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Nonthermal optical response of superconductor-insulator-normal metal-insulator-superconductor tunnel structures

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Power Load and Temperature Dependence of Cold-Electron Bolometer Optical Response at 350 GHz

Mikhail A. Tarasov, Valerian S. Edelman, Sumedh Mahashabde, and Leonid S. Kuzmin

Abstract—Cold-electron bolometers (CEBs) integrated with twin-slot antennas have been designed and fabricated. Optical response was measured at bath temperatures of 0.06 to 3 K using blackbody radiation source at temperatures of 3 to 15 K. The responsivity of 0.3×10^9 V/W was measured at 2.7-K blackbody temperature that is close to the temperature of the cosmic microwave background. Optical measurements indicate quasi-optical coupling efficiency of up to 60% at low phonon temperature and low signal level. Estimations for bolometer responsivity were made for practical range of bath temperatures and blackbody radiation temperatures. The estimated ultimate dark responsivity at 100-mK bath temperature can approach $S_V = 10^{10}$ V/W and reduces down to 1.1×10^8 V/W at 300 mK for a device with absorber volume of 5×10^{-20} m³.

Index Terms—Cold-electron bolometer (CEB), electron-phonon interaction, superconducting tunnel junctions, twin-slot antennas.

I. INTRODUCTION

CAPACITIVELY coupled cold-electron bolometer (CEB) consists of a nanoabsorber and two superconductor-insulator-normal metal (SIN) tunnel junctions connected to planar antenna, schematic view, and scanning electron microscope (SEM) image shown in Fig. 1. In this bolometer, a normal metal strip, thermally isolated from the environment, is heated by incident radiation. The change in temperature is then measured by SIN junctions. The signal power is coupled to the absorber through the capacitance of tunnel junctions, dissipated in the absorber, and removed back from the absorber as hot electrons by the same SIN junctions by the bias current. Electron cooling serves as strong negative electrothermal feedback improving characteristics of the CEB, i.e., time constant,

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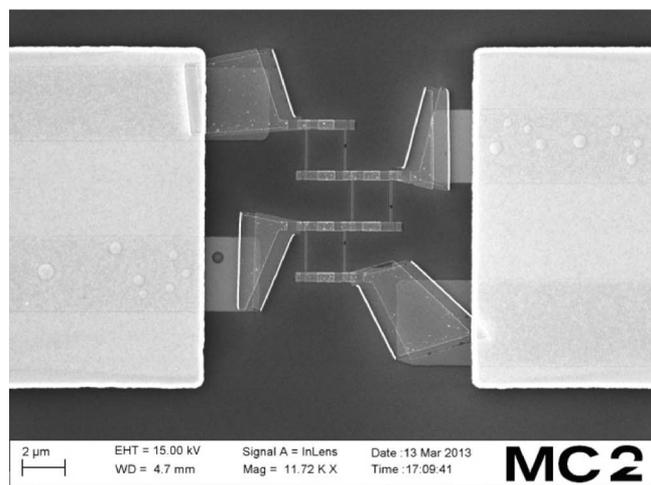
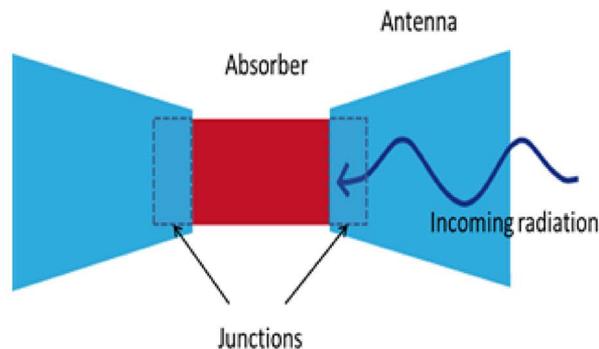


Fig. 1. Schematic view and SEM image of SINIS bolometer with a normal metal absorber, Al superconducting electrodes, and AlO_x tunnel barrier. Three such bolometers are connected in parallel for microwave signal and in series for output readout.

responsivity, and noise-equivalent power (NEP) [1]. Thus, CEB can be a candidate for measuring of cosmic microwave background (CMB) radiation.

