Final report of the 2012-2013 P2IO project:

Capteurs cryogéniques de nouvelle génération pour l'observation en Astrophysique et Cosmologie.

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Project goals

The goal of our project was the development of an innovative cryogenic sensor with direct applications to Astrophysics and Cosmological observations. Low temperature bolometer arrays have recently played a key role to this domain (Planck and Herschel space missions, South Pole Telescope observations…) and now pave the way to some major future projects concerning CMB B-mode polarization and X-ray space observations. Furthermore, several projects on particle physics, related to rare event search (neutrino physics, dark matter), are based on similar very low temperature detectors. The present P2IO project allowed the development of very sensitive high impedance Transition Edge Sensors (TES), based on amorphous Nb_xSi_{1-x} meander shaped thin films ($x \approx 0.14$). This solution combines the high sensitivity of a "classical" TES device with the possibility to use high impedance read-out electronics, based on JFET or HEMT transistors. In addition, NbSi TES can be easily adapted to a large variety of experimental requirements.

Description of work achieved

The project involved the CSNSM, IAS and SAp laboratories. CSNSM was responsible of the TES manufacturing and optimization, low temperature testing and overall organization. IAS was responsible of the low temperature characterization and SAp of the HEMT read-out development and final low noise testing of the device.

Our TES detectors are based on a low temperature calorimetric device principle. The energy deposited into the detector induces a temperature increase that is continually monitored by a superconductor thin film, biased on the middle of its transition (TES). A small temperature variation will give a substantial change in the TES resistance, which is measured by a low noise amplifier (SQUID or transistor based). State of the art TES bolometers attain temperature resolutions of few nano-Kelvin. Translated in terms of energy, X-ray low temperature micro-calorimeters can reach resolutions close to 1eV.

In the frame of our P2IO project it was decided to construct several prototype detectors based on 2x2 mm^2 400μm thick Silicon substrates. 2-inches crystalline Si wafers were used to produce several samples, characterized by different NbSi TES film geometries. After the NbSi TES fabrication, the Si wafer is cut to approximately 350 samples of 2x2 mm^2 that can be tested independently. The fabrication design is illustrated below.

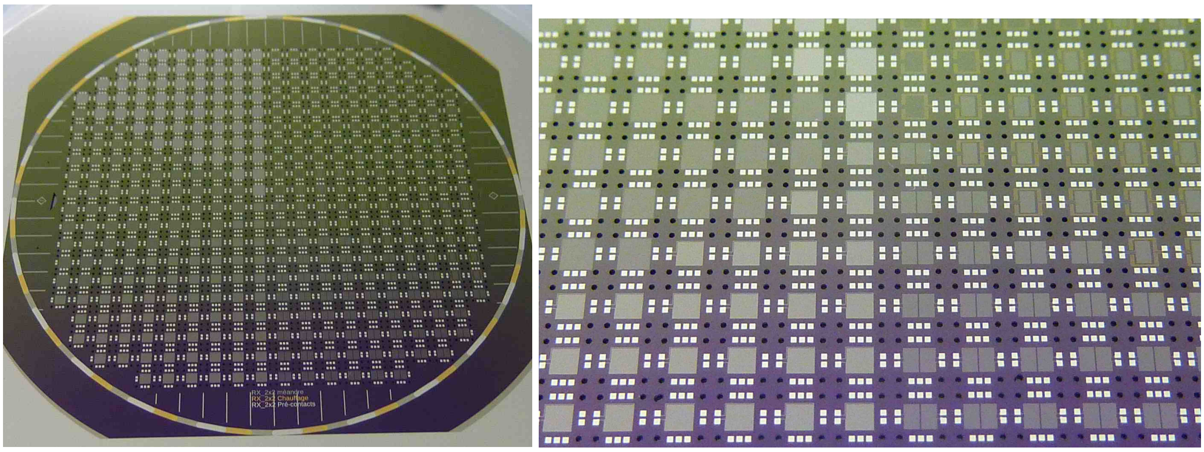

Figure 1. Our design is fitted in a 2 inches wafer. It is composed of 6 different geometries for the NbSi TES, two of them equipped with an Au heater. Each "pixel" has four holes that are crossing the substrate. They can be used to fix the sample to a holder with Kevlar wires.

