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Quench Distribution in Au/YBCO Thin Film Meander Lines with a Au Meander Line Heater

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금선 히터가 있는 금/YBCO 박막 선에서의 퀜치 분포

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Abstract

We investigated quench distribution in Au/YBCO thin film meander lines with a heater. Quench distribution during faults is important for superconducting fault current limter applications, because uniform quench allows application of higher voltages across the meander lines. Au/YBCO thin films grown on sapphire substrates were patterned into meander lines by photolithography. Gold films grown on the rear sides of the substrates were also patterned into meander lines, and used as heaters. Meander lines on the front and the rear sides were connected in parallel. The meander lines were subjected to simulated AC fault currents for quench measurements during faults. They were immersed in liquid nitrogen during the experiment for effective cooling. Resistance of the Au/YBCO meander lines initially increased more rapidly with the rear heater than without, and consequently the fault current was limited more. The resistance subsequently became similar. The resistance distribution was more uniform with the heater, especially during the initial quench. Quench was completed more uniformly and significantly earlier. This resulted in uniform distribution of dissipated power. These results could be explained with the concept of quench propagation, which was accelerated by heat transfer across the substrate from the rear heater.

Keywords : superconducting fault current limiter, $YBa_2Cu_3O_7$, quench

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]. The phase of basic research passed, and efforts are now directed to field applications.

Widespread use of SFCLs requires small size and low cost. To achieve this end, it is necessary to increase the capacity of elements that SFCLs are composed of. Larger capacity allows one to use fewer elements to build up SFCL systems. Then, the system will be smaller, less expensive, and easier to assemble. In order to increase the voltage capacity of SFCL elements, the quench resistance distribution in the elements must be uniform. Thus is because the voltage capacity of the elements is determined by the temperature of the hottest spots in the elements for

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their stable operation. In this work, we investigated the quench distribution in Au/YBCO thin film meander lines with rear side heaters. Uniform quench was induced in the front Au/YBCO meander line.

II. Experimental details

The samples were fabricated from 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 2 mm wide meander lines by photolithography (Fig. 1(a)). A Gold layer were coated on the rear side of the substrates, and patterned into 1mm wide meander lines (Fig. 1(b)) to be used as a heater. The pattern on the rear side was aligned so that it matched with that on the front side.

The quench properties of the Au/YBCO meander lines with a rear side heater were measured using a fault simulation circuit (Fig. 2). The meander lines on the front and the rear sides were connected in parallel. An AC power supply was used as the voltage source, V_0. 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 times. Voltage taps were mounted on pads along the meander lines to measure quench resistance distribution. Voltages and the current were measured simultaneously with a multi-channel data acquisition system. During the measurement, the elements were immersed in liquid nitrogen for effective cooling.

III. Results and discussion

Figs. 3(a) shows the quench properties of the Au/YBCO meander line with and without the rear side heater. With the heater, the current was limited to significantly lower values at the beginning of the fault than without. It became similar soon, and stayed at slightly lower values during the fault. Most of source voltages were applied across the meander lines and the voltages were more or less the same.

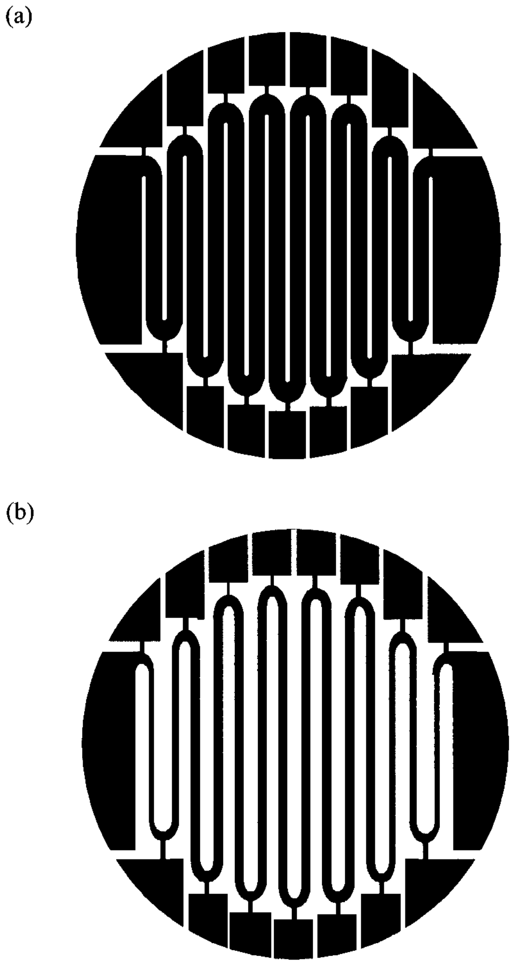

Fig. 1. The patterns of Au/YBCO meander lines (a) on the front side, and (b)on the rear side.

