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Analysis of ultra-thin crystalline silicon solar cells coupled to a luminescent solar concentrator

Michael D. Hughes, Shu-Yi Wang, Diana-Andra Borca-Tasciuc *, Deborah A. Kaminski

Department of Mechanical, Aerospace and Nuclear Engineering, Rensselaer Polytechnic Institute, Troy, NY 12180, United States

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Abstract

Thin-film solar cells require less semiconducting materials and can achieve larger open circuit voltages than their bulk counterpart. However, they often suffer from poor absorption of light, resulting in a lower power output. To improve power generation, thin film solar cells can be coupled to luminescent solar concentrators (LSCs). LSCs can cover large surface areas to inexpensively collect sunlight and concentrate it onto small area photovoltaics (PV). Although LSC–PV systems typically suffer from low efficiency, they have potential for reducing the environmental impact of solar power while improving the power output from solar cells. In this work, the system level performance of ultra-thin film mono-crystalline silicon (c-Si) solar cells attached to an LSC containing Lumogen Red 305 was investigated with the goal of improving the viability of ultra-thin film c-Si photovoltaics. This approach is explored here by coupling ultra-thin film (200 nm) c-Si solar cells to LSCs and examining the performance of the LSC–PV systems under direct AM 1.5 illumination. To determine the coupled LSC–PV system level efficiency, the maximum power output is calculated with a detailed balance method. More than an order of magnitude improvement in the power output of the ultra-thin film c-Si solar cell is accomplished through concentration of light achieved with the LSC. The power output is further increased through spectral coupling of the LSC to the output spectrum of the solar cells using plasmonic structures to enhance solar cell absorption at targeted wavelengths. Results show that enhanced photon absorption in the solar cell improves *both* the efficiency of light transport in the LSC and the solar cell power output.

Keywords: Luminescent solar concentrators; Plasmonic solar cells; System level efficiency; Detailed balance method

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1. Introduction

In a society more environmentally conscious than ever, producing affordable electricity from solar radiation is one of the grand challenges (Grand Challenges for Engineering, 2014). Although silicon based photovoltaics are considered to be environmentally friendly, to mine and purify sands rich in silica for high purity silicon, large scale mining operations are necessary. This process produces hazardous waste and green house gasses (GHG) and increases demand for electricity and fossil fuels (Jungbluth, 2005; Reich et al., 2011). However, the environmental impact associated with producing high purity silicon as well as the cost of manufacturing solar cells can be minimized with thin film solar cells. While bulk silicon solar cells require large amounts of high purity silicon, *thin film* silicon solar cells curtail silicon demand through reduced device thickness. Additionally, with decreasing film thickness, higher light to electricity conversion efficiencies are possible as a result of reduced Auger recombination (Metzger et al., 2001) and larger open

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* Corresponding author.
E-mail address: borcad@rpi.edu (D.-A. Borca-Tasciuc).

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circuit voltages (V_{oc}) (Sandhu et al., 2013). Despite this, the power output of thin film silicon solar cells is limited by poor absorption in the semiconducting layer as a result of the indirect band gap of silicon which causes a reduction in absorption of long wavelength photons with decreasing silicon thickness. This has led to the exploration of a variety of methods to improve optical absorption. A common technique used in *bulk silicon* solar cells is front or back surface texturing (Campbell and Green, 1987). This method is not applicable to thin films as the surface textures are on the same order of magnitude with the film thickness itself (Campbell and Green, 1987) and can result in increased minority carrier recombination near the surface and junctions (Atwater and Polman, 2010).

Employing the plasmonic effect is an alternate method for increasing absorption (Atwater and Polman, 2010). When introducing metallic nanostructures into, or onto, the semiconductor layer, the optical pathlength of light can be increased by way of forward scattering. Specific wavelengths can be targeted by tuning the nanostructure shape, material, placement, and size. Successful absorption enhancement in thin film solar cells has been demonstrated within a wide spectral range through novel combinations of the geometric and material properties of the incorporated nanostructures (Atwater and Polman, 2010).

An additional method for improving the power output from solar cells involves increasing the photon flux at the solar cell surface. To do so, light is collected from large areas and concentrated onto small surface area solar cells by refractive or reflective optics. However, supplementary systems for solar tracking and cooling are often required (Mousazadeh et al., 2009; Royne et al., 2005).

