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Three-Dimensional Point-Focus Spectral Splitting Solar Concentrator System

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Abstract Spectral splitting solar systems are emerging as alternative solutions to multi-junction solar cells for cost effective high efficiency photovoltaic applications. We have recently proposed a low cost single element splitting system based on a prismatic structure able to contemporary split the solar light into its spectral component and concentrate them. Here a new design of the spectral splitter is proposed and the optimization study of the entire solar system (solar splitter and solar cells) is conducted. The considered spectral splitter/concentrator consists of a three-dimensional point-focus system made of a disposition of dispersive elements. The advantages of this new design are discussed in detail and results of the optical simulations are reported. The optical system is then combined with a set of three solar cells, each of them illuminated with a different spectrum band. Simulations with Sentaurus TCAD are carried out with the aim of optimizing the electrical and geometrical properties of the devices. We obtained an overall efficiency of 28 %, which represents a good starting point for spectral splitting solar systems to compete with multi-junction solar cells technology.

Keywords Spectral Splitting Solar Systems, Concentrated Photovoltaic Systems, Optical Simulations, Photovoltaic Cells, Homo-Junctions

1. Introduction

In the last fifty years, the need for alternative and renewable sources of energy has become pressing. This is driven by environmental concerns, increasing demand for energy as well as by the progress in energy technologies. Among all renewable sources of energy, solar energy is by far the most abundant. This aspect, combined with its inexhaustibility, contributes to make this source very intriguing for energy harvesting.

Photovoltaic (PV) technology is among the best ways to harvest this enormous amount of energy. Until now, different PV technologies have been proposed [1] and their capabilities in converting the solar energy into electrical energy have been reported [2]. However, in order to promote PV technologies to plant scale power generation level, some key issues need to be addressed [3, 4]. Addressing issues such as scarcity of raw materials, refinement cost and low efficiencies would allow reaching the grid-parity and making the PV technology costly competitive with other energy harvesting technologies.

So far, different solutions to overcome the limitations of PV technology have been proposed. For single junction devices, attempts to reduce materials costs [5-7] and to increase energy absorption [8-10] have been proposed. However, due to the spectral width of the solar emitted radiation, the efficiency of any single bandgap solid state converter is inherently limited. These limitations have been object of intensive studies by Shockley and Queisser [11] who derived the maximum theoretical efficiencies of single-junction PV devices depending on their bandgap. The simultaneous use of a set of junctions made of different materials to convert the solar light provides a mean to overwhelm these limitations and to achieve higher efficiencies with theoretical limits approaching 85 %. This technological solution can be implemented stacking solar cells one on top of each other in the so called Multi-Junction (MJ) solar cells. The bandgap decreases from the uppermost to the lowermost cell and this allow the radiation that is not converted by the top cell to reach the lower one due to the material's transparency to radiation below its bandgap. However, MJ solar cells impose severe restrictions in terms of material choice and growth processes. Lattice matching problems and consequent defects formation seriously undermine MJ solar cells performances. In order to minimize this problem, the fabrication process of such cells requires epitaxial growth techniques. This approach has been proved to be commercially viable in terrestrial systems only under very high concentration to offset the high cell cost. An alternative technological solution consists in splitting the light into spatially separated spectral region to be converted

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with properly selected single-junction solar cells. Proposed for the first time by *Borden at al.* [12], the main advantage of this approach is the accessibility to a broader group of materials. Indeed, lattice-matching requirement no longer applies since different junctions are not stacked one on top of the other, but are simply disposed in parallel. The validity of this approach is testified by several reports of high laboratory efficiencies, an extensive review of which can be found in [13].

We have recently proposed a two-dimensional single optical element system which integrates the concentrating and spectral splitting actions [14]. The optical element is defined as a set of solid transparent dispersive prisms, each operating independently. They are designed in order to deflect and split a polychromatic collimated light beam from a given direction onto the same area of a receiving target. The resulting concentrated and spectrally divided beam is simply obtained by the superimposition of each prism contribution. The orientation of the set of prisms is such that the light rays of a specific reference wavelength are mapped on the same target as depicted in Fig. 1.

