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SINGLE-JUNCTION SOLAR CELLS FOR SPECTRUM SPLITTING PV SYSTEM

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ABSTRACT: Spectral splitting concentrator photovoltaic system based on a Fresnel lens and two dichroic filters has been developed. LPE grown photovoltaic cells with a single p-n-junction based on AlGaAs, GaAs and GaSb for the wavelength range of 350-1800 nm have been developed and optimized. The effect of etching by means of anodic oxidation of Zn diffused emitter on the behaviour of characteristics of GaSb solar cells was investigated. The total PV efficiency of AlGaAs, GaAs, GaSb solar cells for the module with the splitting of the spectrum optimized for the concentration ratio of 200 suns has been estimated as ~ 37.7 % (AM1.5D).
Keywords: Concentrator Cells, Epitaxy, PV System

1 INTRODUCTION

Among the potential ways of the concentrator-photovoltaic development, the study of systems with a spectrum splitting is quite promising [1-4], along with the use of monolithic cascade A^3B^5 structures [5-6]. The use of selective optical elements in the concentrator modules is a novel tendency in the development of solar power engineering, which allows further improvement in the efficiency of photoconverters using single- and double-junction solar cells that convert various spectral ranges. A high efficiency (~40-50%) is expected for such spectral splitting assemblies. The typical constraints, which are well known for monolithic cascade structures are due to the requirement to fabricate the lattice matched multi-component compounds, can be eliminated as well as the number of intermediate layers (including high-doped layers for tunnel diodes) can be reduced. Also, the rigid requirement of current matching is less severe due to the possibility of different interconnection ways of the cells in the module. Applying the principle of spectral splitting of light allows one to choose semiconductor materials more widely, and the solar cells, which convert high-density solar radiation, can be located separately, thus simplifying both photocells and their assembly. It should also be noted that in contrast to the monolithic tandem structures, which require MOCVD technique for fabrication, the high efficient single-junction (SJ) cells can be grown by much cheaper LPE and diffusion techniques.

2 EXPERIMENTAL

2.1 Splitting photovoltaic system

In this study a spectral splitting concentrator photovoltaic system (SSCPV) has been considered. The system consists of a Frenel lens and dichroic mirror(s), which divide the solar radiation onto two or three beams. In the first case (one filter, two beams) an effective conversion of the solar spectrum can be realized with utilization of dual-junction tandem structures, e.g. GaInP/GaAs and GaInAsP/GaInAs. In the case of two filters and three beams it is possible to reach high conversion efficiency values with the use of tandem GaInP/GaAs structure supplied with two low-bandgap single-junction cells, e.g. GaInAsP (Eg~1.05 eV) and GaSb. Also high conversion efficiency can be obtained for the module with three single-junction cells, which can be grown by a relatively cheap LPE technique.

The elaborated photovoltaic system with spectrum splitting is presented in Fig. 1. The sunlight is concentrated by means of a silicone-on-glass Fresnel lens *4* and falls on multilayer filters *5* and *6*, which split the spectrum to separate portions directing towards each photoconverter the radiation of that spectral range, in which the given cell has the maximum sensitivity. Arrows indicate the path of the rays passed through the optical filters (blue color) and reflected by them (green color).

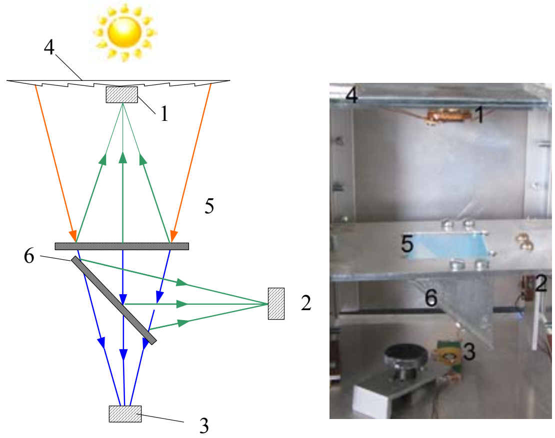


Figure 1: A spectral splitting CPV system: *1* – solar cell based on $Al_xGa_{1-x}As$ with x = 0.3-0.35; *2* - solar cell based on $Al_xGa_{1-x}As$ with x = 0-0.05; *3* - solar cell based on GaSb; *4* - concentrator based on the Fresnel lens; *5*, *6* – optical filters

