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SOLID STATE ELECTRONICS

# Spectral-Splitting Concentrator Photovoltaic Modules Based on AlGaAs/GaAs/GaSb and GaInP/InGaAs(P) Solar Cells

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**Abstract**—A concentrator photovoltaic module with sunlight spectral splitting by Fresnel lens and dichroic filters is developed. The photoelectric conversion efficiency of such a module is estimated at a level of 49.4% when three single-junction cells are used and may reach 48.5–50.6% when a tandem two-junction cell is combined with narrow-band cells. Single-junction AlGaAs, GaAs, GaSb, and InGa(P)As solar sells are fabricated by zinc diffusion from the vapor phase into an *n*-type epitaxial layer. GaInP/GaAs cascade solar cells are prepared by MOS hydride epitaxy. The overall efficiency of the three single-junction solar cells developed for the spectral-splitting module is 38.1% (AM1.5D) at concentration ratio $K_c = 200$x. The combination of the solar cells with the cascade structure demonstrates an efficiency of 37.9% at concentrations of 400–800 suns. The parameters of the spectral-splitting photovoltaic module are measured. The photovoltaic efficiency of this module reaches 24.7% in the case of three single-junction cells and 27.9% when the two-junction and single-junction cells are combined.

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## INTRODUCTION

Interest in spectral splitting of light in photovoltaic (PV) converters has been rekindled in recent years [1, 2]. Although the efficiency of three-junction solar cells (SCs) has already risen to above 42%, it can be raised further using spectral splitting. In this case, the number of active *p*–*n* junctions can be increased, since they can be formed on different substrates. In this work, we describe a spectral-splitting concentrator PV system that was developed and tested.

## 1. APPROACH TO THE PROBLEM

Researchers from the Ioffe Physical Technical Institute have been extensively developing concentrator PV modules over the last decade. These modules consist of silicon-on-glass Fresnel lenses providing a concentration ratio of 300–500 suns and high-efficiency three-junction SCs [3, 4]. In the spectral-splitting system developed, the dimensions of the Fresnel lenses were increased from 4 × 4 to 6 × 6 cm to reduce optical losses. The solar spectrum was split with standard dichroic filters. The advantages of these optical elements are the following: they do not change the direction of light propagation (and therefore can be placed inside the concentrator module), do not absorb light, and can be made by the simple method of vacuum evaporation. However, dichroic mirrors suffer from a number of disadvantages. Specifically, they cannot provide 100% reflection (transmission) and their reflection (transmission) band is limited, being related to the absolute value (the wider the reflection band, the lower the reflection coefficient). For long-term operation of the filter, the reflected light power density was limited by a value of 1 W/cm$^2$ and the cut-off wavelength depended on the angle of incidence of light. These two factors governed the position of the filters inside the concentrator PV module.

Figure 1 shows two possible configurations of the system used in experiments. The main filter was placed at the point where it was normal to the optical axis of the concentrator module. Such an arrangement was selected because the light power density at this point was within tolerable limits and also because this point is degenerate in angle of rotation. This makes it possible to optimize the filter, minimize the shift of the cut-off wavelength for all the collected light, and thereby improve the conversion efficiency.

Three configurations of the system were considered.

In the first one, one filter and two (top and bottom) SCs were used. The well-known highly efficient current-matched GaInP/GaAs cascade structure was used as a top SC, and a single-junction SC converting IR radiation was used as a bottom SC. Such a combination is similar to the well-studied structure with mechanically stacked SCs, where a transparent top cell is absent.

