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FABRICATION, TREATMENT, AND TESTING OF MATERIALS AND STRUCTURES

Thermophotovoltaic Generators Based on Gallium Antimonide

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Abstract—Designs of thermophotovoltaic (TPV) generators with infrared emitters heated by concentrated solar radiation are developed, fabricated, and tested. Emitters made of SiC, W, or Ta of various forms and sizes are studied. To the GaSb-based thermophotovoltaic cells, the efficiency of transformation of thermal radiation of W emitters was 19%. The features of operation of two variants of TPV generators, namely, of cylindrical and conical types, are considered. In a demonstration model of the TPV generator consisting of 12 photocells, the output electric power with conversion of the concentrated solar radiation was $P = 3.8$ W.

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1. INTRODUCTION

Starting from the development in the 1990s of first narrow-gap GaSb-based photoconverters for the use in thermophotovoltaic (TPV) generators, repeated attempts were made to increase the efficiency of such systems with the aim to use them as the source of electric power. The improvement of technology of the GaSb-based photocells [1–5], the development and fabrication of narrow-gap alloy-based photoconverters, and the studies in the region of obtaining high-temperature emitters have led to the development of autonomous low-power TPV generators. However, their efficiency remains low today [6, 7]. The principles, on which the design of such conventional fuel thermophotovoltaic generators is based, are successfully used in the development of TPV systems operating with the use of the concentrated solar radiation [6, 8]. Theoretical calculations and experimental data [7–9] show that the efficiency of photoconverters at a level of ~25–30% ($E_g \sim 0.7$ eV) is attainable in the TPV systems. Specifically, as the degree of concentration of the solar radiation from $K_c = 1000$ to $K_c = 16000$ and the emitter temperature increases from 1400 to 2000 K, the efficiency of the GaSb-based thermophotovoltaic converters increases from 18 to 33% [9].

In this study, two variants of the design of the TPV systems (of conical and cylindrical type) based on photocells obtained by diffusion of Zn into GaSb were considered. The thermophotovoltaic generator of the conical type is developed for the operation with the concentrated solar radiation. The mounted and tested fragment of the cylindrical TPV system consists of 12 photocells. This generator can be used both in the daytime upon heating with the concentrated solar radiation and round-the-clock upon combustion of the fuel.

In the developed test models of the TPV generators, the broad-band emitters based on SiC or refractory metals were used since they have longer service life compared with selective emitters, which rapidly degrade at high radiation densities, while the emitter design is simpler and less laborious to fabricate. Emitters of various configurations were used.

2. EFFICIENCY OF THE TPV CELL

The radiation of emitters heated by the concentrated solar radiation [8, 9] or by a gas burner was converted by the GaSb-based thermophotovoltaic cells. The device structure was formed by diffusion of Zn from the gas phase into the GaSb substrate [10]. The area of photocells was 10×10 mm^2.

Figure 1 shows the dependence of efficiency for measured values of the photocurrent density, fill factor, and open-circuit voltage of the TPV cells under the W emitter in a temperature range of 1600–2000 K. As follows from the presented curve, upon heating the emitter to 1900–2000 K, the conversion efficiency is 19%. For the spectral range of the emitter $\lambda = 400$–1820 nm and on the assumption of 100% return of sub-band photons to the emitter, the calculated efficiency of the GaSb-based photocell is as high as 27%.

3. DESIGN AND FABRICATION OF THERMOPHOTOVOLTAIC GENERATORS

Figure 2 shows the overview of the developed TPV generators consisting of an emitter, module of photoconverters, and concentrator system (or system of supply of gas fuel not shown in Fig. 2). In a conical system, mounting of the cylindrical or planar emitter is possible (Figs. 2a, 2b), while in the photovoltaic module, the quadratic method of mounting of four photo-

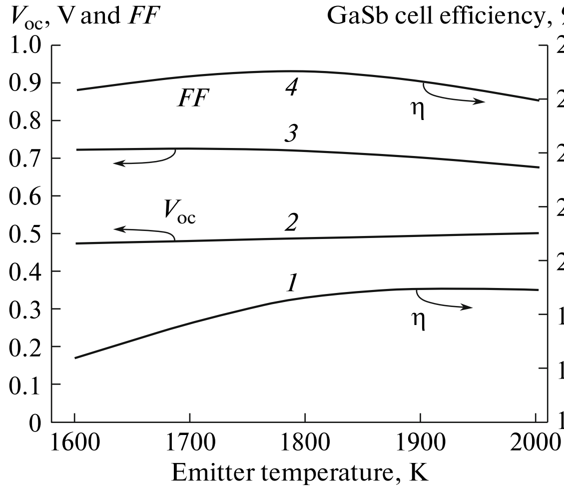

Fig. 1. Dependences of efficiency (curves *1*, *4*), V_{oc} (curve *2*), and fill factor *FF* (curve *3*) of the *I*–*V* characteristic on the temperature of the W emitter for the GaSb-based photocells. The efficiency is calculated for the following conditions: (curve *1*) the entire spectrum of the emitter and (curve *4*) the spectrum in the range λ = 400–1820 nm.

