Study of Superconducting Transition in a Mo/Cu Thin Film Structure and Estimation of Sensitivity of SUBMM Waveband Region TES Bolometers on the Basis of such a Structure

Alexander N. Vystavkin, *Member*, *IEEE*, Alla G. Kovalenko, Sergey A. Kovtonyuk

Abstract — Transition edge sensor (TES) bolometers are using now in more than ten projects of imaging radiometers for ground based and balloon SUBMM telescopes. In this work the temperature dependences of the resistance of bi-layer Mo/Cu structures destined for TES bolometers were measured in the range of 0.05–1.0 K. Using these dependences and the electron energy balance equation the current–voltage and power–voltage characteristics of bolometers on the basis of such structures for the case of a fixed d.c. bias voltage are calculated. The expression for the current increment produced by such a bolometer in response to absorbed radiation power is derived. The noise equivalent power of a realizable bolometers is calculated from the current response in the case when detected signals are amplified by a highly sensitive SQUID.

Keywords—*Radio astronomy, millimeter- and submillimeter-wave detectors, superconducting devices, superconducting radiation detectors, transition edge sensor bolometers.*

I. INTRODUCTION

DURING last three-four years the developments of imaging radiometers based on TES bolometer arrays for more than ten short millimeter – long submillimeter waveband region ground based and balloon telescopes take place in the world (see for example [1-8]. Such developments has been started in Russia too. In this situation further study of different aspects of such radiometers, in particular, TES bolometer arrays for optimization of bolometers themselves, biasing and signal multiplexing systems, optical (quasioptical) cameras etc. is necessary. In this paper we report some investigation results of superconducting transition in a Mo/Cu thin film structure. Results of other said above aspects are given in three more our papers at this Symposium.

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A. N. Vystavkin (corresponding author: phone: 7-095-203-25-05; fax: 7-095-203-84-14; e-mail: vyst@hitech.cplire.ru) , A. G. Kovalenko and S. A. Kovtonyuk are with the Institute of Radioengineering and Electronics of Russian Academy of Sciences, 11 Mokhovaya Street, 125009 Moscow, Russian Federation.

II. SUPERCONDUCTING TRANSITION IN MO/CU THIN FILM BI-LAYER STRUCTURE

It is well known that the use of transition edge sensor bolometers with low transition temperatures (~ 0.3 - 0.1 K) is one of the most promising ways to achieve appropriate sensitvity of radiometers for submillimeter astronomy [9-11, 8]. Since it is important to have temperature of superconducting transition in the range of stable operation of used refrigerator it has been proposed [12] to use the “superconductor-normal metal” bi-layers showing a proximity phenomenon. Changing the thickness of 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 0.05 - 1.0 K have been fabricated and experimentally tested in this work. We have fabricated them in high vacuum magnetron sputtering machine. Mo and Cu layers were deposited on a polished Si wafer in one vacuum cycle from two magnetrons successively by DC magnetron sputtering in argon atmosphere.

The Mo and Cu layers sputtering rate was measured using test samples and profiler; working sample layer thicknesses were determined through sputtering time measurement. Layer thicknesses (nm) of fabricated Mo/Cu samples were:

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

The investigation of film and bi-layer structures surfaces quality on the electron and atomic forces microscopes were fulfilled. Results are shown on Fig. 1 and Fig. 2. Results of investigations on both microscopes show that surfaces are continuous and sufficiently smooth.

The dependences $R(T)$ of 13×1.3 sq. mm size samples have been measured in the $^3He/^4He$ dilution cryostat using four- point method [13]. It occurred that 12-15 nm Mo samples are most sensitive for influence of Cu. Samples with Mo thickness < 12 nm have not transition. Samples with Mo thickness > 15 nm have transition edge temperature > 0.4 – 0.5 K. At these temperatures the Andreev electron reflection phenomenon [14] enhancing the heating of electrons becomes negligible [15].

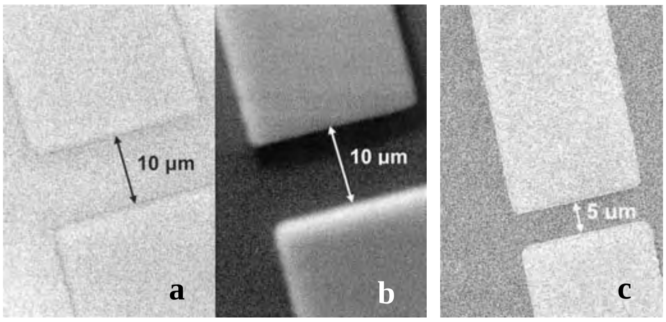

Fig. 1. Investigation results on electron microscope. Mo film in secondary electrons (a) and in reflected electrons (b); Mo/Cu structure in secondary electrons (c).

