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# Experimental Study of a Normal-Metal Hot Electron Bolometer with Capacitive Coupling

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Normal-metal hot-electron bolometer with capacitive coupling (CCNHEB) is a further development of the concept of a normal-metal hot-electron bolometer with Andreev mirrors (ANHEB). It was proposed to eliminate the frequency and energy restrictions inherent in ANHEB, in which Andreev mirrors act efficiently only with relatively long absorbers and at energies below the superconducting gap. An important advantage of the CCNHEB is its simple topology, in which the same tunnel junctions provide thermal decoupling, noise protection, temperature measurement, and it can be used for electron cooling. The temperature response of the bolometer was measured at temperatures down to 260 mK. The observed response $dV/dT = 1.7$ mV/K corresponds to the sensitivity $S = 0.4 \times 10^9$ V/W. The measured noise at the amplifier output with this sample was found to be $V_{na} = 4$ nV/Hz$^{1/2}$, which corresponds to a noise-equivalent power of $10^{-17}$ W/Hz$^{1/2}$. To measure optical response, black-body radiation was used as a source of signal inside the cryostat. The source was a thin NiCr film sputtered on a thin sapphire substrate and suspended by nylon threads. Optical measurements proved to be in good agreement with the dc measurements. © *2002 MAIK "Nauka/Interperiodica".*

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**1. Topology of the samples and their fabrication.** The concept of a normal-metal hot-electron bolometer with capacitive coupling (CCNHEB) was suggested in [1]. The key idea of the design is that the capacitive decoupling replaces Andreev mirrors, which are used for the thermal insulation of an absorber from electrodes in a normal-metal hot-electron bolometer with Andreev mirrors (ANHEB). This allows one to avoid the frequency restriction inherent in the Andreev mirrors, which arises if electrons are superheated above the energy gap. Matching of the absorber impedance at the signal frequency is accomplished through the same capacitors that provide a high potential barrier for hot electrons. For a planar complementary antenna on the silicon substrate, the impedance can be estimated by the formula $Z_{\text{ant}} = 377[2(1 + \varepsilon)]^{1/2} = 80\ \Omega$. The bolometer impedance is the sum of capacitive, inductive, and resistive components connected in series:

$$Z_{\text{bol}} = \frac{2}{i\omega C} + i\omega L + R. \tag{1}$$

For the planar antenna with real impedance, the inductance of the absorber stripe can be counterbalanced by the tunnel junction capacitance. For an absorber length of 10 μm, $Z_L = 20\ \Omega$ at 300 GHz, the required capacitive impedance is 30 fF, which can easily be obtained with tunnel junctions of size $1 \times 0.5\ \mu\text{m}^2$. As a result, an additional band-pass filter forms, which additionally reduces the undesirable action of the thermal background radiation. Simultaneously, the same tunnel junctions act as temperature sensors and provide electron cooling, similar to the Peltier effect in semiconductors.

Samples were prepared on silicon substrates of size $7 \times 7$ mm with 16 contact pads. Each chip included six CCNHEB structures, of which one was integrated with a log-periodic antenna, four integrated with double dipole antennas for central frequencies of 300 and 600 GHz, and one test structure with two additional tunnel junctions was designed for measuring temperature along the absorber stripe (cf. microphotograph in Fig. 1). The contact pads and antennas were fabricated by UV lithography and sequential thermal evaporation of 10-nm Cr, 40-nm Au, and 10-nm Pd layers. The structure of bolometer was formed in a single vacuum cycle by direct electron-beam lithography and shaded evaporation at different angles through a double mask made from PMMA and COPOLYMER photoresists. In so doing, 60 nm Al was evaporated, oxidized for 2 min in oxygen at a pressure of $10^{-1}$ mbar, after which a double-layer Cr/Al film was evaporated at a different angle. The normal metal film in the bolometer was 8 μm long, 0.2 μm wide, and 80 nm in thickness. The resistance of the bolometers with double-layer films consisting of 50 nm Cr and 10 nm Al was about 100 Ω, which was close to the optimal resistance of both log-periodic and double dipole antennas. The results of measuring with a sample containing 50% chromium and 50% aluminum are also presented for comparison. The capaci-

