The electrodynamics of oxide superconductors

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ABSTRACT

We present a brief review of results on the surface impedance of cuprate superconductors, focusing mainly on $YBa_2Cu_3O_{7-\delta}$ (YBCO) and evidence of d-wave superconductivity in that material. We then discuss our recent results on Ba-K-Bi-O thin films, and the effects of DC electric fields on the surface impedance of YBCO films. A summary of our data on high quality thin films and single crystals of the electron-doped $Nd_{1.85}Ce_{0.15}CuO_{4-\delta}$ (NCCO) cuprate superconductor follows. Surprisingly, the measurements on NCCO are consistent with the behavior of an s-wave BCS superconductor, in striking contrast to recent results on YBCO. Finally we discuss some of the interesting potential implications of d-wave superconductivity for microwave applications of the cuprates.

1. INTRODUCTION

Our goal is to understand the nature and origins of superconductivity in the oxide materials, and to determine the optimum conditions for using these materials in high frequency applications. Historically, a great deal has been learned about conventional superconductors by examining their high-frequency electrodynamic properties. It is natural, therefore, to approach the problem of high-temperature superconductivity by probing these materials with time varying electromagnetic fields and carefully studying the response of the superconductor to these external perturbations.

The surface impedance of a conductor is a measure of its response to an electromagnetic field. For a sufficiently thick material at low enough frequencies, the response of a conductor to a plane-wave electromagnetic signal can be characterized in terms of the ratio of electric and magnetic fields parallel to the surface, evaluated at the surface: $Z_s = E_{||}(0)/H_{||}(0)$.[1] The surface impedance is usually thought of in terms of its real (lossy) and imaginary (inductive reactive) components; $Z_s(T,\omega) = R_s(T, \omega) + i X_s(T, \omega)$, where for a sufficiently thick superconductor, the surface reactance, $X_s(T, \omega) = \mu_0 \omega \lambda(T)$, and $\lambda(T)$ is the magnetic penetration depth. Physically, in a sufficiently pure superconductor, the surface resistance, R_s, is sensitive to absorption of radiation by quasiparticles and by Cooper pairs bound by an energy less than $h\omega/2\pi$; and X_s is sensitive to the inductive reactance of the condensed Cooper pairs.

Our intention here is to give an overview of the electrodynamic properties of several oxide superconductors. We begin with a brief historical review of measurements on the cuprate oxide superconductors. We next consider Ba-K-Bi-O, a low-T_c oxide superconductor which is potentially important for thin film applications involving tunneling or low surface resistance. We shall also present some of our results on how DC electric fields can be used to actively control the surface impedance of $YBa_2Cu_3O_{7-\delta}$ in the superconducting state. We shall then review our measurements on the low-T_c electron-doped cuprate superconductor Nd-Ce-Cu-O and discuss the contrasts between this material and YBCO. Finally, we present a brief discussion of the potential ramifications of d-wave superconductivity for microwave applications of the cuprates.

2. SUMMARY OF PAST WORK ON HOLE-DOPED CUPRATES

Among the many oxide superconductors now known, the $YBa_2Cu_3O_{7-\delta}$ (YBCO) and $Bi_2Sr_2CaCu_2O_8$ (Bi2212) materials have been the most extensively studied because of the abundance of high quality thin films and single crystals. Both of these materials are hole-doped cuprates with closely spaced pairs of Cu-O planes in the crystal structure, and relatively short in-plane coherence lengths, $\xi_{ab} \sim$ 10-15 Å for YBCO and $\xi_{ab} \sim$ 8-10 Å for Bi2212. However, because of the unusual structural and physical properties of these materials, there has been a long evolution in our understanding of their electrodynamic properties.

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2.1. Early measurements

The early measurements of the surface impedance of c-axis YBCO films were characterized by high residual losses and strong polynomial temperature dependencies of R_s and λ.[2-4] The surface resistance and penetration depth were seen to drop rapidly below T_c, as expected of a BCS s-wave superconductor. However, this behavior changed markedly at approximately 80% of T_c, below which $\delta R_s(T)$, $\delta\lambda(T) \sim T$ or T^2 typically. Residual losses at 4.2K and scaled to 10 GHz were in the range of approximately 100 mΩ[3,5] in the best c-axis YBCO films. A number of groups found that these measurements were highly sensitive to the microstructure of the materials studied,[6,7] with a clear progression of improvement from ceramic, to polycrystalline film, to oriented film, to single crystal samples. However, all measurements were characterized by high residual losses for $T < 0.8\ T_c$ (compared to the expectations of s-wave BCS theory). Early measurements of the penetration depth in YBCO crystals were found to be largely consistent with s-wave BCS theory.[8]

2.2. Later measurements

With time, more systematic studies of the microstructure dependence of the surface impedance were performed. Laderman, *et al.*, correlated residual losses with DC transport properties and the density of high-angle grain boundaries in c-axis YBCO thin films on MgO substrates.[9] The highest quality thin films, as determined from DC properties and high-angle grain boundary density, to this day have some of the lowest residual resistances observed in YBCO, R_s(4.2K, 10 GHz) ~ 15 $\mu\Omega$, but still retain the polynomial temperature dependencies $\delta R_s(T) \sim T$, $\delta\lambda(T) \sim T^2$, for $T < 0.8\ T_c$. Residual inductivity was also found to scale with the DC properties of the films.[10,11] Quantitative fits to the temperature and frequency dependence of the residual surface impedance of YBCO c-axis films was obtained based upon the weakly-coupled grain model.[9,12,13]

