The Surface Resistance of YBCO Thin Films under a High dc Magnetic Field

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The dc magnetic field dependence of surface resistance $R_s$ of YBa$_2$Cu$_3$O$_{7-\delta}$ (YBCO) thin films were investigated. The YBCO thin films were deposited by co-evaporation method, fabricated by THEVA corp. The $R_s$ of the YBCO thin films were measured by using the dielectric resonator method around 22 GHz and the temperature range below $T_c$ region. The dc magnetic field was vertically applied to the two parallel superconducting thin films. The maximum magnetic field excited by using an NbTi superconducting magnet was 5 T. The $R_s$ values were increased as increasing the applied dc magnetic field. The dependence of the $R_s$ in the YBCO thin films on dc magnetic field was explained qualitatively by Lancaster’s equations for strong pinning limit.

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I. INTRODUCTION

Passive microwave components such as filters [1] and antennas [2] are attractive and useful applications of high-temperature superconductors (HTS) because of their significantly lower microwave loss than that of normal metals. Since microwave surface resistance $R_s$ closely related to the microwave loss in these devices, it is very important to estimate the $R_s$ of the HTS. There are a lot of methods to measure $R_s$ of the HTS thin films such as the wave-guide resonator technique, the planar circuit resonator technique, and the dielectric resonator technique [3–6]. We have recently made some advantages in the development of the measuring of the $R_s$ by using the dielectric resonator method. The parallel plate dielectric resonator is one of the most reliable measurement tools of $R_s$. Non-destructive measurement of the HTS thin films can be performed using the parallel plate dielectric resonator. Therefore, the measuring technique is placed as a standard measurement method by International Electrotechnical Commission (IEC).

On the other hand, high sensitivity pick-up coil using the HTS thin films have been contrived for the medical systems applying the high-magnetic field such as magnetic resonance image (MRI) or electron spin resonance (ESR). By using the HTS pick-up coil to the medical system, improvement of the detection sensitivity and contraction of the medical examination time are expected. However, the putting the superconducting pick-up coil to practical use has not yet been done. So, it is very important and interesting that the experimental investigation of the superconducting properties under the high magnetic fields. There was some experimental reports on the investigation about the dependence of the $R_s$
in the HTS thin films on static magnetic field up to 0.1 T, however, the \( R_s \) measurements for high magnetic field more than 0.1 T has not yet been carried out.

In this paper, we report the experimental results of the dependence of the \( R_s \) in the YBCO thin films on dc magnetic fields by using the dielectric resonator method with high magnetic field applying system.

II. EXPERIMENTAL DETAILS

II-1. \( R_s \) measurement system

The \( R_s \) measurements were performed by using a measurement system with cryocooler and superconducting magnet (Suzuki Shoken Co., Ltd.: SSR-75). A schematic diagram of the \( R_s \) measurement system is shown in Fig. 1. This system has two separated vacuum chambers: one is the space for cavity cooling, and other is that for cooling an NbTi superconducting magnet. These chambers were pumping by using the turbo molecular pump. The detail of the dielectric resonator method was described afterwards. The dc magnetic field was vertically applied to the cavity. The maximum excitation current of the superconducting magnet is approximately 70 A, and is correspond to the dc magnetic field of 5 T. Long semi-rigid cables 1.5-m length were used between the cavity and vector network analyzer (VNA) (HP8722D) to reduce affecting the magnetic field to any other systems.

II-2. Dielectric resonator method

In order to evaluate the microwave properties, the \( R_s \) measurements were carried out by the dielectric resonator method [7, 8]. Fig. 2 shows a schematic diagram for the side view of the resonator. High-quality single crystal of sapphire produced by Kyocera Corporation was chosen as a dielectric rod in order to reduce an effect of dielectric loss tangent (\( \tan \delta \)). The base of the rod is perpendicular to the \( c \)-axis of the crystal. Cylindrical copper housing were used for preventing radiation loss. A pair of the samples were used as conductor plates at both ends of the sapphire rod. Resonance frequency of \( \text{TE}_{011} \) mode was chosen to be...
around 22 GHz. The samples were cooled by a cryocooler. The temperature of the cold stage and bottom of the cavity were measured by two calibrated sensors as shown in Fig. 2. The temperature difference between the two sensors was less than 1 K for wide temperature range. From these results, we used the thermo sensor 1 as the temperature of the samples. The measured samples were co-evaporated YBCO thin films deposited on CeO2/r-sapphire substrates, fabricated by THEVA corp. The YBCO thin films with a 25-mm square were c-axis oriented. The unloaded quality factor ($Q_u$) of the samples was measured by using a VNA. The $Q_u$ of the resonator is obtained from the loaded $Q_l$ as follows [7, 8]:

$$Q_u = \frac{Q_l}{1 - A_t}, \quad A_t = 10^{-I.L.[dB]/20} \quad (1)$$

where $I.L.$ is insertion loss. Using this $Q_u$ values $R_s$ for TE011 mode is given by [7, 8]:

$$R_s = 30\pi^2 I \left(\frac{\lambda_2}{\lambda_0}\right)^3 \frac{\varepsilon_r}{1 + W} \left(1 + \frac{W}{\varepsilon_r}\right) \frac{1}{Q_u}, \quad \lambda_0 = \frac{c}{f_0}, \quad \lambda_g = \frac{2L}{T}. \quad (2)$$

