TPV Systems with Solar Powered Tungsten Emitters

A.S. Vlasov*, V.P. Khvostikov, O.A. Khvostikova, P.Y. Gazaryan,
S.V. Sorokina, V.M. Andreev

A.F. Ioffe Physical-Technical Institute, 26 Polytechnicheskaya, 194021, St. Petersburg, Russia
** e-mail: vlasov@scell.ioffe.ru*

Abstract. A solar TPV generator development and characterization are presented. A double stage sunlight concentrator ensures 4600x concentration ratio. TPV modules based on tungsten emitters and GaSb cells were designed, fabricated and tested at indoor and outdoor conditions. The performance of tungsten emitter under concentrated solar radiation was analyzed. Emitter temperatures in the range of 1400-2000 K were measured, depending on the emitter size. The light distribution in the module has been characterized. 1x1 cm GaSb TPV cells were fabricated with the use of the Zn-diffusion and LPE technologies. The cell efficiency of 19% under illumination by a tungsten emitter (27% under spectra cut-off at $\lambda > 1820$ nm) heated up to 1900-2000 K had been derived from experimentally measured PV parameters. The series connection of PV cells was ensured by the use of BeO ceramics. The possibilities of system performance improvement are discussed.

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INTRODUCTION

A variety of a TPV generator is a solar powered TPV system. Basic distinction of a solar powered TPV system from a common one is the fact that the energy for the emitter heating is received not from the fuel combustion, but is converted from the concentrated sunlight. At the same time the solar TPV systems has major advantages and disadvantages, in comparison with the fuel fired ones. The emitter might be insulated from the air, thus any material (even those, that are oxidized) can be used. Also the emitter can be vacuum insulated, thus solving the problem of convectional losses. The choice of emitter materials is however limited by the fact, that it should absorb the solar radiation.

In solar thermophotovoltaic (STPV) systems, the sunlight is absorbed by an emitter and reemitted as a thermal radiation before illumination of PV cells. STPV system, as a variety of a TPV generator, allows utilizing selective filters/mirrors and sub-bandgap photon reflection to the emitter, which ensures efficiency increase.

Theoretical [1-4] and experimental [5-6] studies show an opportunity to achieve a high efficiency in STPV systems. For ideal system elements, the maximal theoretical efficiency was found to be 85.4 %, which is close to the efficiency of an unlimited

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stack of tandem cells. Expected in practice efficiencies of STPV converters are 20 - 30%.

These are the following key problems arising at the STPV system optimization: providing the high sunlight concentration; changing the emission spectrum of the photon emitter; filtering the radiation to utilize photon recycling process and to reduce the heat impact on photocells; PV cell design including the tandem cell allowing to increase PV conversion efficiency of radiation from the emitter. These problems may be interrelated. For instance, a selective filter may be deposited directly on the photocell surface reflecting long-wavelength radiation back to the emitter, or the photocell itself may play the role of such a filter, if there is a mirror on its back surface, which reflects the sub-bandgap photons nonabsorbed in the PV cell material.

SOLAR TPV SYSTEM DESIGN

Solar concentrators

One of the most important parts of the concentrator photovoltaic module is the solar concentrator itself (figure 1). Because of the use of a high temperature emitter, the solar concentration ratio is not limited and needs to be as high as possible to obtain high emitter temperature values, however keeping the price of the concentrator reasonable. The maximum achievable solar concentration ratio for the terrestrial conditions is 46164x and is determined by the angular dimensions of the Sun. This value can be achieved with an ideal parabolic mirror with an opening angle of 180°. Production of such mirrors is difficult, and the price will be corresponding.