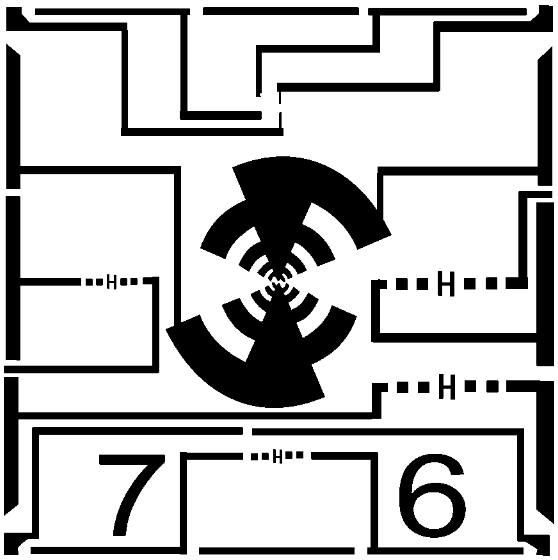


**Fig. 1.** Microphotograph of a bolometer chip with 16 contact pads and six CCNHEB structures. Log-periodic antenna is at the center; two double dipole antennas for the central frequency 300 GHz are on the right and two antennas for 600 GHz are on the left and at the bottom.

tance of tunnel junctions was about 3 fF, so that, for two capacitors connected in series, 100 Ω of bolometer, and intrinsic inductance, the resonance frequency was about 250 GHz.

**2. Experimental results.** The samples were placed on a flat surface of a hyperhemispheric sapphire lens that was mounted on the He3 evaporator of a closed-cycle absorptive cryo cooler (see [2]). The cryo cooler was mounted on the cold plate of a helium cryostat (Infrared Labs [3]) with optical window. Liquid helium vapor was pumped until a temperature of 1.7 K was reached. The minimal temperature in the system was 260 mK. Figure 2 presents the IV curves for one of the samples. These dependences can be used to obtain the temperature dependence of voltage and the sensitivity $dV/dT$ at different temperatures and dc currents (Fig. 3).

To determine the bolometer sensitivity and noise for a real microwave signal, a black-body radiation source with modulated temperature (Haller-Beeman Assoc. Inc.; see [4] for detail) was used as a signal source. The source was a thin NiCr film sputtered on a thin sapphire substrate suspended by thin nylon threads. On passing current through the film, it is heated and starts to radiate. The source was mounted on the cold plate of a cryostat at the base temperature of 1.7 K, and its output horn was directed toward the lens with CCNHEB placed at a distance of several centimeters from the source. After applying a power of several milliwatt from the power supply, a radiation with equivalent temperature of up to 100 K arises. The source is capable of producing modulated signals over a wide frequency range. The dependences of the bolometer response on the bias voltage, as measured in the temperature variation regime (Fig. 4, curve DVT) and for the built-in radiation source (curve DV 249 mV), demonstrate a reasonable agreement with the theoretical estimates.

To estimate the NEP, low-frequency noise was measured at the bolometer output. The frequency dependence was measured for the voltage fluctuation spectral density, and the noise dependence on bias voltage was measured at several frequencies. In the sample with 50 nm chromium and 10 nm aluminum, the noise of bolometer and amplifier at the operating point with maximal response was 4 nV/Hz$^{1/2}$. The dependence of noise spectral density on bias voltage in the white-noise region is shown in Fig. 5 for the sample with 30 nm chromium and 30 nm aluminum. It follows from these measurements that the noise spectral density in amplifier can be put equal to 3 nV/Hz$^{1/2}$, which corresponds to the specifications of an OP27 operational ampli-

