To the Sensitivity Estimation of TES Bolometers for SubMM Radiation Detection Operating at Super Low Temperatures

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Abstract – **The electron energy balance equation was modified to take into account the effect of transfer of hot electron power from TES bolometer absorber combined with the sensor to the biasing circuit with the electron current. Estimation calculations have shown that the power flow connected with said transfer is negligibly small in comparison with the hot electron power transfer to the thin metal film structure and substrate through electron-phonon interactions for studied earlier molybdenum-copper bi-layer thin film structures in 0.08 – 0.4 K temperature range [1]. The obtained equation was used to estimate a ratio of current decrement to incident radiation power (current sensitivity) of the TES bolometers as well. There were no significant reducing changes in the TES bolometers current sensitivity found at fixed bias voltage across the absorber for the studied structures except the case at temperatures 0.3 K and less and, especially, at absorber lengths 1 μ and less when the current sensitivity gain of order of several tens have been calculated.**

Keywords—Astronomy, millimeter- and submillimeter-wave detectors, superconducting devices, transition edge sensor (TES) bolometers.

I. Introduction

Bi-LAYER Mo/Cu structures showing the superconducting transition with critical temperature tailored by layer thicknesses can be used as the basis for the constructing supersensitive transition edge sensor (TES) hot-electron bolometers with combined absorber-sensor [1]. The results of measurements of resistance temperature dependences of such structures were reported at previous Symposium ISSTT-16 [1]. Using said dependences and the electron energy balance equation [2, 1]

$$P_J = U \cdot I = \Sigma v (T_e^5 - T_{ph}^5), \qquad (1)$$

IV- and power-voltage curves of possible bolometers on the basis of measured Mo/Cu structure samples and then parameters of possible bolometers were calculated. In (1) U is the fixed bias voltage, I is the bias current, T_e is the hot-electron temperature, T_{ph} is the temperature of phonons, i.e. of the thin metal film and substrate, $\Sigma \cong 3$ nW·K^{-5}·μm^{-3} is the material parameter taken from [3] where the electron energy balance equation for thin normal metal film bolometer on Si substrate at the same temperatures has been studied, v μm^3 is volume of the bolometer absorber. Definitions for (1) and details of calculations are given in [1] and summary of measured parameters of samples and calculated characteristics of possible bolometers are given in Table I.

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II. Estimation of Effect of Hot Electron Power Flow-Out from Absorber-Sensor to the Biasing Circuit

Mentioned above calculations are made under set of assumptions [1] one of which is that absorber-electrode contacts provide Andreev reflection [4] blocking hot electron power flow-out from the absorber-sensor to the bias circuit. What will happen when contacts will be not Andreev ones but ordinary? To answer this question one may take as a basis the expression for thermal capacity of electrons in metals [5]

$$C_v = \frac{\pi^2}{2} \cdot \frac{Nk^2 T_e}{E_F(0)} \text{ J/K}, \qquad (2)$$

where N is amount of electrons for which the thermal capacity is to be determined, $k \approx 1{,}38 \cdot 10^{-23}$ J/K is Boltzman constant, T_e K is electron temperature, $E_F(0)$ is Fermi energy equal for metals at low temperatures $E_F(0) =$ 1...10 eV [5]. We consider N as an amount of electrons entering absorber-sensor and leaving it simultaneously per second as a current. If so, we may express N through the current I A:

$$N = I / e \text{ s}^{-1}, \qquad (3)$$

where I C/s is electrical current, $e \cong 1.6 \cdot 10^{-19}$ C is electron charge. Taking into account that the temperature of entering electrons is T_{ph} K i.e. the temperature of the thin metal film and substrate (phonons) and the temperature of leaving (hot) electrons is T_e we may obtain from (2) and (3) expressions for powers leaving the absorber-sensor together with hot electrons and entering it together with bias current:

$$P_e = \frac{\pi^2}{2} \cdot \frac{Ik^2 T_e^2}{eE_F(0)} = \beta I T_e^2,\ P_{ph} = \frac{\pi^2}{2} \cdot \frac{Ik^2 T_{ph}^2}{eE_F(0)} = \beta I T_{ph}^2 \text{ W}, \qquad (4)$$

where $\beta = \frac{\pi^2}{2} \cdot \frac{k^2}{eE_F(0)}$. (5)

Adding the difference $(P_e - P_{ph})$ to the right side of (1) we obtain the electron energy balance equation for the case when the effect of hot electron power flow-out from the absorber-sensor to the bias circuit is present:

