A Parallel/Series Array of Cold-Electron Bolometers with SIN Tunnel Junctions for Cosmology Instruments

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***Abstract* - A novel concept of the parallel/series array of Cold-Electron Bolometers (CEB) with Superconductor-Insulator-Normal (SIN) Tunnel Junctions has been proposed for matching with JFET readout. The current-biased CEBs are connected in series for DC and in parallel for HF signal. A signal is concentrated to the absorber through the capacitance of tunnel junctions and additional capacitance for coupling of superconducting islands. Due to dividing power between CEBs in the array and increasing responsivity, the noise matching could be effectively optimized and the photon Noise Equivalent Power could be easily achieved at 300 mK with a room temperature JFET readout.**

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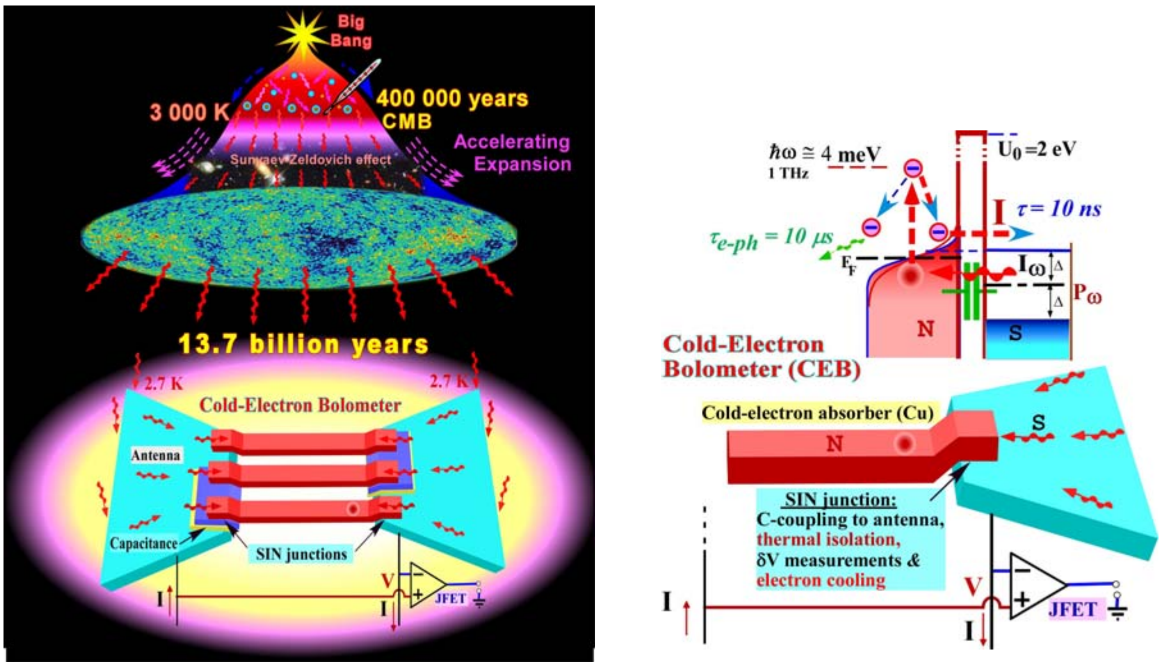
I. INTRODUCTION

Recent cosmology experiments have discovered that the Universe consists mainly of mysterious Dark Energy and Dark Matter [1]. Indeed, in 2006, Nobel Prize was awarded for the experimental observation of anisotropies in the Cosmic Microwave Background (CMB) radiation, and the subsequent realization that the expansion of the Universe is controlled by unknown forces [2]. There are several cosmology instruments (BOOMERanG [3], OLIMPO, B-POL, CLOVER,…) that are being designed to measure anisotropies and the polarization state of the Cosmic Microwave Background (CMB), in particular the *B*-mode polarization, which is generated by primordial gravitational waves. Accurate measurement of the CMB should be done using a new generation of sensitive detectors.

