Superconducting Thermo-Electric Bolometer for Cosmology Instruments

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***Abstract*— A novel type of the zero-biased thermo-electric bolometer (TEB) is proposed. The bolometer is based on a Charge-to-Voltage Converter (CVC) with a Superconductor-Insulator-Normal (SIN) Tunnel Junction and a superconducting absorber. The absorption of photons in the absorber leads to excitation of quasiparticles with some fraction of charge imbalance, tunneling through the SIN junction and generation of voltage. The thermoelectric voltage is determined by accumulation of tunneling charge in an external capacitance. Conversion efficiency is very high and voltage values comparable with a superconducting gap are easily achieved. The zero-biased CVC-TEB can be effectively used for creation of an array of bolometers.**

I. Introduction

Recent Cosmology experiments have discovered that the Universe consists mainly of mysterious Dark Energy and Dark Matter [1]. There are several cosmology instruments that are being designed to measure the polarization of the Cosmic Microwave Background (CMB), in particular the B-mode polarization, which is generated by primordial gravitational waves.

A new design of antennas and a new generation of detectors are needed for these advanced telescopes. These detectors must achieve sensitivities better than $\sim 10^{-18}$ W/Hz$^{1/2}$ and should be realized in large format arrays of detectors (up to 100x100 pixels). Several advanced concepts of bolometers, such as transition-edge sensor [2], cold-electron bolometer (CEB) [3,4], and kinetic-inductance detector, are in the stage of development. In scaling up today's detectors to a large format, we encounter serious problems with overheating of the detector system, which typically has to work at a low temperature. All these problems become even more severe for focal-plane arrays [4], where each pixel is replaced by an array of bolometers (up to 16x16). In a large-scale array with 104 pixels, one has to deal with several million bolometers, each of them contributing to overheating problems.

Here the zero-biased thermo-electric bolometer (TEB) is proposed in order to solve the problem by essentially eliminating the overheating due to the absence of DC bias dissipation. In addition, zero-biased bolometers help to avoid problems caused by complicated electrical circuitry, ground loops, and unwanted interferences. For ordinary metals and semiconductors, the thermo-electric Seebeck coefficient is dramatically decreased at low temperatures. In contrast, superconductors have been shown to have a rather large thermo-electric coefficient if they come in contact with a normal metal or with a different superconductor. Classic experiments in the 1980s using a bulk bimetallic superconducting loop and a SQUID amplifier showed an unexpectedly large thermoelectric response (even reaching five orders of magnitude than that predicted by theory) [5-7]. This situation leads us to reconsider the fundamentals of thermoelectricity, and opens up an opportunity to use superconducting systems for creating a new class of thermoelectric bolometers.

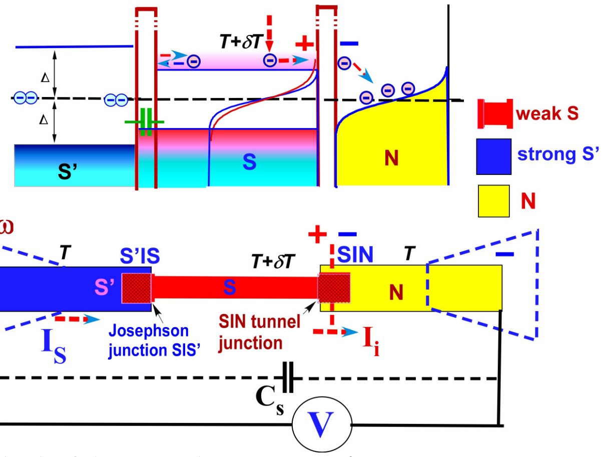

Fig 1. Sketch of the proposed **Thermo-Electric Bolometer based on a Charge-to-Voltage Converter (CVC-TEB)** with capacitive coupling to the antenna. The converter will work in a novel mode as an integrator of charge that has tunneled through the SIN junction to an external capacitor.

A novel type of the zero-biased thermo-electric bolometer (TEB) is proposed. The bolometer is based on a Charge-to-Voltage Converter (CVC) with a Superconductor-Insulator-Normal (SIN) Tunnel Junction and a superconducting absorber. The absorption of photons in the absorber leads to excitation of quasiparticles with some fraction of charge imbalance, tunneling through the SIN junction and generation of voltage. The thermoelectric voltage is determined by accumulation of tunneling charge in an external capacitance. Conversion efficiency is very high and voltage values comparable with a superconducting gap are easily achieved. The zero-biased CVC-TEB can be effectively used for creation of an array of bolometers.

The concept is based on the radically new principle of harvesting energy from the incoming signal, converting this energy to charge in a superconducting nano-absorber, and accumulating the imbalanced charge carriers, which tunnel through an SIN tunnel junction in an on-chip capacitance.

