Resistance Distribution in Thin Film Type SFCL Elements with Shunt Layers of Different Thicknes

Hye-Rim Kim*, Ok-Bae Hyun*, Seung-Yup Lee**, Kwon Kyu Yu***, and In-Seon Kim***

Abstract: Resistance distribution in thin film type SFCL elements of different shunt layer thickness was investigated. The 300 nm thick film of 2 inch diameter was coated with a gold layer and patterned into 2 mm wide meander lines. The shunt layer thickness was varied by ion milling the shunt layer with Ar ions, and also by having the shunt layer grown in different thickness. The SFCL element was subjected to simulated AC fault current for measurements. It was immersed in liquid nitrogenduring the experiment.The resistance distribution was not affected by the shunt layer thickness at applied voltages that brought the temperature of the elements to similar values. This result could be explained with the concept of heat transfer from the film to the surroundings. The resistance distribution was independent of the shunt layer thickness because thick sapphire substrates of high thermal conductivity dominated the thermal conductance of the elements.

Keywords : fault current limiter, superconducting, quench, YBa2Cu3O7

1. INTRODUCTION

The superconducting fault current limiter (SFCL) is a protection gear of new concept that limits the fault current in a few milliseconds. It provides the effect of circuit breakercapacity increase, relaxation of power machine criteria, and enhancement in power system reliability. For this reason there has been active research going on SFCLs [1]-[3]. The phase of basic research passed, and efforts are now directed to field applications.

Practical use of SFCLs requires small size and low cost. To achieve this end, it is necessary to increase the capacity of SFCL elements. Larger capacity allows one to use fewer elements to build up SFCL systems. Then, the system will be smaller, and easier to assemble. The cost will be also reduced. One way to increase the voltage capacity of thin film type SFCL elements is to adjust the thickness of the shunt layer that is coated on the superconducting thin films to disperse the heat generated at hot spots and protect the film surface from the atmosphere. It was proved in the previous work [4] that, when the shunt layer thickness was reduced to a half, the voltage capacity of the SFCL elements increased by 40 %. This means that 40 % fewer elements will be needed to build an SFCL system.

Practical use of SFCLs also requires their stable operation. A necessary condition for the stable operation is uniform temperature distribution in the SFCL element. In this work, we investigated the resistance distribution in SFCL elements based on YBa2Cu3O7 (YBCO) thin films with shunt layers of different thickness.

2. Experimental Details

SFCL elements were fabricated from 300 nm thick YBCO films grown on two-inch diameter sapphire substrates. The YBCO films were manufactured by Theva in Germany. The critical current density of the films was 2.5 MA/cm2 and uniform within 10 %. . In order to disperse the heat generated at hot spots, a gold layer was coated insitu on top of the YBCO film. The gold layer also plays a role of bypass around hot spots, andprotects the film surface from moisture in the air. The Au/YBCO film was patterned into 2 mm wide meander lines by photolithography (Fig. 1).The thickness of the gold layer was varied by ion-milling the 200 nm thick gold layer with Ar ions (Group A). Thereby it could be varied while keeping the same YBCO films. Current-voltage characteristics measured before and after the ion milling showed that superconducting properties of underlying YBCO films were not affected by the ion milling. The shunt layer

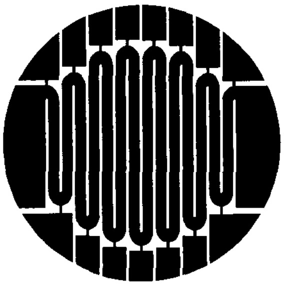

Fig. 1. The pattern of thin film SFCL elements. The element was of 2 inch diameter, and the mender line was 2 mm wide and 42 cm long.

