Numerical Analysis of the Non-cooled Infra-red Sensors based on Different Thermoelectric Wires or Films

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***Abstract* - Calculation and optimization of parameters for thermoelectric sensors of infra-red radiation based on InSb, Bi_2Te_3, antimony and Bi-Sb alloys were realized.**

Sensitivity, time constant and noise equivalent power (NEP) of those sensors were determined at different conditions.

It was fulfilled the comparative analysis of sensors based on wires or films. Both advantages and disadvantages of corresponding constructions were discussed.

The obtained results were compared with experimental data received in Academy of Sciences of Moldova (ASM) and literature data. This comparison confirms a good quality and perspective of studied constructions.

***Index Terms* – infra-red sensors, radiation thermo elements.**

I. INTRODUCTION

Infra-red radiation is widely used in medicine, industry, scientific researches and other fields [1-7]. These circumstances called force the wide development of infra-red techniques, including receivers of infra-red radiation (infra-red sensors).

According to [1, 2, 6 - 9] their main parameters are: sensitivity ε, which is equal to output signal (in Volts) if the falling radiation power is equal to 1 W; minimal detected power (or NEP) P_{min}, when ratio signal: noise is equal to one; time constant τ, which is equal to time necessary for sensor temperature to achieve value $T_0 + (T_1 - T_0)(1 - e^{-1})$. Here T_0 is the environment temperature, T_1 is receiver temperature under influence of the constant radiation stream, and e is base of natural logarithms.

All infra-red sensors may be divided into two big classes [1-7]: thermal (or heat) receivers that use thermal effect of radiation and photoelectric sensors that use the quantum photoelectric effects.

Thermal sensors have less sensitivity and more time constant than photoelectric ones, but thermal sensors do not require the deep cooling, their constructions are simple, they have little weight and dimensions and their parameters practically do not depend on the falling radiation wave length. Therefore they are non-selective, what is very convenient for direct measure of the radiation power, especially in middle and far infra-red region.

If it is actually the heat sensor may be "tuned" in demanded range by means of optical filters [10].

Also there are known pyroelectric receivers of radiation [11]. They have good characterizations, but their use is restricted, because parameters of these receivers get worse drastic if load resistance is less 10^9 Ohm or signal frequency is less 0.1 Hz.

II. RESULTS AND DISCUSSION

In table I there are shown parameters of some infra-red radiation receivers. We tried to choose receivers with best parameters (published in accessible scientific literature), but the only non-cooled receivers working at temperature about 300 K were picked out. Of course receivers working at liquid nitrogen and especially liquid helium temperature have better parameters. But in this situation construction gets complicated, weight and dimensions increase, reliability falls (because it is necessary to use mechanical cooling equipment and thermo cycling). Often these restrictions are unacceptable. All our results in this article have to do with non-cooling sensors working at temperature 300 K.

In numeration (left column of table I) letter T means thermal receivers and letter P means photoelectric ones. In particular 1T is Schwarz thermo element [1], 2T is soviet receiver TP-0,3*3 [1,2], 3T is receiver FT-12 [1], 4T is bolometer BKM-2 [2], 5T is receiver of system Mariner [12], 6T is receiver of Santa Barbara Research Center based on five thermo elements [1]. 7P is photogalvanomagnetic receiver based on PbS (firm Midway [2]), 8P is photo resistor FS-A [2, 3].

Parameter λ_{max} means maximum possible wave length of falling radiation for given receiver. If wave length is more λ_{max} the corresponding receiver can not be used. This parameter is sufficient for photoelectric receivers. For heat receivers it depends on the receiving ground properties and it is practically non-limited for infrared radiation.

Here S is area of the reception ground, other parameters were defined above.

Bismuth, antimony and Bi-Sb alloys are often used to create thermoelectric infra-red sensors [1, 2, 6 and 13]. In particular the most effective infra-red receivers 5T and 6T (in Table I) are fabricated on basis of bismuth and antimony films. On the other hand it seems to be additional possibilities to create efficient sensors based on bismuth, antimony and Bi-Sb alloys.

