PHOTOVOLTAIC CELLS FOR SOLAR POWERED TPV SYSTEMS

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ABSTRACT

In present paper, different aspects of a solar powered TPV system are under theoretical and experimental study, such as heating the emitter of photons by focusing sunlight, returning the sub-bandgap photons by reflecting IR radiation from cell back surface, and estimating the cell conversion efficiency being guided by semi- empirical approaches.

Efficiency of 25% can be obtained in GaSb cells without photon recirculation illuminated by tungsten emitter heated up to 2200-2500 K. Efficiency exceeding 30% can be achieved in GaSb PV cells assuming 90% reflection of sub-bandgap photons back to the emitter. GaSb based TPV photoreceivers of cylindrical and flat geometry were developed and investigated outdoors. Photocurrent density as high as 4.5 A/cm^2 and PV cell efficiency of 14% have been obtained in the modules.

INTRODUCTION

Several attempts have been undertaken during the last decade in theoretical efficiency estimations [1-4] and practical developments [5-8] of solar thermophotovoltaic (STPV) systems. Solar thermophotovoltaic conversion is based on principle of intermediate conversion of highly concentrated solar energy into radiation by heating a photon emitter, and photovoltaic conversion of produced radiation in low-bandgap (E_g = 0.5-0.8 eV) photocells. STPV converter is a complex and closed system, which should be effective if the principle of radiation recirculation is employed. One of the ways for STPV converter efficiency increase is the development of selective emitters matched to the PV cell spectrum. Similar role may play selective optical filters, returning sub-bandgap photons back to the emitter to re-heat it. Such a filter can be made as a dielectric stack (being as a separate element or integrated one, deposited on the cell/ emitter surfaces), or as a metallic reflector on the back surface of the cells. In other words, combination of filters, metal coatings for back reflection and selective emitters open a considerable room for tailoring the energy spectrum accepted in a cell.

Theoretical efficiency limit for a STPV system is 84.5% (almost identical to the efficiency of multistack in tandem-type PV cells), so that expected practical efficiency should apparently be higher than 30%. This estimation has been indirectly confirmed by experiments with conversion of the monochromatic radiation with photon energy just a little higher than the cell material bandgap: ETA = 49% was measured in a GaSb cell under λ=1680 nm radiation [9]. Actually, in a perfect TPV system where spectral selectivity and photon recirculation principles are realized, cell illumination conditions may be close to the case of monochromatic irradiation.

In present paper different aspects of advanced STPV and TPV systems are under theoretical and experimental study such as heating the emitter by sun power, returning the sub-bandgap photons and estimating the conversion efficiency being guided by semi- empirical approaches.

ESTIMATION OF STPV CELL EFFICIENCY

Tungsten mounted in a vacuum bulb has been chosen in this work as emitter for the STPV system to realize high operational temperatures at certain spectral selectivity ensuring better spectral matching with the PV cells. Fig. 1 shows results of conversion efficiency calculations for the case of tungsten emitter illuminating an idealized PV cell (in frame of the Shockley-Queisser model). Zero ohmic losses in PV cell and zero sub-bandgap photon recirculation were assumed in the calculations. Maximum theoretical efficiencies obtained are 20-25% for PV cells with bandgaps of 0.6-0.8 eV illuminated by tungsten emitter heated up to 1800-2500 K.

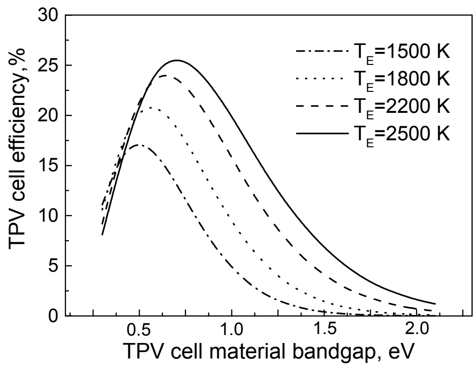

Fig. 1. Calculated efficiency of a PV cell illuminated by tungsten emitter at different temperatures as a function of cell material bandgap.

