JOURNAL DE PHYSIQUE IV
Colloque C6 Supplément au Journal de Physique III, Volume 4, juin 1994

Composite bolometer based on high temperature superconducting $Bi_2Sr_2CaCu_2O_{8+x}$ crystals for application in the far infrared

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ABSTRACT: We discuss the feasibility of a new type of high temperature superconducting bolometer operating in the sub-millimeter region ($\lambda > 300\mu m$) of the spectrum in the temperature range $80K \div 100K$. We use the sharp resistive transition of $Bi_2Sr_2CaCu_2O_{8+x}$ superconducting single crystals as sensitive thermometer. The sensor is thermally coupled to a thin diamond substrate covered on the back side with a bismuth film that performs the absorbtion of the radiation. Such a detector should have large sensitive area and short time response due to the low heat capacity of both crystal and substrate. We describe the results of the electrical bolometric characterization, noise measurements and optical calibration carried out on the first prototype and use them to predict the Noise Equivalent Power (NEP) of a well designed detector.

1. INTRODUCTION

The most sensitive detectors in the infrared are doped semiconducting bolometers ($\lambda > 100\mu m$) and photoconductors ($\lambda < 100\mu m$), both operating at the temperature of liquid ^4He, which show performances close to the photon noise limit. In the infrared between $1\mu m$ and $50\mu m$ liquid nitrogen cooled photovoltaic detectors such as HgCdTe are used which show high performances (Noise Equivalent Power (NEP) $\simeq 10^{-11}W/Hz^{1/2}$), while in the Far Infra-Red band (FIR) relatively low performance 300 K detectors (Golay Cell and Pyroelectric with $NEP \geq 10^{-10}W/Hz^{1/2}$) must be considered.

The development of a high temperature detector should have a great impact for the space astronomy. It is well known that the cryogenic detectors can not be used in very long missions outside terrestrial orbit: in fact, the available cryogenic technology provides us a relatively short operating life of a LHe cryostat (about 2 years for a satellite) and the practical lower limit for passive radiative cooling is 50-60 K. Until now, the observation of the Sun has been made from platform carried at high altitude by balloons or aircrafts, with a small observation time. The observation of giant planets has been carried out up to $50\mu m$, and the FIR spectrum is actually unknown. The commercially available detectors, like Pyroelectrics, Thermopiles and Golay Cells, are not still used for space applications.

However, the availability of high T_c superconducting (HTS) materials with sharp resistive transitions in the range $70 - 100K$ provides an opportunity for the development of an intermediate temperature thermal detector. The temperature of operation can be easily provided by the standard techniques of radiative cooling.

Superconducting bolometers have been realized by several authors [1,2,3]. They use the transition of YBCO films deposited through buffer layers onto thinned sapphire substrates. Also BSCCO film deposited onto $NdGaO_3$ substrate has been proposed for bolometric applications [4]. In both cases the intrinsic limitation to the NEP is due to the heat capacity of the substrate. The linear dimension of the optical absorber must be greater than the maximum wavelength to be detected. An optical system is characterized by the throughput $A\Omega$ that constraints the minimum dimension of the detector if the condition of optimum coupling with the antenna is required:

$$(A\Omega)_{det} = (A\Omega)_{ant}$$

We obtain the following limit for the linear dimension of the absorber:

$$d \geq \frac{2}{\pi}\sqrt{(A\Omega)_{ant}}$$

For measurements of submillimeter radiation with high sensitivity (i.e. high throughput) a large area is required and the availability of a substrate with low heat capacity appear to be the most important task.

The *Signal-to-Noise* ratio is the most meaningful figure of a detector. The intrinsic noise level has predominant contributions from both Johnson and $1/f$ terms [1,2,5]. A useful expression for the *Signal-to-Noise* ratio is given by [6]:

$$\frac{S}{N} = \frac{(A\Omega)_{det}\,\Delta I_{abs}}{\sqrt{\left(Q_J C + H_{1/f} C^2\right)\Delta f}}$$

where ΔI_{abs} is the absorbed flux, Δf is the electrical bandwidth and C is the total heat capacity. The coefficients Q_J and $H_{1/f}$ contain the parameters of noise and detector. We would take a small advantage by increasing the area, if the heat capacity was dominated by the substrate. If the Johnson term is dominant, we obtain:

$$\frac{S}{N} \propto \sqrt{A}$$

The *Signal-to-Noise* ratio become weakly dependent on the sensitive area when the $1/f$ term is dominant. If mostly of the heat capacity comes from other parts of the device (wires, glue, crystal) we obtain that the *Signal-to-Noise* ratio is proportional to the area of the substrate whatever noise term is dominant.

