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Transition Edge Sensors for Long Duration Balloon experiments

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Abstract. Transition Edge Sensors (TES) bolometers are the state of the art of the detectors for experiments working at mm and sub-mm wavelengths. In this paper we briefly review the current experimental situation focusing the attention on the use of TES for Long Duration Balloon experiments.

Key words. Bolometers – TES – SQUID – Multiplexing – LDB

1. Introduction

Experiments for mm and sub-mm astronomy are undergoing a revolution thanks to the use of a new kind of superconducting bolometers, Transition Edge Sensors (TES).

Bolometers are thermal radiation detectors which convert radiation into an electrical signal. They are the most sensitive direct detectors at wavelengths between 200 μ m and 3 mm, a range that includes cosmological and astrophysical studies like Cosmic Microwave Background Radiation (CMB) and sub-mm galaxies. Many past balloon-born experiments made use of semiconductor bolometers including ULISSE (de Bernardis et al. 1992), ARGO (de Bernardis et al. 1993), MAX (Tanaka et al. 1995), BOOMERanG (de Bernardis et al. 2000; Lange et al. 2001), TopHat (Silverberg et al. 2005), MAXIMA (Lee et al. 2001), Archeops (Benoit et al. 2002), BOOMERanG-2K (Masi et al. 2006), MAXIPol (Johnson et al. 2008), and BLAST (Pascale et al. 2008). The performances of semiconductor bolometers are limited by the relatively modest dependence of the resistance of the semiconductor thermistor from the temperature. The innovation of TES consists in the use of the slope R vs T of a superconducting transition, which can be more than 100 times steeper than that of semiconductor. Most of the future LDB experiments will use TES, like OLIMPO (Masi et al. 2005), EBEX (Oxley et al. 2004), SPIDER (Montroy et al. 2006), Blast-pol (Marsden et al. 2008), B-B-Pol (de Bernardis et al. 2008).

A bolometer consists of an absorber of radiation with heat capacity C and a thermistor with negligible heat capacity, that are in perfect thermal contact. Those two elements are then connected to a thermal cryogenic bath, typically at 100 or 300 mK, by means of a weak thermal link of conductance G. The use of cryogenic temperatures is essential to reduce Johnson noise. The absorbed radiation is measured by the thermistor by means of the rise of the detector temperature above the bath temperature. The heat then dissipates through the thermal link and the absorbing element returns

Send offprint requests to: E.S. Battistelli in equilibrium with the thermal bath. The speed of a bolometer is related to the ratio C/G, this is the thermal time constant τ of the bolometer (Mather 1997).

Reduction of the bolometer heat capacity C and of the cross section to cosmic rays is achievable thanks to the use of spider-web absorbers (Mauskopf et al. 1997). This design allows the realization of fast detectors with no need to drastically increase the thermal conductance G and consequently the phonon noise. This is particularly important for LDB experiments since balloons frequently fly in areas with high cosmic ray pollution due to the latitude and the altitude.

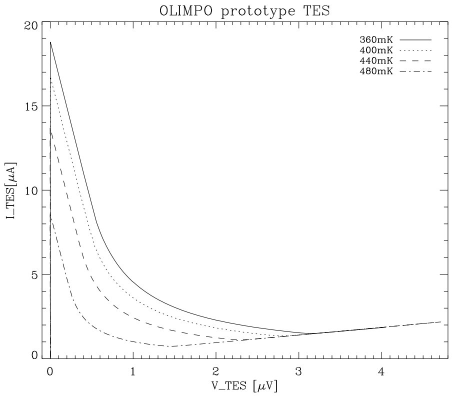

Fig. 1. Load I-V curve of a prototype TES of the OLIMPO experiment for four different bath temperatures. The normal branch is evident as a straight line on the right hand side of the curves, the superconducting transition is the curved central part and the superconducting branch is the vertical line on the left hand side. OLIMPO TES bolometers are fabricated at SRON by members of the Cardiff University and tested in Cardiff and in Rome University. Acknowledgement Dmitry Morozov.

2. Transition Edge Sensors

The working principle of a TES can be described as follows: the detector is voltage biased and kept on its transition between superconducting and normal state at a typical resistance of $R_{TES} \sim (0.3-0.7)R_n$, where R_n is the normal resistance. An input optical power causes the rise of the temperature and consequently of the resistance. Since the TES is voltage biased, and the bath temperature is well below the bolometer critical temperature, the increase of the resistance implies the diminution of the Joule heating $P_J = V^2/R$: this is a negative electrothermal feedback (ETF) that holds the temperature constant. Incoming signal is thus converted into a current. It is necessary to use very accurate and sensitive ammeter to read the low current signal: Superconducting Quantum Interference Devices (SQUID) ensure sensitive, high bandwidth and low noise signal read-out.

