Optimal Cold-Electron Bolometer with a Superconductor-Insulator-Normal Tunnel Junction and an Andreev Contact

Leonid Kuzmin

Abstract— **A novel concept of the optimal Cold-Electron Bolometer (CEB) with a Superconductor-Insulator-Normal (SIN) Tunnel Junction and Andreev SN contact has been proposed. This concept has been developed to improve noise properties of the CEB by increasing current responsivity for SQUID readout (in voltage-biased mode) in comparison with classical CEB concept comprising two SIN tunnel junctions. In this configuration the power of incoming signal is not split between two series junctions and the current response of a single junction is twice larger in comparison with double junction structure.**

The signal is concentrated from antenna to an absorber through capacitance of the tunnel junction from one side and Andreev contact from another side. HF matching is realized by resistance of a normal metal absorber that is independent on tunnel junction parameters. The volume of a normal metal is partly squeezed due to proximity effect of a superconducting electrode from the Andreev contact that also increases efficiency of the electron cooling.

The concept is based on direct electron cooling of the absorber by SIN tunnel junction that serves as negative electrothermal feedback for the signal. Noise properties are considerably improved by decreasing the electron temperature. Ultimate performance of the CEB is determined by optical load converted to shot noise of the signal readout. The goal is to achieve noise-equivalent power (NEP) of the CEB with standard SQUID readout less than photon noise. Ultimate NEP better than photon noise can be achieved practically in wide range of power loads from 0.1 fW (SPICA) to 30 pW (OLIMPO, CLOVER, PILOT). Applicability of the CEB to post-Herschel space missions looks very promising.

Index Terms— **Cold-Electron Bolometer, SIN tunnel junction, Andreev contact, SQUID readout**

I. INTRODUCTION

Cosmology experiments in the last few years (WMAP, BOOMERanG, SDSS) have discovered that the Universe consists of 73% **Dark Energy**, 23% **Dark Matter**, and only 4% ordinary matter. The most shocking news is acceleration of the Universe by unknown forces due to the increasing dominance of a mysterious dark energy. The prove of existence of the Dark Energy and Dark Matter has been recognized by magazine Science as the Breakthrough of the Year [1]. Experiments to resolve the nature of the mysterious dark Universe require a new generation of telescopes with increased accuracy of resolution including polarization CMB measurements. There are several cosmology instruments (CLOVER, EBEX, BICEP, QUIET) that are being designed to measure the polarization in the Cosmic Microwave Background (CMB). The *B*-mode polarization is generated entirely by primordial gravitational waves.

The project OLIMPO is a 2.6 m balloon-borne telescope, aimed at measuring the Sunyaev-Zeldovich effect in clusters of Galaxies. We will use typical requirements on detector system from OLIMPO project for development of optimal concept of bolometer. The OLIMPO detector system consists of four bolometer arrays at 140, 220, 410 and 540 GHz. The bolometer arrays should operate in 300 mK cryostat. The estimated optical loading on the OLIMPO detectors in flight, P_0, determines the required detector parameters and the ultimate sensitivity of the instrument. The optical loading is dominated by emission from the warm telescope plus the emission from the 2.73 K CMB. The power on each detector at 140, 220, 410 and 540 GHz is 4, 6, 14 and 28 pW respectively [2],[3]. From these values we can calculate the fundamental limit to sensitivity from photon noise and express this in terms of an NEP.

A new generation of detectors is needed for these advanced telescopes. One of these technologies is the Capacitively Coupled Cold-Electron Bolometer (CEB) with SQUID readout [4]-[6]. The SQUID readout has been already developed for TES bolometers with typical sensitivity of 1 pA/Hz$^{1/2}$. The goal is to achieve noise-equivalent power (NEP) of the CEB with standard SQUID readout less than photon noise. The CEB is a planar antenna-coupled superconducting detector with high sensitivity and high dynamic range due to use of SIN tunnel junctions for electron cooling and strong electrothermal feedback [4]. To achieve noise matching with SQUID for the estimated in-flight optical power load, a CEB with smaller junction resistance (larger area) has to be used. However, a standard shadow evaporation technique does not give opportunity to do junctions with area more than 1 μm^2. Some optimization of properties should be done to realize noise matching for available area of the junctions or a new technology of SIN junctions should be developed.