An ultra-sensitive Cold-Electron Bolometer (CEB) [4-6] is one of the promising candidates for these experiments. The CEB concept is based on capacitive coupling of nano-absorber to the antenna through SIN tunnel junctions and direct electron cooling of the absorber by the same junctions. The output current of SIN tunnel junctions is used for reading out and as strong negative electrothermal feedback. Due to decreasing temperature of the absorber and removing power incoming to readout system, the CEB provides high sensitivity and high dynamic range. The CEB concept has been accepted as the main detector for 350 GHz channel of BOOMERanG [3]. The main requirement is to develop a CEB array with a JFET readout for 92 channels. The NEP of the CEB should be less than photon noise for optical power load of 10 pW, and polarization resolution better than 20 dB for observations of the CMB foreground polarization.

A novel concept of a parallel/series array of CEBs with SIN tunnel junctions has been proposed for effective matching to a JFET amplifier under high power load [7] (Fig. 1). The main innovation of the CEB array in comparison with a single CEB [4-6] is the distribution of power between N series CEBs, and summarizing the increased response from the array. Effective distribution of power is achieved by a parallel connection of CEBs, which couple to the RF signal through additional capacitances (Fig. 1). The response is increased because the CEB is sensitive to the level of power, and the power is decreased N times for the individual CEBs, with a proportional decrease of absorber overheating. The high sensitivity of the CEB for small power loads has been analyzed theoretically [4-7], and demonstrated experimentally [8].



(a) (b)

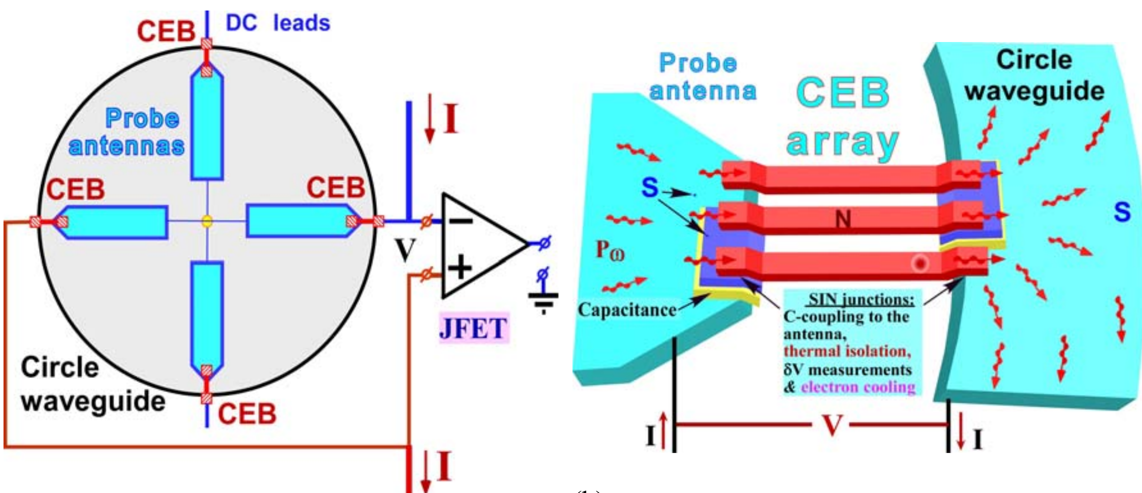
Fig. 1. (a) Schematic of a parallel/series array of CEBs with SIN Tunnel Junctions and JFET readout for the CMB polarization measurements. The current-biased CEBs are connected in series for DC and in parallel for HF signal through the capacitance of an SIN tunnel junction, and additional capacitances; (b) The SIN tunnel junction is used also for electron cooling, and for reading out the signal with a JFET.

A robust two layer technology can be used for fabrication of the CEBs with SIN tunnel junctions. In this paper we analyze a realization of the CEB array for the 350 GHz channel of BOOMERanG.

II. MODEL

For RF coupling we have chosen a system with the direct insertion of the CEB arrays into a 4-probe antenna inside a circle waveguide (Fig. 2) [8,9]. In contrast to the previous concept of the CEB with coplanar lines [10], the RF region is strictly limited by the circular waveguide area. The optimal point for the CEB is shown in the diagram, where the RF current is greatest. The problem of DC biasing the CEB arrays can be solved by interconnecting opposite probes by a narrow strip (say, of width *w*= 1 μm and length *L*= 100 μm) with very high inductive impedance (Fig. 2a).