In the two-dimensional design, the element was extended into the third dimension by the extrusion of the two-dimensional contour. Details on the design process and the underlying equations can be found in [14]. However, this prevents us from obtaining a concentrated and spectral split two-dimensional light pattern that would, in addition to having a higher concentration, create acceptable target cell geometries.

Here we propose the design of a three-dimensional point-focus spectral splitting solar concentrator system. The basic principle behind its functioning is the same explained in [14]. However, this new system is not simply obtained extruding the two-dimensional design. In the following, the mathematical framework used in designing the structure is explained. Furthermore, the study of the minimization of the optical losses at the interfaces of the structure is conducted. The analysis comes together with optical simulations of the system performed with the software TracePro. The concentrated and split light obtained with the optical system is then used as input for solar cell simulations. A set of three photovoltaic devices (Ge, Si and GaAs solar cells) is simulated with Sentaurus TCAD. The goal is to find the optimal configuration in terms of thickness and doping concentration for the conversion of the specific wavelength range. The validity of the overall system is testified by the achievement of high efficiencies, approaching 28%.

2. Optical Design Principles

The optical element is made of a set of transparent dispersive prisms, each of them operating independently. They are designed to deflect and split a polychromatic collimated light beam onto a receiving target. Each of them contributes individually to the formation of the concentrated and spectrally divided beam.

A dispersive prism is an optical element able to split a collimated beam of light according to the wavelength. This is basically due to the dependence of the phase velocity of the optical wave on its frequency. The essential parameters that affect the prism behavior are the angle formed by the entrance facet with the light rays (defined in Fig. 2 as I_1) and the apical angle of the prims (defined as A).

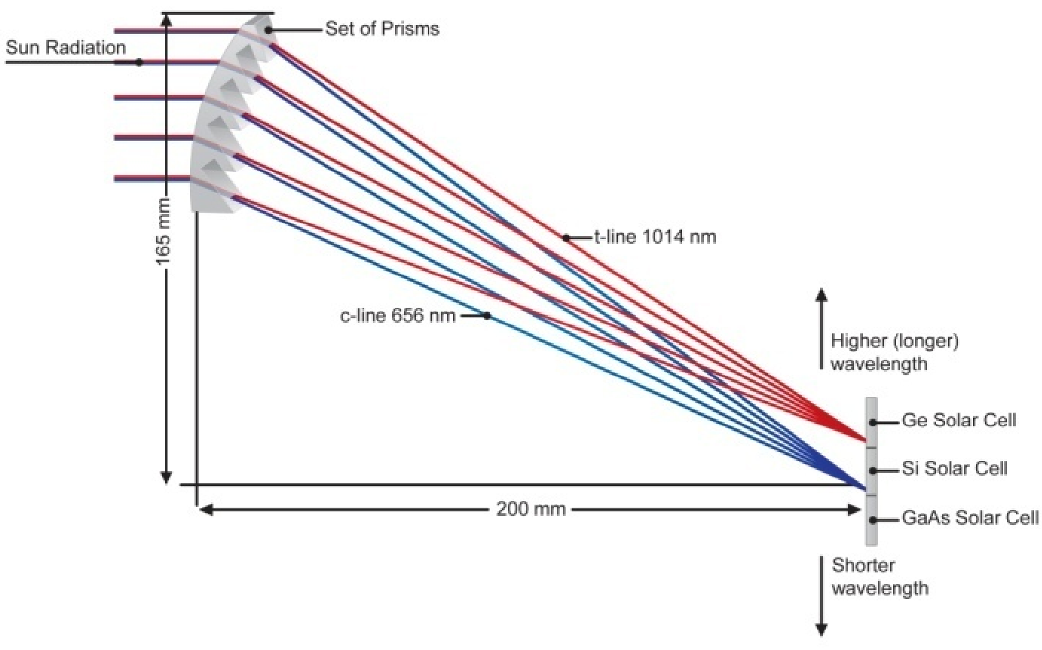

Figure 1. Conceptual drawing of the concentrator/spectral splitting system proposed in [14]. The system is a set of microprisms designed to deflect two reference wavelengths on two distinct points on the photovoltaic receiver

