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Analysis on Recovery in Au/YBCO thin Film Meander Lines

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Au/YBCO 박막 곡선에서의 회복 분석

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Abstract

We investigated recovery in Au/$YBa_2Cu_3O_7$ (YBCO) thin film meander lines on sapphire substrates. The meander lines were fabricated by patterning YBCO films coated with gold layers. The lines were subjected to simulated AC fault current and then small current was applied for recovery measurements. The samples were immersed in liquid nitrogen during the experiment. After the fault, the resistance decreased linearly, first slowly and then fast to zero. The initial slow decrease was due to the decrease of the meander line temperature, whereas the fast decrease was originated from the transition from the normal state to the superconducting state. The recovery speed depended on the size of samples, and was faster in the smaller samples during the whole period of recovery. The experimental results were analyzed quantitatively with the concept of heat transfer within the sample and to the surrounding liquid nitrogen. A heat balance equation was solved for the initial phase of recovery, and an expression for the time dependence of resistance was obtained. The result agreed with data well.

Keywords : recovery, quench, YBCO thin film, heat transfer

I. Introduction

The superconducting fault current limiter (SFCL) is a protection device that limits the fault current in electric power systems in a few milliseconds. For this reason there has been active research going on SFCLs [1-3].

Knowledge on quench properties of superconductors is important for the research and development of SFCLs, because quench property determines their performance. Understanding of the recovery process is particularly important, because in many power systems reclosing of circuit breakers are required after each fault incident to check if the the fault incidence is a real fault. It is necessary that the SFCL is recovered to the normal operation state by the reclosing time.

In this work, we investigated the recovery in Au/$YBa_2Cu_3O_7$ (YBCO) thin film meander lines on

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sapphire substrate. The Au/YBCO meander lines are the core part of SFCLs based on YBCO thin films. Focus was placed particularly on the initial phase of the recovery, because the recovery is slower in this phase causing long recovery time. Resistance of the meander lines after the fault was measured, and the data were interpreted in terms of heat transfer within the meander lines/substrate and to the surrounding liquid nitrogen.

II. Experimental details

The samples were fabricated based on 300 nm thick YBCO films grown on sapphire substrates. The films were purchased from Theva in Germany. The critical current density of the films was around 3.0 MA/cm^2 and uniform within ±5 %. The film was coated in-situ with a gold shunt layer, and patterned into a meander line by photolithography (Fig. 1). A 200 nm thick gold layer was sometimes coated also on the back side of the substrate, and patterned into a meander line. The back Au meander line was used as a temperature sensor that measures the temperature at the back surface of the substrate.

Resistance of the Au/YBCO meander lines was measured using the circuit shown in Fig. 2. The meander line on the front side was connected to a fault simulation circuit. An AC power supply was used as the voltage source, V_o. The fault was simulated by closing a switch connected across the load, S_2, and cut off with switch S_1 several cycles after the fault so that the sample would not be subjected to fault currents for unnecessarily long time. The resistance after the fault was measured by applying low current to the circuit and measuring the voltage across the meander line. The current was low enough for the heat generated in the meander lines to be negligible. The Au meander line on the back side was connected to a DC power suppply, and about 10 mA was applied to the circuit. Voltages and currents were measured simultaneously with a multi-channel data acquisition system. During the measurement, the samples were immersed in liquid nitrogen for effective cooling.