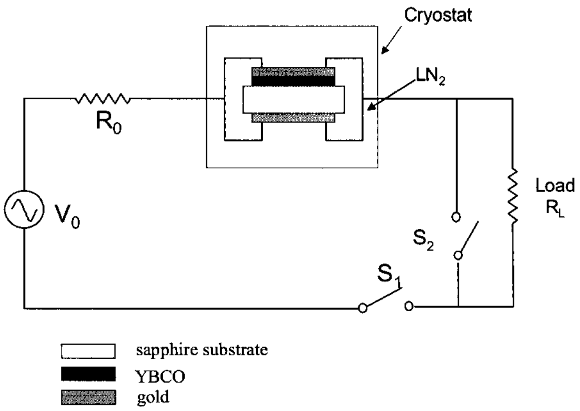

Fig. 2. The quench measurement circuit

The resistance increased more rapidly at the beginning of the fault. It became similar, and stayed at slightly higher values. The average temperature of the mender line 5 cycles after the fault start was 237 K with the heater, and 216 K without. The temperature was estimated from the resistance vs. temperature relation. The dissipated power was significantly lower with the heater. This result is technically important, because power density is related to the stability of the menader line. It is, in turn, related to the voltage rating, when the meander line is used as an element of SFCLs.

In order to see more clearly the changes at the beginning of the fault, a zoomed view is shown in Fig. 3(b). In the current graph, curves for the total current in the circuit and the heater current was added. The current started flowing in the heater as soon as the resistance developed. About 0.5 ms later the current with the heater deviated clearly from that without the heater. The currents became similar about 5 ms later. The voltages were similar during the whole time. The resistance with and without the heater increased rapidly for about 0.6 ms at the very beginning of the fault, then slightly less rapidly, and started deviating from each other. They became similar about 5 ms later. The dissipated power behaved in the similar way. The rapid rise at the very beginning was more prominent than that of the resistance.

Figs. 4(a) and 4(b) presents resistance per unit length of selected stripes in SFCL elements in the Au/YBCO meander lines with and without the heater, respectively. Stripes 1 and 14 are the stripes next to electrodes. The resistance increased more rapidly at the beginning with the heater, as pointed out in the previous paragraphs. It increased more uniformly at the beginning with the heater than without the heater. The uniformity stayed on throughout the fault. Figs.