The tunneled quasiparticles are trapped in normal metal and could not return back if their energy is lower than the superconducting gap of the absorber. The SIN tunnel junction has proven to be self-biased in voltage by the energy accumulated in the capacitor. The built-up voltage would be used for read-out. The CVC allows a substantial increase in the dynamic range by removing incoming power from the absorber to normal electrode.

II. MODEL

The operation of a CVC with unbiased SIN tunnel junction has been analyzed in relation to the CEB with strong electrothermal feedback [3-4,9-12]. The system is described by a heat balance equation for a superconducting absorber coupled to a normal metal by an SIN tunnel junction:

$$P_{SIN}(T_e,T_{ph})+P_{e-ph}(T_{e,}T_{ph})=P_0+\delta P(t) \qquad (1)$$

Here, $P_{SIN}(V,T_e,T_{ph})$ is the cooling power of the SIN junction, P_{e-ph} (T_e,T_{ph}) is the heat flow from electron to phonon subsystems in the superconducting absorber; T_e and T_{ph} are, respectively, the electron and phonon temperatures of the absorber; P_0 and $P(t)$ are incoming RF power.

The current components through SIN junction (Fig. 2a) are described by a current balance equation:

$$I_{tot}(V,T_e,T_{ph})=I_{SN}+I_{NS}+I_{leak}=0 \qquad (2)$$

Full expression for current is

$$I_{tot}=\frac{1}{eR}\int dEN_s(E)\Big[f(E,T_e)-f(E-eV,T_{ph})\Big]-\frac{V}{R_j} \qquad (3)$$

where $Ns(E)= |E|/\sqrt{(E^2-\Delta^2)}$ is the normalized density of states in the superconductor, Δ is a superconducting gap, and $f(E,T)=1/[\exp(E/T)+1]$.

In the case of imbalance of quasielectrons and quasiholes, the SN current is modified to

$$I_{SN}=(1+K_i)I_{e0}-(1-K_i)I_{h0} \qquad (4)$$

where I_{e0} and I_{h0} are current components without imbalance and K_i is imbalance coefficient

$$K_i=\frac{I_{e0}-I_{h0}}{I_{e0}+-I_{h0}}.$$

A bolometer is characterized by its responsivity, and a noise equivalent power. In the self-biased mode, the responsivity, S_V, is described by the voltage response to an incoming power from Eq. 1

$$S_V=\frac{\delta V_\omega}{\delta P_\omega}. \qquad (5)$$

We have made an analysis of a single CVC with power load of P_0 = 20 fW. Absorbed power would create some imbalance of quasielectrons and quasiholes in the absorber [14,15]. The CVC is working as an integrator of charge tunnelled through the SIN junction in an external capacitance:

$$V=\int I_{tot}dt/C_s \qquad (6)$$

The time constant is determined by a subgap resistance R_j and an external capacitance C_S. After applying an RF signal, the voltage is linearly increased and C_S is charged by tunnelling current I_{SN}.

The dependence of current components through SIN junction on a self-biased voltage is shown in Fig. 2 for imbalance coefficient K_i=0.5, tunnel resistance R=1kOhm, T=100 mK and Tc=1.2K. The voltage is increased until saturation point, V_S, where the main tunneling current I_{SN} is compensated by a current through leakage resistance, I_{leak}, and a back current I_{NS} (Eq. 2).

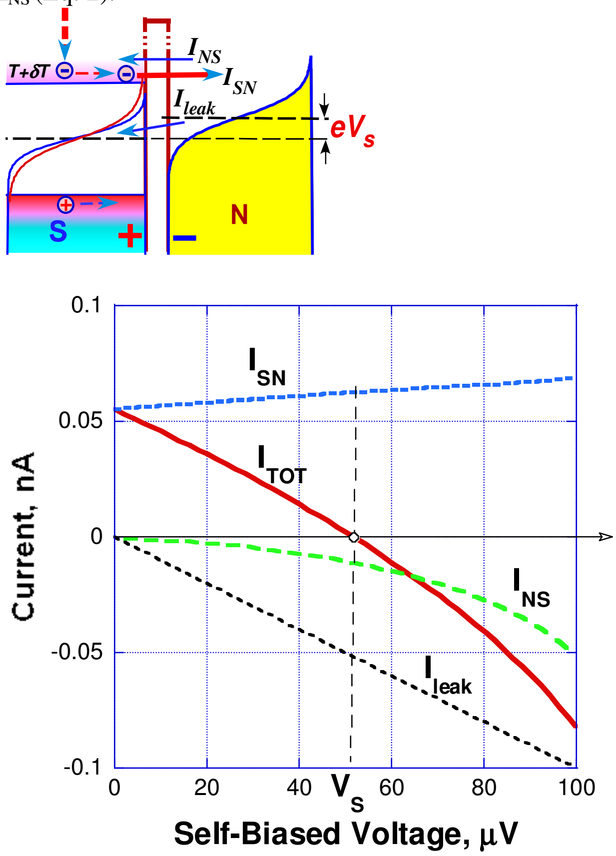

Fig. 2. Three contributions to the SIN tunneling current displayed in the occupancy diagram (a) and dependence of these components on a self-biased voltage. The saturation voltage, Vs, corresponds to current balance of these three components and total current I_{TOT}=0.

