TES Microcalorimeters for PTOLEMY

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Abstract The PTOLEMY project is devoted to directly detect the Cosmic Neutrino Background (CNB). A key point for the project success is the development of a device capable to detect electrons with an energy resolution lower than 0.05 eV. Microcalorimeters based on transition-edge sensors (TES) are among the best candidates since they already reach 0.11 eV of energy resolution for telecomm photons. To further improve the energy resolution, while maintaining a suitable saturation energy, it is necessary to reduce the transition temperature. This could be achieved by proximity effect of a normal-superconducting bilayer. To this aim, TiAu very thin films are under development to demonstrate the feasibility of reaching 0.05 eV energy resolution for light pulses of few eV. Thanks to the high electron stopping power of metals, the penetration depth of low energy incident electrons is limited to few nanometers and, with respect to visible light, we expect a high detection efficiency, while keeping similar dark counts and energy resolution.

Keywords Cosmic Neutrino Background • Transition-edge sensors • Electron

1 Introduction

The PTOLEMY project aims to develop a scalable design for a Cosmic Neutrino Background (CNB) detector, the first of its kind and the only one conceived that can look directly at the image of the Universe encoded in neutrino background produced in the first second after the Big Bang [1]. The

description of the PTOLEMY prototype experimental configuration is reported in reference [2].

The signal for relic neutrino capture on tritium is the observation of electron kinetic energies emitted from a tritium target that are above the β-decay endpoint. To separate the CNB signal from the β-decay endpoint an electron energy resolution of 0.05eV is needed. Microcalorimeters based on transition-edge sensors (TES) [3] are among the best candidates since they already reach 0.11 eV of energy resolution for telecomm photons [4].

In principle the physical detection processes of UV/Vis/IR and low energy particles have many similarities. Photons are detected by means of a direct electron heating and, because the electron-electron interaction is stronger than the electron- phonon interaction, the photon energy is promptly distributed to the whole electron gas in a time scale much shorter than the one to the phonon system. This means that a TES is absorber and detector at same time: it directly measures the electron gas temperature rise after the photon absorption. The consequent excess of heat in the electron gas is slowly released to the phonon system and finally to the substrate that acts as heat sink.

In the case of electrons, if the track-length (that should be hundreds of angstroms) is fully enclosed in the TES metal film, a local small hot spot with hotter electrons is expected. However, thanks to the stronger electron-electron interaction, the primary electron energy should be shared among all the electrons of the TES in a short time, at least in the electron diffusion time over the TES film. The dynamics of the TES cooling is expected to be equal in both cases. It has been already reported in literature that superconducting nanowire single photon detector also detects single electrons with keV energy, but without energy resolution [5].

In conclusion, few differences in the primary energy absorption processes are expected. These could bring about different features of the rising edge of the pulse, like a possible position dependence at very short timescale. At first glance we don't expect any possible effect on the energy resolution because of the intrinsic integration time that is one order of magnitudes larger time scale.

2 Films development

To further improve the energy resolution already obtained with a TiAuTi multilayer [4] it is necessary to reduce the heat capacity of the detector. This can be accomplished with a reduction both of the transition temperature T_c of the multilayer and of the volume of the sensor. The fabrication process has been modified in order to obtain a T_c reduction by proximity effect of a

superconducting-normal bilayer of TiAu. To reduce as much as possible the thickness of the material, a study on the film properties has been carried out.

Ti and Au films were evaporated by e-beam and effusion cell, respectively, at a pressure lower than 8 10^{-8} mbar. Ti films with different thicknesses have been fabricated but, under 20 nm, no T_c was present down to 30 mK, that is the minimum temperature reachable by our ADR fridge (Fig.1 *Left*). For this reason some bilayers with 23 nm constant Ti thickness and increasing Au thickness up to 33 nm have been tested (Fig.1 *Center*). However, the temperature reduction was not as expected from our previous work [6]; a possible reason is a different interface transparency between Au/Ti of our former works and the actual Ti/Au. Thus, in order not to increase too much the overall thickness, we switched to fabricating bilayers with constant Au thickness of 27 nm and variable Ti thickness down to 12 nm. As reported in Fig.1 *Right*, in this way it has been possible to obtain bilayers with T_c lower than 100 mK and overall thickness of 38 nm, less then half the thickness of our former films [4]. Some of these bilayers have been obtained with Ti thickness lower then 20 nm, in contrast to what was obtained in Fig. 1 *Left*. The deposition of Au on Ti film most probably protects them from the oxygen contamination [7] that is known to be the cause for a significant Tc reduction [8].

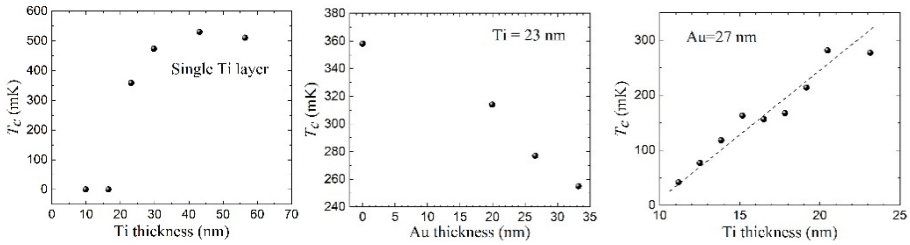

Fig. 1 *Left*: T_c vs thickness of single layer Ti films. The vertical dash line at 20 mK is only a guide; *Center*: T_c vs Au film thickness for bilayers with constant Ti thickness of 23nm; *Right*: T_c vs Ti film thickness for bilayers with constant Au thickness of 27nm. The dash line is only a guide.

