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DIRECT CONVERSION OF SOLAR ENERGY TO ELECTRIC ENERGY

# Photothermoelectric Cell for Thermophotovoltaic Systems and Solar Power Plants with Concentrators

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**Abstract**—We have attempted to justify the appropriateness of the photoelectric and thermoelectric (photothermoelectric) cells in the development of efficient thermophotovoltaic systems and facilities with photoelectric converters and concentrators of solar radiation. These cells are *p–n* structures based on narrow-band semiconductors capable of the simultaneous thermo- and photogeneration of electron–hole pairs under the effects of irradiation. We discuss the reduction of losses in the course energy conversion carried out with a photothermoelectric cell instead of separate thermo- and photoelectric cells. In addition, we describe the characteristic features and estimate the efficiency of photothermoelectric cells in the thermophotoelectric systems and facilities for the photoelectric conversion of the concentrated solar radiation.

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## INTRODUCTION

The terrestrial sources of thermal radiation that operate at 1000–1500°C are characterized by intense heat radiation. Therefore, in the thermophotovoltaic (TPV) systems, it is necessary to cool down the photoelectric cells that convert thermal radiation. The efficiency of these systems is determined by the efficiency of photoelectric cells and continues to be rather low. In the case of facilities for photoelectric conversion of the concentrated solar radiation, it is possible to control the intensity of solar radiation; the efficiency of these facilities is limited by the efficiency of the cooled photoelectric cell mounted in the focal plane of the concentrator. Therefore, the enhancement of the efficiency of the TPV systems and the facilities for the photoelectric conversion of concentrated solar radiation is a topical problem in solar engineering. To establish a new line of research and development in the field of semiconductor voltaics, which we referred to as "photothermovoltaics" in our previous paper [1], we have proposed the idea of creating a photothermoelectric cell based on narrow-band semiconductors, which are capable for simultaneous thermo- and photogeneration of electron–hole (eh) pairs under irradiation. The separation of these pairs by the *p–n* junction leads to high values of the short-circuit current ($I_{sc}$). In [1], we discussed the operation and estimated the efficiency of the solar thermoelectric cell at the radiation intensity equal to 0.1 W/cm$^2$ (one Sun). In this case, to reduce the energy losses of the thermal radiation emitted by the solar thermoelectric cell, it is necessary to use the selective coating and the transparent heat-insulating layer on the front side. It is evident that, in TPV systems [2] with temperature of the thermal radiation source of about 1000–1500°C and in facilities with concentrators of solar radiation [3], the intensity of the converted radiation exceeds 1 W/cm$^2$ (10 Suns). At a working temperature of the thermoelectric cell of about 200°C, the intensity of thermal radiation is much lower than ~0.2–0.3 W/cm$^2$ (2–3 Suns). In the present paper, we discuss the features characteristic of the operation of photothermoelectric cells in thermophotovoltaic systems and facilities for the photoelectric conversion of concentrated solar radiation.

## THERMOPHOTOVOLTAIC SYSTEMS WITH PHOTOTHERMOELECTRIC CELLS

A TPV system consists of the terrestrial thermal radiation source, sa elective emitter (or reflector – filter), and a cooled photoelectric cell based on wide-band semiconductors (with the band gap width $E_g$ = 0.5–0.6 eV), see Fig. 1a [2]. The relatively low efficiency of TPV systems is limited by the efficiency of the cooled photoelectric cells used in them. The energy losses of the converted thermal radiation occur also due to the use of the selective emitter. The implementation of the photothermoelectric cells allows us to improve the aforementioned drawbacks and to simplify the design of the TPV systems, which, in this case, consist of the thermal radiation source and the photothermoelectric cell (Fig. 1b) based on narrow-band semiconductors [1]. The efficiency of this cell increases with increasing temperature.

