NUMERICAL ANALYSIS OF THE NON-COOLED INFRA-RED SENSORS BASED ON DIFFERENT THERMOELECTRIC MATERIALS

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Abstract

Calculation and optimization of parameters for thermoelectric sensors of infra-red radiation based on CdSb, InSb, Bi_2Te_3, antimony, and Bi-Sb alloys have been realized.

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

A comparative analysis of sensors based on wires or films has been made. Both advantages and disadvantages of corresponding constructions have been discussed.

The obtained results have been compared with experimental data obtained in the Academy of Sciences of Moldova (ASM) and literature data. This comparison has confirmed a good quality and perspective of studied constructions.

Introduction

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

According to [1, 2, 6-9] the main parameters of these sensors are: sensitivity ε, which is equal to output signal (in Volts) if the incident radiation power is to 1 W; minimal detected power (or NEP) P_{min}, when the signal to noise ratio is 1; 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 the 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 incident radiation wave length. Therefore, they are non-selective, what is very convenient for direct measurement of the radiation power, especially, in middle and far infra-red region.

If it is required, the heat sensor may be “tuned” in demanded range by means of optical filters [10].

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

Results and discussion

In Table 1, parameters of some infra-red radiation receivers are shown. We tried to choose receivers with best parameters (published in available scientific literature), but only non-cooled receivers working at temperature about 300 K were picked out. Certainly, 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 paper are concerned with non-cooling sensors working at temperature 300 K.

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

Parameter λ_{max} means maximum possible wave length of incident radiation for the given receiver. If wave length is more than λ_{max} the corresponding receiver cannot 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 design thermoelectric infra-red sensors [1, 2, 6, 13]. In particular, the most effective infra-red receivers 5T and 6T (in Table 1) are fabricated on basis of bismuth and antimony films. On the other hand, it seems to give an additional possibility to create efficient sensors based on bismuth, antimony, and Bi-Sb alloys.

For example, miniaturization of sensors and focusing of incident radiation on less receiving ground seems to be important. In this situation, sensitivity increases (due to reduction in thermo conductance) and time constant decreases (due to reduction in 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 a decrease in sensitivity.

Table 1. Parameters of existing infrared sensors.

№	λ_{max}	S, mm^2	ε, V/W	τ, s	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 the Laboratory of Semimetals Physics (Institute of Applied Physics ASM).

The thermo element based on bismuth and antimony was studied. Bismuth wire was n-branch and antimony wire was p- branch. If the sensor was not evacuated, the correspondent calculations gave result $\varepsilon = 5.13$ 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 (from [17]) are shown in Figs. 1 and 2 and in Table 2. In all cases condition S=0.4 mm^2 was fulfilled.

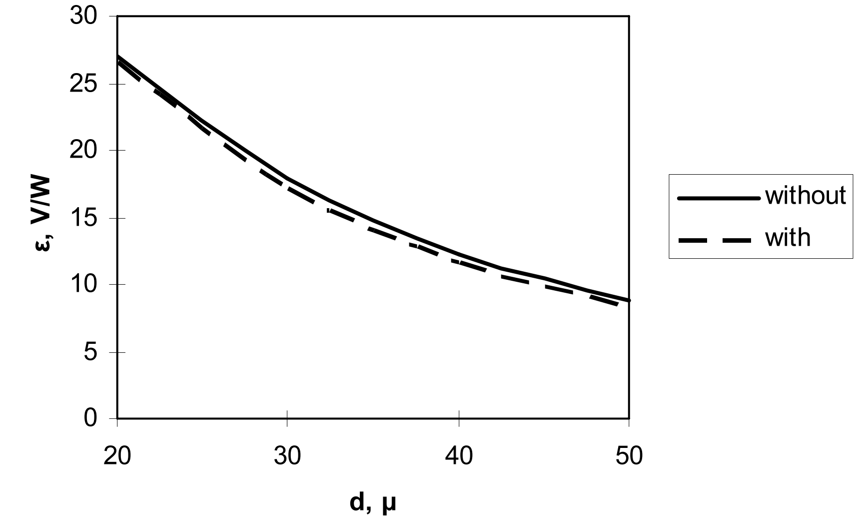

Fig. 1. Infrared sensor based on $Bi_{0.88}Sb_{0.12}$ and antimony wires: dependence of sensitivity on wire diameters (with glass insulation and without it).