A small isolation layer should be placed between strips in the centre of the waveguide. Two opposite CEB arrays are connected in series to get twice higher response for each polarization. The voltage response is measured by a JFET amplifier in a current-biased mode. The main purpose of this concept is to match the total dynamic resistance of the array to the noise impedance of a JFET (~0.6 MΩ). The power should be divided between the CEBs in the array to increase the responsivity due to lower overheating and moderate electron cooling. The high noise impedance of a JFET amplifier is one of the reasons why a low-ohmic TES [11,12] could not be used for this application.



(a) (b)

Fig. 2. (a) Direct connection of CEBs to a 4-probe antenna in circular waveguide [8,9]. CEBs in opposite probes are connected in series by a narrow strip for each polarization. DC connection to JFET amplifier is shown for one polarization. (b) Each probe is really connected to an array of CEBs with series connection for DC and parallel for RF (schematically shown as a single CEB in Figure 2(a). For the RF signal the CEBs are connected in parallel by the additional capacitances between superconducting islands and antenna.

The operation of a CEB array can be analyzed using the heat balance equation for a single CEB [13] taking into account power distribution between the N bolometers:

$$\Sigma\Lambda\left(T_e^5 - T_{ph}^5\right) + P_{SIN}(V, T_e, T_{ph}) + C_v \frac{dT_e}{dt} = \frac{P_0 + \delta P(t)}{N} + 2\frac{V^2}{R_S} + I^2 R_A \qquad (1)$$

Here, $\Sigma\Lambda(T_e^5 - T_{ph}^5)$ is the heat flow from the electron to the phonon subsystems in the normal metal, Σ is a material constant, Λ - the volume of the absorber, T_e and T_{ph} are, respectively, the electron and phonon temperatures of the absorber; P_{SIN} (V,T_e,T_{ph}) is cooling power of the SIN tunnel junctions; $C_v = \gamma T_e$ is the specific heat capacity of the absorber; P_0 and $P(t)$ are incoming RF power, $2V^2/R_S$ is the heat load due to the subgap leakage resistance R_S of SIN junctions, and I^2R_A is the heat load due to the absorber resistance, R_A. We can separate Eq. (1) into the time independent term,

$$\Sigma\Lambda(T_{e0}^5 - T_{ph}^5) + P_{SIN0}(V, T_{e0}, T_{ph}) = P_0/N, \quad (2)$$

and the time dependent term,

$$(5\Sigma\Lambda\, T_e^4 + 2\left(\frac{\partial P_{SIN}}{\partial T} - \frac{\partial P_{SIN}}{\partial V}\frac{\partial I}{\partial T} / \frac{\partial I}{\partial V}\right) + i\omega C_\Lambda)\delta T = \delta P \cdot \quad (3)$$

The first term in (3),

$$G_{e-ph} = 5\Sigma\Lambda\, T_e^4, \quad (4)$$

is the electron-phonon thermal conductance of the absorber. We should stress the strong dependence of G_{e-ph} on the electron temperature. This is a key issue of the array realization of CEBs since this conductance must be decreased in order to improve noise properties. The second term

$$G_{SIN} = \frac{\partial P_{SIN}}{\partial T} - \frac{\partial P_{SIN}}{\partial V}\left(\frac{\partial I}{\partial T} / \frac{\partial I}{\partial V}\right) \quad (5)$$

is the cooling thermal conductance of the SIN junction, G_{SIN}, which gives some electron cooling and help to avoid overheating of the absorber. The overheating would lead to decrease of the voltage responsivity $\delta V/\delta P$ because of strong dependence of this parameter on temperature.

