Highly efficient light splitting photovoltaic receiver

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HIGHLY EFFICIENT LIGHT SPLITTING PHOTOVOLTAIC RECEIVER

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ABSTRACT: This paper presents a spectral beam splitting arrangement providing the basis for a four-junction photovoltaic receiver with virtually ideal band gap combination. A light trapping assembly in form of a 45° parallelepiped applying two spectrally selective beam splitters and three solar cells realizes an approach to reach very high solar-electrical conversion efficiency. The spectral beam splitters developed and used in this arrangement show nearly ideal broadband characteristics to split the solar spectrum into three parts. The solar cell selection includes III-V semiconductors and silicon. They were all fabricated at Fraunhofer ISE and assembled in the receiver setup. The experimental setup demonstrated an outdoor efficiency of more than 34 %.

Keywords: High-Efficiency, Multi-Junction Solar Cell, Light Trapping

1 INTRODUCTION

Multi-junction devices are currently the most successful approaches to reach photovoltaic conversion efficiencies of more than 40 % [1]. They reduce the thermalization and transmission losses by using different band gap material adapted to the solar spectrum. However, the design of monolithically grown multi-junction solar cells is constrained, as all subcells have to produce the same currents. Since the subcells are connected in series, the excess currents are lost in these devices. Moreover, the lattice-matching constraint limits the selection of semiconductor materials that can be grown epitaxially without strong formation of crystal defects.

A multi-junction approach without these constraints is a beam splitting arrangement using spectrally selective filters. The spectral beam splitting concept selects the solar cells and then creates the optimal partial spectra for each solar cell by splitting the solar spectrum with optimized and tuned filters. A beam splitting arrangement includes several separate single- or dual-junction solar cells. Each solar cell is suited to convert the corresponding part of the solar spectrum with highest efficiency, thus especially reducing the thermalization losses of the photovoltaic conversion. Dielectric spectral beam splitter stacks are used to split the incident solar irradiation and to direct it to the different solar cells.

With this approach, the different solar cells can be individually selected and designed. The arrangement allows combining a broad range of materials such as Si, GaInAs, GaInAsP, GaSb and Ge in the multi-junction receiver. The theoretical efficiency limit of such an idealized receiver is slightly higher than for a photovoltaic device with the need for current matching (Figure 1). For instance, the optimal band gap combination of a triple-junction device with current-matching constraint is 1.66, 1.14 and 0.70 eV, whereas the optimum of a device without current-matching is calculated at a combination of 1.84, 1.16 and 0.70 eV (1 MW/m^2, 298 K, AM1.5d ASTM G173-03). Therefore, the device without a current-matching constraint is able to reduce the thermalization loss of high energy photon more effectively. Figure 1 has been calculated with the program code EtaOpt [2]. The efficiency is calculated in the detailed balance limit firstly discussed by Shockley and Queisser for a single-junction solar cell [3,4].

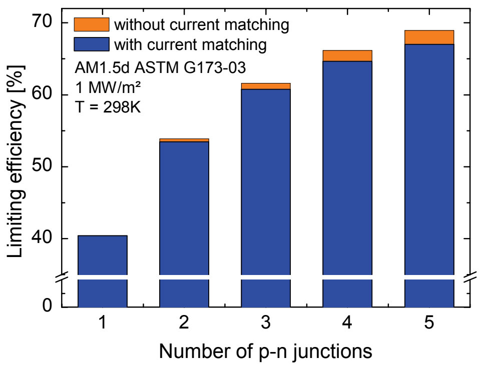

Figure 1: The thermodynamic efficiency limit of a multi-junction solar cell with and without current matching constraint calculated in detailed balance with the program code EtaOpt [2]. The efficiency limit without the current matching constraint is slightly higher. It is a growing advantage shown with increasing number of p-n junctions.

In the past only a few beam splitting PV-receivers were modeled and even less were studied experimentally [5,6,7,8]. In this work we present results on the modeling of such receivers as well as the first experimental receiver setup.