Returning the sub-bandgap photons back to the emitter results in the increase of TPV system efficiency. A part of energy returned to the emitter can be described by the equation:

$$E_{RET} = \int_{\lambda_g}^{\infty} \varepsilon \cdot r \cdot \frac{\varepsilon \cdot RE}{1-((1-\varepsilon)\cdot RE)} d\lambda \,,$$

where ε - spectral emissivity of the emitter; *RE* – return efficiency; *r* – black-body radiation spectrum. This formula accounts for the fact, that returned photons are absorbed and reflected by the emitter in compliance with its spectral emissivity. The cycles of absorptions and reflections are expressed by the geometrical progression. As it is seen from Fig. 2, maximum theoretical PV conversion efficiency exceeds 40% at 100% return efficiency and tungsten emitter temperatures of 1400-2000 K. PV efficiency of about 30% has been estimated at achievable in practice return efficiency of 90%.

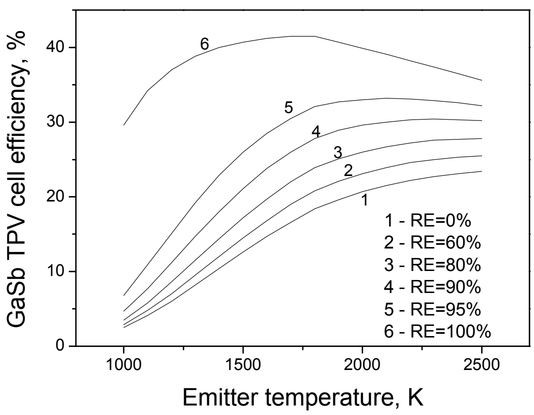

Fig. 2. Calculated efficiency of a GaSb-based PV cell as a function of the tungsten emitter temperature at different sub-bandgap photon return efficiencies.

STPV MODULE DESIGN

In a STPV system with high-temperature emitter, sunlight concentration ratio should be sufficiently high. A two-stage concentrator has been developed for the outdoor experiments. It consists of a pseudo-parabolic 0.45 m^2 mirror with focal distance of 75 cm and a secondary convex lens made of quartz [10]. The concentrator provides 220-270 Watts of sun power coming to the emitter with the aperture of 12 mm in diameter.

Figures 3-6 show the features and elements of the experimental modules of cylindrical and flat geometry.

The role of photon recirculation on emitter temperature was studied in the cylindrical module equipped with Au-coated quartz cylinder (see fig. 4,b). A tantalum emitter of 12 mm in length and 15 mm in diameter was used in this arrangement. The ratio of the transparent area to Au-coated reflecting area of quartz cylinder (reflector view factor) was equal to 0.6. Maximum emitter temperature of 2120 K was obtained under the concentrated sunlight in this case. The achieved emitter temperature was 250° higher than that in the module without reflector.

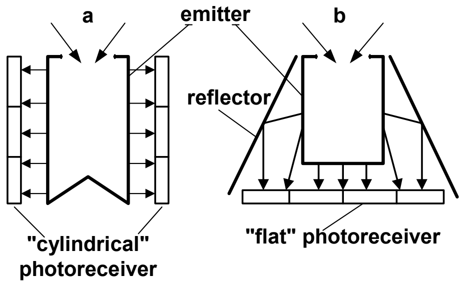

Fig. 3. STPV modules of cylindrical (a) and flat (b) geometry.

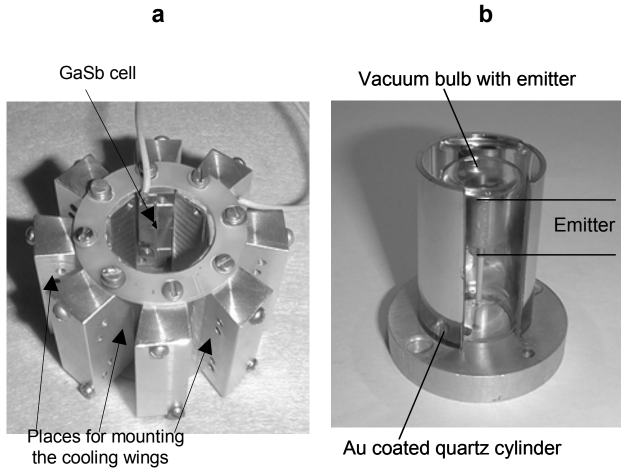

Fig. 4. PV receiver of cylindrical shape (a) with forced air-cooled cells (air-cooling wings are not shown) and arrangement for investigation of the possibility to increase emitter temperature by using an Au-coated quartz cylinder (b).