A bolometer is characterized by its responsivity, noise equivalent power and the time constant. In the current-biased mode, the responsivity, S_V, is described by the voltage response to an incoming power

$$S_V = \frac{\delta V_\omega}{\delta P_\omega} = \frac{\partial V / \partial T}{G_{e-ph} + 2G_{SIN} + i\omega C_\Lambda} \quad (6)$$

Noise properties are characterized by the noise equivalent power (*NEP*), which is the sum of three contributions. For series array of CEBs, the NEP is defined as follows:

$$NEP_{tot}^2 = N * NEP_{e-ph}^2 + N * NEP_{SIN}^2 + NEP_{JFET}^2. \quad (7)$$

Here

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

is the noise associated with electron-phonon interaction [11,12]; NEP^2_{SIN} is the noise of the SIN tunnel junctions, The SIN noise has three components: the shot noise $2eI/S^2_I$, the fluctuations of the heat flow through the tunnel junctions and the correlation between these two processes [13,14]:

$$NEP_{SIN}^2 = \frac{\delta I_\omega^2}{(\frac{\partial I}{\partial V} S_V)^2} + 2\frac{<\delta P_\omega \delta I_\omega>}{\frac{\partial I}{\partial V} S_V} + \delta P_\omega^2. \quad (9)$$

This correlation is a form of the electrothermal feedback discussed earlier by Mather [15]. Due to this correlation the shot noise is increased at 30-50% in contrast to the SCEB in voltage-biased mode where strong anti-correlation decreases the shot noise [8].
The last term is due to the voltage δV and current δI noise of the amplifier (JFET), which are expressed in nV/Hz$^{1/2}$ and pA/Hz$^{1/2}$:

$$NEP_{JFET}^2 = \frac{\delta V^2 + (\delta I * (2Rd + Ra) * N)^2}{{S_V}^2} \qquad (10)$$

The strong dependence on N, decreasing this noise is included in the responsivity S_V, which is proportional to the N.

Along with the exact numerical results the approximate asymptotic formulas are also presented for understanding of basic dependences on number of bolometers. For moderate number of bolometers N, T_e is larger than T_{ph} and asymptotic expressions for T_e and the responsivity can be derived in the first approximation:

$$T_e = \left(\frac{P_0}{N\Sigma\Lambda}\right)^{1/5}, \quad \frac{dV}{dT} = \frac{k}{e}\left[-\frac{(\Delta - eV)}{k}\left(\frac{N\Sigma\Lambda}{P_0}\right)^{1/5} + \frac{1}{2}\right], \quad S_V = \frac{k}{e}\left[-\frac{(\Delta - eV)}{k}\left(\frac{N}{P_0}\right)\right] \qquad (11)$$

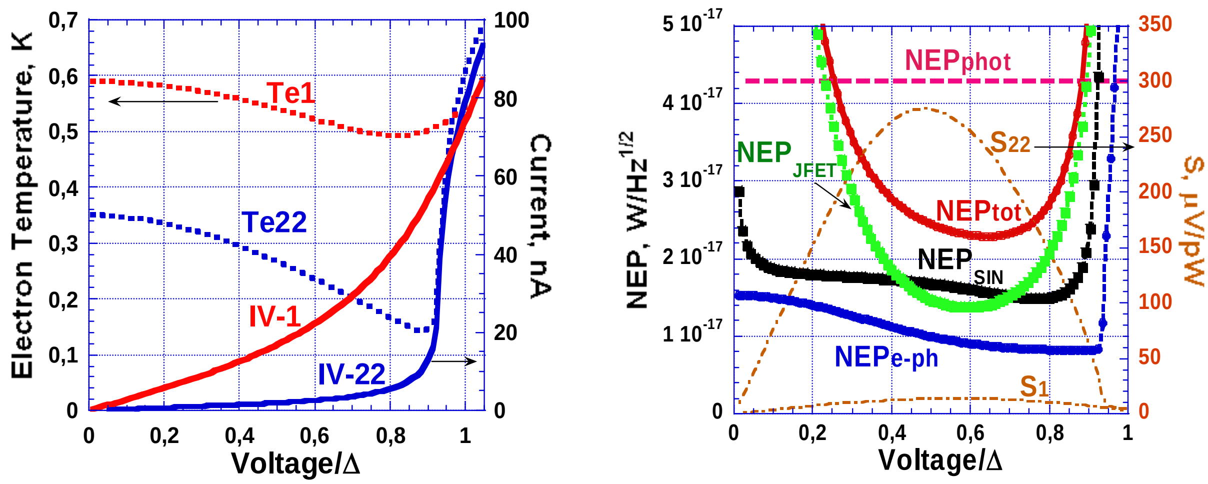
The noise of JFET amplifier can be expressed as

