CASCADE MODULES FOR THERMOELECTRIC CONVERTERS OF ENERGY

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ABSTRACT

Low-power thermoelectric Peltier modules allowing to reduce the temperature of a heat-absorbing surface down to ~240-195 K at an ambient temperature ~293 K have been developed.

Keywords: thermoelectric converter, Peltier modules, solid solution, thermoelement, quality factor.

I. INTRODUCTION

Thermoelectric converters of energy have found wide application in various areas of technique. Especially during last years thermoelectric coolers are applied in photoelectronics to lowering of the temperature of photocells in photoreceiving devices. This is promoted by aspiration to increase operating temperatures of the cooled photodetectors [1, 2].

Thermoelectric refrigerating devices at cold junction temperature not lower ~ 200 K are characterized by high values of efficiency, small weight, cheapness and reliability. Thus, the technologies providing durability of evacuated thermoelectric coolers up to ~ 10 years have been already mastered. However, traditional design, assembly technology, thermoelectric materials used in fabrication of the thermoelectric coolers have a number of shortages that results in increase of their cost price.

On traditional manufacturing techniques of multi-cascade or many-stage thermoelectric coolers with consecutive connection of cascades one-cascade module for each cascade are made separately. Then on the basis of these modules multi-cascade thermoelectric batteries are assembled. At such technology and design inter-cascade ceramic heat junctions and soldered joints in battery create additional thermal resistance and loadings that bring to reduction of refrigerating factor of the thermoelectric battery, increase in power consumption and the time of reaching an operating mode, as well as increase in the cost price of the battery.

II. EXPERIMENTAL RESULTS

In the technology developed by us these shortages are eliminated by assembly of the module in a uniform operating cycle. Thus in four cascade thermoelectric module the top ceramic heat-junction (the heat-absorbing surface) of the second cascade is simultaneously bottom (heat-sink) heat-junction of the first cascade, bottom heat-junction of the second cascade is top heat-junction of the third cascade and bottom heat-junction of the third cascade is top heat-junction the fourth cascade. Thus, a design is considerably simplified and thermal parameters of the module are improved. In our design ceramic heat-junctions from beryllium oxide (BeO) and alumina (Al_2O_3) of ~ 0,7-1,0 mm thickness have been used.

As the thermoelectric material developed by us extruded samples of *n*-$Bi_2Te_{2.7}Se_{0.3}$, *p*-$Bi_{0.5}Sb_{1.5}Te_3$ and *n*-$Bi_{0.85}Sb_{0.15}$ solid solutions with the grain sizes of 1000, 315 and 630 μm accordingly were used. These materials possess close to single crystal samples thermoelectric quality factor Z [3-4]. At the same time their mechanical durability a few times exceeds mechanical durability of a single crystal material that results in significant growth of yield of the thermoelements suitable for assembly of thermomodules. The increased mechanical durability of the extruded material provides also higher reliability of thermoelectric modules and devices on their basis.

Extruded bars of the solid solutions have been received in the following technological sequence: synthesis of a solid solution from initial components; pulverization of the synthesized material and selection of fractions with the corresponding dimensions; fabrication from the selected fraction by a method of cold pressing the briquettes of 30 mm in diameter; extrusion, i.e. passing heated up to a plastic condition briquettes through an mesh in diameter of 6 mm. Pressing of the briquettes was conducted at room temperature and pressure ~ 4 tonne/sm^2.

Technological parameters of the extrusion were the following:

For the solid solution $Bi_{0.5}Sb_{1.5}Te_3$: the extrusion temperature $T_e \approx 663$ K; the extrusion pressure $P_e \approx 8$ tonne/sm^2.

For the solid solution $Bi_2Te_{2.7}Se_{0.3}$: the extrusion temperature $T_e \approx 653$ K; the extrusion pressure $P_e \approx 9$ tonne/sm^2.

For the solid solution $Bi_{0.85}Sb_{0.15}$: the extrusion temperature $T_e \approx 475$ K; the extrusion pressure $P_e \approx 4{,}8$

tonne/sm^2.