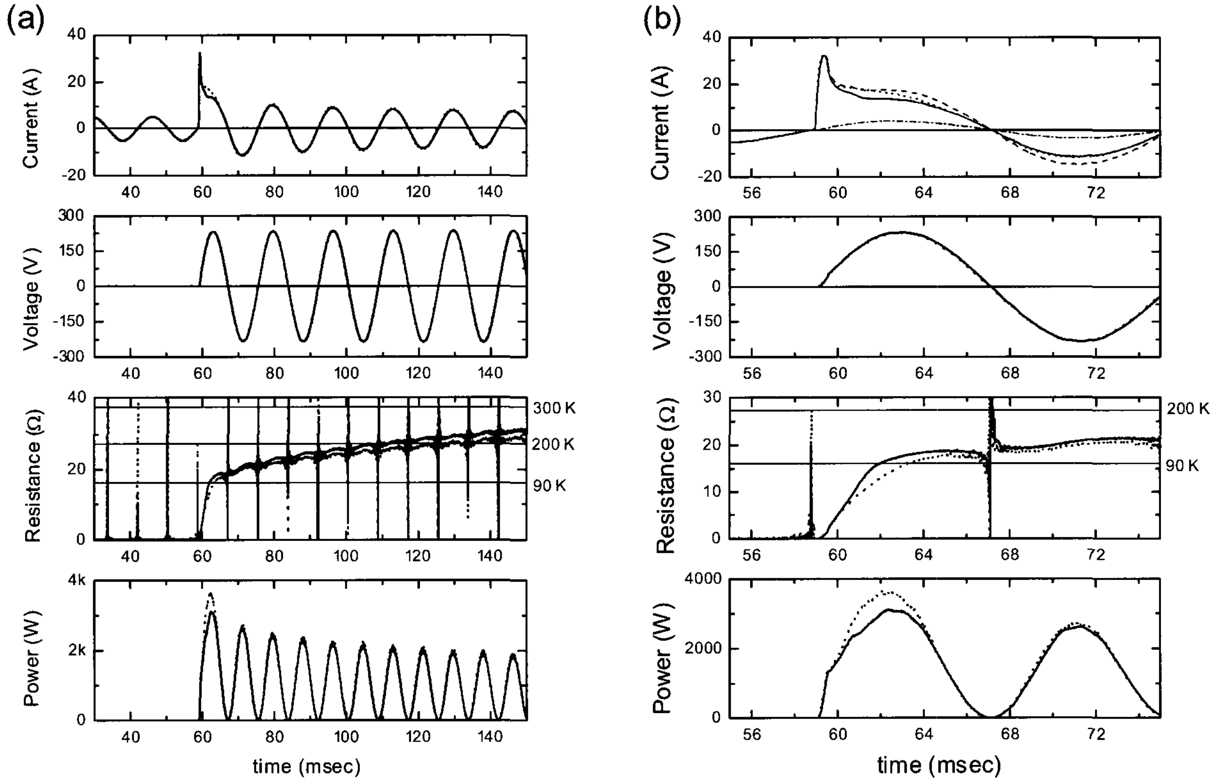

Fig. 3. Quench properties of the Au/YBCO mender line (a) during the whole period of the fault, and (b) at the beginning of the fault. Solid lines are for data with the heater, and dotted lines for data without. In the current graph of (b), the dashed line is for the total current and the dashed-dotted line is the current in the heater.

5(a) and 5(b) shows a expanded view of the initial resistance distribution. In all stripes the resistance increased faster with the heater than without except for about 0.3 ms at the very beginning. For example, it took about 2.3 ms with the heater for quench to be completed in stripes 5, 7, and 10, as compared with 3.5 ms without the heater. The change was more prominent in stripes 13 and 14. Without the heater these stripes did not start quench until 1.2 ms and 1.9 ms after other stripes did. With the heater they started quench 0.4 ms and 0.7 ms earlier. As in other stripes, it took similarly less time for quench to be completed in these stripes with the heater. As a result, the resistance distribution became more uniform. 5 cycles after the fault start, the resistance distribution became as shown in Fig. 6. It was more uniform with the heater. The average temperature of stripes 2~13 ranged from 229 to 244 K with the heater, and 200 to 229 K without the heater. Thus, the highest average stripe temperature was 15 K higher with the heater. The difference between the temperature of hottest spots in the meander line with and without the heater is thought to be even smaller.

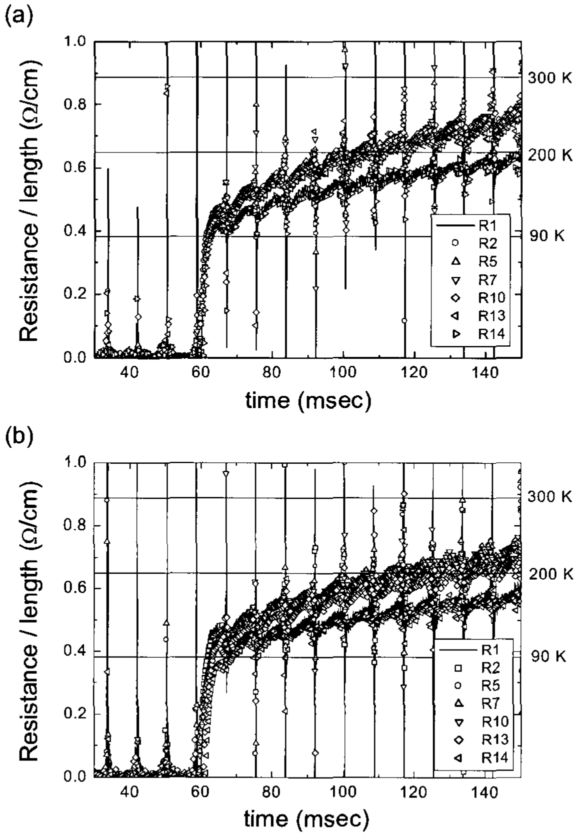

Fig. 4. The resistance distribution in the Au/YBCO meander line (a) with the heater, and (b) without the heater.