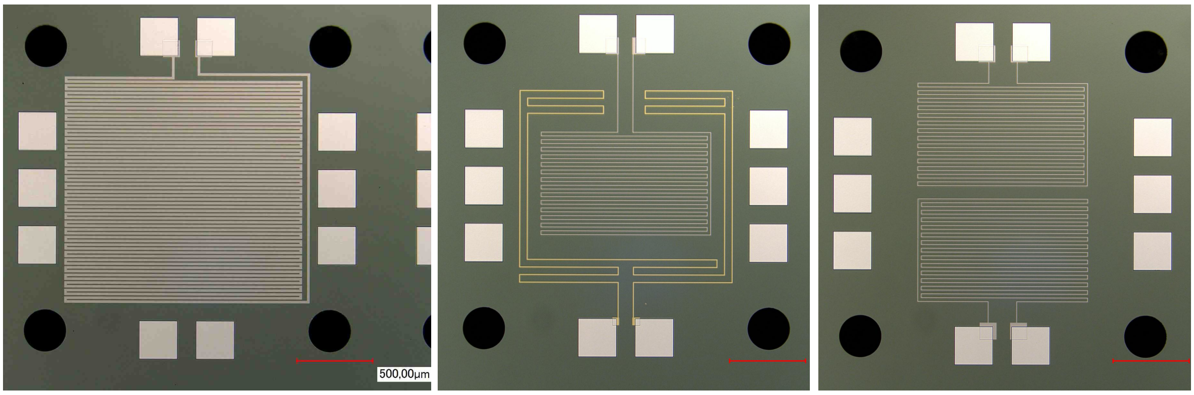

Figure 2. Optical photography of 3 different TES samples. The sample on the middle is composed by a NbSi TES meander (grey line), surrounded by a Au heater (yellow line). This heater can be used to regulate the detector temperature or to increase its dynamic range (negative feedback on the heater). The white squares are Al or Ir pads for ultrasonic bonding. The 2x2 mm^2 Si substrate can be used to absorb visible or X-ray photons. Nevertheless, high energy X-rays (>1keV) create defects into the Si crystal preventing a part of the energy to be detected by the TES sensor. To achieve high-resolution X-ray spectroscopy (1/1000 or below) a suitable absorber, like superconducting Tantalum, can be hybridized or glued on the backside of the Si substrate.

The major challenge of our P2IO project was related to the development of a reliable and reproducible manufacturing process. Approximately ten different processes were tested before converging to the final solution, which gave very satisfactory results. One typical manufacturing problem was related to the quality of the interface between the NbSi TES sensor and the bonding pads, giving non-Ohmic behavior and broad or multiple superconducting transition resistance curves.

The process that we finally approved consists of three consecutive lift-off steps realized by photolithography. At first we deposit a 20nm-thick iridium film for the bonding pads, followed by a 100nm Au film heater and a 30 to 50nm NbSi TES. All these films are realized using high vacuum electron-beam evaporation. The final step consists of an ICP ion etching (Deep-RIE) in order to realize the through holes into the Si substrate. Special care is taken for preparing the sample surface prior to each of the thin film depositions.

The resulting low-temperature NbSi TES resistance curves are illustrated in the following figure.

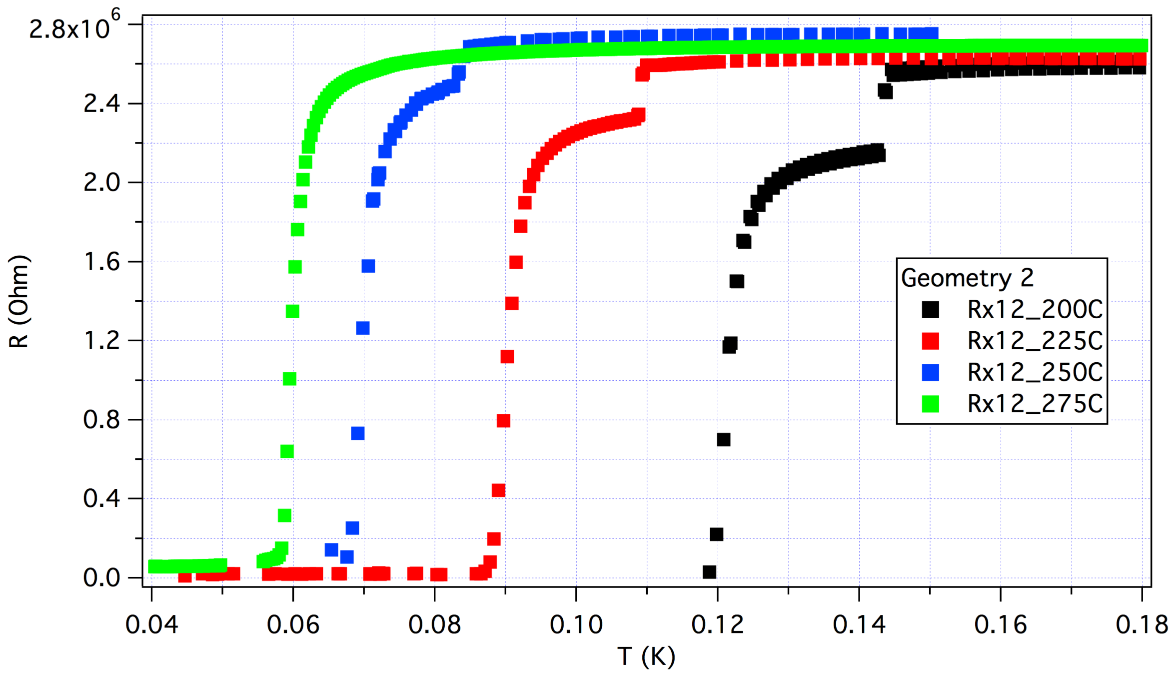

Figure 3. Superconducting transition behavior of four samples (middle geometry of figure 2), coming from the same wafer. Operating resistance is on the MΩ range, optimized to transistor front-end electronics. The samples were annealed during 5 minutes at four different temperatures (200°C to 275°C) in order to adjust their critical temperature Tc (all Tc≈180mK before annealing). This effect is a characteristic property of the NbSi TES films. In the case of X-ray micro-calorimeters, our cryogenic setup will be optimized for 70mK TES. We observe a parasitic transition on the top of three curves, which is characteristic of inhomogeneities of the NbSi meander. These effect disappeared on our latest samples, manufactured with an optimized process.