$$NEP_{JFET}^2 = \frac{\delta V^2}{{S_V}^2} = \frac{\delta V^2}{\left(\frac{k}{e}\right)\left[-\frac{(\Delta - eV)}{k}\left(\frac{N}{P_0}\right)\right]^2} \quad . \qquad (12)$$

Equations show a linear increase of responsivity S on number of bolometers N and linear suppression of NEP_{JFET} on N for given P_0.

III. SERIES ARRAY OF CEB IN CURRENT-BIASED MODE

The proposed mode of CEB operation is a current-biased array with voltage readout by a JFET amplifier. The analysis of a single current-biased CEB with JFET readout has shown that there is no chance to get down to photon noise level for high power load due to decreased responsivity and JFET voltage noise [8, 10]. Typical results for current-biased mode can be seen in Figure 3 and Figure 4 for N=1 (single bolometer). The main reason is degradation of voltage responsivity under high optical power load - due to overheating of the absorber. Figure 3 shows increase of temperature, smearing IV-curve and decrease of responsivity for single CEB.



(a) (b)

Fig. 3. (a) IV curves and electron temperature Te for the array of 22 CEBs and a single CEB; (b) NEP components of the same CEB array for I_{JFET}=5 fA/Hz$^{1/2}$, V_{JFET}=3 nV/Hz$^{1/2}$, R=1 kOhm, Λ=0.01µm^3. The NEP_{tot} is less than NEP_{phot}. At the optimal point, the background limited mode is realized (the total noise is limited by the noise of SIN junctions due to background power load). Responsivity is shown for a 22 CEB array, S22, and for a single CEB, S1, for comparison.

The only chance to achieve a photon noise level is to use a series DC connection of bolometers. However, series HF connections of N bolometers would lead to real problems of junction size (for proper increase of capacitance proportional to N) and overheating of islands. A special innovation has been proposed to combine these requirements: series connection for DC and parallel connection for RF. It could be realized by using additional capacitances for HF coupling as it is shown in Figure 2(b). In this case, the input power is divided between bolometers, the electron temperature is decreased and the CEBs increase responsivity while the output signal is collected from all bolometers.

The estimations were made for the 350 GHz channel of BOOMERanG balloon telescope. For power load of $P0$ = 5 pW per polarization, the photon noise could be estimated as

$$NEP_{phot} = \sqrt{2P_0 * hf} \quad , \quad NEP_{phot} = 4.3*10^{-17} W/Hz^{1/2} \; . \qquad (13)$$

The total NEP of the detector+readout should be less than photon noise: $NEP_{tot} < NEP_{phot}$. We have simulated arrays of CEBs with different numbers of CEBs, from 1 to 26, to achieve a low NEP with JFET readout. Figure 3 shows typical results of an NEP simulation for the optimal array of 22 CEBs. We see that for a range of normalized voltage from 0.6 to 0.9, the total NEP of the CEB array is less than the photon noise. At the optimum point, background limited performance is realized (the total noise is determined by the noise of SIN junctions, NEP_{SIN}, Eq. (9), due to background power load).

