SPECTRAL SPLITTING CPV MODULES WITH AlGaAs/GaAs/GaSb and GaInP/GaAs/InGaAs(P) SOLAR CELLS

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ABSTRACT: Development of a concentrator photovoltaic system with a spectral splitting of the solar light based on a Fresnel lens and two dichroic filters is reported. According to our estimates, the efficiency of such a module can reach 49.4% with the use of three SJ cells, while in combination of tandem DJ cell and low-bandgap cells the efficiency reaches 48.5-50.6%. SJ Solar cells based on AlGaAs, GaAs, GaSb, InGa(P)As were obtained by zinc diffusion from the gas phase in the epitaxial base layer of n-type conductivity. Tandem solar cells based on GaInP/GaAs were grown by MOCVD technique. The overall efficiency of the three single-junction solar cells developed for the module with the spectral splitting of light, was 38.1% (AM1.5D) for the concentration ratio of Kc = 200x. In the module with a cascade solar cells and an InGaAs single junction solar cell the total efficiency was 37.9% in the concentration range of 400-800x. Measurements of a concentrator photovoltaic module with a spectral splitting system have been performed. Photovoltaic module efficiency of 24.7% for the modulus of the three single-junction solar cells and 27.9% for the module with the double-and single junction cells were registered.
Keywords: III-V Semiconductors, Concentrator Cells

INTRODUCTION

Lately an interest in spectral splitting PV approach has been renewed [1,2]. Although an efficiency higher than 42 % was measured for the triple-junction solar cells, the ways of further efficiency increase can be found in a spectral splitting approach mainly due to utilization of greater amount of active p-n junctions, which can be realized due to the sample growth on different substrates. In the current paper a CPV system with a spectral splitting set up has been developed and tested.

1. APPROACH.

Ioffe institute has been intensively developing HCPV modules for the past decade [3,4]. These modules consist of "silicon-on-glass" Fresnel lenses ensuring the 300x-500x concentration ratio on the high efficiency triple-junction PV cell. In the developed system the geometrical dimensions of the Fresnel lenses were increased from 4x4 cm^2 to 6x6 cm^2 in order to decrease the optical losses, appearing with the spectral splitting set-up installation.

For splitting the solar spectrum, dichroic filters (also known as "hot" and "cold" mirrors) have been used. These optical components has several advantages. E.g., they do not change the light propagation direction, which means they can be installed inside the HCPV module, they do not absorb light and can be obtained by a simple vacuum evaporation technique. Although there are several disadvantages, limiting their range of application. The dichroic mirrors do not provide 100% reflection or transmittion values and the bandwidths of reflection/transmittion regions are limited and bound to the absolute values (e.g. the wider the reflection band, the lower reflection coefficient will be). Normally the reflected light power density is limited to a 1 W/cm^2 value for a stable long-term filter operation and, finally, the cut-off wavelength depends on the light angle of incidence. The last two features defined mainly the filter arrangement in the HCPV module. Figure 1 presents two possible system configurations, which hahe been realized. The main filter position is chosen perpendicular to the CPV module optical axis for these reasons: the light power density at this point is below 0.5 W/cm^2, while in the 45^0 inclined position its lower part appears to be exposed to a higher than 1 W/cm^2 concentrated light. Also this position is degenerate on the angle rotation which allows to optimize this filter in a way to have minimal shifts of the cut-off wavelength for all the collected light, which affects the conversion efficiency.

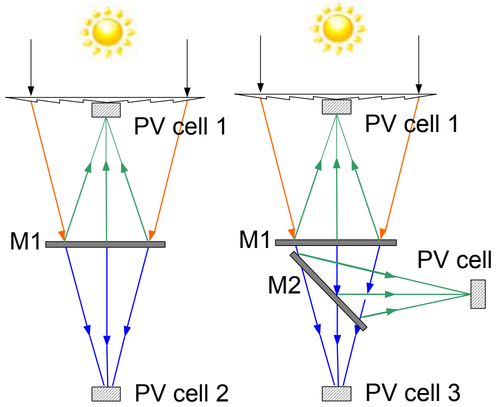

Fig. 1. Schematic of two module configurations with a spectral splitting dichroic filters.