For example it seems to be actual miniaturization of sensors and focusing of falling radiation on less receiving ground. In this situation sensitivity increases (due to reduction of thermo conductance) and time constant falls (due to reduction of mass and heat capacity). It allows removing the old problem of thermoelectric infrared sensors [7], when the rise of sensitivity caused the rise of time constant and lowering of time constant conducted to fall of sensitivity.

TABLE I. PARAMETERS OF EXISTING INFRARED SENSORS

№	λ_{max}	S, mm^2	ε, V/W	τ, sec	P_{min} ($\times 10^{-10}$ $W/Hz^{1/2}$)
1T	-	1 – 5	20 – 90	0.03	0.15 – 0.56
2T	-	0.9	18	0.04	0.44
3T	-	0.4	70	0.1	-
4T	-	1.7	170	0.022	12
5T	-	0.0625	150	0.075	0.51
6T	-	0.0144	280	$1.3*10^{-5}$	1.5
7P	6.2	1.8	1	$2*10^{-7}$	7.4
8P	3	2.4	$1.4*10^{4}$	$3*10^{-5}$	0.22

The elaboration of infra-red sensors based on thin wires seems to be the first step in miniaturization. The correspondent results were published in [14]. Materials parameters were taken from [15, 16] and from measurements realized in Laboratory of Semimetals Physics (Institute of Applied Physcs, Academy of Sciences of Moldova).

The thermo element based on bismuth and antimony was studied. Bismuth wire was n-branch and antimony wire was p- branch. If sensor was not pumped out, the correspondent calculations gave result ε = 5.13 V/W. This result practically coincided with experimental data ($\varepsilon \approx 5 \div 7$ V/W).

The next step was utilization of $Bi_{0.88}Sb_{0.12}$ alloy (instead of bismuth) for n-branch of thermoelectric sensors. The correspondent results [17] are shown in fig. 1, 2 and in table II. In all cases condition S=0.4 mm^2 was fulfilled.

According to fig. 1 sensitivity falls if wires diameters rise, because wire thermo conductance increases. Additional thermo conductance by means of glass insulation get worse the sensors parameters, but this change for the worse is not sufficient.

In accordance with fig. 2 at first NEP falls with diameter rise, because electric resistance decreases and Johnson thermal noise falls. But further rise of diameter leads to increase NEP, because sensitivity falls (see fig. 1). Noise of thermal exchange fluctuations is one-two orders less than Johnson noise.

There were calculated optimal diameters of n- and p- branches (d_n and d_p) to achieve a minimal NEP. Taking into account influence of glass insulation the numerical solution was realized. Results are presented in table II. Here n is number of thermocouples

Further step was utilization of InSb as n-branch and Bi_2Te_3 as p-branch of sensor. Results [17] are shown in table III.

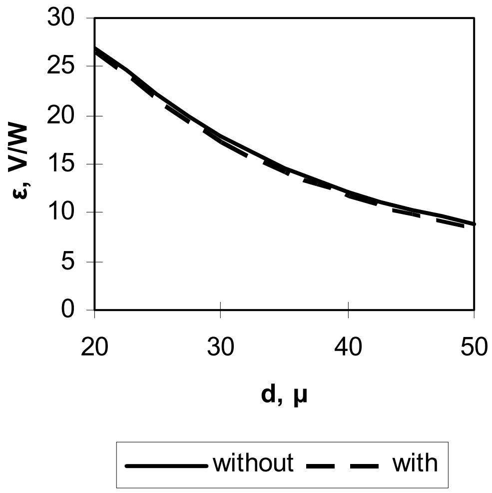

Fig. 1. Infrared sensor based on $Bi_{0.88}Sb_{0.12}$ and antimony wires: dependence of sensitivity on wires diameters (with and without of glass insulation).