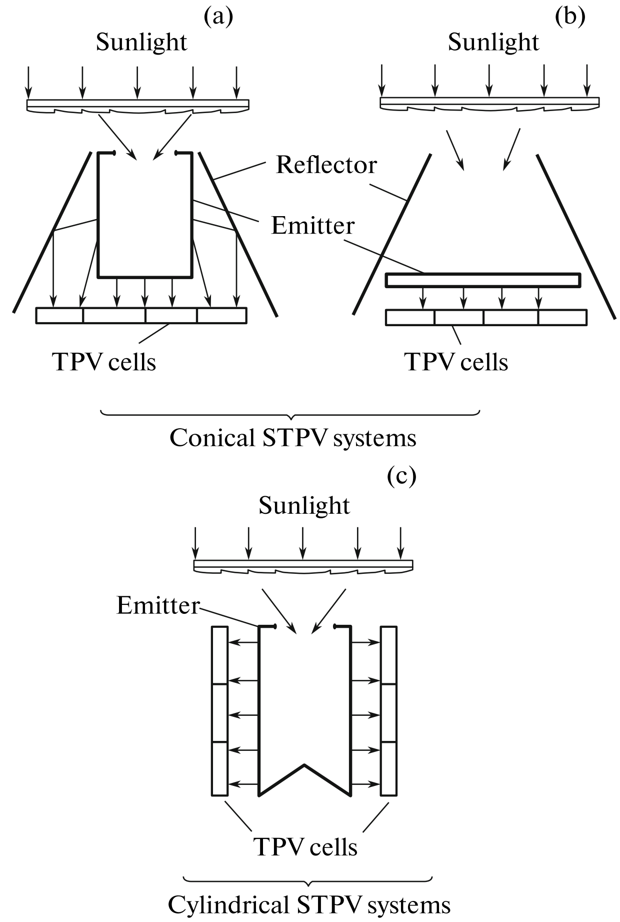

Fig. 2. Schematic representation of experimental thermophotovoltaic systems of various types.

cells is provided. In the cylindrical-type TPV generator (Fig. 2c), the module consisting of 24 photoconverters is composed of autonomous units (in such assemblies, photocells are mounted in threes in a linear array), which are positioned around the emitter.

The conical-type generator is simpler from the point of view of mounting and adjustment, since it includes a considerably smaller amount of photocells. In this system, a mirror reflector of thermal radiation formed on an inner conical surface of the module is provided. The generator design provides the use of a planar emitter, the shape of which is convenient from the technological point of view at the stage of preliminary experiments, for example, in the selection of the emitter materials or increasing its selectivity (planar surface simplifies the performance of processes of photolithography, deposition of selectively emitting oxide films, etc). An additional advantage of the conical-type system is larger freedom in selection of the circuit of electrical connection (in series, in parallel, and in combination) of photocells.

In the cylindrical design, due to the larger amount of photoconverters, the possibility is provided for obtaining a larger output power. The modules of this type are more convenient for the development of hybrid TPV systems operating in the solar–fuel mode. A definite advantage of the cylindrical generator is the possibility of the use of two methods of cooling: air and water (in the conical system, only water cooling is used). The air method of cooling is more economical and relatively simple. However, from the point of view of the efficiency of the heat sink and prevention of overheating of the linear array of TPV converters, the water cooling seems to be more convenient, especially upon heating the emitter to high temperatures.

To attain the maximum efficiency of TPV systems, the design of an emitter with optimal parameters (high thermal conductivity and mechanical stability in the specified working temperature range, selectivity of the emission spectrum and its consistency with the photodetector spectrum, stability to thermal shocks, etc), as well as by shape and size, is an important problem. At high radiation densities, selective emitters are destroyed in most cases; therefore, in the developed prototypes of the solar TPV systems, W, Ta, and SiC broad-band emitters of different design and sizes were used. To avoid contact with air and subsequent oxidation, emitters made of refractory metals were placed either in vacuum or in an atmosphere of inert gases (argon or xenon).