2. THEORETICAL EXPECTATIONS

In the current work we have considered three system configurations:

Variant 1 implies one filter and two PV cells, the top one is a well known high efficient GaInP/GaAs current matched cascade structure and a single-junction IR cell. This combination resembles the well studied mechanically stacked approach without the need for transparent cell fabrication. Variant 2 like in the previous case uses a GaInP/GaAs tandem, but the IR part of the solar spectrum is split to two regions. In the third variant the solar spectrum is also split to three regions, but for the light conversion three single junction cells are used. The advantage of this approach lies in the possibility of fabrication of these cells by means of liquid phase epitaxy and diffusion, which makes them much cheaper.

The calculation implies ideal cells in the Shockley-Queisser model and ideal concentrators with a 300x magnification. The aim of the calculation was to rate the possible system efficiency and receive the optimal filter characteristics. Figure 2 presents the calculated efficiency in the variat 1 (the cells are series connected). As an example, several curves, corresponding to the different filter cut-off wavelengths are shown. The maximum efficiency of 48.5% can be reached for this case. Figure 3 presents the IR part efficiency of the system in variants 1 and 2. It can be seen surprisingly, that the efficiency increase from utilization of the 4^{th} p-n junction is only 2.1%. Such a low difference is due to the losses, introduced by an additional dichroic filter: there are always some losses on the transmission and the transitional region between reflection and transmition is wide.

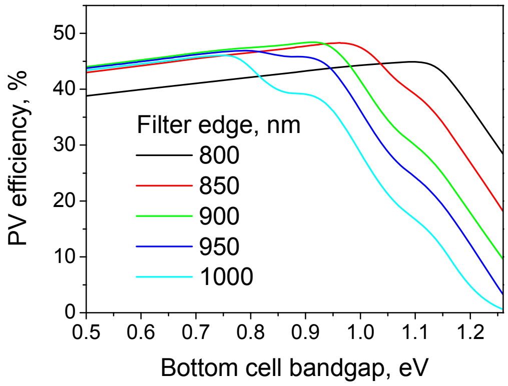

Fig. 2. Efficiency of a module in var. 1 with a GaInP/GaAs top cell. Different curves are obtained for different filter edge wavelengths.

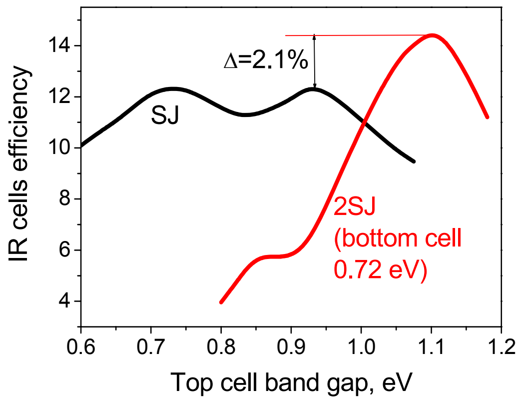

Fig. 3. Efficiencies of IR part of the module, calculated in variants 1 and 2.

Figure 4 presents the results of a calculation for the system in a variant 3 assuming a middle p-n junction to be GaAs based. The maximum value of 49.4% is slightly higher than in variant 1, which is an artifact, that appears due to the absence of a tunnel junction in the structures.