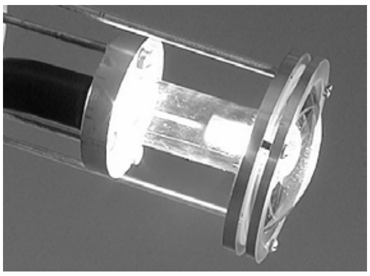

Fig. 5. Tantalum (12 mm dia) emitter inside of vacuum bulb with secondary lens in the focal spot of pseudo-parabolic facet mirror. Using the secondary lens allowed increasing the concentration ratio in 1.5-1.7 times.

In a practical system the role of reflector will play the cells with back surface mirror surrounding the photon emitter. To estimate the expected increase of emitter temperature for different values of return efficiency and view factor in a system with partially reflecting PV cells, tungsten emitter and two-stage concentrator, the special calculations had been conducted.

a b

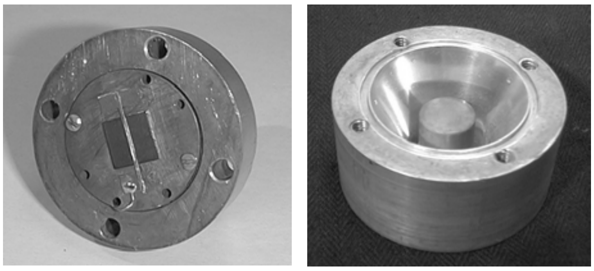

Fig. 6. STPV module with a flat PV receiver (a) and tungsten emitter surrounded by a conical reflector (b).

Described above experimental results with Au-coated cylinder were used for introduction of fitting parameters for the modules with GaSb cells in which absorption of photons with $h\nu > E_g$ takes place. Results of such calculations are shown in Fig.7. As it is seen from Fig. 7, the emitter temperature increase from 90º to 130º may take place at “reflector” view factor of 0.6 and that from 140º to 190º at the view factor of 0.9, if return efficiency increases from 60 to 90%.

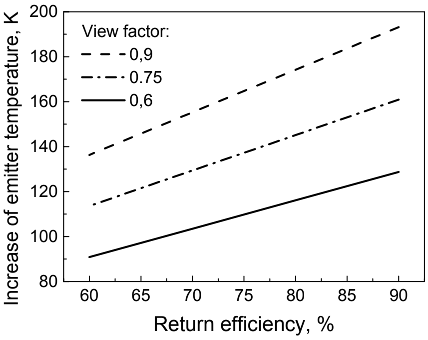

Fig. 7. The increase of emitter temperature versus return efficiency at different values of “reflector” view factor.

TPV CELLS AND PHOTORECEIVER MODULES

GaSb-based cells for cylindrical and flat photoreceivers were developed (Fig. 4,a; Fig. 5,a).

In STPV module of cylindrical type, TPV receiver is placed around the emitter. A copper heat sink cooled by forced air consists of 8 parts. Each part includes 3 TPV cells with total area of 3 cm^2. Emitter is mounted on a ceramic holder in a quartz vacuum bulb (see fig. 5). In this module, inner diameter of photoreceiver is 25 mm. Temperatures of 1800-2100 K were measured in the case of both tungsten and tantalum emitters (12 mm in diameter and 15-25 mm in height) illuminated from described above two-stage sunlight concentrator. The photocurrent density as high as 1.9 A/cm^2 was measured in GaSb cells placed at the distance of 8 mm from the emitter heated up to 1950 K.

In STPV module with flat receiver the GaSb TPV cells were mounted on a copper heat sink of 30 mm in diameter surrounded by a polished aluminum reflector of conical shape (see fig. 5,a,b).

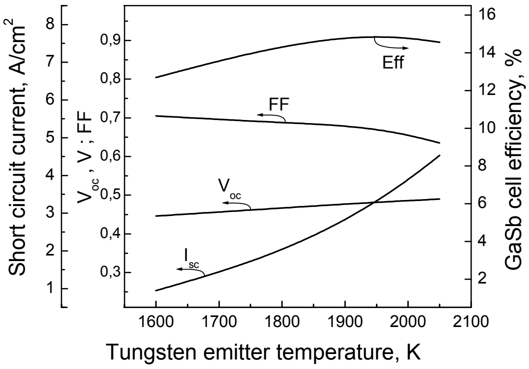

Fig. 8. Dependences of the I_{SC}, V_{OC}, FF and efficiency for GaSb cell vs. tungsten emitter temperature.