We have realized a *composite* bolometer operating at 85K based on a $Bi_2Sr_2CaCu_2O_{8+x}$ (BSCCO phase 2212) crystal superconducting thermometer thermally connected to a $5\mu m$ thick diamond substrate. A deposition of about 1000 Å of bismuth on the back side of the substrate ensures the optical absorbtion in the submillimeter region. In the following section we describe the fabrication of the prototype and the principle of operation. In the section 3 the most important results about the electrical responsivity and noise are shown. Finally, in the section 4 we discuss the optimization procedure.

2. ASSEMBLY AND OPERATION OF THE DETECTOR

The BSCCO single crystal are grown by liquid phase epitaxy (LPE) as c-oriented platelets [7]. With this technique crystal slices few microns thick can be easly obtained and they show electrical properties comparable with those of the epitaxial films grown by the same LPE technique on $NdGaO_3$ (001) substrates [8]. The specific heat of BSCCO (2212) crystals at the mid-point of the transition can be estimated from published data [9]: $C_v \simeq 1.3 Jcm^{-3}K^{-1}$. For a platelet $1mmx2mmx3\mu m$ we compute a heat capacity $C_c = 8\mu J/K$.

Two electrical contacts with an area of $0.12mm^2$ were made on the smooth surface of a $1x2mm^2$ slice by evaporating 2000Å of Silver. The crystal was then annealed in air at about $400°C$ for $1h$ to reduce the resistance of the contacts. The thermal treatment reduces the resistance of the contacts by about four order of magnitude. A copper wire (diameter $50\mu m$, $3.5mm$ long) was glued on each contact by *silver paint* to ensure the electrical connection. The expected contribution to the heat capacity is: $C_w = 27\mu JK^{-1}$. The slice was suspended on a copper ring through the electrical connections and a time constant of $0.14s$ was measured, greater then the expected values of $53ms$. This discrepancy can been explained with a slow thermalization process of the slice due to the low value of the thermal conductivity of BSCCO. This effect becomes negligible respect to the bolometric time constant if smaller slices are considered [10]. We estimate that a $1x1mm^2$ crystal has an internal time constant of $30ms$, to be compared with a value of $48ms$ for the bolometric response.

The thermometer was then glued by *silver paint* on a diamond flake [11], $5\mu m$ thick, with an area of about $7mm^2$. The shadowing produced by the reflecting surface of the BSCCO crystal is about 30%, thus resulting in a reduction of the optical efficiency. Finally, a bismuth film 1000Å thick was deposited on the back side of the substrate by means electron beam evaporation. The heat capacity of the substrate is estimated assuming the specific heat of the diamond: $C_S = 1\mu JK^{-1}$.

The detector was mounted on the cold plate of a liquid nitrogen cryostat and coupled to an optical window (diameter $2.6cm$) through a right reflecting cone. The radiation was incident on the clean surface of the diamond, in order to increase th absorbtion [12]. The throughput of the system was estimated to be $0.54cm^2sr$, appropriate for sensitive measurements of diffuse radiation.

The thermometer was biased with a constant current that keeps the operation point near the midpoint of the transition, where the sensitivity reaches the maximum value and the electrical noise in reasonably low [1,5]. A thermal source (77K blackbody) was placed in front of the window and modulated by means a mechanical chopper. The output signal was amplified with a low impedence transformer at room temperature and sent to a lock-in amplifier.

3. ELECTRICAL AND OPTICAL CALIBRATION

The electrical responsivity was estimated with the the standard technique of the load curve. In the figures 1a and 1b the responsivity data are reported.