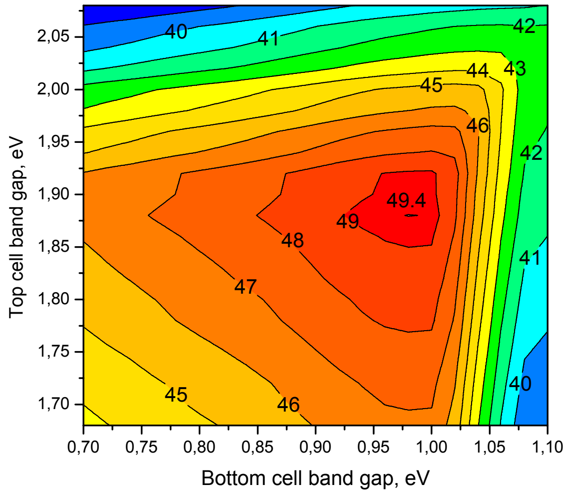

Fig. 4. Efficiency map, calculated for the system in variant 3 with a GaAs middle cell.

3. THE PV CELLS

As was mentioned in the previous section, two approaches have been realized for the visible part of the solar spectrum conversion. The first one uses MOVPE grown GaInP/GaAs monolithic tandem cells. The cell output characteristics are presented in fig. 5. The maximum efficiency of 29.2% has been reached for these cells at 100x AM1.5D conditions.

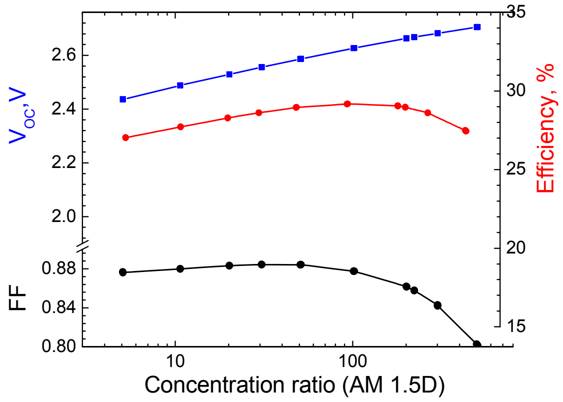

Fig.5. Open circuit voltage, filling factor and efficiency of a GaInP/GaAs double junction tandem cell at different AM1.5D concentration.

All the other cells, discussed below were grown by liquid phase epitaxy and Zn diffusion. This technique, one one hand, is much cheaper, than the MOVPE one, and on the other hand, the efficiency of single junction cells, obtained by LPE might be the same (and in some cases, like, for example, GaSb cells) even higher than MOVPE grown cells. Figures 6 and 7 present the output characteristics of AlGaAs (x_{Al}=0.3) and GaAs based solar cells, used in the variant 3 for conversion of visible solar radiation. The maximum conversion efficiency of 19% at 66X AM1.5D was registered with AlGaAs cells, while the GaAs ones revealed 12.1% @ 200x AM1.5D efficiency for the spectrum cut-off at λ<690 nm.

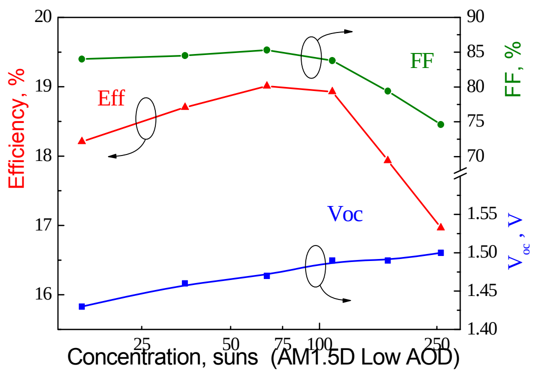

Fig. 6. Open circuit voltage, filling factor and efficiency of an AlGaAs LPE-grown cell.

