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MEASUREMENTS OF THE RF SURFACE RESISTANCE OF HIGH-T_c SUPERCONDUCTORS

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Abstract

An experimental program is being conducted to assess the applicability of high-T_c superconductors for use in high power rf and microwave devices. The program involves the measurement of the rf surface resistance of high-T_c samples at frequencies between 0.15 and 40 GHz and rf surface magnetic fields as high as 640 gauss. Polycrystalline samples were found to have surface resistances which increase monotonically with rf-field amplitude, saturating at high field at a few percent of the normal-state surface resistance just above T_c.

Introduction

The use of high critical-temperature (T_c) superconductors in high-power rf and microwave devices holds promise for improving the efficiency of these devices. In addition, these materials have the potential of eliminating the need for liquid helium. However, to be of use, high-T_c superconductors must be fabricated to cover large areas of complicated geometry and maintain surface resistances less than a few tens of $\mu\Omega$'s in the presence of rf surface magnetic fields of several hundred gauss.

Composite materials in the form of thin films on substrates of high thermal conductivity will be required for high-power rf cavity applications. This is necessitated by the poor thermal conductivity of the high-T_c ceramics.[1] Silver has been shown to be a compatible substrate from a materials-processing standpoint. A variety of samples in bulk form and as films on silver and on dielectric substrates have been obtained, and their rf surface resistances versus frequency, temperature, and rf surface magnetic field have been measured. In this paper, we summarize both our measurement apparatuses and results obtained between 0.15 and 40 GHz at rf fields up to 640 gauss.

Measurement Apparatuses

A number of different resonant cavities have been used to measure the rf surface resistance (R_s) of high-T_c samples.[2] The sample is either inserted in a resonant cavity thus modifying its quality factor[3,4] or it is used as the resonant element of the cavity, thus determining the field profile and the resonant frequency.[5,6] Three types of cavities are used: transverse electromagnetic (TEM) $\lambda/2$ and $\lambda/4$ cavities, and transverse electric (TE) cavities. In the TEM $\lambda/2$ cavity, a rod-shaped sample supported on-axis constitutes a resonant coaxial line whose length corresponds to an integral number of half-wavelengths of the rf field. In the TEM $\lambda/4$ cavity, the sample is a disk which is placed at the base of the inner conductor where the rf surface magnetic field is highest. The length of the inner conductor is approximately a quarter of the wavelength of the fundamental resonant mode, and the fields at the base of the inner conductor have a TEM configuration. In the TE cavity, the sample constitutes the bottom plate of a cylindrical cavity which can be made to resonate in the TE_{011} and/or TE_{012} modes.

The primary frequencies of interest for accelerators are in the range 0.2-2 GHz. The TEM $\lambda/4$ cavity was designed to resonate at 820 MHz, near the center of this band, thus permitting measurements at a frequency representative of accelerators. To do so is important because polycrystalline superconductors have been found to have surface resistances with frequency dependencies which do not scale universally as f^2 in the presence of rf surface fields.[7] Moreover, regarding films on metallic substrates of high thermal conductivity, imperfections in the film will allow rf fields to penetrate into the normal-conducting metal. Since rf losses in the metal are much less frequency-dependent than rf losses in the superconducting film, these imperfections may not be apparent at high frequencies. Both considerations mandate that the samples be evaluated at their intended frequency of application.

The TEM $\lambda/4$ cavity, shown in Fig. 1, was fabricated from sheet niobium and used for measurements of disks at 4.2 K as a function of rf field amplitude. The cavity was flooded with liquid helium so that the temperature of the sample was known unambiguously. The peak rf field amplitude at the surface of the sample was determined from the voltage reading of a calibrated pickup probe.