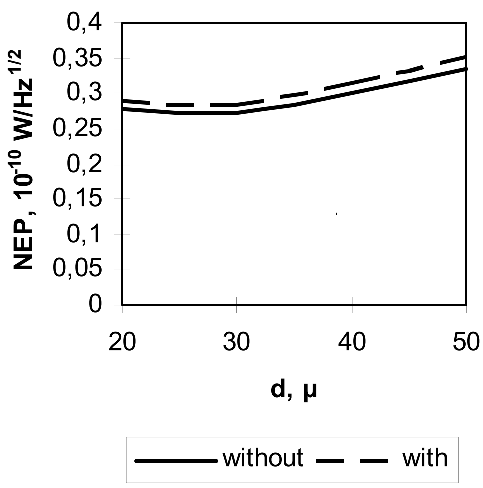

Fig. 2. Infrared sensor based on $Bi_{0.88}Sb_{0.12}$ and antimony wires: dependence of NEP on wires diameters (with and without of glass insulation).

TABLE II. OPTIMAL PARAMETERS OF SENSORS BASED ON THIN WIRES OF $Bi_{0,88}Sb_{0,12}$ (n-BRANCH) AND ANTIMONY (p-BRANCH).

n	d_n, μ	d_p, μ	ε, V/W	τ, sec	P_{min} ($\times 10^{-10}$ $W/Hz^{1/2}$)
1	33	29	21	2.0	0.18
5	15	13	90	2.9	0.20

This construction reveals more sensitivity and less NEP due to big thermo electromotive force (EMF) and little thermo conductivity of these materials.

TABLE III.OPTIMAL PARAMETERS OF SENSORS BASED ON THIN WIRES OF InSb (n-BRANCH) AND Bi_2Te_3 (p-BRANCH).

n	d_n, μ	d_p, μ	ε, V/W	τ, sec	P_{min} ($\times 10^{-10}$ W / $Hz^{1/2}$)
1	52	74	75	6.0	0.105
5	24	35	308	7.3	0.121

According to presented results the use of wires allows to achieve big sensitivity and little NEP especially if the wires of InSb and Bi_2Te_3 are used, but time constant remains big.

This problem may be resolved if thermoelectric wires are replaced by suitable films [18 - 20]. The correspondent constructions were elaborated in Specialized Design-Technology Bureau ASM. Round receiving ground of blacked bismuth was deposited on the mica substratum.

The receiving ground was surrounded with a battery of consequently connected thermocouples. Every thermocouple had a bismuth film (n-branch) and antimony one (p-branch). The silver layer (of round shape) was deposited on the opposite side of substratum. Details of numerical analysis were published in [18]. Temperature distribution was described by Bessel functions. The control calculations (for sensors in air, non-pumped out) gave responsivity 5.2 V/W (in experiment 5 V/W), time constant 0.01 sec. (in experiment 0.01 - 0.015 sec) and resistance 9.2 kOhm (in experiment 10 kOhm). This coincidence confirmed correctitude of chosen calculation methods.

Some obtained results (from [18 - 20]) are presented in figures 3 - 5 and in table IV.

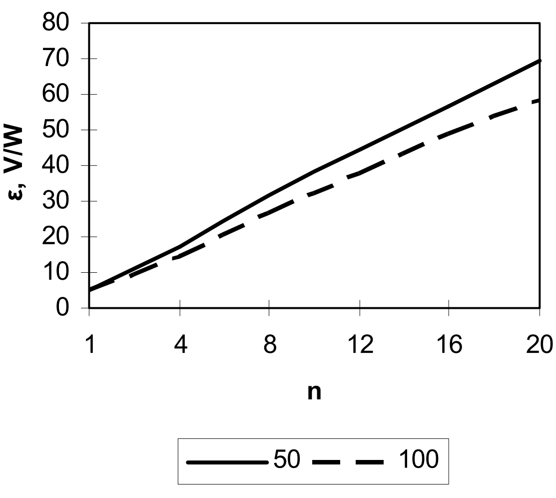

Fig. 3. Dependence of sensitivity on the number of thermocouples. Inscriptions in figures show film thickness (in nanometers).