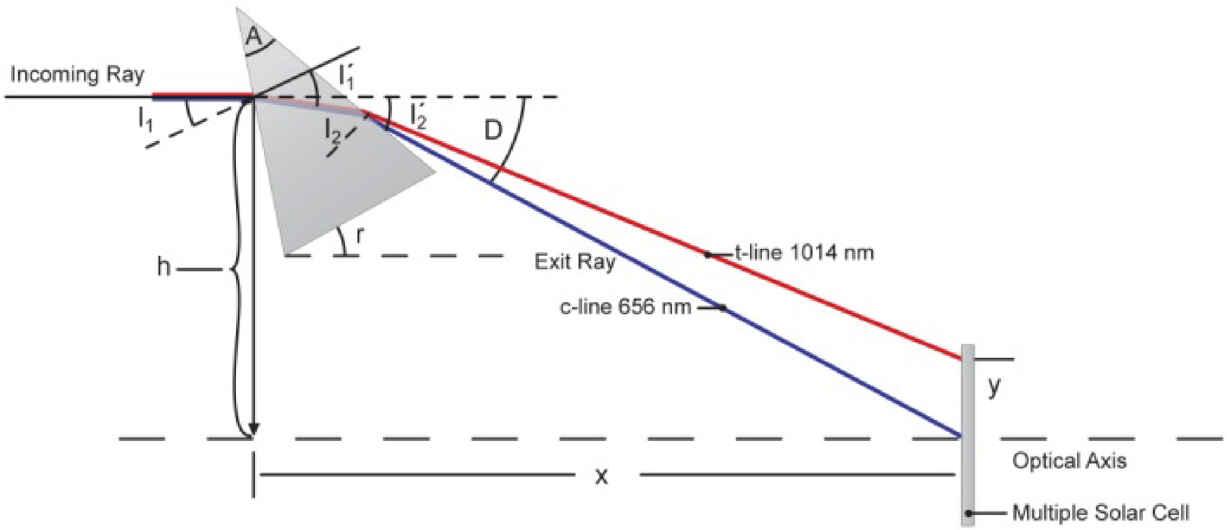

Figure 2. Drawing of a single prism: A is the prism apex angle, I_1 and I_2 are the beam entrance/exit angle with respect to the relevant facets, r characterizes the rotation of the prism basis with respect to the optical axes, while h is the “height” of the entering light beam with respect to the reference center of the focal plane

The index of refraction is indicated with n_λ and it is function of the wavelength of the considered light. The behavior of the n_λ is obviously dependent on the choice of the material. A study of the optimum material for this application is conducted in [14]. To model the optical system, we start by studying the behavior of the single dispersive prism represented in Fig. 2. The deviation angle between the incoming and exiting ray D_λ is:

$$D_\lambda = I_1 - A + \sin^{-1}\left\{ n_\lambda \cdot \sin\left[A - \sin^{-1}\left(\frac{1}{n_\lambda} \cdot \sin(I_1) \right) \right] \right\} \quad (1)$$

By choosing a reference wavelength and optimizing the geometrical parameters such that the incident beam is deflected towards the center of the receiver, the desired deviation $D_{\lambda ref}$ for the reference wavelength reads:

$$D_{\lambda ref} = tg^{-1}\left(\frac{h}{x} \right) \quad (2)$$

where x defines the axis parallel to the direction of the incident light on the prism. In this particular design, the entrance angle is not constrained. This allows optimizing the design of each single prism from equation (1). The final system, composed by several optimized prisms, closely resembles a double Fresnel lens.

In the two-dimensional design proposed in [14], the element was extended into the third dimension simply by the protrusion of the two-dimensional contour. In order to design a three-dimensional point-focus optical element, instead, it becomes necessary to change the angle D_λ. Each prism’s exit facet is tilted with respect to its corresponding input facet by an angle u, such that the exiting light overlaps on the adjacent prism’s output. This tilt angle $\boldsymbol{u}$, is defined via geometry by using Snell’s law such that every corresponding wavelength forms a point on a planar receiver that is no larger than 10 mm in width and height – typical dimensions for photovoltaic devices in a concentrated photovoltaic (CPV) system.