Photovoltaic cells with a single p-n-junction for the wavelength range of 350-1800 nm were developed and optimized. The optical elements (dichroic filters) split the solar radiation into three light beams with wavelengths λ_1=0.35-0.9 µm, λ_2=0.9-1.8 µm or λ_1=0.35-0.6 µm, λ_2=0.6-0.86 µm and λ_3=0.86-1.8 µm. The photovoltaic converters for the short-wave spectral component were produced on the basis of the ternary compounds $Al_xGa_{1-x}As$, where x=0.3-0.35 (Eg_1 =1.86 eV) and $Al_xGa_{1-x}As$, where x=0-0.05 (Eg_2 = 1.42 eV). A possible semiconductor material for long-wavelength spectral ranges is the binary compound GaSb with Eg_3 =0.72 eV. The advantage of such spectral splitting assemblies is that the solar cell for each spectral range and the spectral range itself can be optimized independently.

All the co-designed photocells were 3.5x3.5 mm^2 in size and prepared using the low temperature liquid phase epitaxy or diffusion from the gas phase.

For practical realization of the systems with spectrum splitting, of vital importance is not only the efficiency of separate solar cells *1*, *2*, *3*, but also the high quality and stability of the parameters of the dichroic filters (at continuous wave illumination), which were manufactured by the electron-beam deposition of refractory oxides (ZrO_2, Y_2O_3, SiO_2; the number of layers is 50 or higher) onto a glass base.

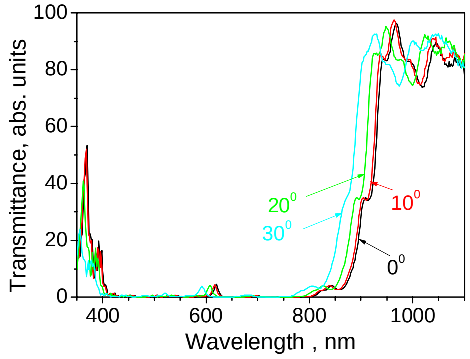


Figure 2: Spectral dependence of the dichroic mirror transmittance at different incident angles. The filter is optimized for 90^0 angle of incidence

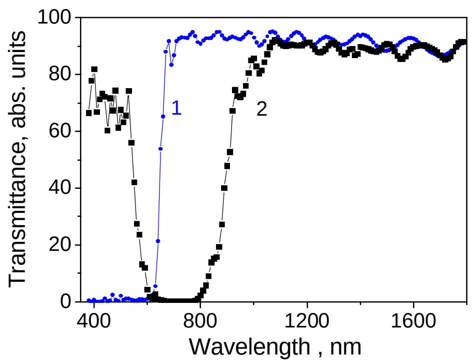


Figure 3: Dependence of the filter transmittance on the incident light wavelength. *1* – filter optimized for 13 degrees of inclination and measured at 0 degrees of inclination, *2* – filter optimized and measured for 45 degrees

One of the problems, accompanying the splitting of light is the need in the solar concentrators, which means, that there always will be a divergence in the light angle of incidence to the dichroic filter. Figure 2 presents an example of a dichroic mirror spectral throughput for different light angles. At small angles (below 10-15 degrees) the changes in the filter characteristics are minimal, while at greater angles the rejection band shifts towards shorter wavelengths more and more rapidly. Such dependence leads to a broadening of the transient range between the transmission and reflection regions, which reduces the conversion efficiency.

The lens dimensions are 60x60 mm^2 and F=105 mm. This gives the incoming light divergence of ±22^0 with the maximum density of light coming at the angle of 16^0. Filter oriented perpendicular to the optical axis (*5* in Fig. 1) can thus be optimized for the incoming light angle of 13-14 degrees, which will provide almost non-distorted spectral characteristic. Filter tilted to the optical axis (*6* in Fig. 1) should be optimized for the axis inclination angle (45^0) since the divergence of the light angle to the optical axis is not degenerate with the filter orientation. This will increase the transient range from rejection to transmission bands. Figure 3 presents the measured transmission curves of dichroic filters utilized in the developed system.