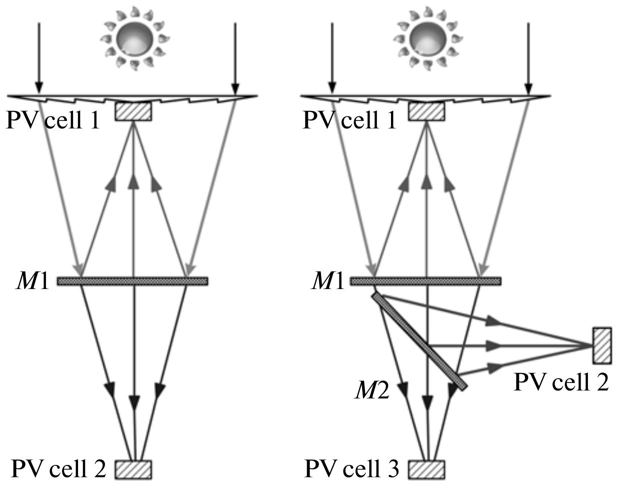

**Fig. 1.** Two configurations of the module with spectrum-splitting dichroic mirrors.

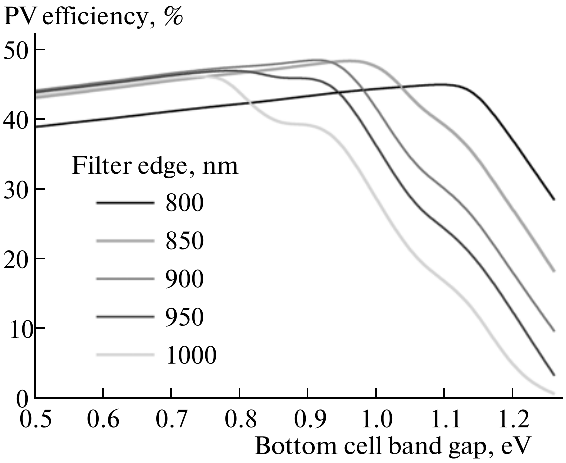

**Fig. 2.** Efficiency of the module in the first configuration with the top SC made of GaInP/GaAs. The curves are taken at different edge wavelengths of the filter.

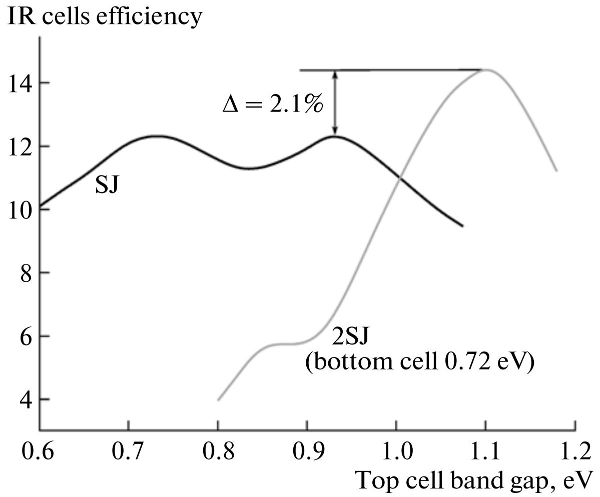

**Fig. 3.** Efficiency of the module's IR-converting part calculated for configurations 1 and 2.

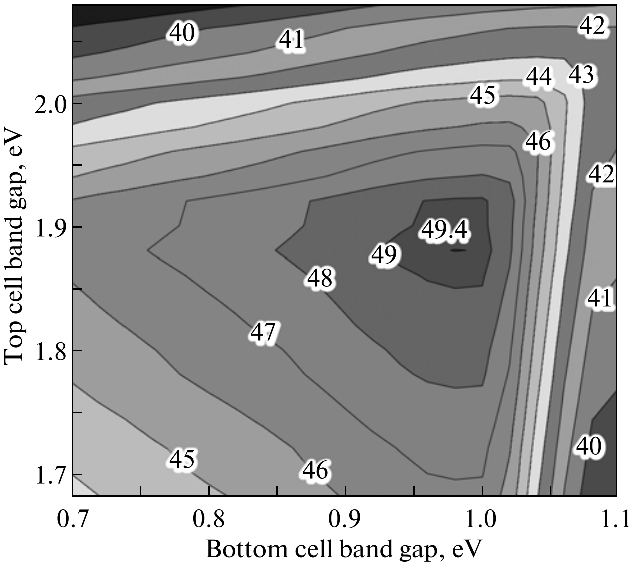

**Fig. 4.** Efficiency map calculated for configuration 3 with the middle GaAs cell.

In the second configuration, as in the previous case, a GaInP/GaAs SC is used but the IR part of the solar spectrum is divided into two parts.

In the third version, the solar spectrum was also divided into three parts but three single-junction cells are applied for PV conversion. The advantage of such an approach is that these cells can be made by liquid-phase epitaxy and diffusion, which makes them much cheaper.