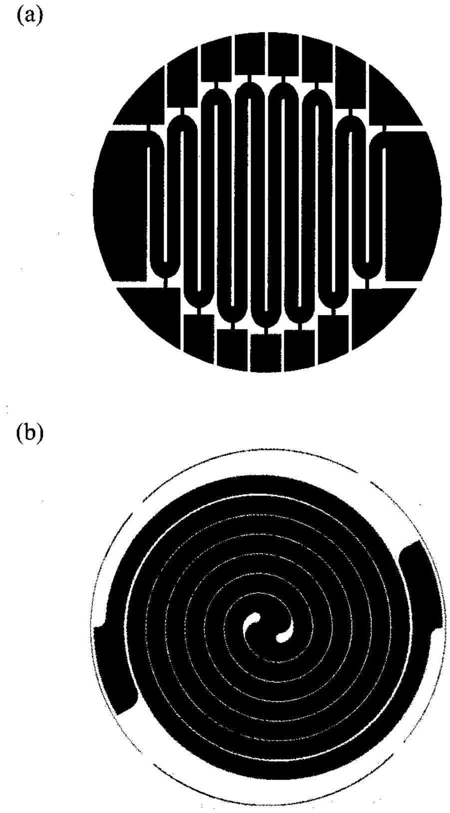

Fig. 1. The pattern of Au/YBCO meander lines (a) on a 2”-diameter substrate, and (b) on a 4”-diameter substrate.

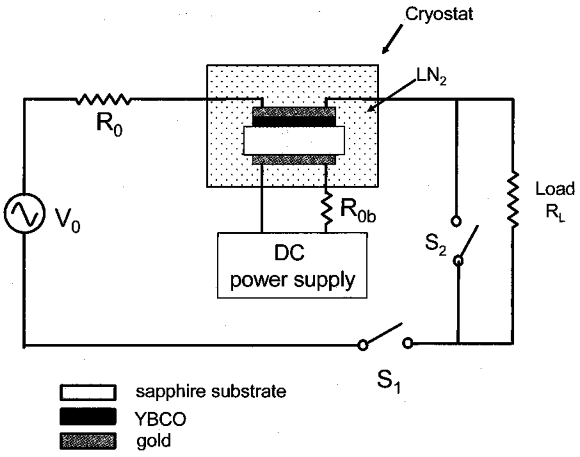

Fig. 2. A schematic diagram of the recovery measurement circuit.

III. Results and discussion

Fig. 3 shows the resistance of the Au/YBCO meander line at applied field strength of 6.7 V_{rms}/cm and fault duration of 5.5 cycles. The resistance was normalized with the room temperature value. Horizontal lines indicate temperature of the meander lines. The temperature was estimated from the relation between resistance and temperature of the gold shunt layer. The figure shows that resistance of the front meander line increased rapidly during the fault. The inset shows the resistance during the fault in detail. The resistance increased very rapidly at the beginning and then more slowly. Mechanism of the resistance increase is described in detail in [4,5]. After the fault was removed, the resistance started decreasing. It decreased first slowly and then faster to zero. It reached zero in 5.1 seconds.

In order to understand the recovery process better, the average temperature of the front and the back meander lines was calculated from the resistance data using the relation between resistance and temperature of meander lines under the assumption that the whole front meander line is in the normal state. The result is presented in Fig. 4(a). The inset shows the average temperature during the fault in detail. For the front meander line some calculated temperature values were below the liquid nitrogen temperature and not shown here; it is obvious that at those data points a part of the meander line is in the superconducting state. In our previous work [6], it was shown that temperatures of the front and the back meander lines on sapphire substrates are the same within experimental errors below 150 ~ 200 K and only slightly different at higher temperatures due to high thermal conductivity of sapphire. This means that the temperature of the back meander line can be taken as that of the front meander line below 150 ~200 K. In other words, the back meander line can be used as a

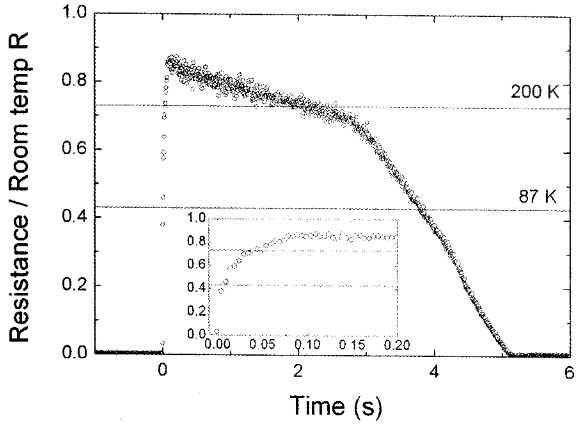

Fig. 3. Resistance of the front meander line at applied field strength of 6.7 V_{rms}/cm and fault duration of 5.5 cycles.