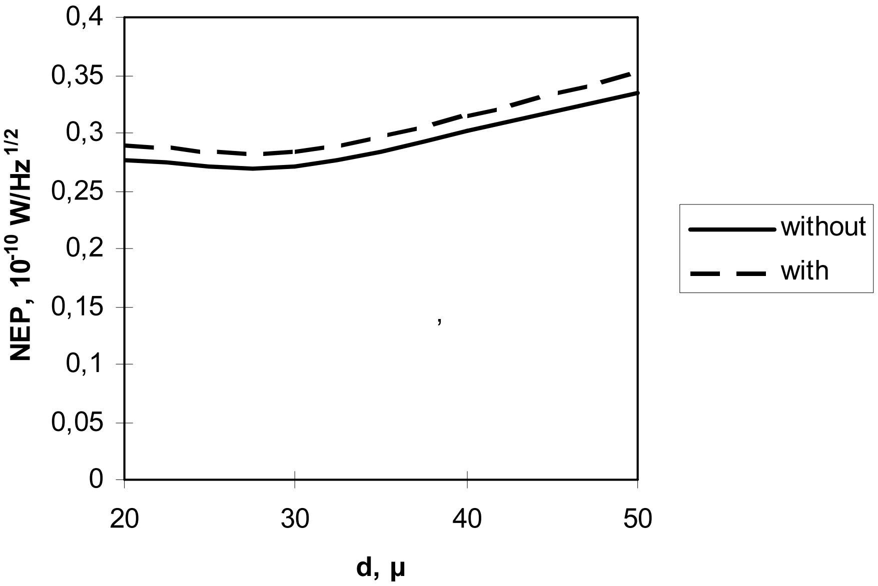

Fig. 2. Infrared sensor based on $Bi_{0.88}Sb_{0.12}$ and antimony wires: dependence of NEP on wire diameters (with glass insulation and without it).

According to Fig. 1, sensitivity decreases if wire diameters increase, since 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 an increase in NEP, because sensitivity decreases (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 2. Here *n* is the number of thermocouples.

Table 2. Optimal parameters of sensors based on thin wires of $Bi_{0,88}Sb_{0,12}$ (n-branch) and antimony (p-branch).

n	d_n, μm	d_p, μm	ε, V/W	τ, s	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

Further step was utilization of InSb as n-branch and Bi_2Te_3 as p-branch of sensor. Results [17] are shown in Figs. 3 and 4 and in Table 3. The main tendencies in Figs. 3 and 4 are similar to those in Figs. 1 and 2 due to the same physical reasons.

This construction reveals higher sensitivity and lower NEP due to high thermo electromotive force (EMF) and low thermo conductivity of these materials. Optimal parameters are shown in Table 3.