Table I

Sample	Sample thicknesses, nm		T_c, K	R_n, Ohm	$\alpha = \frac{T}{R}\cdot\frac{dR}{dT}$	U, μV	S_I, A/W	NEP, W/Hz$^{1/2}$
	Mo	Cu						
1	2	3	4	5	6	7	8	9
a	12	0	0,93	67	1070	-	-	-
b	15	35	0,4	2,9	150	10^{-7}	10^{7}	$4\cdot10^{-19}$
c	12	35	0,27	2,6	320	10^{-8}	10^{8}	$4\cdot10^{-20}$
d	12	100	0,08	0,6	510	10^{-9}	10^{9}	$4\cdot10^{-21}$

(1 - 6) - for 15 x 1.5 mm^2 samples, (7 - 9) – for 8 x 0.8 μm^2 possible bolometers. $S_I = |\Delta I|/P_{rad} = 1/U$, $NEP = \sqrt{i^2_{noise}}/S_I$, $\sqrt{i^2_{noise}}$ is the rms noise current of SQUID readout-amplifier next to the bolometer. In our case $\cong 4\cdot10^{-12}$ A/Hz$^{1/2}$

$$P_J = U\cdot I = \Sigma v(T_e^5 - T_{ph}^5) + \beta I(T_e^2 - T_{ph}^2). \quad (6)$$

Calculations have shown that the value of second member in right side of equation (6) is not higher than 1% of the first member for all values of $R(T_e)$, U, T_e, T_{ph} (two latter ~ T_c) in operating points given in Table I and for minimal of abovementioned value of Fermi energy $E_F(0)$ = 1 eV = 1,6·10^{-19} J. This correlation remains at the reducing of transverse dimensions of possible bolometers down to 0.8 x 0.08 μm^2. Described situation means that the hot electron power flow-out with the electrical current in our considered Mo/Cu structures case is more than two orders less intensive of the hot electron power flow-out owing to the electron-phonon interactions. It is easy to explain: second power flow-out takes place through relatively small contact areas when first one takes place through whole absorber-sensor volume. By this reason IV- and power-voltage curves calculated in [1] for bolometers with Andreev contacts will not differ noticeably from similar curves when contacts are not of Andreev type but ordinary.

Now with the purpose to estimate the current sensitivity and *NEP* of considering bolometers for the case when two mechanisms of hot electron power flow-out are acting we add to (1) in a similar way with [1] a radiation power P_{rad} to Joule power $U\cdot I$ and small additions ΔI and ΔT for current and temperature:

$$U(I+\Delta I) + P_{rad} = \Sigma v\left[(T_e+\Delta T)^5 - T_{ph}^5\right] + \beta(I+\Delta I)\left[(T_e+\Delta T)^2 - T_{ph}^2\right]. \quad (7)$$

We assume that like in [1] the fixed bias voltage U is applied to absorber-sensor what provides the negative electrothermal feedback action in electron system [2]. The equation for small values can be extracted from (7):

$$U\Delta I + P_{rad} \cong 5\Sigma v T_e^4 \Delta T + \beta(T_e^2 - T_{ph}^2)\Delta I + 2\beta I T_e \Delta T. \quad (8)$$

After simple transformation $\frac{U}{R+\Delta R} \cong \frac{U}{R} - \frac{U\Delta R}{R^2} = I - I\cdot\frac{\Delta R}{R} = I + \Delta I$ we have $\Delta I = -I\cdot\frac{\Delta R}{R}$ and $\frac{\Delta R}{R} = -\frac{\Delta I}{I}$. Then taking into account the relation $\alpha \cong (T_e/R)\cdot(\Delta R/\Delta T_e)$ (see Table I) one obtains $\Delta T \cong \frac{1}{\alpha}T\frac{\Delta R}{R} \cong -\frac{1}{\alpha}T\frac{\Delta I}{I}$. Substituting obtained expression for ΔT to (8) and taking into account values of α given in Table I one may see that members containing ΔT are negligibly small in comparison with other ones and we can write:

$$U\Delta I + P_{изл} \cong \beta(T_e^2 - T_{ph}^2)\Delta I. \quad (9)$$

We consider at first the case when contacts to the absorber-sensor are made of a superconductor with high critical temperature providing the Andreev reflection of electrons in the absorber-sensor from these contacts. In this case the member in right side of (9) is absent and we have:

$$U\Delta I + P_{rad} \cong 0. \quad (9')$$

One can obtain from (9') the expression for S_I (see Table I).