2.3. Recent measurements

Recently, detailed measurements on YBCO films have found that $\delta\lambda(T) \sim T^2$, while $\delta R_s(T) \sim T$, with $\lambda(T)$ going into a flatter temperature dependence below approximately 10K.[14] Similar results are obtained for $\lambda(T)$ on Bi2212 crystals.[14] Measurements on YBCO crystals grown at the University of British Columbia show a very sharp drop in R_s below T_c, as well as a striking $\delta R_s(T) \sim T$ and $\delta\lambda\ (T) \sim T$ behavior at low temperatures.[15-16] It is also found that untwinned crystals which show a linear-in-T dependence of the penetration depth also have residual surface resistances as low as roughly 12 to 40 $\mu\Omega$ at 10 GHz[17] (when scaled by ω^2 from 4 GHz and 30 GHz), comparable to thin films of YBCO (mentioned above) at the same temperature and frequency. These results on YBCO crystals are explained in terms of a rapidly decreasing quasiparticle scattering rate below T_c, and a strong linear-in-T dependence of the normal fluid density at low temperatures in the crystals. These results have been qualitatively confirmed with YBCO crystals grown and measured at the University of Maryland.[18]

The differences in $\lambda(T)$ temperature dependencies and in residual resistance, between YBCO crystals and films, have been attributed to the greater quenched disorder in the films. The disorder in thin films limits the decrease in the scattering rate below T_c, resulting in a decrease in the residual resistance.[15,19] Experiments in which Zn was doped into YBCO crystals shows that the residual resistance decreased with increasing Zn content up to at least 0.3% Zn.[19] It was concluded that some defects are required in YBCO to achieve the lowest possible surface resistance, quite contrary to the traditional thinking with low-T_c superconductors.

The most recent results on YBCO have been interpreted in terms of a $d_{x^2-y^2}$ pairing state symmetry for the superconducting ground state. However, no single surface impedance measurement has conclusively demonstrated, beyond any reasonable doubt, the intrinsic pairing state symmetry of the cuprate superconductors. A resolution of this question will only come after all extrinsic effects are understood, and a body of evidence of reproducible measurements on a variety of cuprates is obtained.

3. SURFACE IMPEDANCE OF $Ba_{1-x}K_xBiO_3$

The Ba-K-Bi-O (BKBO) material is an isotropic oxide superconductor without copper-oxygen planes. It is of interest in applications because of its cubic structure, isotropic superconducting properties, and modest T_c ~ 32K in bulk form. Thin films of BKBO have been grown by a number of techniques, and all have lower T_c's than the bulk, ranging up to $T_c \sim 26$ K. We have studied the surface impedance of BKBO films made by a molecular beam epitaxy method, and find behavior largely consistent with isotropic s-wave BCS theory.[20]

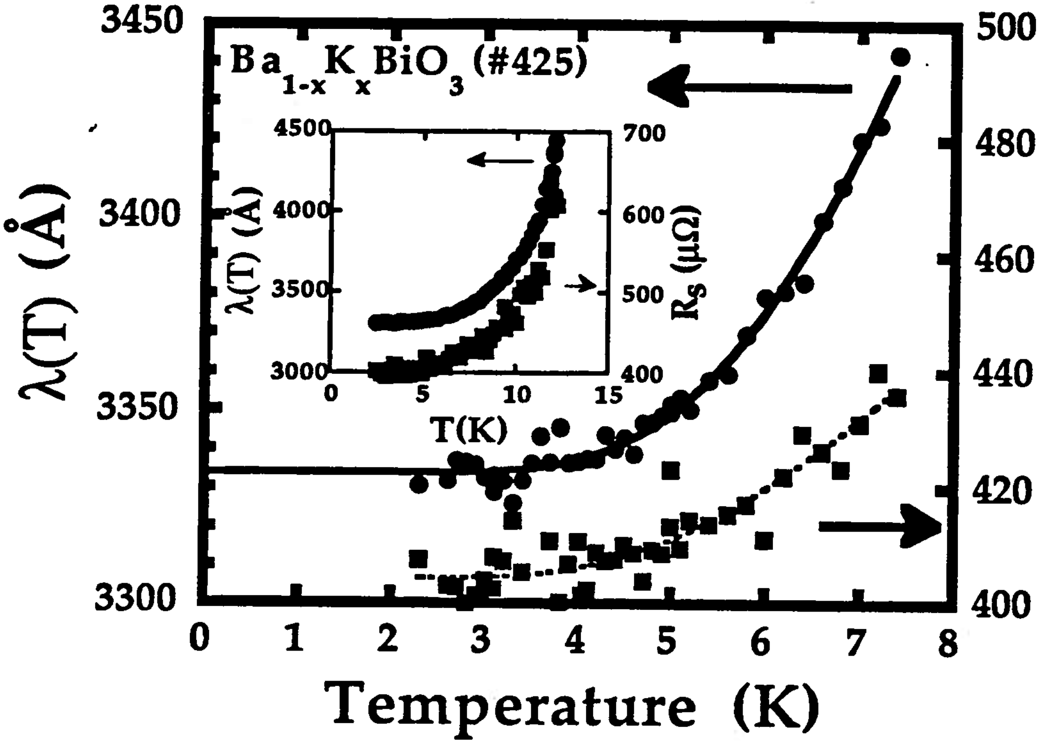

Figure 1. Surface resistance and magnetic penetration depth of 3600Å-thick $Ba_{1-x}K_xBiO_3$ (x ~ .49) thin films on MgO (100) substrates, measured at 6.46 GHz using a 25 μm dielectric spacer in a parallel plate resonator.[20] Solid and dashed lines are s-wave BCS fits. The inset shows data over the entire measurement range. The surface resistance has been corrected for finite film thickness.