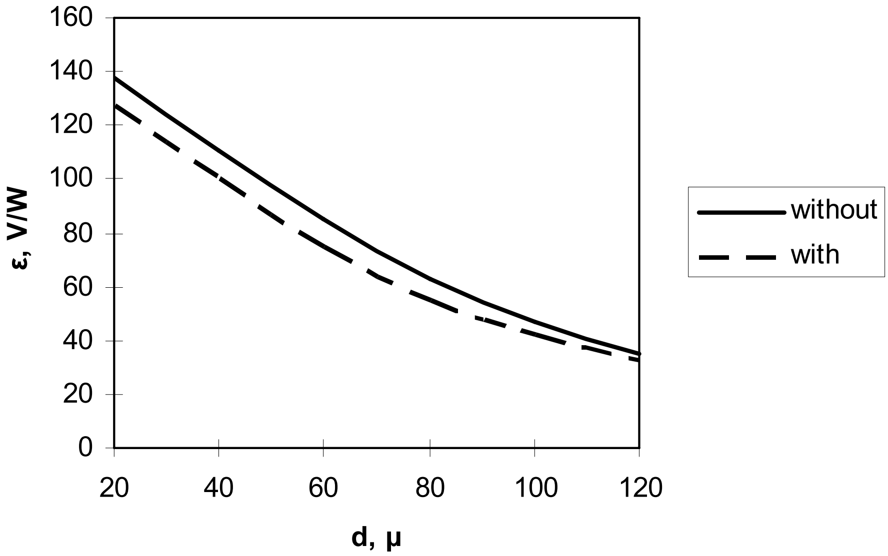

Fig. 3. Infrared sensor based on InSb and Bi_2Te_3 wires: dependence of sensitivity on wire diameters (with glass insulation and without it).

Also there were examined the sensors used InSb as n-branch and CdSb as p-branch [18]. The correspondent results are given in Figs. 5 and 6 and Table 4.

This structure allows increasing sensitivity due to higher thermo EMF in CdSb, but NEP becomes worse due to smaller figure of merit in this material. The diameter dependences in Figs. 5 and 6 are analogous to the ones in Figs. 1-4 due to the same reasons. When number of thermocouples rises the sensitivity increases due to output signal rising. NEP does not decrease because noises rise too.

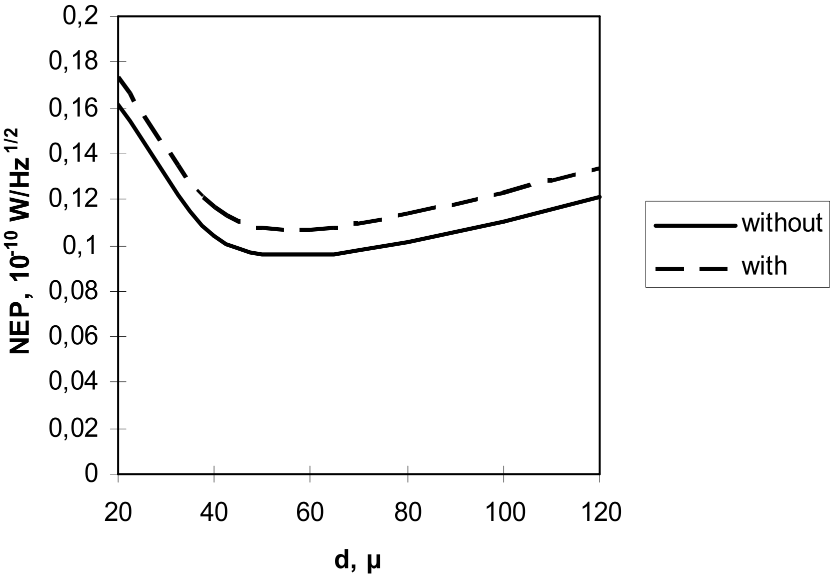

Fig. 4 Infrared sensor based on InSb and Bi_2Te_3 wires: dependence of NEP on wire diameters (with glass insulation and without it).

Table 3. Optimal parameters of sensors based on thin wires of InSb (n-branch) and Bi_2Te_3 (p-branch).

n	d_n, μm	d_p, μm	ε, V/W	τ, s	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

Table 4. Optimal parameters of sensors based on thin wires of InSb (n-branch) and CdSb (p-branch).

n	d_n, μm	d_p, μm	ε, V/W	τ, s	P_{min} ($\times 10^{-10}$ $W / Hz^{1/2}$)
1	16	90	150	6.6	0.51
5	6.6	42	630	8.0	0.57