4. FABRICATION OF TPV MODULES

Solder pastes based on the PbSnAg alloy (the melting point T_m = 180°C) and based on bismuth (T_m = 130°C) were used for cells mounting. As the heat sink,

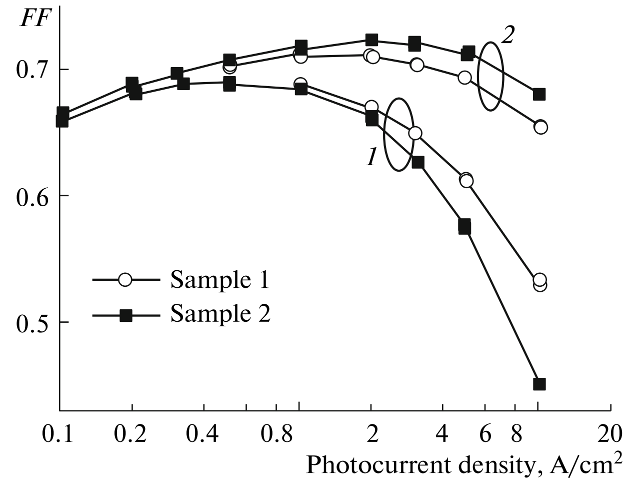

Fig. 3. Dependences of the fill factor of the *I–V* characteristics on the photocurrent density for two GaSb-based cells before (curves *1*) and after (curves *2*) soldering with the use of a high-temperature solder paste (T_m = 180°C). The area of the photocells is 3.5 × 3.5 mm^2.

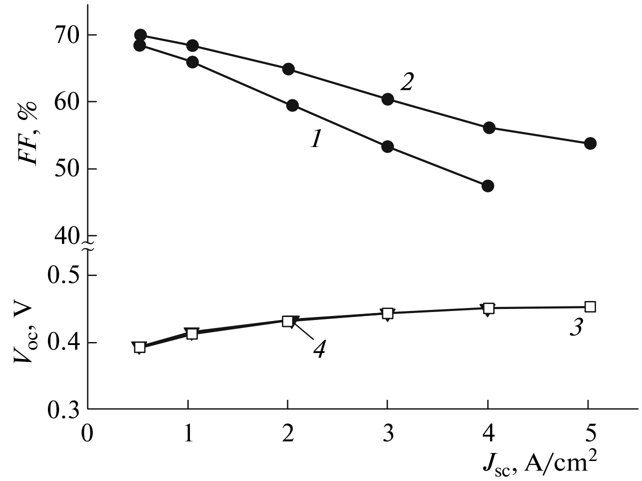

Fig. 4. Dependences of the fill factor of the *I–V* characteristics (curves *1*, *2*) and open-circuit voltage (curves *3*, *4*) on the photocurrent density for the GaSb-based cell before (curves *1*, *3*) and after (curves *2*, *4*) soldering with the use of the low-temperature solder paste (T_m = 120°C). The area of photocells is 10 × 10 mm.

we used Cu plates 2 mm thick. The following demands are usually imposed on the solder paste: the temperature mode of soldering should provide reliable contact and not worsen the electrical characteristics of photoconverters, and soldered joints should not degrade during the entire service life. The main criterion of the quality of mounting is output of suitable photocells and ability of photoconverters to endure the thermal mode of generator operation.

The solder paste based on the PbSnAg alloy was previously used for soldering the GaAs-based photoconverters. The GaSb-based photoconverters are more sensitive to high temperatures; therefore, with the use of the recommended temperature–time mounting mode, noticeable degradation of photocells was observed. During shortening of the time of high-temperature treatment in the course of mounting of the cells with respect to the mode recommended by producers, no noticeable worsening of output characteristics of photocells took place. Figure 3 shows the dependences of the fill factor (*FF*) of the current–voltage (*I–V*) characteristic on the photocurrent density for two photocells 3.5 × 3.5 mm in size before (curves *1*) and after (curves *2*) soldering with the use of the high-temperature paste. Large values of *FF* at current densities as high as 10 A/cm^2 (Fig. 3) indicate that, after mounting, the electrical connections had a rather low resistance. Curves *1* and *2* almost coincide at low current densities (up to 0.5 A/cm^2), which indicates that the selected temperature mode of soldering is optimal. At higher current densities (above 0.5 A/cm^2), an increase in *FF* of soldered cells compared with unsoldered cells is observed; we believe that this is due to improvement of the quality of the contact. The open-circuit voltage of the photocells at current densities from 0.1 to 10 A/cm^2 before and after mounting remained constant. However, yield with the rapid soldering mode was 60–70%; therefore, study of mounting of the photocells with the bismuth-based paste was performed (the use of solder pastes with lower values of T_m is not suitable because of the risk of melting of the solder during use of the TPV system).