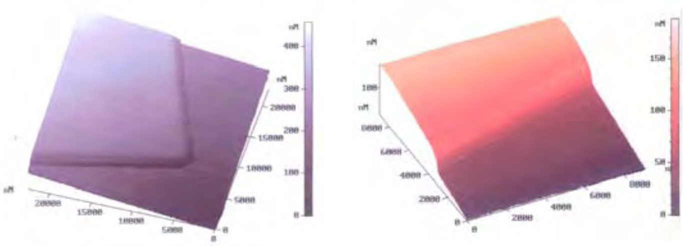

Fig. 2. Investigation results on atomic forces microscope. The surface roughness of 15 nm Mo layer is δ_{Mo} = 0.25 nm (a); the surface roughness of 15/35 nm Mo/Cu bi-layer is δ_{Cu} = 0.41 nm (b).

The thickness 12 – 15 nm is close to Cooper pairs coherent distance. The proximity phenomenon is clearly seen from the shown dependences moving from (a) to (d) at Fig. 3 and Table. $R(T)$ dependence for pure Mo film of 12 nm thickness is given for comparison. It has shown transition temperature of 0.93 K, which is expected value for Mo. The transition temperature decreases with the increasing of the Cu layer thickness. Simultaneously the resistance of bi-layer structure getting smaller. It is seen as well a possibility of the transition edge temperature fitting by means of layers choice. Low resistance is the reason that functions of absorber and thermometer are shared by most of authors to optimize a receiver scheme in case of antenna-coupled bolometer [5]. We have proposed the way how to avoid this circumstance using the planar antenna-microstrip transformer (see paper of S. V. Shitov & A. N. Vystavkin at this Symposium). The parameter $\alpha = (T/R)\cdot dR/dT$ 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. These parameters are given in the Table. Comparing thicknesses of Mo layers of samples b and c and their transition edge temperatures one may find that 5 Å of Mo layer thickness accuracy correspond to approximately 5% of temperature accuracy.

III. Estimation of sensitivity of bolometers based on Mo/Cu structures

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

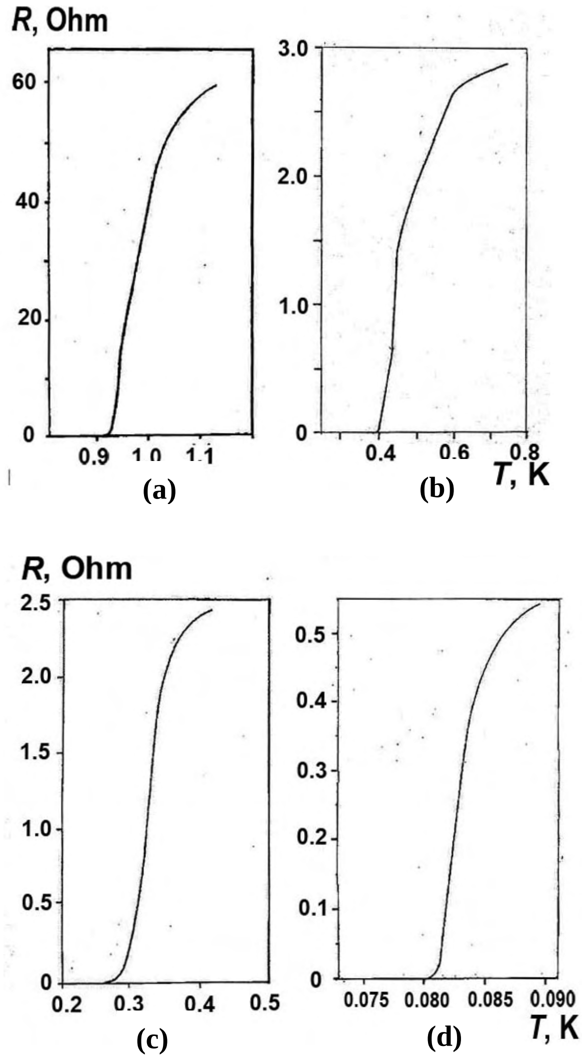

Fig. 3. Results of measurements $R(T)$ dependences of Mo/Cu samples which main parameters are given in the Table.

