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Current-biased transition-edge sensors based on re-entrant superconductors

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Abstract

Transition-edge sensors are widely recognized as one of the most sensitive tools for the photon and particles detection in many areas, from astrophysics to quantum computing. Their application became practical after understanding that rather than being biased in a constant current mode, they should be biased in a constant voltage mode. Despite the methods of voltage biasing of these sensors are well developed since then, generally the current biasing is more convenient for superconducting circuits. Thus transition-edge sensors designed inherently to operate in the current-biased mode are desirable. We developed a design for such detectors based on re-entrant superconductivity. In this case constant current biasing takes place in the normal state, below the superconducting transition, so that following the absorption of a photon it does not yield a latching. Rather, the sensor gains energy and shifts towards the lower resistant (*e.g.*, superconducting) state, and then cools down faster (since Joule heating is now reduced), and resets in a natural way to be able to detect the next photon. We prototyped this kind of transition edge sensors and tested them operational in accordance with the outlined physics. The samples used in experiments were modified compositions of YBCO-superconductors in a ceramic form (which, as we discovered, reproducibly demonstrates re-entrant superconductivity). In this presentation we report their composition, methods of preparation, and the detection results. This approach, in some areas, may have practical advantage over the traditional voltage-biased devices.

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Keywords: re-entrant superconductivity; single-photon detectors; thermal feedback; current bias

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1. Introduction

Transition edge sensors (TES) became an instrument of choice for demanding measurements across the electromagnetic spectrum from millimeter [Lee *et al*. (1996), Kosowsky *et al*. (2003), Schwan *et al.*, (2003)] to gamma rays [Cunningham *et al.* (2002), Miyazaki *et al.* (2003)] as well as neutrinos [Cabrera *et al.* (1985)] and big molecules [Bassi *et al.* (1981), Twerenbold *et al.* (1996), Hilton *et al*. (1998)]. They have been used in studies of dark matter and super symmetry [Abusaidi *et al*. (2000), Agloher *et al.* (2002)], compositional analysis of materials [Wollman *et al.* (2003)], and the fields of quantum computing and information [Miller *et al*. (2003)]. They extended single-photon calorimetry down to near infrared [Cabrera *et al*. (1998)], with possible extension to far infrared [Irwin and Hilton (2005)].

The idea of TES is based on the narrowness of the superconducting transition and was expressed by Andrews (1938) and Goetz (1939). Despite the effect was demonstrated almost immediately afterwards [Andrews (1942), (1949)], it was not until the introduction of voltage biasing with negative electro-thermal feedback [Irwin (1995)] when the explosive development of TES has started. The issue is that in the current-biased mode superconductors may runaway from the operational point because of fluctuations near the normal state, or triggered by the detection energy input and subsequent Joule heating. This effect is sometimes called latching.

In this report we introduce a concept of superconducting current-biased TES, which is inherently free of latching. The proof-of-principle experiments, which demonstrate the operability of this device as a cryogenic bolometer are performed. We also introduce a novel high-temperature re-entrant superconductor.

2. Operational principle

Our concept is based on the so-called re-entrance superconductivity (Fig. 1). Physical mechanisms of re-entrant superconductivity are not yet very clear. Moreover, they may be related to different origins. However, this is not precluding various applications. Independently of the mechanism, the re-entrant superconductors would allow not only traditional biasing at $T<T_c$, but also at $T<T_r$, (these biasing points shown by circles in Fig. 1). In the latter case, when current biased, the superconductor will move towards higher temperatures in response to the particle/photon energy deposition, and *lower* its resistance: no latching will take place. This is in contrast to traditional materials, which yield an opposite result and require voltage biasing to eliminate thermal runaway. In our case when biased at T_r (Fig. 1), the voltage at constant current across the sample will become lower, which will allow to record the event, and even quantify the amount of deposited energy (*i.e.,* determine the “color” of the photon). After this deposit of energy, the Joule dissipation in the sample decreases, its temperature starts moving down, and it moves fast to the working point.

