evaluated using any one of many approximations for Z_0. We used the expression given by Wheeler,[14] substituting $b=818\ \mu$m, $w=150\ \mu$m, $t=0.3\ \mu$m, and $\epsilon_r=10.1$ to obtain

$$\alpha_c=(1.92\ \Omega^{-1}\text{m}^{-1})R_s. \tag{6}$$

Now that an approximate expression has been found between α_c and R_s, the surface resistance of the Y-Ba-Cu-O ground plane may be related to the measured Q of the resonator by combining Eq. (2) and Eq. (6) to yield

$$R_s=(17.3\ \Omega/\text{GHz})f/Q, \tag{7}$$

where f is in GHz. Note that Eq. (7) is generally applicable to any material used for the bottom ground plane provided that its losses are "small," yet dominate the losses due to the Nb.

The corresponding expression for the surface resistance of our all-Nb resonator is

$$R_s=(0.47\ \Omega/\text{GHz})f/Q. \tag{8}$$

The substantial difference of the prefactor in Eq. (8) from that of Eq. (7) stems from the fact that the losses in the all-Nb resonator are dominated by the losses in the 150-μm-wide center conductor, as opposed to the 1.27-cm-wide ground plane for the Y-Ba-Cu-O case. Note again that the calculation does not take into account the superconducting penetration depth. This assumes greater importance for the center conductor and consequently limits the accuracy of Eq. (8).

Two different Y-Ba-Cu-O films and a gold film, as well as the all-Nb structure, were measured at 4.2 K. The two Y-Ba-Cu-O films differ in their transition temperature. Film No. 1 has a onset of 95 K, a midpoint of 84 K, and zero resistance at 72 K, while film No. 2 has an onset of 94 K, a midpoint of 78 K, and zero resistance at 63 K. The rf magnetron sputter-deposited Nb films have a T_c of 9.1 K, and the 10-μm-thick electron-beam-deposited gold film has a room-temperature resistivity of 2.3 $\mu\Omega$ cm and a resistivity ratio of $R(298\text{ K})/R(4.2\text{ K})>100$.

The input power to the Y-Ba-Cu-O structure was -8 dBm and the insertion loss at resonance ranged around 35 dB. For the gold measurements the input power was -3 dBm and the insertion loss about 50 dB. The capacitive gaps in the Nb center conductor were chosen to optimize the weak coupling for the Y-Ba-Cu-O measurement. Note that the lower loss of the Nb ground plane in the all-Nb resonator then causes this resonator to be too tightly coupled to input and output. As seen from Eq. (1), this produces an artificially low Q for the conductor losses. The values of the surface resistance for the all-Nb resonator have been corrected for this over coupling, and are in excellent agreement with all-Nb resonators measured previously.[15] Finally, data could not be obtained at all frequencies because the resonances are easily obscured (due to the weak-coupling design) by the presence of electrical feedthrough or undesired modes in the resonator package.

The surface resistance for each ground plane is plotted as a function of frequency in Fig. 2. Clearly, the surface resistance of the Y-Ba-Cu-O films substantially exceeds that for Nb. Below 2 GHz, however, the Y-Ba-Cu-O surface resistance is lower than that for the Au. For Y-Ba-Cu-O No. 1, the frequency dependence of the surface resistance yields $R_s \propto f^{1.9}$, while for Y-Ba-Cu-O No. 2 $R_s \propto f^{1.8}$. The all-Nb resonator data give $R_s \propto f^{2.2}$. For a superconductor, the surface resistance is expected to vary approximately as the square of the frequency.[16] Consequently, the Y-Ba-Cu-O resonator data confirm that we are indeed measuring the rf losses in a superconductor.

The measurement on gold confirms the accuracy of extracting the surface resistance from the Q with Eq. (7). The solid line for the gold in Fig. 2 is that predicted[17] by the theory with no adjustable parameters. For gold, in the clean limit, we would expect $R_s \propto f^{2/3}$. The measured data agree with the theory as $R_s \propto f^{0.67}$.

Note that the Y-Ba-Cu-O film with the higher T_c (No. 1) has lower surface resistance as would be expected. Yet better films should have significantly lower rf losses. The substantial difference between the Nb surface resistance and the Y-Ba-Cu-O surface resistance indicates that our Y-Ba-Cu-O films are presently limited by residual losses. Given the polycrystalline nature of these films it seems quite possible that their rf losses are dominated by the presence of lower T_c (or even nonsuperconducting) material in the grain boundaries. Presumably, Y-Ba-Cu-O No. 1 then has better material in the grain boundaries than Y-Ba-Cu-O No. 2.

In Fig. 3, the surface resistance is plotted as a function of temperature for the two Y-Ba-Cu-O films at the frequencies shown. The temperature range is quite limited due to the T_c of the Nb. The data show only a weak dependence on temperature, supporting the contention that the surface resistance is limited by residual losses. The rapid rise near 8 K for Y-Ba-Cu-O No. 2 stems from the losses in the Nb that dominate as the Nb approaches its transition temperature. Measurements across the full temperature range of the Y-Ba-Cu-O would require a resonator structure in which all the conductors are Y-Ba-Cu-O thin films. Such measurements await the deposition of Y-Ba-Cu-O films on low-dielectric-loss substrates, so that the substrate losses do not dominate the conductor losses. The measurements also require Y-Ba-Cu-O films with substantial critical current densities, since the current density[18] in the center conductor (in our geometry) typically exceeds 10^6 A/cm^2 for Q values above 10^5.

