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Experimental study of superconducting transition in a molybdenum–copper thin film structure showing the proximity phenomenon and the estimation of the sensitivity of TES bolometers on the basis of such a structure

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Abstract

Mo/Cu bi-layers with different layer thickness values showing superconducting transitions in the temperature range 0.08–1.0 K have been experimentally studied. The temperature of the superconducting transition can be adjusted to the stable temperatures of refrigerators used at the space radio telescopes using the proximity phenomenon by varying the thickness of Mo and Cu layers. The estimation of the noise equivalent power of TES bolometers on the basis of such structures using measured dependences of Mo/Cu structure resistances on temperature and electron energy balance equation is fulfilled.

Highly sensitive receivers based on direct detectors of sub-millimeter range photons are needed for space radio astronomy [1,2]. The use of transition edge sensor bolometer with low transition temperatures ($\sim$0.3–0.1 K) is one of the most promising ways to achieve appropriate sensitivity [3,4].

Since it is important to have temperature of superconducting transition in the range of stable operation of used refrigerator it has been proposed to use the superconductor-normal metal bi-layers [3] showing a proximity phenomenon [5]. Changing the thickness of superconductor and normal metal layers the temperature of the superconducting transition of the whole bi-layer structure can be adjusted to the desired value.

Toward this end the Mo/Cu bi-layers with different layers thickness showing the superconducting transition in the temperature range 0.08–1.0 K have been experimentally tested. The sample fabrication procedure comprising the deposition of two layers of Mo and Cu successively on a polished silicon wafer of 430 μm thick by means of the DC magnetron sputtering in argon atmosphere was used. Samples cut into pieces of $24 \times 1.5\,mm^2$ size with the following Mo/Cu layers thickness (nm) have been fabricated:

8/0, 8/30, 8/50, 8/100; 12/0, 12/30, 12/50, 12/100; 15/50, 25/50, 35/50, 50/50; 10/40, 15/35, 20/30, 30/20.

Dependences of resistance versus temperature $R(T)$ have been measured in a $^3He/^4He$ dilution refrigerator using the four-point method. The transition edge temperature of samples with Mo thickness 12 and 15 nm turned out to be the most

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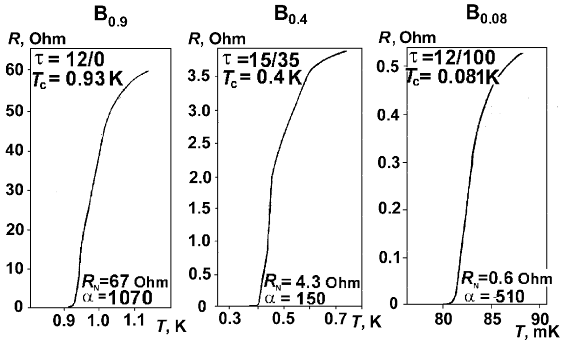

Fig. 1. Dependences $R(T)$ for Mo/Cu samples $B_{0.9}$, $B_{0.4}$ and $B_{0.08}$ of $24 \times 1.5\,mm^2$ size; Mo and Cu thickness values $\tau = t_{Mo}/t_{Cu}$ (nm/nm); critical temperatures T_c, normal resistances R_N and parameters α of samples are given on graphs.

sensitive to Cu thickness. Such samples have shown transition temperatures in the range $\sim$0.1–0.4 K, which is required for bolometer operation. Samples with thinner Mo layer did not show a superconducting transition at all. $R(T)$ dependences for Mo/Cu thickness values 15/35 and 12/100 (nm/nm) are shown in Fig. 1 together with $R(T)$ dependence for pure Mo film of 12 nm thickness.

The proximity effect is clearly seen from the Fig. 1. The transition temperature decreases with increasing thickness of the Cu layer, simultaneously the resistance of bi-layer structure getting smaller. The pure Mo film has shown transition temperature of 0.93 K, which is expected value for Mo.