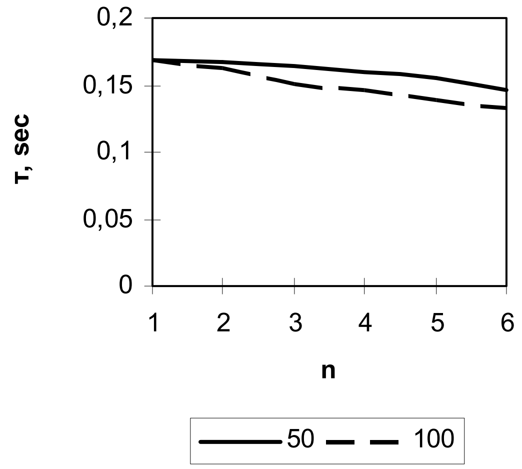

Fig. 4. Dependence of time constant on the number of thermocouples. Inscriptions in figures show film thickness (in nanometers).

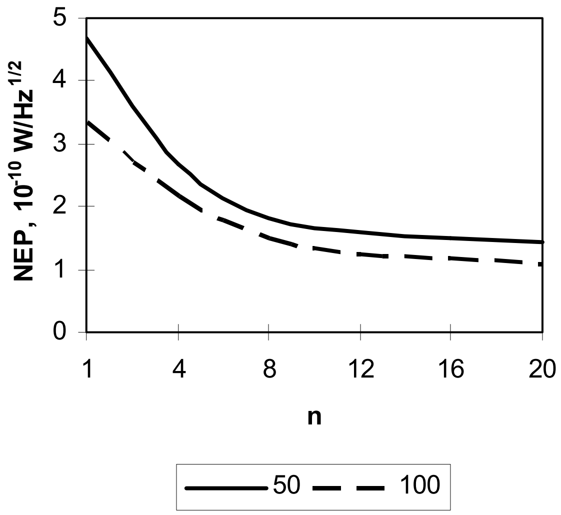

Fig. 5. Dependence of NEP on the number of thermocouples. Inscriptions in figures show film thickness (in nanometers).

According to fig. 3 - 5 responsivity rises when number of thermocouples increases, because summary thermo EMF rises, but increase of thermo conductance across thermocouples restrains rise of responsivity. Also increase of film thickness leads to rise of thermo conductance and decrease of responsivity.

When number of thermocouples increases, both thermo conductance and thermal capacity rise, but thermo conductance rise faster and time constant falls. Also when film thickness rises time constant falls due to rapid increase of thermo conductance.

NEP falls when number of thermocouples increases, because responsivity rises. But increase of electrical resistance and Johnson thermal noise restricts this fall. Also NEP falls when film thickness increases, because resistance decreases.

The optimized constructions parameters are shown in table V.

TABLE IV. OPTIMAL PARAMETERS OF THE FILM RECEIVERS OF INFRARED RADIATION.

№	*p, Tor*	*ε, V/W*	*τ, sec*	P_{min} ($\times 10^{-10}$ $W/Hz^{1/2}$)
1	760	11	0.0041	8.8
	10^{-4}	110	0.044	0.88
2	760	160	0.006	2.9
	10^{-4}	1400	0.048	0.32
3	760	340	0.006	2.5
	10^{-4}	2900	0.048	0.32

Here *p* is air pressure in working field of sensor. Construction parameters of cases 1, 2, 3 are shown in tableV. Here *l, w, d* are accordingly length, width and thickness of films, *D* is diameter of receiving ground, *n* is number of thermocouples.

According to table V we may conclude that miniaturization of infra-red sensor allows to rise responsivity due to little thermo conductance and big summary thermo EMF. Also miniaturization reduces NEP due to big sensitivity. Small sensors have little time constant due to little heat capacity.

TABLE V.CONSTRUCTION PARAMETERS OF CASES 1, 2, 3 FROM TABLE IV.

№	*l, μ*	*w, μ*	*d, nm*	*D, mm*	*n*
1	1000	100	50	1	20
2	500	2	100	0.1	35
3	500	1	100	0.1	75

III. CONCLUSION

Comparison of data from table I and tables II - IV shows that studied sensors may have a wide application due to big sensitivity, small NEP and relatively little time constant. For example sensitivity may be one order more and NEP may be 1.5 times less.

These parameters may be achieved due to big thermo EMF and high figure of merit in studied materials. Also it is important to create an optimal structure.

Therefore the further elaboration of these structures seems to be an actual problem.

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