As a result, I_{tot}=0 in this point.

Some asymptotic expressions in the limit $V_S \ll \Delta/e$ can be obtained for the self-biased voltage as a reaction to the power P_0

$$V_s=I_{SN}*R_j. \qquad (8)$$

and voltage-to-power responsivity

$$S_V=K_i\frac{R_j*e}{\Delta}. \qquad (9)$$

Due to integration principle (6), the voltage can achieve quite high values. The proper tunnel resistance should be selected to get optimal noise properties with maximum response (9) and to avoid saturation when V_S is approaching to Δ.

Noise properties are characterized by the noise equivalent power (*NEP*), which is the sum of three contributions:

$$NEP_{tot}^2 = NEP_{SIN}^2 + NEP_{e-ph}^2 + NEP_{AMP}^2 . \qquad (10)$$

Here $NEP^2{}_{SIN}$ 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 junction and the correlation between these two processes [9]:

$$NEP_{SIN}^2 = \frac{\delta I_\omega^2}{(S_V / R_d)^2} + 2\frac{<\delta P_\omega \delta I_\omega>}{S_V / R_d} + \delta P_\omega^2 . \qquad (11)$$

The second term in Eq.10 is the noise associated with electron-phonon interaction [10, 11] and the last term is due to the voltage δV and current δI noise of the amplifier (JFET), which is expressed in $nV/Hz^{1/2}$ and $pA/Hz^{1/2}$:

$$NEP_{AMP}^2 = \frac{\delta V^2 + (\delta I * Rd)^2}{S_V{}^2} . \qquad (12)$$

III. SIMUATION RESULTS

A self-biased voltage Vs and voltage response dVs/dT was simulated using a heat balance equation (1), current balance equation (2) and full expression for SIN junction current.

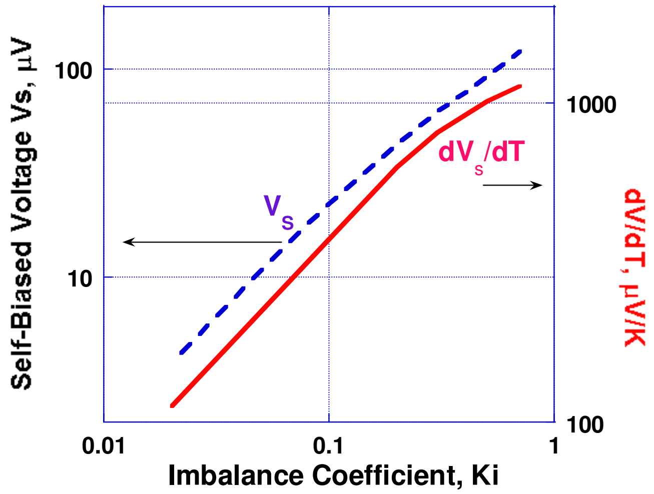

Fig. 3. Dependence of a self-biased voltage, V_S, and a thermopower responsivity, dVs/dT, on the imbalance coefficient K_i.

In dependence on frequency, superconducting gap and energy dependence of transparency of SIN tunnel junction, the various imbalance coefficients (4) could be realized. The Fig. 3 shows dependence of voltage response and NEP components on the imbalance coefficient K_i in the range from 0.02 to 0.7. The parameters of the SIN junction are the same as used in Fig. 2: tunnel resistance R=1kOhm, T=100 mK and Tc=1.2K.

The dependence of saturation voltage Vs and noise components on junction resistance R are shown in Fig. 4.