A cost-effective Fresnel lens technology can be applied for concentrator fabrication. Small Fresnel lenses are often used for conventional PV concentrator systems. Larger concentrators are necessary for STPV modules. A Fresnel lens based two-stage sunlight concentrator system developed for solar TPV system is shown in figure 1. It consists of a Fresnel lens 0.36 m^2 in area and 0.75 m focal length and a secondary quartz concave-convex lens. The light distribution in the spot was measured by scanning with a GaSb PV cell with a ∅1 mm aperture mounted on a water-cooled stage. It can be seen from figure 2, that more than 90% of the energy is collected by

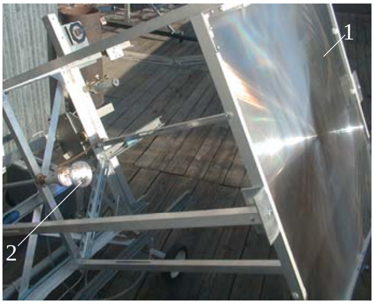

FIGURE 1. Two-stage concentrator based on a primary Fresnel lens (1) and a secondary quartz concave-convex lens (2).

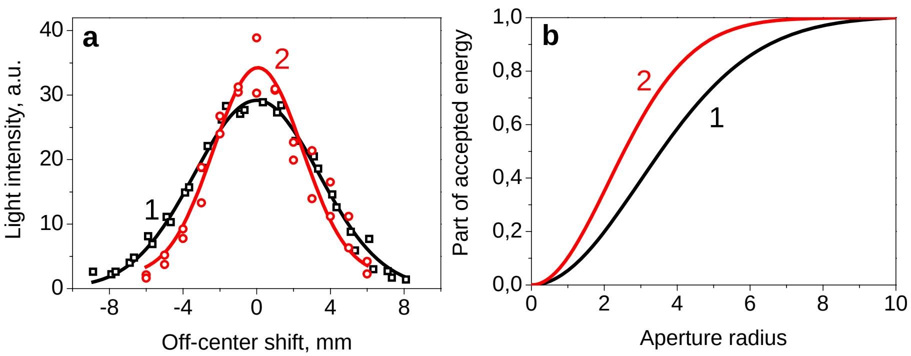

FIGURE 2. (a) – Measured light distribution in the developed concentrating system: Fresnel lens without (1) and with (2) a secondary lens; (b) – Part of energy hitting the aperture of given radius without (1) and with (2) a secondary lens.

the ∅10 mm aperture, which corresponds to 4600x concentration ratio, and is rather high for this simple construction of a concentrator system.

The material (PMMA) of commercially available Fresnel lenses is, however, characterized by a poor outdoor stability. Recently, a technology for Fresnel lenses of a composite structure was developed: the microprisms are formed of the transparent silicone rubber contacting with the front silicate glass sheet as a protective superstrate. Such a type of Fresnel lenses ensures much better environmental stability owing to the use of high stable silicate glass, protecting the Fresnel lens made of silicone rubber, which is also characterized by high stability under the action of outdoor conditions. These Fresnel lenses are very promising for fabrication of concentrator PV modules and have perspectives for low cost STPV systems.

Solar TPV Modules Based on GaSb PV Cells

The developed TPV module of the solar TPV system is schematically shown in figure 3. It was tested at the Ioffe Institute with both: outdoors with the Fresnel lens set up, shown in figure 1, and with a solar simulator [7], consisting of a high power (5 - 10 kW) Xe lamp and an ellipsoidal reflector. The tungsten (or tantalum) emitter is placed

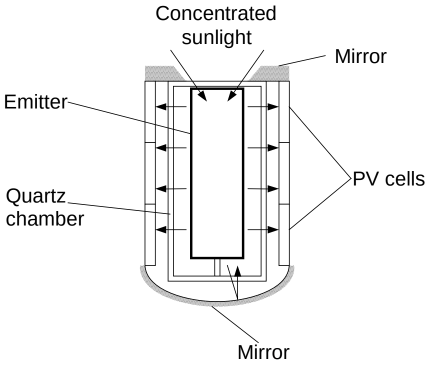

FIGURE 3. Schematic drawings of the developed STPV module.

in a quartz chamber filled with a rare gas (Ar or Xe) to prevent it from oxidation. The chamber may be sealed (figure 5). The sealed emitter was tested under concentrated sunlight for hours and no mechanical damage was found on the bulb surface. The PV cells surround the emitter, being mounted on the inner side of a cooled cylindrical base.

Emitters for solar TPV systems

In solar TPV systems, the sunlight is concentrated on an emitter. Hence, the first objective, the emitter should conform to is the following: it should absorb the energy with the maximum possible efficiency. Then, it should transfer it to the PV cells.

