MICROWAVE FIELD DEPENDENCE OF SURFACE RESISTANCE FOR HIGH-T_c SUPERCONDUCTING $YBa_2Cu_3O_{7-x}$ FILMS

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Abstract

We have studied the dependence of the microwave field at 13 GHz on the surface resistance of high-T_c superconducting $YBa_2Cu_3O_{7-x}$ films. The microwave field varies from the weak field (Meissner effect region) to the field about 400 A/m. The sample $YBa_2Cu_3O_{7-x}$ film with c-axis normal to the surface was prepared by laser ablation method on to a copper substrate 36 mm in diameter. From the H-dependence of the surface resistance the rf critical current density $J_{crf}(T)$ was determined by grain boundary weak-links model. J_{crf} about 2.8×10^5 $\mathrm{A/cm^2}$ at 20 K and about 4×10^4 $\mathrm{A/cm^2}$ at 77 K were obtained. $J_{crf}(T)$ was expressed as $J_c(T) \propto (1-T/T_c)^m$ with m 0.6, 1.2 and1.4 for our three high-T_c samples.

1 INTRODUCTION

The high-T_c superconductors open up many possibilities for practical applications in various fields. A rapid progress has been made in understanding the new superconductors, developing better high-T_c material and fabricating many high-T_c devices or systems such as multilayer SQUIDs, thin film or thick film compact filter, hybrid oxide devices, textured wires and tapes (power transmission cables, motors, transformers, magnets) with bulk form, and so on.

Of our interest is to study the possibility to the application of a high-T_c material in an accelerator cavity. For a high-power accelerator not only must high-T_c films be deposited on large-area metallic substrates of complex shape, but lower microwave power loss in high power levels is essential as well. In conventional superconducting rf cavity, the accelerating gradient is limited by such as the heating caused by the induced rf currents at its surface, the critical field or the superheating critical field, and so on. The dc critical current density J_c of Nb is about $10^6 \sim 10^7$ $\mathrm{A/cm^2}$ at 4.2 K, the rf critical current density J_{crf} is $\geq 10^4$ $\mathrm{A/cm^2}$[1]. While, for high-T_c films the dc critical current density $J_c > 2\times10^6$ $\mathrm{A/cm^2}$ at 77 K was reported for thin films; $J_{cfp} > 10^6$ $\mathrm{A/cm^2}$[2] (determined by the flux-pinning strength of the grains) in dc magnetic field can be easily achieved at low temperatures. However, at microwave frequencies, the behavior of the rf critical current density is still unclear. The field dependence of microwave surface resistance is one of the sensitive probe to determine the rf critical current density, and the suitability of high-T_c material for superconducting rf cavity.

Three regimes (Meissner-Ochsenfeld phase at low field, mixed phase at intermediate fields and a normal metallic phase at high fields) of observed behavior can be classified[1] as R_{res} (residual loss) proportional to H^2, H and $|H_{sat} - H|$, respectively. For the surface impedance of a superconductor to have its simple form $Z_s = R_s + j\omega\mu\lambda$ independent of H, it is necessary that the superconductor remains in the Meissner state. The mixed state[3] may occur at a low critical magnetic field depending on the material quality. For dc field, many studies[4] in the phase diagram, vortex dynamics, and order parameter effect on the critical state have been done experimentally and theoretically for type II superconductors. Of particular interest of this paper is the rf behavior of $YBa_2Cu_3O_{7-x}$(YBCO) films in the critical state, i.e., when magnetic flux has partially penetrated into the sample in the form of quantized vortices. We present experiment results of the microwave field dependence on the surface resistance of YBCO films at several points of temperature, which yields the intergranular $J_{crf}(T)$.

2 CRITICAL STATE

The microwave response of YBCO has been interpreted in terms of several microscopic models. However, the only one for which there is quantitative comparison between theory and experiment is the model of Portis et al.[5] based on the interaction between the microwave currents and free or pinned fluxons created by an external field. When vortices move along grain boundaries driven by the Lorentz force, the dissipation appears. The surface power absorption per unit area is given by $P_s = R_s J_s^2 / 2$, where $J_s = \int J dx = H_s$ (H_s is the peak microwave field) is the peak surface current density, giving for the absorption rate $P_s = R_s H_s^2 / 2$. The work performed in one rf period per unit is the integral over a cycle $W_s = \int H d\phi_s$. The surface flux density is given by $\phi_s = \int B dx = H^2\mu / 2 J_c$ based on the critical-state field gradient related to the critical current density J_c by $dH/dx = \pm J_c$. Thus, the surface resistance can be expressed as $R_s = (4\mu_0/3)(\omega/2\pi)(H_s/J_c)$. The field dependence R_s is linear in the magnitude of H_s. The $R_s(H)$ gives the value of the critical current density

$$J_c\left[\mathrm{A/cm^2}\right] = \frac{0.167 \cdot f[\mathrm{GHz}]}{R_s[\Omega] / H_s[\mathrm{A/m}]} \qquad (1)$$

where J_c is the intergranular rf critical current density or the Josephson junction rf critical current density.