2.2. Theoretical expectations of spectral splitting efficiency

Optimization of the spectral splitting system implies both engineering of PV cells band gap and dichroic filter characteristics. Calculations of the developed module efficiency have been performed.

The calculations implied ideal PV cells in a Shockley-Queasier model and filter characteristics based on experimentally measured ones, presented in Fig. 3. Optimization process consisted of the two stages: first for each band gap optimal filter rejection edge was obtained and after that the system efficiency was calculated. The series connection of the cells was assumed. Figure 4 presents the results of such calculation for the system with three single-junction cells with a GaAs middle cell. The expected module maximum efficiency of 49.4% is reached in the ideal system with the band gap combination of 1.88-1.42-1.0 eV.

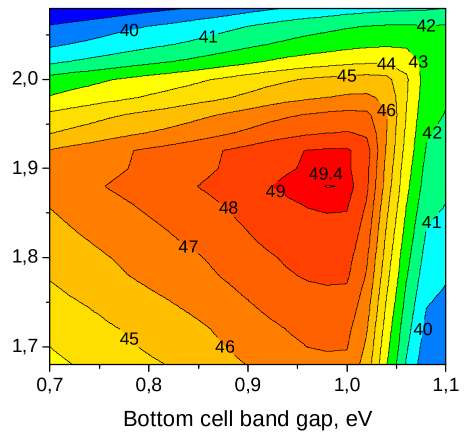


Figure 4: Efficiency of a SSCPV system (300 X concentration ratio) with three single junction cells with a 1.42 eV middle cell

2.3 AlGaAs based cells

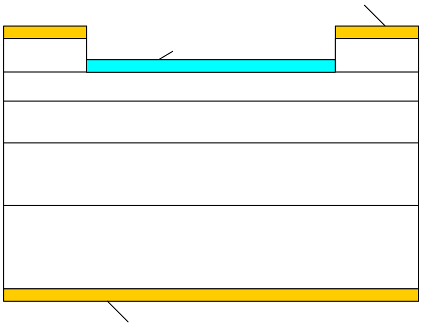
Solar cells for short wavelength region were fabricated on the base of the ternary compound $Al_xGa_{1-x}As$ with a different composition of aluminum by using the low-temperature (T<600 ^{0}C) LPE technique in a piston boat with the limited (0.3 μm) melt thickness. The multilayer AlGaAs/GaAs cell heterostructures consist of *n*-GaAs-substrate, *n*-AlGaAs layer back surface field (BSF), *n*-GaAs base, *p*-GaAs emitter, *p*-AlGaAs window and p^+-GaAs cap contact layer [7, 8].

The main advantages of such AlGaAs solar cell structures are:

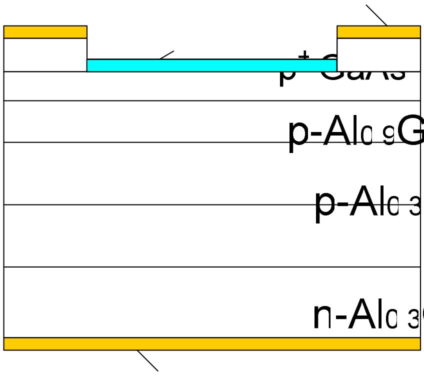
improved collection of charge carriers from the base region due to the presence of the back surface field;

high values of obtained photocurrent, which is achieved by reducing the thickness of the wide window to 0.03-0.05 μm;

reduced contact resistance and improved contact reliability due to improved adhesion of metal to the surface of the top p^+-GaAs layer.The main parameters of the layers are given in Fig.5, a,b.



a)



b)

Figure 5: Structure of a solar cell based on $Al_xGa_{1-x}As$: a) x = 0.3-0.35, b) x=0-0.05

The postgrowth treatment included the local removing of the p^+-GaAs cap layer between the photolitographically shaped contact grid fingers. ZnS and MgF_2 films were used as antireflection coatings.

Figure 6 shows the spectral characteristics of a solar cell with the aluminum content in the base layer x=0.35. The maximum current density measured at AM1.5D and λ=340-688 nm was 15.2 mA/cm^2. Figure 7 presents the measured dependence of the fill factor, the open circuit voltage and the conversion efficiency on the solar radiation concentration rate for the above mentioned cell. The maximum conversion efficiency was 19.01 % at 66 X solar radiation concentration Kc (AM1.5D) and η=17.6 % at 200 X.