The samples with the area of 10 × 10 mm were investigated. Evaluation of the quality of electrical connections was also performed under pulsed illumination in this case (Fig. 4). Upon increasing the photocurrent density, the filling factor of the *I–V* characteristic of the soldered cell drops noticeably less compared with the sample before mounting. This behavior can be probably attributed to a decrease in the contact resistance after soldering. As is evident from Fig. 4, mounting of photocells with the use of the bismuth-based paste (T_m = 120°C), as well as the use of the high-temperature solder, does not lead to a variation in the open-circuit voltage. In the course of mounting with the use of the low-temperature paste in the temperature–time mode recommended by the producer, the output of suitable photocells was 90–95%.

5. THE CONICAL-TYPE TPV SYSTEM

For the designs of TPV generators shown in Fig. 2, the maximum photocurrent density (J_{sc} = 4.5 A/cm^2 at V_{oc} = 0.48 V and *FF* = 65%) was experimentally obtained for the photocell in the conical-type system under irradiation of a planar SiC-based emitter. The appearance of the conical-type TPV generator with a cylindrical and a planar emitter is shown in Figs. 5a and 5b, respectively. Since the planar emitter provided

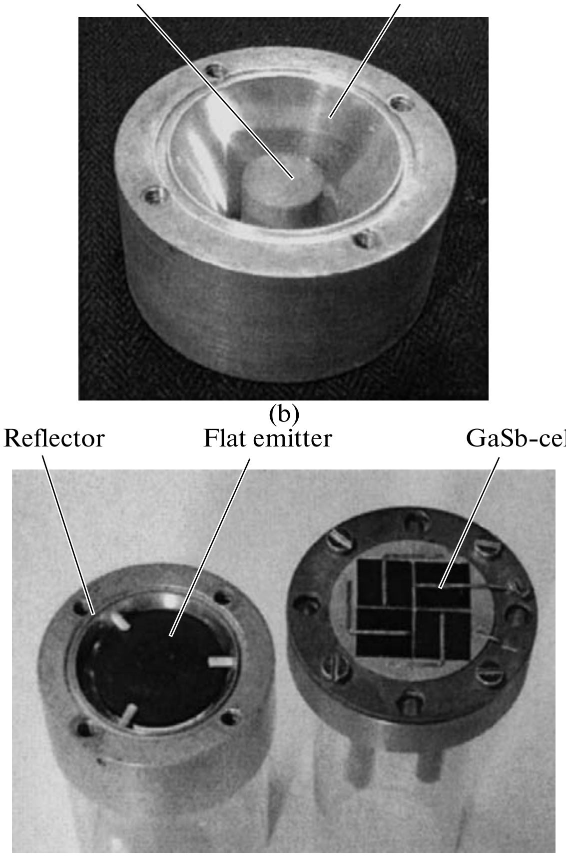

Fig. 5. Conical-type TPV generator (a, b) with cylindrical (W) and plane (SiC) emitter and (c) with four connected in series GaSb-based cells 10 × 10 mm in size each.

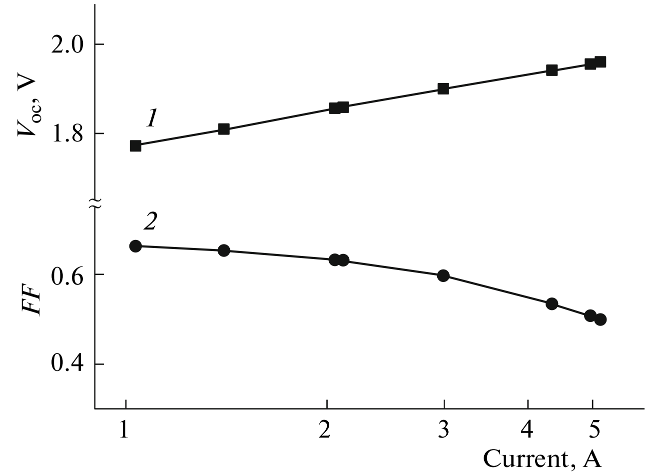

Fig. 6. Photocurrent dependences of the open-circuit voltage V_{oc} (curve *1*) and the fill factor of the *I*–*V* characteristic (curve *2*) for the module consisting of four GaSb-based cells connected in series. Measurements are performed under the pulsed illumination.

larger values of J_{sc} and output power, in the most of experiments, the emitter shaped as a disc made of SiC or W 28 mm in diameter and 2 mm thick was used.