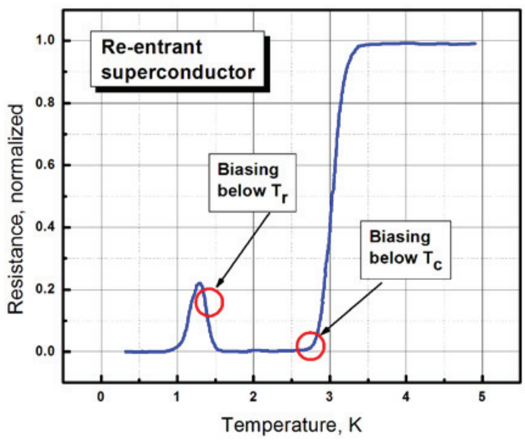

Fig. 1. Exemplary R(T) behavior of a re-entrant superconductor. Two biasing options are reasonable for the TES operation.

3. High-temperature re-entrant superconductor

Various re-entrant superconductors exist (see, *e.g.*, Muller and Narozhnyi (2001)). In our experiments we used a modified high-temperature superconductor $YBa_{2-x}Sr_xCu_3O_ySe_z$ which we recently discovered (full report on these materials will be presented elsewhere).

3.1. Material preparation

Polycrystalline samples have been synthesized using standard ceramic materials route. Powders of Y_2O_3, $SrCO_3$, $BaCO_3$ and SrS (*Alfa Aesar*) have been used in stoichiometric proportions to form initial compositions $YBaSrCu_3O_6Se$ and $YBaSrCu_3O_7$. After thorough mixing, the powders have been calcinated at 900°C for 100 minutes, and then re-grounded, mixed again, and pelletized for second thermal treatment in accordance to Fig. 2a.

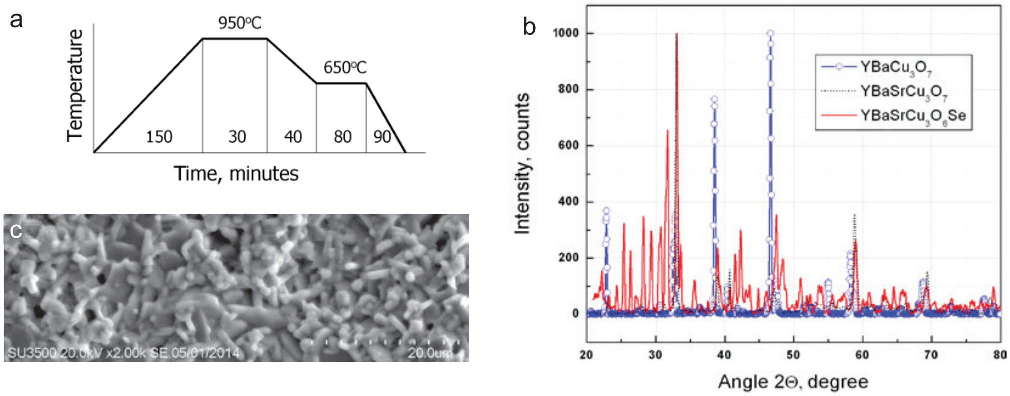

Fig. 2. (a)- Temperature profile of final heat treatment of pellets; (b)-X-ray diffractograms of resultant materials; (c)- granular structure of polycrystalline $YBaSrCu_3O_3Se$.

As a result of thermal treatments the intended composition $YBaSrCu_3O_6Se$ loses about 10% of its initial weight. It was interesting to analyze its final composition (Table 1).

Table 1. EDS data (Oxford Instruments SDD-X-Max, with AZtec).

Area 1 (atomic %)	Area 2	Area 3
O=52.7	O=51.4	O=64
Y=20.2	Cu=22.9	Cu=22.9
Cu=13.9	Y=9.6	Y=9.6
Ba=10.1	Ba=9.2	Ba=9.2
Sr=2.9	Sr=6.3	Sr=6.2
Se=0.2	Se=0.5	Se=0.6

Presence of Se, though looks small, seems to be essential, as clear from insets to Fig. 3 below.

