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TPV CELLS BASED ON Ge, GaSb AND InAs RELATED COMPOUNDS FOR SOLAR POWERED TPV SYSTEMS

V.P.Khvostikov, V.D.Rumyantsev, O.A.Khvostikova, P.Y.Gazaryan, N.A.Kaluzhniy, V.M.Andreev
Ioffe Physico-Technical Institute
26 Polytechnicheskaya, 194021, St.Petersburg, Russia

ABSTRACT: Solar powered TPV systems allow using the high-temperature (> 2000ºC) vacuum emitters that insures promises for their efficiency increase. Theoretical estimations show that efficiencies exceeding 30% can be achieved in solar TPV systems characterized by the high efficiency of sub-bandgap photon recirculation. GaSb based cells with Zn-diffused emitter were developed. GaSb TPV cell efficiencies of 27-28% can be achieved at black body temperature > 2000 K assuming 90% reflection of sub-bandgap photons from the cell to emitter. TPV cells based on the p-GaAs/p-Ge/n-Ge heterostructure have been fabricated by the MOCVD, LPE and Zn-diffusion process for TPV and PV solar applications. InAsSbP/InAs cells were fabricated with the widened photosensitivity in the infrared range up to 3.5 µm.
Keywords: TPV cells, efficiency, reflectance.

1. INTRODUCTION

Only a few attempts have been made in the development [1-2] and theoretical estimation [3-4] of the solar thermophotovoltaic (STPV) converters. However, this approach has many advantages, one of which is a possibility to develop a hybrid solar-powered/fuel-fired (at night periods) system. A high power density radiated from the photon emitter in a STPV converter makes the conditions of photocell operation to be similar to the operation of the concentrator solar cells. Significant reserves for increase in STPV efficiency lie in a possibility for secondary action of photoconverters (Figure 1) on a radiation source (emitter of photons). Such a possibility is completely absent in solar PV systems. The STPV converter is a complex and more closed system, which should be more effective, if the principles of radiation recirculation and heat recuperation are employed.

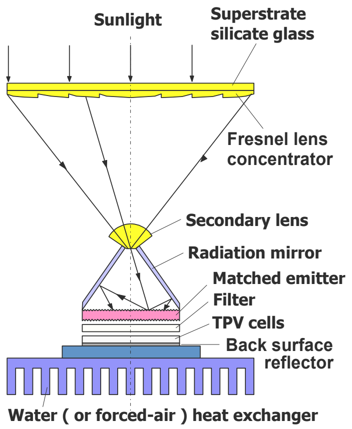

Figure 1: Concept for solar powered TPV system

There are three key problems arising at optimization of a STPV system: tailoring the emission spectrum of the photon emitter; filtering the radiation to organize photon recycling process and to reduce thermal load on the photocells; cell design allowing realization of the highest PV conversion efficiency of radiation with a given spectrum. These problems may be interconnected. For instance, selective filter as a part of the system may be situated between the photon emitter and photocell reflecting long-wavelength radiation back to the emitter. But the role of such a filter may be played by a photocell itself, if there is a mirror on its back surface, which reflects the radiation, nonabsorbed in the photocell material.

2. THE EFFICIENCY POTENTIAL OF THE SOLAR TPV CONVERTERS

In STPV systems solar energy is concentrated in the absorber through an inlet hole, but a part of power is lost due to radiation through the same hole. The inlet aperture size and correspondingly back radiation losses cannot be chosen very small because the concentration ratio K_S for sunlight is limited. The back thermal radiation increases drastically and absorber/emitter efficiency decreases as the emitter temperature rises.

Fig. 2 shows the calculated STPV efficiency in dependence on the emitter temperature, which varies only due to variation of the emitter size. The return to the emitter efficiency of radiation with $h\nu < E_g$ varied in the range of 50-90% at concentration ratio of $8{\cdot}10^3$. It is seen that in every case the curves have an optimum. The drop in the efficiency with lowering down temperature is explained by the decrease of the conversion efficiency of the GaSb PV cell, whereas the drop at high temperatures is associated mainly with rise of losses at radiation through the absorber aperture.