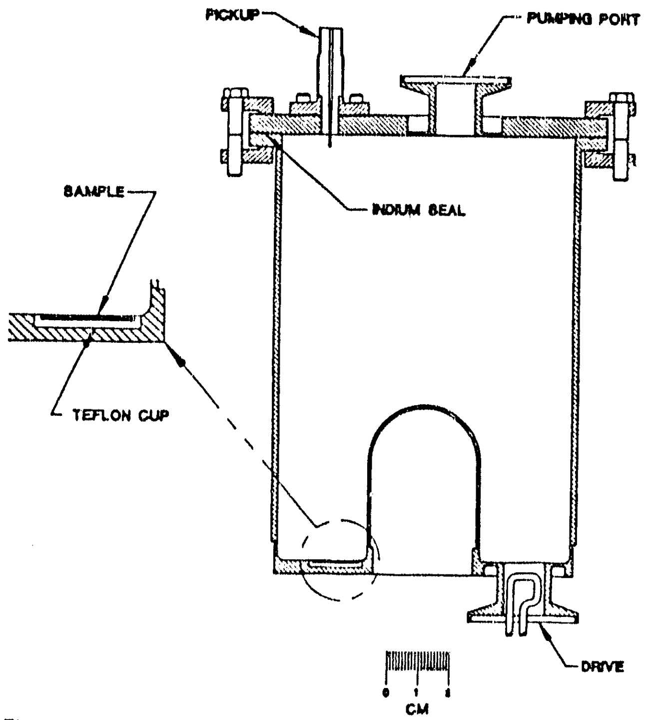

Figure 1. TEM $\lambda/4$ niobium resonator for surface resistance measurements on disk-shaped samples at high surface rf magnetic field.

Isothermal measurements of R_s of bulk rods as a function of rf field amplitude were performed using TEM λ/2 cavities. The temperature of the sample was maintained by flooding the cavity with cryogen.

The dependence of R_s on temperature at low rf surface magnetic fields was determined by cooling the TEM λ/2 or TE cavities with liquid helium, which was then boiled away allowing the sample to warm slowly while data was acquired.

The frequency ranges and capabilities of these apparatuses are described in Tab. 1. Additional details on the cavities and the measurement techniques are provided elsewhere.[4-5,7-9]

Results

Bulk Polycrystalline Samples

Bulk YBCO Rod. A series of measurements at low rf field amplitude (B_{rf}) were taken on a YBCO rod at 4.2 K and 77 K.[7] The rod was stored in air for ten months and the measurements were repeated. In addition, low-field measurements were also made after storing the sample in vacuum for 38 days. The data from the various time periods agreed, indicating that the rf properties of the sample were stable. The lowest R_s measured was ≤1.1μΩ at 4.2 K and 175 MHz.

The low-field behavior of R_s was characterized by a sharp transition between the superconducting state and the normal state. The frequency dependence of R_s was approximately quadratic at all temperatures below $T_c \approx 91$ K and was approximately square-root just above T_c. The temperature dependencies did not follow either BCS theory or a single power law over a wide temperature range.

The dependence of R_s on the rf field amplitude at the center of the YBCO rod was measured at T=4.2 K and 77 K. The surface resistance increased monotonically as B_{rf} was raised, passing through a transition region characterized by a strong B_{rf}-dependence, and saturating at a value roughly 5% of the normal-state surface resistance just above T_c. The sample remained superconducting through the highest field achieved, $B_{rf} \approx 640$ G (at 77 K and 19[illegible] MHz). In the transition region, R_s was strongly dependent on temperature and exhibited a frequency dependence which was approximately quadratic. In the high-field region, on the other hand, R_s showed a weak dependence on both temperature and frequency. Thus, the frequency dependence of the surface resistance of this polycrystalline superconductor was ambiguous in the sense that it was affected by the rf field; f^2-scaling was not universally valid.

Bulk BKBO. R_s versus rf field amplitude was measured for two bulk samples of $Ba_{0.6}K_{0.4}BiO_3$ (BKBO) using the TEM λ/4 cavity. BKBO, which exhibits a transition temperature of 30 K, has an isotropic cubic lattice structure in both the normal and superconducting state.[10] This differs from the perovskite ($CaTiO_3$)-like structure of YBCO and BSCCO which is anisotropic in the c-direction. Estimates of the coherence length of YBCO along this axis give a value between 0.2-0.4 nm, which is similar to the distance between the Cu-O layers.[11,12] Thus, obtaining a high degree of granular orientation with the ab-plane parallel to the rf magnetic field becomes important for optimizing high frequency performance of perovskite superconductors. BKBO, because its structure is isotropic, may avoid this requirement. The samples tested consisted of a bulk polycrystalline pellet with a diameter of 20 mm and an irregularly shaped melt fragment with an approximate area of 25 mm^2. The data is plotted in Fig. 2. R_s increased monotonically with field amplitude in a manner similar to the YBCO rod.