In this paper, we will analyze an optimal configuration of CEB with one SIN junction and Andreev SN contact instead of a traditional CEB with two SIN junctions in series.

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II. CONCEPT OF AN OPTIMAL BOLOMETER WITH ONE SIN TUNNEL JUNCTION AND SN ANDREEV CONTACT

To increase efficiency of CEB for current readout, an optimal configuration of CEB with capacitively coupled SIN junction and Andreev SN contact has been considered (Fig. 1). This concept has been proposed to improve noise properties by increasing responsivity of the CEB for SQUID current readout (in voltage-biased mode). In this configuration the power of incoming signal is not split between two series junctions and the current response is realized by a single junction increasing twice responsivity in comparison to double junction structure. It should lead to decrease of amplifier noise and the junction shot noise. The volume of a normal metal is partly squeezed due to proximity effect of a superconducting electrode from the Andreev contact that further increases efficiency of the electron cooling without degradation of HF coupling.

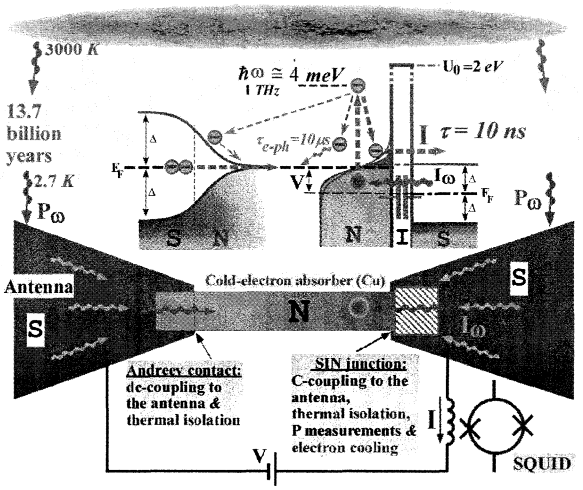

Fig 1. Schematic of the **optimal Cold-Electron Bolometer (CEB) with capacitive coupling to the antenna** and a SQUID readout. The CEB comprises a planar superconducting antenna and an absorber coupled through capacitance of SIN tunnel junction and SN Andreev contact. The SIN tunnel junction is used also for electron cooling and power measurements by SQUID readout system.

The signal is concentrated from an antenna to the absorber through capacitance of the tunnel junction and Andreev contact. HF matching is realized by resistance of a normal absorber that is independent on tunnel junction parameters.

The concept is based on *direct electron cooling* of the absorber that serves as strong *negative electrothermal feedback* for the signal. This feedback is analogous to the TES (transition-edge sensor) [6] but artificial dc heating is replaced by *direct electron cooling* to minimum temperature. It could lead to a principle breakthrough in realization of supersensitive detectors. Noise properties are considerably improved by decreasing the electron temperature. The loop gain of electrothermal feedback could exceed 1000. The response time is reduced by electrothermal feedback to 10 ns in comparison with the intrinsic e-ph time constant of 10 μs.

The CEB in voltage-biased mode gives opportunity to increase dynamic range by removing all incoming power from supersensitive absorber to the next stage of readout system (SQUID) with higher dynamic range. The CEB with one SIN junction and one Andreev contact has almost twice higher responsivity than the traditional CEB with two SIN junctions in series. It gives opportunity to realize ultimate noise properties. However, the strength of electron cooling is higher in double junction structure due to two junctions working for cooling. Due to this reason improvement of responsivity and other related properties is less than two times.