2 RECEIVER CONCEPT

2.1 Receiver arrangement

Our concept is based on a light trap in form of a parallelepiped which distributes incident radiation onto the different solar cells (Figure 2). The sunlight is partly directed to the next solar cell by reflection at the beam splitter or solar cell surface. Hence, the arrangement provides several absorption possibilities for each partial spectrum which means the light is trapped inside the receiver. In order to reduce optical losses, it is reasonable to absorb the high energy light at the first place inside the assembly instead of transferring it through the arrangement, because the spectral beam splitter will cause losses during the transfer at each reflection due to non-ideal transmission and reflection. Theses losses will be higher, if the first partial spectrum (300-850 nm) is transferred, as a result of its higher energy and photon density.

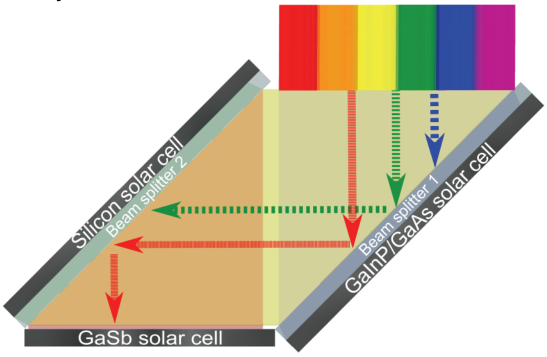

Figure 2: Light trapping arrangement used in form of a 45° parallelepiped including two beam splitters and three solar cells. The sunlight reflected at filters or solar cells is directed to the next solar cell inside the arrangement, thus reducing optical losses. Solar cell 1 (here GaInP/GaAs) and 2 (here Si) are covered with spectrally selective filters.

The beam splitters are directly connected to the solar cells to maximize the transmission by minimising the interface reflections. A transparent silicone is used which has a refractive index close to glass substrate.

Monolithic dual-junction solar cells can be employed to increase the number of p-n junctions of the receiver in order to realize a receiver with more than three p-n junctions. However, they implement a current-matching constraint for the partial spectra, which is even more difficult to optimise, because of the additional parameter caused by the beam splitter characteristic.

A beam splitting approach increases the active solar cell under one sun conditions. In our case the 45° parallelepiped increases the cell area by the factor of ~4. An optimized architecture could reduce this slightly. This is why the irradiance in a one sun system, as it is the case in the first receiver setup, is strongly reduced on each solar cell. Moreover, the spectrum splitting additionally reduces the irradiance due to the lower energy of each partial spectrum in comparison with the full spectrum. Therefore, a spectrum beam splitting receiver for one sun operation needs solar cells working under low irradiance of down to ~50 W/m^2. In our receiver especially the second and third solar cells operate at this low irradiance.

However, the beam splitting is beneficial in a concentrator application, because each solar cell receives a lower concentration than the total receiver due to the spectrum splitting, thus reducing the impact of an increased solar cell area by allowing a higher total receiver concentration.

2.2 Beam splitter integration

There are several options to integrate the spectral beam splitters into the light trap. However, two approaches seem to be the most promising. Firstly, the deposition of the filter on a glass substrate with an additional interconnection layer between the beam splitter and the solar cells reveals good results in simulations (Figure 3). Furthermore, the deposition of a dielectric multi-layer stack onto a glass substrate is well understood. A broadband filter for the usage in a photovoltaic application is an enhancement of existing selective filters and therefore a straight forward solution. The optical connection can be realized by using a transparent silicone, which has a low absorption in the range of 300-1200 nm and a refractive index close to the glass substrate.

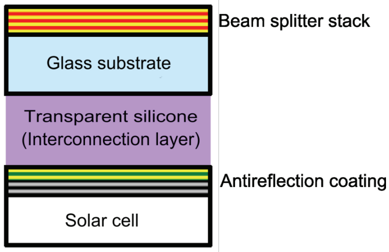

Figure 3: Stack of a spectrally selective beam splitter deposited on a glass substrate and the solar cell covered with an anti-reflection coating. Both parts are optically connected by a transparent silicone.

The second option of integration is the direct deposition of the filter stack onto the solar cell as an advanced coating. This option would strongly reduce the complexity of the stack shown in Figure 3. Especially for small beam splitting receivers of the same or similar arrangements as shown in Figure 2 and solar cells in the range of 2-3 mm have to make use of direct deposition in order to reduce the height of the beam splitter/solar cell stack and avoid a beam displacement. An application of a beam splitting receiver in a concentrator module with high concentration factors of up to 1 MW/m^2 and therefore high current densities in the solar cells will require a small receiver setup in order to deal with the ohmic losses.