The simplest way to obtain a selective emitter is the use of refractory metals, tungsten, for example, whose emissivity increases in the visible and near-IR regions up to 0.45 - 0.47, with a drop to 0.1 - 0.2 in the IR region [8]. Most metals, such as tungsten or tantalum, are oxidized at high temperatures, however the advantage of a solar TPV module is in the possibility to protect the emitter by inserting it in a quartz bulb, filled with a rare gas. The emitter can be made in a form of a cylinder with a sealed bottom. In this case it can be considered as a cavity, the emissivity of which can be calculated by solving the following set of iterative equations [9]:

$$\varepsilon_{ef}(M_i) = \varepsilon(M_i) + R(M_i)\left[\int_{F_1} K(M_i,N_1)\varepsilon_{ef}(N_1)dF_{N_1} + \int_{F_2} K(M_i,N_2)\varepsilon_{ef}(N_2)dF_{N_2}\right], \quad (1)$$

where ε_{ef} (N) is the effective emissivity of the cavity aperture, $K(M_i,N)$ – the geometrical coefficient describing the view angle of heat exchanging surfaces (the view angle of a unit area on one surface to a unit area on another surface), F_1, F_2 – cylindrical and flat surfaces of the emitter, $\varepsilon(M_i)$ –emissivity and $R(M_i)$ – reflectance of the cavity material. Temperature is assumed constant over the surface. Precise calculation implies multiple order of reflection to ensure equality of the heat emitted by the cavity surface and the heat absorbed by the cavity itself and emitted through the aperture. The absorptance of a ∅12 mm tungsten cylinder 15 - 45 mm in length increases by a factor of 2 – 3 compared to the pure tungsten, reaching the maximum value of AA = 0.8 at 500 nm (figure 4). The total absorption efficiency of cylindrical

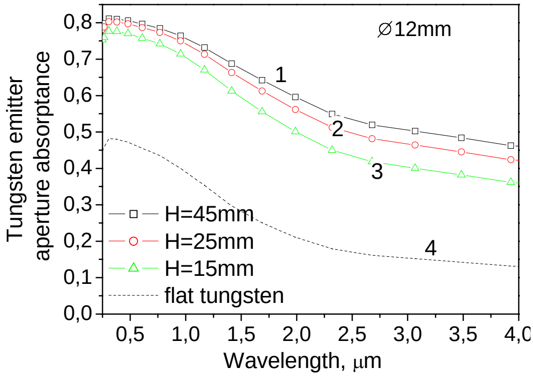

FIGURE 4. Theoretical spectral dependence of the tungsten emitter ∅12 mm aperture absorptance for different emitter lengths. The emitter temperature is 1600K.

FIGURE 5. A Tantalum emitter situated in an Ar filled bulb under illumination from solar simulator

tungsten emitters appears to be about 0.6 - 0.7 for the AM1.5 solar spectrum.

Theoretical calculations of the emitter temperature compared with the experimental measurements revealed the high level of convectional losses of about 30% [10]. Longer emitters showed the temperatures even lower than expected. This is explained by growing convectional losses that accompany the emitter surface increase, which was not taken into account. These losses can be significantly decreased by inserting the emitter in a thermos-like double wall bulb. Also a vacuum atmosphere can be created in the emitter chamber. The estimation based on the I-V measurements of GaSb test cells showed, that the total power output of the system has a maximum for emitters of 35 - 45 mm in length, which corresponds to the emitter efficiencies of 0.8 - 0.85, expected in calculations [4].

GaSb TPV cells

The cells were prepared by two-stage Zn diffusion process. The cell efficiency of 19% under illumination by a tungsten emitter heated up to 1900 - 2000 K has been derived from experimentally measured PV parameters (figure 6). This value is close to the theoretical maximum of ~ 22% for GaSb cells illuminated by a tungsten emitter. PV conversion efficiency of 27% was estimated for the spectrum cut off at 1820 nm.