III. MODEL

For analysis we use a concept of CEB with strong electrothermal feedback due to electron cooling analyzed in detail in Ref. [4]. The operation of CEB can be analyzed using heat balance equation [4],[9]:

$$P_{cool}(V,T_e,T_{ph})+\Sigma\Lambda(T_e^5-T_{ph}^5)+\frac{V^2}{R_j}+I^2R_{abs}+C_\Lambda\frac{dT}{dt}=P_0+\delta P(t) \quad (1)$$

Here, $\Sigma\Lambda(T_e^5-T_{ph}^5)$ is the heat flow from electron to the phonon subsystems in the absorber, Σ is a material constant, Λ - a volume of the absorber, T_e and T_{ph} are, respectively, the electron and phonon temperatures of the absorber; $P_{cool}(V,T_e,T_{ph})$ - cooling power of the SIN tunnel junction; $C_\Lambda = \Lambda\gamma T_e$ is the specific heat capacity of the absorber; Rj – resistance of tunnel junction; Rabs – resistance of the absorber; *P(t)* - the incoming rf power. We can separate Eq. (1) into the time independent term,

$\Sigma\Lambda(T_{e0}^5 - T_{ph}^5) + P_{cool\,0}(V,T_{e0},T_{ph}) = P_0$, and the time dependent term,

$$\left(\frac{\partial P_{cool}}{\partial T} + 5\Sigma\Lambda T_e^4 + i\omega C_\Lambda\right)\delta T = \delta P. \quad (2)$$

The first term, $G_{cool} = \partial P_{cool}/\partial T$, is the cooling thermal conductance of the SIN junction that gives the negative electrothermal feedback (ETF); when it is large, it reduces the temperature response δT because cooling power, P_{cool}, compensates the change of signal power in the bolometer. The second, $G_{e-ph} = 5\Sigma\Lambda T_e^4$, is electron-phonon thermal conductance of the absorber. From Eq. (2) we define an effective complex thermal conductance which controls the temperature response of CEB to the incident signal power

$$G_{eff} = G_{cool} + G_{e-ph} + i\omega C_\Lambda \quad (3)$$

In analogy with TES [7], the effective thermal conductance of the CEB is increased by the effect of electron cooling (negative ETF).

Here we assume that the SIN tunnel junction is voltage-biased, and the current is measured by SQUID [4],[6]. The sensitivity of the device is then characterized by the current responsivity S_I, which is the ratio of the current change and the change in the power load of the bolometer,

$$S_I = \frac{\partial I_\omega}{\partial P_\omega} = \frac{\partial I/\partial T}{G_{cool}+G_{e-ph}+i\omega C_\Lambda} = \frac{\partial I/\partial T}{G_{cool}}\frac{L}{(L+1)[1+i\omega\tau]} \quad (4)$$

where $L = G_{cool}/G_{e-ph} \gg 1$ is ETF gain and

$$\tau = C_\Lambda/G_{e-ph} = \tau_0/(L+1) \quad (5)$$

is an effective time constant, $\tau_0 = C_\Lambda/G_{e-ph}$ ($\cong 10\mu s$ at 100 mK).

Strength of electrothermal feedback is estimated as:

$$L(\omega) = \frac{G_{cool}}{G_{e-ph}(1+i\omega\tau)} = \frac{\partial I / \partial T}{G_{cool} + G_{e-ph} + i\omega C_{\Lambda}} \qquad (6)$$

Noise properties are characterized by the *NEP*, which is the sum of three different contributions:

$$NEP^2_{total} = NEP^2_{e-ph} + NEP^2_{SIN} + \frac{\delta I^2}{S_I^{\ 2}}. \qquad (7)$$

$$NEP^2_{e-ph} = 10 k_B \Sigma \Lambda (T_e^6 + T_{ph}^6) \qquad (8)$$

is the noise associated with electron-phonon interaction; NEP^2_{SIN} is the noise of the SIN tunnel junctions, and the last term $\delta I^2/S^2_I$ is the noise of an amplifier (SQUID), δI, which is expressed in pA/Hz$^{1/2}$.

