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THE LIMITS OF THERMOELECTRIC COOLING FOR PHOTODETECTORS

The results of research on the limiting capabilities to use thermoelectric cooling for photo-detectors are presented. The introduction of modern technologies for IR detectors allows shifting their operating temperature from the cryogenic region to the range of 120 – 200 K. It is shown that such temperatures can be achieved by thermoelectric cooling through use of new up-to-date approaches in the development and manufacture of stage thermoelectric modules. Such approaches are: first, using optimal functionally graded materials based on Bi-Te for the legs of cooling modules, secondly, using Bi-Sb alloys for n-type legs in low-temperature stages and arrangement of these stages in optimally homogeneous or optimally inhomogeneous magnetic field . Based on the results of computer simulation it was determined that practical introduction of these approaches in the development of modules assures the level of thermoelectric cooling of IR detectors up to 120 K with sufficient energy efficiency.

Key words: photo detector, IR detector, thermoelectric cooling.

Introduction

Semiconductor photodetectors are widely used for IR radiation recording and IR imaging in modern terrestrial and space equipment, systems for astronomical observations, automatic star tracking, in night vision devices, etc. Detectors with photoelectric conversion of IR signal possess good threshold characteristics (spectral sensitivity, detectability) and fast response. However, this requires photodetector cooling down to cryogenic temperatures [1]. Cooling is necessary to reduce thermal generation of charge carriers in a semiconductor photosensitive element. Thermal carriers transitions compete with optical ones, which results in the large value of dark noise in uncooled devices.

The operating temperature of photodetector is related to the operating range of IR detector wavelength and depends on material and technology of photosensitive element. Modern cooled IR sensors are efficient at temperatures below 200 K [1]. For cooling such devices there have been specially developed and used microcryogenic systems based on gas cryogenic Stirling machine which is combined with a cryostatted photodetector into a single design [2-6]. They assure photodetector cooling temperature 75 to 150 K. The main shortcoming of such systems is their high cost. Such mechanical cooling systems make IR sensor systems bulky, expensive and not very reliable, preventing from a wide practical use of IR devices. Medium-wave (3 – 5 μm) and long-wave (5 – 30 μm) IR sensors operated without cryocooling, are required for many important practical applications.

Scientific investigations of recent decade have demonstrated that good threshold characteristics of the sensors of medium and long-wave IR range can be assured with the operating temperatures of photodetectors considerably higher than cryogenic ones [7, 8]. These temperatures are easily achieved with the aid of thermoelectric cooling [9, 10] which in this case is more reasonable as compared to the mechanical method for cold production.

The objective of this work is to analyze the capabilities of thermoelectricity for cooling sensor devices and to determine the reasonable operating temperature range of photodetectors with thermoelectric cooling.

The results of research

Thermoelectric cooling is widely used to assure the required operating temperature of IR detectors [1, 9, 10]. Photodetector arranged on the heat-absorbing pad of thermoelectric cooling module is, as a rule, mounted into a sealed case whose base is in a good thermal contact to heat exchanger.

Single-stage thermoelectric modules are used for shallow cooling (down to 250 K) of IR sensors and for temperature stabilization of the so-called uncooled photodetectors of visible and IR range. Cooling of IR sensors to operating temperature 230 K is provided by two-stage thermoelectric coolers (TEC), to 210 K – by three-stage TEC, to 190 K – by four-stage TEC. Characteristics of such TEC (maximum temperature difference ΔT_{max}, cooling capacity Q_{max}, voltage U_{max}, supply current I_{max}) that are stocked, for instance, for IR detectors of VIGO company, are listed in Table 1 [10].

Table 1

Characteristics of stage TEC for cooling IR detectors [10]

	2-stage TEC	3-stage TEC	4-stage TEC
$T_{detector}$, K	~ 230	~ 210	~ 195
Q_{max}, W	0.36	0.27	0.28
ΔT_{max}, K	92	114	125
U_{max}, V	1.3	3.6	8.3
I_{max}, A	1.2	0.45	0.5

Multi-stage modules are produced by various companies. Table 2 lists the characteristics of stage modules of leading companies. The modules are manufactured of conventional thermoelectric materials based on *Bi-Te* with a homogeneous distribution of impurity concentration in thermoelement legs.

Therefore, thermoelectric coolers nowadays provide cooling of IR sensors to 190 K. Such devices are small-size, mechanically stable, highly reliable with a life cycle up to 20 years. The main disadvantage of thermoelectric cooling is its low energy efficiency.

As was already mentioned, for IR detectors with the operating temperatures in the range of 70 to 150 K use is made of microcryogenic Stirling systems [3-5]. These are energy-efficient coolers. With cooling capacity in the range of 100 to 600 mW their coefficient of performance achieves the values of 10^{-2} to $3\cdot10^{-2}$.

At the same time, recent investigations have shown that introduction of current advanced technologies for IR detectors allows shifting the operating temperature of IR detector from the cryogenic region to the range of 150 to 200 K [8, 11-13]. In so doing, its threshold characteristics are not degraded. At the present time such temperatures can be achieved via thermoelectric cooling through use of new up-to-date approaches in the development and manufacture of stage thermoelectric modules.

One of such approaches is to use functionally graded thermoelectric materials (FGTM) for thermoelement legs [14]. These are materials with the optimal inhomogeneity of the main thermoelectric properties, namely thermoEMF α, electric conductivity σ and thermal conductivity κ.

The second approach is to use materials of improved efficiency in low-temperature region. An example of such materials can be *n*-type *Bi-Sb* alloys. These alloys have high thermoelectric figure of merit at temperatures below 160 K, which in addition increases in a magnetic field. The use of optimally inhomogeneous magnetic field further increases the efficiency of cooling modules of such materials [15].

