High Resolution Thermal Imaging of Hotspots in Superconducting Films

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***Abstract*—Thermal imaging of hotspots in bridge structures of YbaCuO thin films is presented with micrometer resolution. Hotspots formed by passing transport currents are observed using a method based on the temperature dependence in the photoluminescence of a polymer thin film deposited on the superconductor. The hotspots are self maintained and have hysteretic behavior. An external magnetic field changes their behavior. The temperature distribution over the bridge and in its vicinity can be observed with a resolution better than 0.1 K. Also details of the experimental method will be reported.**

***Index Terms*—Bridge, hotspot, transport current, YBCO.**

I. Introduction

THERMAL imaging at cryogenic temperature is achieved by measurement of photoluminescence from a polymer film deposited on a flat surface. The polymer film is excited by ultraviolet light. The emission intensity is temperature dependent. The method was developed for electronic failure analysis at room temperature by Kolodner and Tyson [1], [2]. It is a non-contact method, but requires a 1 μm thick polymer film deposited on the sample. The polymer is easy to deposit and to remove. The advantage of this method is the spatial resolution which is limited by diffraction of visual light. The spatial resolution is one order of magnitude better than infrared cameras. At room temperature the method has been shown to have a temperature resolution of 6 mK and a spatial resolution of 0.7 μm. The method was developed for cryogenic temperature by Hampel *et al.* [3] who studied superconducting microwave filters. The thermal images presented in this report have two order of magnitude better spatial resolutions.

II. Experimental Setup

The experimental setup is based on a standard fluorescence microscope. The setup is shown in Fig. 1.

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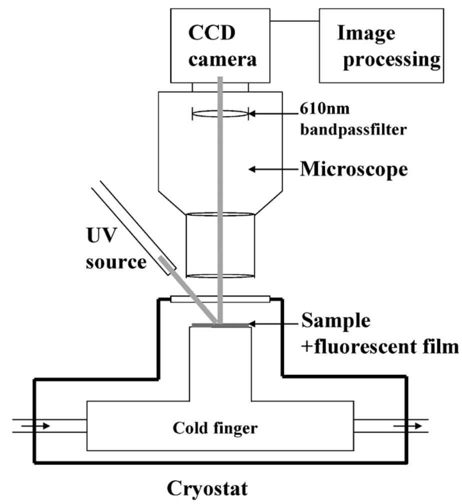

Fig. 1. Experimental setup for thermal imaging at cryogenic temperature. A fluorescent polymer film is deposited on the sample surface in advance.

The sample is mounted in a Janis ST-500 continuous flow cryostat designed for use in microscopy. The optical window is Suprasil, allowing UV-light to excite the sample. The UV-source is a Hamamatsu LC6 with a 200 W mercury-xenon lamp, UV transmission filter and an optical light-guide. The microscope is a standard Leica DMR with a 10 nm bandpassfilter at 610 nm. The microscope images the fluorescent polymer film on a Qimaging Retiga EXI CCD camera. The camera has 1360×1036 pixels and 12-bit digital output. The camera and the transport current source are controlled with Labview on a PC. The post-processing of the images is performed in Matlab.

III. Model for Hotspot in Superconducting Bridge

A. Model

An electric transport current is sent through a narrow bridge of superconducting film. Above the critical current there will be vortices moving across the bridge and a voltage drop and heat dissipation appears in the bridge. The heat dissipation can create a normal state in the superconducting bridge where the heat dissipation is much larger. This is illustrated in Fig. 2.

There are therefore two stable situations for the bridge: 1) a superconducting state with low heat dissipation and where the temperature of the bridge equals to substrate temperature, and 2) a normal state with large heat dissipation where the temperature is increased above Tc for the superconductor. A model and experimental results for these stable self-heating hotspots is given by Skocpol [4]. Self-heating hotspots are observed in three different YBCO bridges by thermal imaging in this report.