TABLE
Main parameters of Measured Samlles

Sample	Layer hickness, nm		T_c, K	R_N, Ohm	$\alpha = \frac{T}{R}\cdot\frac{dR}{dT}$
	Mo	Cu			
a	12	0	0.93	67	1070
b	15	35	0.4	2.9	150
c	12	35	0.27	2.6	320
d	12	100	0.08	0.6	510

(i) 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 [16].

(ii) 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 each to other at least in the vicinity of transition edge.

(iii) The absorber of bolometer is voltage-biased to provide stable mode of operation and negative electro-thermal feedback [17]. The absorber is connected to the bias circuit through superconducting electrodes with high enough critical temperature to assure Andreev electron reflection [15] at bolometer absorber-electrodes boundaries.

(iv) The IV-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 [17, 12]:

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

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 [18,19], 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 [19] 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 IV-curves we assume the temperature T corresponding right to the beginning of the increase of resistance from zero (see Fig. 3) as T_{ph} in equation (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 with the equation (1) what means that the equation (1) controls the IV-curve of strongly nonlinear bi-layer structure. This gives the possibility to calculate IV-curves using the measured dependences $R(T)$ and equation (1) keeping in mind the assumption (II). The length[1)] and width of structures were reduced from 13×1.5 mm^2 proportionally to 8×0.8 μm^2 keeping in mind the assumption (I). 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 IV-curves calculations we approximate the total bi-layer structure thickness of samples b, c and d by their Cu layers thickness values equal to 35 nm and 100 nm respectively because these

layers determine structure resistances. The results of current-voltage curves calculation are shown in Fig. 4. In the same figure the dependences of dissipated d.c. 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 [12]. The difference of results in [12] in comparison with Fig. 2 is that the positive slope portions of IV-curves at very small bias voltages are absent in our case. The reason is that we don't take into account critical current and besides a non-controlled small resistance connected in series with bi-layer structure occurring in [12] is absent in our case for three structures. Nevertheless we suppose that the obtained IV-curves can be used for estimation of the sensitivity of possible bolometers based on the studied Mo/Cu bi-layer structures.

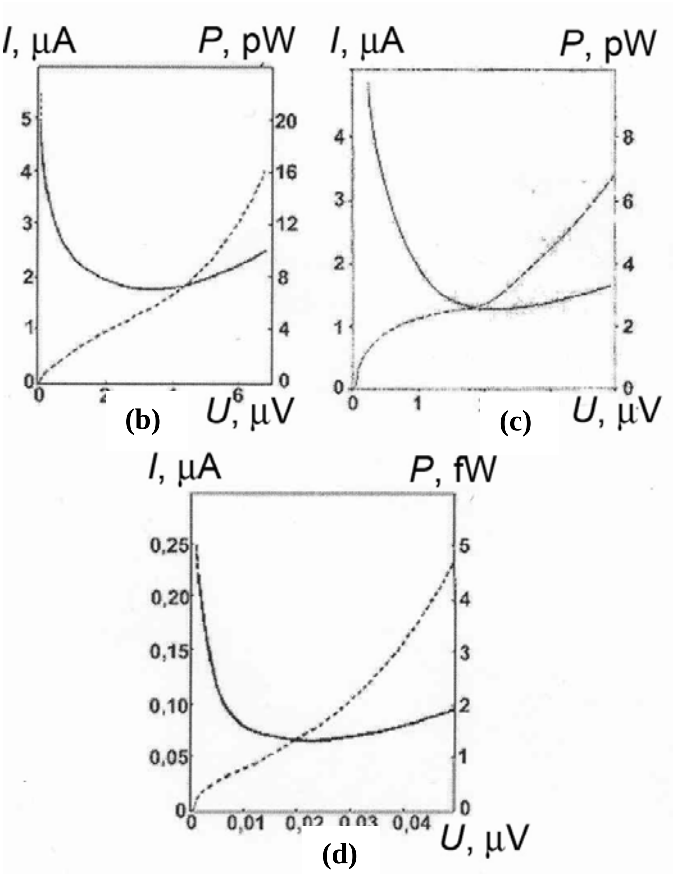

Fig. 4. Calculated current-voltage (solid lines) and power-voltage (dashed lines) characteristics of constructed TES bolometers based on data of three measured Mo/Cu bi-layer structures at T = 0.4 K, T = 0.27 K and T = 0.08 K respectively.

