Conversion efficiency in a solar splitting system

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Abstract. In this paper we report on concentrator photovoltaic system made by splitting the solar system based on separate Si, GaAs, and InGaN solar cells. The SSCPV module was fabricated and conversion efficiency up to 24.8% was achieved for the concentration factor of 12.8 that is in correlation with theoretical predictions.

1. Introduction

Concentration of solar radiation is a well-recognized and attractive method to increase the efficiency of photovoltaic systems. It reduces the area of expensive solar cells of a factor roughly equal to the concentration factor and makes feasible to use high-efficiency semiconductor materials of the solar cell cost-effectively. In addition, the concentration permits the collection of solar energy with low cost focusing systems such as concave mirrors or plastic Fresnel lenses. The greater the concentration, the higher the efficiency becomes. Higher concentration allows using smaller multi-junction (MJ) cells, thus making higher efficiency solar cells more cost attractive which further increases the photovoltaic system efficiency. The most efficient concentrator photovoltaic (CPV) cells today are 4-junction III-V tandem cells [1]. However, these cells have a number of deficiencies and difficulties in a fabrication:

1. The bandgaps of the solar cells (SCs) junctions that can be used are limited by the materials system;
2. Since the subcells are monolithically connected in tandem, the current of the entire cell is determined by the subcell with the lowest current;
3. Variations in the solar spectrum due to environmental changes such as atmospheric vapor change the current distribution in the cells and the overall efficiency;
4. The cells have to be electrically connected by tunnel junctions;
5. The III-V materials used are sensitive to the thermal environment; therefore efficient cooling is needed.

A higher efficiency and more flexible CPV system can be made by splitting the solar spectrum using dichroic mirrors between several single-junction (SJ) SCs [2-5]. Instead of the use of various materials connected in tandem, they can be optimized for the spectral components independently and the outputs combined remotely. Thus, spectral splitting concentrator photovoltaic system (SSCPV)
uses the best available solar cell technology over a narrow spectral range where the cells can be more easily optimized. It avoids problems of current matching and makes it more feasible to optimize the arrangement of bandgaps.

2. Calculations of spectral splitting efficiency
In this paper we discuss conversion efficiency of the SSCPV based on separate SCs. Figure 1 shows the simplest concept of splitting the solar spectrum into three ranges. Main components of the SSCPV module (figure 2) are given below:
1. Fresnel lens to concentrate the incident light;
2. Collecting lens to focus the solar beam on the solar cell;
3. Cold mirror to separate infrared and visible portions of the solar spectrum;
4. Dichroic mirror to split the spectrum into ultraviolet + blue and the rest of the visible spectrum;
5. InGaN, GaAs, Si (Ge) SCs.

The optical elements (cold mirror, dichroic mirror) split the solar radiation into three light beams. The SCs for the short-wavelength spectral component could be based on the ternary compounds InGaN/GaN (or InGaP/GaP) and GaAs/AlGaAs. Possible semiconductor materials for long-wavelength spectral ranges were considered to be crystalline silicon (c-Si), germanium (Ge) or the binary compound GaSb.

The advantage of such spectral splitting assemblies is that the SC for each spectral range and the spectral range itself can be optimized independently.

![Figure 1](image1.png)

**Figure 1.** Standard solar emission spectrum AM1.5-Global. Dash lines show boundaries of spectral ranges. The numbers 1, 2 correspond to the different variants of the spectral splitting.

![Figure 2](image2.png)

**Figure 2.** Schematic of the assembled SSCPV module.

The calculations were made by using software based on finite element method. The software was developed to simulate nitride-based and arsenide-based SCs. It allows two-dimensional (2D) simulation of the band diagram, generation rate of electron-hole pairs inside the structure, electron and hole transport inside the structure, radiative and non-radiative carrier recombination rate, electric field distribution, current-voltage ($I-V$) and power-current ($P-I$) characteristics. The software implements 2D drift-diffusion model with account for such features as elastic strain in the heterostructure layers and its effect on the valence band structure, as well as existence of spontaneous electric polarization and piezoeffect in III-nitride materials. According to the model, electrons and holes obey Fermi-Dirac statistics. Electron-hole generation rate at the point with $z$-coordinate within the $j$-th layer is calculated using the expression (1):

\[
G_j = \frac{1}{
\end{equation}
where $M$ is the concentration degree of solar irradiation, $\alpha_j(z)$ is the absorption coefficient of the $j$-th layer, $n_j(z)$ is the refraction coefficient of the $j$-th layer, $I_j(z, E)$ is the light intensity at the point with $z$-coordinate, $P(E)$ is the spectral power density corresponding to the AM1.5-Global solar spectrum.

For simulation, the solar spectrum was divided into three spectral ranges: larger than 2.48 eV (less than 500 nm), in the range from 1.7 eV to 2.48 eV (500-725 nm), and smaller than 1.7 eV (more than 725 nm) (variant 1) and larger than 2.48 eV (less than 500 nm), in the range from 1.38 eV to 2.48 eV (500-900 nm), and smaller than 1.38 eV (more than 900 nm) (variant 2). A commercially available cold mirror having cut-off wavelength of 725 nm is used in variant 1. The cold mirror having cut-off wavelength of 900 nm in the variant 2 corresponds to the bandgap of the GaAs SC. The InGaN SC that intends for operation in the spectral range less than 500 nm is a SJ structure containing two layers with a gradient change of In content having n-type conductivity and p-type conductivity, respectively, and an active layer sandwiched between them. The GaAs SC that is for spectral range from 500 nm to 725 nm (or 900 nm) consists of the following layers: p-AlGaAs, p-GaAs, n-GaAs, n-AlGaAs. The c-Si SC that is for the spectral range more than 725 nm (or 900 nm) consists of two layers of different conductivity types. The properties of the SCs based on the data presented in [6-8] are summarized in Table 1. It is necessary to note that hole mobility in the InGaN material reflects rather optimistic scenario. However lower values do not seriously influence on the results obtained.