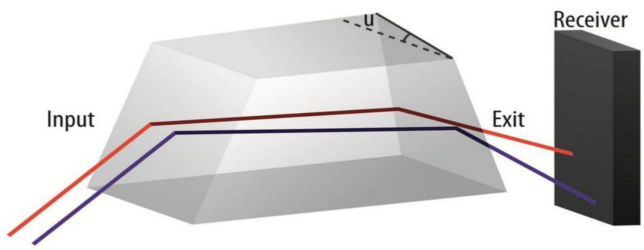

Figure 3. Schematic illustration of one prism in the point-focus optical element. Note the angle $\boldsymbol{u}$ corresponding to the tilt the exit facet has with the entrance facet

Fig. 3 shows a schematic representation of $\boldsymbol{u}$ in one prism constituting the 3D optical element. The value of the tilt angle varies along the dimensions of the concentrator in both transverse directions with respect to the incident light.

Fig. 4 shows one possible design of the three-dimensional optical element. Simulations performed with a commercial raytracing software tool (TracePro) testify that this system is capable of geometric concentration ratios reaching up to 210 for any given wavelength. This condition was determined setting properly the deviation angle D_λ and the tilt angle $\boldsymbol{u}$, while maintaining a minimum average weighted optical transmission efficiency of 76%. The uppermost value for the concentration ratio is determined by the number of prisms in the optical element.

In order to maintain a high optical efficiency, the choice of the material plays a fundamental role. Polycarbonate (PC) was found to be an appropriate candidate for the given application, given its transparency in the 400 nm – 1300 nm region and its dispersive qualities.

Figure 4. Pilot 3D point-focus solar spectral splitting optical element

3. Spectral Splitting Solar System

The spectral splitting solar system we propose consists of the optical element previously introduced and a set of solar cells aimed at converting the spectrally separated solar rays.

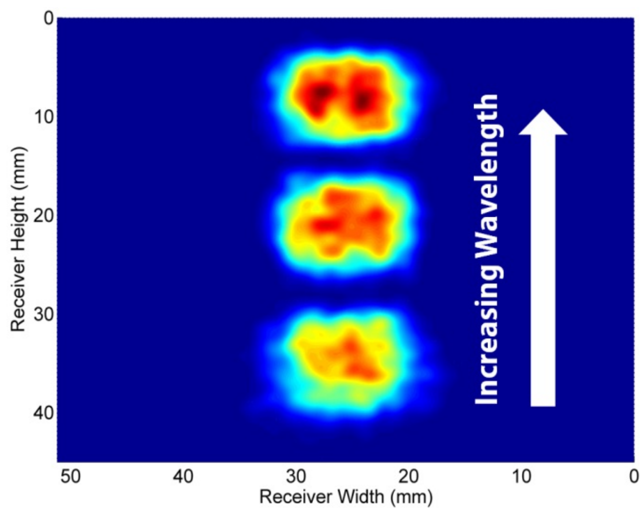

Figure 5. Simulated flux map of three discrete wavelength regions

First of all, we designed the optical element in order to allow for the separation of the solar spectrum into p bands, in which p corresponds with the number of solar cells. For this study, we have chosen p to be equal to 3, where each solar cell is obviously made of different materials (in the specific case GaAs, Si and Ge). The spectral content of each band has to be optimized in relation to the quantum efficiency (QE) of each photovoltaic device. In order to minimize the energy losses due to 'hot carriers' thermalization, the spectral content of each band is determined by considering as a limit the energy corresponding at each bandgap. By doing so, considering the well-known relation between the energy and the wavelength, we managed to divide the solar spectrum into 3 regions: below 780 nm to be absorbed with a GaAs solar cell, from 780 to 1100 nm to be absorbed with a Si solar cell and above 1100 nm to be absorbed with a Ge solar cell. For each band region, the total intensity as well as the spatial distribution of rays is simulated. The results of optical simulations conducted with TracePro are reported in Fig. 5.

The three light spots obtained with optical simulations are then used as input for solar cell simulations performed with TCAD. A schematic of the simulated solar cell structures is reported in Fig. 6, while in Fig. 7 the External Quantum Efficiency (EQE) of each simulated device is shown.