The normalized resistive transitions, with respect to the normal resistance just before the transition occurrence, for some of our bilayers are reported in Fig.2.

3 Detector development

As stated in section 1, we expect a similar behavior of the TES response for both visible/near-infrared photons and electrons. This allows the development of the detector to be based on single photon detection experiments, for which knowledge and experimental setup are already available [9].

PTOLEMY project needs a microcalorimeter with an energy resolution $\Delta E_e = 0.05$ eV at 10 eV [2] while, up to now, an energy resolution of $\Delta E = 0.11$ eV at 0.8 eV, obtained with a TES with T_c=106 mK, 100 μm^2 area and 45 nm of Ti and Au thicknesses has been demonstrated [4]. Taking into account that there is a dependence of the energy resolution on the detected energy [10] that, based on our previous experiment results [11], can be approximated by $\Delta E \propto E^{1/3}$, the PTOLEMY request can be translated into $\Delta E_{NIR} = 0.022$ eV at 0.8 eV.

The TES energy resolution is proportional to $\Delta E \propto T_c^{3/2} t^{1/2}$ [3], where t is the Ti film thickness which is the larger heat capacitance contribution. Since we obtained a Ti thickness reduction of more than 3 times with respect to the TES used in [4], ΔE_{NIR} can in principle be reached with a T_c ~50 mK. At the present moment, using the films described in the previous section, we have already obtained a 20 µm x 20 µm device with a sharp transition at 70 mK (Fig. 3). This result indicates the good quality of the films produced and the possibility of shortly reaching the goals set for the energy resolution of the detector. The optical characterization of the TES as single photon detectors at near-infrared wavelengths will start soon.

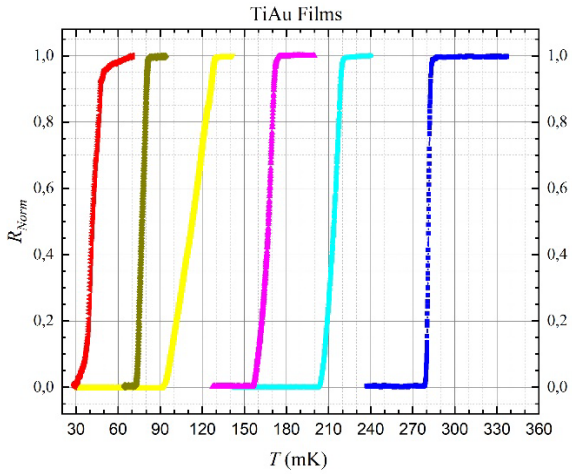

Fig. 2 Normalized resistive transition, with respect to the normal resistance just before the transition, for some bilayer films of Fig. 1 *Right*. The excitation current is 1µA. The transition temperatures span from 281 mK to 42 mK. (Color figure online)

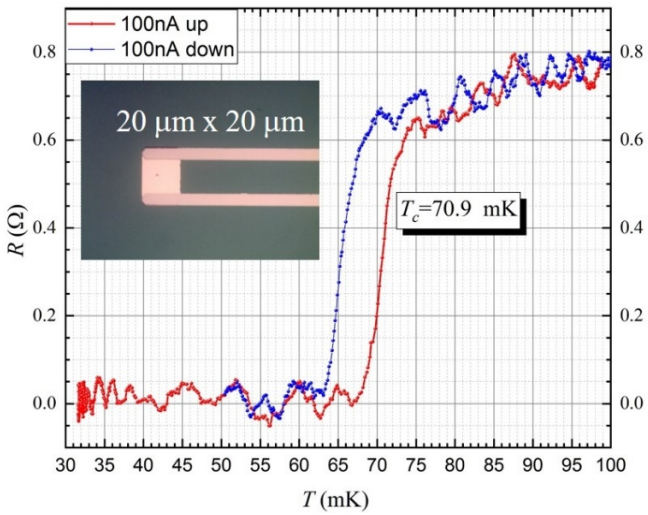

Fig. 3 Resistive transition for a TiAu bilayer TES with 12 nm of Ti and 27 nm of Au. The hysteresis is due to the Joule heating induced from the bias current when the acquisition is done from normal to superconductive state. In the inset, a picture of the sample with an area of 400 μm^2 . The leads are made with Nb sputtered films. (Color figure online)

4 Conclusion

The PTOLEMY project aims to directly detect the CNB and one of its key elements is the development of a microcalorimeter that must detect the energy of impinging electrons with an energy resolution of $\Delta E_e = 0.05$ eV at 10 eV. We have presented our latest results on the development of TiAu bilayer where films with 38 nm of overall thickness and transition temperature down to 42 mK have been obtained. TES detectors with T_c of 71 mK and transition width of few mK have been fabricated, giving a glimpse of the possibility to obtain in a reasonable short time the required performance. The detector area of the PTOLEMY prototype will be defined as the project progresses and it will be obtained with TES array and readout multiplexing.

Thanks to the high electron stopping power of metals, the penetration depth of incident electrons is limited to few nanometers and, with respect to visible light, we expect a high detection efficiency, while similar dark counts and energy resolution. This point deserves to be investigated and a test with a cold e-gun will be planned. For the application of the microcalorimeter to the PTOLEMY experiment, the use of TES arrays will be required, which implies a read-out based on SQUID - multiplexing.

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