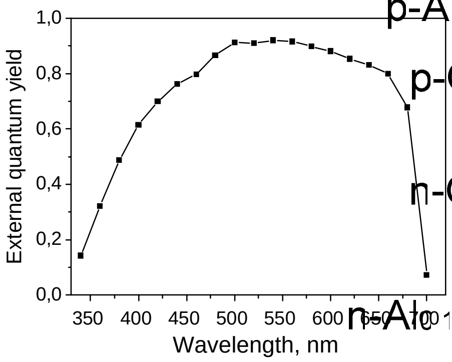


Figure 6: Spectral response of the solar cell based on $Al_{0.35}Ga_{0.65}As$

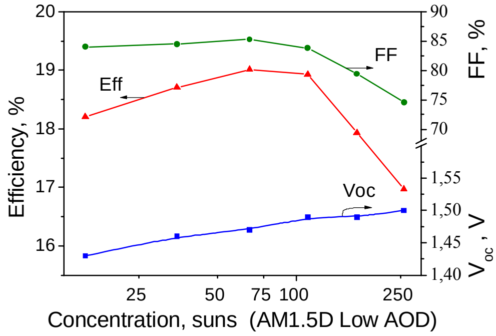


Figure 7: Dependences of efficiency, V_{oc}, and fill factor of the solar cell based on $Al_{0.35}Ga_{0.65}As$ upon the sunlight concentration ratio

For the solar cells based on $Al_xGa_{1-x}As$ with x=0-0.05, the high crystalline quality of grown layers, and the optimization of the heterostructure and the reflection losses yielded an external quantum efficiency close to the maximum value in a wide spectral range (Fig. 8).

The maximum value of the photocurrent density measured under AM1.5D (λ=340-920 nm) spectrum is 28.7 mA·cm^{-2}. The maximum efficiencies of 12.1 % under AM1.5D conditions at concentration ratio of ~200 X were obtained in the best solar cells (Fig.9).

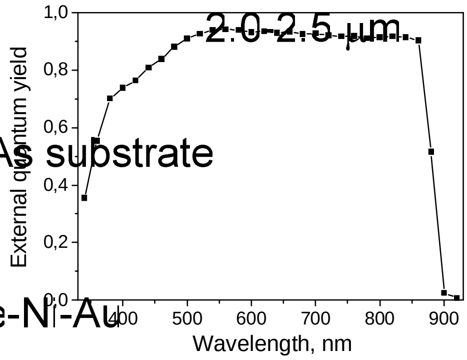


Figure 8: The spectral response curve of $Al_xGa_{1-x}As$ solar cell (x = 0-0.05)

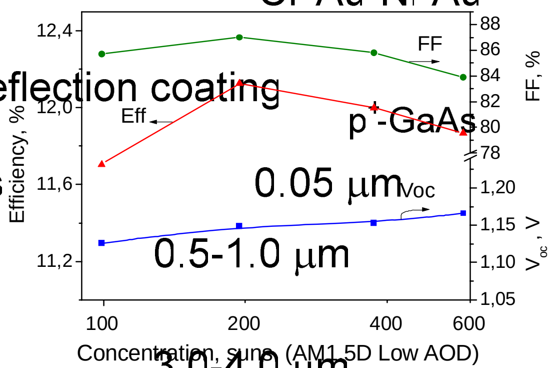


Figure 9: I-V characteristics of $Al_xGa_{1-x}As$ (x = 0-0.05) solar cell

2.4 GaSb based cells

The structure (Fig. 10) of the narrow-band solar cells based on GaSb were manufactured by two-step diffusion of Zn from the gas phase and optimized for application in the systems with a spectral splitting at high-density radiation. The ratio of the diffusion length of minority carriers and the depth of p-n-junction is crucial in achieving the maximum efficiency of the sunlight conversion. To optimize the standard technological cycle of manufacturing the solar cells based on GaSb [9, 10] the depth of p-n junction was precisely varied by means of anodic oxidation [11] and the basic characteristics of the photocell were measured. The depth of the initial *p-n* junction was about 850 nm. Fig. 11 shows the original SIMS profile of Zn after 4-hour diffusion without etching and SIMS profiles after of emitter in the range d=80-560 nm. The thickness of the extracting p^+-layer was varied in the range d=80-680 nm (the specific rate of the GaSb layer thickness reduction by anodic oxidation was around 2.0 nm/V [12]). This study has shown that the structures obtained convert optimally the concentrated solar radiation upon thinning the diffusion-produced p-n junction by 320 nm.