We calculated the efficiencies of these modules, assuming that the Shockley junctions are ideal ($A = 1$) and so are concentrators with a concentration ratio of 300x. The aim of the calculation was to estimate the efficiency of the system and optimize the characteristics of the filters. Figure 2 plots the calculated curves of the PV efficiency for the first configuration (where the cells are connected in series). Several curves taken at different cutoff wavelengths of the filter are presented. In this case, the maximal value of the efficiency may reach 48.5%. Figure 3 shows the efficiency curves for the IR part of the system in configurations 1 and 2. Note that the rise in the efficiency due to the use of the fourth *p–n* junction is as small as 2.1%. Such a small contribution is associated with losses inserted by the additional dichroic filter: transmission losses are always present, and the transition range between reflection and transmission is rather wide.

Figure 4 shows calculation data for the third configuration, where a GaAs-based structure is used as the

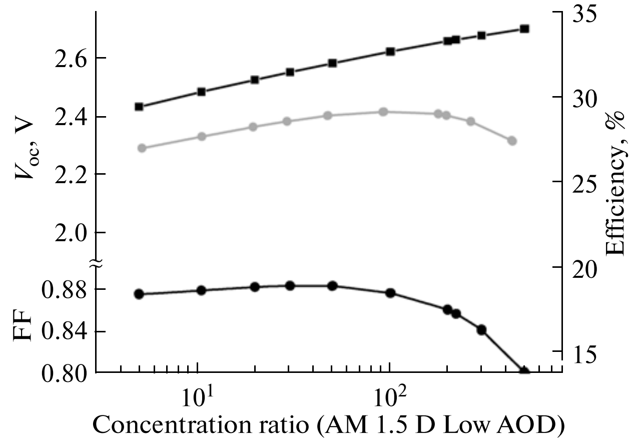

**Fig. 5.** Open-circuit voltage, fill factor of the current–voltage characteristic, and efficiency of the two-junction tandem GaInP/GaAs SC at different concentration ratios (AM1.5D).

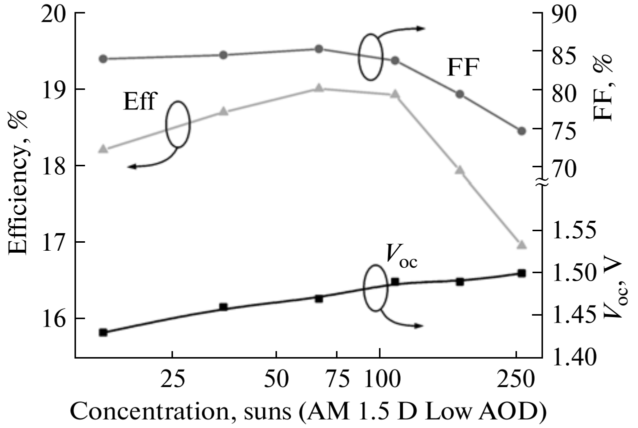

**Fig. 6.** Open-circuit voltage, fill factor of the current–voltage characteristic, and efficiency of the AlGaAs SC obtained by liquid-phase epitaxy.

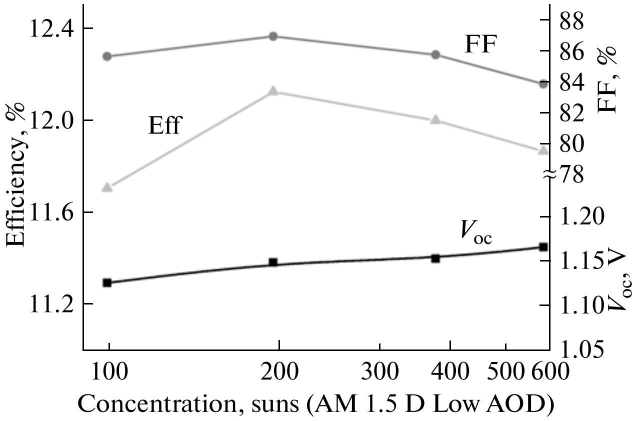

**Fig. 7.** Open-circuit voltage, fill factor of the current–voltage characteristic, and efficiency of the GaAs SC obtained by liquid-phase epitaxy. The efficiency was calculated for the spectrum cut off at λ < 690 nm.

