Dependences of microwave surface resistance of HTS thin films on applied dc magnetic fields parallel and normal to the substrate

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Abstract. We investigated the dc magnetic field and temperature dependences of microwave surface resistance (R_s) of high-temperature superconductor (HTS) films. Previously, we reported that the surface resistance $R_s^{(n)}$ under a dc magnetic field applied normaly to the substrate increased when increasing the applied magnetic field. For NMR application, we have to examine the $R_s^{(p)}$ under the dc magnetic field parallel to the substrate. We measured the $R_s^{(p)}$ of the YBCO and DyBCO thin films with a thickness of 500 nm deposited on a MgO (100) substrate using the dielectric resonator method at 21.8 GHz, and a dc magnetic field of up to 5 T. In a zero magnetic field, the values of $R_s^{(n)}$ and $R_s^{(p)}$ were 0.35 mΩ at 20 K. Under the dc magnetic field, the $R_s^{(n)}$ and the $R_s^{(p)}$ also increased with increasing magnetic field, however, the $R_s^{(p)}$ had a lower magnetic field dependence and the value was about 1/10 of that of the $R_s^{(n)}$. The $R_s^{(p)}$ at 16.4 T and at 700 MHz could be estimated by the two-fluid model. The $R_s^{(p)}$ value was about 1/2600 compared with that of copper at 20 K. As a result, we clarified that 500 nm thick YBCO and DyBCO thin films could provide advantages for NMR application.

1. Introduction

The microwave surface resistance (R_s) of high-temperature superconductor (HTS) thin film is approximately two or three orders of magnitude smaller than that of the conducting metals usually used in the microwave frequency region. Because of this characteristic, passive microwave devices, such as filters [1] and antennas [2], have been widely investigated. Applications of HTS films with low R_s under a high magnetic field have been proposed, such as pick-up coils for magnetic resonance imaging and nuclear magnetic resonance (NMR). In order to realize these microwave devices, it is necessary to select and evaluate HTS materials by precise R_s measurement. For example, Honma et al. studied the R_s of YBCO thin films under high magnetic fields up to 12 T [3]. According to their study [3], the R_s of HTS films increases rapidly according to applied magnetic fields and thus it is thought that superconducting NMR pick up coils is difficult. However, in their experiment, a magnetic field was applied normaly to the substrate-plane, defined as $R_s^{(n)}$. In this study, a magnetic field was applied parallel to the substrate, defined as $R_s^{(p)}$. It is important to know how the $R_s^{(p)}$ behaves in a high magnetic region. However, there were few experimentally reports.

In this paper, we measured the $R_s^{(p)}$ of $YBa_2Cu_3O_y$ (YBCO) and $DyBa_2Cu_3O_y$ (DyBCO) superconducting films under high dc magnetic fields up to 5 T and investigated whether or not these materials are valid for NMR pick-up coils.

2. Experimental

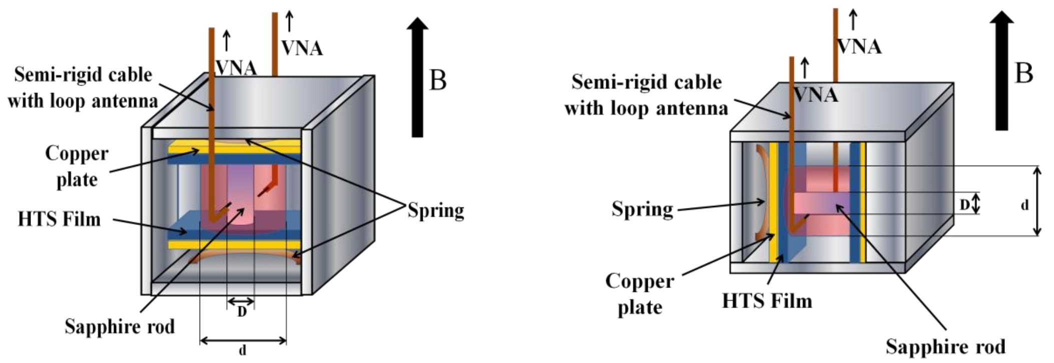
We measured the $R_s^{(p)}$ in dc magnetic fields using the dielectric resonator method [4-7] and a superconducting magnet with NbTi (Suzuki Shokan Co., Ltd.: SSR-75). The dielectric resonator method is an international measurement standard for the R_s of HTS superconducting films [8].The R_s measurement system was described in detail in Ref. [7]. The resonator frequency of the TE_{011} mode was set to 21.8 GHz. In the cavity, we set the HTS films as shown in Fig. 1. Fig. 1 (a) represents the measurement cavity for $R_s^{(n)}$, and Fig. 1 (b) represents the measurement cavity for $R_s^{(p)}$. Therefore, the field was (a) normal and (b) parallel to the substrate-plane of the HTS films.

