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3D-printed concentrator arrays for external light trapping on thin film solar cells

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ABSTRACT

After our recent demonstration of a 3D-printed external light trap on a small solar cell, we now consider its potential for large solar panels. An external light trap consists of a parabolic concentrator and a spacer that redirects the photons that are reflected by the solar cell back towards the solar cell. These retro-reflections enable higher absorptance and improved power conversion efficiency. Scaling a single external light trap such that it covers a large solar panel has disadvantages in terms of height and cost of the external light trap. These disadvantages can be overcome by deploying an array of concentrators as the top part of the external light trap. We present an optimization study of concentrator arrays for external light trapping. We fabricated 3D-printed external light traps with a square, hexagonal and circular compound parabolic concentrator to test their suitability for concentrator arrays. The 3D-printed traps were placed on top of an organic solar cell which resulted in a significant enhancement of the external quantum efficiency. The required transmittance of these concentrator arrays is calculated as a function of the parameters of both the concentrator and the solar cell. We compare the theoretical and experimentally determined optical performance of the different concentrators. Finally, the prospects of external light trapping are analyzed and we give guidelines for improvements of the external light trap design.

1. Introduction

Thin solar cells benefit from low bulk recombination of excited charge carriers. Hence the performance of a thick solar cell generally improves by reducing its thickness provided that the absorptance stays constant. Therefore, large efforts have been made to obtain high absorptance in thin solar cells by modifications of the solar cell surface to obtain internal light trapping [1,2]. However, these internal cell modifications often have a negative impact on the material quality and the electrical performance of the solar cell. For example, by texturing the surface of crystalline silicon (c-Si) solar cells the surface recombination velocity increases due to the enlarged surface area [3,4]. For other cells like nanocrystalline silicon (nc-Si) the growth of a solar cell on top of a textured scattering surfaces is challenging [5–7] while for organic solar cells texturing is less effective [8]. It is thus challenging to realize the full theoretical potential of internal light trapping for most solar cells and there is a need for better light trapping methods [9]. We demonstrate an external light trapping method that can complement or even replace internal light trapping and which moreover can be directly applied on all solar cells.

Fig. 1 illustrates the concept of an external light trap: a concentrator focuses the sunlight through a small aperture before the light reaches the photovoltaic device. Most of the reflected (and radiatively emitted) light by the solar cell is reflected back to the solar cell by the reflective coating of the cage. Therefore, there is a higher probability for a photon to be absorbed. This photon recycling enables higher power conversion efficiency [10–14]. Moreover, external light trapping enables new photovoltaic devices that, for example, can facilitate spectrum splitting [15,16].

The theoretical energy conversion efficiency limit of external light trapping surpasses that of conventional internal light trapping [17,18,13]. This is mainly due to the improved electrical quality of

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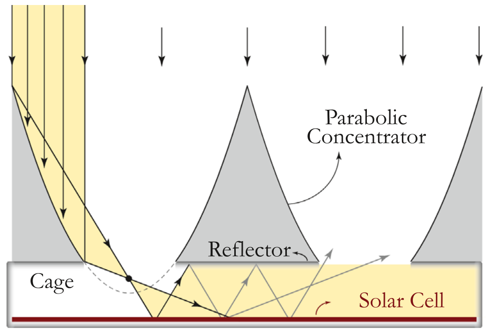

Fig. 1. Schematic illustration of a parabolic concentrator array for external light trapping. Light is focused through a small aperture. The spacing between the concentrator and the solar cell allows the light beam to expand. Most of the light that is reflected by the solar cell is reflected back to the solar cell. A small fraction (determined by the aperture area) of the light can escape out of the cage.

thin solar cells and the potential recycling of radiative emission. Recently, we demonstrated a broadband absorption enhancement by applying one external light trap on a ~1 cm^2 nanocrystalline silicon solar cell [14]. A light trap that covers a larger solar cell area can be made of a single tall concentrator, but this translates to high material costs and weight, and moreover it is aesthetically unattractive. The use of an array of small concentrators overcomes these disadvantages. We present an optimization study of the design of concentrator arrays suited for external light trapping. Furthermore, we compare the theoretical and experimental transmittance of a square, hexagonal and circular 3D-printed parabolic concentrator. Previously, a light trap incorporating a micro-lens array has been shown to be successful on an organic solar cell [19,20]. Here, a low cost fabrication method is presented that requires less fabrication steps and is industrially scalable.