The extruded materials have passed annealing at ~ 600 K (for chalcogenides) and 500 K (for $Bi_{0.85}Sb_{0.15}$) during 2 hours.

From the extruded bars in spark cutting installation branches of thermoelements was cutted.

At cutting the bars for branches of thermoelements a broken layer of 5-15 μm thickness is created on cutting surface [5], bringing to significant deterioration of their quality factor [6]. For removal this broken layer the surfaces of branches were processed by electrochemical etching on special installation in solution NaOH + $C_4H_6O_6$ + H_2O for branches on the basis $Bi_2Te_{2.7}Se_{0.3}$ and KOH + $C_4H_6O_6$ + H_2O for branches on the basis of $Bi_{0.5}Sb_{1.5}Te_3$ and $Bi_{0.85}Sb_{0.15}$. A time of electrochemical etching was 20÷25 s, density of the current passing through the sample was 0,5 A/sm^2.

Commutation of thermoelements was carried out by an alloy of composition: mass %: 57 Bi + 43 Sn with melting temperature ~ 413 K. At appropriate technologies of commutation with the specified alloy transition resistance of contacts and adhesion work have values 10^{-5}÷10^{-6} Ohm·cm^2 and 700-800 mC/m^2 accordingly.

Efficiency of the solid solutions on the basis of bismuth telluride has strongly pronounced temperature dependence and possesses the greatest value in an interval of temperatures 290-300 K. And though a maximum of quality factor for both hole and electronic compositions is possible to shift to lower temperatures, its absolute value falls with reduction of the temperature [7]. In the operating mode of cascade Peltier modules branches of thermoelements of various cascades are in various temperatures. Therefore when developing and manufacturing multi-cascade thermoelectric coolers it is necessary to make cascade optimization of parameters of branches of thermoelements. Experiments have shown that in 150-330 K temperature interval optimum parameters for thermoelectric extruded materials on the basis of the solid solutions p-$Bi_{0.5}Sb_{1.5}Te_3$ and n-$Bi_2Te_{2.7}Se_{0.3}$ correspond to values at ~ 300 K presented in Table 1.

Table 1

Cascade optimization of parameters of thermoelectric materials

Number of cascades	Operating temperature intervals, K	Type of the conductivity	Parameters at 300K	
			σ, $Ohm^{-1}\cdot cm^{-1}$	α, μV/K
I	330-230	p-$Bi_{0.5}Sb_{1.5}Te_3$	1000±100	210±10
		n-$Bi_2Te_{2.7}Se_{0.3}$	900±100	210±10
II	250-170	p-$Bi_{0.5}Sb_{1.5}Te_3$	700±100	225±10
		n-$Bi_2Te_{2.7}Se_{0.3}$	70±100	230±10
III, IV	200-150	p-$Bi_{0.5}Sb_{1.5}Te_3$	650±50	235±5
	55	n-$Bi_2Te_{2.7}Se_{0.3}$	550±50	245±5

Optimum parameters of branches on the basis of the extruded samples of n-$Bi_{0.8.5}Sb_{0.15}$ solid solution were determined experimentally from temperature dependence of their thermoelectric properties.

At designing Peltier modules theoretical conclusions and the formulas given elsewhere [8, 9] were used.

The optimum ratio of the dimensions of branches of each cascade was determined on the basis of expressions [8]:

$$\left(\frac{l}{S_t}\right)_n\left(\frac{l}{S_t}\right)_p=\sqrt{\frac{\sigma_n\chi_n}{\sigma_p\chi_p}}\;;\quad\left(\frac{l}{S_t}\right)_{opt}=I\sqrt{2\sigma\chi\Delta T}$$

where l_n, l_p, S_n, S_p, σ_n, σ_p, χ_n, χ_p the length, cross-section, specific electrical conductivity and heat conductivity factor of n-and p-branches accordingly, I - current strength, ΔT – temperature drop. Here temperature dependence of the specified parameters also was taken into account.