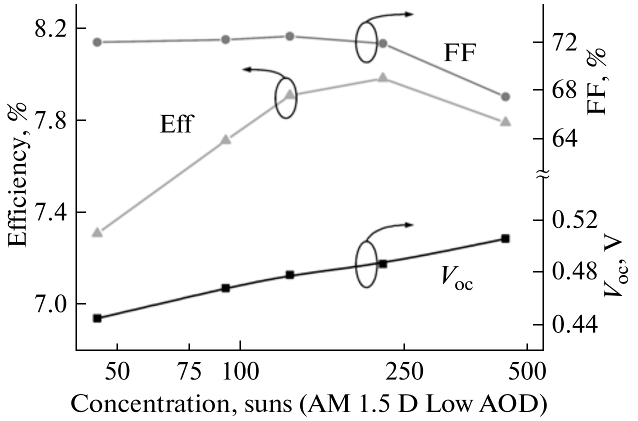

**Fig. 8.** Open-circuit voltage, fill factor of the current–voltage characteristic, and efficiency of the optimized GaSb SC obtained by liquid-phase epitaxy. The efficiency was calculated for the spectrum cut off at λ < 880 nm.

third *p–n* transition. Here, the maximal efficiency, 49.4%, is slightly higher than in the first configuration because of the absence of the tunnel junction.

## 2. PHOTOVOLTAIC CELLS

As has been already noted in the previous section, two approaches to visible solar spectrum conversion were implemented. In the first case, monolithic tandem GaInP/GaAs cells grown by MOS hydride epitaxy were used. Their output characteristics are presented in Fig. 5. The maximal efficiency achieved with such cells is 29.2% at a concentration ratio of 100x (AM1.5D spectrum).

The rest of the cells discussed below were obtained by liquid-phase epitaxy and zinc diffusion. This method is much cheaper than MOS hydride epitaxy, but the efficiency of single-element SCs obtained by liquid-phase epitaxy may be the same as (and sometimes even higher, e.g., in the case of GaSb cells, than) that of cells grown by gas-phase epitaxy. Figures 6 and 7 present the output characteristics of the AlGaAs ($x_{Al} = 0.3$) SCs and GaAs structures used in configuration 3 to convert the visible solar light. The maximal conversion efficiency, 19%, was observed in the AlGaAs cells at a concentration ratio of 66x, whereas the GaAs cells have an efficiency of 12.1% at cutoff wavelength λ = 690 nm.

The IR part of the solar spectrum was converted with GaSb cells prepared by the step diffusion of zinc (for details of this process, see [5]). The output characteristics of the GaSb SCs used in the module are presented in Fig. 8. The efficiency of these cells was 8% at a concentration ratio of 250x (AM1.5D).

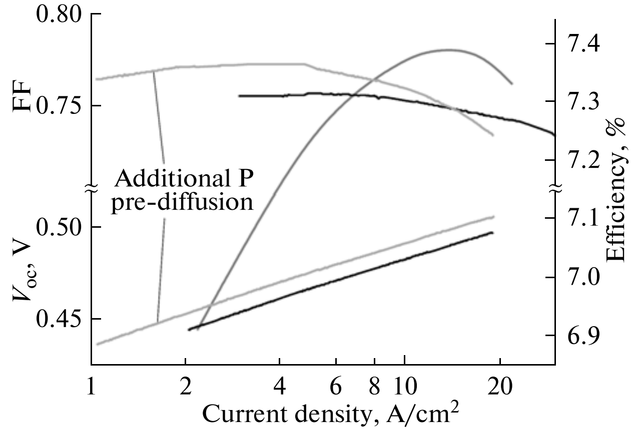

**Fig. 9.** Open-circuit voltage, fill factor of the current–voltage characteristic, and efficiency of the optimized inverted *n–p* GaInAs SC with and without prediffusion of phosphorus and indium.

GaInAs and GaInAsP cells were fabricated following the inverted *n–p* approach, where the InP substrate is used as a wide-gap window. Such an approach makes it possible to reach a high fill factor of the current–voltage characteristic at a current density of 10 A/cm$^2$ or higher. The structures were preannealed in the phosphorus vapor to improve their parameters; specifically, the external outer efficiency, fill factor of the current–voltage characteristic, and open-circuit voltage $V_{oc}$ increase [3]. Figures 9 and 10 show the output characteristics of the GaInAs and GaInAsP SCs ($E_g \sim 1$ eV). Their efficiencies equaled 7.4% and 4.1%, respectively, at a concentration ratio of 500–600x (AM1.5D).