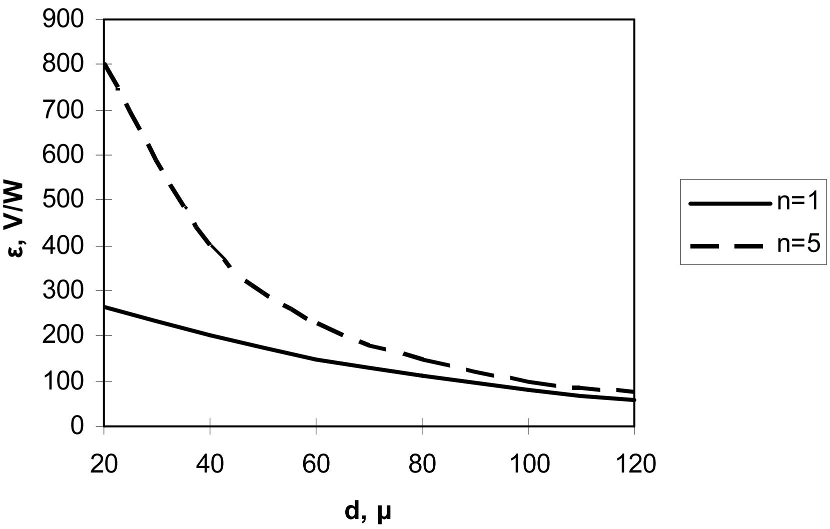

Fig. 5. Infrared sensor based on InSb and CdSb wires: dependence of sensitivity on wire diameters (inscriptions in legend show number of thermocouples).

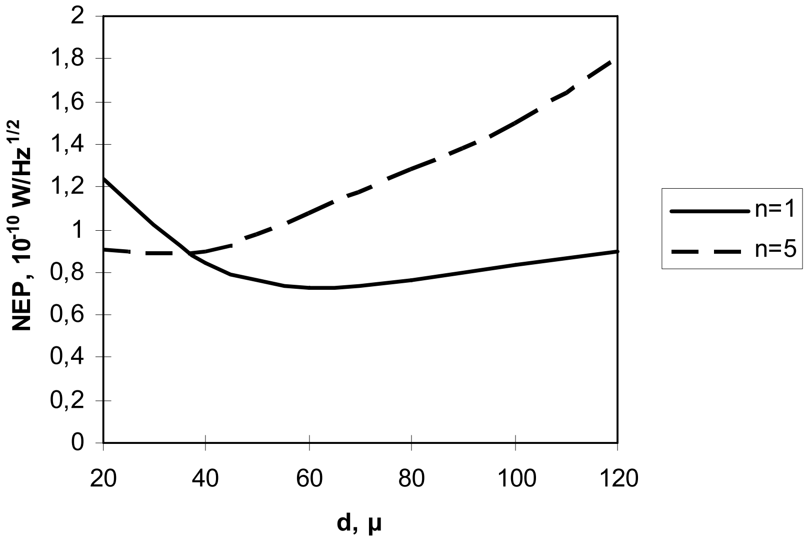

Fig. 6. Infrared sensor based on InSb and CdSb wires: dependence of NEP on wire diameters (inscriptions in legend show number of thermocouples).

According to the presented results, the use of wires allows us to obtain high sensitivity and low NEP, especially if the wires of InSb and Bi_2Te_3 or CdSb are used, but time constant remains high. This problem may be solved if thermoelectric wires are replaced with suitable films [19, 20].

The correspondent constructions were elaborated in Specialized Bureau on Design and Technology (ASM). Round receiving ground of blacked bismuth was deposited on the mica substratum.

The receiving ground was surrounded with a battery of series 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 [19]. 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 s. (in experiment 0.01÷0.015 s) and resistance 9.2 kOhm (in experiment 10 kOhm). This coincidence confirmed correctitude of chosen calculation methods.

Some obtained results (from [19, 20]) are presented in Figs. 7 and 8 and in Table 5.