The surface impedance is measured using a parallel plate resonator technique.[21] Two congruent superconducting thin films are brought face-to-face with a Teflon dielectric film in between, forming a two-dimensional microwave resonator. The quality factor Q of each resonance is inversely proportional to the surface resistance of the films, while the resonant frequency shift with temperature is related to the change in magnetic penetration depth of the films. It is found that the surface resistance and magnetic penetration depth in BKBO are both activated over a large gap at low temperatures, $2\Delta(0)/k_BT_c = 3.8 \pm 0.5$ (see Figure 1). The zero temperature penetration depth was found to be $\lambda(0) = 3300 \pm 200$ Å in the films. One of the main drawbacks of this material at present are the rather large residual losses, $R_s(0) \sim 400$ μΩ at 6.46 GHz, substantially higher than that obtained with NbN or YBCO, but still better than copper at the same temperature and frequency.[5] However, one should note that this situation is very similar to that of NbN early in its development. The surface resistance of NbN was at first also quite high, comparable to the present results on BKBO.[20] The losses in NbN are now less than 6 μΩ at 10 GHz, 4.2K, making them very attractive for low-T_c microwave devices.[20] Because of its apparent s-wave nature, we have every reason to believe that further improvements in the preparation of BKBO films will eventually result in excellent microwave loss properties, as well as applications in Josephson junction circuitry.

4. ELECTRIC FIELD EFFECT ON THE SURFACE IMPEDANCE OF THIN $YBa_2Cu_3O_{7-\delta}$ FILMS

All of the cuprate superconductors have physical properties which depend strongly on the carrier doping of the copper-oxygen planes. Most studies of these doping effects involve chemical substitution or variation of the oxygen content of the material. Several groups have discovered that essentially equivalent studies can be performed at fixed chemical stoichiometry by making a thin superconducting film as one plate of a high dielectric constant capacitor. By applying a potential difference between a counter electrode and the superconductor, excess charge (of either sign) can be induced in the superconductor. This excess charge is screened out from the bulk on the length scale of the Thomas-Fermi screening length, thought to be about 5 - 10Å in the cuprates. Hence, if a thin film of YBCO can be used as a capacitor plate, one can achieve significant fractional changes in the carrier concentration, $\delta n/n$, where n is the carrier density in the copper-oxygen planes. Recent advances in the deposition of high dielectric strength $SrTiO_3$ (STO) has made it possible to produce very large modulation of surface charge densities. Potential applications of this technology include active microwave devices such as switches, variable attenuators, and variable delay transmission lines.