The noise of the NIS tunnel junctions, NEP^2_{SIN}, has three components: shot noise $2eI/S^2_I$, the fluctuations of the heat flow through the tunnel junctions and the correlation term between these two processes

$$NEP^2_{SIN} = \delta P^2_{\omega} - 2\frac{\delta P_{\omega}\delta I_{\omega}}{S_I} + \frac{\delta I^2_{\omega}}{S_I^2}. \qquad (9)$$

It is necessary to take into account the effect of the electron cooling of the metallic strip by the SIN tunnel junction. For every chosen voltage we first solve the heat balance equation, find the electron temperature in the metallic strip, and then we determine current responsivity and *NEP*.

IV. COMPARISON OF THE CEB WITH ONE TUNNEL JUNCTION AND SN CONTACT AND CEB WITH TWO TUNNEL JUNCTIONS

The analysis of the Cold-Electron Bolometer (CEB) shows that the optimal configuration of the is a CEB with a voltage-biased SIN Tunnel Junction and an Andreev SN contact. The optimal readout is a SQUID amperemeter.

We have analyzed the concept of an optimal hot-electron bolometer in the presence of the typical background power load (P_0 = 4 pW) [3] for fixed sensitivity of the SQUID-amplifier (0.5 pA/Hz$^{1/2}$) [8].

Photon noise: $$NEP_{phot} = \sqrt{2P_0 * hf}\ . \qquad (10)$$

For channel 140 GHz: NEPphot= 2,7*10^{-17} W/Hz$^{1/2}$.
The total NEP of CEB should be less than photon noise.

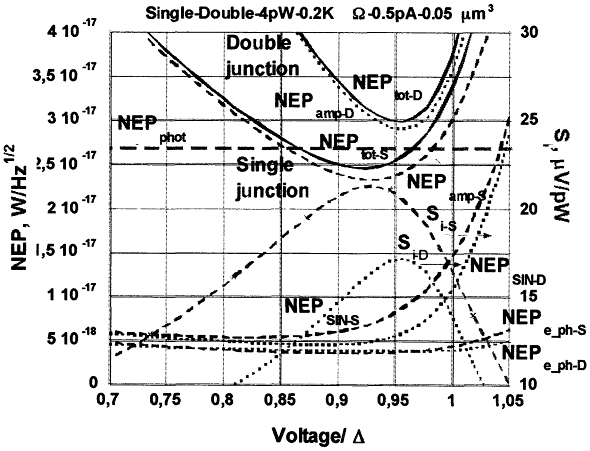

Fig. 2. Total NEP and NEP components for the single junction CEB (solid lines) and for the double junction CEB (dashed lines). The NEPphot= 2,7*10^{-17} W/Hz$^{1/2}$. Current resposivity Si is shown for both cases referred to the right axis. Parameters: i_{amp}=0.5 pA/Hz$^{1/2}$ (SQUID), R=0.2 kOhm (one junction), Vol=0.03um^3(single junction) and 0.05um^3(double junction), power load P_0 = 4 pW.

The Fig. 2 shows results of simulation for Single Junction CEB (SJ-CEB) and Double Junction CEB (DJ-CEB) for maximum area of tunnel junction, 0.5 μm^2, available by shadow evaporation technique . Volume of absorber is larger for DJ-CEB due to the additional tunnel junction. The Fig. 2 shows decrease of the total NEP for SJ-CEB in comparison to DJ-CEB. The level of NEPphot has been achieved for SJ-CEB. This improvement is achieved mainly due to decrease of a NEPamp (SQUID) related directly to the responsivity Si (7). The responsivity is determined mainly by cooling conductance Gcool (4). The Gcool is increased twice for two junction CEB (2). For series connection of two junctions it leads to twice decrease of current responsivity (4).