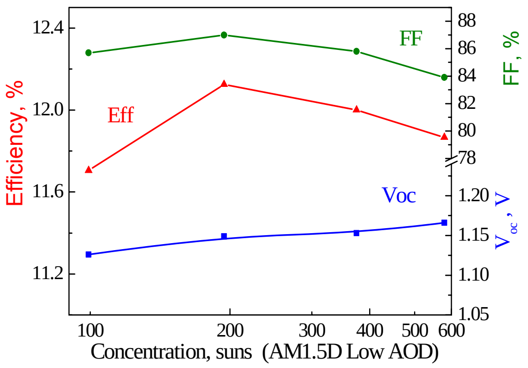

Fig. 7. Open circuit voltage, filling factor and efficiency of a GaAs LPE-grown cell. The efficiency is calculated for the spectrum cut-off at λ<690 nm

For the IR part of solar spectrum conversion, GaSb and GaInAs(P) cells have been fabricated. The GaSb cells were obtained by a double stage Zn-diffusion technique. First diffusion step is used for the active p-n junction formation, while the second one is made only under the contacts and introduces additional built-in electric field helping to gather the photogenerated current. The process of cell fabrication implies precise etching of the surface layer (~0.5 μm) containing high concentration of electrically neutral dopants. The resulting cell output characteristics are shown in fig. 8. The efficiency of 8.0% has been measured at 250x AM1.5D.

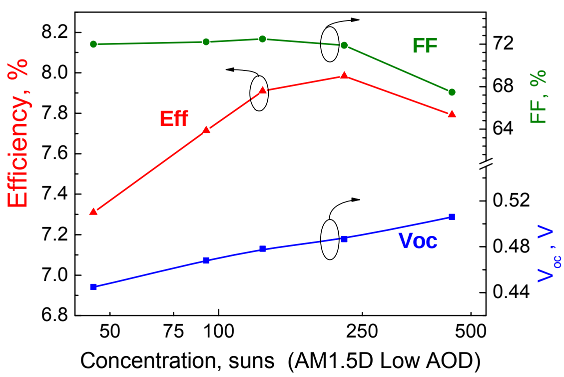

Fig. 8. Open circuit voltage, filling factor and efficiency of an optimized GaSb LPE-grown cell. The efficiency is calculated for the spectrum cut-off at λ<880 nm

The GaInAs and GaInAsP cells were produced in "inverted" n-p scheme, where the InP substrate is used as a wide band gap window. This scheme allows to reach high values of filling factor at current densities up to 10 A/cm^2 and higher, although the conversion spectrum is cut-off at λ<950 nm. The p-n junction was obtained by a Zn diffusion technique. It was found, that a preliminary annealing of the layers in phosphorous vapors leads to an improvement of all characteristics: EQE, FF and V_{OC} are increased. The Zn diffusion itselfs also was carried out in the presence of phosphorous vapours. Figures 9 and 10 show the output characteristics of an InGaAs and AnGaAsP (Eg~1 eV) cells. Efficiencies of 7.4 and 4.1 % have been registered for these cells at 500-600x AM1.5D.

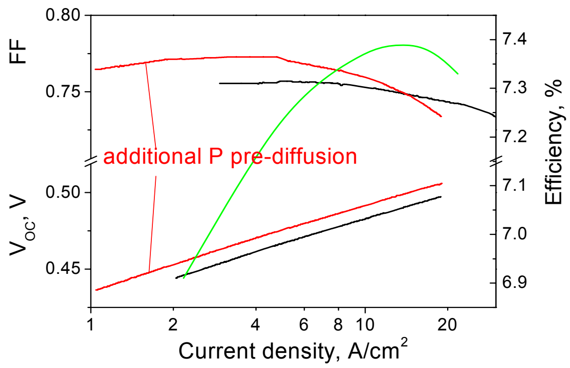

Fig. 9. Open circuit voltage, filling factor and efficiency of an optimized n-p GaInAs inverted cell with and without P,In pre-diffusion.