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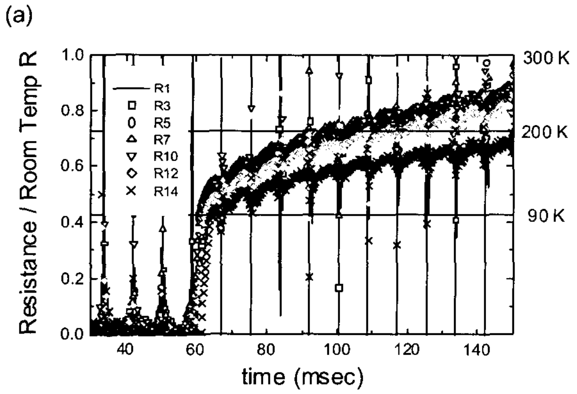
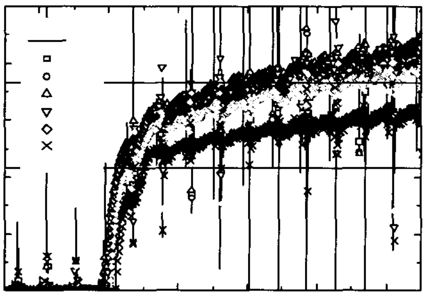
thickness was also varied by having the shunt layers grown in different thickness on YBCO films (Group B).

The resistance distribution in SFCL elements with different shunt layer thickness was measured using a fault simulation circuit. An AC power supply was used as the voltage source, and the fault was simulated by closing a switch connected across the load. Voltages and the current were measured simultaneously with a multi-channel data acquisition system. Voltage taps were mounted on pads along the meander lines tomeasure quench resistance distribution. For Group A SFCL elements, the distribution in SFCL elements with 200 nm thick gold was first measured. Then, the elements were ion-milled by around 50 nm, and the distribution was measured again. This step was repeated until the shunt layer was around 50 nm thick. The shunt layer thickness was estimated from the room temperature resistance of the elements. During the measurement, the elements were immersed in liquid nitrogen for effective cooling.

3. Results and Discussion

The average temperature of SFCL elements with the shunt layer thickness of around 200, 100, and 50 nm, both Groups A and B, reached around 250 K at 5 cycles after the fault at applied voltages of 180, 250, and 380 V, respectively [4]. Reduced thicknessincreases the quench resistance, and hence decreases the dissipated power. This enables the use of higher applied voltage, and yet maintains the temperature of SFCL elements below 250 K.





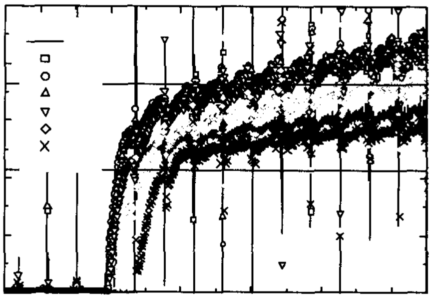


Fig. 2. The resistance distribution in SFCL elements of Group A with the shunt layer thickness of (a) 200 nm, (b) 93 nm, and (c) 43 nm at applied voltages of 180, 250, and 380 V, respectively.

Figs. 2(a), (b), and (c) show the resistance of selected stripes in SFCL elements of Group A with the shunt layer thickness of 200, 93, and 43 nm at applied voltages of 180, 250, and 380 V, respectively. R1, , and R14 in the legends denote the resistance of stripes 1, , and 14, respectively (Fig. 1). Resistance divided by the room temperature resistance was shown instead of the resistance itself to make comparison easier. The room temperature resistance was 35.5, 76.4, and 166.6 W, respectively, for the shunt layer thickness of 200, 93, and 43 nm. The range of SFCL temperature was similar except for some minor differences. The resistance was more or less uniform except at the edge during quench in all cases. Quench started at around the same time, especially in center stripes, and increased in the similar fashion. There were some minor differences. At the shunt layer thickness of 100 nm, quench at the edge started slightly later than at 200 nm and was not completed in the first half cycle. This behavior stayed on, and the range of the resistance became slightly wider. At 50 nm, this phenomenon was more prominent.

In order to see the resistance distribution more clearly, the resistance of SFCL elements with different shunt layer thickness at 5 cycles after the fault is presented in Fig. 3(a) as a function of the distance from the center of the element. The distance was measured perpendicular tothe meander line. In Fig. 3(b) the resistance normalized to the value at the center is shown to see the distribution even more clearly. Overall, the resistance distribution is similar. The resistance was all relatively uniform except at the edge.