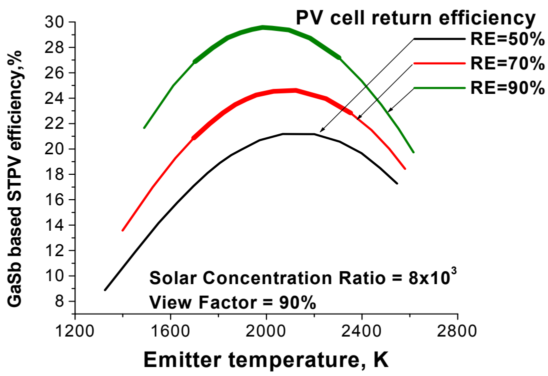

Figure 2: Calculated dependences of GaSb based STPV systems efficiency versus black-body emitter temperature for various PV cell return efficiencies.

Efficiency of 30% could be obtained in STPV system based on GaSb cells with 90% efficient sub-bandgap photon recirculation (Fig.2). The system efficiencies higher than 35% can be achieved in STPV systems with sunlight concentration higher than 10^4 suns and with selective emitters matched to cell sensitivity.

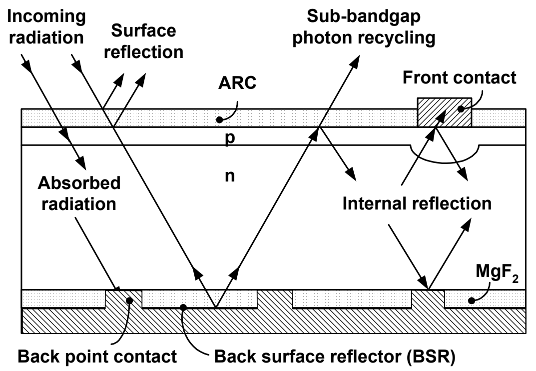

Figure 3: Photon absorption, reflection and recycling processes in TPV cells.

Photon recirculation efficiency depends mainly on the cell reflection of sub-bandgap photons. Fig.3 shows the main factors, which determine the reflectance of the developed TPV cells: 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 contacts have been studied in GaSb and Ge TPV cells, developed in this work.

3. GaSb BASED TPV CELLS

Photocell structures based on gallium antimonide were formed by the low-temperature zinc diffusion from the gas phase into GaSb wafers [5, 6] in a quasi-closed volume. Being a shallow acceptor, zinc is often used for doping III-V semiconductors, since it possesses sufficient volatility and is characterized by high Zn solubility in the solid phase.

Back-surface reflection of non-absorbed sub-bandgap photons in a TPV cell allows maximizing the efficiency of a STPV system owing to possible reabsorption of these photons in the radiator. GaSb TPV cell efficiencies and photocurrent densities calculated on the basis of measured values of fill factor and open circuit voltage, as well as the photosensitivity spectrum curve, are plotted as a function of a black body IR-emitter temperature for the different reflections of sub-bandgap photons in Fig.4.

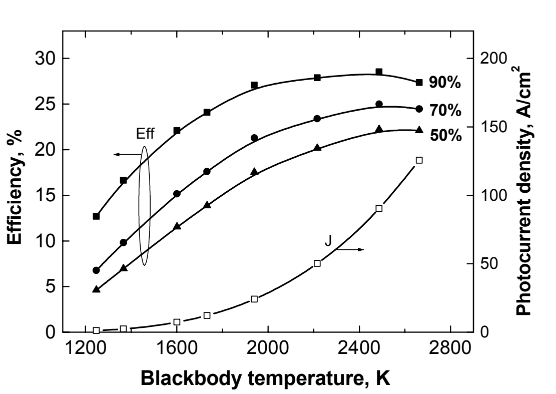

Figure 4: GaSb TPV cell efficiencies and photocurrent densities versus the black body IR-emitter temperature. 50%, 70%, and 90% reflections of sub-bandgap photons from the cell to the emitter are assumed.

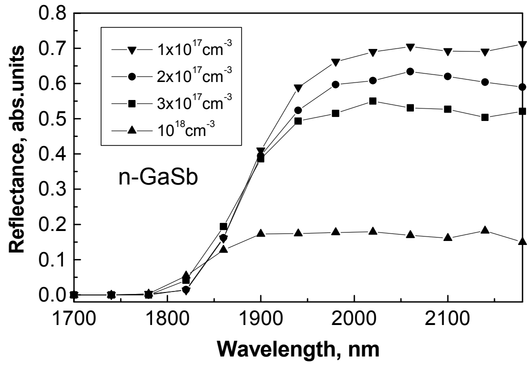

Figure 5: Reflectance of n-GaSb samples (450 μm thick) with different doping level of GaSb. The samples have the front ZnS/MgF_2 ARC coating and MgF_2/Au back-surface mirror.