Let us consider the operation of the photothermoelectric cell, the band scheme of which is shown in Fig. 2. The band gap width $E_g$ can be chosen within the 0.15–0.50-eV range. It is necessary for the cell thick-

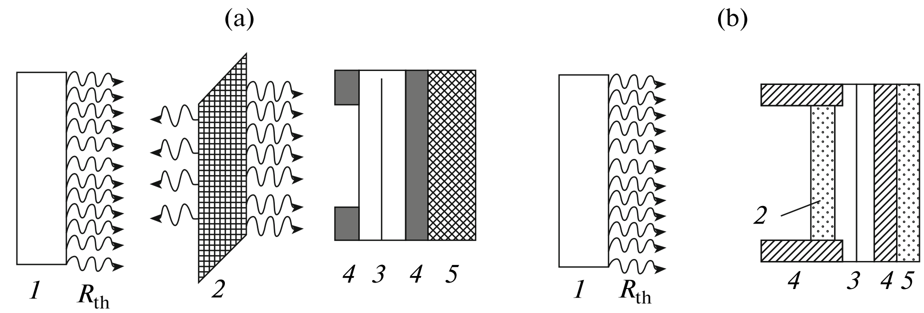


**Fig. 1.** (a) Main parts of a thermophotovoltaic facility: (*1*) thermal radiation source; (*2*) selective emitter (or reflector – filter); (*3*) photoelectric cell, *p–n* junction; (*4*) ohmic contacts; (*5*) radiator; (*6*) thermal radiation, $R_{th}$. (b) Parts of a thermophotothermovoltaic facility: (*1*) thermal radiation source; (*2*) photothermoelectric cell–transparent heat insulation layer; (*3*) *p–n* junction; (*4*) ohmic contacts; (*5*) heat insulation layer.

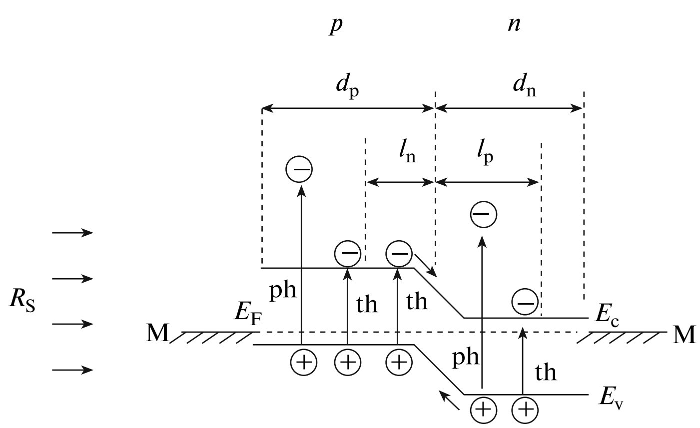


**Fig. 2.** Schematic diagram illustrating the band structure at the *p–n* junction of a photothermoelectric cell: M are metallic contacts; ph and th are photo- and thermoexcitation of eh pairs, respectively; $l_n$ and $l_p$ are diffusion paths of electrons and holes, respectively; $d_n$ and $d_p$ are widths of the *n* and *p* layers, respectively; $R_S$ is solar radiation.

ness $d_p + d_n$ to be sufficient in order to ensure the complete absorption of all photons of the thermal radiation with energies exceeding $E_g$, which induce the photogeneration of eh pairs. The eh pairs generated by light and heat in the layers with thickness $l_n$ and $l_p$ are separated by the *p–n* junction and generate the photothermal EMF of the cell ($V_{oc}$ is the open-circuit voltage). The heat generated due to the recombination of eh pairs in the layers of thickness $d_p - l_n$ and $d_n - l_n$ also give rise to eh pairs. The excess energy of the photoinduced electrons undergoes thermalization and leads to the heating of the *p* and *n* layers; moreover, it can also generate a certain number of eh pairs by means of impact ionization. Most likely, in this case, the mechanism underlying the heating of the layers is quite fast, unlike the case of heating due to heat transfer caused by the temperature gradient in solids. Photons with energies below $E_g$ can be absorbed by the rear Ohmic contact layer and contribute to the heating of the *p–n* structure. The thermal radiation, which is incident on 1 $cm^2$ of the photothermoelectric cell area and has power $J_0$, is converted to the energy of the photo- and thermogenerated eh pairs, which determines the values of the short-circuit current $I_{sc}$ and heat $Q$. A certain part of the heat is lost due to the intrinsic radiation emitted by the photothermoelectric cell from the frontal surface and the convective energy losses from the frontal and rear surfaces. Let us denote the heat lost per second as $Q_l$. The, the efficiency is determined by the ratio

$$\eta = \frac{J_0 - Q_l}{J_0}.$$

Energy losses, which limit the efficiency of photoelectric cells due to the thermalization of photoinduced electrons and unabsorbed photons with energies below $E_g$, do not occur in the photothermoelectric cell, since the band gap width in the semiconductors used in these cells is much smaller than that in Si, $CuInSe_2$, and CdTe, which are widely used in the commercial production of the photoelectric cells. In photothermoelectric cells, there are no energy losses

