Laser scanning imaging and local characterization of superconducting properties in high- T_c thin film multiturn coil

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Received 10 June 1994; revised manuscript received 26 July 1994

Abstract

Low-temperature scanning laser microscopy has been used to investigate the spatial variation of the critical temperature T_c and critical current I_c in thin-film high- T_c multilayer structures that include dielectric layers. The method is described and measurements are presented on an $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ -based multiturn coil with SrTiO_3 insulating layer. We found that the critical temperature T_c of the $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ top layer, from which the return strip of the coil is formed, is higher than that of the $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ base layer. The critical current of the coil is limited by the quality of the $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ base layer and not by the edges of the crossovers.

1. Introduction

Methods to investigate the spatial variation of the critical temperature T_c and the critical current I_c in structured multilayers provide relevant information for the development of high- T_c superconducting electronic devices. These devices consist of active components, such as Josephson junctions or three terminal devices, and passive components such as resistors, inductances, capacitances and circuitry, which is discussed here. In circuitry several aspects are of importance [1], such as the quality of the various superconducting layers (indicated by T_c and the critical current density j_c), the insulation in the crossovers (occurrence of shorts), growth of layers over edges in underlying structures, and the T_c and I_c of superconducting interconnects. Spatially resolved measurements reveal critical points in the structures and help to examine the effect of a change in the fabrication process.

Low-temperature scanning electron microscopy (LTSEM) has recently been used to locally characterize high- T_c multilayer structures [2,3]. Charging effects, however, complicate the characterization of superconducting layers that are covered by dielectric layers. In this paper we present low-temperature scanning laser microscopy (LTSLM). Using the electrically neutral optical radiation instead of an electron beam eliminates the difficulties associated with charging.

As a test structure a planar multiturn coil was investigated. In this structure all the basic elements of planar circuitry are present: a base and a top $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ (YBCO) layer separated by an insulating SrTiO_3 (STO) layer, a superconducting interconnect to provide a contact between the innermost coil winding and the returnstrip, and insulating crossovers to separate the returnstrip from the other coil windings. We found that the T_c of the top YBCO layer was higher than that of the base YBCO layer.

The quality of the top layer was not suppressed above the edges of the coil windings structured in the base YBCO layer. The critical current of the coil was found to be limited by the base YBCO layer.

2. Experimental procedure

The LTSLM set-up is schematically shown in Fig. 1. A detailed description is given in Ref. [4]. We use a 2 mW He–Ne laser with a wavelength $\lambda=633$ nm. The beam intensity is sinusoidally modulated at a frequency f_m , and attenuated by a polarizer to about 0.2 mW before the laser beam is transmitted through a microscope and focused on the sample to a 2 μm diameter Airy disk. The sample is placed in an optical cryostat on a copper stage whose temperature is stabilized in the range 65–120 K with an accuracy of 5 mK. The cryostat is placed on an XY-table and can be translated, with a minimum displacement of 0.5 μm , by means of stepper motors. The structure under investigation is DC current biased and the voltage over the structure is detected as a function of the laser spot position by a lock-in amplifier at the modulation frequency f_m .

At $T > T_c$, the response signal δV is solely due to a local temperature rise δT (bolometric response). This response is proportional to both the bias current and the resistance change $\delta R(T)$ in the heated area, with

dimensions determined by the frequency-dependent thermal healing length $\eta(f_m)$, which can be considered to be the spatial resolution in this temperature range. Its value is determined by the specific heat and heat conductivity of the substrate–film composite and decreases (as $1/\sqrt{f_m}$) with the modulation frequency, from a few tens of microns at low frequencies to a few microns at 80 kHz [5].

At $T \leq T_c$, besides the bolometric component, also a non-bolometric component, due to direct interaction of the radiation with the Cooper pairs [6], contributes to the response. It is characterized by a very short rise time and its amplitude is therefore almost independent of the beam intensity modulation frequency, in contrast to the bolometric component. At a certain modulation frequency the non-bolometric component becomes dominant and then the spatial resolution is limited only by the size of the light-perturbed region, which is practically equal to the light spot diameter.