The photocurrent density J_{SC}= 4.5 A/cm^2, open circuit voltage V_{OC} = 0.48 V and fill factor FF = 0.65 have been measured in GaSb cell in this type of module at maximum temperature.

The cell efficiency exceeding 14% under illumination by tungsten emitter heated up to 1800-2100 K had been derived from experimentally measured PV parameters (see fig. 8) and the fact that actual photocurrent density was only two times lower in comparison with ultimate situation when cell is placed directly near the emitter surface.

TPV CELLS WITH BACK SURFACE REFLECTOR

Efficiency increase in an STPV system may take place if high enough return efficiencies at sub-bandgap photon recycling are realized (see fig. 2).

Fig.9 shows the main processes, which determine light reflectance from a TPV cell: photon reflection from the front surface; reflection from the back surface; and internal reflection/absorption. The influence of the cell thickness, substrate doping level and back surface contact design on sub-bandgap reflection was studied with respect to GaSb TPV cells under development. The dependences of the infrared radiation reflection coefficient for GaSb samples on their free carrier concentration and thickness were studied as well.

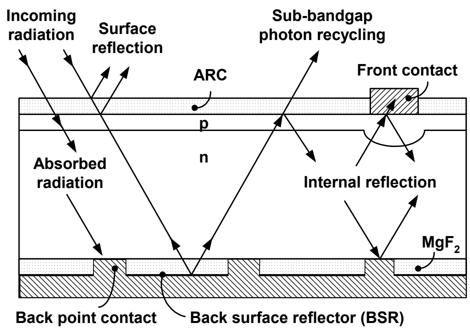

Fig. 9. Photon absorption, reflection and recycling processes in TPV cells with a back surface reflector.

To obtain a high reflection coefficient at back surface, point-type ohmic contacts were fabricated within small holes in an intermediate MgF_2 layer, which were next covered by Au (or Ag) layer. All samples had ZnS/MgF_2 ARC coatings.

Maximum reflectance of 80% at wavelengths longer than 2.0 μm (see fig. 10) has been measured for 170 μm thick GaSb cells ($n = 2x10^{17}$ cm^{-3}).

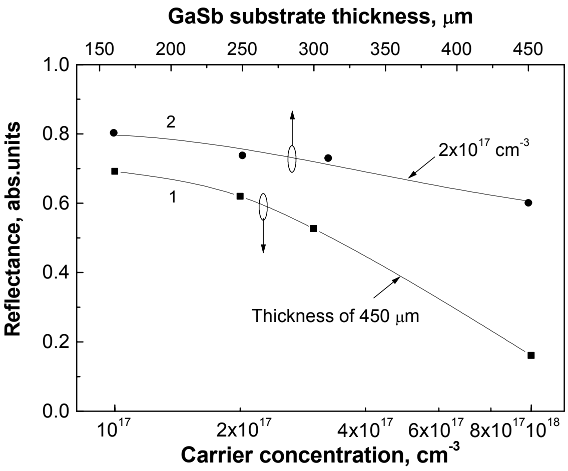

Fig. 10. Reflectance of n-GaSb samples vs carrier concentration (450 μm thick - curve 1) and thickness ($n = 2x10^{17}$ cm^{-3} - curve 2) at wavelength λ = 2100 nm.

CONCLUSIONS

Maximum photocurrent density as high as 4.5 A/cm^2 and efficiency exceeding 14% have been obtained in the GaSb-based cells under illumination from tungsten photon emitter heated in its turn by concentrated sunlight up to 1800-2100 K. Efficiency can be increased in STPV modules owing to sub-bandgap photon recirculation. It has been calculated that GaSb STPV efficiencies exceeding 30% are achievable at tungsten emitter temperatures higher than 1750 K assuming 90% reflection of sub-bandgap photons from cells to the emitter. GaSb cells with back surface reflector have been fabricated to ensure the photon recirculation. Maximum measured reflectance for sub-bandgap photons was about 80% in cells with GaSb substrates of 170 μm in thickness with a doping level of $n=2\cdot10^{17}$ cm^{-3}.

Further increase in STPV system efficiency can be achieved using the improved selective emitters made of composite structures. It may be an emitter made of silicon carbide (sunlight absorber) and coated with tungsten film (radiator), or microtexturized tungsten emitter [11], or the other materials and structures with better radiation selectivity [6]. Another way is creation the narrow-bandgap tandem TPV cells, spectrally matched with proper emitters.

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