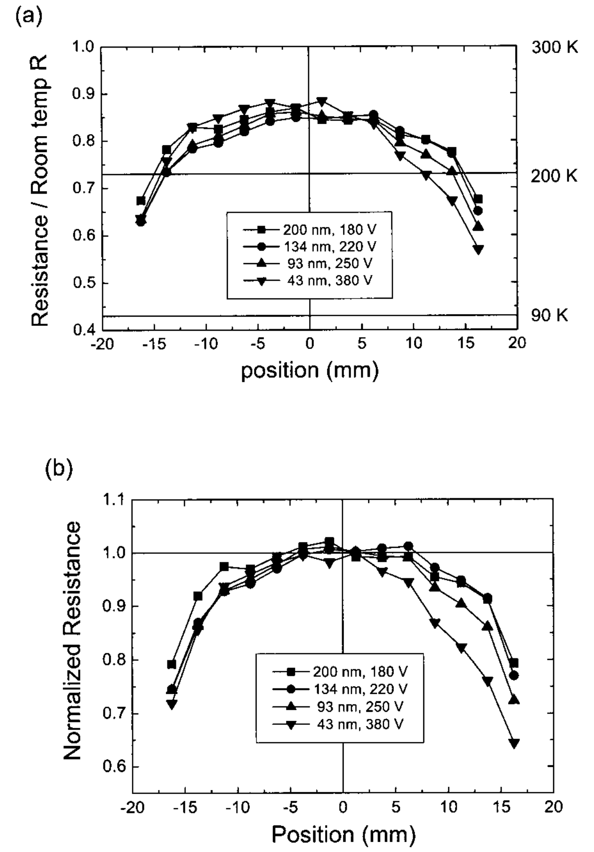


Fig. 3. Distribution of (a) resistance of the SFCL elementof group A, and (b) the resistance normalized to the value at the center at 5 cycles after the fault.

This is important because it means the dissipated power was not concentrated at one location but distributed relatively evenly among most of the stripes. The minor difference mentioned in the previous paragraph can be seen in the figure.

The results could be understood quantitatively with the concept of heat transfer from the SFCL element into surroundings. Detailed description of the concept can be found in [5], and the concept will be described only briefly here. A part of the heat generated in the meander line is transferred to surroundings, and the remainder increases the temperature of the meander line. Since the resistivity of metal generally changes linearly with temperature, the resistivity of the SFCL element increases as the temperature increases. A heat balance equation (1) describes this concept in a mathematical form. Equation (2) describes the change of the resistivity with temperature.

$$\nabla(-\kappa\nabla T) + c\frac{\partial T}{\partial t} + \alpha(T - T_b)\delta(z - d) + \alpha'(T - T_b)\delta(z + d_s)$$
$$= p = J^2\rho$$
(1)

$$(T) = a\,T + b \qquad (2)$$

where k, c, α′, , *c*, T_b, d_s, *d*, and *p* are thermal conductivity, specific heat, coefficients of heat transfer per unit area from the front and the back surface of the element to the cooling bath, cooling bath temperature, the thickness of the sapphire substrate and of the conductor, and dissipated power per unit volume, respectively. a and b in (2) are constants. The first term on the left-hand side of (1) describes the heat transferred to the neighboring part, and is responsible for the resistivity distribution. The second term describes the heat used to increase the stripe temperature. Last two terms describe the heat transferred from the front and the back surface of the element to the cooling bath. With reasonable assumptions and boundary conditions, the resistivity can be expressed analytically as follows:

$$\frac{\rho(x)}{\rho(0)} = \frac{1 - p\cosh g_x(x - x_0)/\cosh(g_x L_x/2)}{1 - p/\cosh(g_x L_x/2)} \qquad (3)$$

where $g^2_{x(y)} = A/(2D_{x(y)})$.

with $D_{x(y)} = \int_{-d_s}^{d} \kappa_{x(y)} \frac{T'_z(z)}{T'_z(d)} dz$,

$A \approx \alpha - J^2 a d_{Au}$,

and where p =$(aJ^2 d_{Au}/\alpha)$ tanh $(g_y L_y/2)/(g_y L_y/2)$. $L_{x(y)}$, T_z, and d_{Au} are the distance between electrodes, the z-dependent component of $T' = T - T_b$, and the thickness of the gold layer, respectively.In this equation, g expresses the uniformity of the resistivity, and p the difference between the resistivity at the center and the edge. The larger is g, the more uniform the resistivity is.