To determine the local T_c (defined as the temperature for which δV is maximal) and the transition width ΔT_c , the laser spot is positioned on the point of interest, the sample is slowly cooled down and the voltage is recorded as a function of temperature. Low bias currents are used to minimize non-bolometric effects. As the transition from the normal to the superconducting state occurs, the voltage response rises due to the increased dR/dT . It reaches a maximum value and vanishes when the critical current I_c of the sample region under irradiation becomes larger than the bias current. It should be noted that the local heating δT must be kept small compared to ΔT_c to measure the local $dR/dT(T)$ correctly. The laser beam intensity is chosen so that an appropriate signal/noise ratio is obtained, but δT is never larger than 0.1 K. This value can be considered as the temperature resolution in determining the local T_c and ΔT_c .

Fig. 1. LTSLM set-up schematic.

3. Measurements

The $8\frac{1}{2}$ turn planar coil that we have investigated is a 3-layer structure of YBCO/STO/YBCO on a STO (100) substrate, fabricated by pulsed laser deposition and structured by Ar ion beam etching (Figs. 2(a) and (b)). The fabrication procedure is described in Ref. [7]. In the 130 nm base YBCO layer

Fig. 2. (a) Coil schematic. (b) Cross section of crossover and interconnect.

Fig. 3. Resistance vs. temperature curve for the complete coil.

an $8\frac{1}{2}$ -turn spiral was patterned with a linewidth of 15 μm and a spacing between the lines of 5 μm. The base layer is covered by a 250 nm thick STO insulating layer. The 28 μm wide returnstrip is prepared from the top YBCO film having a thickness of 400 nm. A window etched in the STO film provides an edge-type superconducting interconnect between the returnstrip and the innermost coil winding.

In Fig. 3 the resistance of the complete coil is shown as a function of temperature, measured at a bias cur-

rent I of 200 μA. A relatively broad transition is observed, caused by the degraded critical temperature of the base YBCO layer. This is obvious from Figs. 4(a–c), where three LTSLM voltage images are presented, corresponding to the beginning ($T=88.7$ K), the midpoint ($T=84$ K) and the tail (78.7 K) of the resistive transition of the coil. In these images the darker areas correspond to higher voltage amplitudes. From these figures it is clear that the critical temperature of the returnstrip is higher than that of the coil windings. In Fig. 4(a), besides a strong response from the returnstrip, a response is also observed from the parts of the windings within about 100 μm of the returnstrip as a result of the relatively large thermal healing length. Increasing the modulation frequency would improve the spatial resolution but decrease the amplitude of the output signal, and since a large background voltage originating from the resistive coil windings is present, this was not applied.

In Fig. 4(b) (84 K) a clear response of the coil windings is observed. At this temperature the coil windings are in the midpoint of the resistive transition, as is obvious from Fig. 5. In this figure the curves $\delta V(T)$ for two positions of the laser beam are presented. Curve a is obtained from a point in the crossover of the returnstrip over the outer turn of the coil, whereas curve b was obtained from a point in the outer turn at a distance of 100 μm from the returnstrip. For the returnstrip a narrow transition was observed in the temperature range from 88.5 to 89.2 K. Below 88.5 K the response of the returnstrip is much smaller than that of the underlying coil windings. The response amplitude $\delta V(x, y)$ of the cross sites is higher than in the unshielded spiral parts. This is partly due to the fact that the returnstrip serves as an additional absorber of incident laser power, which decays inside the medium according to $P=P(0)\exp(-z/\alpha)$ (z is the coordinate on the axis normal to the film surface, α is the optical-absorption length). The value of α in YBCO film is 60 nm [8] for the 2 eV optical quanta we use. The three-layer structure, therefore, transmits nearly no laser power, whereas the single-base YBCO layer transmits about 12% of it. Taking into account that the layers have good thermal coupling, the δT in the crossover regions, and hence the response $\delta V(x, y)$ of the base layer at the cross-sites, will be higher than in the uncovered regions. Besides this, neighboring