Table 1. Apparatuses for rf Measurements.

Cavity	Frequencies	Capabilities
TEM λ/2 Cu	150-600 MHz	Large samples (rods); R_s at high B_{rf} - rf breakdown.
TEM λ/2 Cu	600-1500 MHz	Large samples (rods); R_s at high B_{rf} - rf breakdown.
TEM λ/4 Nb	840 MHz	Disks 24-36 mm diameter; R_s at high B_{rf} - rf breakdown.
$TE_{011,012}$, TEM λ/2 Cu, Nb	1.5-4 GHz	Large samples - disks to 200 cm^2; Single crystals - short rods.
$TE_{011,012}$, Cu	8.0-12.4 GHz	Large samples - disks to 20 cm^2.
$TE_{011,012}$, Cu	12.4-18 GHz	Medium samples - disks to 7 cm^2.
$TE_{011,012}$, Cu, Nb	28-40 GHz	Small samples - disks to 1.7 cm^2; Single crystals.

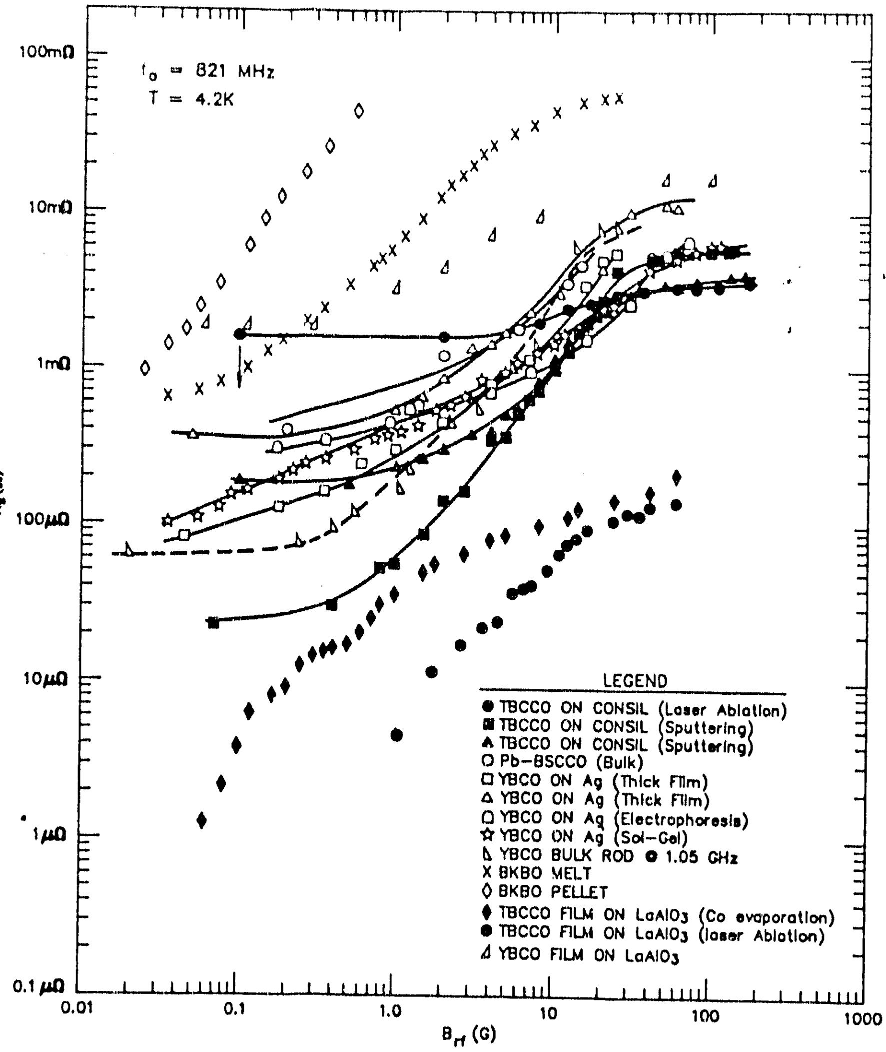

Figure 2. Surface resistance versus peak rf magnetic field at 821 MHz and 4.2 K for a variety of samples. For comparison, the 1050 MHz data of Ref. 7 for the YBCO rod is also shown. The laser ablated TBCCO sample was not coated on the edges and the low-field surface resistance is probably due to the silver substrate.