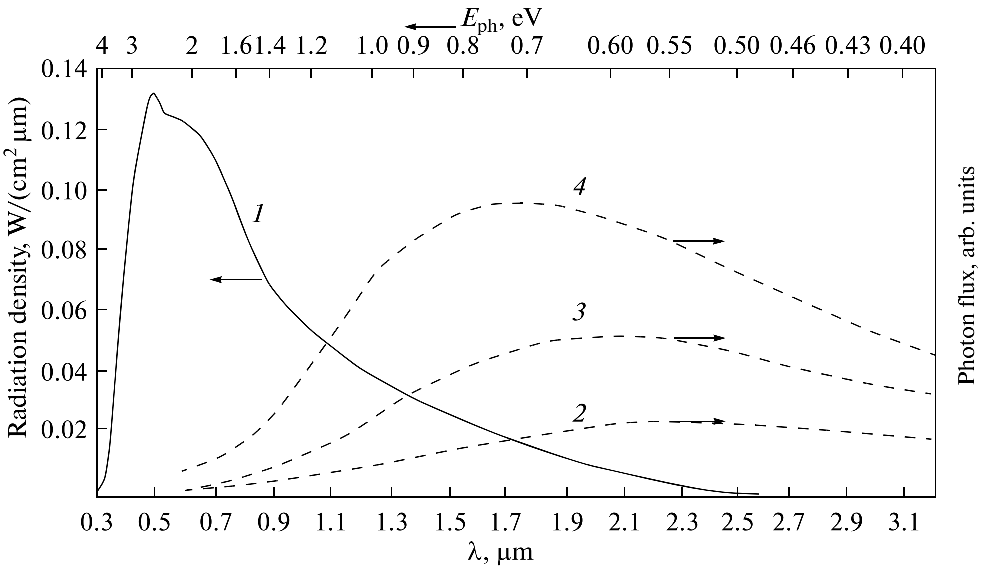


**Fig. 3.** (*1*) Spectral distribution of the solar radiation at the sea level in the case of clear sky; (*2–4*) photon flux densities for black-body radiation corresponding to 1300, 1500, and 1700 K, respectively.

inherent to the thermoelectric cells, which occur in the branches of thermoelectric circuits, where more than 90% of the recombination of thermogenerated eh pair takes place [1].

In the case of photothermoelectric cells, the thickness (of the branches) is limited by $d_p$ and $d_n$, which do not exceed several microns. As was mentioned above, the heat released over the course of recombination generates eh pairs. A specific feature underlying the implementation thermophotoelectric cells for the conversion of the thermal radiation of terrestrial heated objects to electrical power is related to the possibility of changing the intensity spectrum of the thermal radiation source as a function of temperature. In Fig. 3, we show the spectral dependence of the thermal radiation for the absolute black body at temperatures of 1300, 1500, and 1700 K. According to the Stefan–Boltzmann equation, the intensity of the thermal radiation is $I = \sigma T^4$, where σ is the Stefan–Boltzmann constant, $\sigma = 5.67 \times 10^{-12}$ W/(cm$^2$ K$^4$), and $T$ is the absolute temperature. At $T = 1300$ K, the radiation intensity $I = 16.2$ W/cm$^2$ (162 Suns). By changing the temperature of the source of the thermal radiation or the distance between the source and the photothermoelectric cell, it is possible to change the temperature of the photothermoelectric cell in a wide range of 100–600°C. To achieve the maximum efficiency of the thermophotovoltaic system (Fig. 1b), at a fixed value of $E_g$ in the semiconductor used in the cell, it is necessary to heat it to the temperature at which the useful heat is completely converted to the energy of thermally generated eh pairs.