3.2. Superconducting characteristics

Magnetization vs. temperature for this material is shown in Fig. 3a, which corresponds to the re-entrant superconductivity. Resistivity is measured with the 4-probe technique, at 0.3 mA current, with periodic reverting of its direction to eliminate thermoelectric signal in the measuring circuit (Fig. 3b). Magnetic momentum is measured using commercial SQUID-magnetometer (S-700, Cryogenic Inc.).

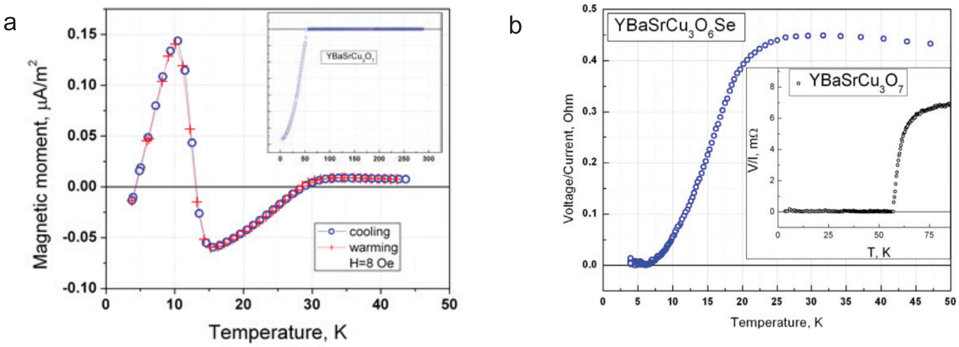

Fig. 3. Measured (a) magnetic and (b) resistive characteristics of $YBaSrCu_3O_6Se$. Insets: the same for $YBaSrCu_3O_7$.

As follows from these data, in absence of *Se*, the re-entrant superconductivity is also absent.

4. Testing the prototype detector

To prove the suggested operational principle, we tried a very simple bolometric detector. A ceramic button, 4 mm in diameter and 1 mm in thickness, has been biased in a constant current mode using 2 indium contacts close to its circumference (Fig. 4a). Two other contacts for voltage probe have been located oppositely on the same face of the button, also close to its circumference. The pellet was mounted on a cold finger in the closed cycle optical cryostat (PT/ST 405, Cryomech Inc.). An external laser beam was directed through the cryostat window onto the center of the pellet, between the contact pads. The window itself was covered by foil with a small hole allowing only the laser beam to reach the sample. A chopper was used to obtain the detector response in the AC mode (Fig. 4b). We used a He-Ne laser with λ=630 nm, maximum power ~0.5 mW, and beam diameter ~1.5 mm. Voltage measurements were performed by Keithley 2182 A. Sample holder was cooled down to 2.72 K and held at that temperature. Attenuation was achieved using neutral filters. During the measurements the direction of the detector current was reverted to exclude thermoelectric pick-up.

At full laser beam intensity, the optimum DC current through the sample, maximizing the detector response, was found to be 0.5 mA (Fig. 5a). As clear from this figure at smaller values of the bias current *I*, the voltage across the detector is reduced when the laser beam is on. At larger currents the situation reverts, and at about 0.6 mA of bias current the voltage at laser action is bigger than without it. Associating the action of laser beam with the bolometric effect, we can explain this result by self-heating re-adjustment of the biased point at increasing values of the current. Initial biasing at $I=0$ was at 2.7 K, *i.e.*, on the re-entrant branch of the R(T) curve (Fig. 3b). At higher currents the biased point passed the valley, and climbed up the main transition curve. Thus at lower biased currents laser energy deposit reduced the resistance of the detector, and at higher currents – increased it.