In a conical system, the emitter was placed into a mirror cone and mounted over a module consisting of four sequentially connected photocells (Fig. 5c). The cells were mounted on a BeO ceramic plate preliminarily soldered to a Cu base. The choice of the BeO ceramics as an electrically insulating base is caused by high thermal conductivity of this material (240–260 W/(m K), which exceeds the thermal conductivity of ceramic insulators made of Al_2O_3 (18–30 W/(m K) or of AlN (180 W/(m K). Another advantage of BeO is a good match by the linear expansion coefficient to GaSb ($\alpha_{GaSb} = 7.75 \times 10^{-6}$ K^{-1}, $\alpha_{BeO} = 7.2$–8.0×10^{-6} K^{-1} at 293–673 K).

Table 1. Parameters of the module consisting of four GaSb-based TPV cells

	I_{sc}, mA	V_{oc}, V	*FF*, %
Cell no. 1	1032	0.449	63.68
Cell no. 2	1040	0.445	64.32
Cell no. 3	1078	0.443	64.06
Cell no. 4	976	0.404	64.01
Module consisting of four cells	1046	1.782	66.27

In Table 1, the characteristics of separate photocells of the module and assembly of four converters with their connection in series are listed. The variation in the parameters of the module (fill factor of the *I*–*V* characteristic and open-circuit voltage) with increasing values of the photocurrent is shown in Fig. 6. As the intensity of illumination increases, the fill factor of the load characteristic of the module varies insignificantly (from 66 to 63%) in the range of photocurrents up to 2 A. The further increase in the photocurrent leads to a decrease in the *FF* to 55% at 5 A. Therefore, for the developed TPV cells, the operational conditions are optimal, at which the value of the generated photocurrent does not exceed 2 A.

6. THE CYLINDRICAL-TYPE TPV SYSTEM

For the cylindrical-type TPV system, linear arrays of three GaSb photocells soldered in the row and connected in parallel were fabricated (Fig. 7a) and characteristics of such autonomous units were studied. Parallel connection of photoconverters is necessary for the compensation of luminous fluxes (especially in the solar TPV system) when the length of the linear array of photocells exceeds the emitter length. In the complete variant of the TPV module, a section assembly consisting of eight separate units surrounding the emitter is assumed (Fig. 7b) and arranged in parallel to the unit axis. Such an assembly simplifies the process of mounting a large number of photocells and makes it

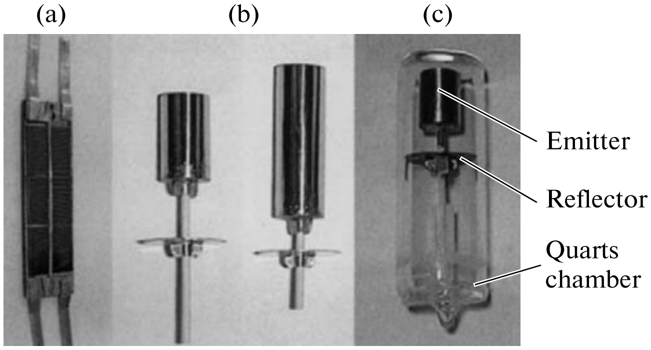

Fig. 7. (a) Linear array consisting of three parallel connected GaSb-based photocells mounted (b, c) along the W cylindrical emitter.

possible to replace the units if necessary, while their total number provides a proportional increase in the heat and electrical power of the entire system.

For the connection in series of separate linear arrays of photoconverters, the use of electrical insulating materials with high thermal conductivity is required. From this point of view, the BeO ceramics possesses the best properties. The influence of the material and thickness of the ceramic on heating of the photocell with the SiC-based emitter were studied (Fig. 8). The photocell was soldered to the ceramic substrate, which was mounted on a cooled Cu base using the solder paste (Fig. 8, see inset). The SiC-based emitter arranged at a distance of 4–5 mm from the cell was heated with the electric current to 1000–1600°C. The tests were performed for ceramic materials with strongly differing values of thermal conductivity, namely, BeO (0.5 mm thick) and Al_2O_3 (0.5 and 1 mm thick). The temperature of heating was determined from variation in the angle of slope of the *I–V* characteristic of the GaSb-based photocell in realistic exploitation conditions of the TPV system compared with the angle of slope of the *I–V* characteristic of the photocell measured under the pulsed illumination at room temperature.

As follows from Fig. 8, at high temperatures, an increase in the values of V_{oc} compared with the measurements under the pulsed illumination is observed. From here, it follows that, at high current densities (~4 A), overheating of the cell does not exceed 30–40°C on average (V_{oc} decreases almost linearly as the temperature is lowered and exhibits a rate of 1.5–1.65 mV/°C [11]). For usual operation modes of the TPV cells, their overheating with respect to room temperature is ~17–25°C; it rather weakly (4–5°C) depends on the material and thickness of the ceramics. For the photocells soldered to the Cu base without ceramic insulation and with the Al_2O_3 ceramics 1 mm thick, we fixed the maximum difference in overheating temperatures (~10°C) was registered.