Fig. 4. Voltage images $\delta V(x, y)$ of the coil at $I=200 \mu\text{A}$, $f_m=80 \text{ Hz}$ and various temperatures T . (a) $T=88.7 \text{ K}$, (b) $T=84 \text{ K}$, (c) $T=78.7 \text{ K}$. The grey-scale is not the same for these graphs.

coil windings, thermally coupled by the returnstrip, also contribute to the increased response observed from the cross sites. The local T_c 's and ΔT_c 's of the windings ranged from 81 to 84 K and from 10 to 13 K, respectively. The T_c of the interconnect is determined by the T_c of the base YBCO layer.

In the segments that are parallel to the returnstrip the resistive transition extends to lower temperatures

than in the segments perpendicular to it (Fig. 4(c)). This is possibly due to the substrate polishing procedure or a slight miscut of the sample. If we rotate the sample 90° this effect is still observed and is presumably not a measurement artifact. A similar result was found for a second coil on the same substrate.

To measure the quality of the returnstrip separately without the influence of the coil windings, a

Fig. 5. Voltage response as a function of temperature from (a) a point on top of a crossover, and (b) a point in the outer coil winding at a distance of 100 μm from the crossover.

Fig. 6. Visualization of the resistive transition in a separate returnstrip ($I = 70 \mu\text{A}$, $f_m = 1 \text{ kHz}$).

second sample was studied containing only a returnstrip crossing over disconnected coil windings, with dimensions comparable to those of the previously discussed coil. In Fig. 6 LTSLM images are shown for this sample as a function of temperature. The modulation frequency f_m is 1 kHz, resulting in a sufficiently low thermal healing length to reveal a difference in quality between the parts of the returnstrip on top of a crossover and the parts between the crossovers. Between the crossovers T_c is about 89.5 K with a transition width of 0.2 K, whereas the crossovers have a T_c of 87.5 K (with a maximal spread of 0.5 K) and a ΔT_c of 4 K. Below 85.5 K the returnstrip is

Fig. 7. Voltage response $\delta V(x, y)$ at $T = 75.8 \text{ K}$ and $I = 0.6 \text{ mA}$, indicating the weakest cross sections of the coil.

completely superconducting. No evidence was found for a particularly suppressed T_c at the edges of the crossovers.

The LTSLM technique was used to indicate the “weakest” cross sections, limiting the critical current of the entire coil. Fig. 7 shows the voltage response $\delta V(x, y)$, reflecting the spatial distribution of resistive regions in the coil, at $T = 75.8 \text{ K}$ and $I = 0.6 \text{ mA}$. The image was obtained at a frequency $f_m = 40 \text{ kHz}$ where the response has mainly a non-bolometric origin. For this coil the cross sections with lowest critical currents are situated neither in crossovers nor in the interconnect area but in the winding segments that are parallel to the returnstrip and look like dark dashes perpendicular to the current flow direction. For coils with higher critical currents, fabricated on other substrates, we found that the critical current is limited by the interconnect [7]. LTSLM studies revealed that in that case the critical current is limited in particular at the position indicated by ‘a’ in Fig. 2(b) where, in the used configuration, considerable etching into the substrate occurs.

4. Conclusions

In conclusion the LTSLM is shown to be able not only to obtain the local variation of T_c and ΔT_c and

to indicate “weak” cross sections with reduced critical current in superconducting thin film structures, but also to characterize in such a way every layer of a multilayer device separately. Using laser irradiation instead of an electron beam solves the problems arising from charging effects in LTSEM, the spatial resolution being about the same. YBCO-based planar multiturn coil structures were investigated. The base YBCO layer had a lower T_c than the top YBCO layer. The critical current was limited by the base YBCO layer and not by the crossovers. The LTSLM method can be applied to any high- T_c thin film structure even if dielectric layers are included.

Acknowledgement

This work was partly supported by the ‘Dutch Organisation for Scientific Research’ (NWO).

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