RF AND MICROWAVE EXPERIMENTS ON \( Y_{1.85} \text{Ba}_{2.3} \text{CuO}_{4} \) AND \( \text{La}_{1.86} \text{Sr}_{0.16} \text{CuO}_{4} \)

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The newly discovered high \( T_c \) superconductors\(^{1,2,3}\) have created tremendous interest, both as regards their fundamental properties and for possible applications at rf and microwave frequencies. We have been studying the electromagnetic response of the 40K \( \text{La}_{2-x} \text{Sr}_x \text{CuO}_4 \) and the 93K \( \text{RE}_{2} \text{Ba}_{2} \text{Cu}_3 \text{O}_y \) (\( \text{RE} = \text{Y, Er, Nd, Dy, Yb} \)) superconductors over a very wide spectral range from rf to optical frequencies with two broad objectives:

1. Firstly, to understand the fundamental nature of the superconducting state, e.g. is it the well-known BCS s-wave state or do we now have a fundamentally new type of superconductor? Electromagnetic probes are of particular significance for the high \( T_c \) superconductors, since they are sensitive only to the electronic state, unlike other traditional probes of the superconducting state such as ultrasonic attenuation or specific heat. The latter are strongly influenced by the phonon system, which is heavily populated at these high temperatures.

2. Secondly, we are also examining the potential of these materials for applications at rf, microwave and mm-wave frequencies.

We have carried out measurements of the surface resistance \( R_s \) and the penetration depth at 10 GHz and 1MHz. Most of the measurements to date are on polycrystalline \( \text{La}_{1.86} \text{Sr}_{0.16} \text{CuO}_4 \) (LSCO) and \( Y_{1.85} \text{Ba}_{2.3} \text{CuO}_4 \) (YBCO). The samples were prepared by first mixing thoroughly the appropriate oxides (of La or Y and Cu) and carbonates (Ba or Sr) and reacting at 900 \( ^\circ \)C (for YBCO) or 1000\( ^\circ \)C (for LSCO). The reacted mixture was then ground, pelletised and sintered at the reaction temperature. The samples had typical transition widths of less than 1K (YBCO) and 2K (LSCO). X-ray studies reveal the samples to be single phase with no evidence of additional phases. Single crystal and thin film samples are also currently being studied.

Our first measurements\(^4,5\) of the surface resistance were carried out in a Cu cavity resonant in the \( \text{TE}_{011} \) mode at 9.85 GHz. The cavity was loaded with sapphire to reduce its dimensions. The sample, in the form of a sintered disc of dia. 1cm. and thickness 2 mm. formed the bottom wall of the cavity. This technique enabled us to measure \( R_s \) between \( T_c \) and 0.8\( T_c \) - at lower temperatures, the absorption in the superconductor was unmeasurable in this configuration due to the large Cu background. Due to the large thermal contraction of the cavity and the sapphire dielectric, the frequency shift data could not be analysed meaningfully to obtain the temperature dependence of the penetration depth.

In order to eliminate the two main drawbacks of the above technique, viz. the limited sensitivity and the inability to measure the penetration depth, we successfully devised and implemented a novel technique\(^6\) which employs a Pb-plated fully superconducting cavity maintained at 4.2K. The sample was thermally anchored to a sapphire rod and placed in the center of the cylindrical cavity. The
sample-sapphire assembly was thermally insulated from the cavity walls, and its temperature could be varied between 4.2K to as high as 200K. The cavity characteristics are dominated by the sample surface impedance, since the Pb walls, which are maintained at 4.2K, have negligible absorption. This technique was used with great success to measure $R_s$ and $\Delta\lambda$ between 4.2K and 100K for YBCO and LSCO.

Measurements of the screening properties at 1 MHz were carried out using a simple variant of the Schawlow and Devlin technique. The superconductor in the form of a disc was placed in a coil, which formed part of a tank circuit. The frequency of the tank circuit was monitored as a function of temperature, and changes in the resonant frequency were directly related to the penetration depth in the sample.

**Normal state properties**

It is important to note the unusual properties of the normal state of the high $T_c$ superconductors. The resistivity, typically 800$\mu \Omega$-cm for the sintered ceramics, is 2 orders of magnitude greater than that for an elemental metallic superconductor. Our measurements at 9.58 GHz of the normal state surface resistance yield 0.44 $\Omega$/sq. for YBCO and 0.23 $\Omega$/sq. for LSCO. These values agree reasonably well with those calculated from the classical skin effect - thus the electrodynamics in the normal state appears to be just like an ordinary metal in the classical limit.

The high resistivity appears to be intrinsic, and is probably due to a high degree of electron-electron scattering in these materials.