In a TPV generator PV cells operate at high current densities and close to the heat

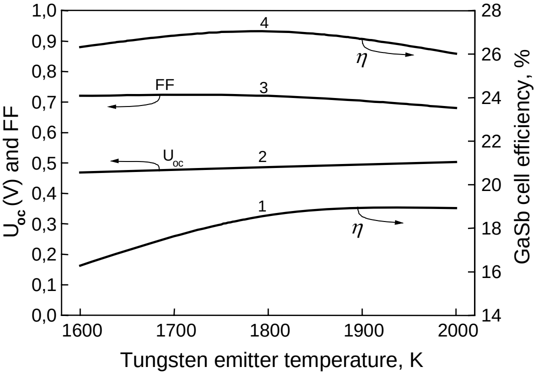

FIGURE 6. Open circuit voltage (V_{OC}, curve 2), fill factor (FF, curve 3) and efficiency (curves 1, 4) of GaSb TPV cell as a function of tungsten emitter temperature. Efficiency was estimated under the following radiation conditions: under the full radiation spectra (curve 1) and under spectra cut-off at

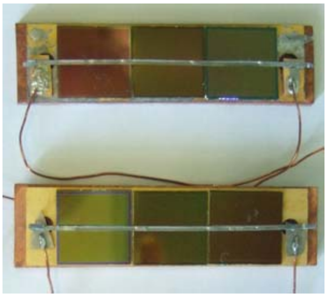

FIGURE 7. 1x1 cm^2 GaSb cells mounted on BeO ceramic plates.

source. Thus an effective water cooling is required. Also a series connection of the cells is desirable, as the voltage output of a GaSb cell is less than 0.5 V. To fulfill these conditions, BeO ceramics was used. It has the electrical resistivity of more than 10^{14} Ω/cm with the best thermal conductivity of 250 W/K·m. The thermal expansion coefficient of BeO ceramics is $6 \cdot 10^{-6}$ K^{-1} being close to that of GaSb in the temperature range of 20 - 150ºC. Mo/Ni/Au contact composition to the BeO substrate allows to solve the problem of adhesion of GaSb cells to ceramics. The cells were mounted on 40x11 mm BeO ceramic plates in parallel (3 cells) (figure 7) and the plates were connected in series.

Solar TPV module characterization

While optimizing the system, one of the most important parameters is the emitter size. Its diameter is determined by the focusing system and in our case of the Fresnel lens set up is 10-12 mm. Its length determines the emitter efficiency, i.e. part of radiation that reaches the PV cells and, as it was shown previously, should be in the range of 30-50 mm for the given diameter [10]. Considering large convectional losses, not included in those calculations shorter emitters were used.

Due to technical reasons the distance between the emitter and the cells is 9-10 mm in our STPV module, as the cells and the emitter should be insulated. With these emitter lengths the illumination of the cells is nonuniform. The short circuit current of the cell situated in the middle is 1.3 times higher than that of the side ones (figure 8, a). In this figure the PV cells are illuminated by a 30 mm tungsten emitter and the curves are corrected, considering each PV cell integral quantum efficiency measured under thermal irradiation. Such a difference is explained mainly by the change in the view angle of the emitter from 70 degrees on the edge to 120 degrees by sides. Considering that the thermal irradiation from the hot surface has a hemisphere distribution (i.e. the intensity of the radiation do not depend on the angle to the surface but only from the cell to emitter distance), this is to some extend proportional to the total irradiation of the cells. Shorter emitters reveal even higher nonuniformity of the PV cell irradiation. Our measurements showed, that the maximum performance can be reached with a 25 mm long emitter (figure 8, b).