When small submillimeter radiation power P_{rad} is absorbed by TES bolometer at fixed bias voltage $U = const$ the equation (1) has to be modified to

$$U^2 / [R(T_e) + \Delta R] + P_{rad} = \Sigma v [(T_e + \Delta T_e)^5 - T_{ph}^5],$$

(2)where P_{rad} is added to the Joule power and small increments ΔR and ΔT_e are added to the resistance $R(T_e)$ and

1) 13 mm – distance between potential probes.

the temperature T_e. The equation for small values can be extracted from (2):

$$-\frac{U^2\Delta R}{R^2(T_e)}+P_{rad}\cong\Sigma v5T_e^4\cdot\Delta T_e. \quad (3)$$

After simple transformations using expressions $I+\Delta I = U/(R+\Delta R)$ and $\alpha\cong(T_e/R)\cdot(\Delta R/\Delta T_e)$ one obtains the expression for the current responsivity of TES bolometer

$$S_I=\frac{-\Delta I}{P_{rad}}=\frac{1}{U}/[1+(5/\alpha)/(\Sigma vT_e^5/P_J)]. \quad (4)$$

From (1) we have $\Sigma vT_e^5/P_J\le 1$ and from results of measurements we also have $\alpha>100$. So

$$S_I=\frac{-\Delta I}{P_{rad}}\cong\frac{1}{U}, \quad (5)$$

what practically coincides with analogous expression in [4] with the difference that in our case radiation energy is absorbed directly by TES. Besides.given here derivation of the expression for the current responsivity S_I of TES bolometer reflects clearly the mechanism of negative electrothermal feedback.

Minimal values of the voltage bias U take place in the vicinity of the transition edge. From Fig. 4 $U_{0.4}\cong 10^{-7}$ μV, $U_{0.27}\cong 10^{-8}$ μV and $U_{0.08}\cong 10^{-9}$ μV for structures at T = 0.4 K, T = 0.27 K and T = 0.081 K respectively. The noise equivalent power of TES bolometers $NEP=\sqrt{i_{noise}^2}/S_I$ [3] where $\sqrt{i_{noise}^2}$ is root-mean-square noise current of a readout-amplifier next to the bolometer. We have SQUID readout-amplifier with $\sqrt{i_{noise}^2}\cong 4\cdot 10^{-12}$ A/Hz$^{1/2}$. With this readout-amplifier we have $NEP_{0.4}\cong 4\cdot 10^{-19}$ W/Hz$^{1/2}$, $NEP_{0.27}\cong 4\cdot 10^{-20}$ W/Hz$^{1/2}$ and $NEP_{0.08}\cong 4\cdot 10^{-21}$ W/Hz$^{1/2}$. Of course these are just estimation values and measurements of real bi-layer structures IV-curves and bolometer *NEP*'s are needed. The preparations for such measurements are now in progress.

The obtained results give a possibility of the better understanding of the TES bolometer operation mechanism as well as show the way of the adjustment of its layer thickness values to a stable temperature of the used refrigerators and permit the preliminary estimation of the noise equivalent power of bolometers during their fabrication and bolometer sample selection for the mounting of receivers with bolometers.

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References

[1] J. G. Staguhn, D. J. Benford, F. Pajot, T, A. Ames, J. A. Chervenak, E. N. Grossman, et al., “Astronomical demonstration of superconducting bolometer arrays”, *Proc. SPIE, Millimeter Submillimeter Detectors Astronomy*,2003, v. 4855, pp. 100-107.

[2] D. J. Benford, M. J. Devlin, S. R. Dicker, K .D. Irwin, P. R. Jewell, J. Klein, et al., “A 90 GHz array for Green Bank Telescope”, *Nuclear Instruments and Methods in Physics Research,* A 520, 2004 (Proc. of the 10th Intern. Workshop on Low Temperature Detectors – LTD-10, Genoa, Italy, July 7-11, 2003), pp. 387-389.

[3] R. F. Silverberg, S. Ali, A. Bier, B. Campano, T. C. Chen, F. S. Cheng, et al., “A bolometer array for the spectral energy distribution (SPEED) camera”, ibid, pp. 421-423.