Unlike refractive and reflective concentration techniques, luminescent solar concentrators (LSC) are an inexpensive and aesthetically pleasing alternative, easily incorporated into the built environment (Correia et al., 2014). A schematic of an LSC with solar cells attached at two edges is shown in Fig. 1. LSCs can inexpensively cover large surface areas for the collection of light using sheets of polymers such as poly(methyl methacrylate) (PMMA) embedded with small amounts of fluorescent materials. Small area solar cells, placed at the LSC edges, receive light concentrated through fluorescence and internal reflection. Through concentration of light, the flux of photons at the solar cell surface is improved (Carrascosa et al., 1983; de Cardona et al., 1985; Desmet et al., 2012; Drake et al., 1982; Kennedy et al., 2008; Loh and Scalapino, 1986; Sark et al., 2008; Slooff et al., 2008; Wilson et al., 2010), and in turn the power output is enhanced.

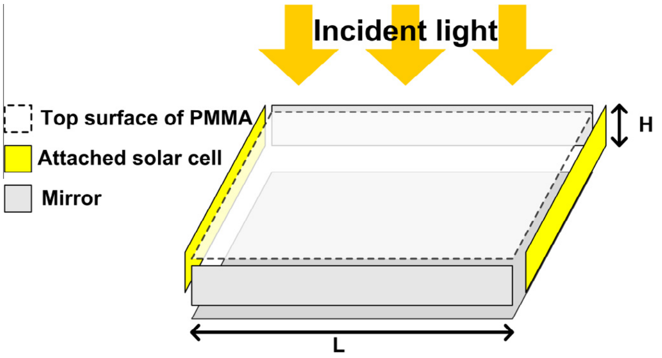

Fig. 1. Schematic of an LSC with solar cells attached to two sides. LSCs are often made from a planar sheet of transparent polymer (e.g. PMMA) embedded with fluorescent species. Mirrors are placed at the bottom surface and on the sides not covered by solar cells. *H* and *L* refer to the height and length of the LSC, respectively.

Inspired by the potential environmental and performance benefits of thin film solar cells and LSCs, the objective of this paper is to theoretically investigate, for the first time, the use of *ultra-thin film c-Si* (200 nm) solar cells in LSC–PV systems. Although the c-Si layer of solar cells is often significantly thicker, there is a strong interest in developing ultra-thin c-Si solar cells, mainly to reduce manufacturing costs and enable the use of flexible substrates (Yuan et al., 2007; Mallick et al., 2010; Spinelli et al., 2012; Trompoukis et al., 2012; Spinelli and Polman, 2014; Brongersma et al., 2014). Fabricating a 200 nm thick silicon layer can be achieved starting from thicker wafers and employing separation by implantation of oxygen (SIMOX) or similar techniques (Utteridge et al., 2000; Wang et al., 2013). Parallel studies are carried out on pristine ultra-thin film c-Si solar cells as well as cells with improved spectral coupling to the LSC, realized using plasmonic structures tuned in size, shape, and placement. To determine the overall LSC–PV system efficiency, η_{LSC-PV}, the maximum power output is calculated with a detailed balance method. This analysis takes into account the output spectrum of the LSC as well as the absorption characteristics of the solar cell. To the best of the authors' knowledge, it is the first time such an analysis has been performed in this manner for an LSC–PV system. This unique methodology allows for the quantification of enhancements achieved through efficient light transport, reduced device thickness, and improved spectral coupling. For the system employing plasmonically enhanced solar cells, improvements in the efficiency of light transport in the LSC and η_{LSC-PV} as a result of enhanced spectral coupling are discussed. Lastly, the η_{LSC-PV} of all systems under consideration is reported and compared to the most up-to-date experimental results published in the literature.

2. Simulation methods

In an LSC–PV system, the light incident on the LSC surface is concentrated to the edges where solar cells are placed. Through absorption of photons above the bandgap energy of the semiconductor, electrical power is generated. To model this process, light transport within the LSC, absorption by the attached solar cells, and electrical response of the solar cell must be simulated. To do so, the absorption spectra of the ultra-thin film c-Si pristine and plasmonic solar cells are used in Monte Carlo simulations to determine the absorbed photon flux in the cell.