Dissipated power distribution is important in terms of the stability of the meander line. The distribution with and without the heater is shown in Figs. 7(a) and 7(b), respectively. It was more uniform with the heater throughout the fault. The uniformity was most prominent in the first half cycle. The peak value of power per unit length ranged from 680 to 780 W/cm with the heater, in contrast to 610 to 1,100 W/cm without the heater. This tells that the Au/YBCO meander line was more stable with the heater.

The results could be understood with the concept

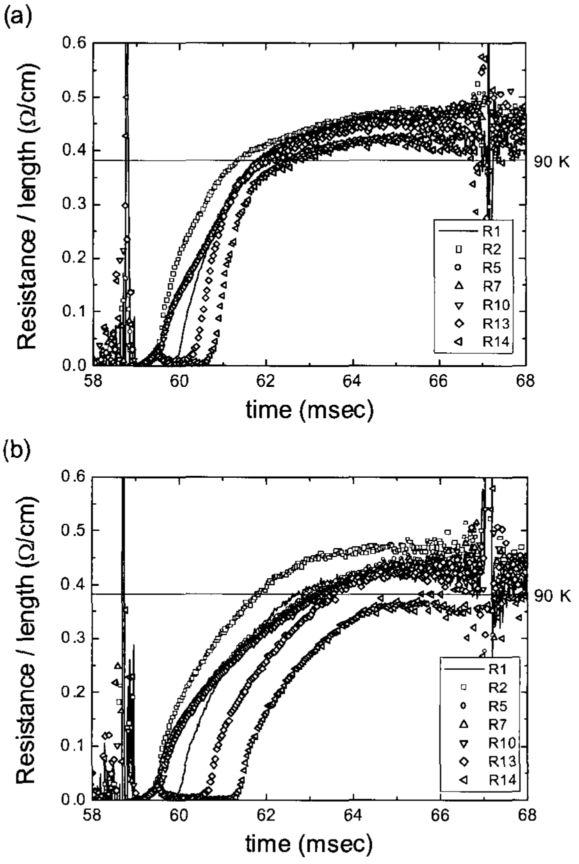

Fig. 5. The resistance distribution in the Au/YBCO meander line at the beginning of the fault (a) with the heater, and (b) without the heater.

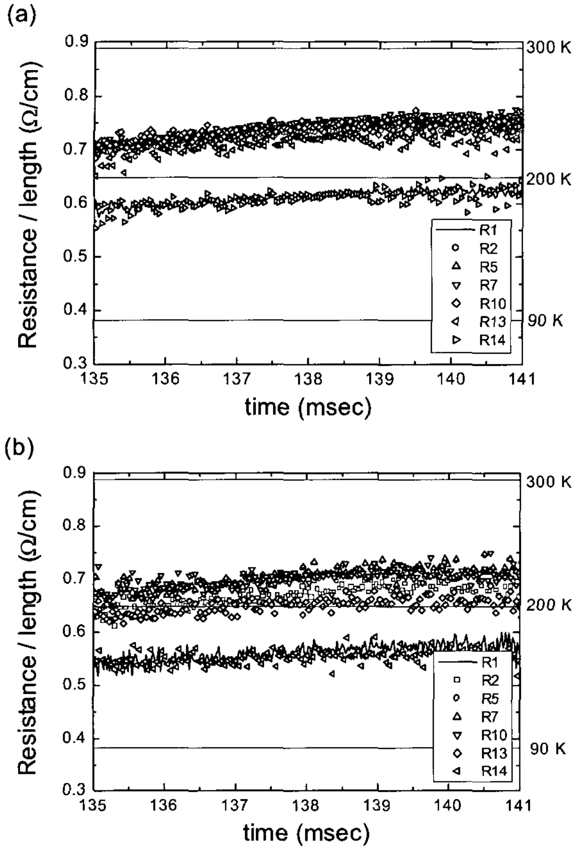

Fig. 6. The resistance distribution in the Au/YBCO meander line 5 cycles after the fault start (a) with the heater, and (b) without the heater.