[4] T. C. Chen, A. Bier, B. A. Campano, D. A. Cottingham,,F. M. Finkbeiner, C. O’Dell, E. Sharp, R. F. Silverberg, G. Wilson, “Development of molybdenum-gold proximity bilayers as transition edge sensors for the SPEED camera”, ibid, pp. 446-448.

[5] M. J. Myers, W. Holzapfel, A. T. Lee, R. O’Brient, P. L. Richards, D. Schwan, A. D. Smith, H. Spieler, H. Tran, “Arrays of antenna-coupled bolometers using transition edge sensors”, ibid, pp. 424-426.

[6] W. Duncan, D. Audley, W. Holland, D. Atkinson, T. Baillie, M. Cliffe, et al., “SCUBA-2 arrays to system interfaces”, ibid, pp. 427-430.

[7] M.D. Audley, W.S. Holland, W.D. Duncan, D. Atkinson, M. Cliffe, M. Ellis, et al., SCUBA-2: A large format TES array for submillimeter astronomy, ibid, pp. 479-482.

[8] J. E. Ruhl, P. A. R. Ade, J. E. Carlstrom, H. M. Cho, T. Crawford, M. Dobbs, et al., “The South Pole Telescope”, *Proc. SPIE (Intern. Symp. on Astronomical Telescopes)*, 2004. www.spt.uchicago.edu/extweb/spt_spie_2004.pdf.

[9] P. L. Richards, C .R. McCreight, “Infrared detectors for astrophysics”, *Physics Today*, February 2005, pp. 41-47..

[10] J. Zmuidzinas, P. L. Richards, “Superconducting detectors and mixers for millimeter and submillimeter astrophysics”, *Proc. IEEE*, 2004, v. 92, # 10, pp. 1597-1616.

[11] “Detector needs for long wavelength astrophysics”, *A report by the infrared, submillimeter and millimeter detector working group* (June 2002), Young E. – the Chair of working group, after the Far-infrared, sub-mm & mm detector technology workshop, NASA, Monterey, California, 1 - 3 April, 2002,

[12] K. D. Irwin, G. C. Hilton, J. M. Martinis, B. Cabrera, “A hot-electron microbolometer for X-ray detection using a superconducting transition edge sensor with electrothermal feedback”, *Nucl. Instr. and Meth*., 1996, A370, pp.177-179.

[13] A. N. Vystavkin, V. V. Dmitriev, V. V, Zavialov, A. G. Kovalenko, S. A. Kovtonyuk, A. A. Cnebotarev, “Investigation of superconducting transition in bi-layer molybdenum-copper structure showing proximity phenomenon”, *Radiotekhnika i Elektronika* (in Russian), 2003, v. 48, # 7, pp. 874-876.

[14] A. F. Andreev, “Thermal conductivity of superconductors intermediate state”, *Soviet Phys. ZhETP*, 1964, v. 46, # 5, pp. 1823-1828.

[15] A. N. Vystavkin, “Supersensiting hot-electron microbolometer with Andreev electron reflection phenomenon for submillimeter radio astronomy”, *Radiotekhnika i Elektronika* (in Russian), 2001, v. 46, # 7, pp. 806-815.

[16] N. R. Werthamer, “Theory of the superconducting transition temperature and energy gap function of superposed metal films”, *Phys. Rev*., 1963, v. 132, # 6, pp. 2440-2445.

[17] K D. Irwin, “An application of electrothermal feedback for high resolution cryogenic particle detection”, *Appl. Phys. Lett.,* 1995, 10 April, 66 (15), pp. 1998-2000.

[18] M. Nahum, J. M. Martinis, “Ultrasensitive hot-electron microbolometer”, Appl. Phys. Lett. ,1993, 63(22), pp. 3075-3077.

[19] A. N. Vystavkin, D. V. Shuvaev, L. S. Kuzmin, M. A. Tarasov, E. Andersted, M. Willander, T. Claeson, “Normal metal hot-electron bolometer with Andreev reflection in superconducting electrodes”, J. of Exp. and Theor. Phys., 1999, 88 (3), pp. 598-602.

[20] S. Lee, J. Gildemeister, W. Holmes, A. Lee, and P. Richards, “Voltage-biased superconducting transition-edge bolometer with strong electrothermal feedback operated at 370 mK,” *Appl. Opt.*, 1998, v. 37, #.16, pp. 3391–3397.