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Gas-Fired Thermophotovoltaic Generator Based on Metallic Emitters and GaSb Cells

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Abstract—A prototype compact TPV generator with a propane burner (pressure 2 bar) and a metallic netted emitter has been developed and tested. A photovoltaic generator unit with 24 (1×1 cm^2) GaSb cells has been fabricated. The fabrication technology of photovoltaic cells has been optimized. It is shown that the data obtained can be used to select the starting bulk material for fabrication of photovoltaic cells with similar output parameters. It has been experimentally demonstrated that, to achieve maximum efficiency, it is necessary, in addition to using photovoltaic cells with similar characteristics, to provide identical conditions of their operation (temperature, illuminance).

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1. INTRODUCTION

A thermophotovoltaic (TPV) generator is a system comprising an emitter that is, as a rule, heated by burning-fuel energy to temperatures of 1000–1500°C and photoelectric converters transforming the generated thermal IR radiation directly to electricity. The efficiency of systems of this kind is limited by quite a number of factors. For example, the thermal radiation spectrum contains a rather large fraction of inconvertible long-wavelength radiation. The compact dimensions of the TPV generator require that the distance between the emitter and photoconverter be made shorter, with the result that the current density in the photovoltaic cells increases and their temperature becomes higher. Among the main advantages of TPV generators can be mentioned the absence of moving parts, which must provide a long service life and the possibility of using any kind of fuel. Below are presented the results of our study aimed at improving the characteristics of TPV generators.

2. DESCRIPTION OF THE SYSTEM

2.1. Emitters

Figure 1 schematically shows the TPV generator we developed, which comprises a mixer (*1*), combustion chamber (*2*), emitter (*3*), nonselective protecting filter (*4*), photovoltaic cells (*5*), and cooling system (*6*). The emitter should be made of a high-melting material resistant to corrosive atmosphere. As a rule, the emitters are fabricated from a ceramic (oxide or oxide-free) or refractory metals [1]. Oxide ceramics (most frequently, these are Er or Y oxides individually or in a matrix of aluminum oxide) have a selective emission spectrum with a band that can be matched to the photoresponse spectrum of a converter. The main obstacle to wide use of oxide ceramics is the poor stability against thermal cycling, which leads to their disintegration. Oxide-free ceramics (SiC, Si–SiC, $MoSi_2$) are substantially more resistant to the effect of high temperatures but have a nonselective emission spectrum. Most refractory metals also have a continuous emission spectrum with a certain selectivity, which, as a rule, manifests itself as an increase in the emission capacity in the visible spectral range.

In the system being described, we used metallic emitters made of a Kanthal refractory alloy (FeCrAl) in the form of netted cylinders. The developed surface of such cylinders and the burner design enabled a flameless surface combustion mode providing the best heating of the emitter and the fullest utilization of the

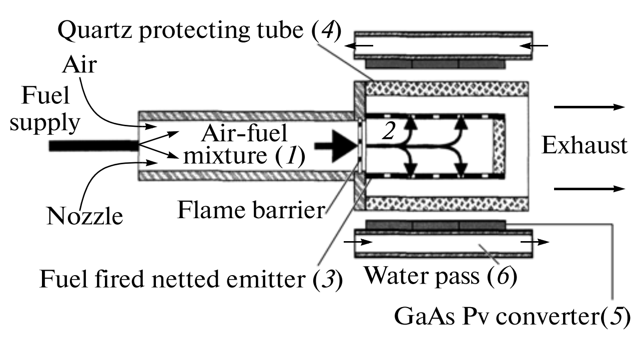

Fig. 1. Schematic of the TPV generator designed by the authors. (*1*) Mixer, (*2*) combustion chamber, (*3*) netted filter, (*4*) protective quartz glass, (*5*) photoconverters, and (*6*) water-cooled case.

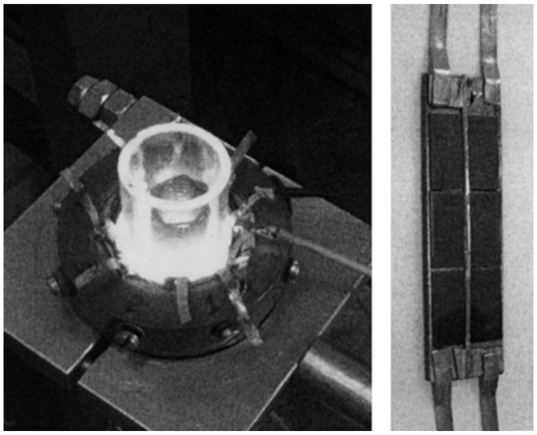

Fig. 2. Photograph of the operating TPV generator developed by the authors (left) and photogenerating linear array (right).