V. DEPENDENCE OF THE NOISE PERFORMANCE ON BATH TEMPERATURE

Responsivity of the CEB is very sensititve to the electron temperature of the absorber. The next step would be to check influence of the bath temperature on an NEP.

The Fig. 2 shows comparison of the NEP of a Single Junction CEB at two bath temperatures: 300 and 100 mK.

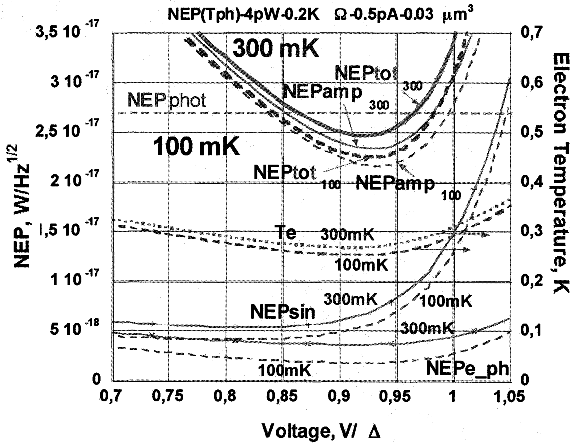

Fig. 3. The NEP of the single junction CEB in dependence on voltage for two bath temperatures: 300 mK (solid lines) and 100 mK (dashed lines). Electron temperature of absorber Te referred to the right axis is shown for the same bath temperatures. Parameters of the CEB are the same as for Fig. 2: i_{amp}=0.5 pA/Hz$^{1/2}$(SQUID), R=0.2 kOhm, Λ=0.03um^3, P_0 = 4 pW, NEPphot= 2,7*10^{-17} W/Hz$^{1/2}$.

Simulations show *that dependence of NEPtot on bath temperature is surprisingly very weak* (Fig. 3). The reason can be clear seen from the electron temperature Te dependence. For bath temperatures 300 and 100 mK the Te is approximately the same at the level of 250 mK. This level is determined mainly by high power load of 4 pW and is not sensitive to bath temperature (through e-ph conductance).

VI. DEPENDENCE OF THE NOISE PERFORMANCE ON JUNCTION RESISTANCE

Taking into account high power load it is reasonable to test the junction with lower resistance (higher cooling ability). The Fig. 4 shows comparison of NEP for two values of junction resistance: 0.2 kΩ and 0.1 kΩ. Other parameters are the same as for SJ-CEB in Fig. 2 and 3.

Simulations show that *dependence of NEPtot on junction resistanse is very strong* (Fig. 4). The reason can be clear

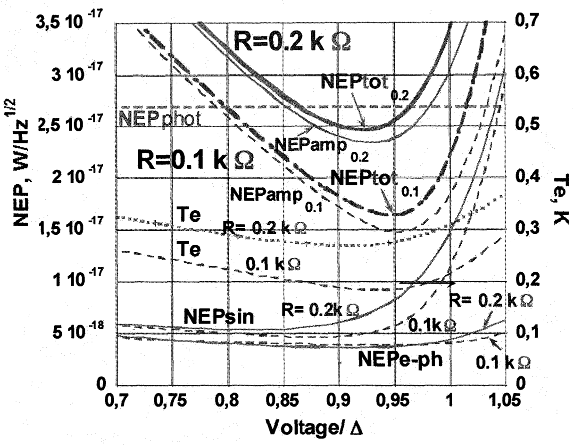

Fig. 4. Dependence of the NEP of a single junction CEB on voltage for two SIN junction resistances: 0.2 kΩ (solid lines) and 0.1 kΩ (dashed lines). Electron temperature of absorber Te (right axis) is shown for the same junction resistances. Other parameters are as for Fig. 2 and 3.

seen from electron temperature Te dependence. For higher ohmic junction, the Te is at the level of 270 mK when for lower ohmic one, the Te is around 180 mK due to stronger cooling conductance. This leads to lower level of energy quantization of hot electrons in the absorber [4] with proper increase of current response on incoming power. Proportionally, the NEPamp is decreased leading to decrease of NEPtot. It is interesting to stress that other NEP components are not changed too much due to this decrease of Te due to other dominating reasons of their origin.