Influence of values of heat conductivity factor of ceramic heat-junctions on minimal temperature of the heat-absorbing surface of modules on the example of heat-junctions from beryllium oxide (BeO) and alumina (Al_2O_3) has been investigated. Specific heat conductivity of ceramic plates from BeO and Al_2O_3 are accordingly 2.10 and 0.34 W/m·K at ~ 300K [10, 11]. It is seen that heat conductivity of BeO is ~ 7 times higher than heat conductivity of Al_2O_3 and is close to heat conductivity of steel and lead. Specific resistance of BeO and Al_2O_3 at 300K equals ~ 10^{14} Ohm·cm [10, 11]. It is found out that in the case of two, three and four-cascade modules application of BeO heat-junctions the temperature of heat-absorbing surface T_a by 3÷5 K lower than in the case of using Al_2O_3 heat transitions.

Dependences of T_a for modules on the ambient temperature (from 293 to 375 K), pressure in operating volume (volume where thermo-battery is placed), current strength, time (from the moment of switch-on of the thermo-battery's supply current) and thermal loading on a heat-absorbing surface have been investigated. These studies have enabled us to determine: optimum supply current strength of the module (current strength at which T_a of the module in a stationary mode is minimal), time for reaching an operating mode (time required for achievement T_a a value of temperature of this surface under operating in stationary mode), real refrigerating capacity (cold productivity) of the module, as well as the maximal operating ambient temperature and the maximal pressure of air in operating volume at which T_a remains in limits of minimally achievable temperature. Studies of parameters of modules were carried out under conditions in which heat sink from heat releasing surfaces is realized by natural convective heat transfer to an environment.

Basic parameters of the developed thermoelectric Peltier modules are presented in Table 2.

Table 2

Basic parameters of thermoelectric modules at the ambient temperature ~ 293 K

Number of cascades	Voltage supply, V	Power consumption, W	Minimal temperature of the heat absorbing surface, K	Refrigerating capacity, W	Time of achieving of the minimal temperature, s	Area of the heat absorbing surface, mm^2
1	4.0	14	250	2.5	40	32×24
1	1.3	2.7	241	0.8	30	10 ×10
1	0.45	0.9	239	0.2	25	7×7
2	0.65	1.3	220	0.12	45	3×4
3	2.1	4.2	205	0.10	70	4×4
4	6.0	6.0	195	0.08-0.1	90	4×7

Depending on supply current strength and its direction the temperature of a heat-absorbing surface of modules can change in an interval 195-375K with accuracy ± 0.3 K (Fig. 1).

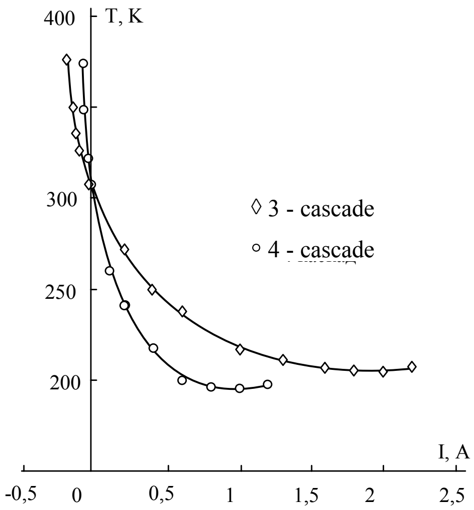

Fig. 1. Temperature of a heat-absorbing surface on supply current strength

The developed modules can be applied in thermoelectric coolers for photodetectors, also as devices of physical experiment at studies of temperature dependence of thermoelectric, photo-electric, optical and other parameters of various objects (crystals, radioelements, photo-cells, etc.) in 195-375K of temperature interval. The specified one-cascade modules can be used also as thermoelectric Zeebek batteries for direct transformation of thermal energy in electric one.

III. CONCLUSION

Thus, low-power thermoelectric Peltier modules allowing to reduce the temperature of a heat-absorbing surface down to ~240-195 K at an ambient temperature ~293 K have been developed.

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