In this given point we consider in more details the action of said above negative electrothermal feedback in electron system of absorber-sensor [2]. The fixed bias voltage and very sharp dependence of the absorber-sensor resistance on electron temperature (see [1]) leads to the arising of an electron thermostat. When a deviation of electron temperature takes place in this thermostat by any reason this deviation leads to the variation of the absorber-sensor resistance and consequently of the current through it. This current variation has such direction that the change of dissipated Joule power $U\Delta I$ compensates the variation of electron temperature. For instance when the reason of electron temperature variation is the incident radiation power P_{rad} absorbed by the absorber the Joule power change $U\Delta I$ is equal to P_{rad} with opposite sign. The described mechanism of negative electrothermal feedback was discovered by Irvin [2]. Described consideration will be useful in subsequent discussion.

We return to the equation (9). One factor is more now in the electron thermostat operation [see (6)]. This is the hot electron power flow-out with the electrical current, i. e. $\beta I(T_e^2 - T_{ph}^2)$. The corresponding member $\beta(T_e^2 - T_{ph}^2)\Delta I$ has appeared in (9). One may obtain the expression for bolometer current sensitivity from (9) when the hot electron power flow-out with the electrical current takes place:

$$S_I = \frac{-\Delta I}{U\Delta I - \beta\left(T_e^2 - T_{ph}^2\right)\Delta I} = \frac{1}{U(1-\eta)}, \quad (10)$$

where
$$\eta = \frac{\beta\left(T_e^2 - T_{ph}^2\right)}{U}. \quad (11)$$

One may see from (10) that in considered case the bolometer current sensitivity is gained in comparison with the case when the hot electron power flow-out to the bias circuit is absent owing the blocking it by Andreev reflection. This gain is explained by the action of negative electrothermal feedback. The member $\beta(T_e^2 - T_{ph}^2)\Delta I$ in (9) reduces the hot electron power flow-out with the electrical current owing to the reducing of this current for value ΔI. This means that hot electron temperature is increasing. As a result of this increasing the negative electrothermal feedback increases the value of current reducing more. Something similar to iterative process is arising and stops when the power equilibrium will be restored, i. e. the equation (9) will be satisfied. To estimate η determined by (11) and then current sensitivity gain determined by (10) one has to know the Fermi energy $E_F(0)$ and to calculate β. We estimate η for lower value $E_F(0)$ of given above ones, i.e. $E_F(0)$ = 1 eV = 1,6 $\cdot 10^{-19}$ J. Results of estimation using temperatures and bias voltages given in Table I are summarized in Table II. The bolometers with dimensions $l \times w \sim 0.1 \times 0.2$ and 0.8×0.08 μm^2 based on the structures **c** and **d** respectively have $\eta \approx 0{,}98$ and gain ≈ 50. In other cases η is small in comparison with unit and, consequently, current sensitivities and *NEP*'s are practically the same as in the absence of the hot electron power flow-out to biasing circuit with electrical current (Table I).

Table II

Samples	Transverse dimensions of absorber-sensor $l \times w$, μm^2	η
b - d	~ 80 × 8	~0.01...0.02
b - d	~ 8 × 0.8	~ 0.1...0.2
c	~ 0.1 × 0.2	→ 1
d	~ 0.8 × 0.08	→ 1

III. CONCLUSION

- Modified electron energy balance equation containing the member taking into account the transfer of hot electron power from TES bolometer absorber-sensor to the biasing circuit with the electron current is derived.
- Analysis made on the basis of this equation has shown that the hot electron power flow-out from the TES bolometer absorber-sensor to the bias circuit in case of bi-layer Mo/Cu thin film structures is negligibly small in comparison with the hot electron power flow-out from electron system to the metal film and substrate through electron-phonon interactions. This hot electron power flow-out to the bias circuit has not noticeable influence on IV- and power-voltage characteristics of TES bolometers.
- The hot electron power flow-out from the absorber-sensor to the bias circuit does not deteriorate the bolometer current sensitivity. On the contrary, at rather small transverse dimensions and low temperatures of bolometers it leads to the regenerative gain of the current sensitivity.
- To achieve a practical realization of the regenerative gain phenomenon the thorough investigation of material characteristics as well as fabrication technology and design development are needed.

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