Solar Energy Materials & Solar Cells 159 (2017) 212–218

Contents lists available at ScienceDirect

Solar Energy Materials & Solar Cells

journal homepage: www.elsevier.com/locate/solmat

Interstitial light-trapping design for multi-junction solar cells

A. Mellor*, N.P. Hylton, S.A. Maier, N. Ekins-Daukes

Department of Physics, Imperial College London, London SW7 2AZ, United Kingdom

ARTICLE INFO

Article history:
Received 9 July 2016
Received in revised form
24 August 2016
Accepted 6 September 2016
Available online 20 September 2016

Keywords:
Multijunction
Radiation hardness
Light trapping
Nanophotonics

ABSTRACT

We present a light-trapping design capable of significantly enhancing the photon absorption in any subcell of a multi-junction solar cell. The design works by coupling incident light into waveguide modes in one of the subcells via a diffraction grating, and preventing these modes from leaking into lower subcells via a low-index layer and a distributed Bragg reflector, which together form an omnidirectional mirror. This allows the thickness of the target subcell to be reduced without compromising photon absorption, which improves carrier collection, and therefore photocurrent. The paper focuses on using the composite structure to improve the radiation hardness of a InGaP/Ga(In)As/Ge space solar cell. In this context, it is shown via simulation that the Ga(In)As middle-cell thickness can be reduced from 3500 to 700 nm, whilst maintaining strong photon absorption, and that this leads to a significantly improved end-of-life photocurrent in the Ga(In)As middle cell. However, the design can in general be applied to a wide range of multi-junction solar cell types. We discuss the principles of operation of the design, as well as possible methods of its fabrication and integration into multi-junction solar cells.

1. Introduction

III-V Multi-junction solar cells (MJSCs) are presently the highest efficiency photovoltaic (PV) technology. For terrestrial applications, there is significant research and development aimed at improving the efficiency of MJSCs under concentrated sunlight beyond the present record of 46% [1] towards 50% and above, at which point they have the potential to compete favourably with wholesale electricity prices [2]. In space, the emphasis is on improving the efficiency at end of life, which requires both improvements in beginning-of-life efficiency as well as radiation hardness [3]. In this work, we present a light-trapping structure designed specifically to enhance the photocurrent in a subcell of a multi-junction solar cell. This has the potential to improve any type of MJSC in which one or more subcells suffers from low diffusion lengths. Its most immediate application is to improve the radiation hardness of space solar cells.

Multi-junction solar cells consist of a stack of subcells based on different semiconductor materials [4]. The thickness of each subcell is designed as a trade-off between two competing demands; the subcell must be thick enough that photons in the corresponding wavelength range be strongly absorbed, and thin enough that carriers be efficiently collected. If the carrier diffusion length is too low – compared to the photon penetration depths in the material – a good trade-off cannot be found and the efficiency of the solar cell suffers as a result.

In space, this problem is exacerbated since the solar cells are subject to high-energy irradiation. This causes material degradation leading to a reduction in carrier diffusion lengths [5]. In the InGaP/Ga(In)As/Ge solar cells presently used in space, this effect is most pronounced for the Ga(In)As middle cell, which limits the total current generation at the end of space missions [6].

There are a number of III-V materials presently used in high-efficiency MJSCs that have low diffusion lengths, such as GaInAsN (Sb) [7] and relaxed InGaAs [8]. There are also proposals to use materials such as GaAsBi [9], whose diffusion length is believed to be low [10], and GaAsBiN [11], whose diffusion length is unknown. Future development in MJSCs will involve increasing the number of subcells to achieve higher efficiencies. This will require the use of new materials and/or metamorphic configurations with relaxed layers, both of which are likely to present the problem of low diffusion lengths.

The problem of low diffusion lengths can be addressed by so-called light-trapping techniques. Optical structures are incorporated into the solar cell, which increase the optical path length within the absorber layer. This allows the thickness to be reduced while maintaining high absorption, thus improving carrier collection and overall photocurrent. Light trapping has been applied to a wide range of single junction solar cells, including those based on c-Si [12–15], a-Si [16,17] and GaAs [18,19].

In recent work, we investigated the use of Al nanoparticle

* Corresponding author.
E-mail address: mellor_alex@hotmail.com (A. Mellor).