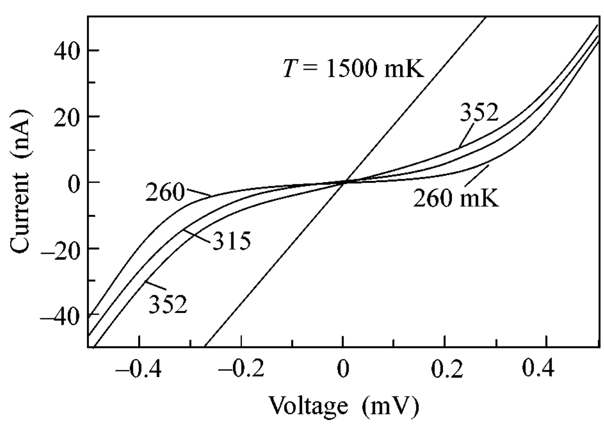


**Fig. 2.** Current–voltage characteristics of bolometer, as measured at temperatures from 260 mK to 1.5 K.

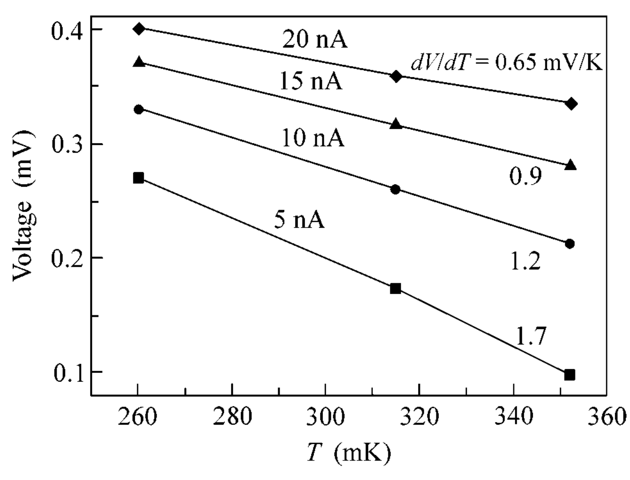


**Fig. 3.** Temperature dependences of the voltage on bolometer for various bias currents.

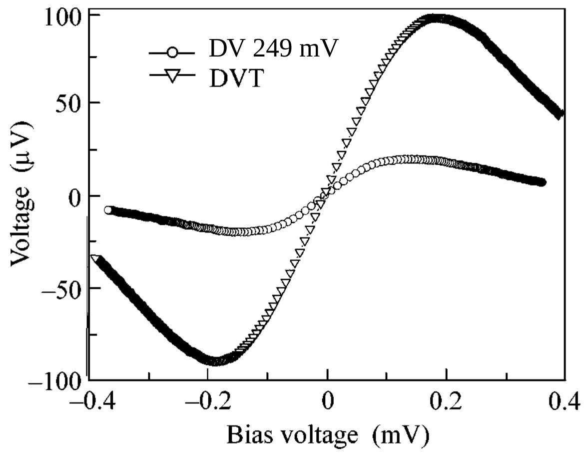


**Fig. 4.** CCNHEB voltage response (curve DVT) to a change in temperature and (curve DV 249 mV) to the black-body radiation.

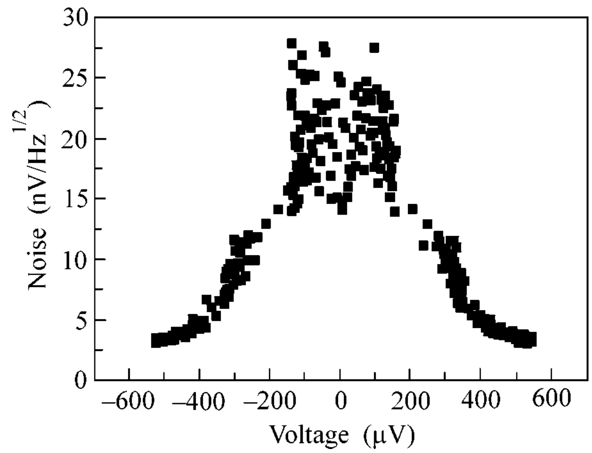


**Fig. 5.** Dependence of the noise in the range 1–10 kHz on the bias voltage on a bolometer with 30 nm chromium and 30 nm aluminum. At biases higher than 500 μV, noise is restricted by the amplifier.

fier—bolometer with an amplifier at the operation point of 200 μV at a level of 6.5 nV/Hz$^{1/2}$ for 3 kHz and higher, and 8.5 nV/Hz$^{1/2}$ for 1 kHz.

High response for the samples with double-layer absorber films is different from the value predicted by a simple theory for SIN (superconductor–insulator–normal metal) gauge and may be due to the influence of electron cooling.

**3. Discussion of results and estimate of the CCNHEB sensitivity.** The theoretical values of response for the SIN junction can be obtained using the simple analytic expression

$$I(V, T) = \frac{k}{eR}\sqrt{11TT_c}\exp\left(-\frac{1.76T_c}{T}\right)\sinh\left(\frac{eV}{kT}\right), \quad (2)$$

which gives a good agreement with experimental data for the SIN junction with a purely chromium absorber. This expression can be used to determine maximal temperature response for the SIN junction at various ambient temperatures. For our base temperature of 270 mK, a single junction should have a response of about 0.5 mV/K; to increase it twofold (to 1 mV/K), electron temperature should be 163 mK. The experimentally observed high values of response can be explained by the combined action of two mechanisms: electron cooling and increase of the junction nonlinearity due to the proximity effect, so that it should be considered as an SINS structure, which approaches the SIS* (superconductor–insulator–superconductor with reduced gap) structure in the zero-temperature limit.

The noise in a structure consisting of two tunnel junctions connected in series can be calculated using the following simple expression for the current fluctuation spectral density in a single junction:

$$S_I(V) = \frac{2eV}{R}\coth\left(\frac{eV}{2kT}\right). \quad (3)$$

To obtain voltage fluctuations, one should multiply this expression by the dynamic resistance of junctions. It can be found from Eq. (2). The calculated dependences of the dynamic resistance and noise on the bias voltage proved to be close to the measured dependences.