## PHOTOTHERMOELECTRIC CONVERSION OF THE CONCENTRATED SOLAR RADIATION

The concentrated solar radiation is used in combination with expensive photoelectric cells based on III–V semiconductors and their solid solutions. In particular, if the cell incorporates several junctions, the efficiency of these devices can be as high as 35–43% [4, 5]. According to the forecasts of Japanese experts [4], the use of multijunction photoelectric cells exposed to the concentrated radiation leads to an appreciable reduction in the price of the produced electric power. In Fig. 3, we see that, at a source temperature of about 1700 K, the fraction of photons with energies exceeding 1.2 eV in the power of thermal radiation emitted by the source is only a few percents, whereas in the energy spectrum of the solar radiation, the fraction of photons with energies exceeding 1.2 eV is about 70% [6]. It is clear that, in the case of the photoelectric conversion of solar radiation, the composition of this radiation does not change with its enhancement factor. The excess energy of photoinduced electrons generated by photons with energies exceeding 1.2 eV is higher than $E_g = 0.2$ eV by a factor of 5–15. The excess energy of photoinduced electrons can also lead to the generation of eh pairs by impact ionization. Currently, there are several powerful solar energy facilities that convert solar radiation according to the scheme shown in Fig. 4a, including the following successive stages: concentrated solar radiation → heat → mechanical energy → electric power.

It is clear that the implementation of photothermoelectric cells makes the solar power facility simpler

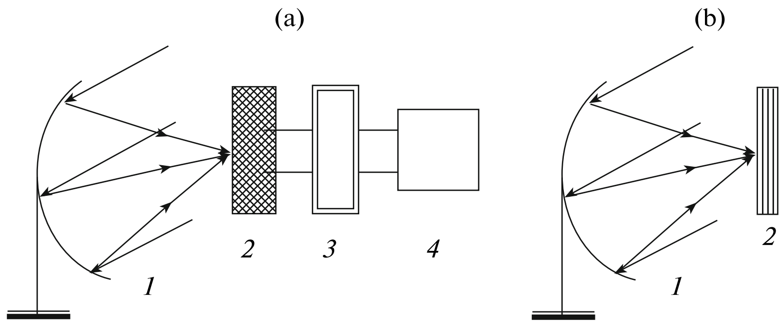


**Fig. 4.** Layouts of (a) solar power facility for the solar energy conversion to electricity: (*1*) concentrator of solar radiation; (*2*) receiver that converts solar radiation to heat; (*3*) heat engine; (*4*) electric power generator and (b) facility for converting concentrated solar radiation to electricity through the use of photothermoelectric cell: (*1*) concentrator; (*2*) photothermoelectric cell.

and leads to a reduction of energy losses that occur in units *2* and *3* shown in Fig. 4.

## CONCLUSIONS

A serious drawback of photothermoelectric cells is that, in the course of their operation, they are heated to relatively high temperatures and, hence, their lifetime is smaller than that of silicon photoelectric cells, which exceeds 20 years. An important characteristic feature of the photothermoelectric cells similar to that of thermoelectric cells is that it is necessary to divide them into low-, intermediate-, and high-temperature devices based on semiconductors with $E_g \approx 0.2$, 0.3, and 0.5 eV that operate at temperatures of about 150, 300, and 500°C, respectively. If it is possible to implement the concept of a photothermoelectric cell and manufacture a high-efficiency photothermoelectric cell, this should give rise to two novel fields of research and development in semiconductor voltaics, which can be referred to as photothermovoltaics and thermophotovoltaics. Progress in photothermovoltaics should lead to the development of the efficient, cheap, and relatively simple TPV systems and facilities for the photothermovoltaic conversion of concentrated solar radiation. The establishment of photothermovoltaics demands long-term large-scale research and development in the field of the physics and technology of semiconductor devices. In particular, the following issues should be addressed:

(1) the theoretical analysis and the corresponding calculations concerning the dependence of the voltaic characteristics of photothermoelectric cells on the parameter of the used semiconductor materials and the geometry of the related *p–n* structures;

(2) manufacturing and studies of photothermoelectric cells based on the available narrow-band semiconducting materials, such as $Bi_2(Se_3)_{1-x}(Te_3)_x$, InSb, PbS, PbTe, InAs, $CdGeAs_2$, and $ZnSnAs_2$;

(3) synthesis and studies of electrical characteristics of novel narrow-band materials.

I hope that the suggested concepts concerning the photothermoelectric cells and the conditions needed to apply them will draw attention from specialists in the fields of photovoltaics, thermophotovoltaics, and thermoelectricity.

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