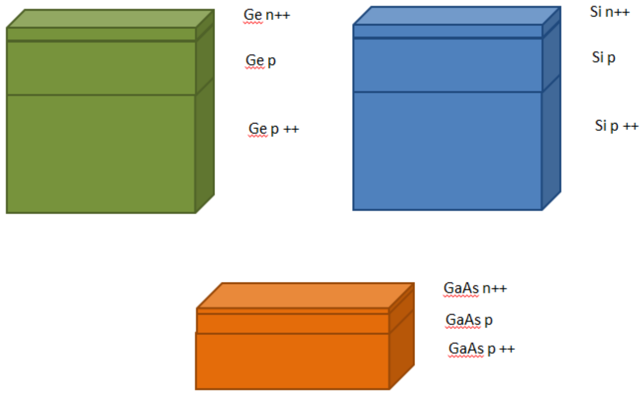

Figure 6. Schematic of the three simulated solar cells (from the top left Ge, Si and GaAs). For all of them, the simulated structure is the following: n++/p/p++

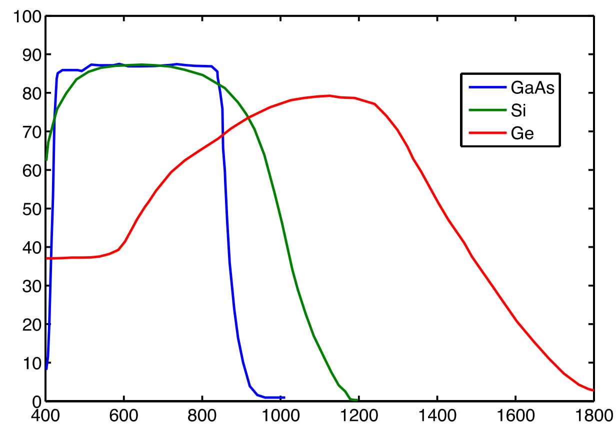

Figure 7. Quantum Efficiency of the three simulated solar cells (GaAs in blue, Si in green and Ge in red)

For each device, a comparison between electrical performances under full spectrum and spectrally separated and concentrated light is carried out. Fig. 8 a, b and c show the Current Density J versus Voltage V curves for GaAs, Si and Ge-based solar cells respectively. In each graph, both the illuminated curves under full spectrum and concentrated/separated light are reported. To be observed that the optimized wavelengths regions are slightly different from the initially considered one.

The configuration of the simulated devices is a result of an optimization process. This has been conducted with the aim of maximizing their efficiencies and thus obtaining the maximum output power out of the spectral splitting solar concentrator. In particular, both the effect of the thickness and the doping concentration in the devices has been intensively studied, similarly to what done in [15]. For example, Fig. 9 shows the normalized efficiency for each simulated device as function of the doping concentration of the emitter. As expected from results reported in literature, the efficiency grows with a quasi-logarithmic trend as the doping concentration increases. These results led us to choose a high doping concentration for the emitter of each device in order to maximize the collection efficiency of the generated carriers. Regarding the efficiencies of each single device, the simulation outcomes show that a considerable increase in the efficiencies of each device is obtained separating and concentrating the solar spectrum.