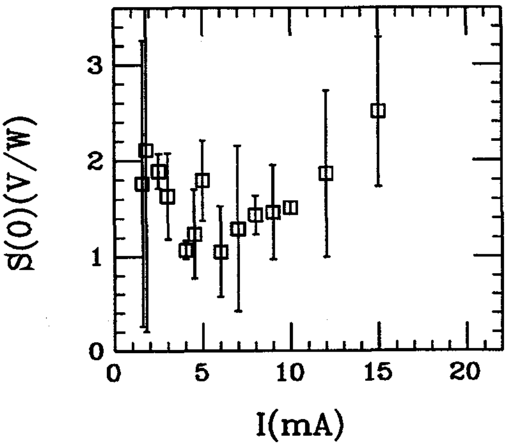

Figure 1a

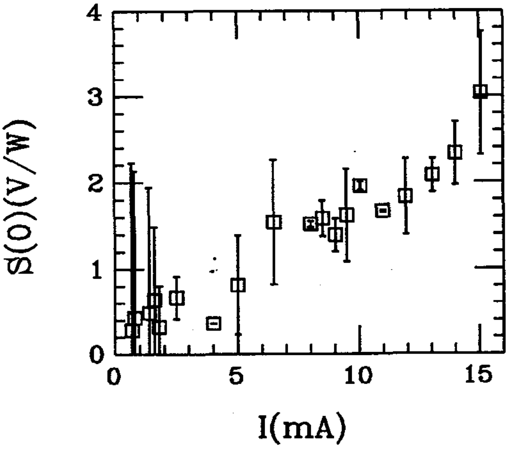

Figure 1b

The behaviour at low currents in figure 1a is due to well understood electrical non linearities [13]. The time constant was about $0.4s$, estimated from the response to an optical power step. This value is about three time greater than that expected, due to the contribution of the glue (from the thickness of the glue layer we estimate a time constant of $0.34s$).

The electrical noise was dominated by the $1/f$ term:

$$V_n^2(f) = \frac{N(T)}{f} R^2 I^2$$

where $N(T)$ is the Hooge's parameter, strongly depending on the temperature. At the midpoint of the transition we measured $N \simeq 1.5 \cdot 10^{-12}$, with a noise level at $10Hz$ and $10mA$ of $2.7nV/Hz^{1/2}$. We compute a noise equivalent power at 10Hz of about $3.0 \cdot 10^{-8} W/Hz^{1/2}$.

The response to submillimeter radiative power was verified by using a proper filtering of the optical frequencies. A fluorogold slab 1.5mm thick, together block filters (mylar, black poliethylen) and a teflon window was used to select radiation at $\lambda > 400\mu m$. In figures 2 and 3 the dependence of the modulated signal on the bias current and temperature are reported.

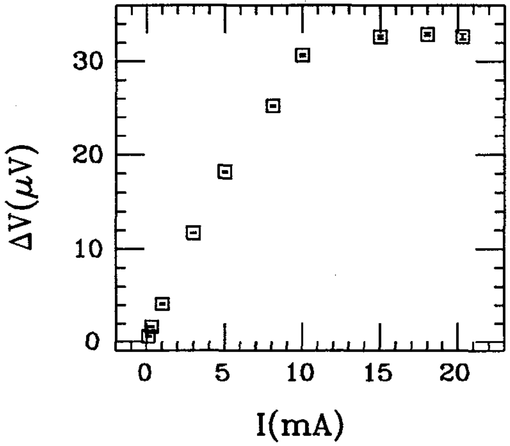

Figure 2

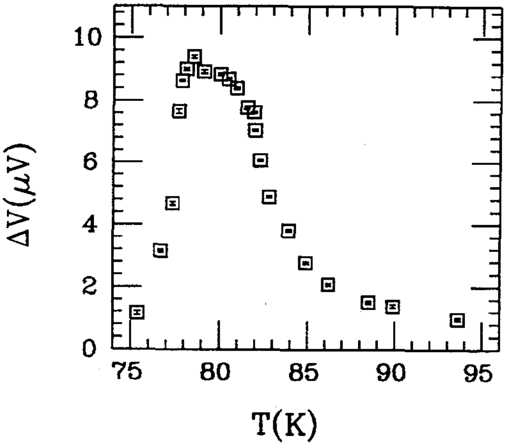

Figure 3

The measured behaviours are in good agreement with those expected from the standard bolometric theory.