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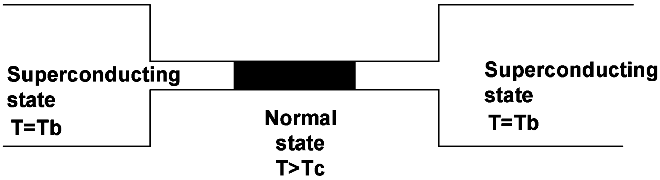

Fig. 2. Model for hotspot in superconducting bridge. The heat dissipation in the normal state raises the temperature above the critical temperature for the superconductor. The hotspot is therefore self-maintained.

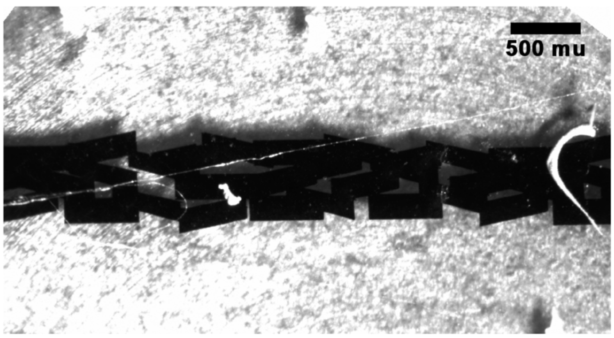

Fig. 3. Optical image of superconducting bridge I.

IV. Thermal Imaging of Superconducting Bridge

A. Superconducting Bridge I

The YBCO bridge I is a network of rectangular plates forming several possible electric paths for the transport current. The total width is 560 $\mu\mathrm{m}$ and the individual paths could be down to 130 $\mu\mathrm{m}$ wide. Fig. 3 shows an optical image of the bridge. The electrical contacts are not shown.

Fig. 4 shows thermal images of bistable states for the YBCO bridge at 84 K. The hotspot at $I = 100$ mA is 13 K above the background temperature. The hotspot at $I = 80$ mA is 7 K above background. The standard deviation of the temperature in the vicinity is measured to 75 mK. At a transport current of 100 mA there is two stable states. Dependent on history, there is either no temperature increase (bottom) or the temperature is increased by several Kelvin to above the Tc (top).

B. Superconducting Bridge II

The YBCO bridge II is a single bridge which becomes narrower. The smallest width is 9 $\mu\mathrm{m}$. Fig. 5 shows an optical image and a thermal image of this bridge at a transport current of 12 mA at 80 K.

The bridge is 9 $\mu\mathrm{m}$ wide. The hotspot is created at 12 mA and disappears at 10.4 mA. The difference in voltage between the dissipating state and the superconducting state is 0.8 V–2 V. This is shown in Fig. 6 where a two-point measurement of voltage versus transport current is plotted.

C. Superconducting Bridge III

Fig. 7 shows an optical image of YBCO bridge III and thermal images of this bridge at a transport current of 50 mA (middle) and 60 mA (bottom) at 84 K. The temperature in the hotspot is measured to 94 K.