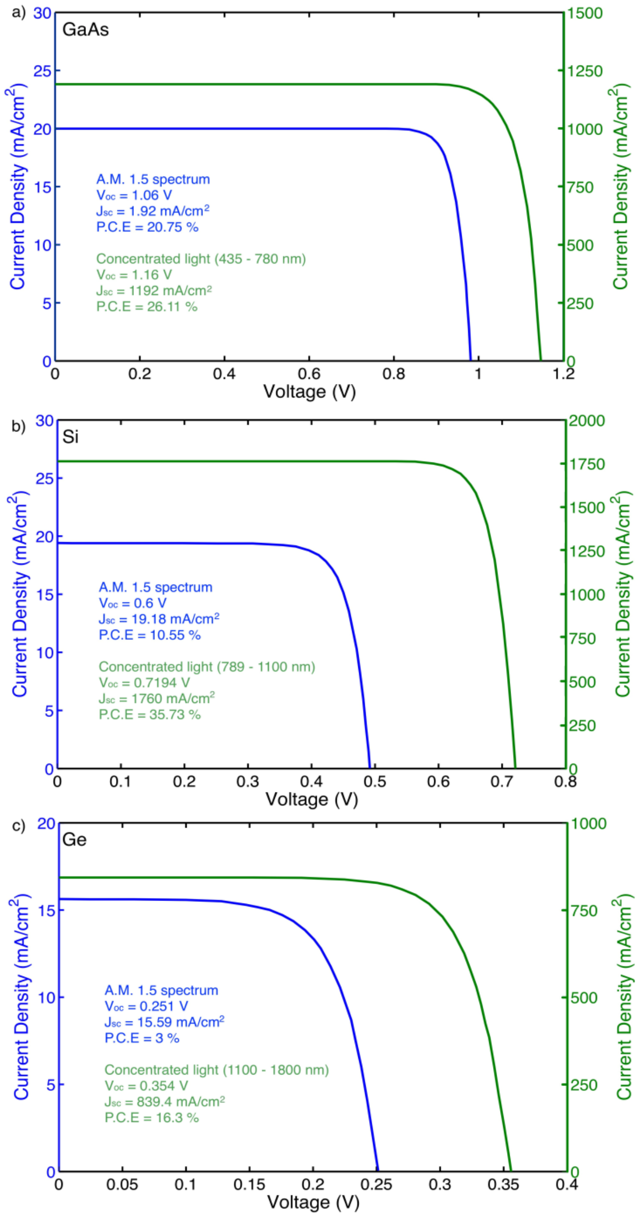

Figure 8. Current density J versus voltage V curves of the three simulated photovoltaic devices [a) GaAs b) Si c) Ge]. For all of them, illuminated curves under full spectrum (blue curve) and concentrated/separated light (green curve) are reported

The combination of the three solar cells with the optical element demonstrated a simulated overall efficiency of 28.71 %, calculated as the ratio of the summation of power from all photovoltaic cells to the exiting power flux from the optical element obtained from optical model simulations. This result proves the potentiality of the system as an alternative to MJ solar cells. We believe that further optimizations on photovoltaic devices (e.g. anti-reflection coatings or light trapping solutions) could increase even more the performance of the overall system.

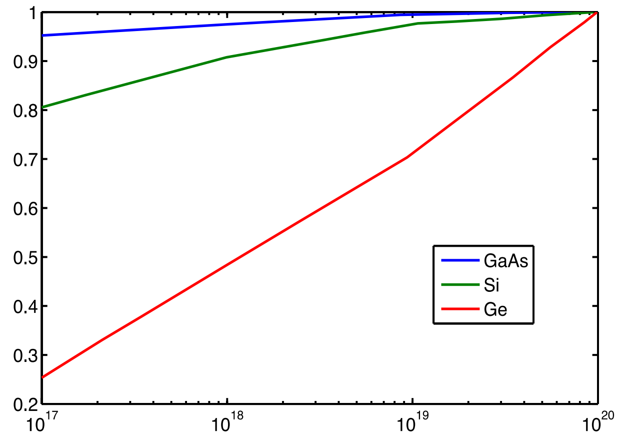

Figure 9. Normalized efficiency versus emitter doping concentration for the three simulated devices (GaAs in blue, Si in green, Ge in red)

4. Conclusions

In this paper, we attempted a generalization and theoretical analysis of a promising approach for single component spectral splitting and concentration of sunlight. An evolution of the design of the previously proposed two-dimensional spectral splitting solar concentrator is presented. In order to design a three-dimensional system, a new degree of freedom (u) is introduced. This resulted in a point-focus system able to concentrate the solar spectrum with an average concentration of 90 suns across the 425nm – 1600nm range with a weighted transmission efficiency of 76%. The proposed photovoltaic system of cells comprised for GaAs for the high-energy region (425nm – 780nm), Ge for the low energy region (1100nm – 1600nm) and Si for the mid energy region (780nm – 1100nm) has been found to perform significantly better under the simultaneously concentrated and split light. Overall system efficiency was found to be in the order of 28%, making spectral splitting technology competing with current MJ solar cells.

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