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Yajie Jiang

Design of Bragg Reflectors in III-V Solar Cells for Spectrum Splitting to Si

Yajie Jiang[1], Mark J. Keevers[1], Martin A. Green[1]

[1]*Australian Centre for Advanced Photovoltaics, School of Photovoltaic and Renewable Energy Engineering, University of New South Wales, Sydney, Australia, 2052*

E-mail: yajie.jiang@unsw.edu.au

Abstract

The use of intermediate distributed Bragg reflectors (DBRs) for spectrum splitting photovoltaics is investigated. An optical model of a lattice-matched (LM) GaInP/GaInAs/Ge triple-junction solar cell (TJSC) with intermediate DBR is developed, in good agreement with measured reflectance. By modifying the composition and thickness of the DBR layers to broaden the reflectance band, we show that a DBR has the potential to provide suitable reflectance for spectrum splitting from the III-V LM TJSC to a Si cell. The DBR approach to spectrum splitting has the advantage of a much reduced angle-of-incidence dependence than the use of a separate dielectric filter.

1. Introduction

The centralised power tower technology is regarded as the most promising approach to concentrator photovoltaics (CPV), which is being developed by Australian company RayGen Resources, consisting of a field of heliostats concentrating the sunlight to a single flat 1-m^2 PV array atop a mast, Figure 1(a) (Lasich et al., 2015). The cells used in the receiver are high performance GaInP/GaInAs/Ge triple junction solar cells (TJSC). One disadvantage of this TJSC is the bottom Ge cell having a much lower bandgap, generating much more current than the other two cells. The extra current is wasted as heat within the cell, increasing challenges in maintaining low operating temperatures where the cells are most efficient. Given this single large receiver, an efficient approach to solve this problem is using spectrum splitting by reflecting some of the excess photons reaching the Ge cell in the TJSC array onto an additional relatively inexpensive array of Si cells. The receiver details of one spectrum splitting approach for a photovoltaic power tower are shown in Figure 1(b).

(a) (b)

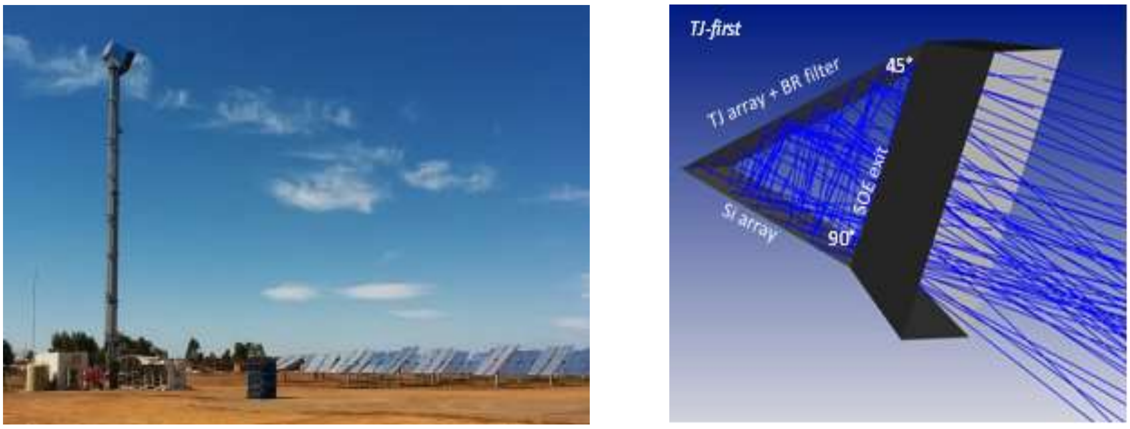

Figure 1. (a) RayGen's central receiver CPV power tower system. (b) Schematic of a V-shaped spectrum-splitting receiver, relevant to this project.