| Property                  | InGaN | GaAs | c-Si  |
|---------------------------|-------|------|------|
| Electron mobility, cm$^2$/((V·s)) | 400   | 6000 | 1350 |
| Hole mobility, cm$^2$/((V·s))     | 50    | 400  | 400  |
| Dislocation density, cm$^{-2}$    | $10^8$| $10^8$| $10^8$|

The total conversion efficiency ($\eta$) for both variants was calculated in accordance with the expression (2):

$$\eta = \sum_i(\eta_i \cdot k_i) = \eta_{\text{InGaN}} \cdot k_{\text{InGaN}} + \eta_{\text{GaAs}} \cdot k_{\text{GaAs}} + \eta_{\text{Si}} \cdot k_{\text{Si}}$$

where $\eta_i$ is the efficiency of $i$-th SC and $k_i$ is the integrated power density in the operating range of $i$-th SC. Table 2 and Table 3 summarize the simulation results.

| SC ($i$) | Operating range $\Delta \lambda$, nm | In-band efficiency concentration of 1000 $\eta_i$, % | Part of the integrated power density ($k_i$), % | $\eta (\sum_i(\eta_i \cdot k_i))$, % |
|----------|--------------------------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------|
| InGaN (1) | < 500                               | 62.5                                          | 18.3                                          | 11.4                              |
| GaAs (2)  | 500-725                              | 53.9                                          | 32.8                                          | 17.7                              |
| c-Si (3)  | > 725                                | 2.6                                           | 48.9                                          | 1.3                               |

Table 1. Properties of InGaN, GaAs, c-Si used in the simulation.

Table 2. Simulated SSCPV total conversion efficiency (variant 1).
Table 3. Simulated SSCPV total conversion efficiency (variant 2).

| SC (i)     | Operating range Δλ, nm | In-band efficiency concentration of 1000 \( \eta_i \), % | Part of the integrated power density \( k_i \), % | \( \sum_i (\eta_i \cdot k_i) \), % |
|------------|------------------------|----------------------------------------------------------|-----------------------------------------------|---------------------------------|
| InGaN (1)  | < 500                  | 62.5                                                      | 18.3                                          | 11.4                            |
| GaAs (2)   | 500-900                | 58.4                                                      | 50.1                                          | 29.3                            |
| c-Si (3)   | > 900                  | 0.4                                                       | 31.6                                          | 0.1                             |

Low in-band efficiency of c-Si SC was due to the low absorption coefficient of c-Si in the considered spectral range. However, c-Si could be easily replaced with Ge to achieve higher total efficiency.

Figures 3, 4 show the following dependencies: in-band efficiency vs. voltage and I-V characteristics for the GaAs, InGaN SCs in the module.

The total conversion efficiency taking into account the optical losses dropped to 19.3-20.8% for variant 1 and 25.7-27.8% (variant 2) depending on the type of transmissive material for cold and dichroic mirrors.

In a more complex concept, although still simple to implement, the spectrum can be split into an arbitrary number of components for which optimized cells can be made. We guess the subcells can all be made using InGaN. Since the general acceptance that the bandgap of InN is ~0.65 eV, InGaN has been recognized as an attractive candidate for efficient covering practically full solar spectrum. The main limitation is the difficulty of growing high-quality InGaN layers with high In content due to the segregation of In during growth. InGaN is not yet sufficiently developed to address the longer wavelength portion of the solar spectrum. For the solar spectrum from near UV to blue, the efficiency of InGaN solar cells is very high. A number of groups have demonstrated very high internal and external quantum efficiencies [9, 10].

3. Experimental results

Figures 5, 6 show the SSCPV module that was fabricated to verify a concept of the spectral splitting system. The measurements were done under solar simulator (Newport) supplied with a Xe lamp, a collimator and a filter to fully simulate the solar spectrum (AM1.5-Global).
The total efficiency of the InGaN, GaAs, Si SCs for the module with the splitting of the spectrum optimized for the concentration ratio of 12.8 suns is given in Table 4. Thus, total efficiency of system with developed cells can be estimated as about 24.8%.

### Table 4. Measured total conversion efficiency of the SSCPV module.

| SC (i)  | Operating range Δλ, nm | In-band efficiency at concentration factor of 12.8 (η_i), % | Part of the integrated power density (k_i), % | η_i · k_i, % |
|---------|------------------------|------------------------------------------------------------|---------------------------------------------|-------------|
| InGaN (1) | < 500                  | 33.3                                                       | 18.3                                        | 6.1         |
| GaAs (2)  | 500-725                | 24.7                                                       | 32.8                                        | 8.1         |
| Si (3)    | > 725                  | 21.7                                                       | 48.9                                        | 10.6        |
| η = Σ(η_i · k_i), % |                                |                                                            |                                             | 24.8        |

### 4. Conclusions
The solar spectrum can be split into three spectral ranges for which optimized cells can be fabricated. This frees the MJ cell from the current-matching constraint, eliminates tunnel diodes and each subcell can be optimized independently. Experimental overall conversion efficiency for the SSCPV module consisting of InGaN, GaAs, Si SCs is equal to 24.8% at the concentration ratio of 12.8 suns. This result correlates with the theoretical predictions.

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