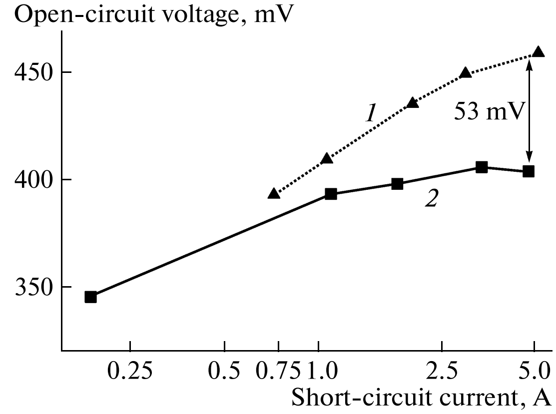

Fig. 3. Open-circuit voltage of a linear array of photoconverters vs. the photocurrent: (*1*) pulsed illumination (T = 25°C) and (*2*) operation in the TPV generator.

energy of burnt fuel. As a result, the maximum emitter temperature was 1400°C. The emitters had an outer diameter of 16 mm and length of 30–50 mm. Figure 2 (left panel) shows a photograph of a unit in operation.

2.2. Design of the TPV Converter

The photoelectric part of the generator consists of eight linear arrays mounted along the axis of the cylindrical emitter. The arrays are connected in series. Each array comprises three 1 × 1-cm^2 GaSb cells connected in parallel. The parallel connection is required, in the first place, for diminishing the loss associated with the nonuniform illumination of the surface of the arrays. In addition, it considerably simplifies the procedure of mounting the photovoltaic cells on heatsink plates. At the same time, the series connection is necessary for raising the output voltage of the unit, because narrow-gap GaSb cells are to be used (U_{opt} = 0.3–0.4 V), and for making lower the resistive loss: in the case of a parallel connection of all the TPV cells, the total current would be as high as 40 A.

In the generator we developed, the photovoltaic (PV) cells operate in the close vicinity of the heat source: the distance from the emitter to the working surface of a PV cell is less than 10 mm. Therefore, it is necessary to provide effective heat removal from the photovoltaic cells. The system under consideration employs forced water cooling. To enable a series connection, heat-conducting Al_2O_3 plates were installed between the cooled case and the linear array of photoconverters (PhCs). The thermal conductivity coefficient of Al_2O_3 is ~30 W K^{-1} m^{-1}, which is substantially lower than that of the BeO ceramic (~250 W K^{-1} m^{-1}). However, our measurements demonstrated that the use of the more expensive BeO ceramic in our TPV generator is unjustified because the difference between the temperatures of PVCs with different insulating materials is only several degrees [2].

Figure 3 shows the dependence of the open-circuit voltage of a linear array on the current density, measured under illumination with a flash-lamp and in an operating generator. This dependence can be used to estimate the temperature of the photovoltaic cell. According to [3, 4], the decrease in the open-circuit voltage of GaSb cells is 1.5–1.65 mV K^{-1}. As a result, the average temperature of the photovoltaic cell in the unit we developed is 45–60°C, depending on the emitter temperature.

2.3. Thermophotovoltaic Cells

The TPV converter comprises 24 photovoltaic cells. To convert the thermal radiation, we used GaSb photovoltaic cells with the maximum photoresponse in the range 0.6–1.8 μm. The cells were fabricated by double diffusion of Zn into a substrate of a material preliminarily doped with Te [5]. The substrates were grown by the modified Czochralski method. The materials, purchased from various manufactures, have different properties, which leads to significant differences in the characteristics of the photoconverters obtained because the diffusion process mostly involves point defects [6].

It is known that GaSb contains a large number of point defects (Ga_{Sb}, Sb_{Ga}, Ga_i, etc.) the concentration of which depends on the growth conditions [7]. The majority of point defects play the role of doubly ionized acceptors with activation energies of ~30 (1+) and ~100 (2+) meV. The presence of Te gives rise to complexes working as an acceptor with a single level at a depth of ~70 meV [7–12].