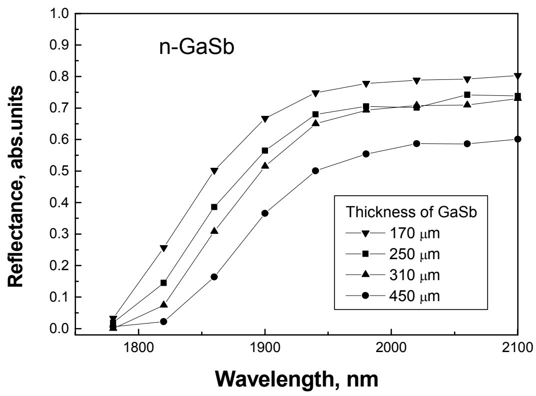

Figure 6: Reflectance of GaSb samples ($n = 2{\cdot}10^{17}$ cm^{-3}) with different thicknesses. The samples have front ZnS/MgF_2 ARC coating and the MgF_2/Au back-surface mirror.

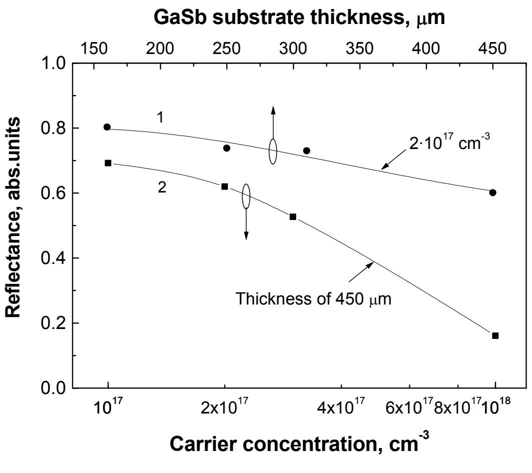

Figure 7: Reflectance of n-GaSb samples (450 μm thick) vs carrier concentration (curve 1) and different thickness (curve 2) of GaSb ($n = 2{\cdot}10^{17}$ cm^{-3}) at wavelength $\lambda = 2100$ nm.

Efficiency of 27-28% is demonstrated in this cell with 90% return efficiency under BB (> 2000 K) radiation.

In the developed GaSb cells, the back-surface mirror consists of MgF_2 and Au layers. Reflection for GaSb (Te) samples with different doping levels has been measured (Fig. 5, 6, 7). All samples have ZnS/MgF_2 ARC coating. Maximum reflectance of 80% at wavelengths more than 2.0 μm was obtained for GaSb cells (170 μm thick) with $n = 2 \cdot 10^{17}$ cm^{-3} (Fig. 6, 7).

4. Ge BASED TPV CELLS

Ge photovoltaic cells based on GaAs/Ge heterostructures were produced by MOCVD deposition, LPE growth and Zn diffusion from the gas phase. PV cell fabrication process consists of MOCVD growth of a planar GaAs layer on the surface of a Ge substrate, deposition of Si_3N_4 dielectric coating, opening of windows in the insulator, and selective diffusion of Zn. The advantages of such a method – comparatively high photocurrent density and open-circuit voltage – can be explained by the planar growth of the wide-gap GaAs window with the most uniform morphology of the growing layer and by the selective diffusion of Zn, as a result of which the p–n junction does not extend to the surface of the photovoltaic cell. The open-circuit voltage increases linearly with increasing photocurrent density to become 0.42–0.43 V at a photocurrent density of 10 A/cm^2. Fig. 8 shows how the fill factor FF, V_{oc}, and the cell efficiency behave as the sunlight concentration increases. Photocurrent density of 28.9 mA/cm^2 was obtained in GaAs/Ge cell under AM0 spectrum cut off at $\lambda < 900$ nm. The efficiency reaches its maximum of 5.5–5.7% at a 200-fold sunlight concentration. The obtained efficiency of a Ge cell is higher than reported earlier for Ge cells measured in the same condition.