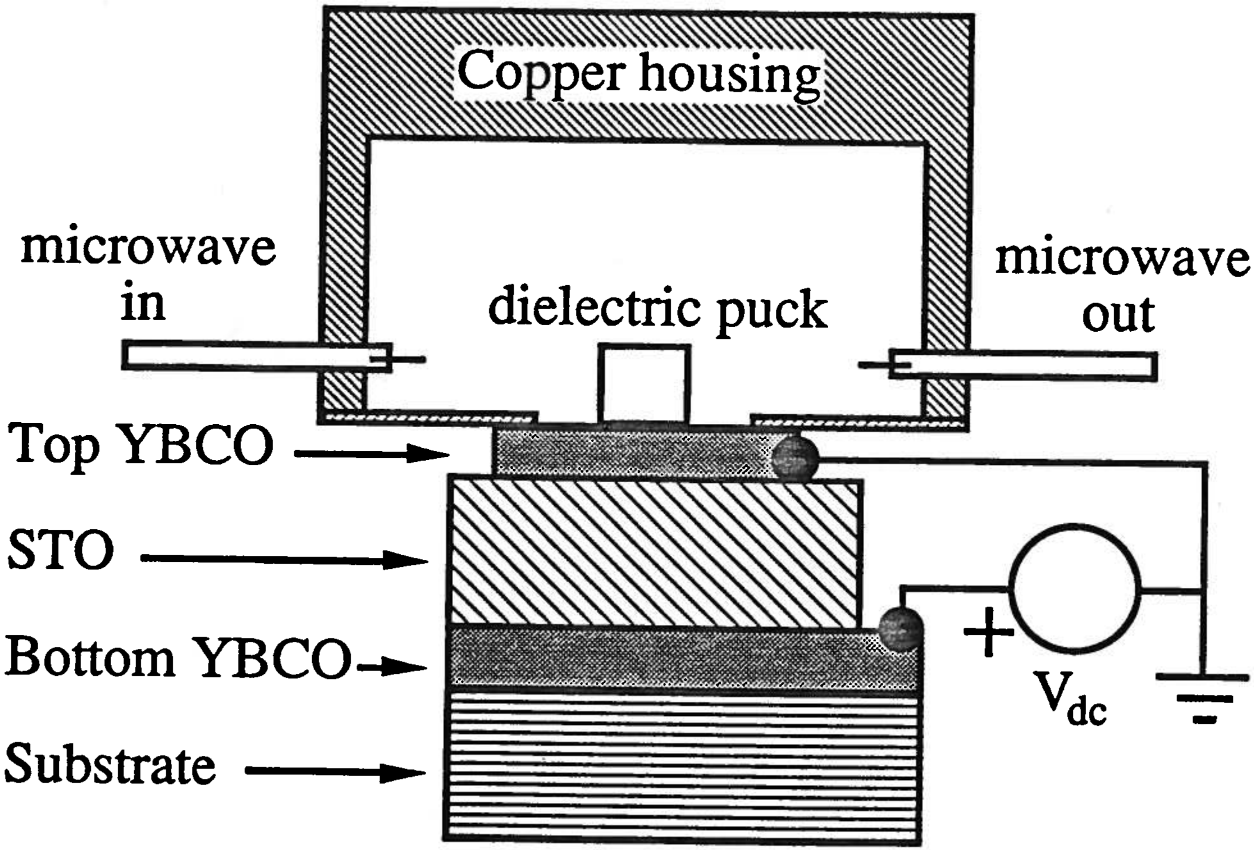

Figure 2. Schematic of the microwave measurement setup (<u>not drawn to scale</u>). The microwave surface impedance of the trilayer is modulated by the gate voltage V_{DC} applied between the top and bottom YBCO layers.

We have investigated the effects of varying the carrier density on the surface impedance of a YBCO film at fixed chemical composition.[22] A trilayer heterostructure of YBCO/STO/YBCO is deposited, and separate contacts are made to the two YBCO layers. Figure 2 shows the experimental setup for the active microwave measurements. A sapphire puck (4.5 mm diameter, 2.2 mm high) is placed on top of the trilayer, forming a loaded dielectric microwave resonator as the end-wall for a cylindrical copper housing. The dielectric resonator is excited in the $TEM_{01\delta}$ mode at approximately 24.7 GHz. The quality factor of the resonance is inversely proportional to the losses in the trilayer, and the frequency shift is proportional to the change in surface reactance of the trilayer. A DC voltage is applied between the two superconducting films *in situ*, during the microwave measurement. This voltage induces excess charge on the plates, and the effect of this charging on the surface impedance can be deduced from the change in Q and resonant frequency (see Figure 3).

As can be seen in Fig. 3, at T = 25 K and low bias, $|V_{DC}| < 10$ V, the response of the trilayer is dominated by the change in dielectric properties of the intermediate STO layer. At higher bias, the change in the surface impedance of the top YBCO film can be shown to dominate the response. It is found that when hole carriers are introduced into the 800 Å thick top film of YBCO (T_c = 84 K), the surface resistance at 24.7 GHz decreases by $\delta R_s/\delta V_{DC} = -0.25\ \mu\Omega/V$, and the surface reactance also decreases by $\delta X_s/\delta V_{DC} = -1.8\ \mu\Omega/V$.[22] A simple two-fluid analysis of these observations leads to the conclusion that essentially all of the holes introduced into the film by charging join the superfluid, with negligible fractional change in the population of the normal fluid.[22]

Although these effects are small, they demonstrate that the high frequency conductivity of the cuprates are directly dependent on the carrier concentration in the copper-oxygen planes. The data in Figure 3 show that the effects of adding holes to the cuprates. Unfortunately, because of the asymmetric breakdown properties of the STO dielectric layer, we cannot extensively explore the electron-doping direction beyond the low-bias regime in this device. Further work with electron-doping in other device structures will be published in the future.[23]