3 EXPERIMENTS

3.1 YBCO film samples

The fabrication of YBCO was described elsewhere[6,7] in detail. An yttria-stabilized-zirconia(YSZ)/Cr film was used as a buffer layer to control the orientation of the YBCO film on copper substrate which is essential for high thermal conductivity in application for accelerator cavities. The Cr underlayer was found to be essential to protect copper against oxidation, resulting in good adhesion of the YSZ layer on copper. The copper substrate disk(36 mm in diameter, 3 mm in thickness) were polished to mirror-like, and ion-plated with o.5 mm Cr layer, subsequently sputter-deposited with the texturing in-plane YSZ buffer layer as thick as 0.8 mm by using a modified bias sputtering technique. Finally it was deposited by YBCO film (1.5~2 mm in thickness) using the laser ablation technique. In our experiments three Samples (EC230, EC231 and EC232) made by this method were characterized as c-axis normal to the film surface by x-ray diffraction and untexturing in plane by pole figure.

3.2 The experimental set-up

The experimental set-up for the microwave H-dependence on R_s of YBCO films is shown in Fig.1. The cavity (33 mm in diameter, 19 mm in length and 13.6 GHz TE_{011} mode) consists of a copper host cavity and an endplate. The cavity can be set to a fixed point of temperature from 11 K to 300 K by a closed-cycle refrigerator and a 50 W heater controlled by a temperature controller. At a fixed temperature, network analyzer automatically determined the resonance peak f_0 and a half-power points Δf from which the loaded quality factor was calculated. The incident power P_{in} of the cavity varies from a low field level (~1A/m) up to high (~500A/m). The coupling coefficient β_1 was tuned to about 0.8 near a critical coupling, which is determined from the reflection coefficient by the network analyzer. β_2 was set to very loose (~ 0.001).

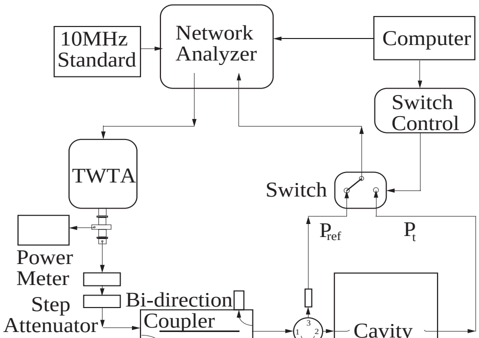

Figure 1: The experimental set-up for measurement of the field dependence on the surface resistace.

By this configuration β_2 is negligible in comparison with β_1, Q_0 can be evaluated as $Q_0 \cong Q_L(1+\beta_1)$. While, as Ref. [7,8] mentioned, the data of microwave surface resistance of copper $R_{s,Cu}(T)$ was obtained previously. The surface resistance of high-T_c films can be calculated. Consequently, the transmission power P_t is also negligible in comparison with the reflection power P_{ref}; the dissipation power P_d of the cavity was simply found from P_{in} and P_{ref} as $P_d \cong P_{in} - P_{ref}$, where P_{ref} is evaluated by P_{in} and β_1. For TE_{011} the magnetic field as a function Q_0 and P_d in the cavity can be deduced from the definition of Q_0. The definition of Q_0 is in terms of the stored energy U, angular frequency ω_0, and P_d as $Q_0 = \omega_0 U / P_d$. The maximum of magnetic field related to Q_0 and power loss can be expressed as

$$\left|H_{r,\max}\right| = 0.325\left(\frac{\varepsilon_0}{\mu_0}\right)^{1/4}\left(\frac{1}{a}\right)\left(\frac{\lambda_r}{l}\right)^{3/2}\sqrt{P_d Q_0} \qquad (2)$$

where $a = 16.5$ mm and $l = 19$ mm are the radius and length of the cavity. Therefore, $R_s(H)$ of YBCO films at different temperatures was obtained.

4 RESULTS AND DISCUSSION

Figure 2 is one representative of our experimental results $R_s(H)$ at temperature fixed to 20, 30, 50, 60, 70 and 80 K for sample EC231. The R_s is independent of H in lower field region. This R_s value is consistent with the data obtained previously[8] in the Meissner effect regime as a thin line shown in Fig.3. This thin line $R_s(T)$ in high accuracy was obtained by using copper and niobium demountable cavities after the data correction described elsewhere[8]. When $H_{r,\max} > 100$ A/m, as shown in Fig.2, and 3, the surface resistance $R_s(H)$ become apparently larger than the data in low field, and increases linearly when H increases. In terms of $R_s(H)$, the rf critical current density can be extracted with Eq.(1) from the linear regime of $R_s(H)$. The rf critical current density for our three samples EC230, EC231 and EC232 were obtained as shown in Fig.4. At 20 K, J_c for sample EC231 and EC232 is about 2.8×10^5 A/cm^2; J_c for sample EC230 is about 4×10^4 A/cm^2. At 77 K, 4×10^4 A/cm^2 for EC231 and EC232, and 1.2×10^4 A/cm^2 for EC230 were obtained. J_c of