The parameter $\alpha = (T/R)\mathrm{d}R/\mathrm{d}T$ which characterizes the sharpness of the superconducting transition has been derived in the vicinity of the superconducting transition edge temperature (T_c) for three measured samples. They are given in Fig. 1.

With the purpose to estimate a noise equivalent power of TES bolometers on the basis of the studied structures we have calculated I–V-curves of possible bolometer microstructures using the assumptions:

(1) The shape of $R(T)$ and the critical temperatures of Mo/Cu bi-layer structures are functions of layers thickness and practically do not depend on transverse dimensions, i.e. length and width, as long as they are much greater than the coherence distance for Cooper pairs in normal metal and superconductor: ξ_n, $\xi_s \approx 100 - 10$ nm [5].

(2) The dependences $R(T)$ corresponding to the measurements described above taken at small bias currents and $R(T_e)$ when electrons are heated by current of comparatively large value are close to eachother at least in the vicinity of the transition edge.

(3) The absorber of bolometer is voltage-biased to provide stable mode of operation and negative electro-thermal feedback [3]. The absorber is connected to the bias circuit through superconducting electrodes with high enough critical temperature to assure Andreev electron reflection [6] at bolometer absorber-electrodes boundaries.

(4) The I–V-characteristic of the TES bolometer connected to the voltage-biasing circuit as well as the negative electro-thermal feedback are controlled by the electron energy balance equation [7,8]

$$P_J = U^2/R(T_e) = \Sigma v(T_e^5 - T_{ph}^5), \qquad (1)$$

where the left side term $P_J = U^2/R(T_e)$ is the Joule power incoming to the electron system from the bias circuit and heating electrons and the right side term is the hot-electron power flowing from the electron system to the thin metal film lattice and the substrate, U is the fixed bias voltage, T_e is the hot-electron temperature, $R(T_e)$ is the resistance of the bolometer depending on electron temperature. The right side of (1) is written in analogy to the electron energy balance equation for the normal metal hot-electron bolometer [9,10], T_{ph} is the temperature of phonons, i.e. of the film lattice and substrate, $\Sigma \cong 3$ nW K^{-5} μm^{-3} is the material parameter taken from [10] where the electron energy balance equation for thin normal metal film bolometer on Si substrate at the same temperatures has been studied, v is volume of the bolometer absorber.

In our calculations of I–V-curves we assume the temperature T corresponding right to the beginning of the increase of resistance from zero (see Fig. 1) as T_{ph} in Eq. (1). The stable values of $R(T_e)$ together with T_e and consequently current I through the bolometer bi-layer structure are established at given bias voltage U in accordance

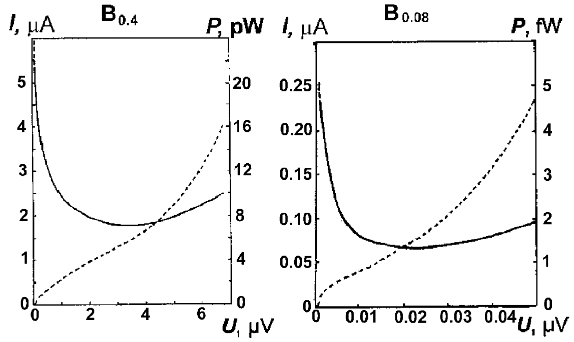

Fig. 2. Calculated current–voltage (solid lines) and power–voltage (dashed lines) characteristics of two designed TES microbolometers based on data of two measured Mo/Cu bi-layer structures at $T = 0.4$ and 0.08 K, respectively.

with Eq. (1) what means that Eq. (1) controls the *I–V*-curve of strongly nonlinear bi-layer structure. This gives the possibility to calculate *I–V*-curves using the measured dependences $R(T)$ and Eq. (1) keeping in mind the assumption (2). The length[1] and width of structures were reduced from $15 \times 1.5\,\text{mm}^2$ proportionally to $8 \times 0.8\,\mu\text{m}^2$ keeping in mind the assumption (1). Since the length-to-width ratio of the absorber remained the same like in case of measured samples—the absolute values of their resistances and temperature dependences remain the same as well. For *I–V*-curves calculations we approximate the total bi-layer structure thickness of samples $B_{0.4}$ and $B_{0.08}$ by the Cu layer thickness equal to 35 and 100 nm because these layers determine structure resistances.