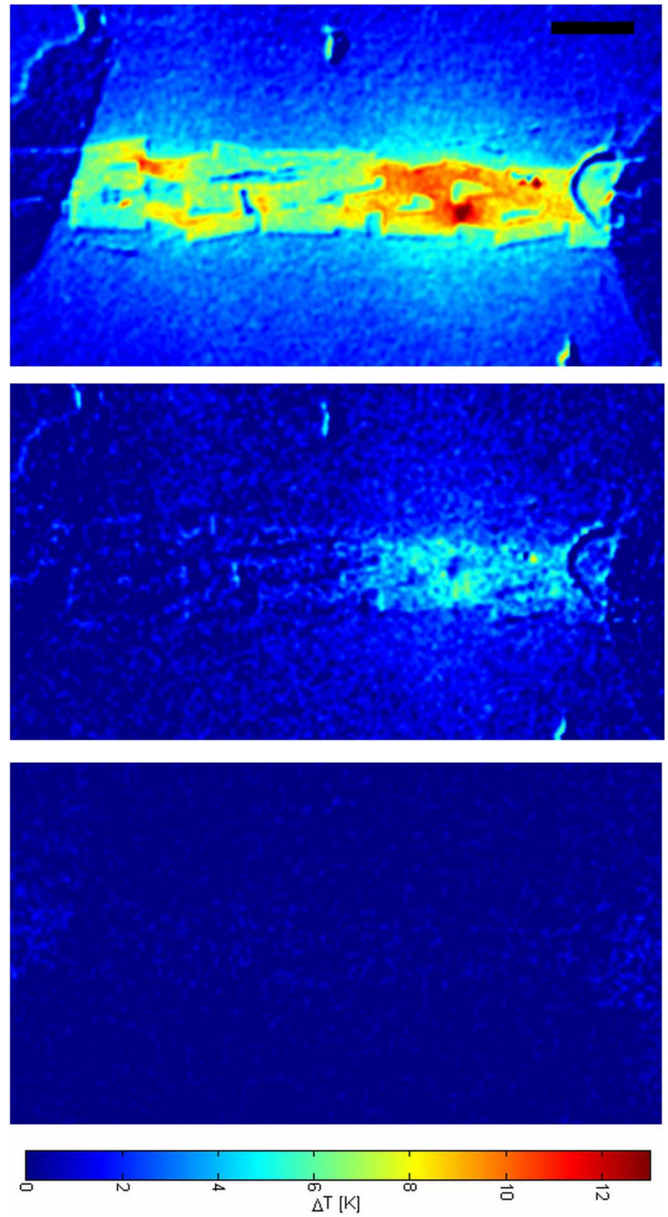

Fig. 4. Thermal images of superconducting bridge I with transport current. The transport current is 100 mA (top), 80 mA (middle) and 100 mA (bottom). The images show the bistable behavior of the bridge. The bridge is in normal or superconducting state for the same transport current at 100 mA. At 80 mA only part of the bridge is in normal state. The scale bar is 500 $\mu\mathrm{m}$.

The optical image (top) shows part of two superconducting bridges. The structure to the right shows two connections to electrical pads. Total there will be four pads allowing four-point measurement of the voltage drop in the bridge. The lower horizontal bridge is 5 $\mu\mathrm{m}$ wide. The setup for this bridge had another wider bridge in parallel. The transport current is therefore not comparable to the other bridges in this report. The middle image shows that a single hotspot is created. Measurement of the voltage drop shows that the hotspot is created at 46 mA where there is a voltage drop of 280 mV. At 58 mA the whole bridge is heated and the voltage drop is larger than 20 V. The bridge also shows the hysteretic behavior as in Fig. 6. The hotspot disappears at 28 mA.

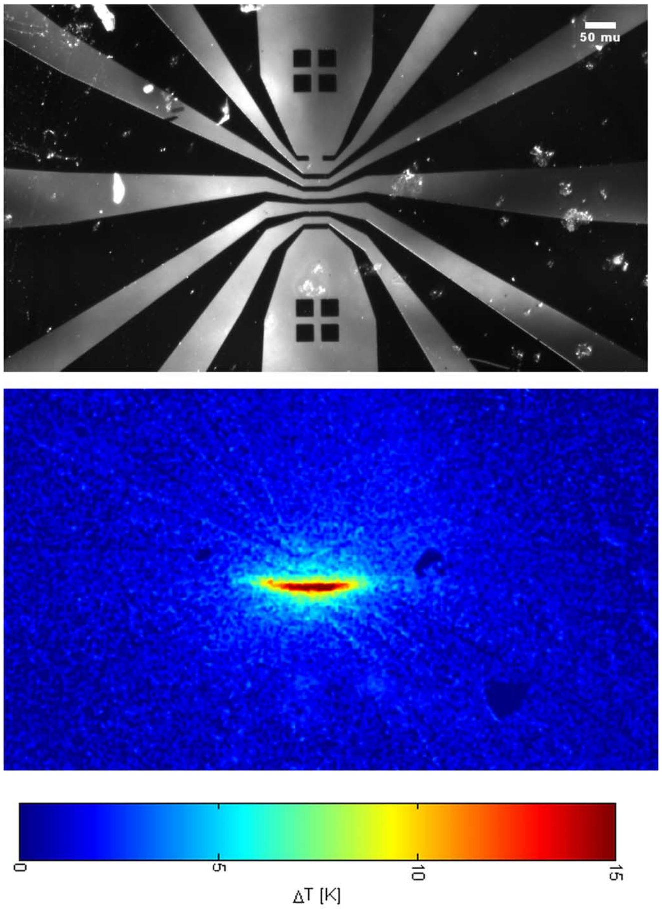

Fig. 5. Optical and thermal image of superconducting bridge II with 12 mA transport current.