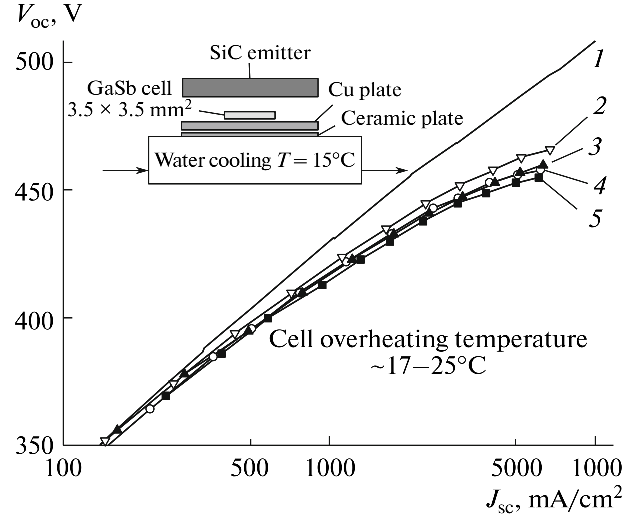

Fig. 8. Study of various ceramic substrates. Measurements under the pulsed illumination (curve *1*), $T = 25$°C, measurements under SiC; (curve *2*) Cu; (curve *3*) BeO 0.5 mm thick; (curve *4*) Al_2O_3 0.5 mm thick; and (curve *5*) Al_2O_3 1.0 mm thick.

The presented results show that fairly high-cost and highly toxic BeO ceramics have no obvious advantages over lower-cost and safe insulating materials Al_2O_3 or AlN (thermal conductivity of the latter is higher than that of Al_2O_3). Taking into account the complexity of the operation with highly toxic BeO ceramics, in the developed TPV system, the Al_2O_3 substrates 0.5 mm thick were used.

6.1. Emitters for a Cylindrical System

In the solar cylindrical TPV system, cylindrical emitters with a sealed bottom (Figs. 7b, 7c) of various sizes were used. The additional improvement of the emitter design is the mounting of a W reflector with the deposited Au or TiN layer ~1 μm thick under the bottom of the cylinder (Figs. 7b, 7c). The reflector is used for the return of the radiation not entering the photoconverters to the emitter. This return should lead to an increase in the emitter temperature and to an increase in the efficiency of the TPV conversion of solar radiation in general due to a decrease in heat energy losses. The Ta or W emitters and reflectors were mounted on a ceramic Al_2O_3 rod. Since the emitter was heated to high temperatures, whereas the refractory metals rapidly oxidize upon heating in air, it was placed into a protective chamber in vacuum or into the atmosphere of inert gases (Fig. 7c). The protective chamber was made of refractory quartz glass and had an outer diameter of 24 mm, inner diameter of 20 mm, and height of 62 mm.

Cylindrical emitters with a wall 0.05 mm thick, 12 mm in diameter, and with a variable length (15, 22, 25, 30, 35, and 45 mm) were studied. The cylindrical

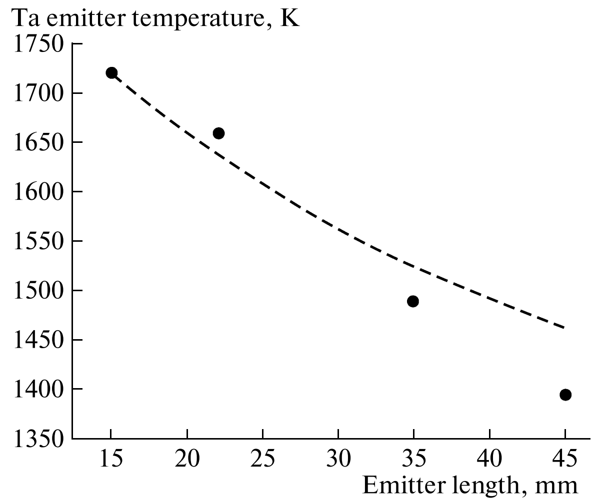

Fig. 9. Temperature of the Ta emitter against its length (emitter diameter is 12 mm). The points are the experimental values (the solar radiation is concentrated by the Fresnel lens with an area of 0.6×0.6 m^2), the dashed line corresponds to the calculated data).

