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Surface Resistance of YBCO Thin Films under High DC Magnetic Fields

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Abstract. We have studied the magnetic dependence of the surface resistance (Rs) of YBa_2Cu_3Oy (YBCO) thin films by changing the direction of an applied magnetic field by mean of a micriostrip line resonator method (MLRM). We measured Rs(0), Rs(90) and Rs(45) to which the direction of the applied magnetic field was respectively normal, parallel and at 45º to the film surface. In the low temperature region, (below 40 K), the Rs(0) had low magnetic dependence; however, the Rs(90) and Rs(45) had high magnetic dependence, even below 10 K. We examined the magnetic field dependence of Rs (90) and Rs(0) using the London equation, and found that Rs(90) in the higher temperature region could be mostly explained by the theory.

1. Introduction

Recently, applications of HTS using low surface resistance under high dc magnetic fields have been proposed, for example as the material for MRI and NMR pickup coils. Youngi et al reported the effect of employing a superconducting MRI pickup coil made with superconducting wire. They found an improvement in detection sensitivity [1]. The key required characteristic of such applications is low surface resistance under a magnetic field of several tesla. However, to permit the use of a superconductor for NMR pickup coil material, its surface resistance needs to be sufficiently small under higher magnetic fields. It is necessary to examine whether the surface resistance of HTS films in high magnetic fields is smaller than that of conventional conductors.

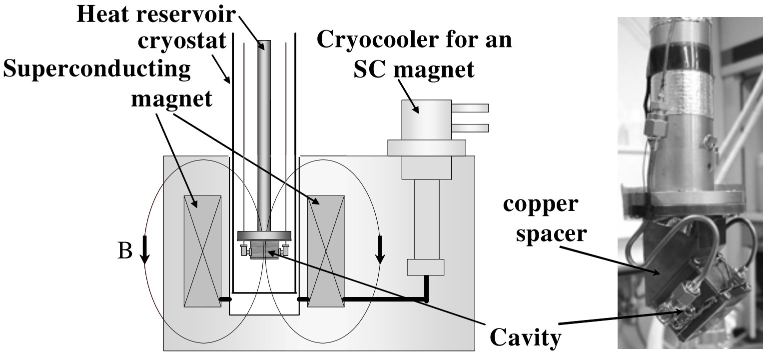
Powel et al reported the microwave surface resistance of YBCO thin films in dc magnetic fields from 0 to 4 tesla [2]. A dc magnetic field was applied normal to the film surface. The surface resistance increased with increasing dc magnetic field. However, it was found that surface resistance under 4 tesla at 5 K was only 5 times greater than when exposed to no magnetic field. This means that YBCO thin film has potential applicability to NMR pickup coils. To apply an HTS thin film as the pickup coil material for NMR, it is necessary to examine the surface resistance under different magnetic field directions.

In this paper we show the results of magnetic field dependence of Rs measured using the microstrip line resonator method (MLRM). The directions of the applied magnetic field were normal to, parallel to and 45º to the film surface. The measurement temperature was varied from 6 K to 80 K, and the applied dc magnetic field was varied from 0 to 5 tesla.

2. Experimental procedure

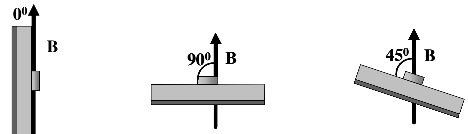
The Rs of the YBCO thin films under a magnetic field was measured using the MLRM. Details of this measurement method can be found in ref. 3. An MLRM has the advantage of allowing the direction of the applied magnetic field to be changed easily. We adopted three directions; normal, parallel and 45° to the film surface. Figure 1 is a schematic diagram and a photograph of the measurement equipment. The direction of the magnetic field was adjusted by inserting a cooper spacer between the cavity and the cooled head as shown in Figure 1. (The piece shown in Figure 1 is a spacer for 45°.) A platinum resistance set in the cavity measured the sample temperature.

Figure 2 shows the definition of the magnetic field direction applied to a sample while measuring the surface resistance using the MLRM. The direction of the applied magnetic field was varied: normal, parallel, and 45° to the film surface as shown in the Figure. Each measured Rs is written as follows: Rs(90), Rs(0) and Rs(45).



(a) Superconducting magnet (b) Cavity

Figure 1. Schematic drawing and picture of measuring system.

