DEVELOPMENT OF AN HTc THERMAL CONVERTER

E. MONTICONE, U. POGLIANO
Istituto Elettrotecnico Nazionale “Galileo Ferraris” Torino, 10135 - Italy
phone: +39-0113919436, fax:+39-0113919448, e-mail: emonti@ien.it

A. M. CUCOLO, V. LACQUANITI
Department of Physics and INFM Unit, University of Salerno, 84081 Baronissi
ITALY

Abstract

Thermal converters at cryogenic temperature have been recently developed in some metrological laboratories. By means of these devices high sensitivity measurements at the level of 1 mV can be performed. In this paper we report on the evaluation of high critical temperature (HTc) device characteristics. Experimental results show that this device, which operates at liquid nitrogen temperature, has the capability to detect variations of 10^{-11} Watt and could allow direct precision measurements in the 10 mV range.

Introduction

Thermal converters are usually employed in metrological laboratories as accurate standards for the transfer of ac voltage and current to the equivalent dc quantities [1]. In these devices the ac-dc transfer difference is evaluated by applying in sequence an ac and a dc signal to a heater and by monitoring its temperature rise due to the Joule heat by means of thermocouple array or thermoresistive element. In the last years conventional wire multijunction thermal converters have been replaced by devices based on micromachining process and thin metal films deposition which show a comparable performance but wide frequency range and lower cost [2]. The accuracy of a thermal converter is defined in terms of ac-dc transfer difference due both to thermoelastic and electromagnetic effects. Thermoelastic effect depends on temperature rise on the heater and it is mainly manifested at low frequency, while beyond 50-100 Hz the contribution to the ac-dc transfer difference of this effect is almost constant. Electromagnetic effects depend on the stray parameters in the converter and generally increase as the frequency increases. The sensitivity of a traditional thermal converter is usually of few V/W while the noise is dominated by Johnson noise estimated in some nW/Hz^{1/2} [3]. This sensitivity is not sufficient to perform high resolution transfer measurements in millivolt ranges, without employing large bandwidth amplifiers, which are affected by a non-negligible noise and whose gain is not generally accurate in the whole frequency range.

Superconducting-resistive transition-edge thermometer to sense the temperature rise produced by the electrical power dissipated in a heater can enhance by several orders of magnitude the sensitivity in comparison with that of the traditional thermal converter [4]. This improvement is similar to that of cryogenic bolometers with superconducting thermometers, which have been used for power measurements in a wide range of applications as infrared detectors [5] and x-ray photon detectors [6]. From the thermal characterization of these devices a thermal conductance close to 10^{-5} W/K and a responsivity of 10^5 V/W have been obtained [7], which is about three order of magnitude higher than that of room temperature thermal converters and allows us to use these devices for ac-dc transfer for measurements at the level of 1 mV.

In this work, we analyze the reliability of thermal converters based on HTc transition-edge thermometer which operating at liquid nitrogen temperature enables a more compact, cheap and user-friendly system which respect to He liquid. The superconductive properties of several HTc thin film materials and different architectures which optimize the thermal insulation have been considered in order to maximize the device responsivity.

Fabrication of the device

For the preliminary experiments a specific device has been fabricated. YBa_2Cu_3O_{7-δ} films were deposited in oxygen atmosphere by on-axis dc sputtering technique on substrate of SrTiO_3 with orientation (100). The oxygen pressure of the chamber during deposition was held at 3.0 mbar with constant gas flow. Voltage and current during deposition were 240 V and 150 mA respectively and the deposition rate measured at 1.5 cm from target 1.6 nm/min. The substrate was heated up to 890 °C during deposition. After deposition, the vacuum chamber was filled with oxygen at 1 bar and the samples were kept at a temperature of 560 °C for 15 minutes. X-ray diffraction pattern of YBa_2Cu_3O_{7-δ} films showed
(001) reflections, indicating a highly preferential orientation with the film C axis normal to the surface. The film was patterned in strips 50 µm wide and 3.5 mm long by standard photolithography process followed by wet etching in an aqueous solution of 1% HNO3. The contact pads were realized by a gold deposition of 500 nm through a mechanical mask. To minimize the contact resistance the sample were annealed at 500 °C in oxygen atmosphere for 1 hour.

Structure of the sensor

On the backside of the chip a 100 Ω resistor was stick on by GE varnish. The chip was suspended in a structure where the temperature was monitored by a silicon diode and stabilized by a homemade temperature controller. For the thermometer were used as electrical leads low thermal conductance manganin wires of 50 µm while for the resistor connections were used 50 µm diameter Cu wires to minimize unwanted source of heating.