We used the photoluminescence (PL) technique for diagnostics of the starting material. For this purpose, a method for quantitative analysis of the shape of a PL spectrum has been developed [13]. This method makes it possible to estimate the concentration of native point defects (N_A) in a tellurium-doped sub-

Table 1. Results of an analysis of the shape of PL spectra in comparison with the results of Hall coefficient measurements

Sample	n(Hall), 10^{17} cm^{-3}	n(PL), 10^{17} cm^{-3}	N_A(PL), 10^{17} cm^{-3}	N_A(Hall), 10^{17} cm^{-3}
N178	5.5	5.0	2.3	3.0 (1.0)
RG5	2.4	2.4	2.1	3.5 (1.2)
N591	2.5	2.4	1.8	2.6 (0.85)

Table 2. Parameters of the I–V characteristic, obtained from measurements of the dark zero-series-resistance characteristics

Sample	J_0^{rek}, 10^{-5} A cm^{-2}	J_0^{diff}, 10^{-9} A cm^{-2}	N_A(PL), 10^{17} cm^{-3}
N178	8	4.9	2.3
RG5	6	26	2.1
N591	4	1.9	1.8

strate. Table 1 lists the results of a numerical analysis of the PL data in comparison with those obtained from Hall measurements. The concentration of the native defects was found by using the theoretical calculation procedure reported in [14]. It can be seen in Table 1 that the results of the PL analysis well correlate with the values obtained by the Hall measurements.

An increase in the defect concentration adversely affects the characteristics of the photoconverters. Figure 4 shows low-wavelength portions of the spectral characteristics of three PhCs fabricated by following the same technological pathway from three different substrates (Table 1). It can be seen that the structure with the lowest defect concentration has the best sensitivity in the wavelength range 1300–1800 nm, which may be indicative, for a diode with a short emitter, of longer free carrier lifetimes. However, these changes are insignificant and cannot heavily affect the efficiency of the entire TPV system.

Deeper distinctions are observed in the current–voltage (I–V) characteristics of the devices under study. Figure 5 shows zero-series-resistance dark I–V characteristics of the diodes under consideration, and Table 2 lists parameters extracted from these characteristics. It can be seen that J_0^{rek} increases with the defect concentration, which adversely affects the shape I–V characteristic: the open-circuit voltage and the fill factor. At the same time, the PhCs operate in our TPV generators at high photocurrent densities (1–2 A cm^{-2}), at which the shape of the load characteristic is also controlled by the diffusion component.

Figure 6 shows how the fill factor of the load characteristic depends on the photocurrent density for two structures fabricated on substrates purchased from different manufacturers. According to PL data, the concentration of point defects in sample RG5 is lower than that in sample N178; however, differences in the technological growth conditions (e.g., the stoichiometric composition of the starting phase, growth temperature, etc.) may change the qualitative composition of defects. According to calculations, a decrease in the concentration of defects of one type is accompanied by an increase in the concentration of defects of another type [7, 15, 16]. This may lead to significant differences in the properties of the devices fabricated.

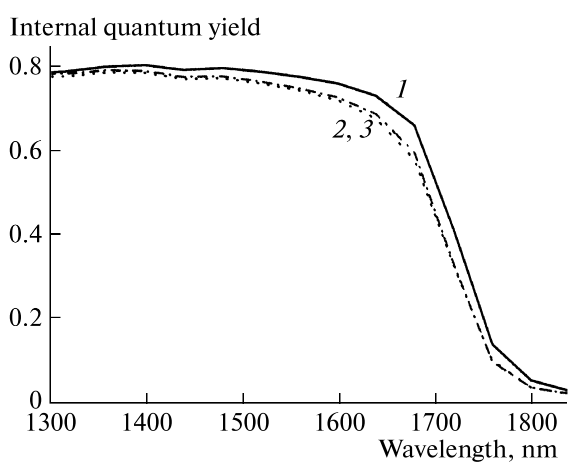

Fig. 4. Long-wavelength portions of the spectral characteristics of the internal quantum yield for the following structures: (*1*) N591 ($N_A = 1.8 \times 10^{17}$ cm^{-3}), (*2*) RG5 ($N_A = 2.1 \times 10^{17}$ cm^{-3}), and (*3*) N178 ($N_A = 2.3 \times 10^{17}$ cm^{-3}).