Due to the high resistivity, the skin depths in the normal state are rather large - typically 20 $\mu$m at 10 GHz. These values may be compared with 0.66 $\mu$m for Cu at room temperature. At lower frequencies, we find that a 1 mm sample is completely transparent in the normal state at 1 MHz. Once again these results are consistent with the classical skin effect.

**THE SUPERCONDUCTING STATE**

Historically, microwave studies have played an important role in elucidating the nature of the superconducting state in "low $T_c$" materials. Such measurements yield information on the temperature dependence of the gap parameter, nature of the pairing through the coherence factors and the density of states, and have been essential in confirming the applicability of the BCS theory.

The principal conclusions of our results on $R_s$ and $\lambda$ (see Fig. 1 and 2) may be summarised as follows:

- The temperature dependence of $R_s$ and $\lambda$ for both YBCO and LSCO are similar, suggesting that the superconducting state is the same in the 40K and the 93K superconductors.

- Near $T_c$, the onset of decreasing absorption (i.e. of $R_s$) can be approximately described by the Mattis-Bardeen formulation of the electromagnetic response of a BCS s-wave superconductor, however a greatly reduced response of the superfluid fraction appears to be required, presumably due to strong scattering
and hence reduced mean free path.

A striking feature of the $R_s$ data is that the onset of decreasing absorption near $T_c$ is much more gradual than is seen in the “low $T_c$” superconductors. To realise why this is unusual, one needs to note that at 10 GHz, $\hbar \omega / kT_c \sim 0.12$ for Sn, $2 \times 10^{-2}$ for LSCO and $7 \times 10^{-3}$ for YBCO. Since in the BCS theory $R_s \propto (\hbar \omega / kT_c)^{1.5-2.0}$, the absorption in the high $T_c$ superconductors should be about 2 orders of magnitude lower than for a low $T_c$ superconductor, say Sn, at the same reduced temperature. Instead we find that $R_s/R_n$ is comparable for YBCO and Sn in the range $0.8T_c$ and $T_c$.

In order to quantitatively understand this aspect, we have devised a simple extension of the BCS theory which accounts for the observed temperature dependence near $T_c$. As is well known, $R_s$ increases strongly with decreasing mean free path, which may arise due to strong quasiparticle scattering. The principal effect of increased scattering is to greatly reduce the superfluid response, which can be quantitatively represented as $\sigma_{2,\text{eff}} = \sigma_2/\eta$, where $\sigma_2$ is the imaginary part of the Mattis-Bardeen conductivity ($\sigma = \sigma_1 - i \sigma_2$) in the local limit. $\eta$ represents the effects of inelastic scattering, and enters into the expression for the surface impedance as $Z_s/R_n = (2i/\sigma_1 - i \sigma_2/\eta)^{1/2}$. The $R_s$ data for YBCO and LSCO is reasonably well-described near $T_c$ by the above expression, using BCS expressions for the density of states and the temperature dependence of the gap, with $\eta = 63$ for YBCO and 43 for LSCO. In contrast, $\eta = 2$ fits the data for the elemental BCS superconductor Sn. In the “dirty” limit theory, $\eta = (\lambda_{\text{eff}}/\lambda_c)^2 \approx 0.83 (\xi_0/\lambda)$, and is a measure of the reduction in the screening response of the superfluid due to reduced mean free path. Thus we conclude that in both the oxide superconductors, the BCS s-wave theory appears to describe the $R_s$ data at least to first order near $T_c$, provided a greatly reduced superfluid response in invoked.

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**Fig. 1.** Surface resistance $R$ vs. $T$ for YBCO and LSCO at 10 GHz.

**Fig. 2.** Change in penetration depth at 10 GHz vs. temperature $T$ for YBCO and LSCO.
• However, when one looks at the temperature dependent data in detail, structure is observed, in the form of “wiggles” in the temperature dependence of both $R_s$ and $\Delta \lambda / \Delta T$ in both YBCO and LSCO, occurring at the same value of reduced temperature (approximately $0.96 T_c$ and $0.9 T_c$), even though the $T_c$'s of the two materials are widely different. We have observed these features in several samples and believe these are fundamental, and unlikely to be due to metallurgical imperfections such as mixed phases. These features are not describable in terms of a BCS s-wave model, and may imply structure in the temperature dependence of the gap parameter, or a new description of the quasiparticle excitations in these superconductors.