Table 2

Characteristics of stage modules of leading companies

Company	Module	Number of stages	Module characteristics			
			ΔT_{max}, K	Q_{max}, W	U_{max}, V	I_{max}, A
Marlow Industries USA [marlow.com]	SP402-01AB	3	111	0.5	7.5	4.5
	NL3040	3	98	0.5	4.5	6.5
Ferrotec USA [ferrotec.com]	9530/119/045B	3	111	9.7	8.6	4.5
Thermion Ukraine [thermion-company.com]	3TMCO6-070-15	3	116	0.6	5.3	0.9
	4TMB04-099-C112	4	126	0.27	6.5	0.5
	5TMB06-113-B1224	5	130	0.57	6.4	1.2
	5TMB10-164-X1224	5	136	1.8	10.2	3.7
Komatsu Japan [kelk.co.jp]	K3MC011	3	114	6.2	7.5	5.1
	K4MB005	4	134	3.6	15.3	5.1
	K5MB002	5	145	1.5	14.7	4.8
RMT.ltd Russia [rmtltd.ru]	3MDS04	3	116	0.27	5.7	0.4
Laird Technologies USA [lairdtech.com]	MS3	3	118	3.6	6.5	6.5
	MS4	4	122	2.7	7.6	3.5
	MS5	5	123	2	14.5	1.6
Tellurex USA [tellurex.com]	M3	3	98	6.6	7.8	3.6
	M4	4	112	3.4	15	3
OJSC “OSTERM SPB” Russia [osterm.ru]	PE3	3	117	3	6.5	6.5
	PE4	4	125	3.75	7.8	5.4
	PE5	5	133	8	16	7.1

Table 3 lists the results of estimated characteristics of low-temperature stage thermoelectric modules assuring cooling to temperature below 200 K at a tempertaure of heat-releasing surface 300 K. Maximum coefficient of performance was calculated with regard to the above-mentioned approaches. The calculations employed computer methods developed on the basis of optimal control theory [14].

It was determined that to achieve the temperatures of 160 to 200 K it is sufficient to use three-four-stage modules whose thermoelements are made of *Bi-Te* FGTM. Such FGTM can be created by forming a respective inhomogeneous distribution of impurities in material or changing its composition.

For cooling down to temperatures of 150 to 120 K a four-stage module of *Bi-Te* FGTM should be supplemented with low-temperature stages. In these stages it is reasonable to use for *n*-type legs the alloys based on *Bi-Sb*. At room temperature the figure of merit Z in *n-BiSb* is about $0.8{\cdot}10^{-3}$ K^{-1}, at low temperatures Z increases, reaching $5{\cdot}10^{-3}$ K^{-1} at 100 K. Magnetic field further increases this value to $8 - 9{\cdot}10^{-3}$ K^{-1} [15]. In this case *n*-type *Bi-Sb* FGTM, i.e. material with the varying main thermoelectric parameters α, σ, κ, can be obtained by optimally changing the induction of a magnetic field where this material is placed. For further increase in the coefficient of performance one can use a combination of optimal inhomogeneity function of the field and optimal inhomogeneity of *Bi-Sb* material obtained by varying its composition [15]. Unfortunately, up to now in the arsenal of thermoelectricity there are no *p*-type materials with a similar magnetic field dependence of the figure of merit. Therefore, for *p*-type legs it is necessary to use FGTM based on traditional *Bi-Te* composition.

Table 3

Estimated values of low-temperature TEC characteristics

Cooling temperature T_c, K	Number of stages	Coefficient of performance, ε_{max}	Power at thermal load Q_0 = 10 mW, W, W	TEC material
200	3	$4\cdot10^{-2}$	0.25	*Bi-Te* FGTM
190	3	$2.5\cdot10^{-2}$	0.4	*Bi-Te* FGTM
180	4	$1.2\cdot10^{-2}$	0.83	*Bi-Te* FGTM
170	4	$5\cdot10^{-3}$	2.0	*Bi-Te* FGTM
160	4	$2\cdot10^{-3}$	5.0	*Bi-Te* FGTM
150	5	$8\cdot10^{-4}$	12.0	4 stages – *Bi-Te* FGTM, 1 upper stage – *n-BiSb* in the inhomogeneous magnetic field, *p-BiTe* FGTM
140	6	$3\cdot10^{-4}$	33.5	4 stages – *Bi-Te* FGTM, 2 upper stages – *n-BiSb* in the inhomogeneous magnetic field, *p-BiTe* FGTM
130	7	$1.8\cdot10^{-4}$	50.0	4 stages – *Bi-Te* FGTM, 3 upper stages – *n-BiSb* of nonuniform composition, in the inhomogeneous magnetic field, *p-BiTe* FGTM
120	7	$6\cdot10^{-5}$	170.0	4 stages – *Bi-Te* FGTM, 3 upper stages – *n-BiSb* of nonuniform composition, in the inhomogeneous magnetic field, *p-BiTe* FGTM
110	8	$1.4\cdot10^{-5}$	710.0	4 stages – *Bi-Te* FGTM, 4 upper stages – *n-BiSb* of nonuniform composition, in the inhomogeneous magnetic field, *p-BiTe* FGTM
100	9	$2.4\cdot10^{-6}$	4160	4 stages – *Bi-Te* FGTM, 5 upper stages – *n-BiSb* of nonuniform composition, in the inhomogeneous magnetic field, *p-BiTe* FGTM

Conclusions

The results of this research testify that practical use of modern technologies in the manufacture of modules allows expanding the temperature range of thermoelectric method of cooling IR sensors and can assure the operating temperatures of IR detectors up to 120 K with sufficient energy efficiency.

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