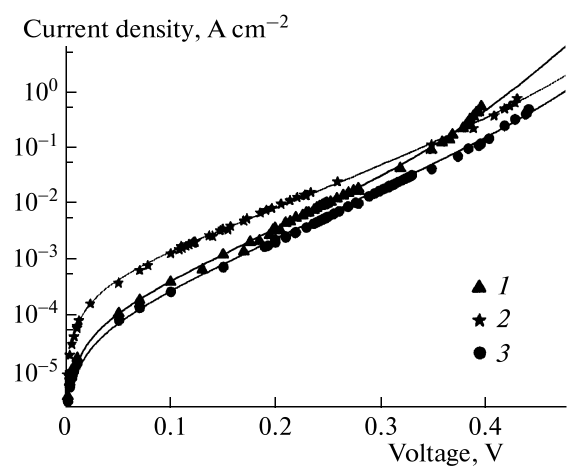

Fig. 5. Zero-series-resistance dark I–V characteristics of photoconverters based on the following structures: (*1*) RG5, (*2*) N178, and (*3*) N591. Solid lines: theoretical curves approximating the experimental values.

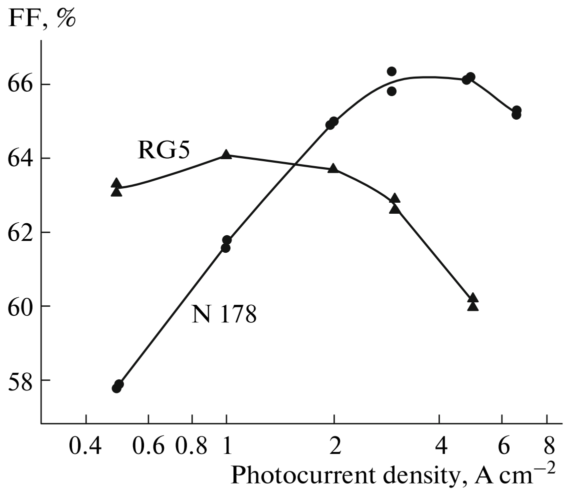

Fig. 6. Fill factor FF of the load characteristic vs. the current density for two photovoltaic cells: N178 and RG5.

For example, the parameters J_0^{diff} of these structures differ by more than an order of magnitude.

Figure 7 shows cross-sectional micrographs of two cleaved structures (N591 and RG5) obtained by scanning electron microscopy (SEM). It can be seen that the *p*–*n* junction depths are 484 and 443 nm, respectively. It can, however, be noticed that the contrast of the micrograph of sample RG5 is substantially higher. Taking into account that the initial doping levels of $(2.4–2.5) \times 10^{17}$ cm^{-3} and the mobilities in both the substrates are the same, we can assume that the differences are due to the doping impurity diffusion profiles. These profiles are, in all probability, also responsible for differences in J_0^{diff}: the sharper contrast in sample RG5 may mean a faster transition from the *p*-type region to the *n*-type region and, consequently, a higher concentration of Zn atoms in the space charge region of the *p*–*n* junction.

Figure 8 illustrates how the efficiency of conversion of the thermal radiation from the tungsten emitter depends on temperature. The converters we developed demonstrate rather high efficiencies of 16–19% at emitter temperatures as high as 2000 K. It should be noted that the photoconversion efficiency can be raised further if the emission from the emitter is made more selective, e.g., by using composite materials based on Er oxide [17].

Figure 9 shows load characteristics of the TPV generator measured at two different fuel flow rates. It can be seen that the fill factor of the load characteristic of the whole TPV generator (52–56%) is substantially lower than the fill factor of the constituent photovoltaic cells, which is, as a rule, larger than 60% (Fig. 6) and exceeds 65% for soldered structures [2]. Such a significant drop may be due to differences in the initial characteristics of the PhCs used, on the one hand, and to differences in their temperatures, on the other hand. Indeed, an increase in the emitter temperature is accompanied by a rise in the average temperature of the photovoltaic cell, manifested as a decrease in the open-circuit voltage. Measurements of the *I*–*V* characteristics of photogenerating linear arrays demonstrated >10°C differences in the photoconverter temperatures and, because the photoresponse edge of the GaSb photovoltaic cells lies near the maximum in the spectral density of emission, even a small change in the temperature of the photovoltaic cell leads to a noticeable change in the generated photocurrent. All these circumstances cause an additional increase in the loss associated with the mismatch between the elements.

Thus, to obtain the best results, it is necessary, in addition to using photovoltaic cells with close output characteristics, to pay considerable attention to the uniformity of the operation conditions of the photoconverters, which is the subject of further development.