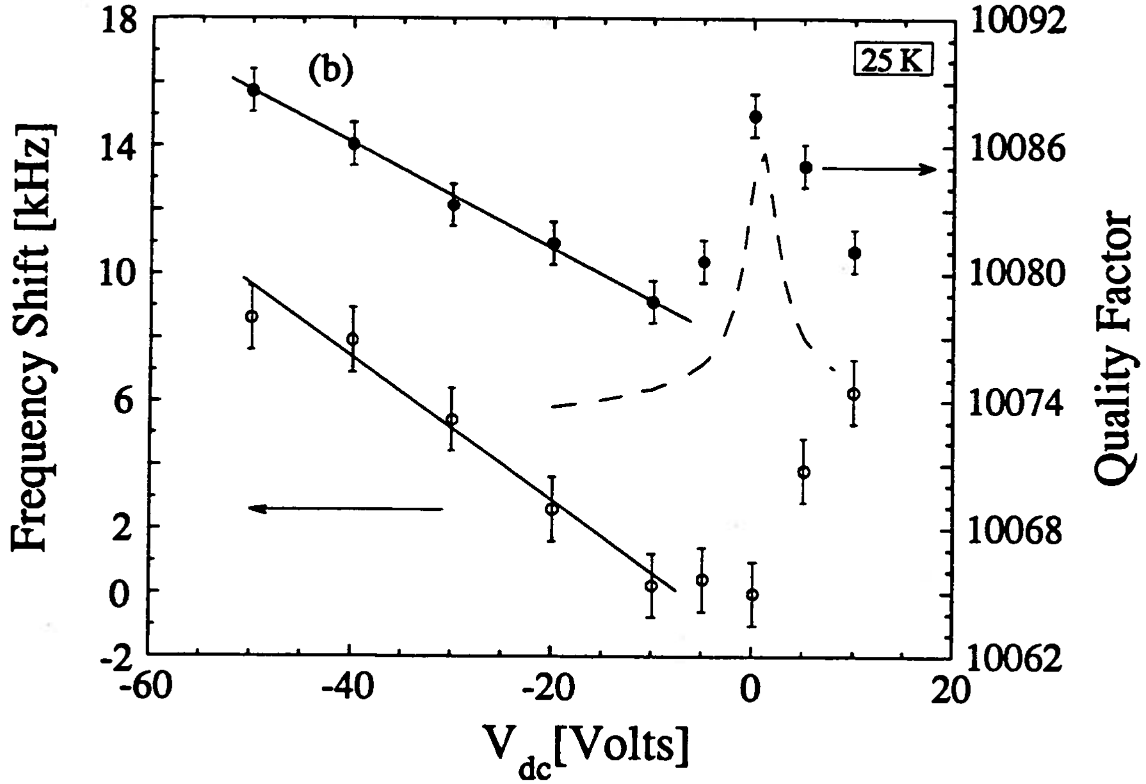

Figure 3. Microwave response of a YBCO/STO/YBCO trilayer (which loads a dielectric resonator) at 25 K and 24.7 GHz, as a function of DC bias voltage between the superconducting films. The dashed line represents the relative dielectric constant of the STO in arbitrary units, measured at 120 Hz. The solid lines are linear fits to the data used in the two fluid analysis of Reference 22.

5. SURFACE IMPEDANCE OF Nd-Ce-Cu-O

$Nd_{1.85}Ce_{0.15}CuO_{4-\delta}$ (NCCO) is a relatively simple cuprate from the standpoint of its crystal structure and superconducting properties. We have carefully studied this simpler material to complement the surface impedance data which has accumulated on the high-T_c hole-doped cuprates. Because the crystal structure of NCCO at the optimum doping for superconductivity is tetragonal, there is no twinning present in these samples. Also, since there are no other conducting layers besides the copper-oxygen planes, there is no significant interruption of the conduction paths, as is found for instance in twinned YBCO samples. NCCO has also a single copper-oxygen plane per unit cell, so there are no complications from inter-planar transitions, as well as fewer opportunities to introduce stacking faults when the material is grown from the vapor or liquid phase. Finally, since the in-plane coherence length is substantially larger in NCCO [$\xi_0 \sim 80$ Å] as compared to YBCO and Bi2212 [$\xi_0 \sim 10 - 15$ Å], one would expect this material to be much less susceptible to the effects of weakly-coupled grains on the electrodynamic properties. However, NCCO is known to be more anisotropic than YBCO, and has substantially lower critical current densities at the same reduced temperature.[24,25] Hence the effects of weakly coupled grains may still be present in the NCCO films. NCCO is simple, yet it retains the basic ingredients of cuprate superconductivity: the copper-oxygen plane, along with the antiferromagnetic insulating properties found at low-doping in the cuprates.

NCCO samples were prepared in both thin film and single crystal form. Thin films have been grown by pulsed laser deposition in an N_2O atmosphere. Substrates used include $LaAlO_3$ (LAO) (NCCO film thickness ~ 5000 Å) and Yttria-stabilized Zirconia (YSZ)-buffered sapphire substrates (NCCO film thickness ~ 2600 Å). Details of the film growth procedure and microstructure analysis are in the literature.[24,25] Single crystals were grown by the directional solidification technique, also documented extensively in the literature.[26] A great deal is known about the microstructure of our NCCO samples. First, there is no superlattice modulation observed in either the thin films or single crystals studied. The films grow in the T' phase with the c-axis normal to the buffered sapphire substrate. A low density of a-axis orientated grains were found in only the NCCO films on LAO by cross-sectional TEM.[27] X-ray phi-scans show no evidence of the 45° mis-oriented grains[28] which are so abundant, and correlated with high residual losses, in YBCO.[9] Also, x-ray rocking curve measurements show in-plane misorientation between grains to be less than 0.4°, also quite good compared to YBCO films.[28] RBS channeling yields on the films are as low as 11%, indicative of good quality, but not quite as good as the best YBCO films which show a 3% channeling yield. The high channeling yield is indicative of a greater density of point defects in NCCO films as compared to YBCO films. The only impurity phase identified in the films is $Nd_{0.5}Ce_{0.5}O_{1.75}$ (NCO) which is a nominally insulating material present at the 2% volume level, or below.[27] Note that all measurements on thin films were performed on as-prepared samples.

For single crystal samples of NCCO it was found that the as-grown samples showed multiple superconducting transitions. A procedure was developed to etch the crystals in HCl, and anneal them to homogenize the oxygen and cerium distributions. Upon several iterations of this procedure, the crystals showed very sharp single-phase superconducting transitions with T_c's slightly higher than those of the thin film samples.[29]

The microwave measurements were performed in a cylindrical superconducting Nb cavity with the sample perturbing the TE_{011} resonant mode. The sample was positioned in the center of the cavity on a sapphire hot-finger[30] which could be temperature controlled independently from the Nb cavity. The background temperature dependence of the sapphire and substrate dielectric constant and loss tangent do not significantly influence the data presented here.[29] The RF magnetic fields are parallel to the Cu-O planes of the sample producing shielding currents mainly in the Cu-O planes. Shielding from currents in the c-direction make a negligible contribution to the frequency shift and Q of the resonator.

6. RESULTS ON Nd-Ce-Cu-O

The residual surface resistance of NCCO crystals and NCCO films on LAO were found to be in the range of several milli-Ohms at 9.6 GHz, 2.2K.[29] This is typical of early samples of YBCO crystals and films. Recently we have examined NCCO films grown on YSZ-buffered sapphire substrates.[31,32] We found that the residual surface resistance at 9.6 GHz was reduced from the milli-Ohm range to below 100 $\mu\Omega$, making them comparable in loss to typical YBCO films and crystals at 4.2K.