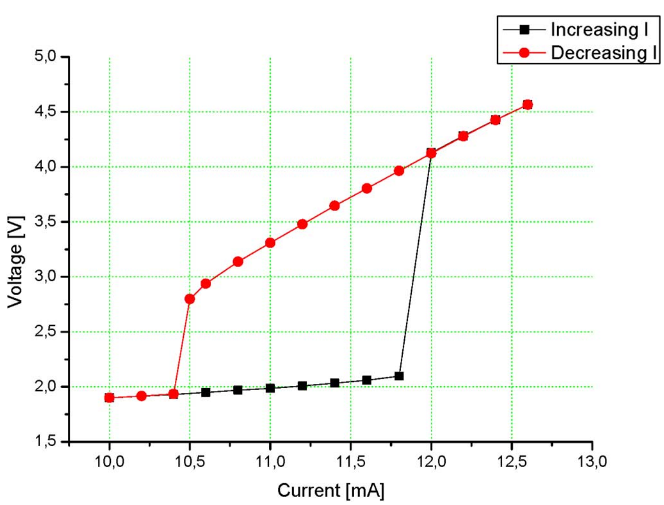

Fig. 6. Voltage versus transport current for superconducting bridge II. A hotspot is created at 12 mA and disappears at 10.4 mA.

D. Hotspot Initiated by Applied Magnetic Field

In a magnetic field the hotspot is initiated at lower transport current than 12 mA for the superconducting bridge II. Fig. 6 shows there is no hotspot appearing by increasing the transport current from 0 mA to 11.8 mA. Fig. 8 shows that a hotspot is created at 11.8 mA if there is an external magnetic flux density of 52 mT perpendicular to the bridge. After the creation of the hotspot, it is stable even without the magnetic field since the normal state of the bridge is self-heating. This is the hysteretic behavior indicated by Fig. 6. The hotspot is not initiated at once when the transport current is ramped from 0 mA to 11.8 mA. The bridge can be in superconducting state for seconds before the hotspot is created. This is shown in Fig. 8 where a hotspot is created 3 seconds later than ramping of the transport current. This behavior indicates a slow temperature increase in the superconductor by moving vortices before the hotspot is created. The heating in the superconducting state is not observed due to low temporal resolution of 2 seconds. The temporal resolution is the exposure time of the CCD camera and can be reduced. But this will reduce the temperature resolution as shown by Kolodner and Tyson [1]. The temperature increase by collective moving vortices is too low to be observed with the setup, but further