• We had specifically designed the low temperature experiment to seek for an $\exp(-\Delta/kT)$ dependence of $R_s$. As displayed in Fig. 1, we observe a rather large absorption even at 4.2K in both LSCO and YBCO. It is not clear at the moment whether the large absorption is due to an extra (large) residual resistance, as is observed in all superconductors at sufficiently low reduced temperatures. However, the data for $R_s(T)$ - $R_s(4.2K)$ cannot be fitted to a $\exp(-\Delta/kT)$ behaviour for any reasonable choice of $\Delta$. Such a dependence would of course be contained in the BCS s-wave description, as has been observed in all “low $T_c$” superconductors, and would also provide an independent determination of the gap parameter.

• Penetration depth The penetration depth data, when plotted in reduced parameters as $\lambda(T)/\lambda(T_c)$ vs $T/T_c$, is identical for both LSCO and YBCO, further confirming that the superconducting state is the same in both the superconductors (Fig.2).

However, the data definitely do not agree with the simple $(1-t^4)^{-1/2}$ behaviour nor with the detailed BCS form - the latter would predict a very sharp variation near $T_c$, unlike the data which is much broader. Our electromagnetic results may be contrasted with muon spin resonance data, which appear to agree with a BCS s-wave temperature dependence for YBCO, but not in LSCO.

It is interesting to note that the total variation in the penetration depth, and hence the reactance, is enormous, in going from the normal state to the fully superconducting state, in contrast to pure metallic superconductors. For instance $\lambda(0)/\lambda(T_c) < 10^{-4}$ at 1MHz and $\lambda(0)/\lambda(T_c) < 10^{-2}$ at 10 GHz, which is to be compared to $> 10^4$ for Sn. The electromagnetic measurements do not directly yield the zero temperature penetration depth $\lambda(0)$. Indirect estimates based upon the modified BCS analysis mentioned above yield $\lambda(0) \sim 419$ nm for YBCO and 340 nm for LSCO, which are slightly larger than other estimates.

POTENTIAL FOR APPLICATIONS AT RF & MICROWAVE FREQUENCIES

The potential for the utilisation of superconductors in applications in rf, microwave and mm-wave devices has long been recognised. The main reasons why superconductors provide attractive alternatives to conventional metallic materials are: (a) the very low absorption possible in the superconducting state, which finds applications in devices such as ultra stable clocks, transmission lines, filters, etc.
and (b) the ability to withstand high fields without significant dissipation, which finds application in cavities, accelerator structures, high power transmission, etc.

The high $T_c$ superconductors, particularly the 93K $\text{RE}_1\text{Ba}_2\text{Cu}_3\text{O}_y$, are very attractive, since refrigeration problems would be greatly minimised at the higher temperatures involved. Our measurements (Fig. 1) of $R_s$ indicate the following relevant features:

1. the high dc resistivity in the normal state, leading to a correspondingly high $R_s$ and large $\lambda_n$. This is relevant for applications, since the reduced absorption in the superconducting state has to occur from the rather high values in the normal state. Since the high resistivity appears to be due to an intrinsic mechanism, significant improvements in the normal state microwave absorption are unlikely to occur as material processing techniques improve in sophistication.

2. the improvement in $R_s$ in the superconducting state, is not as dramatic as one would expect for a pure, elemental superconductor with the same ratio of $\omega/\lambda_n$, as discussed earlier. As a consequence, $R_s$ for YBCO is lower than for Cu only at temperatures below about 70K. Our analysis in terms of the modified BCS theory indicates that the onset of $R_s$ may be dramatically improved by increasing the mean free path.

3. The large values (Fig. 1) of $R_s$ at low temperatures. It is not clear at the moment whether this is an intrinsic effect, or due to non-superconducting impurities, such as oxygen-deprived regions. Experiments on single crystal specimens, and also ceramics processed by different techniques, with attention to oxygen annealing, are expected to clarify this important question.

A variety of devices are feasible: cavities, filters, waveguides, microcircuits, etc.. As a demonstration, we have fabricated a fully superconducting cavity made of YBCO, by coating a Cu cavity with the superconductor in the form of a powder. The Q of the cavity as a function of temperature is displayed in Fig.3. The dramatic improvement in Q below the transition is clearly observed. The low residual Q is, we believe due to a third binding element, and not due to the superconductor. (The data of Fig.1 for $R_s$ would imply a Q of $10^6$ at 4.2K).

The construction of useful devices requires the fabrication of the materials in a variety of useful shapes and configurations, such as bulk monolithic structures, and structures coated by different techniques, such as chemical, mechanical or by vapour deposition. Given the level of effort presently focussed on these superconductors, the fabrication problems are expected to be

Fig.3 $Q$ of a 10 GHz cavity coated with YBCO powder. The dashed line represents the theoretical $Q$ inferred from the theory of Ref. 5.
overcome rapidly.

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References