These results were obtained with emitters, made of 0.1 mm thick tungsten. According to our measurements, the temperature of the emitter surface is not constant and varies in 50-100 °C. This effect, however, is minor for the light distribution on the

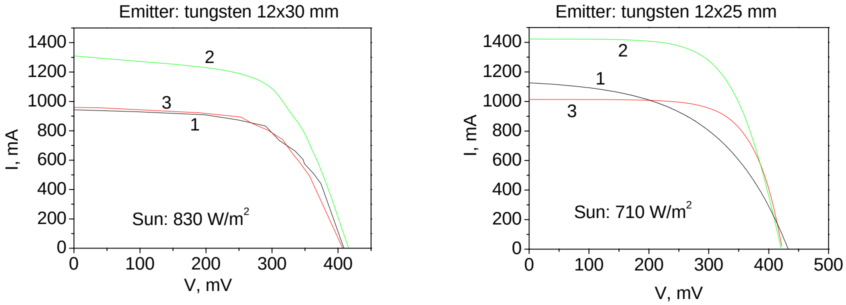

FIGURE 8. Load characteristics of three GaSb cells settled in a row along the tungsten emitter. a – 12x30 mm emitter with solar irradiation Edir = 830 W/m^2 ; b - 12x25 mm emitter with solar irradiation Edir = 710 W/m^2

cell surface. Our experiments with thicker (1 mm thick tungsten) emitters revealed the same difference of the short circuit current on the cells in rows. This means that parallel connection is preferable for the cells in one row, although it is companied with some drop in the FF values, while with a series connection of the cells in a row significant losses of the current on a middle cell would be observed. To avoid this effect, mirrors as shown in figure 3 should be introduced to make the system closed up. This should increase the total current density values and increase the uniformity of the light distribution along the emitter. These mirrors are the subject for the future system improvement.

Current-voltage characteristic of a 3 cell set connected in parallel is shown in figure 9, curve 2 and appears to have a fill factor of 0.59. This I-V curve was obtained with a ∅12 mm tungsten emitter 25 mm in length heated by concentrated with a Fresnel lens solar energy. The irradiation density was ~770 W/m^2. The FF and V_{oc} of the 3 cell set is slightly lower than the initial parameters of the cells used (FF=0.61-0.62 and U_{oc}=0.42-0.43 V). The power output of this module appears to be 0.672 W, which, presumably, will give at least 5.4 W of the total STPV power output.

Higher values can be expected for higher irradiation densities, use of vacuum insulated emitter, use of ∅10 mm emitters with a secondary lens, as the emission

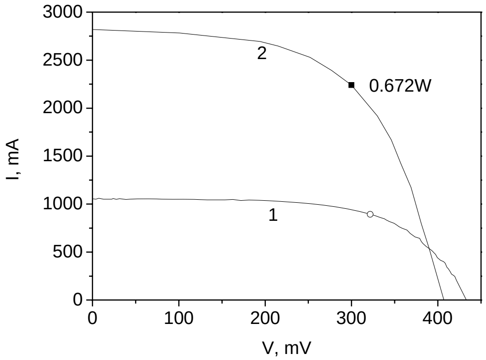

FIGURE 9. Load characteristics of a 1x1 cm^2 cell under flash lamp (curve 1) a 3x1 GaSb cell set measured in a STPV system with a tungsten emitter (curve 2).

spectrum of the emitter will blue shift and the V_{oc} and FF will be increased. Also a mirror, shielding the escaping radiation from the emitter bottom and the spase between the emitter and PV cells would benefit. PV cells with a backside mirrors or selective filters can be used for emitter temperature increase by the subbandgap photons utilization. Tandem PV cells based on InGaAsSb alloys are also promising for the efficiency increase [4].

SUMMARY

Development of a solar TPV system has been reported. The developed solar concentrators based on a Fresnel lens do not show the maximum performance possible (parabolic mirror would give higher concentration ratios and efficiency). However it has a great advantage of low price, still enabling to reach high concentrations.

A continuous progress takes place in improvement of gallium antimonide PV cells. Efficiencies exceeding 26% for in-band ($\lambda < 1800$ nm) tungsten (1500 - 1900 K) radiation were achieved. The developed GaSb PV cells are most relevant for the use in STPV systems. The cell mount on BeO ceramics revealed good enough thermal stability enabling series connection of the low-voltage GaSb cells.

The whole solar TPV system was examined outdoors. The emitters, sealed in quartz bulb, displayed themselves stable under concentrated sunlight. The power output of 0.762 W was measured with a single 3-cell set and 25x12 mm tungsten emitter under the Sun (770 W/m2) concentrated by a Fresnel lens. The light distribution in the STPV module was analyzed and the ways of system improvement are discussed.

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