Surprisingly, the temperature dependence of the magnetic penetration depth of these films and crystals shows very detailed agreement with the predictions of strong-coupled s-wave BCS theory. This is evident in Figure 4, where the change in penetration depth (proportional to the frequency shift of the resonant mode) with temperature is consistent with an activated behavior, the activation barrier being $2\Delta(0)/k_BT_c \sim 4.1$. Note that activated behavior over the same energy gap is consistent with both the penetration depth change (frequency shift) and increase in surface resistance (shift in 1/Q), as shown in Figure 5. We have also found that the activated behavior is essentially the same in both thin film and single crystal data.[29,31] To our knowledge, there is no other example of such consistency in the temperature dependence of the electrodynamic properties for both films and crystals. Note that this same value for the energy gap was identified by tunneling measurements in the same class of NCCO crystal samples.[33]

Examining our measurements at all temperatures, $2.2K < T < T_c$, we find that the data is also essentially consistent with the predictions of strong-coupled s-wave BCS theory.[34] Figures 4 and 5 show fits of the data for an NCCO thin film on YSZ-buffered sapphire to the s-wave BCS temperature dependence of the magnetic penetration depth and surface resistance. The procedure for choosing the parameters in the fits are guided by other experiments on these films and crystals, and are discussed in detail in references 29 and 31.

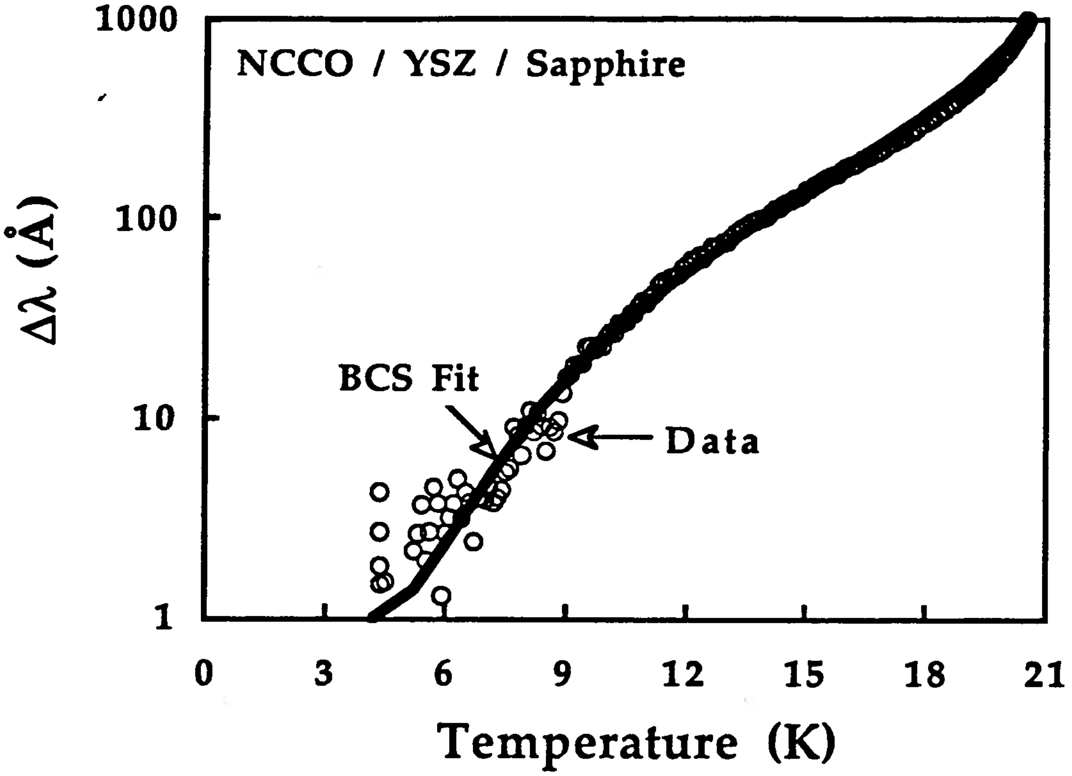

Figure 4. Change in penetration depth $\Delta\lambda(T)$ as a function of temperature at 9.6 GHz for an NCCO thin film on YSZ-buffered sapphire. The solid line represents the BCS calculation[34] with $2\Delta(0)/k_BT_c = 4.1$.[31]

7. DISCUSSION

We wish to compare and contrast these results on NCCO with the body of surface impedance data which exists on the hole-doped cuprates. The most striking difference is the degree of consistency in results on going from film to film and between films and crystals of NCCO. Such consistency is found mainly in the highest quality films and crystals of YBCO, but is rarely found between the film and crystal samples of YBCO. Next, the temperature dependence of the surface impedance up to T_c is much more 'conventional' than either YBCO or Bi2212. NCCO does not show the substantial deviations from the BCS temperature dependence (other than the existence of a residual loss) which are seen in the hole-doped cuprates.[12,15] The fact that the residual losses have been substantially reduced with relatively modest effort also suggests that NCCO may become a useful low-loss, low-T_c superconductor in the future, possibly competing with Ba-K-Bi-O and NbN in microwave applications.[20]

Many questions remain to be answered about the surface impedance of the cuprates. Why do electrodynamics measurements on the other cuprates display non-s-wave BCS behavior? Is it because they are d-wave superconductors, or are there a number of extrinsic effects which are very sensitive to microstructure? Why should NCCO look so much like traditional s-wave superconductors when it too is a *bona-fide* cuprate superconductor? Are defects and disorder playing a major role in the electrodynamics of the cuprate superconductors? We shall further address these questions, and discuss the contrast between NCCO and YBCO, in upcoming publications.[31,32]