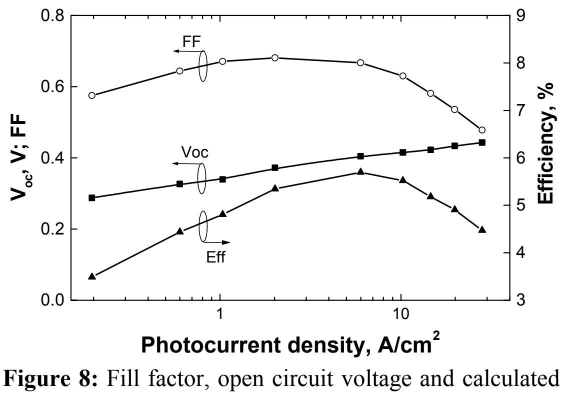

Figure 8: Fill factor, open circuit voltage and calculated efficiency versus photocurrent density for MOCVD GaAs/Ge PV cells. Conditions of illuminations: AMO spectrum cut off at $\lambda < 900$ nm.

TPV and PV cells on the p-GaAs/p-Ge/n-Ge heterostructure with a thin (0.1 μm) GaAs layer were fabricated also by the low-temperature (380 ^{0}C) liquid-phase epitaxy and by an additional Zn-diffusion process into the p-GaAs-n-Ge heterostructure [7]. The advantage of this technology compared to MOCVD, is avoiding the undesirable diffusion of Ga and As atoms from vapour phase owing to much lower growth temperature in LPE process.

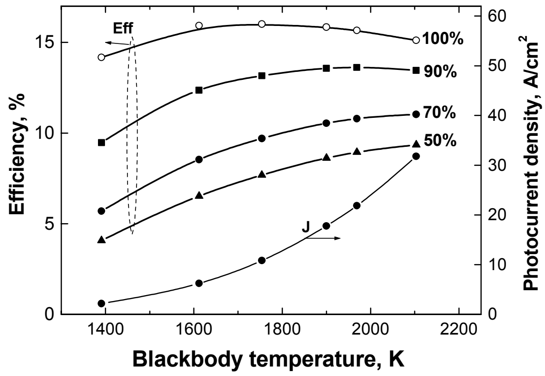

Figure 9: LPE grown GaAs/Ge TPV cell efficiencies as a function of a black-body emitter temperature. 50%, 70%, 90% and 100% reflection of sub-bandgap photons from the cell to the emitter is assumed.

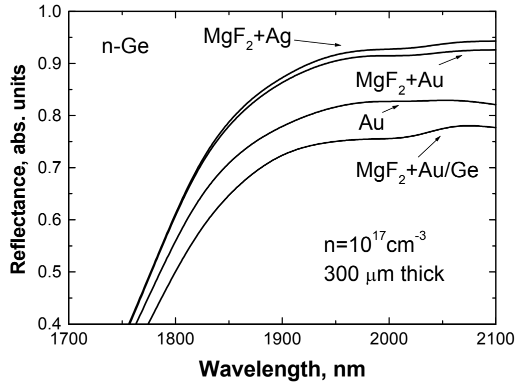

Figure 10: Reflectance vs. wavelength for n-Ge samples with different back surface mirrors. The samples have front ZnS/MgF_2 ARC coating.

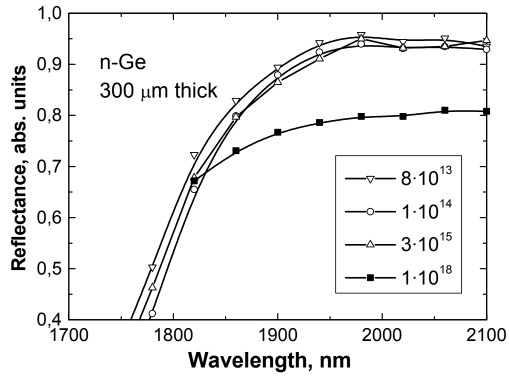

Figure 11: Reflectance vs. wavelength for n-Ge samples with different doping levels. Samples have ZnS/MgF_2 ARC coating and MgF_2/Au back surface mirror.