2Dx, the denominator of $g^2$is the thermal conductance of the SFCL element. Since the sapphire substrate is thick and has high thermal conductivity, its contribution to g^2 is dominant, and the effect of the shunt layer thickness on g^2 is negligible. The effect on A, the nominator of g^2, is negligible as well for the following reason. The SFCL element reaches the same temperature when the dissipated power is the same [4]. Dissipated power = $J^2 r\, d_{Au}$ w l, where w and l are width and length of the meander line. Since w and l are the same for all SFCL elements used in this experiment and since r is the same at the same temperature, J^2 $d_{Au}$is the same at all shunt layer thickness. Therefore, A is the same for all shunt layer thickness. Thus, g^2, that is, the uniformity of the resistivity is not affected significantly by the shunt layer thickness.

In order to understand the origin of the minor differences inthe resistance distribution shown in Fig. 3, the shunt layer thickness was estimated for each of stripe in the meander line, and shown in Fig. 4. The length of stripe #i divided by the room temperature resistance of the stripe, Li / $R_{i,RT}$ = $d_{Au,i}$ w / ρ_{RT}, and is proportional to the shunt layer thickness if ρ_{RT} is assumed to be uniform. The figure shows that the thickness was not very uniform except at 200 nm. It was progressively less uniform as the thickness decreased. This tells that the ion gun that wasused in theion milling was not big enough for uniform milling. Comparison of position dependence of resistance (Fig. 3b) and thickness distribution (Fig. 4b) reveals that the resistance distribution was similar at the position where the thickness distribution was similar. It differed where thethickness distribution differed. This tells that the slight difference in the resistance distribution shown in Fig. 3 was originated from the non-uniform distribution in thickness. If the shunt layer thickness were more uniform, the resistance distribution would be more similar, and be like that for 200 nm. This result is technically important, because it means that the SFCL element with a thinnershunt layer can be operated as stably as that with a thicker shunt. Fig. 5 shows the result of fitting data to (3) with p and gx as fitting parameters. The value of gx that fit data best was 0.31 0.05 /mm.

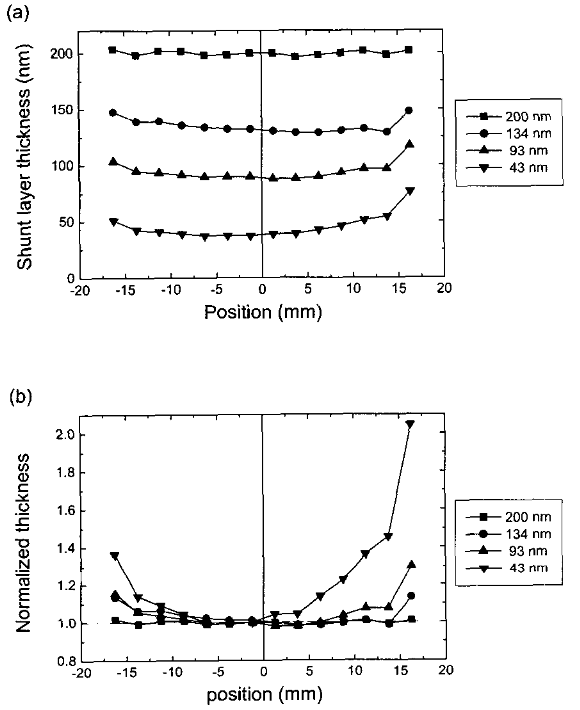


Fig. 4. Distribution of (a) the shunt layer thickness in the SFCL elements of group A, and (b) the thickness normalized to the value at the center.