For CMB temperature of 2.7 K, frequency of 350 GHz, and bandwidth of 100 GHz, the single-mode power load is 0.1 pW and corresponding photon noise is $7 \text{ aW/Hz}^{1/2}$. Radiation of cosmic dust clouds with temperature up to 30 K produces power loads up to 40 pW corresponding to photon noise of $125 \text{ aW/Hz}^{1/2}$. In our previous experiments, we studied series array of 10 CEB bolometers integrated in a cross-slot antenna [2]. In this paper, we integrated CEBs with a twin-slot antenna (see Fig. 2) and measured responsivity in 0.1–30-pW background power range. The double-slot antenna (DSA), also known as twin-slot antenna, is the

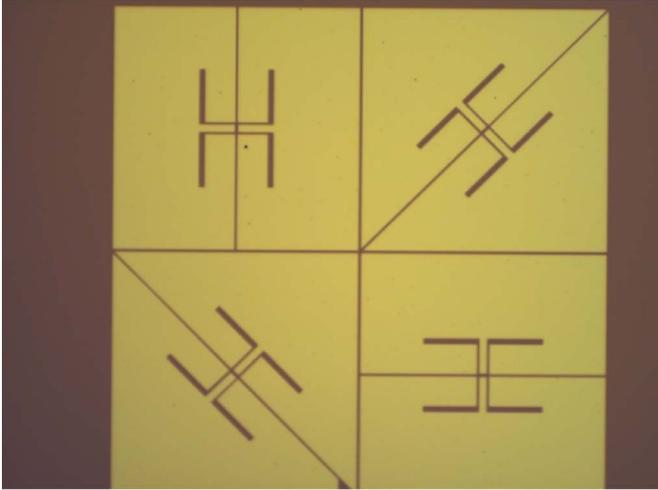


Fig. 2. Optical image of sample with four DSAs. Lines cutting antennas in halves are nonradiating at signal frequency. To avoid compromising the integrity of the ground plane, the nonradiating cuts are shunted by capacitance formed by aluminum oxide sandwiched between aluminum films, rendering these cuts invisible for submillimeter radiation.

most popular type of planar antenna that has been employed in superconductor–insulator–superconductor mixers and hot-electron bolometer mixers [3], [4]. Its spectral and beam pattern characteristics have been studied numerically and experimentally in detail, and its performance is well predicted. Apart from lens coupled slot antenna integrated bolometers, distributed antenna coupled bolometers are an alternative concept for building imaging arrays without lenses or horns for each pixel [5].

II. EXPERIMENTAL RESULTS

Samples with DSA (see Fig. 2) were mounted on an antireflection coated sapphire extended hyperhemispherical lens and irradiated at 350 GHz. For this experiment, a variable temperature blackbody source was fabricated in the form of a flat absorber 25 mm in diameter comprising NiCr film (300 Ω /sq) on a Si substrate. The emissivity of such film is over 90%. The dc or ac current across NiCr film provide changing of blackbody temperature. The blackbody source was also equipped with a temperature sensor connected to the temperature controller. This allowed setting a required temperature in a range between 3 K and 15 K. Due to the small size and proper choice of thermal links, such radiation source has a time constant below 100 ms.

Radiation bandwidth was selected by two bandpass filters placed between the blackbody source and the sapphire lens. Filters were made of thick Cu foil; measured bandwidth is 280–380 GHz with over 20-dB suppression below 280 GHz. Each chip with bolometer structures also contained an array of 100 series-connected SIN thermometers for monitoring of phonon temperature. The sample holder was carefully shielded from stray radiation; wiring is made of twisted pairs thermally anchored on three temperature stages by metal tubes filled with mixture of Stycast epoxy and Cu powder that also serve as RF filter analog to copper powder filters usually used in dilution fridges for RF filtering. A cold container was black painted with Stycast and Bi powder mixture.