In our first experiments [5], the values of the limiting CCNHEB parameters (NEP = $2.5 \times 10^{-17}$ W/Hz$^{1/2}$) were far from the theoretical estimates, because we used non-optimal samples leading to a high noise level in the subsequent signal amplifier. In this work, the slope $dV/dT$ = 1.7 mV/K was obtained for the MF46p6-16 sample at 260 mK. When estimating the voltage response $S = dV/dP = (1/G)dV/dT$, we used the values for the heat conduction $G = dP/dT = 3\Sigma v T^4$, characteristic constant of material $\Sigma = 2.5 \times 10^9$ W m$^{-3}$ K$^{-5}$ (measured in a separate experiment with ANHEB samples calibrated against the dissipated power of a dc power supply in a copper film; for the samples with double-layer absorber films, an additional detailed study is needed for the temperature dependence of the characteristic constant of material), and sample volume $n = 8 \times 10^{-20}$ m$^3$, which gives $G = 5 \times 2.5 \times 10^9 \times 8 \times 10^{-20}(0.256)^4 = 4.3 \times 10^{-12}$ W/K and $S = 1.7 \times 10^3/(4.3 \times 10^{-12}) = 0.4 \times 10^9$ V/W. For the output noise of bolometer and amplifier, $V_{na}$ = 4 nV/Hz$^{1/2}$, the NEP is $V_{na}/S = 6 \times 10^{-18}$ W/Hz$^{1/2}$. An example of the measured NEP is presented in Fig. 6. In the absorber film consisting of normal and superconducting layers, all hot electrons are concentrated in the normal metal film because of the Andreev reflection. This reduces effectively the volume

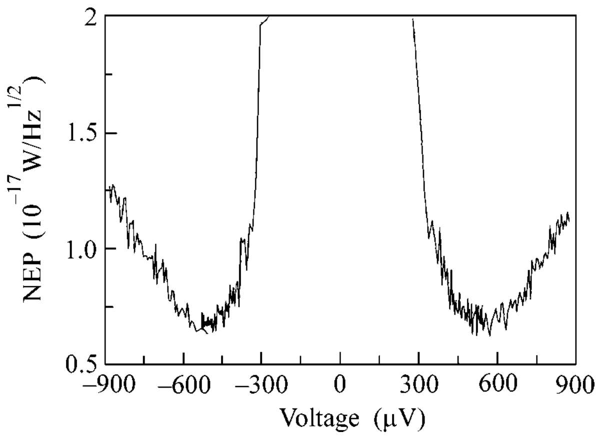


**Fig. 6.** Noise-equivalent power measured for the sample with 30 nm Cr and 30 nm Al in the absorber film.

and, correspondingly, enhances the volt–watt sensitivity. The gain is caused by the effective decrease in the volume of normal metal, the proximity effect, the Andreev reflection, and the electron cooling. An important advantage of a high response is that the requirements to the subsequent amplifier become less stringent.

The electrical NEP presented above should be compared with the optical NEP measured using black-body radiation. For the MF46p6-16 sample with a log-periodic antenna, the radiation linewidth was found to be 5° in the $E$ plane and 30° in the $H$ plane. A decrease in the source radiation temperature was $\eta$ = (3/46)(3/7.7) = 1/40. Moreover, one should take into account the reflection loss at the vacuum/insulator interface, the impedance mismatch, the degree of blackness of the black-body source, the mismatch in the direction of antenna major lobe, and the side lobe loss, which altogether add no less than 10 dB additional loss. As a result, the radiation weakens more than 400 fold. The received radiation power $\Delta P = \eta k \Delta T\ \Delta f = 10^{-13}$ W and a response slope of $0.4 \times 10^9$ V/W should provide a value of 40 μV for the voltage response. The value of 20 μV measured for the voltage response to the black-body radiation is in a good agreement with the measured value.

**4. Conclusions.** Normal-metal hot-electron bolometer with capacitive thermal insulation integrated with planar submillimeter wave antennas have been designed, fabricated, and experimentally investigated. The electrical sensitivity was as high as 1.7 mV/K, the response $S = 0.4 \times 10^9$ V/W, and the noise-equivalent power was $10^{-17}$ W/Hz$^{1/2}$. The measured response to the black-body radiation is in good agreement with the noise-equivalent electrical power measured at various temperatures. The results obtained give evidence for the efficient operation of the bolometer with capacitive thermal insulation.

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