shape of the emitter is necessary to increase the absorption of solar energy, which increases, according to calculations, by a factor of 2–3 compared with a planar emitter. The choice of diameter (10–12 mm) is determined by the parameters of the concentration system that collects 75–80% of the incident radiation. The use of the emitter with a larger diameter leads to a decrease in its efficiency and lowering the absorption ability of the emitter, which manifests itself in a decrease in its working temperature. For cylinders of a smaller diameter, the efficiency of collection of solar radiation worsens, which also worsens the parameters of the system. The emitter length also affects its characteristics, such as efficiency (increases as the length increases), temperature (increases for relatively short emitters (Fig. 9): an increase in temperature provides the better match to the band gap of the photocell), and radiation pattern (longer emitters provide higher uniformity of emission of heat energy).

Table 2. Parameters of the assembly consisting of three GaSb-based TPV cells

	I_{sc}, mA	V_{oc}, V	*FF*, %
Cell no. 1	1	0.456	63
Cell no. 2	1	0.456	63
Cell no. 3	1	0.456	64
Linear array consisting of three cells (under pulsed illumination)	3	0.456	69
Linear array consisting of three cells (under radiation of a halogen lamp)	2.7	0.447	65

Calculations performed according to the theory of emitting voids [12, 13] showed that the efficiency of absorption of solar radiation for such W emitters 10–12 mm in diameter and 20–30 mm in length is 60–70% and depends on the length/diameter ratio.

Figure 9 shows the experimental values (points) and calculated data (dashed curve) for the temperature of the Ta emitter in relation to its length (intensity of solar radiation of 800 W/m^2). Tantalum has an emission spectrum close to that of W, and it was selected due to its simpler mechanical treatment. The temperature was monitored using a pyrometer. All emitters were 12 mm in diameter. It follows from the comparison of the theoretical and experimental data that long emitters have a lower temperature than follows from the calculations. This may be associated with an increase in convective losses upon increasing of the emitter surface, which was not taken into account in calculations.

6.2. Study of the Assembly Consisting of Three Photoconverters for the TPV System

The characteristics of the cells before and after mounting in the linear array of three parallel connected photoconverters are listed in Table 2. In laboratory conditions, the measurements were performed under illumination with the pulsed flash lamp (T = 25°C) and halogen lamp (150 W) mounted along the axis of the system.

The results of the study of the linear array of three parallel connected GaSb-based photocells under pulsed illumination (curves *1*, *2*) and under irradiation with a halogen lamp (curves *3*, *4*) are shown in Fig. 10. As the photocurrent increased from 1.5 to 4 A, the fill factor of the load characteristic of the assembly decreased (curve *3*), which is associated with heating of elements and nonuniformity of their illumination in different parts of the linear array.

The experiments showed that, with the use of the Wemitter 15 mm in length, pronounced nonuniformity of thermal radiation falling on the photocells arranged in different parts of the assembly emerges. This phenomenon leads to a certain decrease in the short-circuit current and in the fill factor of the TPV unit.

Table 3. Short-circuit current density of three TPV cells mounted in a row along the W emitter 25 or 30 mm in length

Cell no.	I_{sc}, A (emitter 30 mm, density of the solar radiation flux of 830 W/m^2)	I_{sc}, A (emitter 25 mm, density of the solar radiation flux of 710 W/m^2)
1	0.94	1.13
2	1.31	1.42
3	0.96	1.01

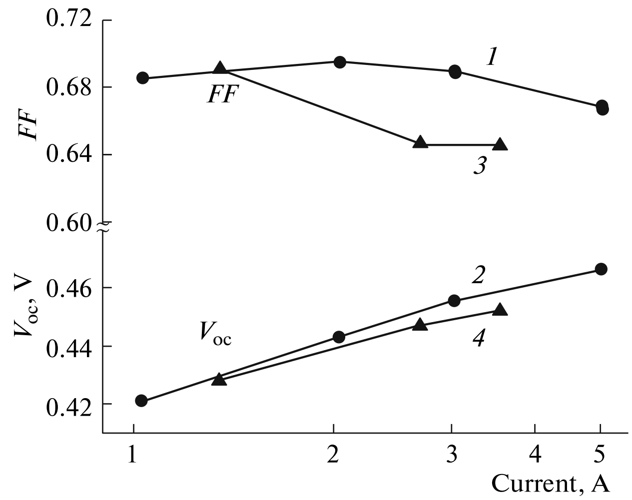

Fig. 10. Photocurrent dependences of the fill factor of the *I*–*V* characteristic and open-circuit voltage for the linear array consisting of three cells under various illumination conditions: curves (*1*, *2*) correspond to the measurements under the pulsed illumination and curves (*3*, *4*) correspond to measurements under the radiation of the halogen lamp.