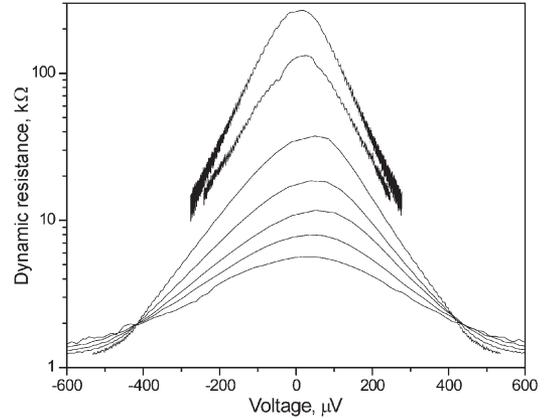


Fig. 3. Dependence values of dynamic resistance on bias voltage for phonon temperatures 274, 281, 295, 302, 309, 317, and 324 mK (curves listed from top to bottom).

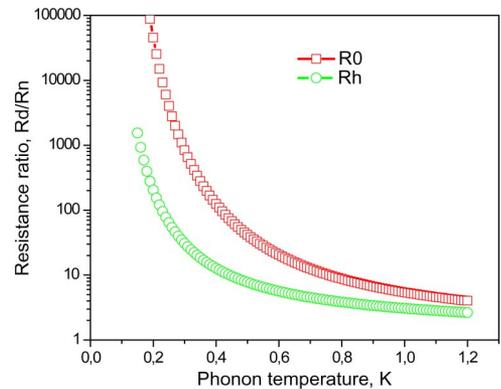


Fig. 4. RR at zero bias voltage R_0 and at half-gap voltage R_h calculated for a pair of SIN junctions without overheating and electron cooling.

Samples with four twin-slot antennas were designed for measuring polarization of incoming radiation. The optimal size of the pixel, according to [6] is $0.5F\lambda = 0.5 * 3.5 * 0.856 = 1.5$ mm, was designed for focal number $F = 3.5$ and wavelength of 0.856 mm. Dimension of each DSA antenna is $240 \mu\text{m} \times 150 \mu\text{m}$. We measured I–V curves in the bath temperature range of 0.06 K–3 K in dilution microcryostat [7] and from resistance ratio (RR) of SIN junction deduced equivalent electron temperature. Analytic relation for RR is given by [8]

$$\frac{R_d}{R_n} = \sqrt{\frac{2kT_e}{\pi eV_\Delta}} \frac{\exp\left(\frac{eV_\Delta}{kT_e}\right)}{\cosh\left(\frac{eV}{2kT_e}\right)}. \quad (1)$$

Typical dependence values of dynamic resistance on bias voltage for several temperatures around 300 mK are presented in Fig. 3, and RR calculated according to (1) is presented in Fig. 4. One can estimate the electron temperature by measuring RR for zero bias V_0 , as well as measuring ratio of resistance at bias corresponding to half the superconducting gap to asymptotic resistance R_h in Fig. 4. The latter is more reasonable because response maximum is usually observed around the half-gap voltage across the bolometer. Fig. 3 shows the dynamic resistance from measurements of one DSA sample, which is qualitatively described by relation (1) without noticeable influence of electron cooling and shunting leakage resistance. The

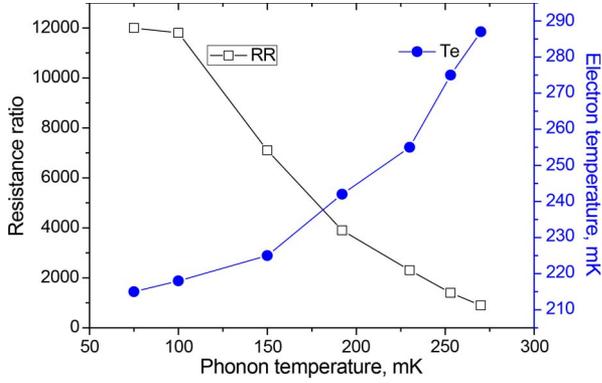


Fig. 5. RR and electron temperature T_e dependence values on phonon temperature for dark measurements of DSA sample.