Due to this strong influence on noise performance, it is reasonable to check influence of R in wider range of values. The Fig. 5 shows dependence of the NEP on junction resistance R from 25 Ω to 400 Ω. The area of junction has been changed proportionally from 8 μm^2 to 0.5 μm^2.

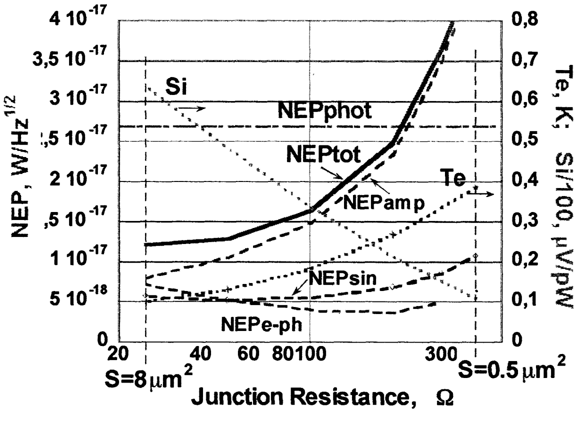

Fig. 5. Dependence of the NEP on resistance of SIN tunnel junction (and area) for the single junction CEB. The electron temperature of the absorber, Te, and responsivity, Si, are shown referred to the right axis. Other arameters are the same as for Fig. 2-4: i_{amp}=0.5 pA/Hz$^{1/2}$, T=300 mK, Λ=0.03um^3, P_0 = 4 pW, NEPphot= 2,7*10^{-17} W/Hz$^{1/2}$, T=300 mK.

Simulations show that *dependence of NEPtot on junction resistanse is very strong* in some region of resistance (Fig. 5). Starting from higher ohmic junctions, one can see strong decrease of total NEP from 400 Ω to 100 Ω related to decrease of NEPamp (dependent on Si). The CEB is moving to background limited operation determined by shot noise due to power load. Then, the total NEP shows some saturation in the region from 100 Ω to 25 Ω related with increase of NEPe_ph. The NEPe_ph is related with volume of absorber (8) and is naturally increased when volume is increased proportionally to the area of the junction.

Final value of NEPtot is much less than NEPphot in the region of R lower than 100 Ohm.

CEB array. This range of resistances could be achieved also by an array of parallel CEBs. The analysis shows that the array will act as a single CEB with a sum of junction areas and parallel connection of resistances of absorbers.

Absorber overheating. Simulations show that dc power dissipated in absorber could lead to additional overheating of the absorber. The effective decision could be to use a *superconducting absorber* with *normal metal traps* [10]. Superconducting absorber would act effectively as a normal metal for frequencies higher than superconducting energy gap (35 GHz for Al) and as a superconductor for dc bias without any dissipation of energy. Another decision is bi-layer of normal metal (Cr) and superconductor (Al) for absorber. In this case we spread the normal metal trap to the whole absorber.

VII. Conclusion

A novel concept of the optimal Cold-Electron Bolometer (CEB) with a Superconductor-Insulator-Normal (SIN) Tunnel Junction and Andreev SN contact has been developed. This concept with standard SQUID readout gives unique opportunity to achieve the NEP less than photon noise for any optical power load.

The key moment is increasing twice the current responsivity of the CEB in comparison with classical CEB with two SIN tunnel junctions. The most important parameter to achieve ultimate NEP is resistance of the junction determining cooling efficiency of the bolometer.

Applicability of the CEB to post-Herschel missions looks very promising for all range of telescopes from ground based to space telescopes.

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