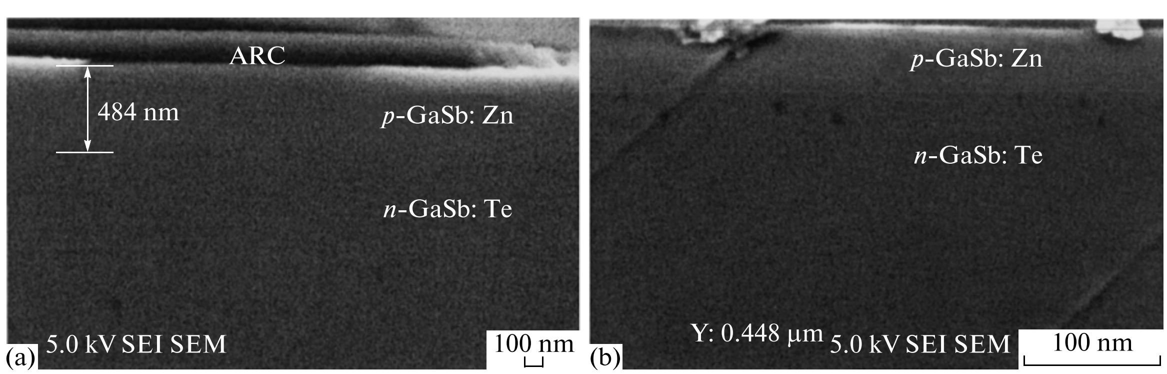

Fig. 7. Cross-sectional SEM images of two structures: N591 (on the left) and RG5 (on the right).

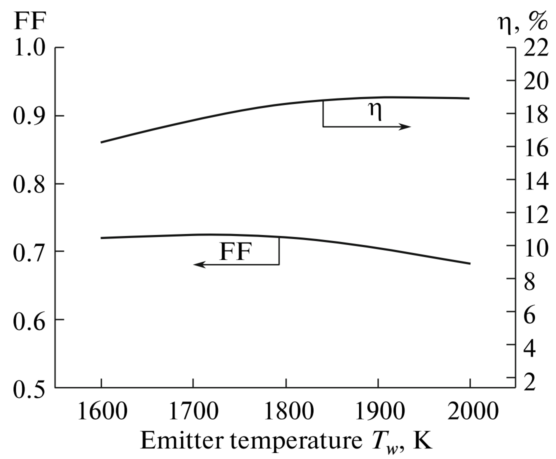

Fig. 8. Efficiency (η) and fill factor (FF) vs. the emitter temperature for GaSb TPV elements.

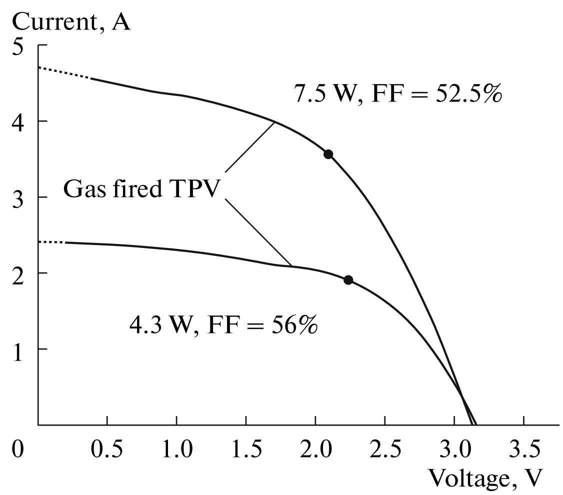

Fig. 9. *I–V* characteristics of the TPV generator designed by us (eight in-series connected linear arrays, each with three 1×1-cm^2 GaSb cells) at two different gas flow rates.

3. CONCLUSIONS

Thus, we have developed a compact pilot thermophotovoltaic generator and tested it. The generator uses 24 1×1 cm^2 GaSb photovoltaic cells. An output power of 7.5 W was obtained at a voltage exceeding 2 V. The average temperature of a photovoltaic cell in an operating generator was less than 60°C at photocurrent densities of up to 2 A cm^{-2}. The efficiency of photoconversion of the thermal radiation from a tungsten emitter was, for the structures based on GaSb, 16–19%, depending on its temperature. It was shown that, to provide the best efficiency of the thermophotovoltaic generator, it is necessary to pay increased attention both to the uniformity of the characteristics of the photovoltaic cells used in the generator and to provision of identical conditions (temperature) of their operation. The properties of the materials and the characteristics of devices fabricated from these materials were analyzed. It is demonstrated that the photoluminescence method can be effectively used for a rapid analysis of GaSb substrates, which is necessary for obtaining structures with close characteristics.

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