UNSW has demonstrated a world record conversion efficiency of 40.6% using spectrum splitting in a CPV submodule (Green et al., 2015). A 'proof of concept' prototype was built for a large power tower photovoltaic system (Figure 2). This spectrum splitting, which diverts the 900-1050 nm spectral band from a TJSC to a Si cell, is realized by using a separate 150-layer dielectric bandpass filter.

(a) (b)

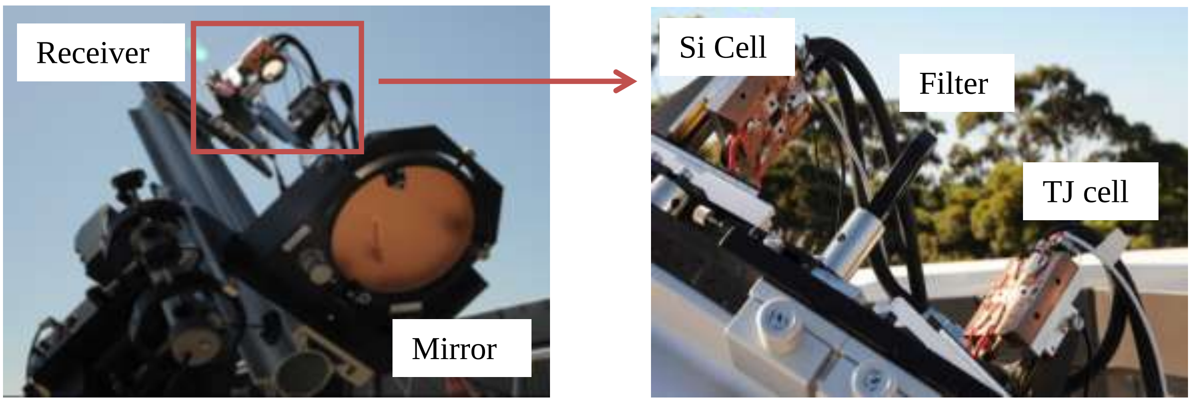

Figure 2. (a) Photograph of the prototype, (b) close-up of the 'receiver' in the prototype.

This work proposes a more cost-effective approach, namely the integration during TJSC fabrication of an intermediate distributed Bragg reflector (DBR), optimised to function as a suitable band-reflect filter, instead of using a separate dielectric filter. This approach could be implemented with little additional cost during manufacture, in contrast to fabrication of discrete dielectric filters.

2. Optical model of a lattice-matched TJSC with intermediate DBR

The state-of-the-art 1-sun terrestrial III-V on Ge TJSC is a 34.1% modified space cell, developed by Azur Space (Bett et al., 2009). We measured the spectral specular reflectance of such a lattice-matched GaInP/GaInAs/Ge TJSC from Azur Space using a Perkin-Elmer Lambda 1050 UV-Vis-NIR spectrophotometer with Universal Reflectance Accessory (URA) at 8° angle of incidence. A reflectance peak at 900 nm is observed, Figure 3(a), which is around the band edge of the GaInAs middle subcell. This reflectance feature is consistent with an intermediate DBR located between the GaInAs middle and Ge bottom subcells (Skachkov, 2014), as patented by Azur Space (Meusel et al., 2014, Meusel et al., 2016, Meusel et al., 2016), intended to reflect non-absorbed band edge photons back into the GaInAs middle subcell to increase photocurrent without significant loss to the Ge subcell.

We have developed an optical model of a commercial TJSC with existing DBR, based on an initial device structure from Ref (Shvarts et al., 2012) and complex refractive index data from SOPRA optical database and Palik handbook (Palik, 1985), such that the simulated and measured reflectance are a close match, Figure 3(a). Optical analysis software WVASE® (J. A. Woollam Co., Inc.) was used to fit the modelled reflectance to the measured data, by allowing the layer thicknesses to be automatically adjusted. A schematic of the resulting TJSC structure with the approximate thickness of each subcell and the intermediate DBR as determined by the optical simulation is shown in Figure 3(b).