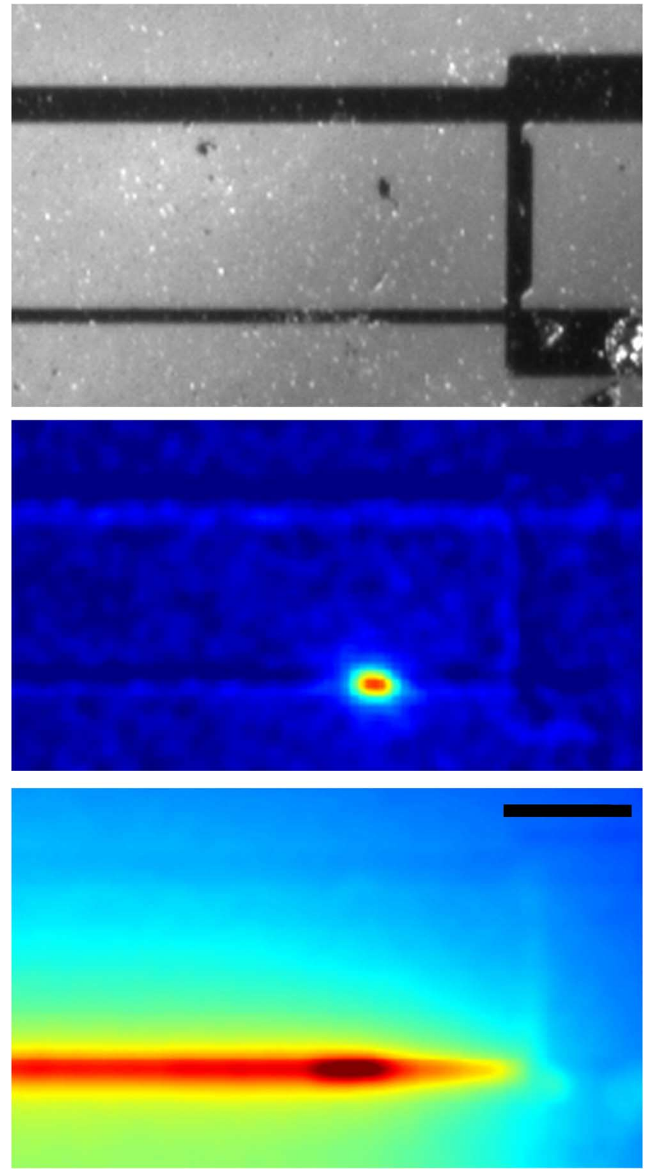

Fig. 7. Optical and thermal images of superconducting bridge III. The total transport current is 50 mA (middle) and 60 mA (bottom), but there is a second bridge in parallel. The temperature in the hotspot is measured to 94 K. The scale bar is 50 $\mu\mathrm{m}$.

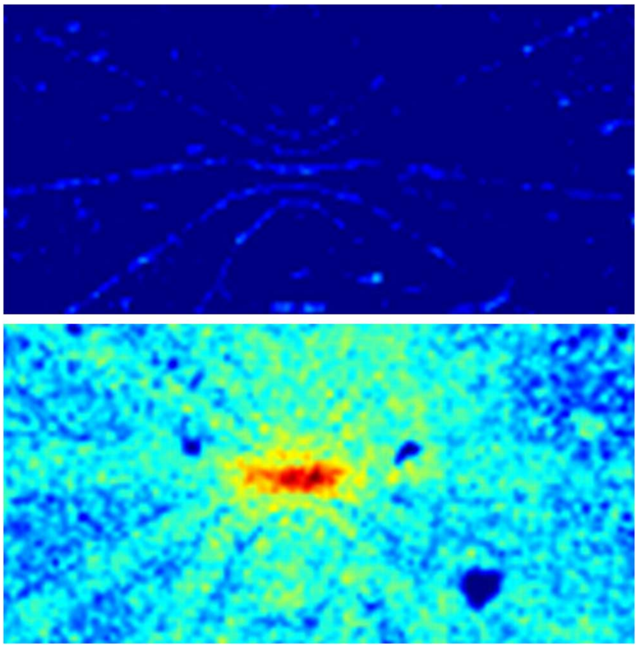

Fig. 8. Thermal images of a hotspot in superconducting bridge II initiated by an external applied magnetic field. The top image show the temperature for the two first seconds of transport current and the bottom image show from 3 second to 5 second. The hotspot is not started unless there is a magnetic flux density of 52 mT.

work with this technique can make heat dissipation in superconducting bridges possible to observe.

V. Conclusion

Thermal imaging of superconductors with micrometer resolution has been shown. This is possible by measuring the fluorescence from a polymer film deposited on the superconductor. The method for thermal imaging is based only on on-the-shelf equipment. Hotspots with dimensions down to 5 $\mu\mathrm{m}$ are located in a superconducting bridge. The temperature resolution for the method has been shown to be 75 mK at 84 K. The temporal resolution is limited by the exposure time of the camera and is 2 s for the thermal images shown in this report.

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