Progress on silicon bolometers for (sub)-millimeter astronomy: from ArTéMiS to future B-Mode detection space missions.

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Abstract— **We present the latest developments on high sensitivity silicon bolometers for (sub)-millimeter astrophysics. Based on the same detectors developed for Herschel-PACS, the submillimeter wide-field camera ArTéMiS has been successfully commissioned at 350 µm on APEX. Results show that it is 5 times faster than the previous instrument (Saboca) in terms of mapping speed. The next generation of all-silicon detectors is under development in our group. They work at 100 mK and are able to reach NEP's around 10^{-18} W/√Hz. Their versatile design enables them to cover the submillimeter to millimeter range. These new detectors are polarization sensitive and can measure directly and simultaneously the Stokes parameters I, Q and U.**

I. Silicon Bolometers for PACS and ARTEMIS

Resistive bolometers have been used with success in (sub)-millimeter astronomy for several decades now. Many instruments (like SCUBA [1], MAMBO [2], SPIRE [3], Planck HFI [4] or LABOCA [5] to name a few examples) using such detectors have made significant scientific breakthroughs in the understanding of star formation processes, galaxy evolution or cosmology. Our group has developed the PACS [6] imaging photometer aboard the Herschel Space Observatory, using such resistive bolometers. It was designed to operate in the 70 to 210 microns band, and it was the most used instrument of Herschel during its lifetime (60% of the scientific time between 2009 and 2013).

The bolometers used for PACS are high-impedance sensors (a few 100 GΩ) that are silicon micromachined. The thermometers are made of silicon doped with phosphorous and boron and follow the Efros-Shklovskii variable range hopping model for the electrical conductivity. The arrays are composed of 256 bolometers, they work at 300 mK and are multiplexed (16 to 1) via CMOS readout electronics. The typical NEP for PACS in the 60 – 130 microns band was 4×10^{-16} W/√Hz.

More recently, these silicon bolometers have been used for the submillimeter camera ArTéMiS [7] that is installed on the 12m APEX [8] telescope in the Atacama desert in Chile. The instrument was commissioned at 350 microns in 2014 and showed very good results. The median NEFD (1s, 1σ) is 600 mJy.s, with best pixels showing an NEFD of 300 mJy.s. With 1650 working pixels, this preliminary and not complete version of ArTéMiS is already 5 times faster than Saboca in mapping speed.

In 2015, ArTéMiS will be upgraded and will be able to simultaneously observe at 200, 350 and 450 microns, with a field of view of 4.7×2.3 arcmin^2 (2.3×2.3 arcmin^2 at 200 microns), and 5760 pixels in total.

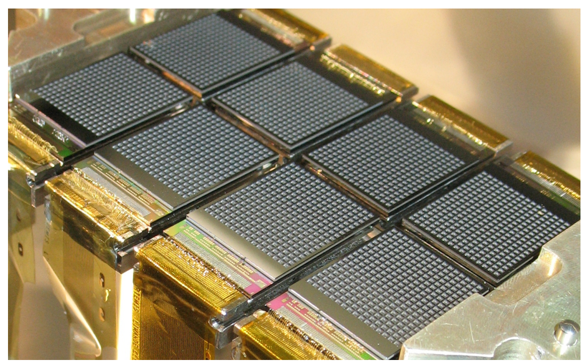

Fig. 1 The 350 µm focal plan for ArTéMiS camera containing 2304 bolometers. Two arrays were not operational because of electrical connectors issues.

Fig. 2 The star forming region NGC6334 (Cat's Paw Nebula) observed at 350 µm with ArTéMiS. ArTéMiS data are in orange, the background image comes from ESO-VISTA observations made in infrared.

II. Current Developments

We have recently started the development of the next generation of resistive bolometers to reach the very high sensitivities needed for the future space missions (like the B-Mode detection mission COrE+ for example). These instruments require detectors that are able to detect photons over a wide frequency range (100 GHz to a few THz), with NEPs around 10^{-18} W/√Hz or below.

Our solution is built on two solid bases: (a) the PACS technology, that gave the highest TRL and very good performances on a world-class space mission (sensitivity, calibration, insensitivity to magnetic fluctuations, very low sensitivity to high energy particles [9]), and (b) the successful development of room-temperature silicon THz micro-bolometers at CEA/LETI [10]. The new detectors are not hybridized by indium bumps anymore like the previous version. They are fabricated following an "above IC" approach where each layer that composes the sensor is grown above the electronic circuit (the "IC", for Integrated Circuit).

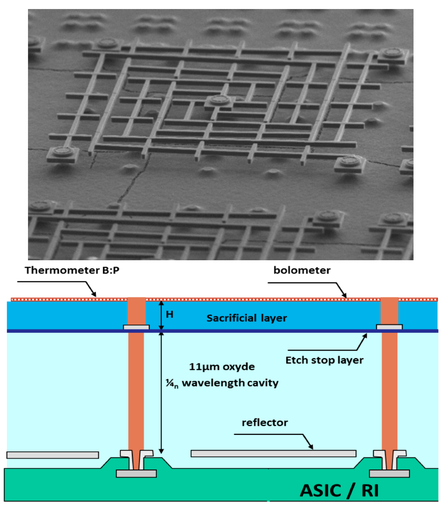

Fig. 3 above: SEM image of one new-generation polarization sensitive pixel. The pixel pitch here is 150 µm. Two interlaced silicon meanders are maintained at 2 µm above the SiO2 layer thanks to Copper Through-Silicon-Vias. Below : schematics of the new bolometers.