Fig. 9 demonstrates dependencies of efficiency, calculated on the basis of measured values of fill factor, open circuit voltage, photosensitivity spectrum curve, and photocurrent density versus blackbody temperature assuming different back surface reflectance. Efficiency of 13% is demonstrated in this cell with 90% return efficiency under BB (> 1700 K) radiation.

Reflectivity measurements of Ge samples with different back surface mirrors and with different doping levels of germanium are represented in Fig.10-11. More than 90% reflection has been observed for Ge samples of 300 μm thick and $n = 10^{17}$ cm^{-3}.

Comparison of the results presented in Fig.9 and Fig.4 shows that efficiencies in Ge cells are less than in GaSb cells. Nevertheless, the developed GaAs/Ge cells have prospects for application in the solar TPV systems taking into account the lower price of Ge wafers and possibility to obtain a higher reflectance (Fig.10, 11) for these cells in comparison with GaSb cells (Fig.5-7).

5. InAs BASED TPV CELLS

By means of LPE growth and Zn diffusion, TPV cells based on p-InAsSbP/(p-n)-InAs structures (Fig.12) were fabricated with the widened photosensitivity in the infrared spectral range up to 3.5 μm. P-n junction in these structures was formed in epitaxial InAs. Halfwidth of the rocking curve (FWHM) of the InAs substrate was 26 arc seconds. In growing the InAs layer 20-30 μm thick a decrease of the FWHM rocking curve took place down to 12 arc seconds, which proofs the necessity for crystallization of epitaxial "buffer" layer on the InAs wafer surface. Lattice-matched InAsSbP (E_g=0.45-0.48eV) quaternary alloy layers were grown on InAs substrates at 850 K by the step-cooling LPE technique, for lowering down the surface recombination rate.

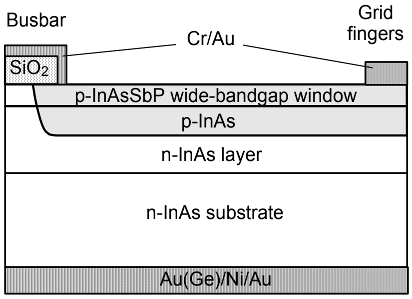

Figure 12: Cross section of a TPV cell based on the p-InAsSbP/p-n-InAs heterostructure.

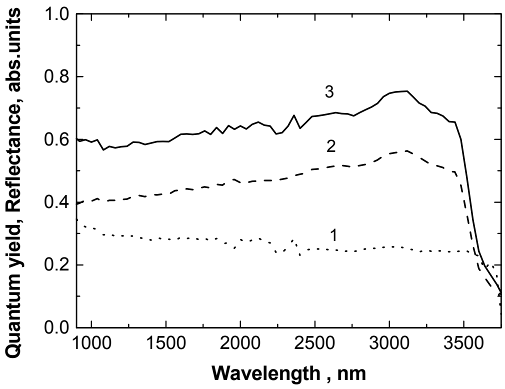

Figure 13: Reflectance (1) and spectral responses (curve 2 - external and curve 3 - internal quantum yields) of a cell based on the p-InAsSbP/p-n-InAs heterostructure.

Developed InAsSbP/InAs TPV cells demonstrate rather high photosensitivity at wavelengths λ=3.5 μm (Fig. 13) and have increased photosensitivity at the range of 1.0-3.5 μm in comparison with p-n InAs cells without wide-bandgap passivating layer [8].

6. CONCLUSION

Calculations show that the efficiencies higher than 30% can be achieved in the solar TPV systems with sunlight concentration of about 10^4 suns and with GaSb cells characterized by high return efficiency of 90%. GaSb TPV cell efficiencies have been calculated on the basis of measured values of fill factor, open circuit voltage and the photosensitivity spectra. Maximum measured efficiencies of 27-28% were achieved at black body temperature > 2000 K assuming 90% reflection of sub-bandgap photons. Maximum measured reflectance is about 80% for the GaSb sample 170 μm thick with doping level of $2 \cdot 10^{17}$ cm^{-3}. Efficiencies of 13% were obtained in GaAs/Ge TPV cells under the black-body (1700 – 2100 K) irradiation assuming the achieved 90% reflection of sub-bandgap photons.

7. ACNOWLEDGEMENTS

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