



## Microwave Electrodynamics of the Antiferromagnetic Superconductor $\text{GdBa}_2\text{Cu}_3\text{O}_{7-\delta}$ .

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The temperature dependence of the microwave surface impedance and conductivity are used to study the pairing symmetry and properties of cuprate superconductors. However, the superconducting properties can be hidden by the effects of paramagnetism and antiferromagnetic long-range order in the cuprates. To address this issue we have investigated the microwave electrodynamics of  $\text{GdBa}_2\text{Cu}_3\text{O}_{7-\delta}$ , a rare-earth cuprate superconductor which shows long-range ordered antiferromagnetism below  $T_N=2.2$  K, the Neel temperature of the Gd ion subsystem. We measured the temperature dependence of the surface resistance and surface reactance of *c*-axis oriented epitaxial thin films at 10.4, 14.7 and 17.9 GHz with the parallel plate resonator technique down to 1.4 K. Both the resistance and the reactance data show an unusual upturn at low temperature and the resistance presents a strong peak around  $T_N$  mainly due to change in magnetic permeability.

The analysis of the temperature dependence of the microwave surface impedance and conductivity is one of the acclaimed methods used to extract information on the pairing symmetry and properties of high temperature cuprate superconductors. However things get more complicated when the material also develops magnetic correlations, due to the localized moments of the rare-earth elements (RE). The effects of paramagnetism and antiferromagnetic long range order may hide the behavior of the superconducting screening length, influencing conclusions about the pairing symmetry, as has been suggested for the electron-doped  $\text{Nd}_{2-x}\text{Ce}_x\text{CuO}_4$  [1].

To address this issue we have focused on the electrodynamic properties of  $\text{GdBa}_2\text{Cu}_3\text{O}_{7-\delta}$  (GBCO), where the  $\text{Gd}^{3+}$  ions carry magnetic moments which align parallel to the *c*-axis and order antiferromagnetically below  $T_N \simeq 2.2$  K in the three crystallographic directions [2].

The samples we have investigated are pairs of identical *c*-axis oriented GBCO epitaxial films, laser ablated on (100)-cut  $\text{LaAlO}_3$  single crystal substrates. The film thickness is 300 nm, the su-

perconducting critical temperature measured by AC susceptibility is 92.5 K and the transition width is 0.3 K.

We measured the effective (due to the finite film thickness) surface impedance  $Z_{Seff}(T, \omega) = R_{Seff}(T, \omega) + iX_{Seff}(T, \omega) = \sqrt{i\omega\mu(T, \omega)/\sigma(T)} \coth \left[ t\sqrt{i\omega\mu(T, \omega)\sigma(T)} \right]$  [3] of the GBCO thin films from 1.4 K to  $T_c$  with the parallel plate resonator (PPR) technique [4,5] at three different resonance frequencies with rf magnetic field in the *ab* plane. Here the first factor on the right hand side is the bulk surface impedance  $Z_S$  and the second factor is the finite thickness correction (*t* is the film thickness), and  $\mu$  and  $\sigma$  are respectively the complex magnetic permeability and complex conductivity. The PPR resonance frequency  $f(T)$  and quality factor  $Q(T)$  data are first converted to changes in surface reactance and surface resistance [5] and then to absolute values using  $X_{Seff}(77K) = 49$  m $\Omega$  and  $R_{Seff}(77K) = 0.48$  m $\Omega$  measured at 10 GHz by the variable spacing parallel plate resonator technique [6].

In Fig. 1 we show  $R_{Seff}(T)$  and  $X_{Seff}(T)$  at 10.4 GHz over the entire measurement temperature range. The high temperature behavior is consistent with a *d*-wave temperature dependence

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for the surface impedance [6]. The deviations from this behavior start below 30 K, where the magnetic effects due to  $\mu(T)$  come into play [7]. Both  $R_{Seff}(T)$  and  $X_{Seff}(T)$  show a minimum at two different temperatures,  $T \approx 25$  K and  $\approx 7$  K, respectively. Then  $R_{Seff}(T)$  and  $X_{Seff}(T)$  increase upon reducing the temperature, and a strong peak is observed in  $R_{Seff}(T)$ .

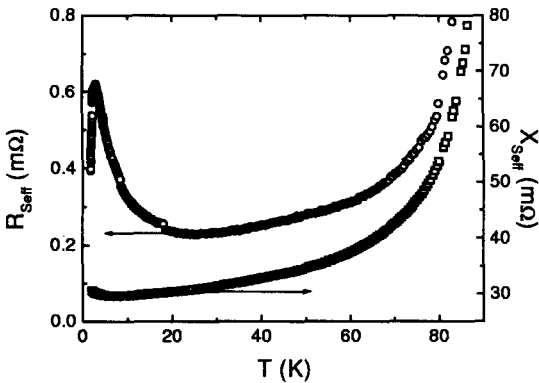


Figure 1. Effective surface resistance  $R_{Seff}(T)$  and reactance  $X_{Seff}(T)$  of GBCO at 10.4 GHz.

The same behavior is found at the other two frequencies with some extra frequency dependence other than the trivial  $X_S \sim \omega$  and  $R_S \sim \omega^2$  observed for superconductors. This is clearly seen in Fig. 2, where we show the data at the three frequencies as modified complex conductivity  $\sigma_m(T, \omega)$ , defined through  $Z_S(T, \omega) = \sqrt{i\omega\mu_0/\sigma_m(T, \omega)}$ . The real part,  $\sigma_{1m} = 2R_S\omega\mu_0/X_S^3$ , presents frequency dependent peaks around  $T_N$ . In the inset to Fig. 2 we show a rescaled imaginary part  $\lambda_m^{-2} = \sigma_{2m}\omega\mu_0 = (\omega\mu_0/X_S)^2$ , where the frequency dependence is less pronounced.

In conclusion strong unusual features are observed in the temperature dependence of surface impedance and conductivity for GBCO. The effects of paramagnetism and antiferromagnetism are shown to have a significant influence on  $\lambda(T)$  and  $R_S(T)$ .

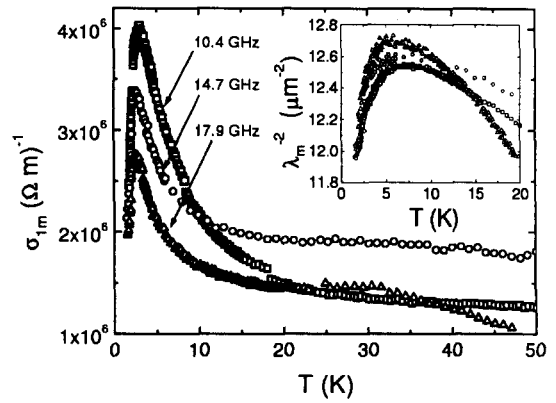


Figure 2. Real part of the modified conductivity  $\sigma_{1m}$  at different frequencies. Inset shows the rescaled imaginary part  $\lambda_m^{-2}$  (same symbols as for the real part).

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