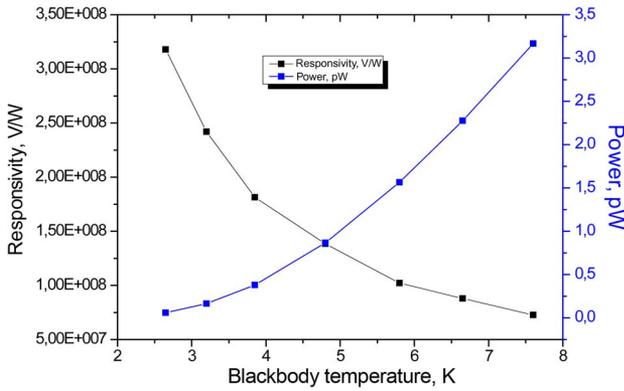


Fig. 6. Radiated power in picowatts and responsivity in microvolts per picowatt dependence values on blackbody temperature.

best obtained RR for dark measurements at 70 mK and zero bias ($V = 0$) approaches $R_d/R_n = 12\,000$ that corresponds to electron temperature of 215 mK (see Fig. 5), which is a clear illustration of unavoidable overheating for our bolometers. This overheating could be explained in part by considering the recent evidence from the literature [9], which connects the Dynes density of states of the superconducting electrode to the environmental impact on the tunnel junction (normal metal–insulator–superconductor junction of the CEB in this case). We unavoidably fill the environment of the detectors with high-frequency radiation from the blackbody that could cause the decrease in the dynamic resistance of the tunnel junctions at zero bias, decreasing the RR.

For optical response measurements, we can calculate the incident power using Planck's formula where h is Planck's constant, f_0 is the central frequency, df is the bandwidth, k is Boltzmann's constant, T_R is the radiation source temperature, and α is the emissivity.

For the single-mode DSA, antenna power irradiated at the antenna is given by

$$P_{\text{incident}} = \frac{\alpha h f_0 df}{\exp\left(\frac{hf_0}{kT_R}\right) - 1}. \quad (2)$$

Absorbed power and corresponding electron temperature of the absorber are presented in Fig. 6. These dependence values were calculated for a signal frequency of 350 GHz, and spectral

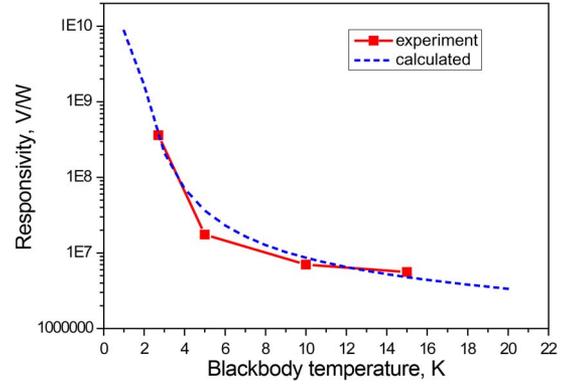


Fig. 7. Experimental and calculated voltage responsivity dependence values on blackbody radiation temperature.

transmission of bandpass, low-pass, and high-pass filters placed between radiation source and bolometer $df = 100$ GHz. The illumination power value for radiation temperature of 5 K is $P_{\text{ins5K}} = 1$ pW.

Dependence values of illuminating power and responsivity on blackbody temperature are presented in Fig. 6. The absorbed power was recalculated from electron temperature of irradiated bolometer according to (3). From the measured I–V curve, we calculate dynamic resistance, compare it with what is expected for ideal SIN junction, and obtain equivalent electron temperature under irradiation. Assuming electron–phonon interaction as the main mechanism of the electron energy relaxation in bolometer

$$P_{ep} = \Sigma \nu (T_e^5 - T_p^5) \quad (3)$$

where $\nu = 5 \times 10^{-20}$ m³ is the absorber volume for our sample, and $\Sigma = 2 \times 10^9$ W/m³K⁵ is the material parameter taken from [10] and [11] for the similar aluminum film with superconductivity suppressed by ferromagnetic impurities. Thus, we calculate the power absorbed in our bolometer. Ratio of incident and absorbed power corresponds to the optical efficiency of the device.