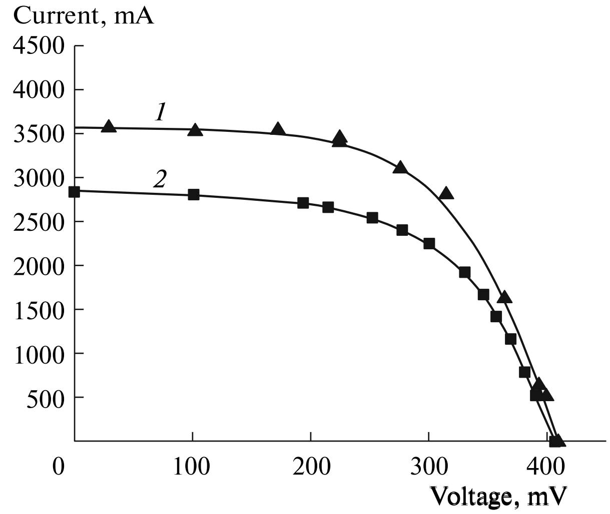

Fig. 11. Load characteristics of the linear array consisting of three parallel connected GaSb-based cells under irradiation of W emitters (curve *1*), 22 mm in length; and (curve *2*) Ta emitters, 25 mm in length. The diameter of emitters is 12 mm.

The TPV assemblies consisting of three photoconverters with the use of W emitters 20–25 mm in length had the highest output power (Fig. 11). The results of measurements of the short-circuit current for the linear array of three cells mounted along an emitter 25 or 30 mm in length are listed in Table 3. It follows from the presented data that I_{sc} with mounting of the emitter 30 mm in length is by 10% lower than for the emitter 25 mm in length despite the higher density of the solar radiation flux (830 W/m^2 versus 710 W/m^2) falling on the concentrator.

6.3. Output Characteristics of the Cylindrical TPV System

The characteristics of the fragment of the TPV system consisting of 12 cells (half of a module) at various intensities of the concentrated solar radiation are listed in Table 4. As the concentrator, the Fresnel lens 60 × 60 cm in size was used. In laboratory conditions, the measurements were performed with the use of a halogen lamp (150 W) mounted along the axis of the module.

The above-presented TPV generators are demonstration models allowing us to evaluate the advantages and disadvantages of each of designs, specifically the importance of lowering the ohmic and optical losses in the entire system. With this purpose, at the next stage of the study, emitters made of selectively emitting materials will be examined and studies targeted to increasing the fill factor of both the separate cell and the entire module as a whole will be carried out. In an industrial variant of the TPV, the number of the cells and, consequently, the output electric power can be increased considerably.

Table 4. Characteristics of the fragment of the TPV system (4 × 3 cells) in conditions of illumination by concentrated solar radiation and a halogen lamp

Measurement conditions	Intensity of solar radiation, W/m^2	I_{sc}, A	V_{oc}, mV	*FF*	*P*, W	*P**, W	Efficiency, %
Measurements under solar radiation	950	3.55	1690	64.1	3.8	7.6	4.5
	880	3.08	1680	65.1	3.3	6.6	4.3
	750	2.29	1650	69.9	2.6	5.2	3.9
Laboratory measurements	Halogen lamp 150 W	3.22	1770	63.5			

Note: *P** are the expected values for the full-scale module consisting of 24 cells.

7. CONCLUSIONS

For thermophotovoltaic conversion of heat radiation of W emitters, the efficiency of the GaSb-based cell attains 19%. For the truncated spectral range (the radiation spectrum of the emitter is cut at $\lambda >$ 1820 nm, i.e., in conditions of imitation of 100% return of subband photons to the emitter), the efficiency of the photocell increases to 27%. To attain the maximum efficiency of the GaSb-based photoconverter, the optimum temperature range of infrared W emitters is $T = 1800-2000$ K.

Two variants of thermophotovoltaic systems (of conical and cylindrical types) operating upon heating the emitter by the concentrated solar radiation are developed and studied. Under the radiation of a plane SiC emitter, the maximum photocurrent density for the cell $J_{sc} = 4.5$ A/cm^2 is attained in this system.

In the cylindrical system, due to a larger number of photoconverters, the possibility of obtaining higher output power is implied. Such designs are more convenient for the development of hybrid TPV generators operating in the solar–fuel mode. The cylindrical system had better characteristics with the use of W emitters 20–25 mm in length. A TPV generator based on 12 GaSb photocells is fabricated. Upon heating the emitter by concentrated solar radiation, the output electric power $P = 3.8$ W is obtained.

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