The thermal source was an Eccosorb slab, that approximates very well the black body emission in the submillimeter region [14]. The optical calibration gives a wavelength-averaged absorbtion of about 20%, respect to an expected value of 0.46% [12]. This difference is due to the mismatch between the impedences of bismuth film and free-space. We also measured a *Signal-to- noise* ratio of 50 at 10Hz and 10mA, compared with a measured value of 200 for a commercial Golay Cell.

4. OPTIMIZATION

The NEP of a $1/f$ limited detector, including the corrections for the electrothermal feedback [15], is given by:

$$NEP(f) = \sqrt{\frac{N_0}{f}} G\alpha^{b/2-1}\sqrt{1+\omega^2\tau^2}$$

where a power-law behaviour for the Hooge's parameter $N = N_0\alpha^b$ is assumed and G is the thermal conductance. For BSCCO crystal we found that $b \simeq 3 \div 4$ below the mid-point and the NEP is a decreasing function of the temperature. In the higher part of the transition we found $b \sim 0$ and the NEP increase with the temperature, so that an optimum point exists.

New samples has been fabricated that use $1x1mm^2$ BSCCO slices, copper wires with a diameter of $25\mu m$ and $3mm$ long, $3x3mm^2$ diamond flakes. The estimated heat capacity is about $11\mu JK^{-1}$ with a time constant of $54ms$. The internal relaxation time is about $30ms$. We can estimate an optimum value of the NEP if the contribution of the glue is neglected:

$$NEP_{min}(10Hz) \simeq 6 \cdot 10^{-10} W/Hz^{1/2}$$

comparable with those of commercial detectors. The heat capacity of the substrate should be the 10% of the total, so that we can take full advantage of the high throughput.

REFERENCES

[1] Verghese S., Richards P.L., Char K., Sachtjen S.A., (1991) *IEEE Trans. Magn.*, MAG-27, 3077.

[2] Verghese S., Richards P.L, Char K., Fork D.K., Geballe T.H., (1993) *J. Appl. Phys.*, preprint.

[3] Brasunas J.C., Lakew B., (1994), *Appl. Phys. Lett.* , 64, 777.

[4] Bottiglione A., Epifani M., Balestrino G., Milani E., Montuori M., Maritato L., Ruosi A., Scafuro R., (1993), *J. Appl. Phys.*, 74, 704.

[5] Rosenthal P., Hammond R.H., Beasley M.R., Leoni R., Lerch P., Clarke J., *IEEE Trans.Mag.*, MAG-25, 973, 1989.

[6] Bottiglione A., Epifani M., in press on *Proceedings of "International school of space science"*, L'Aquila, August 1991.

[7] Balestrino G., Gambardella U., Y.L. Liu, Marinelli M., Paoletti A., Paroli P., Paterno' G., (1988), *J. Crystall Growth*, 92, 674.

[8] Balestrino G., Marinelli M., Milani E., Paoletti A., Paroli P., (1991) *J. Appl. Phys.*, 70, 6939.

[9] Okazaki N., Hasegawa T., Kishio K., Kitazawa K., Kishi A., Ikeda Y., Takano M., Oda K., Kitaguchi H., Takada J., Miura Y., (1990) *Physical Review B*, 41, 4296.

[10] Epifani M., (1994), *Ph.D. Thesis*, Universitá di Roma "La Sapienza".

[11] Balestrino G., Marinelli M., Milani E., Paoletti A., Pinter I., Tebano A., Paroli P., (1993), *J. Appl. Phys.*, 82, 879.

[12] Carli B., Iorio-Fili D., (1981) *J. Opt. Soc. Am.*, 71, 1020.

[13] Epifani M., (1994), in press on *J. Appl. Phys.*.

[14] Halpern M., Gush H.P., Wishnow E., De Cosmo V., (1986), *Appl. Opt.*, 25, 565.

[15] Mather J.C., (1984), *Appl.Opt.*, 23, 584.