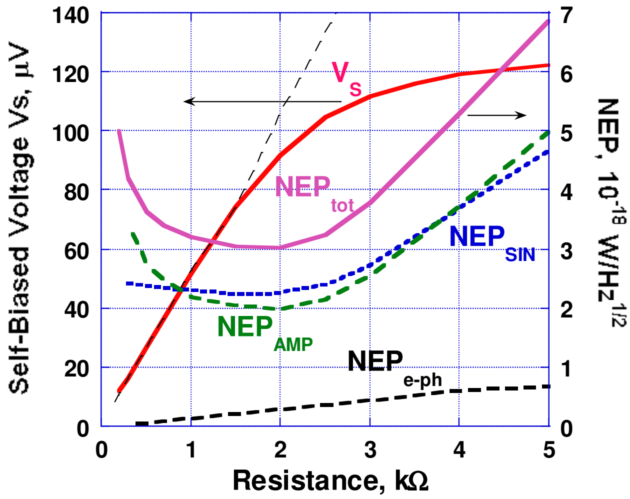

Fig. 4. Dependence of a self-biased voltage, V_S, and noise components on junction resistance R. Asymptotic dependence of V_S on R (Eq. 8) is shown by a dashed line.

The voltage V_S is deviating from linear asymptotic (8) when approaching to Δ. Responsivity S_v is decreased in this region that leads to increase of the bolometer noise. The optimal $NEP_{tot}=3*10^{-18} W/Hz^{1/2}$ is at R=2kOhm. This value is comparable with the photon noise level of $NEP_{phot}=3.2*10^{-18} W/Hz^{1/2}$ for 350 GHz.

The noise is determined by the noise of SIN tunnel junction coursed by transferring of incoming power P_o. Voltage response in this point is 92 µV. It is not reasonable to increase further this response because CVC is approaching to the saturation of responsivity near Delta. For a typical value of JFET noise of 2 $nV/Hz^{1/2}$, we estimate $NEP_{amp}=2*10^{-18} W/Hz^{1/2}$. Electron-phonon noise is at a very low level of $2*10^{-19} W/Hz^{\wedge 1/2}$, which is typical for superconducting absorbers at low power load.

In dependence on frequency, the various imbalance coefficients could be realized. The Fig. 5 shows dependence of voltage response and NEP components on the imbalance coefficient K_i in the range from 0.02 to 0.7.

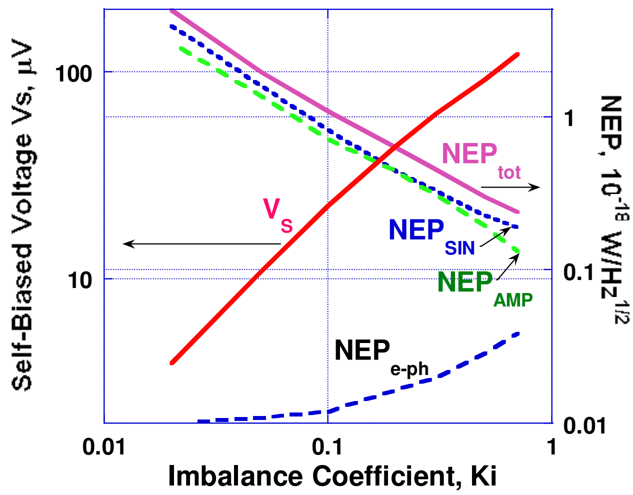

Fig. 5. Dependence of a self-biased voltage, Vs, and NEP components on the imbalance coefficient K_i.

Voltage Voltage V_S is increased approximately linearly when K_i is increased. Proportionally, NEP_{tot} is decreased due to the dependence of NEP_{SIN} and NEP_{AMP} on S_V. $NEP_{e\text{-}ph}$ is practically not dependent on K_i. These dependences show the importance of high branch imbalance for the realization of the low noise TEB. The factors required to achieve high branch imbalance are: the involvement of self-biased SIN junction in process of absorption, application for frequencies comparable with Δ, and maximum use of energy dependent transparancy of the SIN junctions [15].

IV. Discussion

The analysed parameters of CVC are promising for the creation of series array of bolometers for effective matching to a JFET amplifier in analogy to a CEB array [13,16]. The series arrays with large number of bolometers (64 or 256) can be effectively used for focal plane antenna [5,16]. The typical applications are balloon and ground-based telescope with an expected power load of 5 pW. Power will be distributed between N bolometers, avoiding overheating of bolometers and leading to the increase of total responsivity. The great advantage is also the zero dc impedance of superconducting absorbers in the array of N bolometers in contrast to bolometers with resistive absorbers. Zero-biased CVC could overcome problems of overheating for large format arrays of detectors (up to 100x100 pixels) due to the absence of bias heating the cold stage.

V. Conclusions

In conclusion, a novel concept of the CVC-TEB with SIN tunnel junction and superconducting absorber provides important advantages. The CVC is acting in a new mode as an integrator of charge in an external capacitance and could give high voltage response and good noise performance. By operating in a zero-biased mode, it reduces power dissipation, simplifies schematic, and paves the way to large scale multi-pixel arrays. Practical limitations, including imbalance coefficient and role of an SIN tunnel junction in quasiparticle excitation, have yet to be determined.

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