of heat propagation in the sample. As the quench starts in the Au/YBCO meander line, Joule heat is generated. A part of the heat generated is transferred to the neighboring part of the sample and to liquid nitrogen. The remainder increases the temperature of the stripe. The heat transferred from the neighbor also contributes to the temperature increase. Detailed description of the heat transfer concept can be found in [4]. As the quench starts in the Au/YBCO meander line, the current start flowing in the rear meander line. Consequently, heat is generated both in the front and the rear meander lines, and the rear one acts as a heater. Since, unlike the front line, the resistance of the rear line is nearly uniform, so is the generated heat. Most of the heat generated is lost to the surrounding liquid nitrogen, but some is transferred to the front meander line through the 0.5 mm thick

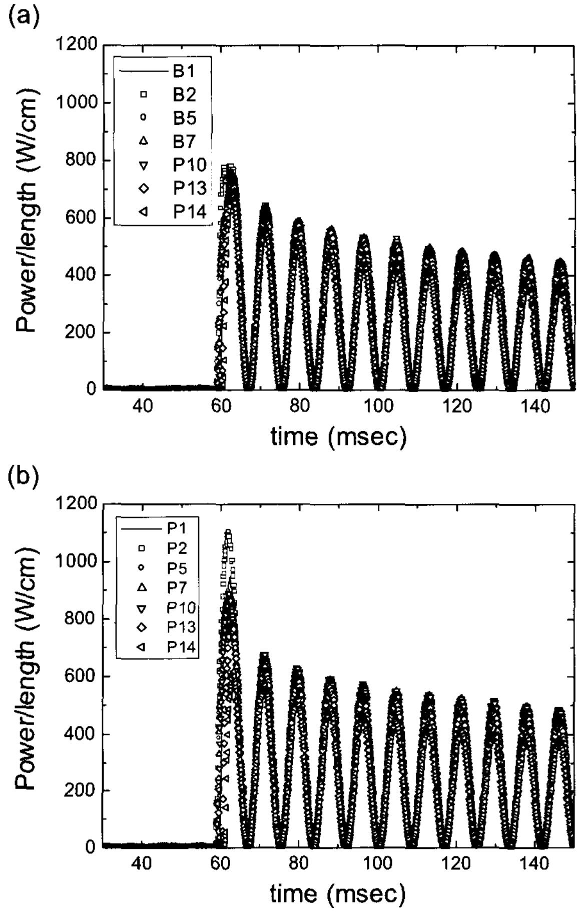

Fig. 7. The dissipated power distribution in the Au/YBCO meander line (a) with the heater, and (b) without the heater.

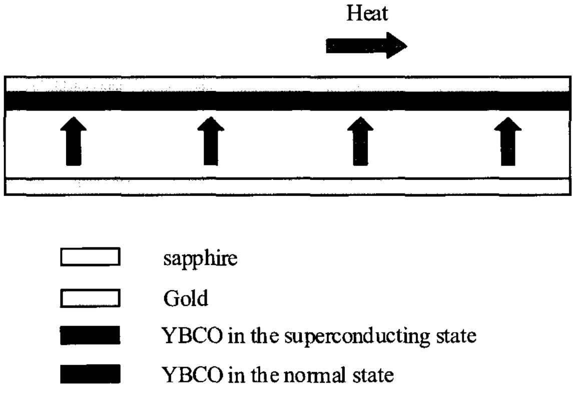

Fig. 8. A model of heat propagation

sapphire substrate (Fig. 8). This heat transforms the superconducting part of YBCO into the normal state. As a result, the part of YBCO far away from the quench start point, e.g., stripes 13 and 14 in Fig.5, starts quench relatively early. Without the heater, it has to wait until the heat propagated several centimeters sideways through the front meander line and the substrate.

IV. Conclusion

We investigated quench distribution in Au/YBCO thin film meander lines with a rear side heater. Resistance of the meander lines initially increased more rapidly than without the heater, and the fault current was limited more. The resistance subsequently became similar. The resistance distribution was more uniform with the heater, especially during the initial quench. Quench was completed more uniformly and significantly earlier. This resulted in uniform distribution of dissipated power. This is technically important, because it means the meander line becomes more stable with the heater. It allows application of higher voltages across the meander line.

Acknowledgments

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