In summary, we have used a stripline resonator technique to quantitatively measure the surface resistance of Y-Ba-Cu-O thin films. The measurements at 4.2 K yield a frequency dependence, over a wide frequency range, very close to that expected for a superconductor. The values of the surface resistance are comparable to those

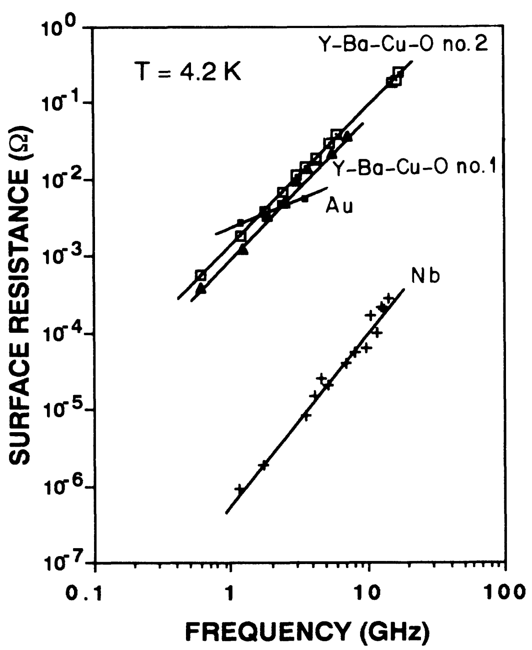

FIG. 2. Surface resistance as a function of frequency, at 4.2 K, for two different Y-Ba-Cu-O thin films, a Au film, and a Nb film. The T_c (midpoint) for Y-Ba-Cu-O No. 1 is 84 K and for Y-Ba-Cu-O No. 2 is 78 K. The solid lines through the Y-Ba-Cu-O and the Nb data represent best fits. The solid line for the gold is theoretical.

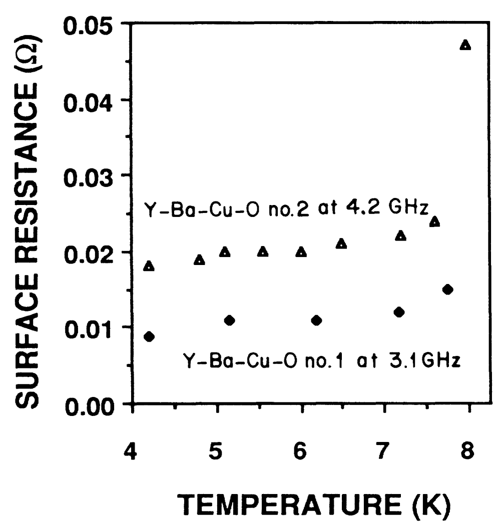

FIG. 3. Surface resistance as a function of temperature for the two Y-Ba-Cu-O thin films shown in Fig. 2. Note that the two films were measured at different frequencies.

for gold films although still substantially higher than those for Nb films. The Y-Ba-Cu-O films have also been measured over a narrow temperature range from 4 to 8 K. The weak temperature dependence of the surface resistance confirms that we are indeed measuring the rf losses in the Y-Ba-Cu-O, which are dominated by residual losses. We believe these losses stem from the presence of undesired material in the grain boundaries of the films, and, consequently, the losses for single-crystal films should be considerably lower.

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[18]The stripline resonator measurements can be used to set a lower bound on the critical current density in the center conductor. For our geometry, the current density in the center conductor is given by $J = 2\times10^5(QP/n)^{1/2}$ A/cm^2, where n is the harmonic number and P is the input power in watts. The critical current density is obtained by increasing the input power until the resonance breaks down. This only sets a lower bound as other factors can disturb the resonance before the actual critical current density is reached. Note that electrical contact does not need to be made to the center conductor, which simplifies the examination of large current densities.

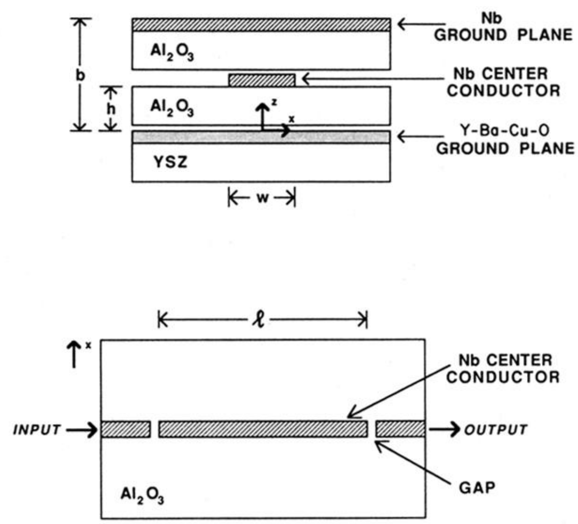

FIG. 1. (a) Cross-sectional view of stripline resonator. (b) Top view of center conductor. Actual Nb center conductor is in meander-line pattern to provide longer length.