Polycrystalline Films

BSCCO Thick Films. Thick films of BSCCO were fabricated by applying high-viscosity slurries on silver.[8] Two different processing techniques were used; "4336" samples were produced using powders derived form the compound $Bi_4Sr_3Ca_3Cu_6O_x$, and a "2212" sample was produced using powders derived from $Bi_2Sr_2Ca\,Cu_2O_x$. The 4336 samples had diameters of 1.3 cm and 15 cm, and the 2212 sample had a diameter of 5.1 cm.

The rf surface resistance of these samples was measured as a function of temperature at low rf field amplitude (≤0.1 G) using three of the copper TE cavities described in Tab. 1.[8] The 4336 samples had $T_c \approx 81$ K, and the 2212 sample had $T_c \approx 83$ K. The surface resistances measured at low temperatures were approximately consistent with a quadratic frequency dependence and changed gradually to a square-root dependence as the temperature was raised, indicating that the rf performance of the 4336 and 2212 films were comparable despite their different processing procedures. At low temperatures, the 2212 sample behaved like room-temperature copper at the X-band frequencies of the rf fields to which it was exposed. An increase of surface resistance with rf field was noticed during the course of conducting these experiments, but this behavior was never quantified.

Films on Silver Substrates. A wide variety of films on silver substrates were measured using the TEM λ/4 cavity. The samples ranged in size from 24 mm to 36 mm in diameter by 0.5 mm thick, and in most cases the films covered all surfaces of the substrate. Visual inspection of the samples revealed flaws such as cracks, discoloration, incomplete coverage of the substrate, etc., which were more pronounced in some samples than in others. A plot of R_s versus B_{rf} for each sample at 4.2 K and 821 MHz is provided in Fig. 2.

The YBCO films were each made by one of the following processing methods: high-viscosity slurry, electrophoretic deposition, or sol-gel. The TBCCO films on silver were made by sputtering or laser ablation. The Pb-doped BSCCO was a highly textured bulk sample (i.e., not a film) of $Bi_{1.6}Pb_{0.4}Sr_2Ca_2Cu_3O_y$ of dimensions 20 mm diameter by 0.5 mm thickness. The introduction of lead into the BSCCO lattice results in zero DC resistance at temperatures near 110 K[13]. While the data span a large range of materials and fabrication techniques, all the samples share the property of being polycrystalline.

The qualitative behavior of the curves in Fig. 2 is similar for each material. R_s increases monotonically with field amplitude through a transition region characterized by a strong field dependence, and then saturates at high field at a value of a few percent of the normal-state surface resistance just above T_c. This is the same behavior of the YBCO bulk rod described above; for comparison, the data at 1 GHz and 4.2 K of the rod is also shown.

TBCCO Films on Dielectrics. We measured two films of TBCCO on $LaAlO_3$, one of diameter 30 mm made by co-evaporation, and the other of diameter 10 mm made by laser ablation. By comparison with the films on silver, these films showed a marked reduction in R_s; however, they still exhibited an increase in R_s as field strength was increased (see Fig. 2). These results suggest that the high-field behavior may be due to the polycrystalline nature of the samples rather than the intrinsic properties of the superconductors. Consequently, single crystals and epitaxial films on dielectric substrates may show a much reduced field-dependence of the surface resistance.

Conclusions

A figure of merit for the use of high-T_c superconductors in high-power rf applications is surface resistance in the presence of high rf surface magnetic fields. For example, superconducting resonators for particle accelerators will require surface resistances no higher than a few tens of $\mu\Omega$'s at rf field amplitudes as high as a few hundred gauss and at frequencies in the range 0.2-2 GHz. Our data indicate that for high-T_c materials at low rf fields, sufficiently low surface resistances are achieved, but at high fields (e.g., $\geq$30 G) the surface resistances are too large by a factor typically ~100. This is a serious problem for high-power applications which was identified over two years ago.[5,9] It needs to be mitigated by a suitable process of materials engineering. In light of these results, niobium and its alloys will likely remain the materials of choice in the near future for high-power rf applications.

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