We favored the deposition on glass in the first setup in order to evaluate the best filter characteristic possible in a photovoltaic application and to use existing experiences in filter deposition.

2.3 Solar cells

The spectral beam splitting receiver provides full freedom in material selection. Therefore, we optimized the solar cell or band gap selection by calculation the detailed balance limiting efficiency with the program code EtaOpt [2]. Figure 4 shows an efficiency limit contour plot of a four-junction beam splitting system assuming a fixed $Ga_{0.51}In_{0.49}P$/GaAs solar cell and just varying the second and third solar cell in band gap. The dual-junction solar cell was chosen in order to increase the number of p-n junctions of the receiver and represents the most efficient and well known high band gap solar cell type. Figure 4 is calculated for 1 MW/m^2 irradiation (AM1.5d ASTM G173-03) at 298K and gives a good basis to select a well suited combination of band gaps. A high concentration ratio was assumed in order calculate the efficiency potential of an idealized four-junction beam splitting receiver. The local maxima do not change their position much by changing the concentration ratio and therefore the same band gaps for the one sun receiver setup can be used. The calculated contour plot as shown in Figure 4 helped to select the second and third solar cell. A Si solar cell as medium band gap device and a GaSb solar cell as low band gap converter provide a set of band gap materials which has a limiting efficiency close to the global maximum in assembly with the $Ga_{0.51}In_{0.49}P/GaAs$ solar cell. The limiting efficiency of this band gap combination is 64.4 %. The three solar cells are all fabricated at Fraunhofer ISE [9].

The contour plot also shows four local maxima of efficiency which is due to the shape of the solar spectrum and to the missing current matching constraint in the receiver. Low efficiency gradients are shown in the area defined by the band gap range 0.9-1.15 and 0.5-0.7 eV for the second or third solar cell. In this area the limiting efficiency of the receiver stays between 64-65.3 % revealing a freedom in material selection. Thus, the beam splitting receiver provides a window of possible material selections all showing high limiting efficiencies. This is an indication of a low sensitivity to spectral changes which is an important limiting factor of multi-junction devices under terrestrial operation.

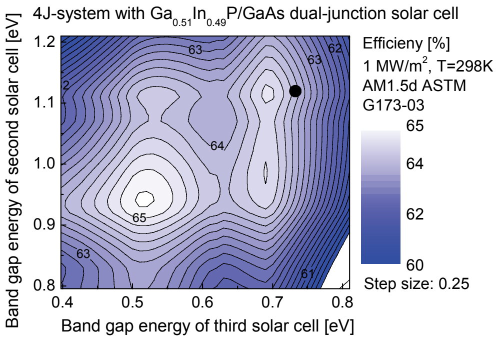

Figure 4: Detailed balance calculations of the four-junction beam splitting receiver. The calculation assumes a fixed $Ga_{0.51}In_{0.49}P/GaAs$ solar cell (1.88 and 1.43 eV) and varies the medium and low band g+ap sub cells (here second and third solar cell). The black dot indicates our material choice representing a Si and GaSb solar cell (1.12 and 0.73 eV) with an efficiency limit of 64.4 %.

3 OPTICS AND EXPERIMANTAL RESULTS

3.1 Beam splitters

The beam splitting approach includes the application of spectrally selective optical elements which are non-absorbing and provide a step function characteristic for the design angle of 45° incidence, ideally. Our system design includes two spectral beam splitters with cut-off wavelength at 850 and 1080 nm, respectively. They both show a short-pass characteristic transmitting the sunlight between 380 and 850 (1080) nm and reflect the incoming beam between 850 (1080) and 1800 nm. In Figure 5 the transmission characteristic of beam splitter 1 with cut-off wavelength at 850 nm is shown and compared to the ideal short-pass characteristic. The graph plots the simulated transmission of beam splitter 1 in the receiver setup, here denoted "simulated system". In order to verify the transmission of the deposited filters, which is not possible to measure in the receiver setup, we measured the transmission as deposited on a glass substrate. The characteristic is also shown in Figure 5 and is denoted "measured single". This measured results are compared to a simulation of the same beam splitter stack under the same conditions, here denoted "simulated single". The measurement and simulation are in excellent agreement as it is shown. Hence, it can be assumed that the "simulated system" characteristic is close to the real filter characteristic in the receiver. The transmission of the "simulated/measured single" characteristics show lower values due to additional reflections at the rear side of the glass substrate, which do not occur in the receiver setup due to the silicone interconnection layer.