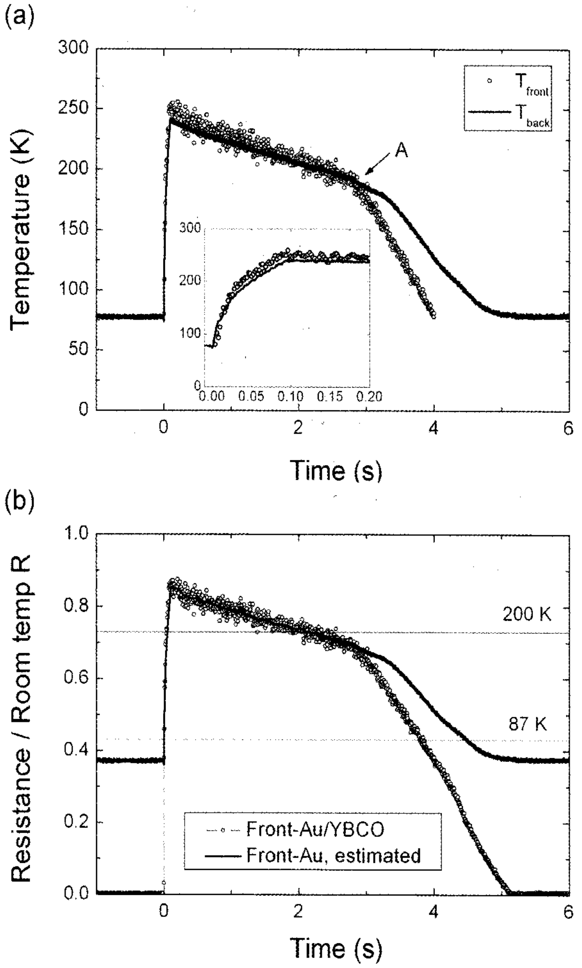

Fig. 4. (a) Temperature of the front and the back meander lines calculated from the resistance data under the assumption that the whole front line is in the normal state, and (b) resistance of the front Au/YBCO meander line and estimated resistance of the front Au line. Applied field strength was 6.7 V_{rms}/cm, and fault duration of 5.5 cycles.

temperature sensor for the front meander line in that temperature range. The figure shows that the curve for the front meander line deviates significantly from the curve for the temperature sensor after point A. The deviation is thought to be because a part of the front meander line recovered the superconductivity. Up to point A the whole front meander line stayed in the normal state. The resistance decrease comes from the decrease in the meander line temperature. At point A the front meander line started recovering the superconductivity. In order to see this more clearly, the resistance of the Au layer in the front meander line was estimated from the temperature and shown in Fig. 4(b), along with the resistance data for the front meander line. When the whole front meander line is in the normal state, its resistance is nearly the same as that of the Au line. As a part of the meander line recovers superconductivity, the resistance of the meander line starts deviating from that of the Au layer. In other words, from point A, the resistance decrease is mainly due to transition from the normal state to the superconducting state.

Recovery data for Au/YBCO lines on substrates of different size are compared in Fig. 5. The behavior was similar. In both cases the resistance decreased first slowly and then fast. However, the decrease rate was different. The resistance of the Au/YBCO line on a 2 inch-diameter substrate decreased faster than that on a 4 inch-diameter substrate during the whole recovery process. Even though the resistance was about the same initially, the resistance of the Au/YBCO line on a 2 inch-diameter substrate reached zero in 2.1 seconds, whereas that on a 4 inch-diameter substrate reached zero in 5.1 seconds.