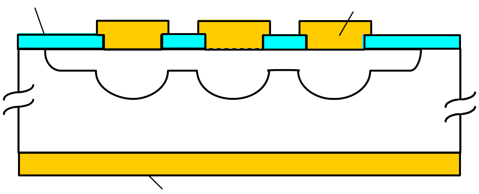


Figure 10: Structure of a solar cell based on GaSb

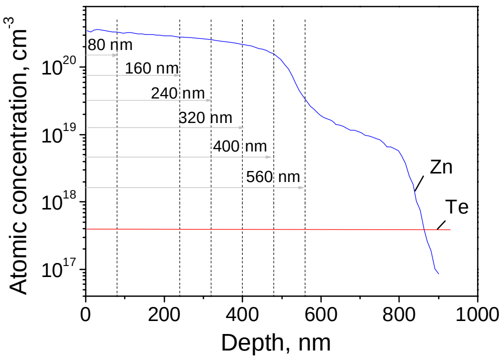


Figure 11: SIMS diffusion profiles of Zn doping in the GaSb cell structures

The maximum value of FF is found at the concentration ratio within the range of 75-100 X at the etching depth of about 600 nm (Fig. 12)

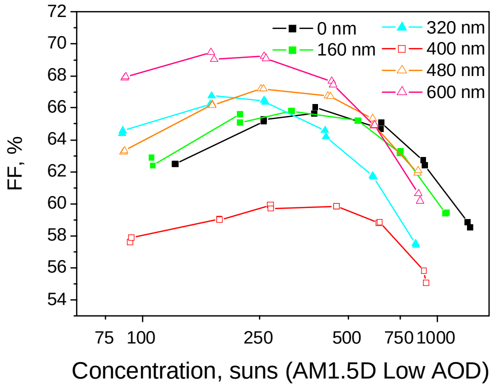
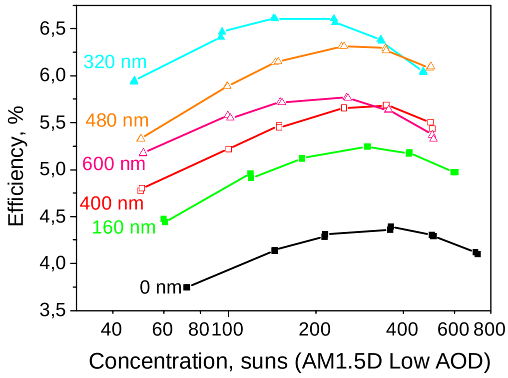
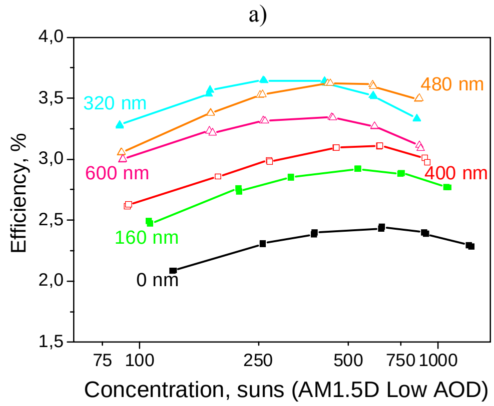


Figure 12: Dependence of the open circuit voltage (a) and fill factor (b) on the concentration ratio for a GaSb cell at different etching depth of a *p*-emitter

Fig. 13 presents the dependencies of the GaSb cells efficiency for the truncated spectral bands (λ=900-1820 nm and λ=1180-1820 nm) on the concentrations ratio at various etching depths of the diffused heavily-doped p^+-layer. The improvement of general characteristics of GaSb cells in the case of the optimal etched p^+-layer gives the gain of cell efficiency at Kc=200 X respectively at 36 and 38 relative %.



a)



b)

Figure 13: Dependencies of the efficiency (AM1.5D, 1000 W/m^2) on the etching depth of the *p*-emitter for GaSb cells: a) λ=900-1820 nm, b) λ=1180-1820 nm

Similar dependencies show the maximum contribution of this element to the overall efficiency of the system with a spectrum splitting at Kc~200 for spectral range λ=900-1820 nm is ~ 8.0 %. Thus, from point of view maximum efficiency optimum p/n junction depth is 0.23 μm after diffusion depth 0.83 μm.

