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Geometry and materials considerations for thin film micro-concentrator solar cells

Sascha Sadewasser

International Iberian Nanotechnology Laboratory, Av. Mestre José Veiga s/n, 4715-330 Braga, Portugal

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ABSTRACT

Using concentrated sunlight for photovoltaic energy conversion has long been identified as a way to make cost-intensive solar cell materials and devices more cost effective. The recently proposed micro-concentrator approach for $Cu(In,Ga)Se_2$ brings concentrator photovoltaics from the centimeter and millimeter scale down to the micrometer scale, with the goal of reducing the amount of critical raw materials. We show here that the micro-concentrator approach has large benefits in terms of the heat dissipation and that heat management on the micro-scale allows the use of concentration factors as high as 1000× without any special cooling efforts. Specifically, we show that line-shaped micro-concentrator solar cells need to be either smaller than 50 µm wide, or be used at low concentration factors below 100×. In contrast, island-shaped micro-concentrator solar cells show improved efficiencies at cell sizes of $(100\ \mu m)^2$ and concentration factors up to 1000×. Additionally, we consider different materials for the substrate and the lens array for light concentration in view of their heat management capacities. The results presented here provide design guidelines for the further development of thin film micro-concentrator solar cells, applicable to a variety of materials systems, e.g. $Cu(In,Ga)Se_2$, CdTe, or metal halide perovskite solar cells.

1. Introduction

Electricity generation from solar energy is generally believed to be a cornerstone of the future energy supply, since it is abundant and essentially free-of-charge. The recent efficiency improvements of thin-film solar cells such as those based on $Cu(In,Ga)Se_2$ (CIGSe) (Jackson et al., 2016; Chirilă et al., 2011), CdTe (Green et al., 2017), and metal halide perovskites (Green et al., 2014, 2017; Brenner et al., 2016) make these materials very promising for large-scale exploitation in solar electricity generation. However, there are some concerns about the use of the critical raw materials In, Ga, and Te (Wadia et al., 2009), and about the toxicity of Cd and Pb in these highly absorbing semiconductor compounds (Zayed and Philippe, 2009; Babayigit et al., 2016). Several research directions aim at reducing the use of critical raw materials. Novel materials, e.g. the kesterite compounds $Cu_2ZnSn(S,Se)_4$ and similar have been investigated for the last decade or so, however, efficiencies are currently limited to ~12.6% (Wang et al., 2014). With the aim to reduce In and Ga in solar cell devices, the absorber layer thickness has been reduced up to a factor of 8–10 in several studies (Naghavi et al., 2016). Due to increased rear-contact recombination in thin devices, efficiency improvements have been achieved by introducing a point-contact passivation layer at the rear contact (Vermang et al., 2013, 2014). This approach is limited to a thickness reduction of ~10 times; further reduction would lead to incomplete absorption of the sunlight. Thus, materials savings are also limited to a factor of ~10 in this approach. For the case of the toxic Pb in metal halide perovskites, replacement by less toxic metals as Sn, Ge, or Sb has been realized (Hu et al., 2017). However, efficiencies are currently not comparable to perovskite solar cells based on lead halide.

A different approach to realize significant materials savings of toxic or critical raw materials is the so-called micro-concentrator solar cell concept (Paire et al., 2013a). The idea is to laterally confine the CIGSe material to the micrometer or sub-millimeter scale and then use a lens array to optically concentrate incoming sunlight onto a regular array of these micro solar cells. The materials savings potential of this concept is proportional to the concentration factor of the sunlight. An additional advantage of this concept is the potential efficiency gain by means of an increased open circuit voltage due to the concentrated illumination.

Proof of concept studies have demonstrated the feasibility of the micro-concentrator concept leading to efficiencies as high as ~21.3%, using thin films of co-evaporated CIGSe material and reducing its active area by either etching away material (Paire et al., 2015) or by using shadowing (Paire et al., 2013b). Very recently, the fabrication of micro solar cells has also been demonstrated using a materials-efficient deposition process. Locally confined electrodeposition was used to fabricate CIGSe lines (Duchatelet et al., 2016) and islands (Sadewasser et al.,

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E-mail address: Sascha.Sadewasser@inl.int.

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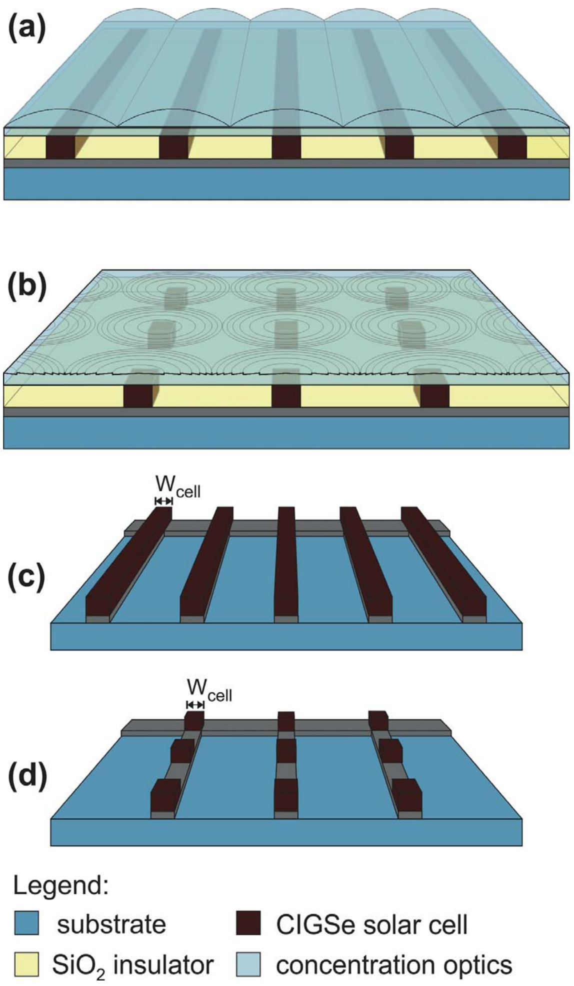