Earlier, the dependence of responsivity on dc power up to 10^9 V/W at 100 mK and 10^8 V/W at 300 mK was measured in [12], and here we present measurements of optical responsivity that is affected by background power load, optical, and impedance mismatches. Theoretical and experimental dependence values of responsivity on radiation temperature are presented in Fig. 7. This dependence is very sharp and shows the importance of reduction for both background power level and phonon temperature. Reducing radiation temperature below 1 K, we still observe overheating at the level of 100 fW, which comes from some background radiation and RF interferences.

We estimate optical efficiency up to 0.6 for low temperature and low signal. To obtain $\text{NEP} = 30$ aW/Hz^{1/2} for such bolometer, the phonon temperature should be below 0.2 K, and the background radiation temperature should be below 2.5 K. For $\text{NEP} = 2$ aW/Hz^{1/2}, phonon temperature should be below 0.1 K and background radiation temperature should be below 1.6 K.

III. DISCUSSION

According to [13], the performance of superconductor–insulator–normal metal–insulator–superconductor (SINIS) bolometer is strongly inverse dependent on electron temperature and absorbed power. The maximum voltage responsivity in the best case at the bias point around the half of the superconducting gap voltage is

$$S_V = \frac{dV}{dP} = \frac{k}{e\Sigma\nu T_e^4}. \quad (4)$$

From this equation, we obtain dark responsivity $S_d(100 \text{ mK}) = 10^{10} \text{ V/W}$ and $S_d(300 \text{ mK}) = 1.1 \times 10^8 \text{ V/W}$. The experimental electrical power responsivity of 10^9 V/W at 100 mK obtained in [12] for dc heating of the absorber corresponds to electrical NEP = 3 aW/Hz^{1/2}. Even lower NEP < 0.3 aW/Hz^{1/2} can be successfully measured with superconducting transition-edge nanobolometer at reduced levels of overheating well below 10 fW [14], but the aim of this paper is to estimate the performance of bolometer in realistic conditions of relatively high level of background power load. We can recalculate responsivity dependence on absorbed power as

$$S_V = \frac{k}{e(\Sigma\nu)^{0.2} P^{0.8}}. \quad (5)$$

The calculated responsivity is $S_V = 2 \times 10^8 \text{ V/W}$ at 100 fW and $3.5 \times 10^7 \text{ V/W}$ at 1 pW. These estimations are made for our case of $\Sigma = 2 \times 10^9 \text{ W/(m}^3\text{K}^5)$ and $\nu = 5 \times 10^{-20} \text{ m}^3$. It means that we can expect $\text{NEP}_{\text{bol}} = 1 \text{ aW/Hz}^{1/2}$ for our amplifier noise of 10 nV/Hz^{1/2}.

Another figure of merit for receiver performance is the level of photon noise given by

$$\text{NEP}_{\text{phot}} = (2\text{Phf})^{1/2}. \quad (6)$$

For the presented bolometer and experimental setup, the photon noise is not observed due to limitation by amplifier noise. If the total noise is reduced down to 1 nV/Hz^{1/2}, then photon noise could be observed at absorbed power below 0.4 pW. For single CEB with JFET readout, there is no chance to get photon noise level for power load above 1 pW due to decrease in responsivity and a JFET voltage noise [15].

For background power load of 38 pW, the estimated responsivity is $2 \times 10^6 \text{ V/W}$, $\text{NEP}_{\text{bol}} = 1 \text{ fW/Hz}^{1/2}$, and the corresponding photon NEP is $\text{NEP}_{\text{phot}} = 130 \text{ aW/Hz}^{1/2}$. Hence, observation of photon noise at such power load is not achievable for single bolometer design.

The fundamental limit of thermal energy fluctuations or phonon noise is [13]

$$\text{NEP}_{\text{phonon}} = [10\Sigma\nu (T_e^6 + T_{\text{ph}}^6)]^{1/2} \quad (7)$$

where $\text{NEP}_{\text{phonon}} = 0.2 \text{ aW/Hz}^{1/2}$ at 100 mK and $4 \text{ aW/Hz}^{1/2}$ at 280 mK, which is well below both photon and bolometer NEPs. Estimations of responsivity and NEP levels for amplifier noise of 10 nV/Hz^{1/2}; phonon temperatures of 100, 200, and 300 mK; and power loads of 0.01–38 pW are collected in Table I.