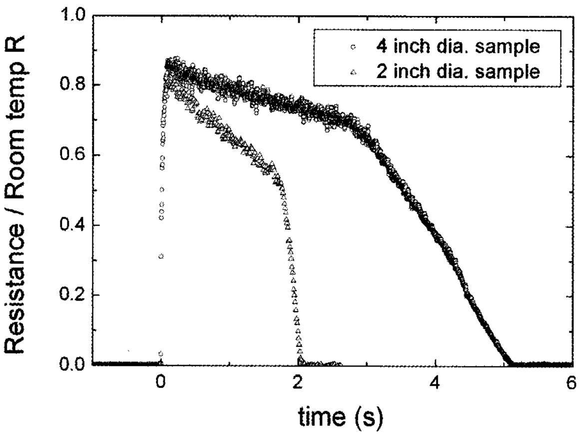

Fig. 5. Resistance of Au/YBCO lines on sapphire substrates of different size.

The observed recovery behavior can be quantitatively explained in terms of heat transfer within the sample and to the surroundings. As mentioned in the introduction, focus is placed here on the initial phase of recovery. After the fault is removed, Joule heat is no longer generated, and the heat accumulated in the sample during the fault is transferred to the surrounding liquid nitrogen. A heat balance equation describes this in a mathematical form:

$$c\frac{\partial T'}{\partial t} + \{\alpha\delta(z) + \alpha'\delta(z+d)\}T' + \nabla \bullet (-\kappa \nabla T') = 0, \qquad (1)$$

where $T' = T - T_b$.

Here, c, α, α', d, κ, and T_b, are specific heat, coefficient of heat transfer per unit area from the front and the back side to surroundings, thickness of the sample, thermal conductivity, and heat bath temperature, respectively. Terms on the left-hand side describe the heat release that decreases the sample temperature (the first term), and the heat transferred from the sample to surroundings and neighboring parts (the second and the third terms).

The temperature of the Au/YBCO line during the initial phase of recovery, when the whole front meander line is in the normal state, is expressed as [7]:

$$T'(x,y,t) = T_0'(t)\left(1 - \frac{\cosh(gx)\cosh(gy)}{\cosh(gL/2)\cosh(gL/2)}\right) \qquad (2)$$

where g^{-1} and L is the cooling depth and the size of the meander line area, respectively. $T_0'(t) \approx T'(0,0,t)$, which is the temperature at the center of the sample, for $L/2 >> g^{-1}$, which is the case here.

Integrating (1) over volume of the sample leads to:

$$c\frac{\partial T_0^{'}}{\partial t}+\left\{\frac{\alpha+\alpha'}{d}+g^2\frac{F}{V-F}\right\}T_0^{'}=0$$

$$\text{where } F=\int\left(\frac{\cosh(gx)\cosh(gy)}{\cosh(gL/2)\cosh(gL/2)}\right)dv,\text{ and} \qquad (3)$$

$$V=\int dv.$$

In the case of $L/2 >> g^{-1}$, this equation becomes:

$$\frac{\partial T_0^{'}}{\partial t}+\left\{\frac{\alpha+\alpha'}{c}\frac{1}{d}+\frac{4}{S}\frac{\kappa}{c}\right\}T_0^{'}\approx 0 \qquad (4)$$

where S is the surface area of the meander line. This equation tells that the recovery behavior is determined by thermal parameters and dimensions.

The thermal parameters, c, α, and κ, depend on temperature, particularly at lower temperatures, as shown in Fig. 6(a). The specific heat of sapphire increases steadily with temperature. The increase slows down somewhat at higher temperatures. The heat transfer coefficient is small when the temperature difference between the sample and the liquid nitrogen, T ', is larger than around 30 K. In this region, the liquid nitrogen goes into the film-boiling phase. The coefficient decreases with temperature. The decrease slows down at higher temperatures. The thermal conductivity of sapphire is fairly high at lower temperatures. It, however, decreases rapidly with temperature up to 150 ~ 200 K, and the decrease then slows down.