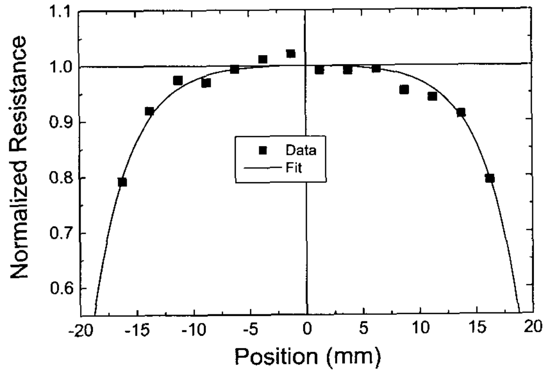


Fig.5. Normalized resistance distribution data and a fit to (3) for an SFCL element of Group A with the shunt layer thickness of 200 nm at 5 cycles after the fault. Applied voltage of 180 V.

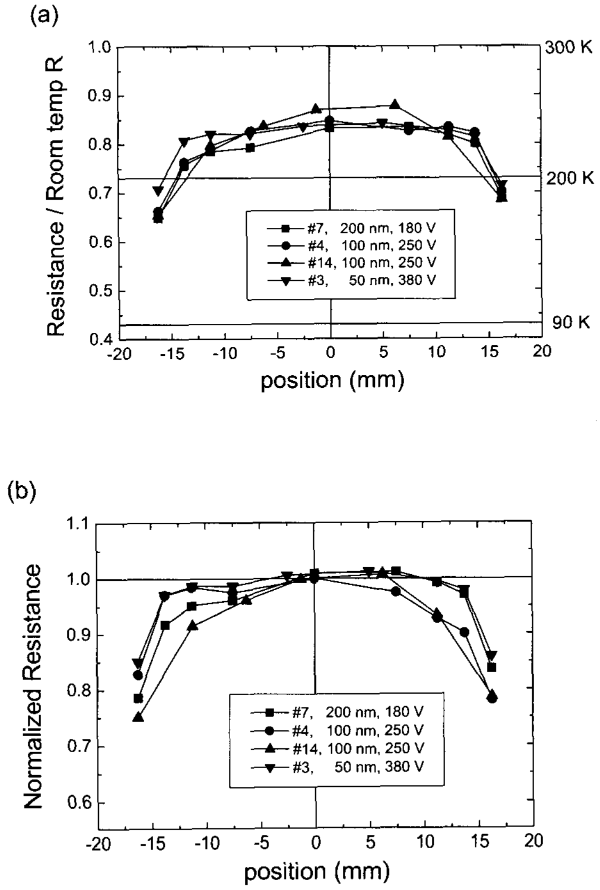


Fig. 6. Distribution of (a) resistance of SFCL elements of group B divided by the room temperature resistance, and (b) the value normalized to the center resistance at 5 cycles after the fault.

Figs. 6(a) and (b) show the resistance distribution in SFCL elements of group B with different shunt layer thickness. The distribution did not have a clear pattern. Both of elements #4 and #14 had shunt layers of around 100 nm thickness: 106 nm and 108 nm thick, respectively. Nevertheless they have noticeably different resistance distribution. Among the four elements, element #3 with 50 nm shunt layer thickness had the most uniform distribution, and element #14 with 100 nm thickness the least uniform distribution. Thickness distribution was all as uniform as that for 200 nm in Fig. 4(a). The result that resistance distribution in SFCL elements of group Bdid not have a clear pattern confirms that the resistance distribution is not affected significantly by the shunt layer thickness. It indicates that it is influenced more by the properties of the underlying YBCO films.

4. Conclusion

The resistance distribution in SFCL elements of different shunt layer thickness was investigated. The distribution was not affected significantly by the shunt layer thickness at applied voltages that brought the temperature of the elements to similar values. This result originated from the fact that thick sapphire substrates of high thermal conductivity dominated thermal conductance of the elements. The result is technically important in terms of stable operations of the SFCL elements with thinner shunt layers.

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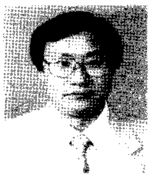

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