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Cold-electron bolometer as a photon-noise-limited detector with on-chip electron self-cooling

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After discovering the electron cooling by Superconductor-Insulator-Normal metal (SIN) tunnel junctions, significant efforts were applied to obtain an effective on-chip cooler for mm/IR detectors. We have developed a Cold-Electron Bolometer (CEB) with effective direct electron self-cooling of the absorber [1], [2]. A photon-noise-limited pixel, consisting of an array of CEBs with self-cooling, is realized for OLIMPO Balloon Telescope for incoming power P_{in} up to 60 pW at phonon temperature T_{ph} = 310 mK. Operation of the bolometer at electron temperature less than phonon temperature significantly increases its sensitivity so that the noise equivalent power goes beyond the photon-noise-limited mode, which means that the internal bolometer noise is smaller than the noise of incoming signal [3]. We demonstrate the electron cooling from 310 to 120 mK without signal and from 410 to 225 mK for Pin = 60 pW at 350 GHz. The proposed technology is a potential replacement for the high-cost dilution refrigerators for space applications.

The cold electron bolometer is a SINIS structure, integrated in a planar antenna, designed to absorb terahertz radiation at certain frequency. Its SEM image is shown in Fig.1. The normal metal is made of aluminum with suppressed superconductivity, the tunnel barrier is formed by oxidation of aluminum and the superconducting electrodes are made of clean aluminum. All layers are deposited on a Si substrate by method of shadow evaporation. The volume of the normal absorber is just 0.02 μm^3.

A single CEB can absorb up to 0.3-0.5 pW of power before it saturates. In order to fulfill the requirements of high power load for OLIMPO mission, we connected 192 single CEBs in one array. Each bolometer is integrated in a dipole antenna. The array is tuned to have its maximal absorption at 350 GHz. The experiments have shown that the efficiency of absorption for fabricated samples is more than 50%.

The cold electron bolometer is well described by the heat balance equation for normal absorber with resistance R_N:

$$P_{abs} + I^2R_N + V^2/R_{leak} = 2*P_{COOL} + \sum \mathcal{V}(T_e^2 - T_{ph}^2), \quad (1)$$

where I - tunnel current, V - voltage drop across one SIN junction, P_{abs} - absorbed power, R_{leak} - leakage resistance of SIN junctions, P_{COOL} - cooling power of SIN junctions, $\sum$ - electron-phonon constant, $\mathcal{V}$ - volume of the absorber, T_e and T_{ph} are electron and phonon temperatures of the absorber, respectively.

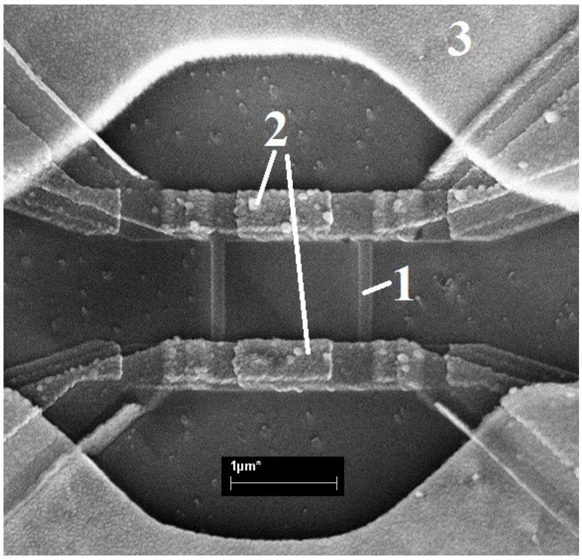

Fig. 1. SEM image of a single cold electron bolometer integrated in a gold dipole antenna. 1 - normal absorber, 2 - SIN junction, 3 - antenna.

The fabricated samples have been cooled in a dilution cryostat down to 310 mK and irradiated by a black body source through a set of quasi-optical filters for 350 GHz. The voltage response and voltage noise at several black body temperatures from 2K to 46 K have been measured, using room temperature ultralow noise amplifiers AD745.

We have compared the experimental IV-curves with Eq. (1) and found that our samples can be fitted very well with the following parameters: critical temperature of superconductor 1.24 K, phonon temperature 310 mK, $\sum$=1.3 nW/K^5/μm^3, normal resistance of SIN junction 1.6 kΩ, R_{leak}=25 MΩ, R_N=50 Ω.

The main characteristic of any detector is the noise equivalent power (NEP). The modern bolometers for astronomical applications are required to have intrinsic NEP less than the photon NEP of incoming signal, i.e. the detector has to be limited by the photon noise. We have shown in a set of our experiments, that we indeed can see the photon noise in our detectors in a broad range of incoming powers from 20 to 60 pW.

The NEP of the bolometer array is shown in Fig.2 for the case of zero incoming power. One can see good agreement between measured and theoretical values. The optimal operational point of the bolometer can be chosen at the minimal NEP around 12 mV. At this voltage the largest contribution to the bolometer NEP comes from the noise of SIN contacts, which is the sum of shot noise of current through a tunnel junction, noise of heat flow and correlation between them. Next largest NEP component is amplifier NEP. Whereas NEP due to electron-phonon interaction is significantly smaller than other NEP components and can be even disregarded.

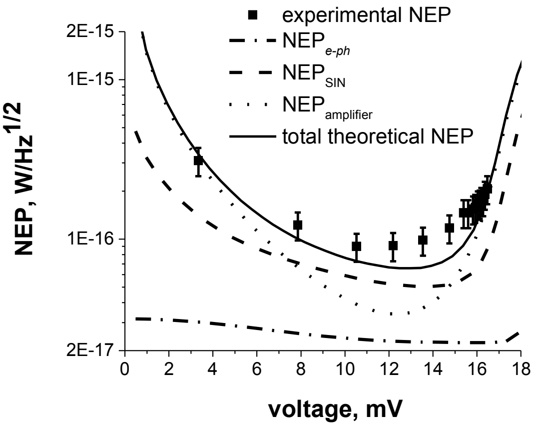

Fig. 2. Noise equivalent power versus voltage on the bolometer array with zero power load. The phonon temperature 310 mK.

In Fig. 3 we show NEP of the same bolometer array but for high power load 60 pW, which corresponds to 32 pW of absorbed power. Now we have one more NEP component - photon noise of absorbed power (straight gray line in Fig. 3). One can see that at voltages 11-12 mV the photon NEP goes a bit higher that all other NEP components together, which means that the detector is photon limited.

Analyzing our data, we found that for black body temperatures above 20 K, the phonon temperature of the sample also increases and can be higher than the cryostat temperature. For example for Fig. 3 the phonon temperature was 380 mK. But even with this overheating the samples show photon limited mode of operation.

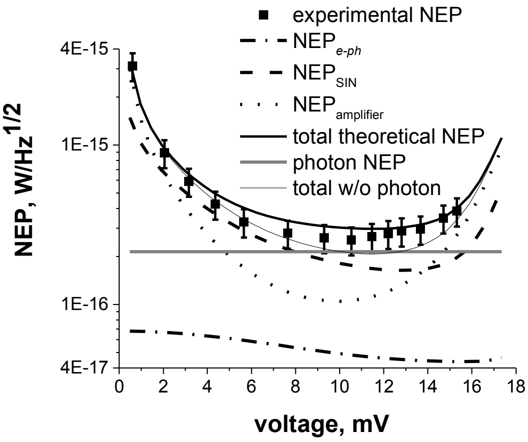

Fig. 3. Noise equivalent power versus voltage on the bolometer array. Radiated power 60 pW. Absorbed power 32 pW.

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