The ratio of specific heat to heat transfer coefficient, c/α, is roughly proportional to $(T\text{-}T_b)$, as shown in Fig. 6(b): that is, $c/\alpha \approx h\ T'$, where $h \approx 1.2$ s/(cm·K). On the other hand, the ratio of specific heat to thermal conductivity, c/κ, is roughly proportional to $(T\text{-}T_b)^2$ below 250 K (Fig. 6(c)). In other words, $c/\kappa \approx k\ T'^2$, where $k \approx 1.6 \times 10^{-4}$ s/(cm^2·K^2). Substituting these relations into (4) leads to:

$$\frac{\partial T_0^{'}}{\partial t}+\frac{1}{h^{'}d}+\frac{4}{Sk}\frac{\kappa}{T_0^{'}}\approx 0 \qquad (5)$$

where $h' \equiv c/\{(\alpha'+\alpha)T'\}$. This equation can be

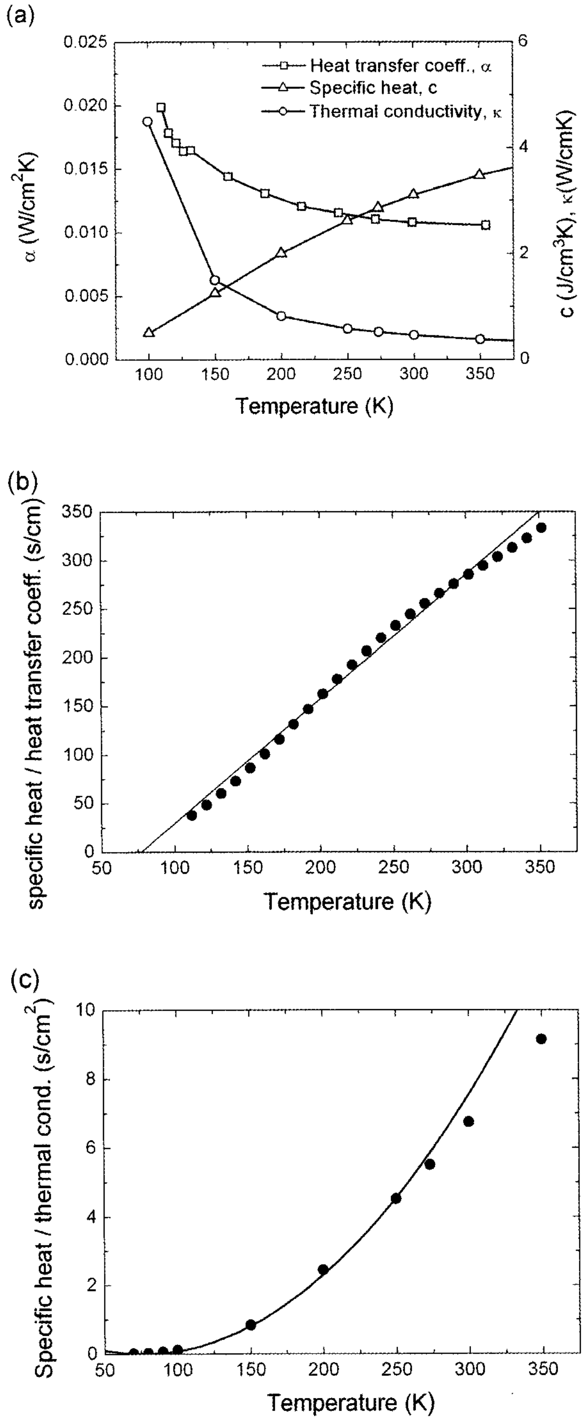

Fig. 6. Temperature dependence of (a) thermal parameters, values of which were taken from literatures [8], (b) c/α, and (c) c/κ.

solved analytically, and the solution is:

$$t = -A\left(T_0'(t) - T_0'(0) - B \ln \frac{T_0'(t) + B}{T_0'(0) + B} \right), \tag{6}$$

where $A = h'd$, and $B = 4h'd/(Sk)$.

This equation tells that faster recovery requires smaller specific heat, larger heat transfer coefficient, thinner substrates, higher thermal conductivity, and smaller surface area, as expected.