2.5 Total module efficiency

The efficiency of solar cells for the module with the splitting of the spectrum optimized for the concentration ratio of 200 suns is given in Table I. Thus, total PV efficiency of system with developed cells can be estimated as about 37.7 %.

Table I: Efficiency of developed solar cells and spectrum splitting system

№	Type of cell	Eg, eV	Concentra-tion ratio	Efficien-cy, %
1	AlGaAs	1.86	200	17.6
2	GaAs	1.42	200	12.1
3	GaSb	0.72	200	8.0
total				37.7

2.6. Measurements of a SSCPV module.

Preliminary measurements of the developed SSCPV module (Fig.1) have been performed. The measurements were done under a flash-lamp solar simulator supplied with a collimator and a filter to fully simulate the solar spectrum (AM1.5D low AOD). Figure 14 presents the I-V curves of the developed module with AlGaAs-GaAs-GaSb cells. It can be seen that the current of the middle GaAs cell and the top AlGaAs one are very close. In fact slightly poorer performance of the AlGaAs cell is due to its poorer quantum efficiency, which is the subject for the further optimization. The fill factor of the AlGaAs cell I-V curve under nonuniform illumination conditions appears to be much lower, which is also the subject for further cell optimization. Yet the efficiency of the module is quite low first of all due to a poor performance of the Fresnel lens. The available Fresnel lens total efficiency is only 60±5 %, according to our measurements. The PV efficiency of the cells with the spectral splitting set-up in the SSCPV module is thus 10.6-9.7–4.4 %. With optimized concentrators of at least 80 % efficiency this will provide approx. 20 % of the module efficiency.

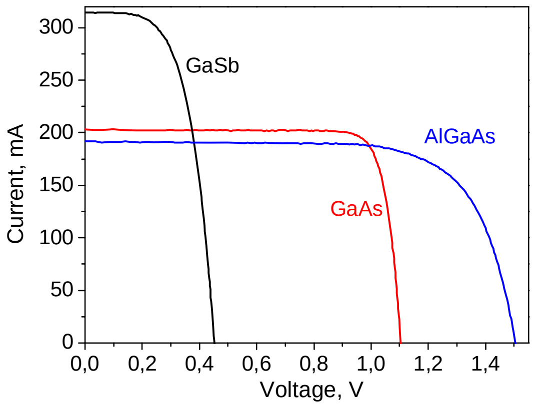


Figure 14: I-V curves of the SJ solar cells installed in the developed SSCPV module under 1 sun (AM1.5D low AOD) flash-lamp solar simulator

The excess current losses of the GaSb cell can be compensated via proper connection of the cells. The most appropriate way seems to be interconnection of the AlGaAs and GaAs cells in parallel by three, while GaSb cells can be connected in parallel by two cells. Next all the arrays are connected in series. Thus a module fragment of 3x2 cells will exhibit the best performance for the use with the developed cells.

3 SUMMARY

Systems with spectrum splitting allow simplifying the technology for manufacturing cascade photovoltaic converters, ensure the feasibility for converting the sunlight of high density, give freedom for choosing a type of electrical commutation of solar cells (in parallel or in series), which allows eventually rising the total efficiency of sunlight conversion. LPE grown photovoltaic cells with a single p-n-junction for systems with spectrum splitting based on AlGaAs, GaAs and GaSb for the wavelength range 350-1800 nm are developed and optimized.

Total PV efficiency of AlGaAs, GaAs, GaSb solar cells for the module with the splitting of the spectrum optimized for the concentration ratio of 200 suns is 37.7 %. The PV efficiency of the tested cells with the spectral splitting set-up in the SSCPV module was 10.6-9.7–4.4 %, which provides the measured module PV efficiency of 24.7 %.

4 ACKNOLEDGMENTS

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