Thus, the total efficiency of the SCs used in the different configurations was 27.5% + 7.4% = 34.9% in configuration 1, 27.5% + 4.1% + 0.5 × 7.4% = 35.3% at a concentration ratio of 500x in configuration 2, and 17.6 + 12.1 + 8.0 = 37.7% at a concentration ratio of 200x (AM1.5D) in configuration 3.

## 3. SPECTRUM-SPLITTING CONCENTRATOR MODULE

The efficiencies of the cells in the concentrator module differ from those measured on the test bench because of the dichroic filters present in the module and the nonuniform distribution of solar radiation in the focal plane. The filters were fabricated by vacuum evaporation of transparent oxide layers on a glass substrate.

The table summarizes the results of taking the current–voltage characteristics of the spectral-splitting concentrator module on the test bench at different concentration ratios (AM1.5D). The measurements were taken under the flash lamp of a solar simulator equipped with a collimator.

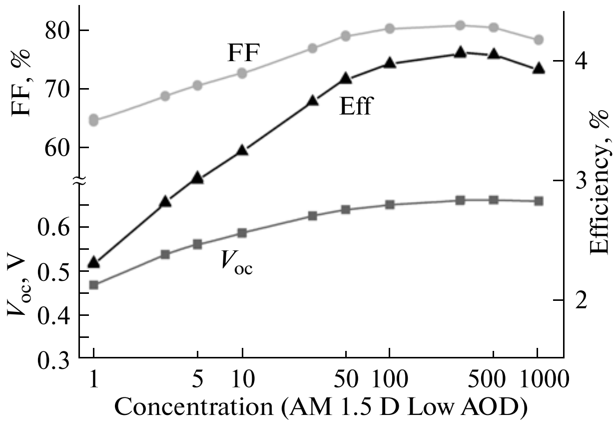

**Fig. 10.** Open-circuit voltage, fill factor of the current–voltage characteristic, and efficiency of the optimized inverted *n–p* GaInPAs SC.

It should be noted that the current of the lower IR-converting cells in configurations 1 and 3 is roughly 1.5 times greater than the current of the cells converting the visible part of the spectrum. The excess current can be compensated for using appropriate (series or parallel) 3 × 2 connection with minimal energy losses. Actually, the overall PV conversion efficiency of the module in configuration 1 equals 27.9% and decreases only slightly to 27.7% in the case of 2 × 3 connection. In configuration 2, the efficiency is still lower than in configuration 1, which results from an inappropriate combination of the bandgap of the middle cell with the characteristics of the second filter (although the latter were selected based on calculation data). This indicates problems inherent in the two-filter configuration: the transmission curve of the filter may somewhat differ from the calculated one, and the absorption edge of the InGaAsP SC depends not only on the composition of the solution but also on growth conditions. Thus, the use of four junctions presents considerable difficulties and, moreover, the contribution of the

Results of taking the current–voltage characteristic of the spectral-splitting concentrator module on the test bench at different concentration ratios (AM1.5D)

| Configuration | SC material | $I_{sc}$, mA | Efficiency, % | Overall efficiency, % |
|---|---|---|---|---|
| 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 | |

fourth junction is rather small. It may therefore be concluded that a monolithic cascade GaInAsP/GaInAs SC aimed at converting the IR part of the solar spectrum should be designed for a system with dichroic filters to take advantage of the fourth *p–n* junction. The efficiency of the system in configuration 3 is much lower than the sum of the partial efficiencies of the SCs, which in the first place is associated with optical losses in the AlGaAs cell. The overall efficiency is 24.7% in the case of the 3 × 2 connection and 21% for the 2 × 3 connection. The efficiency of the latter system can, however, be improved by optimizing the wide-gap AlGaAs cell for high-current-density operation.

## CONCLUSIONS

A concentrator module with spectral splitting by Fresnel lens and dichroic filters is developed. The efficiency of such a module may reach 48–50% according to calculations. Three configurations of the system with different SCs and dichroic filters are implemented. The overall efficiency of the SCs varies from 34.9% to 37.7%. The PV efficiency of the module is within 24.7–27.9% with the possibility of loss minimization.

## ACKNOWLEDGMENTS

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