To test the performance of the external light traps we use organic solar cells (OSCs). For these cells there are currently no adequate light trapping methods. The absorptance of a thin OSC is relatively low. Although a thick OSC has a high absorptance, a thick cell design is not desirable: due to the high bulk recombination loss the internal quantum efficiency (IQE) is relatively low [21,22].

Internal light trapping schemes based on the Lambertian scattering can realize a significant path length enhancement factor for high refractive index solar cells as the escape probability scales as $P_{escape} = 1/n^2$. However, they are less effective for low refractive index solar cells like organic solar cell materials (n~2) [23–25,8].

Moreover, it is difficult to scatter the broadband sunlight effectively in OSCs. Macroscopic surface textures efficiently scatter the light in relative thick crystalline silicon solar cells. However, this method cannot be directly applied to thin OSCs as scattering by geometric features smaller than the wavelength of light is not effective [26].

Due to the lack of a sufficient light trapping method there has been interest for alternative light trapping methods like arranging solar cells in a macroscopic V-shape in which incoming light hits both flanks of a V-shaped solar cell several times [22,27,28]. This is an effective method to enhance the total absorption, but it complicates the fabrication considerably. Due to the enlarged area the light is effectively diluted which reduces the injection level and the corresponding open circuit voltage of the solar cell. Moreover, the enlarged surface area will increase surface recombination and deteriorate the dark current. These disadvantages are absent for external light trapping where the optical path is prolonged without using more solar cell material.

2. Experimental: design of the concentrator

Metallic parabolic concentrators with a square and a hexagonal top shapes can be arranged in an array. Figs. 2a and d show a square concentrator that is composed of four parabolic segments. These square concentrators can be arranged in a square array as shown in Fig. 2g. In a similar way a hexagonal array can be made as shown in Fig. 2b, e and h. Circular concentrators cannot completely fill a plane. To overcome this filling problem the circular concentrators can be truncated at four sides to enable the formation of a square array as illustrated in Fig. 2c, f and i. In a similar way a hexagonal array of circular concentrators can be made. In between the neighboring concentrators there are sharp peaks which are fragile and challenging to fabricate.

The transmittance of the concentrator is a key-parameter for the performance of the external light trap. Incoming light that travels in a straight line towards the aperture of the concentrator is transmitted without being reflected by the concentrator. The main part of the light is reflected one or more times at the reflective concentrator surface before going through the aperture to enter the cage. The exact number of reflections depends on the geometry of the parabolic concentrator. At each reflection a small fraction of the light is absorbed by parasitic losses at the reflective surface of the concentrator. The averaged transmittance of a concentrator therefore decreases with increasing geometric concentration factor (C), where C is defined as the following area ratio:

$$C = \frac{A_{cell}}{A_{aperture}}.$$

To determine the optimal concentrator geometry we calculated the average transmittance of incoming light propagating parallel to the central axis of the concentrator. The transmittance of light originating from other angles depends on the parabolic shape of the concentrator [29]. Diffuse light is only partly transmitted by the concentrator. The maximum transmitted power (P_{trans}) of isotropically distributed diffused light (P_{diff}) is $P_{trans} = (1/C) \cdot P_{diff}$ [30]. Sun tracking will yield the best averaged transmittance of the concentrator as all rays of the direct sunlight will be transmitted through the aperture. However, external light trapping can be more cost effective without diurnal sun tracking which is possible: at low concentration factors ($C < 10\times$) a static concentrator can still accept the direct sunlight for around 8 h per day [31].

It is difficult to determine the transmittance of a hexagonal concentrator analytically and therefore we performed ray tracing. Fig. 3a shows three different rays at paraxial incidence with a different number of reflections at the concentrator surface. Depending on the origin, a ray hits the hexagonal concentrator a certain number of times. Fig. 3b indicates the number of reflections for a large number of rays. The average number of reflections for this concentrator with $C = 15\times$ is 1.43. From this ray tracing the transmittance is approximated by the average transmittance of all rays assuming a wavelength and angle-independent reflection coefficient of 95%.

Fig. 4 shows the calculated transmittance of the concentrators as a function of the concentration factor. The right inset depicts the average number of reflections at the concentrators before a ray is transmitted. For the circular and square concentrators this average converges to 1 and 2 reflection(s) respectively. Therefore, the transmittance of these concentrators converges to R and R^2 respectively. There is no convergence for the hexagonal concentrator.

Rounded ridges in between neighboring concentrators will inevitably form during fabrication due to, for example, limited fabrication accuracy and limited material strength. We assume that these limitations translate to ridges having a width Δ. The fraction of the total area covered by ridges (f_{ridge}) is shown in Fig. 5. Light