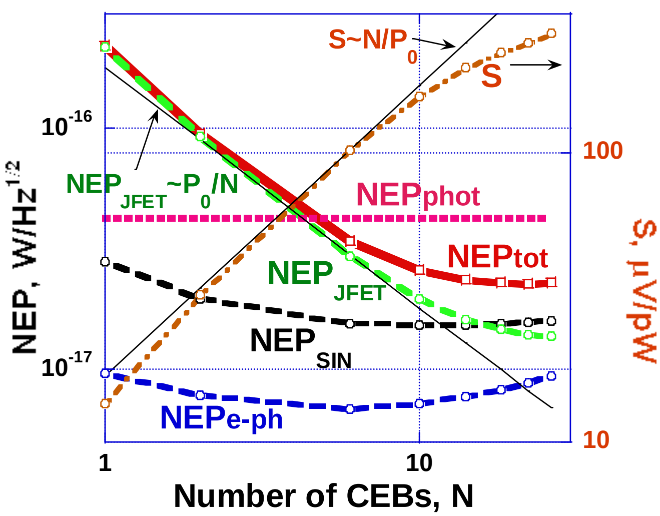


Fig. 4. NEP components and photon NEP in dependence on the number of CEBs in a series array. The parameters of CEBs are the same as in Fig. 3. The responsivity *S* is shown for illustration of the effect of the CEB number. Thin lines show asymptotics for S (11) and NEP_{JFET} (12).

The dependence of the noise components on the number of bolometers is shown in Figure 4. The total NEP decreases to a level less than photon noise for a number of CEBs larger than 6 (3 for each probe). It is achieved mainly through the suppression of the JFET voltage noise component due to increased responsivity (10). Figure 4 demonstrates a strong linear increase of the responsivity proportional to N when the number of bolometers is increased. This dependence is well supported by linear asymptotic (11). The noise of the JFET (12) is proportionally decreased, which is the main goal of this realization. Around the optimum point (N=22) the NEP_{JFET} is less than NEP_{SIN}, which is a manifestation of background-limited operation. The NEP_{SIN} increases proportionally to $\sqrt{N}$ (according to eq. 7), but decreases due to decrease of the heat flow (and current) and an increase of the responsivity S. These two effects approximately compensate each other, and NEP_{SIN} is not sensitive to the number of the bolometes. The most surprising result is that the NEP_{eph} (7, 8) is not increased proportionally to the number of bolometers when the total volume of absorber is increased proportionally to N. The reason is due to a compensation of this dependence by some decrease in T_e that is in the 6^{th} power for NEP*eph* (8).

The optimal number of CEBs in series array is determined mainly by power load P_o and the volume of absorber Λ. The general rule of array design is the following: the number of bolometers, N, should be increased to split P_o between bolometers up to the point when $P_0/N= P_{ph}$, where $P_{ph} =T^5_{ph}\, \Sigma\Lambda$. The phonon power is determined by only one parameter, the volume of the absorber, Λ. There is no need to increase the number of bolometers more than this figure, because the optical power loading in each bolometer becomes less than the power from phonons. Responsivity is saturated beyond this level.

For very small absorber volume, the optimal number of bolometers is determined by the interplay between amplifier noise and junction noise. The main rule here is to decrease the amplifier noise by increasing the number of CEBs to a level of junction noise less than that of photon noise, using well-working approximation (12).

IV. SUMMARY

We have analyzed a novel concept of a parallel/series array of Cold-Electron Bolometer (CEB) with an SIN tunnel junctions and JFET readout for realization of the requirements of BOOMERanG balloon telescope.

The analysis of a single current-biased CEB has shown that there is no chance to achieve photon noise level for high optical power load due to the degradation of responsivity and mismatch with JFET. However, the problem can be overcome using an array of CEBs for splitting a power load between the number of bolometers and increasing responsivity of the series array. The special innovation has been proposed for RF matching using parallel connection of bolometers by special capacitance between superconducting islands and the antenna. Simulations show that this parallel/series array of CEBs in current-biased mode could be used for any power load to achieve photon noise level with a JFET amplifier. The volume of the absorber should be rather small, which can be easily achieved by nanolithography fabrication. In particular, for the 350 GHz channel of the BOOMERanG project with a power load of 5 pW, the CEB array noise less than photon noise can be realized at 300 mK with a standard room-temperature JFET amplifier.

Direct RF coupling of CEBs to a 4-probe antenna have been proposed. It has been shown that the CEB is an ideal antenna-coupled bolometer that can be easily integrated to any antenna system on a bulk or membrane substrate. The applicability of the CEB to BOOMERanG and similar polarometer missions looks very promising with JFET readout. There is no competition from a low-ohmic TES (transition-edge sensor), because the TES could be matched only with SQUID readout and no chance to match it with JFET readout.

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