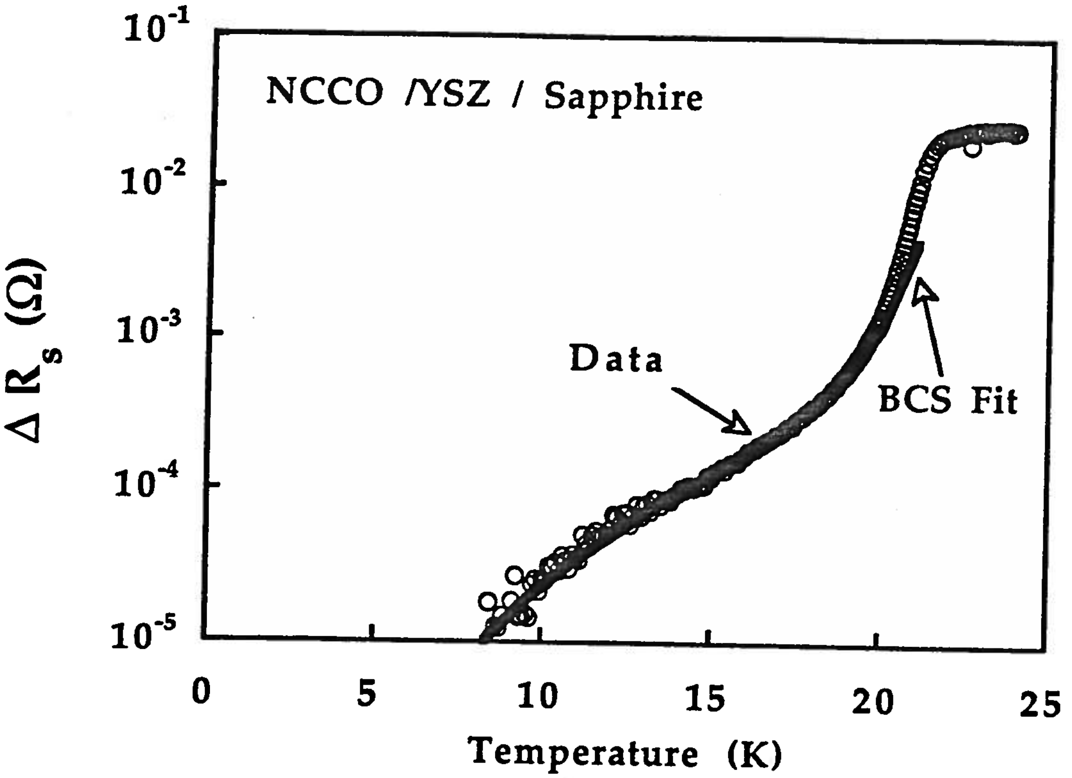

Figure 5. Change in surface resistance, ΔR_S vs temperature for a NCCO thin film on buffered-sapphire at 9.6 GHz with a BCS calculation (solid line) with $2\Delta(0)/k_BT_c = 4.1$.[31]

8. WHAT IF THE CUPRATES ARE d-WAVE SUPERCONDUCTORS?

In this section, we would like to speculate about the implications of d-wave superconductivity on the applications of the cuprates to high frequency technology. We rely mainly on the theoretical arguments of P. Hirschfeld, *et al.*, and P. Lee, and explore the properties of both "pure" and "disordered" d-wave superconductors.

8.1 "Pure" d-wave superconductors

First, since the d-wave pairing state involves lines of nodes in the energy gap on the Fermi surface, a perfect cuprate will have a non-zero density of low-lying excited states down to arbitrarily low energies. This means that the surface resistance of such a material will not be thermally activated at low temperatures. P. Lee has estimated the minimum conductivity associated with a "pure" d-wave superconductor, and finds[35] (in 3 dimensions) $\sigma_{min} \sim (e^2/h)\ (\xi_0/a\ s)$, where ξ_0/a is the ratio of the in-plane coherence length to the lattice parameter, and s is the inter-layer spacing. In the low temperature limit in the superconducting state, where $\sigma_2 >> \sigma_1$, the limiting surface resistance will be $R_{smin} \sim (\mu_0\omega)^2\ \lambda^3\ \sigma_{min}/2$. For YBCO ($\lambda \sim 1500$ Å, $\xi_0/a \sim 4$, $s \sim 7$Å) at 10 GHz the estimate gives $R_{smin} \sim 10^0$ μΩ, roughly an order of magnitude lower than the lowest R_s ever recorded in YBCO in the microwave range. This would imply that the surface resistance of YBCO can still be further improved by making more ordered samples, at least if this "pure" d-wave picture is appropriate for YBCO films, crystals, and ceramics. This estimate also indicates that pure cuprates with shorter ξ_0 will have lower residual surface resistances. Hence the lowest R_{smin} should be found in the material with the greatest T_c, although the improvement may not be so great upon going from a material with $T_c = 90$K to one with $T_c = 150$K.

The magnetic penetration depth in a "pure" d-wave superconductor should increase linearly with temperature at low temperatures, $\lambda(T) = \lambda_L + c_1\ T$, $(T << T_c)$ where $c_1 \sim \ln 2\ \lambda_L/(\Delta_0/k_B) \sim 2$ to 4 Å/K for YBCO.[36,37] This value is surprisingly close to the observations of Hardy, *et al.*, in twinned YBCO crystals,[16] but is clearly not appropriate for the data on YBCO thin films and powders, or for NCCO. Superconductors with such a strongly temperature dependent penetration depth would clearly not be desirable for precision delay lines or high stability oscillators.