TABLE I
ESTIMATIONS OF RESPONSIVITY AND NEP

T, mK,	100	300	100	200	300	300
Power, pW	0.01	0.01	0.1	1	5	38
Resp, V/W	10 ¹⁰	10 ⁸	3*10 ⁸	3.5*10 ⁷	10 ⁷	2*10 ⁶
NEP _{bol} , W/Hz ^{1/2}	10 ⁻¹⁸	10 ⁻¹⁶	5*10 ⁻¹⁷	3*10 ⁻¹⁶	10 ⁻¹⁶	10 ⁻¹⁵
NEP _{photon} , W/Hz ^{1/2}	2*10 ⁻¹⁹	2*10 ⁻¹⁹	6*10 ⁻¹⁸	2*10 ⁻¹⁷	4.6*10 ⁻¹⁷	1.3*10 ⁻¹⁶

In practical cases, the responsivity is limited by a total power load. With the increase of absorbed power, the responsivity in (5) is reduced as $1/P^{0.8}$. To keep it high, one can try to reduce bolometer volume, but this leads to an increase in electron temperature and finally to suppression of response even more. Increase of volume brings less suppression of response but no improvement. Responsivity can be sufficiently increased by using an array of bolometers. In this case, power absorbed in each bolometer is N times less, and responsivity for each bolometer is $N^{0.8}$ times more; hence, the voltage response for single bolometer is slightly less, but total response of series array is higher. When connected in series for dc, this brings N times more signal; thus, the voltage responsivity for array is

$$S_{\text{varr}} = \frac{kN^{1.8}}{eP^{0.8}(\Sigma\nu)^{0.2}}. \quad (8)$$

As example for 280-mK phonon temperature, if we assume that electron temperature should not increase above 300 mK, it corresponds to single bolometer absorbed power of 70 fW. For 1-pW signal, this power should be distributed in 14 bolometers. For 10 pW, it should be 143 bolometers. The limiting factor for increasing the number of bolometers is the phonon power and phonon noise (7); thus, according to [15], the number of bolometers should not be more than

$$N < \frac{P_{\text{bg}}}{\Sigma\nu T_{\text{ph}}^5}. \quad (9)$$

For measurements of signal above 0.1 pW, we use arrays of bolometers connected in parallel for incoming signal and in series for readout at the output. In a previous work [2], we use ten bolometers for each polarization in a cross-slot antenna. At present, we have three bolometers in a twin-slot antenna. Topologically, it is difficult to fit more than ten bolometers in a planar antenna even at 350 GHz, and for higher frequencies, it is more challenging. Alternative to a single-mode antenna can be a focal plane array of many antennas, but this approach is facing problems of input signal matching and noise mismatch for output amplifier. Parallel connection of bolometers both for input and output with voltage bias and current readout can overcome both of these problems. In this case, a superconducting quantum interference device (SQUID) readout amplifier should be advantageous compared with a convenient JFET room-temperature amplifier.

IV. CONCLUSION

Voltage response of CEB integrated in a DSA has been investigated with respect to phonon temperature and power load. Estimation of dark responsivity up to 10^{10} V/W and its decrease below 10^7 V/W at 5-pW power load corresponds to experimental dependence measured with blackbody signal source at 2 K–15 K radiation temperatures. With amplifier voltage noise of 10 nV/Hz^{1/2}, such responsivity corresponds to NEP from 1 to 100 aW/Hz^{1/2}. Further improvement of CEB performance can be using focal plane array of planar antennas with single or multiple bolometers in each array element, parallel connection of such bolometers at the output, voltage bias, and SQUID readout. In such configuration, incoming power is divided between antenna array elements with bolometers, which allows preserving high responsivity by decreasing overheating for each bolometer.

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