Fig. 1. Illustration of different micro solar cell geometries for (a) 1D and (b) 2D light concentration with line-shaped and island-shaped micro solar cells, respectively. Additional materials savings can be achieved by structuring the Mo back contact into lines connected by a bus bar for (c) line-shaped and (d) island-shaped micro solar cells. Here only the substrate, back contact and micro solar cells are illustrated.

2017) in the range of ~100 µm and leading to efficiencies of ~5% and ~0.3%, respectively.

Typical concentrator solar cells are realized on the cm length scale and require passive or active cooling to compensate for the considerable temperature increase due to the concentrated sunlight (Royne et al., 2005). For micro solar cells, it has been shown experimentally and by simulations that the temperature increase can be maintained to a few °C (Paire et al., 2011; Sadewasser et al., 2017). Finite element simulations have shown that the temperature increase can be kept to below 9 °C for concentration factors as high as 900x, if the micro solar cell size is lower than 10^4 µm^2 (Sadewasser et al., 2017).

Here we present a detailed analysis of the heat management in micro-concentrator solar cells giving a special consideration to geometry, materials, and materials savings aspects. We compare island- and line-shaped solar cells requiring concentration of light either in two dimensions (2D) or one dimension (1D), respectively (Fig. 1). Different materials for the substrate and for the concentration optics are explored in view of their heat management capacities. The presented results provide guidelines for the further development of the micro-concentrator solar cell approach to the increasing community active in this field.

2. Method

We used three dimensional (3D) finite element method (FEM) simulations to simulate the heat management in micro solar cells using COMSOL®. The simulated micro solar cell devices consisted of the substrate coated with a 1 µm thick Mo layer as back contact. The substrate was varied in material and thickness, reflecting frequently used substrates in current research, development, and industry settings. The simulations comprise soda-lime glass (SLG) as a rigid substrate, and steel and polyimide as flexible substrates. The thickness of these substrate materials was varied between 10 µm and 2 mm, with a detailed analysis for the most common thicknesses of 2 mm for the SLG and 25 µm for the steel and polyimide. In the case of a steel substrate, diffusion blocking layers of Al_2O_3 (500 nm thickness) or enamel (130 µm thickness) were analyzed.

For the simulation, a square-shaped unit cell was considered, consisting of the substrate, the diffusion blocking layer (if included), the Mo layer (1 µm thickness), the Cu(In,Ga)Se_2 absorber, surrounded by an insulating SiO_2 (both 2 µm thickness), a ZnO (1 µm thickness), and a top quartz glass (1 mm thickness), resembling the optical lens. The side walls of the unit cell are set to thermally insulating to model an arbitrary repetition of the unit cell. The shape of the lens is not reflected in the simulations, neither is the ~50 nm thick CdS buffer layer. Neglecting the lens shape is justified, since for a Fresnel lens (see Fig. 1(b)), the depth of the surface structuring is negligible compared to the thickness of the glass. The thin CdS layer is neglected, since it has similar thermal conductivity and heat capacity as the CIGSe material and will therefore have a negligible impact on the results due to the small thickness. We consider two different micro solar cell shapes, a line shape for the case of 1D light concentration (Fig. 1(a)) and an island shape for 2D light concentration (Fig. 1(b)). In both cases, the CIGSe micro solar cell is surrounded by a SiO_2 insulator layer. Additionally, a variation of the back contact geometry is considered, either a thin film fully covering the substrate, or in the form of lines with the width of the micro solar cells (Fig. 1(c) and (d)).

When the solar cell is illuminated through the lens, the light is focused on the CIGSe solar cell only. We assume a power of 1000 W/m^2 multiplied by the concentration factor. In principle, a fraction of 15–25% of this power is converted into electricity and therefore will not contribute to heating up the CIGSe micro solar cell. We neglect this fraction and consider the full incoming power as a heat source, thus overestimating the heating effect. The top and bottom surface of the unit cell are cooled by convective cooling (10 W/m^2).

The concentration factor is calculated based on the considered geometry and sizes. For island-shaped micro solar cells, the concentration factor is $C_{island} = (L_{unit}/W_{cell})^2$, where L_{unit} is the side length of the unit cell and W_{cell} is the width of the micro solar cell. For line-shaped micro solar cells, the concentration factor is given by $C_{line} = L_{unit}/W_{cell}$, where W_{cell} is the width of the micro solar cell. In this case, the length of the micro solar cell comprises the full length of the unit cell L_{unit}.

As reference, a regular thin film solar cell geometry was modeled where the Mo layer and the CIGSe layer are fully extending over the unit cell (the insulating SiO_2 layer is not present in the reference thin film solar cell). In this case illumination by one sun is modeled. The reference solar cell is also covered with the top glass, to account for the cover glass used in solar cell modules.

3. Results

3.1. One dimensional vs. two dimensional concentration

The concentration of sunlight into the micro solar cells can be realized by line-shaped lenses onto line-shaped solar cells, or by lenses that focus the light on a single spot, for island-shaped solar cells. In the first case, the light is concentrated in 1D, while in the latter case light is