The present P2IO project has also contributed to the realization of a dedicated low noise amplifier based on HEMT front-end transistors. This development took place at SAp-IRFU, under the responsibility of Claude Pigot and Xavier de la Broise.

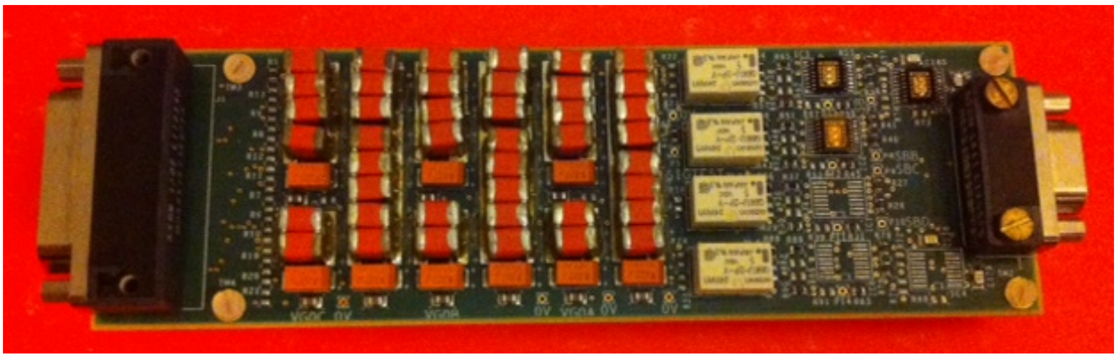

Figure 4. Read out circuit with 6 parallel HEMT-input channels. HEMT transistors where manufactured at LPN-Marcoussis laboratory by Yong Jin.

Testing of the global performances of our TES meander detectors coupled to the HEMT amplifier will be performed in the coming months. Optimizing energy resolution and dynamic range will be a key feature for future X-ray multiplexed arrays.

Publications

Due to the important manufacturing progress that had to be accomplished before the realization of reliable NbSi meander-shaped TES we didn't submitted any articles during the P2IO project period. However, the current status of the detector and read-out device is sufficient mature to consider a dedicated publication.

Relevance of the project within P2IO and specific added value for P2IO

The realization of the present project, thanks to the P2IO funding, allowed us to develop a very promising low temperature detector device with potential applications to X-ray imaging. Several P2IO laboratories are supporting the future ATHENA+ space mission (2028), requiring an X-ray calorimetric detector for the 100eV-15keV energy range. Our NbSi TES cryogenic detector combined with a HEMT based multiplexing scheme is an interesting solution to such type of missions. Beyond the X-ray calorimeters, high impedance TES are also very interesting for low temperature visible light detection and for large mass rare event search bolometers. Neutrino-less double beta decay using low temperature scintillating bolometers and direct dark matter search are typical examples. We are very confident that the present P2IO project is able to offer substantial improvement to all these fields.

Possible valorization of the project

As described above, the present project has several applications to the Astroparticle domain, to observational Cosmology and to Particle Physics, in particular neutrino physics. The development of specific NbSi TES devices for all these fields will be considered. Based on the experience acquired during the present PIO project, dedicated demonstrators to new experiments could be quite easily realized

Expenses

- **CSNSM : 36k€** (expenses related to the CTU-IEF nanofabrication facility + CSNSM NbSi co-deposition clean room expenses + cryogenic tests of the TES)
- **IAS : 17k€** (purchase of a resistance bridge and temperature controller + cryogenic tests of NbSi detectors (liquid-He…))
- **IRFU/SAp : 17k€** (Sample fabrication and tests at PTA nanofabrication facility of Grenoble + HEMT electronics development and preamplifier fabrication)

Future of the project after P2IO funding

The present project clearly initiated a new type of high impedance TES, having several interesting applications to low temperature detection. In the coming months we plan to measure the ultimate performance of our device, using HEMT front-end electronics read-out. Realization of a 1000 pixel array in the frame of ATHENA+ space mission will be considered.

NbSi TES sensors can be easily optimized for different substrates and at any temperature in the 0-2K range. Existing projects using massive absorbers for dark matter search or double beta decay, like EDELWEISS and CUORE, could be advantageously equipped with such sensors. In addition, NbSi TES sensitivity to out of equilibrium phonons will be investigated and could bring a further benefit.

We would finally like to point out our recently submitted ANR project, aiming to develop a low temperature visible light detector based on an innovative concept of direct photon absorption into a NbSi TES meander.