The strong ETF established in a Superconducting TES results in many advantages with respect to standard Semiconductor bolometers. Standard bolometers show ETF too, but the strength of the feedback is proportional to steepness of the R vs T curve. The effective time constant is reduced with respect to the pure thermal time constant τ. The ETF also reduces thermal fluctuations and effectively the Johnson noise. Further advantages of the ETF include that the detector is almost insensitive to the common fluctuations of the cryogenic system: the responsivity depends only on the characteristics of the bias circuit. It is also remarkable that the ETF linearizes the response and extends the dynamic range of the detector; also, over certain ranges of signal power and bias voltage, a TES self-biases its temperature within the transition (Irwin et al. 2005). The use of detectors with low impedance implies also a drastic reduction of the microphonics that afflict standard bolometers technology. This is giving a strong impulse to the use of cryogenic system, based on pulse tubes and mechanical cryocooler although this does not applies to LDB.

There are also disadvantages in the use of TES. Differently from standard bolometers, TESes have a definite saturation power. If the incident power is much larger than what they are designed for, detectors go normal, saturate, and cannot work. It is thus crucial to have an accurate evaluation of the background power to properly design a TES camera. In fact, this problem is somehow mitigated in LDB experiments since the main variable source of the background is the atmosphere, that has a quite low emission and variability at balloons altitude compared to ground based experiments. Also, it is worth stressing that both the detectors and the SQUID read-out system are very sensitive to the magnetic field and its variations. This can degrade their performance in various ways and cause lost of data due to the failures of the SQUID-based read-out system. This implies the need of an optimum magnetic shielding, using combination of high-permeability and superconducting shields, and careful characterization of the array during observations. Dedicated software has to be developed in order to continuously characterize and tune up an array of TESes during observations every time the magnetic and temperature conditions are believed to change (Battistelli et al. 2008).

The intrinsic noise of TES is generally dominated by the phonon noise of the thermal conductance G, that is much larger than the contribution of Johnson and read-out noise. A great effort is being put by the scientific community to theoretically understand the different kinds of high- or low-frequency excess noise, that can afflict TESes significantly reducing their performances Irwin et al. (2005). The total intrinsic noise of a TES has anyway to be compared with the photon noise of the background (sky, telescope, cryostat window, etc.), that limits the accuracy of the measurements. As an example, the evaluation of the background noise for a typical balloon experiment, like OLIMPO, is between 2-4 10^{-17} W/$\sqrt{Hz}$, depending on the working frequency and bandwidth in the mm range. Typically, TESes work in Background Limited Infrared Photodetection (BLIP) condition, that means that the total noise of the detector is much lower than the photon noise of the background.

One way to characterize a TES is by acquiring a load (I-V) curve ramping downwards the TES bias. Curves are analyzed to calculate the detector bias that drives the bolometer to 30% of its normal resistance, R_n (or another predefined percentage of R_n) (see figure 1).

3. SQUID and read-out

As mentioned, radiation detected by a TES is read-out using Superconducting Quantum Interference Devices. SQUIDs are closed superconducting rings with two Josephson junctions in parallel. SQUIDs measure the magnetic field exploiting the interference typical of the Josephson junctions. If a circuit is inductively coupled to a SQUID, it can also be used as an ammeter. Single- or multiple-stage configurations are adopted in mm and sub-mm cameras depending on the number of pixels and the particular adopted configuration. Typically each SQUID has two magnetic inputs, one coming either from the TES or from the previous SQUID stage, and a second one coming from a feedback coil. The input magnetic signal is converted into a voltage response whit a response which is strongly non-linear. The bias voltage oscillates between two limiting curves with the change of a single magnetic quanta inside the loop between the two Josephson junctions.

Because of the intrinsic non-linearity of the SQUID's response, a flux lock loop (FLL) is used to calculate the correct flux to be sent to the feedback coil to compensate for changes in detector current and to keep the amplification chain in a linear regime. Dedicated room-temperature read-out electronics operate analog or digital integrators that actively keep the output signal from the SQUID at a predetermined value and supply feedback currents. This feedback value constitutes a measurement of the optical input power and is the nominal acquired signal. Particular attention has to be payed in the read-out electronics design for LDB. Stability, reliability, low power consumption, self-recovery and radiation hardness are the goals to be achieved.

4. Arrays of Transition Edge Sensors

The way to improve the sensitivity of a pixel array when the detectors are photon noise limited is to increase the number of pixels. TES are fabricated using standard planar microelectronic process (i.e. lithography) which facilitates the process of fabrication of large format arrays. One of the challenges in building large arrays is the development of thermal supports and wirings allowing to easily put a large number of pixels in a small area, compatible with the telescope focal plane. The use of bulk or surface micromachining allow to fabricate arrays larger than 1000 detectors. The auto-biasing capability of the TES allows to share the same bias lines between different bolometers even when presenting slightly different characteristics.