8.2 Disordered d-wave superconductors

In reality, most cuprate superconductors used in applications are in thin film form and are often highly defective. The fact that thin film T_c's are often several degrees below those of single crystals is a sign that the films are either not optimally doped, or have sufficient disorder to decrease T_c by a "pair-breaking" effect. Both sources of a suppressed T_c involve some kind of disorder in the conducting layers of these materials. The effects of disorder on the properties of a d-wave superconductor are not entirely understood and are currently the subject of intense theoretical and experimental investigation. However, a few general remarks can be made about disorder.

In conventional s-wave superconductors, there are two types of defects which must be considered. Non-magnetic defects which produce elastic scattering have very little effect on superconductivity (Anderson's theorem). Magnetic impurities, on the other hand, break time-reversal symmetry, thus interfering with the Cooper pairing process. This results in a substantial decrease in T_c, as well as a modification of the BCS density of states. The singularity in the density of states at the gap energy is smeared out, and states begin to fill into the gap as magnetic impurities are introduced. At a critical concentration of magnetic impurities, an s-wave superconductor becomes "gapless," meaning that there are single particle excitations available even at zero energy. By the time this concentration is reached, the T_c of the material is just a small fraction of its original value.

In a d-wave superconductor things are somewhat different. Because of the symmetry of the d-wave state, non-magnetic impurities now become pair-breakers as well.[38] The effect of disorder on the electrodynamic properties depends on the strength of the interaction of an individual scattering event, c, which is the cotangent of the scattering angle in the collision. The limit $c \to \infty$ corresponds to weak scattering (Born approximation), and $c \to 0$ is strong scattering (unitary limit). It is found theoretically that any amount of disorder causes "gapless" behavior in any three-dimensional d-wave superconductor.[36] The magnetic penetration depth would then vary as $\lambda(T) \sim \lambda_0 + c_2 T^2$, $(T << T_c)$ where $c_2 \sim \pi k_B^2 \lambda_L/(3.8\, \Gamma^{1/2} \Delta_0^{3/2})$, Γ is proportional to the density of strong scatterers, n_i, and λ_0 is related to the London penetration depth.[36]

In the presence of disorder, theory predicts a crossover temperature T^* between a low temperature "gapless" regime, and a high temperature "pure" regime. Estimates of $T^* \sim .83\, (\Gamma\, \Delta_0/k_B^2)^{1/2}$ show that it increases roughly as the square root of the number of strong scatterers, $n_i^{1/2}$, as does $(\lambda_0 - \lambda_L)/\lambda_L$.[36] The penetration depth should therefore follow a general temperature dependence of the form $\lambda(T) \sim \lambda_0 + a\, T^2/(T^* + T)$. From this, one can estimate that $c_2 \sim c_1/T^*$, so for a typical YBCO film with $T_c = 90K$ and $T^* \sim T_c/4$, $c_2 \sim 0.2$ Å/K^2, surprisingly close to the values measured in YBCO films,[14] and that obtained from the low temperature $(T << T^*)$ expansion of an empirical fit to experimental data: $\lambda(T) = 1500Å/(1-(T/T_c)^2)^{1/2}$.[39-41]

The losses in the "pure regime" $(T^* < T << T_c)$ in a d-wave superconductor may give us some insight into the losses at higher temperatures in the cuprates. At temperatures greater than T^*, but with a very low density of strong scatterers such that the measurement frequency $f >> \Gamma\Delta_0/(h\, k_B T)$, one expects $\sigma_1 \sim n_i$,[42] and therefore $R_{s,pure} \sim \sigma_1 \sim n_i$, so that the losses will increase with impurity density, as one expects for s-wave superconductors. This case probably pertains only to the purest of single crystals. However, for much more defective materials (remember $\Gamma \sim n_i$) such that $f << \Gamma\Delta_0/(h\, k_B T)$, one expects $\sigma_1 \sim n_i^{-1}$,[42] and $R_{s,pure} \sim n_i^{-1}$, quite different from the clean limit. In this limit, the losses will actually decrease with additional non-magnetic disorder![19] However, the reduction in T_c due to the presence of strong scatterers is roughly $\Delta T_c/T_{c0} \sim \Gamma/\Delta_0$ and scales with n_i. Since it is more practical to make device materials with a large density of defects (especially in thin film form), a compromise must be found between the defects added to reduce the pure limit loss, and the need to keep the transition temperature substantially greater than the operating temperature of the device.

Finally, P. Lee has proposed that disorder in d-wave superconductors may lead to localization of low-lying quasiparticle states near the nodes of the energy gap.[35] This proposal may account for our observations of activated behavior in the surface impedance of NCCO.[29,31] In addition, it may also allow for the creation of s-wave-like cuprate materials which can mimic the low-loss properties of traditional isotropic s-wave superconductors.

9. CONCLUSIONS

In summary, we have reviewed the evolution of our understanding of the electromagnetic properties of several of the oxide superconductors. The lower T_c oxides (BKBO,NCCO) have a behavior consistent with s-wave BCS theory, while the higher T_c oxides seem to be consistent with d-wave electrodynamics. NCCO, in contrast to the hole-doped cuprates, behaves as if it had a single-valued and large gap ratio throughout the entire temperature range below T_c. Many of the observations on YBCO at low temperatures are consistent with the predictions for disordered d-wave superconductors. However, our results for NCCO, a true cuprate superconductor, do not seem to be compatible with the d-wave picture, at least for moderate amounts of disorder.

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