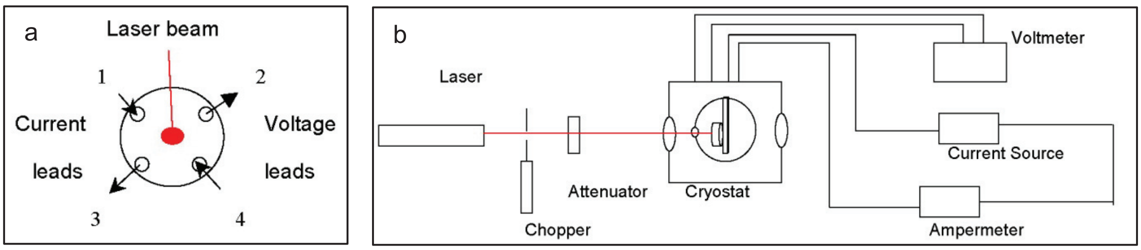

Fig. 4. (a) - Schematics of the detector biasing; and (b)-experimental setup.

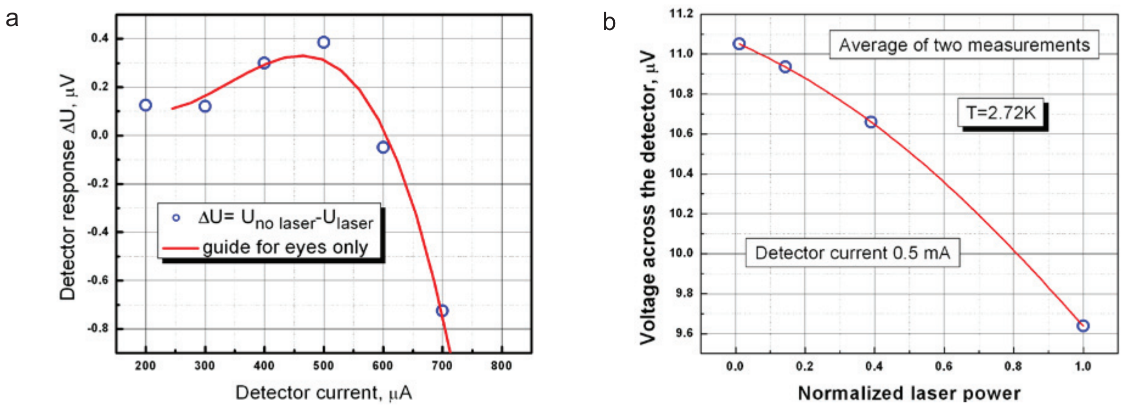

Fig. 5. (a)-Maximum response and sign reversal at increasing bias current; (b)-shift of voltage across the detector at different intensity of laser radiation. Lines are guides for eyes only.

The voltage across the detector at the optimized value of the current $I=0.5mA$ on the re-entrant branch of the R(T) curve is shown in Fig. 5b for different values of the incident laser power.

5. Discussion and conclusion

As follows from Fig. 5b, action of energy deposit indeed reduces the voltage across the detector, which is biased in its re-entrant normal state. This voltage at applied constant current is proportional to the resistance of the device. It decreased monotonically with the increasing values of laser intensity, thus demonstrating bolometric effect.

One should notice some difference between the re-entrant temperatures in Figs. 3a and 3b. However, it is easily understandable: in the case of magnetic measurements the sample was in He atmosphere, with no heat supply. Also the magnetic momentum is mainly defined by the volume of granules in the polycrystalline sample (Fig. 2c). Meanwhile, the resistivity is majorly defined by the intergranular coupling. Also, the measuring current is heating the sample, so the transition occurs at lower temperatures. In case of the detector, the operational current is even higher (0.5 mA vs. 0.3 mA) than in Fig. 3b. Additionally, in the former case the laser beam is elevating the average temperature of the sample. This raise in temperature also means that the actual temperature in Fig. 5b is higher than the indicated temperature 2.72 K which corresponds to the cold finger temperature. Ability to tune the bias point of the detector by adjusting the bias current may become useful in applications. The measured dependences in Fig. 5 are demonstrating that this simple detector prototype behaves as it should, and there are little doubts that in a thin-film layout it will be able to serve as current-biased energy-dispersive device.

To summarize, we have suggested a non-latching current-biased TES detector concept based on the negative electro-thermal feedback of re-entrant superconductors. We combined newly discovered high-temperature superconducting material with this concept to demonstrate the prototype detector. This device when further developed may become a useful member in the family of transition-edge sensors.

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