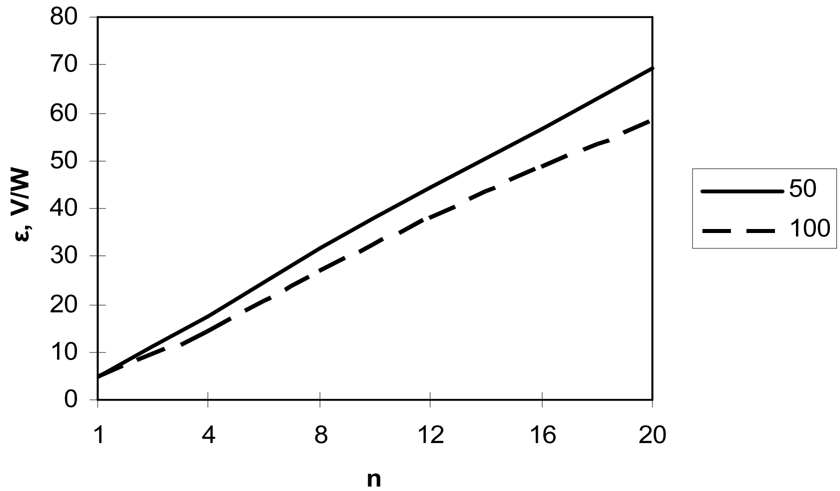

Fig. 7. Dependence of sensitivity on the number of thermocouples. Inscriptions in the figure show film thickness (in nanometers).

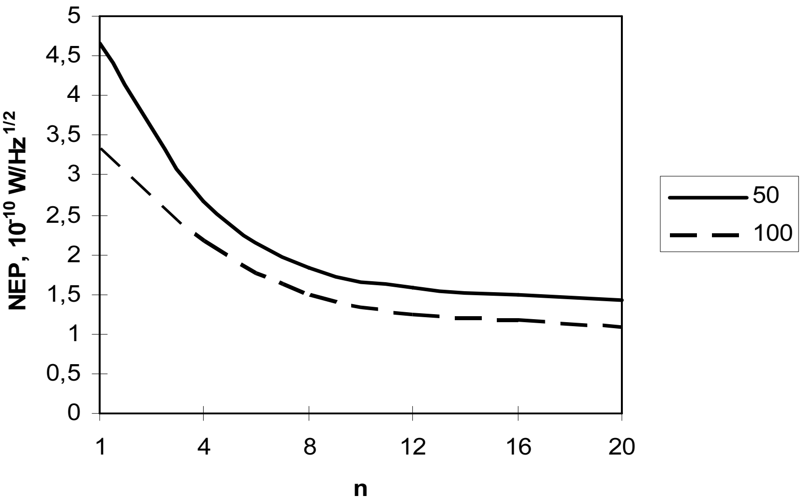

Fig. 8. Dependence of NEP on the number of thermocouples. Inscriptions in the figure show film thickness (in nanometers).

According to Fig. 7, 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.

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 5.

Table 5. Optimal parameters of the film receivers of infrared radiation.

№	*p, Tor*	*ε, V/W*	*τ, s*	*R, Ohm*	P_{min} ($\times 10^{-10}$ $W / Hz^{1/2}$)
1	760	11	0.0041	6200	8.8
	10^{-4}	110	0.044	6200	0.88
2	760	160	0.006	$1.4 \cdot 10^5$	2.9
	10^{-4}	1400	0.048	$1.4 \cdot 10^5$	0.32
3	760	340	0.006	$5.9 \cdot 10^5$	2.5
	10^{-4}	2900	0.048	$5.9 \cdot 10^5$	0.32

Here p is the air pressure in working field of the sensor. Construction parameters of cases 1, 2, and 3 are shown in Table 6. Here l, w, and d are the length, width, and thickness of films, respectively, D is the diameter of the receiving ground, n is the number of thermocouples.

According to Table 6, we may conclude that miniaturization of infra-red sensor allows us to rise responsivity due to low thermo conductance and high total thermo EMF. Also miniaturization reduces NEP due to high sensitivity. Small sensors have low time constant due to low heat capacity.

Table 6. Construction parameters of cases 1, 2, and 3 from Table 5.

№	*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

Conclusions

Comparison of data from Table 1 and Tables 3, 4, and 5 shows that studied sensors may be widely applied due to high sensitivity, low NEP, and relatively low time constant. For example, sensitivity may be one order higher and NEP may be 1.5 times lower.

These parameters may be achieved due to high 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 urgent problem.

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