The high impedance thermometer is distributed along a long and thin silicon meander (1µm × 1.5 µm cross section). The absorption of the wave is achieved through the combination of vertical resonance (quarter wave cavity) and horizontal resonance (metallic pattern deposited on the meander, forming two networks of planar antennas). By design, the pixel is adapted to the relatively short waves (80-150 µm). To reach longer wavelengths, we developed a system based on an anti-reflecting layer that can be tuned to enhance the absorption in a particular band [11]. This system is able to provide very good spectral response in the millimeter domain (absorption above 85 %), see figure 4.

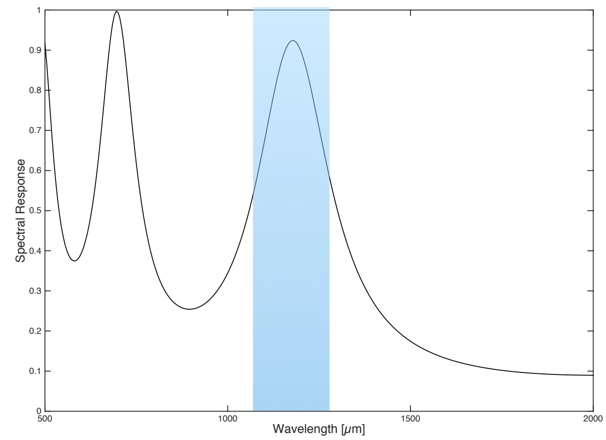

Fig. 4 Spectral response of the new bolometers (simulation), showing good absorption in the 1.2 mm band.

The high sensitivity is obtained mainly by reducing the working temperature down to 100 mK. We have measured the R(T) of doped silicon down to 100 mK and checked that it follows the Efros-Shklovskii law (figure 5). The low temperature greatly improves the R(T) slope, as well as the thermal conduction, thanks to the specific properties of crystalline silicon (compared to Si_3N_4 for example). We estimate that with our new design we can reach NEP of the order of 3×10^{-18} W/√Hz.

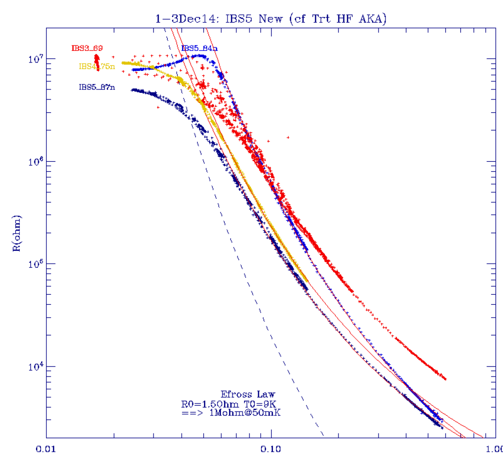

Fig. 5 Measurements of the impedance vs temperature for several Si:P:B samples. They follow the Efros-Shklovskii model down to 70 / 80 mK where we reach experimental limitations.

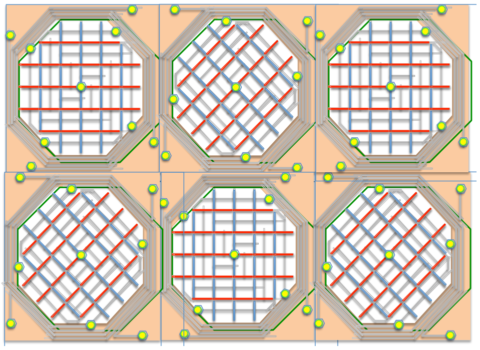

Fig. 6 Possible focal plane configuration to detect the polarization. Each pixel can detect both TE and TM components (blue and red patches). If each pixel is rotated 45 degrees about each neighbour, it is possible to directly measure the (I, Q, U) Stokes parameters, without external modulation.

These new detectors can be used to detect the polarization of the incoming wave, in a COrE+ like mission. Such pixels contain two independent meanders, each one matched to a TE or TM component (see figure 3). If the neighbouring pixels are arranged like on figure 6 (45 degrees rotation between each other), then it is possible in theory to simultaneously measure the 3 Stokes parameters I, Q and U, without the need of a modulating system like a rotating plate or a specific scanning strategy.

III. Conclusions

Following the development of the PACS camera, we have built the ArTéMiS submillimeter camera that will soon be fully operational on the APEX telescope. The next generation of silicon bolometers is now under development. The first tests are ongoing, in particular the measurement of sensitivity and spectral response. These detectors should be able to detect polarization with high sensitivity over a broad range of wavelengths.

Acknowledgment

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