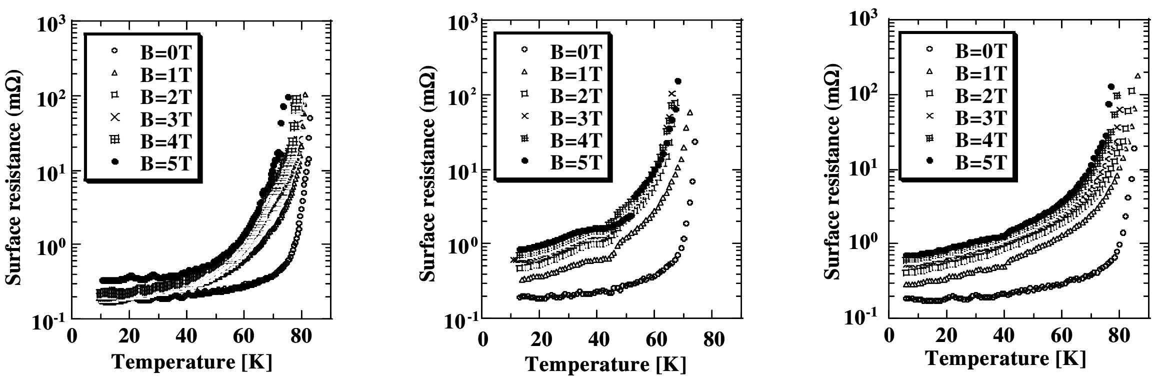


(a) 0° (b) 90° (c) 45°

Figure 2. The definition of a magnetic field direction applied to a sample

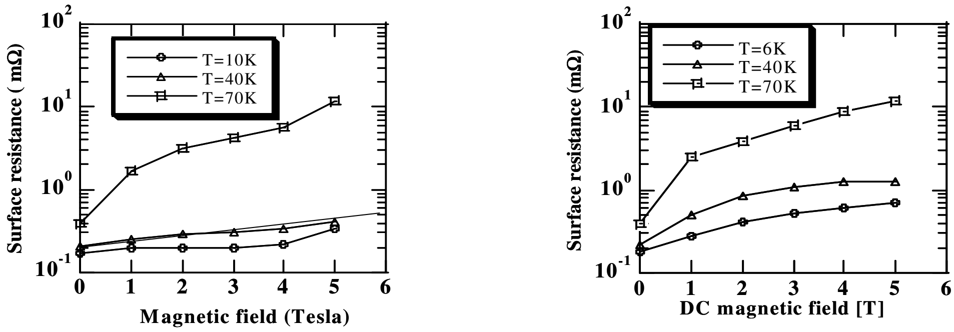
3. Results

The temperature dependence of Rs(0), Rs(45) and Rs(90) is shown in Figure 3 (a), (b) and (c). Rs(0), Rs(45) and Rs(90) increase with increasing temperature and with increasing applied magnetic field;



(a) Rs(0) (b) Rs(90) (c) Rs(45)

Figure 3. Temperature dependence of the surface resistance of YBCO thin film.



(a) Rs(0) (b) Rs(90)

Figure 4. Magnetic field dependency of the surface resistance of YBCO thin film.

however, the dependency differs in each case. When a magnetic field was applied parallel to the thin film surface, (parallel to the CuO_2 plane), the Rs(0) showed a low temperature dependency in the under 40 K region, but the Rs(0) increased rapidly in the over 40 K region. However, when a magnetic field was applied perpendicular to, and at 45º to the film surface, the Rs(90) and Rs(45) increased with increasing temperature and with increasing applied magnetic field, even in the low temperature region. To further clarify the difference, the Rs(0) and Rs(90) vs. applied magnetic fields are shown in Figure 4 (a) and (b). The Rs(0) measured at 10 K increased by only approximately 3 times under 5 tesla; however, Rs(90) measured at 10 K was approximately 7 times larger.