Device parameters

A thermal converter consists of a thermometer and a resistor in thermal contact realized on a structure at temperature T weakly coupled to a cold bath with temperature $T_0$ by a link with thermal conductance G. The good thermal contact between resistor, where the ac and dc power are dissipated, and thermometer is established using substrate with large thermal diffusivity. The main parameters, which characterize the device, are the responsivity S, the NEP (Noise Equivalent Power) and the time constant. $S$ is evaluated from the response of the thermometer $\Delta V$ on the power dissipated on the resistor $P$. The temperature change $\Delta T$ due to a power $P$ on the resistor implies a resistance change of the thermometer of $\alpha R \Delta T$, where $\alpha = (1/R)dR/dT$. For a bias current $I$ we have $\Delta V = \alpha IR\Delta T$ and remembering that $\Delta T = P/G$, $\Delta V = \alpha IRP/G$ from which:

$$S = \frac{\alpha IR}{G}$$

However, the current can not increase indefinitely but due to a thermal feedback is limited to $I = I_{\text{max}} = (0.3G/\alpha R)^{1/2}$. In this case, the thermal conductance $G$ is substituted by an effective thermal conductance $G_e = G - I^2R\alpha$ and the time constant by an effective time constant $\tau_e = C/G_e$ where $C$ is the thermal capacitance of the substrate. The maximum responsivity is given by substitution of $I$ with $I_{\text{max}}$ in (1), $S = 0.78(\alpha R/G)^{1/2}$. Several noise sources can reduce the sensitivity of a thermal sensor but in optimized devices and measurement systems at low temperature the noise is dominated by phonon noise and often for high temperature superconductor by 1/f noise. The overall NEP is given by adding the squares of the values of separate noise sources:

$$\text{NEP}^2 = 4KT^2G + S_e(\omega)/|S|^2$$

The first term arises from the passage of phonon through the thermal conductance. The second term is due to the excess voltage noise of the HTc film, which often represents the limiting factor of the sensitivity.

Eq.(1) and Eq.(2) show that optimal design of device required a G as low as possible. On the order hand, to keep time constant $\tau$ at a reasonable value also the thermal capacitance must be reduced at the same extension.

**Experimental results**

The samples was mounted in a cryostat, designed for insertion into storage dewars, evacuated by a root pump under $10^{-2}$ mbar. The measurements were realized biasing the thermometer resistance by a current source Kiethley mod. 220 and the output voltage was measured by a multimeter HP mod. 34401. The temperature was measured by silicon diode biased at a constant current of 10 µA.

In Fig.1 the curves of the thermometer resistance vs. the temperature as function of the bias current are shown. The R-T behaviour shows a fast transition between 92.2 K and 92.5 K with a resistance that falls from 200 Ω to 15 Ω and a complete transition below 91.5 K.

In Fig.2 the derivative of resistance of the temperature of the curves in fig.1 are shown. The maximum of $dR/dT$ is close to the mid-point of the transition and is about 900 Ω/K at 92.3 K, with a transition width of 0.3 K. The narrow transition and the ratio between strip resistance at room temperature and before transition higher than 5 shows the high quality of the YBa$_2$Cu$_3$O$_{7-δ}$ films.

![Fig. 1 Thermometer resistance vs. the temperature as function of the bias current.](image-url)
Fig. 2 Derivative of the resistance as function of the temperature (dR/dT) of the curves in Fig.1. The maximum of is close to the mid-point of the transition and about 900 Ω/K at 92.3 K.

In Fig.3 is drawn the change of the thermometer resistance as function of the time obtained by heating the resistor placed to the backside with a current of 440 μA applied for periods of about 400 s. Fitting the experimental data of Fig.3 with an exponential law a time constant of 100 s and a maximum resistance change of 15 Ω have been evaluated.

Discussion

The responsivity calculated from relation S=ΔV/P with the above data and I=100 μA is ~75V/W. Using this value, the thermal conductance can be evaluated from (1) with dr/dT=700 Ω/K, to be G= 9x10^-3W/K. The main contribution to G are usually conduction to electrical leads and conduction to the gas that surrounds the device. In this case the second term is made negligible by pumping the cryostat below 0.01 mbar. The wires of manganin have a thermal conductance of G=4kA/L= 1.6x10^-6 W/K with k=0.04W/Kcm, A=2x10^-5 cm^2 and L=1cm, while for Cu wire we found G=2.2x10^-4 W/K with k=5.5W/Kcm, A=2x10^-5cm^2 and L=1cm.

Calculation shows that the main contribution to thermal conduction is due to Cu wire and can be reduced of 2 order of magnitude using manganin wire. However, the response of the device is very slow due to the large thermal capacitance of the chip C=Gr=0.09J/K. An acceptable value of τ is reliable by substrate volume reduction of factor 100 or using silicon micromachining technique [8].

The NEP calculated by (1) (neglecting 1/f noise) with the above data is 2x10^-11W/H^1/2. It is dominated by the phonon noise and can be reduced by optimization of thermal design of at least 4-5 times.

The calculated NEP represents the lower difference in the ac-dc transfer which can be measured. Therefore this device would be able to measure a 16 mV level with a sensitivity of few parts in 10^6.

Conclusion

In this work we show that YBCO films with sharp transition can be used as thermometer to improves the performance of present thermal converters, which are limited by low sensitivity and high intrinsic noise at room temperature. The design of a optimum devices should give a thermal conductance below 10^-5 W/K, and thus NEP lower than 10^-11W/H^1/2 and responsivity higher than 1000V/W. These value enables measurements of ac-dc transfer difference with a sensitivity of few parts in 10^6 down to 16 mV.

References


