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Temperature Behavior of Superconducting Fault Current Limiters during Quenches

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퀜치 시 초전도 한류기의 온도

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Abstract

We investigated temperature behavior of superconducting fault current limiters (SFCLs) during quenches. Knowledge on temperature behavior during quenches is important to the design of SFCLs, because the temperature of SFCLs is related to their stability. SFCLs were fabricated by patterning Au/$YBa_2Cu_3O_7$ thin films grown on sapphire substrates into meander lines by photolithography. A gold film grown on the back side of the substrate was patterned into a meander line, and used as a temperature sensor. The front meander line was subjected to simulated AC fault currents, and the back line to DC current. They were immersed in liquid nitrogen during the experiment for effective cooling. Overall, temperature at the back side of SFCLs was close to that at the front side. It was closer at the beginning of faults, and at lower applied voltages. Temperature distribution at the back side was even except at the edge, as at the front side. These results tell that the whole SFCL was heated to similar degree during quenches, and that effective cooling of SFCLs at the back side is as important to the stability of SFCLs as at the front side. The results could be explained with the concept of heat transfer within the film.

Keywords : quench, superconducting, fault current limiter, temperature

I. 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 breaker capacity increase, and enhancement in power system reliability. For this reason there has been active research going on SFCLs [1-3].

Knowledge of the quench properties of superconductors are important for the research and development of SFCLs because quench property determines their performance. Although there has been a considerable amount of work done on quench properties of low temperature superconductors, there was not much work done on those of high temperature superconductors.

The temperature behavior of SFCLs is particularly important for their research and development because

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it is closely related to their stabiliy. In this work, we measured the temperature at the front and the back sides of SFCLs based on $YBa_2Cu_3O_7$ (YBCO) thin films coated with a gold layer. Data were interpreted in terms of heat transfer within the film.

II. Experimental details

The samples were fabricated based on 300 nm thick YBCO films grown on two-inch diameter 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 2 mm wide and 42 cm long meander line by photolithography (Fig. 1(a)). Rated current (critical current) of the meander line was 22 A at 77 K. A gold layer was coated on the back side of the substrate, and patterned into a 1 mm wide and 42 cm long meander line (Fig. 1(b)). The Au meander line was used as a temperature sensor that measures the temperature at the back surface of the SFCLs. The pattern on the back side was aligned so that it matched with that on the front side.

The temperature behavior 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. Various voltages up to 280 V_{rms}(6.7 V_{rms}/cm) including the rated voltage of the meander line (230 V_{rms}, 5.5 V_{rms}/cm) was applied to examine the effect of the applied voltage. 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 magnitude of fault current was set with R_0 (= 1 Ω) and not varied, because in a previous work it was found that the magnitude of fault current did not affect the quench behavior of the meander line. The Au meander line on the back side was connected to a DC power suppply. The nominal applied current was 20 mA, at which the heat generated in the Au meander line is negligible. Voltage taps were mounted on pads along the meander lines on both the front and back sides of SFCLs to measure the temperature distribution. Voltages and currents were measured simultaneously with a multi-channel data acquisition system. During the measurement, the elements were immersed in liquid nitrogen for effective cooling.

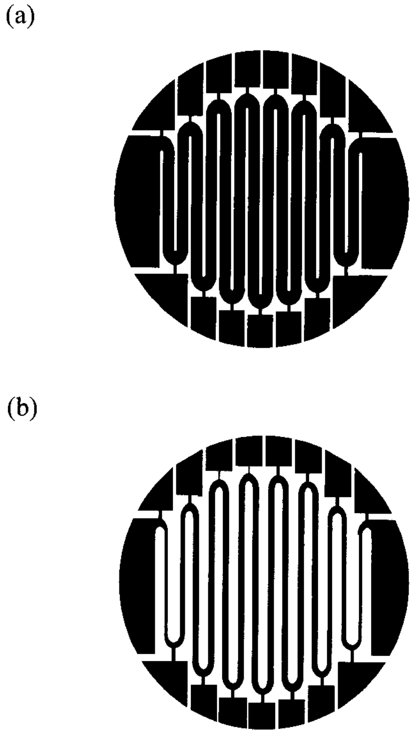

Fig. 1. The pattern of meander lines
(a) on the front side, and (b) on the back side.

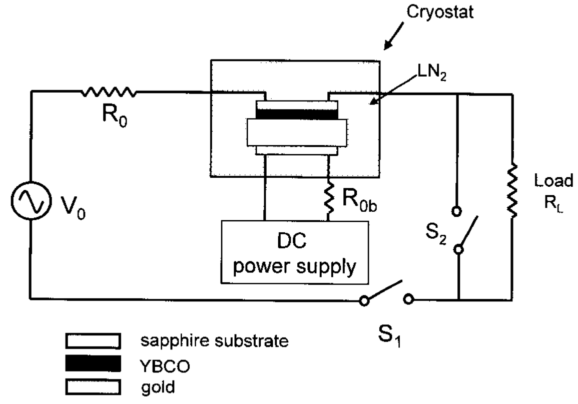

Fig. 2. A temperature measurement circuit.