The simulated characteristic of beam splitter 1 reveals to be nearly ideal except the absorption in the UV (300-500 nm). The transition region between transmission and reflection is in the range of 50 nm.

By weighting the transmission with the solar spectrum (AM1.5d ASTM G173-03) the quality of the beam splitters can be assessed. Beam splitter 1 and 2 both show a weighted transmission of 96.4 % between 380 and 850 (1080) nm. This high transmission will reduce the voltage loss in the receiver system due to reflection of high energy photon to the second or third solar cell in the light trap. A voltage loss occurs when a high energy photon is not absorbed by the optimal solar cell with highest band gap possible, but by a lower band gap solar cell, thus generating a lower photovoltage.

It is even more important that the beam splitter show a high reflection in the reflection band. Non-ideal reflection characteristic (R<100 %) will lead to a photon loss, because transmitted photons with higher wavelength than the absorption edge of the solar cell underneath will not contribute to the photocurrent generation. The achieved reflectance between 850 (1080) and 1800 nm reach spectrally weighted values of 98.1 % (beam splitter 1) and 97.2 % (beam splitter 2).

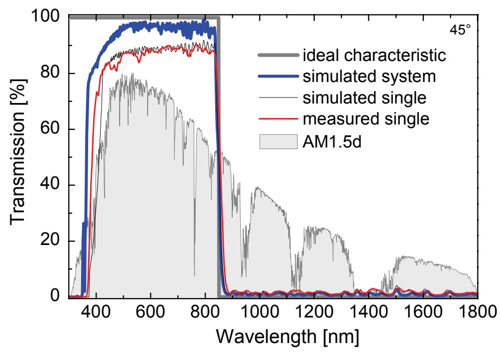

Figure 5: Optical transmission of beam splitter 1 as function of wavelength with cut-off at 850 nm in comparison to the ideal characteristic. The blue line (simulated system) shows the simulated characteristics for the receiver setup with 45° incidence. The red line (measured single) shows the measured transmission of the fabricated beam splitter on a glass substrate and is close to the theoretical simulation (simulated single).

The beam splitters are based on dielectric two material stacks deposited on glass. Figure 6 shows the simulated refractive index profile of beam splitter 1 with the boundary layers air (n=1) in the front and silicone (n=1.41) on the backside. A periodic step function describes the change in refractive index of the two metal oxides (here TiO_2 and SiO_2) stacked on each other. The stack contains 220 layers realizing the simulated design of beam splitter 1, thus requiring a very good process control during deposition.

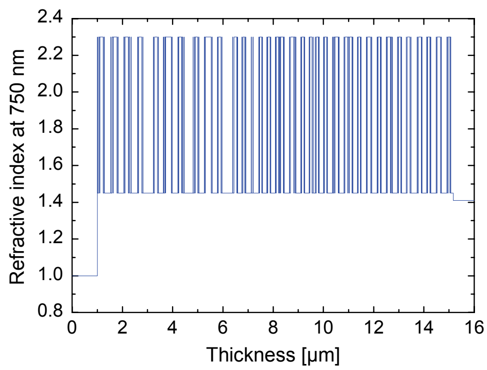

Figure 6: Simulated refractive index profile of spectral beam splitter 1. A periodic step function design was used to realize the band stop filter. The design contains 220 layers of TiO_2 and SiO_2 stacked on each other.

The simulated distribution of thicknesses is shown in Figure 7. There are four lines of thicknesses showing layer thicknesses mainly around 10-30 nm, around 100 nm (TiO_2) and 200 nm (SiO_2). This is due to the optimization algorithm which starts with a periodic Bragg filter stack.