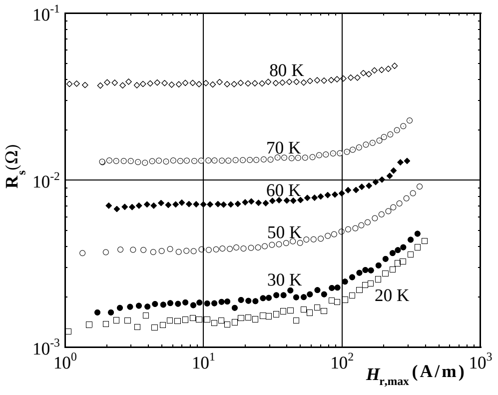

Figure 2: The dependence of the microwave field on the surface resistance for the YBCO sample EC231.

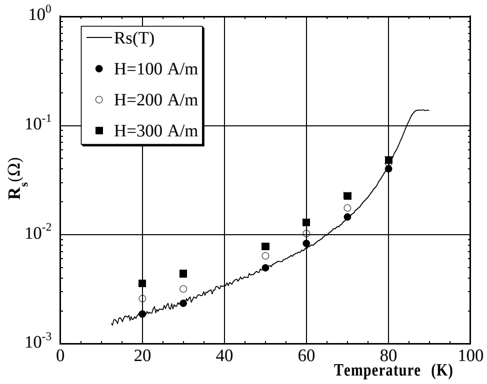

Figure 3: The T-dependence of the surface resistance at different magnetic field.

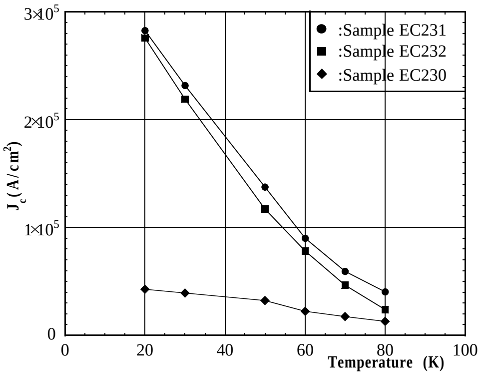

Figure 4: The T-dependence of the rf critical current density for YBCO samples EC230, EC231 and EC232.

EC230 is almost one order lower than one of EC231 and EC232 at 20 K.

For these three samples, there is no big difference in their structure (c-axis normal to the film, untexturing in a-b plane). However, the film surface quality of EC230 is poorer than the other two samples examined by the optical microscopy. At microwave frequencies, current flow for both type I and II superconductors is concentrated at the high-T_c surface and decays exponentially from the surface with a London penetration depth. The rf J_c is sensitive to the surface quality , which is different of dc volume current density since the dc J_c is uniformly distributed across the cross section for type II superconductors.

For this measurement itself, several issues require discussion. First, according to the expression of H in TE_{011} mode, H_r becomes the maximum when $z = 0$ and $r \cong 0.5a$, or $z = l$ and $r \cong 0.5a$, which shows that the maximum of H is located at the endplate. It is useful to measure a H-dependence with this method. Second, by this method in TE_{011} mode, H direction is normal to c-axis (or parallel to the ab plane), the current flows within the a-b plane. Thus, our results only reveal the behavior along the a-b plane. Other kind of sample (c-axis in plane) is necessary for the investigation of their anisotropic properties. In addition, the feed power to cavity is limited by the host copper cavity because the temperature is no longer fixed if the heating in copper becomes larger than the cooling capacity of the refrigerator. The maximum field about 400 A/m was achieved for our measurement at the fixed temperature. For measurement in a higher field regime, we will investigate it by immersing the experimental set-up into liquid nitrogen or liquid helium.

$J_c(T)$ expressed as $J_c(T) \propto (1 - T/T_c)^m$ with $m \approx 2$ is in Ref.[9], and $m \approx 1$ in Ref.[10]. For our data, m equal to 1.2, 1.4 and 0.6 were obtained for EC231, EC232 and EC230, respectively. These m values suggest again that the film surface quality has a strong effect on its properties. For EC231 and EC232, $J_c(T)$ may be expected as a linear T-dependence. In addition, it is necessary to emphasize that our YBCO films are granular, not single crystal. The granular structure and grain size were observed by the Scanning Electron Microscopy, which gives the grain size about $0.6 \sim 0.8\ \mu$m. Thus, the behavior of the critical current density is dominated by weak-links between grains.

For our data results it is worth to note that the rf J_c of YBCO films at 77 K is the same order as the rf J_c of niobium at 4.2 K. This result implies that there is a potential for the application of the high-T_c superconductors in the rf cavity. Although many other aspects of high-T_c material properties are still lacking, e.g., for our measurement E_{acc} is quite low only about 0.1 MV/m corresponding to $H_{s,max}$ 400 A/m (converted by the empirical formula as $H_{s,max} / E_{acc} = 50\ O_e / 1\ MV$ in the conventional superconducting rf cavity), we can expect that much future progress of the high-T_c superconductor will lead its real application to the rf cavity.

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