III. Results and discussion

Fig. 3 shows the resistance of the Au meander line at 6.7 V_{rms}/cm (280 V_{rms}) on the back side of an SFCL along with that of the Au/YBCO meander line on the front side. The resistance was normalized with the room temperature resistance to show the temperature of meander lines. Temperature of the meander lines can be estimated from the linear relation between their resistance and temperature. For the meander on the front side, data right after the quench start was not shown, because in this time range there still exist superconducting parts and it is difficult to estimate the temperature unambiguously. The figure shows that the temperature at the back side was quite close to that at the front side. The former was around 310 K at 7 cycles after the fault, when the latter was around 332 K. it was even closer at the beginning of the fault. This means the temperature of the SFCL is quite uniform in the vertical direction, the direction perpendicular to surfaces of the SFCL. It also means that a lot of heat will be transferred from the back surface of the SFCL to the surrounding liquid nitrogen. This explained a lot of bubbles generated at the back surface during quenches. The SFCL needs to be positioned in ways that bubbles can escape easily from the back surface as well as from the front surface.

The temperature at the back side of the SFCL was even closer to the front side at lower applied field strength. Fig. 4 presents the temperature on the front and the back sides of the SFCL at applied field strength of 5.5 V_{rms}/cm (230 V_{rms}) and 3.6 V_{rms}/cm (150 V_{rms}). It can be seen that temperatures are closer to each other than at 6.7 V_{rms}/cm. They are almost the same at 3.6 V_{rms}/cm. These results were universal for Au/YBCO meander lines on sapphire substrates in liquid nitrogen.

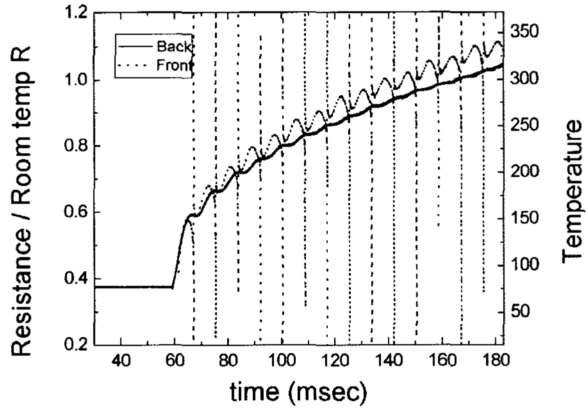

Fig. 3. Resistance normalized with its room temperature value of meander lines on the front and the back sides of an SFCL. Applied field strength was 6.7 V_{rms}/cm (280 V_{rms}).

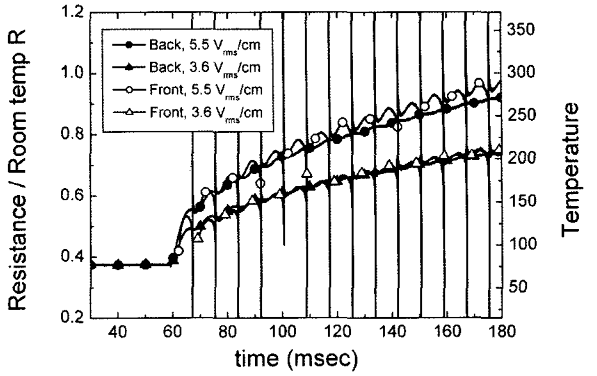

Fig. 4. Temperature of meander lines on the front and the back sides of an SFCL for selected field strength.

Fig. 5 shows the temperature of the selected stripes on the front and the back sides of the SFCL. As shown in Fig. 1(a), the meander line consists of 14 stripes. Stripes 1 and 14 are the stripes located next to electrodes. Stripe 7 is one of two center stripes. The temperature distribution at the back side was similar to that at the front. The temperature was fairly uniform in all areas of the meander line except at the edge area, where it was somewhat lower. At all stripes including stripes 1 and 14, the temperature at the back side was close to that at the front side. In order to see this more clearly, the temperature at 7 cycles after the fault is plotted as a function of position in Fig. 6. The temperatures at the front and back sides are fairly close to each other and have similar position-dependence. At field strength of 6.7 V_{rms}/cm, the difference between temperatures at the front and back sides was larger than that of neighboring stripes on one side. At lower field strength, the difference was smaller.