http://dx.doi.org/10.1016/j.solmat.2016.09.005
0927-0248/

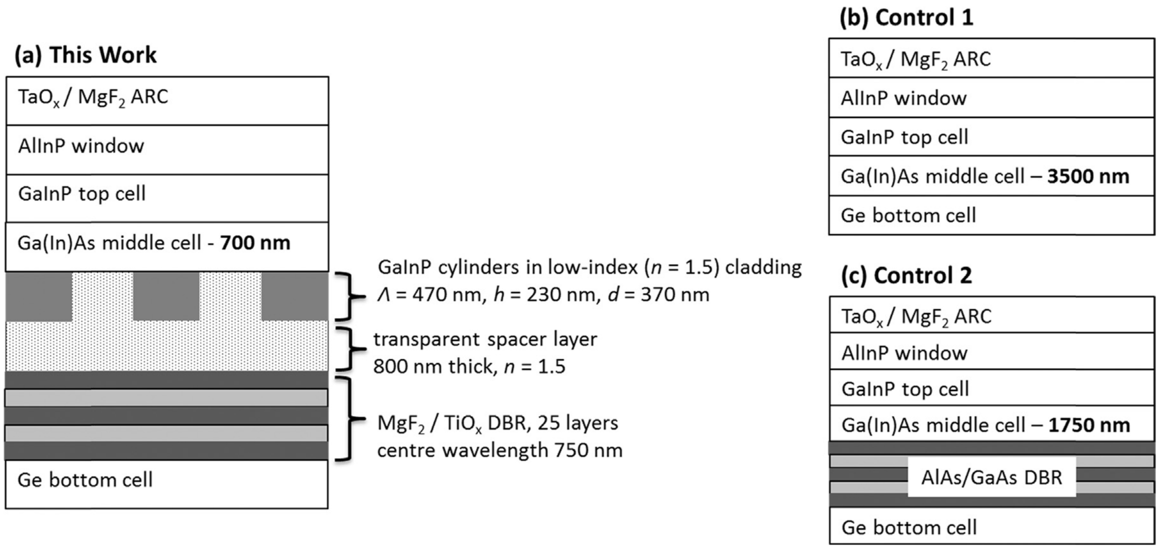

Fig. 1. Schematic diagram of the solar cell structure studied in this work. Specific details of electrical components such as contact fingers, capping layers, tunnel junctions and lateral transport layers are not shown. (a) The solar cell incorporating the light trapping structure presented in this work. (b) Control solar cell number 1, which has no DBR (c) Control solar cell number 2, which has a DBR between the middle- and bottom cells.

arrays embedded in the anti-reflection coating (ARC) of a InGaP/Ga(In)As/Ge solar cell as a means of improving the photocurrent in a thinned Ga(In)As subcell [20]. The presence of the nanoparticle array was found to improve the carrier collection efficiency, but also reduce transmission into the solar cell (see also Ref. [21]). The losses outweighed the gains over wide range of nanoparticle array dimensions studied. In addition to transmission losses, the structure suffered from the lack of an omnidirectional wavelength-selective mirror between the Ga(In)As and Ge subcells. These results highlight the problems in applying light trapping to a MJSC architecture if the target subcell for enhancement is not the bottom cell.

In the present work, we present a light trapping design for multi-junction solar cells, in which the light trapping structure is positioned interstitially between two of the subcells of the device. The design comprises the combination of a diffraction grating, a low-index transparent spacer layer, and a distributed Bragg reflector (DBR), which synergistically trap light inside the target subcell. The diffraction grating couples incident photons into oblique modes within the target subcell, whilst the combination of low-index transparent spacer layer and DBR form a wavelength-selective near-omnidirectional mirror between the target subcell and the subcells beneath. Finally, the period of the diffraction grating is chosen so that incident light is only coupled into the optical modes in the device that are effectively reflected by this mirror.

The light trapping design is first presented in Section 1 with specific application to a InGaP/Ga(In)As/Ge solar cell. The performance of the solar cell is investigated using electro-optical simulation method, which is described in Section 2, and that has been experimentally validated in Ref. [20]. In Section 3, the simulation method is used to predict the enhancement that can be achieved in the Ga(In)As subcell of a InGaP/Ga(In)As/Ge solar cell. The calculations show that the light trapping-structure allows the Ga(In)As subcell to be thinned from 3500 nm to 700 nm without compromising absorption, and that this significantly improves the radiation hardness. In Section 4, the principles of operation are described in the context of a generic multi-junction solar cell. The interstitial location of the light trapping structure requires that the solar cell be fabricated as a mechanical stack, adding to the complexity of the manufacture; this is discussed in Section 5.

2. Solar cell structure and light trapping design

The solar cell structure under investigation is shown in Fig. 1. The host solar cell is a GaInP/Ga(In)As/Ge triple-junction solar cell with AlInP window and MgF_2/TaO_x anti-reflection coating (ARC). The Ga(In)As subcell thickness is 700 nm, considerably less than the 3500 nm that would be considered optically thick in this material. The optical light-trapping structure is positioned between the Ga(In)As and Ge subcells. From top to bottom, the light trapping structure consists of.

- A diffraction grating consisting of an array of GaInP cylinders, with a period, diameter and height of $\Lambda = 460$ nm, $d = 370$ nm and $h = 230$ nm, respectively, embedded in a transparent, low-index ($n = 1.5$) cladding
- a transparent spacer layer, with refractive index $n = 1.5$ and a thickness of 800 nm
- an MgF_2/AlO_x distributed Bragg reflector (DBR) with 25 layers and a centre wavelength of 750 nm

The rationale for choosing these parameters is described in Section 4.

Two control structures are also considered for comparison; these are shown in Fig. 1(b) and (c). Both have the same basic structure as above. Control 1 - shown in Fig. 1(b) - has no optical nanostructures, and has a Ga(In)As subcell of thickness 3500 nm, which is considered optically thick for this material. Control 2 - shown in Fig. 1(c) - has an DBR positioned between the Ga(In)As and Ge subcells, and has a Ga(In)As subcell thickness of 1750 nm. The DBR in Control 2 is AlAs/GaAs, which is compatible with monolithic fabrication. It has 25 layers and a centre wavelength of 850 nm. The Ga(In)As subcell thicknesses and centre wavelength in the control cells were optimised computationally.

3. Simulation method

The optical absorption in the different layers of the nanostructured device was calculated by rigorous coupled wave analysis (RCWA) implemented using the software package GdCalc® [22]. This calculates the depth-dependent absorption in the different subcells, which, to a good approximation, can be considered equal