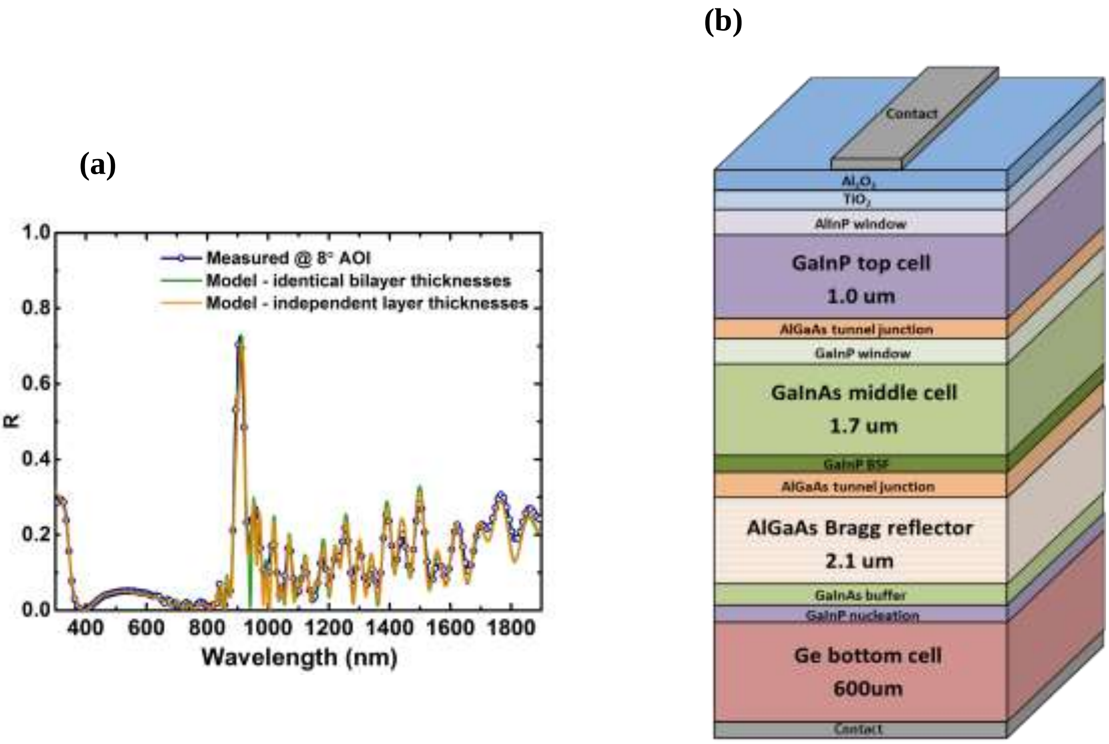

Figure 3. (a) Modelled and measured specular reflectance of an Azur Space 1-sun terrestrial lattice-matched TJSC with intermediate DBR. (b) Schematic cross-section of the LM TJSC structure (not to scale).

3. Design of an intermediate DBR for band-reflect spectrum splitting

For this lattice-matched TJSC, optimal spectrum splitting to a Si cell is achieved by diverting the 900-1050 nm spectral band. Assuming no change in the DBR bilayer materials and number of bilayers, a reasonably effective band-reflect filter was modelled as shown in Figure 4(a). The 16 bilayers in the original design were divided into two sets of 8 bilayers to provide a broader reflection band, each set with a different bilayer thickness. Furthermore, by including a MgF_2 layer to form a 3-layer $MgF_2/Al_2O_3/TiO_2$ AR coating, reflectance losses to the top and middle cells are greatly reduced. By doubling the number of Bragg layers to two sets of 16 bilayers, the reflect band of the TJSC is enhanced significantly compared with the original design. An effective DBR based band-reflect filter providing current matching for the TJSC was modelled, Figure 4(a).

