MICROWAVE FIELD DEPENDENCE OF SURFACE RESISTANCE FOR HIGH-$T_c$ SUPERCONDUCTING YBa$_2$Cu$_3$O$_{7-x}$ 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$_2$Cu$_3$O$_{7-x}$ films. The microwave field varies from the weak field (Meissner effect region) to the field about 400 A/m. The sample YBa$_2$Cu$_3$O$_{7-x}$ 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 $2.8 \times 10^4$ A/cm$^2$ at 20 K and about $4 \times 10^4$ A/cm$^2$ at 77 K were obtained. $J_{crf}(T)$ was expressed as $J_{crf}(T) \propto (1 - T/T_c)^m$ with $m$ 0.6, 1.2 and 1.4 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, 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 $10^6$ to $10^7$ A/cm$^2$ at 4.2 K, the rf critical current density $J_{crf}$ is $\geq 10^4$ A/cm$^2$[1]. While, for high-$T_c$ films the dc critical current density $J_c > 2 \times 10^6$ A/cm$^2$ at 77 K was reported for thin films; $J_{crf} > 10^6$ 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 $R_{cu}$ (residual loss) proportional to $H^2$, $H$ and $|H_{sat} - H|$, respectively. For the surface impedance of a superconductor to have its simple form $Z_s = R_s + j\omega \mu L$ 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$_2$Cu$_3$O$_{7-x}$ (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 $P_s = R_s J_{crf}^2 / 2$, where $J_{crf} = \int dx = H_s / 2J_c$ is the peak microwave field) is the peak surface current density, giving for the absorption rate $P_s = R_s H_{sat}^2 / 2$. 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 $\phi_s = \int B dx = H_s^2 / 2J_c$ 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 $R_s = (4\mu_0 / 3)(\alpha / 2\pi)(H_s / J_{crf})$. 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

$$J_c[A/cm^2] = \frac{0.167 \cdot f[GHz]}{R_s[\Omega]} / H_s[A/m]$$ (1)
where \( J_c \) is the intergranular rf critical current density or the Josephson junction rf critical current density.

\[ J_c \]

### 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, 19 mm in length and 13.6 GHz thin line shown in Fig.3. This thin line is a representative of our experimental results \( R_c(H) \) at temperature fixed to 20, 30, 50, 60, 70 and 80 K for sample EC231. The \( R_c \) is independent of \( H \) in lower field region. This \( R_c \) 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 \( R_c(T) \) in high accuracy was obtained by using copper and niobium demountable cavities after the data correction described elsewhere\[8\]. When \( H_{r, max} > 100 \text{ A/m} \), as shown in Fig.2, and 3, the surface resistance \( R_s(H) \) becomes 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 10^3 A/cm^2; \( J_c \) for sample EC230 is about 10^4 A/cm^2. At 77 K, 4x10^4 A/cm^2 for EC231 and EC232, and 1.2x10^4 A/cm^2 for EC230 were obtained. \( J_c \) of

\[ J_c \]

By this configuration \( B_2 \) is negligible in comparison with \( B_1 \). \( Q_0 \) can be evaluated as \( Q_0 \equiv Q_r(1 + B_1) \). While, as Ref. [7,8] mentioned, the data of microwave surface resistance of copper \( R_c(DB)(T) \) 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 \( P_r \); the dissipation power \( P_d \) of the cavity was simply found from \( P_{in} \) and \( P_{ref} \) as \( P_d \equiv P_{in} - P_{ref} \), where \( P_{ref} \) is evaluated by \( P_{in} \) and \( B_1 \). For TE011 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 \( \omega_0 \), 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

\[ H_{r, max} = 0.325 \left( \frac{\rho_0}{\mu_0} \right)^{1/4} \frac{1}{a} \left( \frac{\lambda_e}{l} \right)^{3/2} \sqrt{P_d Q_0} \]  

where \( a = 16.5 \text{ mm} \) and \( l = 19 \text{ mm} \) 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 \( H_{r, max} > 100 \text{ A/m} \), as shown in Fig.2, and 3, the surface resistance \( R_s(H) \) becomes 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 10^3 A/cm^2; \( J_c \) for sample EC230 is about 10^4 A/cm^2. At 77 K, 4x10^4 A/cm^2 for EC231 and EC232, and 1.2x10^4 A/cm^2 for EC230 were obtained.
EC231 and EC232, film surface quality has a strong effect on its properties. For EC230, respectively. These values suggest again 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 $H_{s,max} / E_{acc} = 50 \text{ O}_c / 1 \text{ MV}$ 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.

4 REFERENCES

[8] Jian-Fei Liu et al., to be published.