In the initial phase of recovery, the resistance of Au/YBCO lines decreases with decreasing temperatures: $R = a\,T_{av} + b = a\,T_{av}' + \beta \approx a\,T_0' + \beta$, where $\beta = a\,T_b + b$. The resistance of Au/YBCO lines can be then expressed as follows:

$$t = -\frac{A}{a}\left(R(t) - R(0) - aB \ln \frac{R(t) - \beta + aB}{R(0) - \beta + aB} \right) \tag{7}$$

For resistances not much lower than the initial resistance, (7) can be approximated to:

$$t \approx -\frac{A}{a} \frac{R(0) - \beta}{R(0) - \beta + aB} \left(R(t) - R(0) \right), \tag{8}$$

or, equivalently,

$$R(t) \approx R(0) - \frac{a}{A} \frac{R(0) - \beta + aB}{R(0) - \beta} t \tag{9}$$

Thus, the resistance decreases more or less linearly with time.

Using the values of h and k given above, temperature dependence of resistance was calculated for the Au/YBCO meander lines on 2-inch and 4-inch diameter sapphire substrates (Figs. 1(a) and 1(b)). The result is presented in Figs. 7 and 8, respectively, along with data. For the meander line on a 2-inch substrate, $h' = h/2$ gave the best fit to data. This indicates that cooling of this sample by liquid nitrogen at the back surface is similar to that at the front surface. On the other hand, for the meander line on a 4-inch substrate, $h' = h/1.2$ gave the best fit to data. This indicates that cooling of the sample at the back surface is weaker than that at the front surface. The calculation results prove that data can be understood quantitatively with the concept of heat transfer.

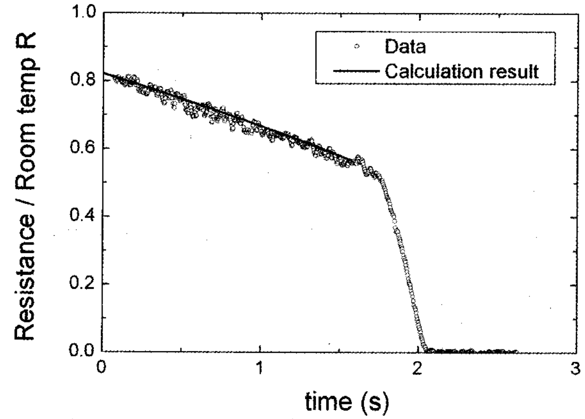

Fig. 7. Calculation result for resistance of the Au/YBCO meander line on a sapphire substrate of 0.043 cm thickness and effective diameter of 2 cm. Data are also shown for comparison.

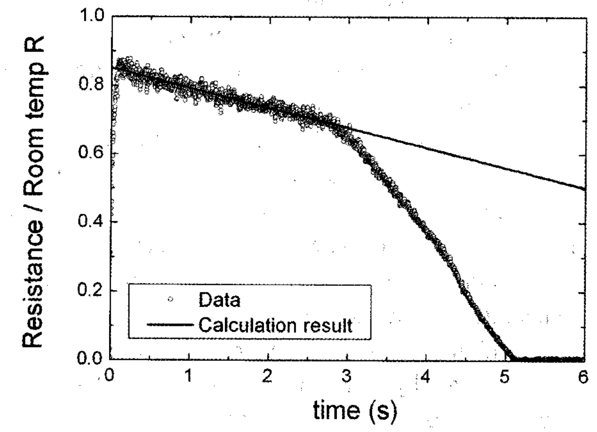

Fig. 8. Calculation result for resistance of the Au/YBCO meander line on a sapphire substrate of 0.053 cm thickness and effective diameter of 4.5 cm. Data are also shown for comparison.

IV. Conclusion

We investigated recovery in Au/YBa$_2$Cu$_3$O$_7$

(YBCO) thin film meander lines on sapphire substrates. After the fault, the resistance decreased linearly, first slowly and then fast. The initial slow decrease was due to the decrease of the meander line temperature, whereas the fast decrease was originated from the transition from the normal state to the superconducting state. The recovery was faster in the smaller samples during the whole period of recovery. The experimental results were analyzed quantitatively with the concept of heat transfer within the sample and to the surrounding liquid nitrogen. The result agreed with data well. The result of this work will be applied to the design of SFCL elements with short recovery time.

Acknowledgments

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