These results can be understood in terms of heat propagation in the SFCL. As the quench starts in the Au/YBCO meander line, Joule heat is generated. The heat increases the temperature of the meander line. As the temperature deviates from the surroundings, a

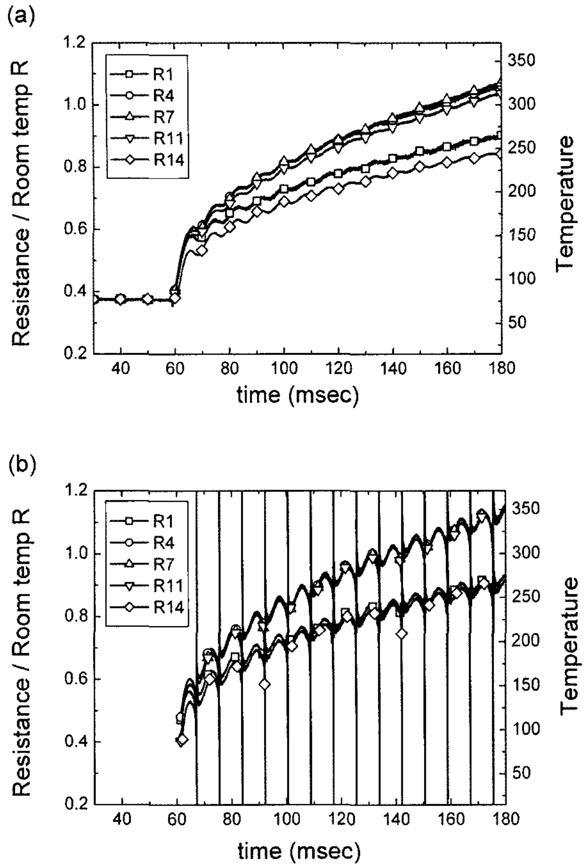

Fig. 5. Temperature of the selected stripes (a) on the back side, and (b) on the front side of the SFCL. Applied field strength was 6.7 V_{rms}/cm (280 V_{rms}).

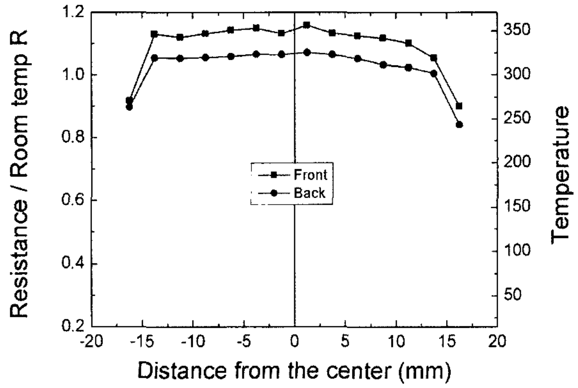

Fig. 6. Temperature distribution at the front and the back sides of the SFCL at 7 cycles after the fault. Applied field strength was 6.7 V_{rms}/cm.

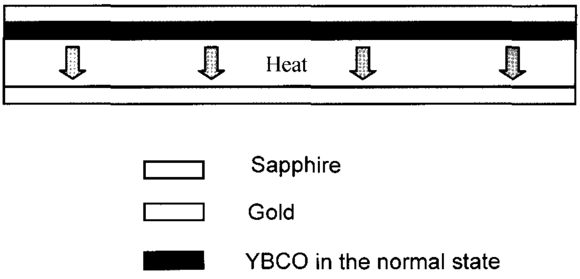

Fig. 7. A model of heat propagation.

part of the generated heat is transferred to liquid nitrogen and to neighboring parts of the SFCL. Detailed description of the heat transfer concept can be found in [4].

The heat transferred from the Au/YBCO meander line to neighboring parts increases their temperature. The transferred heat can be expressed mathematically as $-\kappa \nabla^2 T$, where κ is the thermal conductivity of the sapphire substrate. Since the temperature variation is small in horizontal direction as can be seen from Fig. 6, the heat flows in the vertical direction (Fig. 7) to the sapphire substrate and increases temperature of the substrate. The transferred heat is then expressed as $-\kappa\, \partial^2 T/\partial z^2$. The observation that the temperatures at the front and the back side were close to each other means that κ is high, especially at the beginning of the fault and at lower electric field strength. This coincides with the fact that the thermal conductivity of sapphire is as high as that of metals at liquid nitrogen temperature, and that it decreases as the temperature increases. As a matter of fact, Fig. 3 and 4 show that the temperatures at the front and the back side were almost the same when they were below about 200 K.

IV. Conclusions

We investigated the temperature behavior in superconducting fault current limiters during quenches. The temperature at the back side of SFCLs was close to that at the front side. It was closer at the beginning of faults, and at lower applied voltages. Temperature distribution at the back side was uniform except at the edge, as at the front side. These results tell that the whole SFCL was heated to similar degree during quenches, and that effective cooling of

SFCLs at the back side is as important to the performance of SFCLs as at the front side. This observation should be reflected in the design of SFCLs.

Acknowledgments

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