The massive increase of the number of the SQUID read-out wires into a cryogenic experiment would however create problems of thermal input especially for Long Duration Balloons where the experiment life time is typically limited by the holding time of the cryogenic liquids in the cryostat. Multiplexing techniques enable the reduction of the number of wires reaching the cold stage of a cryostat housing the detectors and effectively enable a large increase of the number of pixels in mm and sub-mm cameras. In a multiplexed camera, groups of TESes and/or SQUIDs share the same wires and are biased and read-out at different frequencies or at different times. Two kinds of multiplexing techniques have in fact been developed: frequency domain multiplexing (FDM) (Yoon et al. 2001) and time domain multiplexing (TDM) (Chervenak et al. 1999).

In a typical TDM system, each TES is coupled to a first stage SQUID (SQ1) and the signals from all the SQUIDs of one section (eg. one column) of an array are summed and coupled to a second stage SQUID (SQ2). Rows of SQ1s are sequentially turned on so that the signal from one TES at a time per column is passed to that column's SQ2. Many mm and sub-mm experiments use Time Domain Multiplexers developed at the National Institute of Standard and Technology (NIST) (de Korte et al. 2003; Irwin et al. 2001) (see figure 2). These include ground based experiments like SCUBA2 (Holland et al. 2006), ACT (Fowler et al. 2007), ClOVER (Audley et al. 2006), BICEPII and SPUD (Kovac et al. 2007) and balloon born experiments like SPIDER (Montroy et al. 2006). In the NIST TDM, TESes are coupled to a three

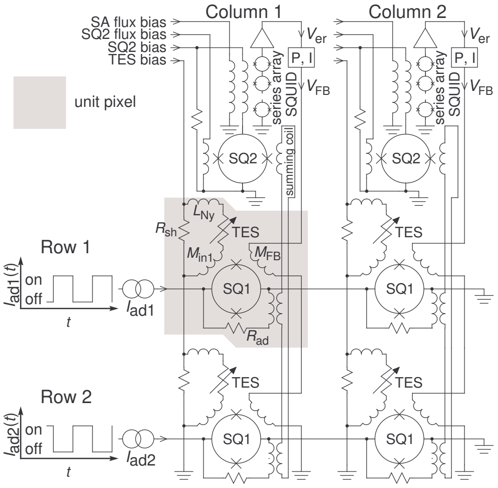

Fig. 2. Schematic of a 2-row × 2-column SQUID TDM developed at NIST. Each TES is inductively coupled (M_{in1}) to its own SQ1. An inductive summing coil carries the output signals from all SQ1s in a column to a common SQ2. Rows of SQ1s are sequentially addressed, using I_{ad}, so the signal from one TES at a time per column is passed to that column's SQ2. Finally, the output of each SQ2 is routed to a SA amplifier and then to room-temperature electronics. The SA output, or error signal (V_{er}), is processed by a FLL to keep the SQUIDs in a linear regime. Acknowledgement Randy Doriese

stage SQUID multiplexer. Every column of the multiplexer comprises of a few tens of SQ1s (typically 30 or 40) coupled to one single second stage SQUID (SQ2). An inductive summing coil is what carries the output signals from all SQ1s in a column to the common SQ2. The signal from each SQ2 is then amplified by a high gain SQUID Series Array (SA). The TESes and the first two SQUID stages typically operate at temperatures of 100 or 300 mK, while the SAs are usually at a warmer stage, typically at 4 K. Sub-arrays of more than 1300 pixels can be controlled by NIST TDM.

In a FDM system, each TES is connected to a tuned resonant LC circuit and is biased with an alternating current. Multiplexed TESes are biased at different frequencies of several hundreds of kHz up to 1 MHz. The signals are summed and read-out by a single SQUID and are processed and demodulated by room-temperature electronics.

Several mm experiments use the FDM developed at Berkeley University (Lanting et al. 2001). These include the ground based telescopes APEX-SZ (Dobbs et al. 2006) and SPT (Ruhl et al. 2004) and the balloon born experiment EBEX (Oxley et al. 2004).

Among TDM and FDM, the former seems to show the highest level of readiness both in terms of stability and criticality of the magnetic shielding. However, FDM seems to be more promising for future over-a-thousand pixels arrays.

5. Conclusions

Most future mm and sub-mm LDB experiments plan to use TES with SQUID read-out. TES are the most sensitive detectors at mm waveleghts and typically work in BLIP conditions. Multiplexing techniques enable the massive increase of detectors in telescope focal planes with arrays of more than 1000 pixels. LDB experiments are the natural path-finder for future space-born experiments that are already being designed.

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