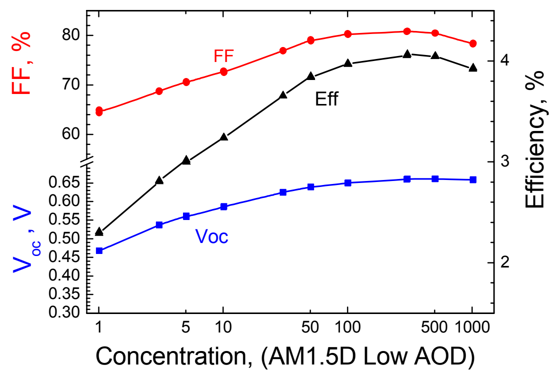

Fig. 10. Open circuit voltage, filling factor and efficiency of a n-p GaInPAs inverted cell.

To summarize this section, total cell efficiency, used in variant 1 is 27.5+7.4=34.9% at 500x, in variant 2 – 27.5+4.1+0.5x7.4=35.3, and in variant 3 - 17.6+12.1+8.0=37.7% at 200x AM1.5D.

4. THE HCPV MODULE WITH A SPECTRAL SPLITTING SET-UP

The results of HCPV module measurements differ from those, registered for the cells alone, due to the presence of a dichroic filter(s) and nonuniform distribution of solar radiation in the focal plane. The filters were obtained by a vacuum evaporation of transparent oxide layers on a glass substrate. For concentrating the solar radiation "silicon-on-glass"

Fresnel lenses with 6x6 cm^2 square aperture and 10.5 cm focal length have been developed.

Table 1 summarizes the results of I-V curves measurements of a spectral splitting HCPV module test bed in different configurations under AM 1.5D conditions. The measurements were performed under flash lamp solar simulator, supplied with a collimator. It should be noted, that the current of an IR sensitive cell is approx. 1.5 times higher than that obtained with the visible sensitive cells, and thus the excess current might be compensated by a proper 3x2 parallel / series connection with minimal energy losses. In fact, the PV efficiency of a variant 1 module is 27.9% (which is a sum of efficiencies), while in the 2x3 connected case, the efficiency lowers to 27.7% only. Variant 2 reveals even lower performance than var. 1, which results from the unproper combination of the mid cell band gap and/or the second filter characteristics, although their parameters were chosen according to the performed calculations. This result indicates the difficulties, that appear with the two-filter configuration: the actual filter transmittance curve may slightly differ from the calculated one and the InGaAsP cell absorption edge depends not only on the alloy composition, but also on the growth and post-growth conditions. Thus the 4-junction approach seem to be quite difficult and the profit of a 4th junction in this way seem to be very low. The system efficiency in var. 3 is much lower than the cell sum of efficiencies, which comes mainly from the undesirable Ohmic losses in the AlGaAs cell. Optimization of this cell should raise the module efficiency greatly.

Table 1. The PV cell efficiencies, registered in the spectral splitting CPV module.

Var. No	Cell	I_{SC}, mA	PV Eff., %	Sum of eff., %
1	InGaP/GaAs	255	21.7	27.9
	InGaAs	387	6.2	
2	InGaP/GaAs	255	21.7	26.2
	InGaAsP	138	3.1	
	InGaAs	98	1.4	
3	AlGaAs	192	10.6	24.7
	GaAs	203	9.7	
	GaSb	315	4.4	

The presented module PV efficiencies can be improved in the future. Mainly, the dropping FF values of high band gap cells can be satisfied by a proper grid step and layer structure. This will make the difference in the module vs cell alone performance lower. The var. 2 approach seem to be poorly-founded. For the 4-junction approach a monolithic double junction InGaAsP/InGaAs technology must be developed.

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SUMMARY.

The spectral splitting HCPV approach based on a Fresnel lens and dichroic mirrors has been developed and reported. The presented calculations make a promise for a high efficiency values to be reached in such systems. Three system variants with different cell and dichroic filter combination were suggested and embodied. The total PV cell performance varied from 34.9 to 37.7%. The PV efficiency of the module ranged from 24.7 to 27.9% with good chances for a connection with minimal losses.

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