The film thickness and crystalline properties of the measured YBCO and DyBCO thin films are listed in Table 1. These films were deposited on MgO (001) substrates by the thermal co-evaporation method. The crystalline of the films was evaluated by $\theta/2\theta$ and φ-scan X-ray diffraction. The $\delta\gamma$ was the full-width half-maximum (FWHM) of the rocking curve of the (005) peak of the films. The $\delta\varphi$ was the FWHM of the φ-scan of the (102) plane of the thin film. From table 1, the $\delta\gamma$ values of the YBCO and DyBCO films were lower than 1.2 degree and the $\delta\varphi$ values were lower than 1.7 degree, respectively. Therefore, the crystalline properties of the measured YBCO and DyBCO thin films were almost the same.

3. Results and discussion

3.1. Temperature dependence of $R_s^{(n)}$ and $R_s^{(p)}$

Fig. 3 shows the temperature dependence of the $R_s^{(n)}$ and $R_s^{(p)}$ of 500 nm thick YBCO and DyBCO thin films in a zero magnetic field at 21.8 GHz. The $R_s^{(n)}$ [3] and $R_s^{(p)}$ values at 20 K were both 0.35mΩ. Measurement error between each cavity was less than 5 percent.

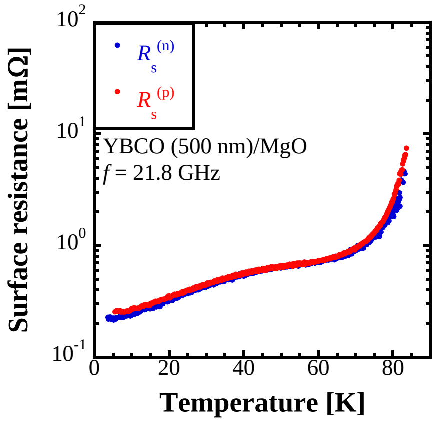


(a) (b)

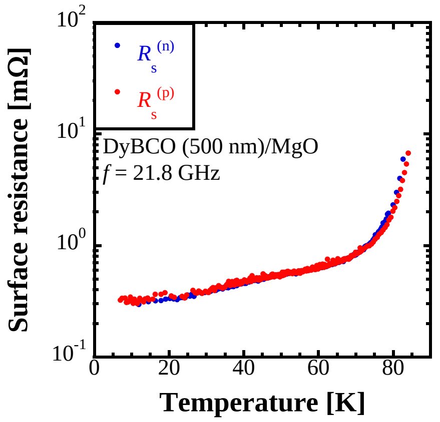
Fig. 1. Schematic drawing of cavity for (a) $R_s^{(n)}$ and (b) $R_s^{(p)}$

Table 1. Crystalline properties of YBCO and DyBCO thin films (Produced by THEVA)

HTS thin films	$YBa_2Cu_3O_{7-\delta}$	$DyBa_2Cu_3O_{7-\delta}$
Substrate	MgO (0.5 nm thickness)	
Cap layer	CeO_2 (30 nm thickness)	
Thickness [nm]	500	
$\delta\gamma$ [deg.]	1.09	1.17
$\delta\varphi$ [deg.]	1.63	1.3



(a)



(b)

Fig. 3. Temperature dependence of $R_s^{(n)}$ and $R_s^{(p)}$ for (a) YBCO and (b) DyBCO thin films with a thickness 500 nm in a zero magnetic field.