Here, $f_0$, $c$, $L$, $\varepsilon_r$, and $W$ are the resonance frequency, light velocity, and the ratio of electric field energy stored outside to inside the rod. The tan $\delta$ of the sapphire rod, tan $\delta \sim 10^{-7}$, can be neglected for the $Q_u \sim 10^5$ at 22 GHz.

III. RESULTS AND DISCUSSION

III-1. Dependence of $R_s$ on temperature

Fig. 3 shows a typical resonant curve of YBCO-sapphire-YBCO resonator for TE011 mode operating at 4.5 K. The $Q_l$ and $Q_u$ were $6.58 \times 10^5$ and $8.70 \times 10^5$, respectively. Using the $Q_u$ and Eq. (2), the $R_s$ values was calculated. The $R_s$ value under a zero external magnetic field at 4.5 K was 0.11 m$\Omega$ at 21.8 GHz, and approximately three orders of magnitude smaller than that of normal metal.

The $Q_u$ for YBCO-sapphire-YBCO resonator were measured at several temperatures below $T_c$. Fig. 4 show the $Q_u$-$T$ and $R_s$-$T$ characteristics in the YBCO thin film.
FIG. 3: A typical resonant curve of YBCO-sapphire-YBCO resonator for TE_{011} mode at 4.5 K.

FIG. 4: $R_s$-$T$ characteristics of YBCO thin films at 21.8 GHz.

Note that the $R_s$ values measured by this method are the average values for the two samples, however, we considered that the $R_s$ values for each sample were nearly the same because of the YBCO thin films were fabricated by the same batch.

III-2. Dependence of the $R_s$-$T$ characteristics on dc magnetic field

Fig. 5(a) shows the dependence of resonant curve on dc magnetic field at 4.5 K. The $Q_u$ values are decreased as increasing the magnitude of the dc magnetic field. The center frequency for $B = 1$ T is shifted to high frequency region as increasing the applied dc magnetic field, however the center frequencies more than $B = 2$ T are shifted to low frequency region as increasing the applied dc magnetic field.

Fig. 5(b) shows the dependence of the $R_s$ on dc magnetic field at 4.5 K. Up to magnetic field of 0.4 T the surface resistance is practically constant. For $B > 0.4$T, the $R_s$ values are increased as increasing the magnitude of the dc magnetic field. Lancaster has expected that the relation between the $R_s$ to the applied dc magnetic fields. The $R_s$ for
FIG. 5: Dc magnetic field dependence of resonant curve (a) and $R_s$-$T$ characteristics (b) at 22 GHz and 4.5 K.

The strong pinning limit is given by [9]:

$$R_s(B) = R_s(0) + \frac{B\Phi_0\eta\omega^2}{2\lambda_L \kappa_p^2} \quad \text{(Low field limit)} \quad (3)$$

$$R_s(B) = \frac{\eta\omega^2}{2\kappa_p} \sqrt{\frac{B\Phi_0\mu_0}{\kappa_p}} \quad \text{(High field limit)} \quad (4)$$

Here, $R_s(0)$, $\eta$, $\lambda_L$, and $\kappa_p$ are the surface resistance for $B = 0$, viscous drag coefficient, London penetration depth, and restoring force constant in the pinning potential well (Labusch parameter) [9]. The other symbols are the standard meanings. The theoretical $R_s$-$B$ curves for low and high field limits were calculated using these equations and plotted to Fig. 5(b). The experimental data is found to be in good agreement with theoretical data.

IV. CONCLUSION

The dependence of surface resistance $R_s$ in YBa$_2$Cu$_3$O$_{7-\delta}$ (YBCO) thin films on dc magnetic field were measured. The $R_s$ of the YBCO thin films fabricated by THEV A were measured by using the dielectric resonator method around 22 GHz and the wide temperature range. The $R_s$ values were increased as increasing the magnitude of the dc magnetic field. The dependence of the $R_s$ in the YBCO thin films on dc magnetic field are explained by Lancaster’s equations for strong pinning limit.

References