There is a broad distribution of angles of incidence (AOI) on the receiver of the centralised power tower (see Figure 1(b)), which could limit the benefits of spectrum splitting using a dielectric filter due to the sensitivity of the latter to AOI. Using the Perkin-Elmer spectrophotometer with URA, we measured the reflectance of the Azur Space lattice-matched TJSC for 8-60° incident angles, and determined the cut-on and cut-off wavelengths (defined as 50% of the reflectance maximum) of the narrow reflectance band at 900 nm, and found good agreement with our simulated values, Figure 4(b). The good agreement for the angular response of the TJSC validates the optical model and increases confidence in the subsequent spectrum-splitting DBR simulations. The DBR approach exhibits a greatly reduced sensitivity to AOI compared with dielectric filter design, which could enhance the benefits of spectrum splitting, Figure 4(b).

(a) (b)

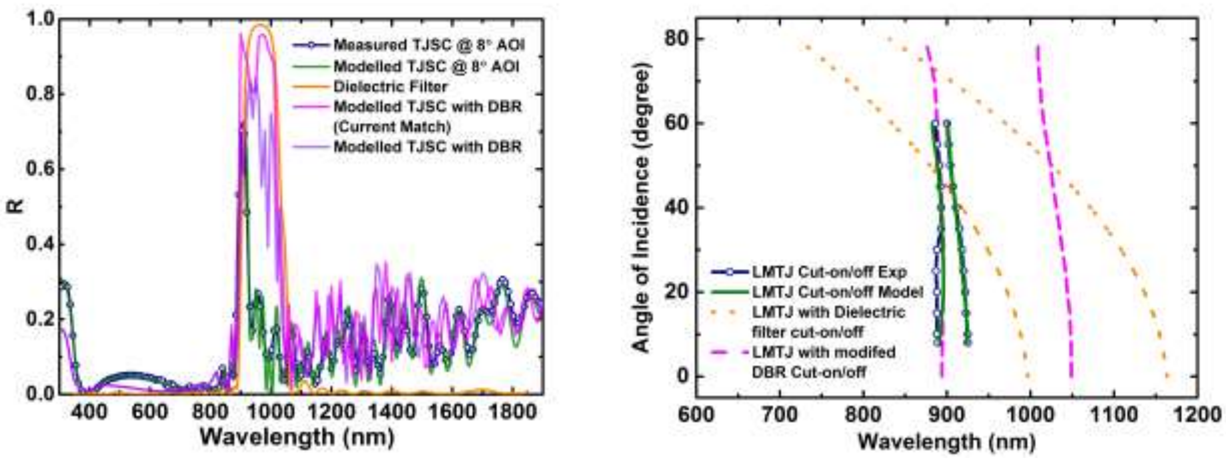

Figure 4. (a) Measured and modelled specular reflectance of a lattice-matched TJSC with intermediate DBR, and reflectance of the TJSC with an intermediate DBR design for spectrum splitting. (b) AOI response of intermediate DBR in a TJSC versus a band-reflect dielectric filter.

In addition to spectrum splitting for a lattice-matched TJSC to a Si solar cell, the intermediate DBR approach also has potential application to other III-V solar cells for spectrum splitting to a Si solar cell, such as single junction GaAs or double junction GaInP/GaAs cells by incorporating suitable spectrum splitting DBR designs.

4. Conclusion

In this work, we propose to modify the internal distributed Bragg reflector in the lattice-matched triple junction solar cell so that it acts as a band-reflect filter to spectrum split otherwise wasted light (nominally 900-1050 nm) to a Si solar cell. The proposed DBR does not require the use of external optical filters, which normally are complex high-pass, low-pass or bandpass filters consisting of many dielectric layers. It also exhibits a greatly reduced sensitivity to angles of incidence (AOI) compared with dielectric filter design, which could enhance the benefits of spectrum splitting.

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