3.2. DC magnetic field dependence of $R_s^{(n)}$ and $R_s^{(p)}$

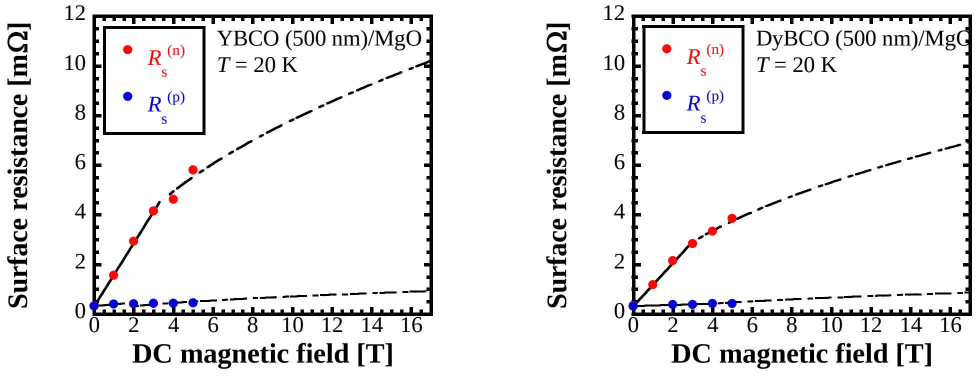
Fig. 4 shows the dc magnetic field dependence for the R_s of YBCO and DyBCO thin films with a thickness of 500 nm in a dc magnetic field between 0 and 5 T at 20 K. The $R_s^{(n)}$ and $R_s^{(p)}$ values of the two materials increased with a dc magnetic field up to 5 T. However, the value of $R_s^{(p)}$ had low magnetic dependence compared with $R_s^{(n)}$. The value of $R_s^{(p)}$ was about 1/13 for YBCO and 1/9 for DyBCO compared with the $R_s^{(n)}$. These results could be explained by using the two-fluid model for high frequency and low magnetic field limits [10].
Under a low magnetic field, the R_s is given as follows,

$$R_s(B) = R_s(0\mathrm{T}) + \frac{B\Phi_0}{2\lambda_L \eta_{\mathrm{low}}(B,T,d)} \qquad \left(B \ll \frac{\omega\mu_0\lambda_L^2}{\Phi_0\hat{\mu}}\right) \quad (1).$$

Under a high magnetic field, the R_s is given as follows,

$$R_s(B) = \sqrt{\frac{\omega\mu_0\Phi_0 B}{2\eta_{\mathrm{high}}(B,T,d)}} \qquad \left(B \gg \frac{\omega\mu_0\lambda_L^2}{\Phi_0\hat{\mu}}\right) \quad (2).$$

Here, B is the magnitude of the applied dc magnetic field, d is the thickness of films, ω the angular frequency, Φ_0 the flux quantum, μ_0 the vacuum permeability, λ_L the London penetration depth, $\hat{\mu}$ the dynamic mobility and η the viscous drag coefficient which is related to the motion of the magnetic flux. We considered η as a function of the magnetic field and temperature [3]. In Fig. 4, solid lines represent the fitted data of R_s under a low magnetic field calculated using Eq. (1). Dotted lines represent fitted data of R_s under a high magnetic field calculated using Eq. (2). In low magnetic regions, $R_s^{(n)}$ increased linearly with the applied magnetic field. In high magnetic regions, $R_s^{(n)}$ also increased proportional to the square root of the magnetic field. The values for the $R_s^{(n)}$ of YBCO and DyBCO thin films increased linearly with the applied magnetic field up to 5 T respectively. Meanwhile, the $R_s^{(p)}$ of various materials displayed extremely low magnetic field dependences up to 5 T. Therefore, in thin films with strong intrinsic pinning, motion of flux was reduced.



(a) (b)

Fig. 4. The dc magnetic field dependence of $R_s^{(n)}$ and $R_s^{(p)}$ at 20 K

An R_s value of 25 μΩ at f = 700 MHz, T = 20 K, B = 16.4 T was required for NMR pick-up coils. The $R_s^{(p)}$ of YBCO and DyBCO were 0.94 and 0.88 μΩ respectively. These values were about 1/2650 and 1/2840 compared with that of copper. These results show that 500 nm thick YBCO and DyBCO thin films could provide advantages for NMR pick-up coil materials. For NMR application, HTS materials need not only possess low R_s, but also have a high critical current density (J_c). We will continue to consider HTS pick-up coils for NMR application in the future.

4. Conclusion

In this paper, we investigated the dc magnetic field and temperature dependences of microwave surface resistance ($R_s^{(n)}$, $R_s^{(p)}$) in HTS films for NMR application. The $R_s^{(p)}$ value shows low magnetic field dependence compared with $R_s^{(n)}$. This behavior is caused by the layered structure of YBCO and DyBCO thin films. The motion of flux was hindered. The estimated values of 500 nm thick YBCO and DyBCO thin films at f = 700 MHz, T = 20 K, and B = 16.4 T were 0.94 and 0.88 μΩ respectively. These values were lower than 25 μΩ, which was less than 1/1000 of the R_s of copper. From these results, we clarified that YBCO and DyBCO thin films could provide advantages for NMR application.

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