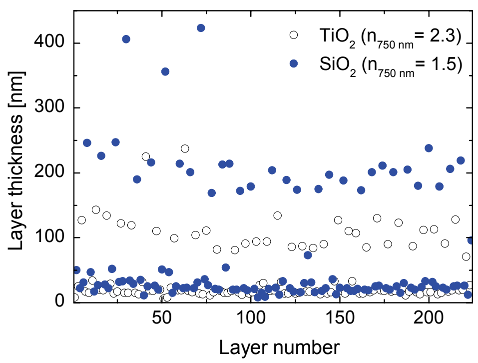

Figure 7: Simulated distribution of thicknesses of spectral beam splitter 1. The thicknesses of the layers are distributed around four lines of thicknesses which is a result of the optimisation algorithm starting from a Bragg filter stack.

3.2 System Performance

The spectral beam splitting receiver was set up and measured under outdoor conditions at ISE in Freiburg, Germany in July 2009. An aperture of 2.51 cm^2 was applied to the receiver which was equipped with 2x2 cm^2 solar cells under 45° illumination (GaInP/GaAs, Si) and a 1.4x2 cm^2 GaSb solar cell at the bottom inside the light trap. The receiver arrangement was put into a black box in order to minimize stray light entering the receiver. It was then measured under direct normal irradiance (DNI) by applying a collimator tube with an angle of view of 1.7°. The measurement has been done in series connection of the three solar cells. This was necessary due to a limitation in measuring a low voltage GaSb solar cell at the outdoor module measurement setup. Although, as the series connection induces some losses to the receiver it is still demonstrating an efficient operation possibility (Figure 8). The best outdoor I-V measurement shows an efficiency of 34.3 % under direct normal irradiance of 863 W/m^2. The separate measurement of each solar cell would lead to an even higher efficiency. However, as the partial spectra contain about the same amount of photons, the photocurrents of each of the three solar cells is similar. Therefore, the losses induced by the series connection are relatively low. Measurements of the photocurrent revealed a mismatch of 11 % on 28th of July in Freiburg. The current limit was caused by the Si solar cell under this condition which indicates a blue rich spectrum.

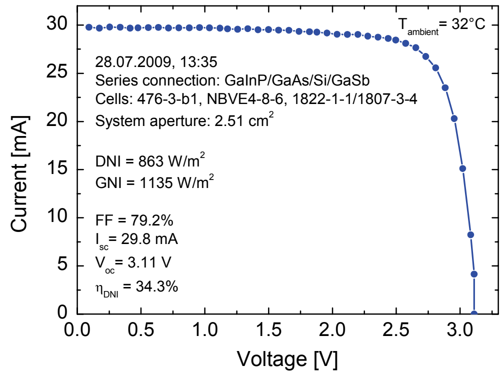

Figure 8: Outdoor I-V curve of the receiver prototype measured with series connected solar cells at the Fraunhofer ISE outdoor test stand in July, 2009. A collimator tube is applied to the receiver which in consequence only receives direct sunlight. The total spectral beam splitting receiver shows an efficiency of 34.3 % referring on the direct normal irradiation (DNI).

4 SUMMARY AND CONCLUSION

We presented a spectral beam splitting receiver (light trap) in form of a 45° parallelepiped with two spectrally selective beam splitters and three solar cells providing a nearly ideal band gap combination. The optimized design of the light trap led to the use of a four-junction solar cell system applying a GaInP/GaAs, a Si and a GaSb solar cell which were all fabricated at Fraunhofer ISE. Two spectral beam splitters with short-pass characteristics are applied in the receiver and generate three partial spectra. They were designed and simulated as a two material stack and deposited on a glass substrate optically connected to the solar cells. The transmission and reflection measurements show nearly ideal broadband characteristics with transmission in the range of 96 % and reflections of about 98 %. The beam splitters and the solar cell selection were used to build an experimental setup. Outdoor measurements on the receiver setup demonstrate an efficiency of above 34 %.

The beam splitting approach is showing to be an attractive path to reach very high efficiencies of above 40 % under concentrated sunlight. This results from the non-constrained material selection and low loss spectral beam splitters.

5 ACKNOWLEDGEMENTS

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