The results of current–voltage curves calculation are shown in Fig. 2. In the same figure the dependences of dissipated DC power in absorber as a function of bias voltage are given as well. The common shape and order of magnitude of values of these dependences are like for dependences measured directly for similar bi-layer structure [8]. The difference of results in Ref. [8] in comparison with Fig. 2 is that the positive slope portions of *I–V*-curves at very small bias voltages are absent in our case. The reason is that we do not take into account critical current and non-controlled small resistance connected in series with bi-layer structure occurring in [8] is absent in our case for both structures. Nevertheless we suppose that the obtained *I–V*-curves can be used for estimation of the sensitivity of possible bolometers based on the studied Mo/Cu bi-layer structures.

The current-to-power (A/W) sensitivity of the TES bolometers in accordance with Ref. [3] is

$$S_I = |\Delta I|/P_{\text{rad}} = 1/U,$$

where ΔI is the current response for the absorbed radiation power P_{rad} and U is the voltage bias in the vicinity of the transition edge. From Fig. 2 $U_{0.4} \cong 10^{-7}$ μV and $U_{0.08} \cong 10^{-9}$ μV for structures at T=0.4 and 0.081 K, respectively. The noise equivalent power of TES bolometers $NEP = \sqrt{\overline{i^2_{\text{noise}}}}/S_I$ [3], where $\sqrt{\overline{i^2_{\text{noise}}}}$ is root-mean-square noise current of a readout-amplifier next to the bolometer. We have SQUID readout-amplifier with $\sqrt{\overline{i^2_{\text{noise}}}} \cong 5 \times 10^{-12}\ \text{A/Hz}^{1/2}$. With this readout-amplifier we have $\text{NEP}_{0.4} \cong 5 \times 10^{-19}\ \text{W/Hz}^{1/2}$ and $\text{NEP}_{0.08} \cong 5 \times 10^{-21}\ \text{W/Hz}^{1/2}$. Of course these are just estimation values and measurements of real bi-layer structures *I–V*-curves and bolometer NEPs are needed. The preparations for such measurements are now in progress.

The obtained results give a possibility of the better understanding of the TES microbolometer operation mechanism as well as of the adjustment of its layer thickness values to a stable temperature of the used refrigerators, the preliminary estimation of sensitivity of microbolometers during fabrication and sample selection for the ready microbolometers mounting.

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[1] 15 mm—distance between potential probes.

References

[1] A.N. Vystavkin, D.V. Chouvaev, T. Claeson, et al., 10th International Symposium on Space Terahertz Technology, 16–18 March, Charlottesville, USA, 1999.
[2] A.N. Vystavkin, Radiotechnika i Electronika 46 (7) (2001) 806–815 (in Russian).
[3] K.D. Irwin, G.C. Hilton, D.A. Wollman, J.M. Martinis, Appl. Phys. Lett. 69 (13) (1996) 1945–1947.
[4] B.S. Karasik, W.R. McGrath, H.G. LeDuc, M.E. Gershenson, Supercond. Sci. Technol. 12 (1999) 745–747.
[5] N.R. Werthamer, Phys. Rev. 132 (6) (1963) 2440–2445.
[6] A.F. Andreev, J. Exp. Theor. Phys. 19 (1964) 1229–1231.
[7] K.D. Irwin, Appl. Phys. Lett. 66 (15) (1995) 1998–2000.
[8] K.D. Irwin, G.C. Hilton, J.M. Martinis, B. Cabrera, Nucl. Instr. and Meth. A 370 (1996) 177–179.
[9] M. Nahum, J.M. Martinis, Appl. Phys. Lett. 63 (22) (1993) 3075–3077.
[10] A.N. Vystavkin, D.V. Shuvaev, L.S. Kuzmin, et al., J. Exp. Theor. Phys. 88 (3) (1999) 598–602.