4. Discussion

Mark et al. discussed the surface resistance of Type II superconductors under dc magnetic fields [4]. Lancaster modified their results and obtained the magnetic field dependence of a surface resistance [5]. The magnetic field dependence of Rs is expressed with following formula.

$$\mathrm{Rs} = \frac{\sigma_1 \varpi^2 \mu_0^2 \lambda_L^3}{2} + \frac{\Phi_0}{2\lambda_L \eta} \mathrm{B} \qquad \left(\mathrm{B} < \frac{\omega \mu_0 \lambda_L^2}{\Phi_0 \Gamma}\right) \tag{1}$$

$$\mathrm{Rs} = \left(\frac{\omega \mu_0 \Phi_0}{2\eta}\right)^{1/2} \mathrm{B}^{1/2} \qquad \left(\mathrm{B} > \frac{\omega \mu_0 \lambda_L^2}{\Phi_0 \Gamma}\right) \tag{2}$$

Where, ϖ, μ_0, λ_L, Φ_0, Γ are the angular frequency, permeability of free space, London penetration length, fluxoid, and dynamic vortex mobility, respectively. The η is the viscous drag coefficient. These typical values of YBCO (listed in table 1) are put into equations (1) and (2), and rewritten using the following formulas. To equalize the measured Rs in a non-magnetic field with calculated Rs using Equation (3), we adjusted the value of electric conductivity.

$$\mathrm{Rs} = 0.18\times10^{-3} + 3.45\times10^{-3}\,\mathrm{B}\ (\Omega), \quad (\mathrm{B} < 1.35\mathrm{T}) \tag{3}$$

$$\mathrm{Rs} = 4.16\mathrm{B}^{1/2}\times10^{-3}\ (\Omega), \ (\mathrm{B} > 1.35T) \tag{4}$$

Figure 5 shows the Rs(0) and Rs(90) measured at 10 K, at 40 K and at 70 K, and Rs calculated using Formula 3 and Formula 4 using the value of $k_p=10^4$ (Nm^{-2}) and $\eta = 10^{-6}$(Nsm^{-2}) are shown as the symbols of ○ and ●, respectively. The symbol △ is the calculated data by Equation (3) using $k_p=10^5$ (Nm^{-2}) and $\eta = 10^{-5}$(Nsm^{-2}). The magnetic dependence of Rs(0) and Rs(90) measured at 70K is mostly in agreement with the values of ○ and ●, and Rs(90) measured at 40 K is quite similar to the values of △. The k_p is the pinning potential well (Lubusch parameter) Since YBCO thin film has a large pinning potential compared with bulk samples, the surface resistance under high dc magnetic fields can be explained by Equation 3 using a large k_p.

From the magnetic field dependence of the measured surface resistance, it is possible to estimate the Rs(0) and Rs(90) under a 15-tesla magnetic field. These Rs(0) and Rs(90) are approximately 0.6 mΩ and 2 mΩ, respectively. The surface resistance of copper film at 15 tesla and at 10 K can be estimated at 3 mΩ using a two-fluid model. The results show that a YBCO-film NMR pickup coil operated over

Table 1 Parameters used of a YBCO thin film

parameter	
σ_1(10K)	$4.7\times10^7/\Omega\cdot$m
σ_1 (40K)	$5.3\times10^7/\Omega\cdot$m
λ_L	3.0×10^7m
η	(a) 10^{-6}Nsm^{-2} (b) 10^{-5}Nsm^{-2}
κ_p	(a) 10^4Nsm^{-2} (b) 10^5Nsm^{-2}
Γ	2.8×10^6

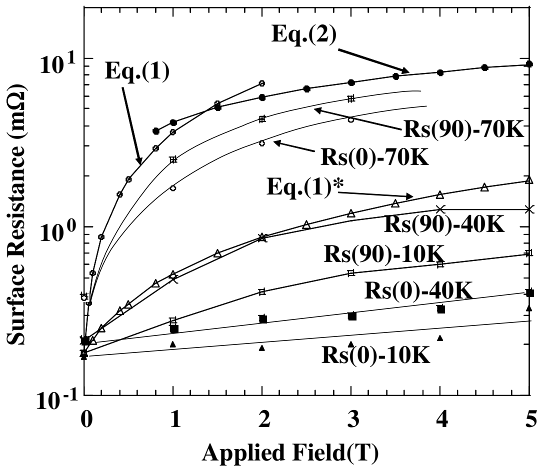


Figure 5. Measured and calculated Rs vs. applied magnetic fields.

15 tesla would provide no major advantage.

5. Conclusion

We examined the magnetic dependence of Rs of YBCO thin film by changing the direction of the applied field to the film surface. In the low temperature region (below 20 K), the Rs(0) showed quite a small magnetic dependence; however, Rs(90) and Rs(45) showed a high magnetic dependence even in the low temperature region. It is possible to estimate the Rs(0) and Rs(90) under a 15-tesla magnetic field. From the estimated value, it is found that YBCO film would provide only minor advantages if used for an NMR pickup coil operated at over 15 tesla.

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