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Bifacial *n*-type silicon solar cells for upconversion applications

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A B S T R A C T

Upconversion of sub-band-gap photons has the potential to increase the efficiency of solar cells significantly, but requires modification of the solar cells. In this paper, we present a calculation framework to assess the efficiency of a combined bifacial silicon solar cell upconverter device, which is then used to optimize the solar cell's front and rear side anti-reflection coatings. Our calculations show that an upconverter can increase the efficiency of an optimized solar cell by 3.0% relative. Subsequently, planar bifacial *n*-type silicon solar cells were fabricated with optimized anti-reflection coatings. An upconversion layer – containing the upconverter phosphor β-$NaY_{0.8}Er_{0.2}F_4$ embedded in the polymer perfluorocyclobutyl – was attached to the rear side of the solar cells and an external quantum efficiency arising from the upconversion of sub-band-gap photons of 1.69% was measured under 1508 nm monochromatic excitation with an irradiance of 1091 W/m^2. This corresponds to a value of 0.15 (W/cm^2)$^{-1}$ when normalized to the irradiance, constituting a five-fold increase compared to the previously best published normalized values that were achieved without optimized solar cells.

1. Introduction

Solar cells made from materials with one single band-gap do not fully utilize the solar spectrum. Silicon (Si) photovoltaic (PV) devices fail to capture about 20% of the incident energy, with sub-band-gap photons being not effectively harvested. Upconversion (UC) of such sub-band-gap photons can minimize these losses [1,2] and high efficiency gains due to the application of upconverters to Si solar cells have been theoretically predicted [1,3,4]. The theoretical limit for the efficiency of a Si solar cell (band-gap 1.117 eV) with additional upconverter, illuminated by non-concentrated light, is reported to be 40%, compared to a radiative limit efficiency of the solar cell alone of 33.25% [4]. However, while a 20% relative increase in efficiency due to the addition of an upconverter is predicted, experimental results have demonstrated only very small increases in overall device efficiency [5–7]. Shalav et al. investigated bifacial Si solar cells, with an upconverter layer containing microcrystalline hexagonal sodium yttrium fluoride doped with 20% erbium ions, β-$NaY_{0.8}Er_{0.2}F_4$, attached to the rear side. They reported an external quantum efficiency (EQE) of the combined upconverter Si solar cell device of 3.4% under monochromatic excitation with a wavelength of 1523 nm and an irradiance of 24,000 W/m^2 [8]. The upconversion quantum yield, and consequently also the EQE of a system that utilizes sub-band-gap photons by upconversion, increases with the incident irradiance. Therefore, efficiency values are commonly normalized to the irradiance to make the values more comparable [9]. The values reported by Shalav et al. correspond to a normalized efficiency of 0.014 (W/cm^2)$^{-1}$ (the unit of the normalized efficiency is also commonly written as cm^2/W in literature) [5]. Fischer et al., using the same UC material, determined an EQE of 0.34% for an excitation wavelength of 1523 nm and a considerably lower monochromatic irradiance of 1090 W/m^2, resulting into a higher normalized value of 0.03 (W/cm^2)$^{-1}$[6].

Many challenges need to be overcome in order to realize a successful upconversion photovoltaic device (UC PV device), including the development of highly efficient upconverter materials [6–8,10] that can achieve good performance under realistic irradiance values. In addition, another key reason for the low performance that has not been examined yet is that the solar cells used in the experimental works were not adapted to the application of an UC layer at the rear [5–8]. In this work, we address the

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question how crystalline Si solar cells can be adapted to maximize the overall efficiency by the addition of an upconverter system. In this context, the ideal solar cell should fulfill three criteria: firstly, the solar cell should have a very high transmittance for photons with wavelengths $\lambda > 1200$ nm in order to illuminate the UC layer located on the rear side of the device. Secondly, the solar cell should have a high EQE when illuminated from the rear with photons emitted by the upconverter. These two requirements mean that the solar cell needs to have an adapted, bifacial functionality. Thirdly, the solar cell itself needs to have a high overall efficiency to ultimately optimize the UC PV device.

The increased transmission can be achieved by adapted anti-reflection coatings (ARCs). An early work describing the optimization of single- and double-layer ARCs considering as well the need for effective surface passivation can be found in Ref. [11]. In the context of spectral management, ARCs have been optimized for the emission for organic dyes, for example in Refs. [12,13]. In Ref. [5], the use of adapted ARCs was suggested to increase UC efficiencies, but no devices with optimized ARC have been fabricated yet.

In the first part of this work, we focus on the optimization of ARCs and present a simulation framework that allows us to assess the performance of solar cells with attached upconverter. The framework includes the simulation of the solar cell performance under standard front side illumination, the optical properties of the solar cell that determine the illumination of the upconverter, a parameter model of the upconverter behavior, and the performance of the solar cell under rear-side illumination from the upconverter.

The model of the upconverter is based on the widely used β-$NaY_{0.8}Er_{0.2}F_4$ phosphor, which exhibits efficient UC luminescence predominantly at 980 nm when excited with wavelengths around $\lambda = 1523$ nm [6,14–16]. One disadvantage of this upconverter material is that it only utilizes a 100 nm wide spectral range efficiently. Therefore, we assume the use of a second idealized luminescent material that has a broad absorption spectrum and emits in the absorption range of the upconverter as suggested by Strümpel et al. [17], a concept also called spectral concentration. Furthermore, we assume a system geometry, in which this luminescent material is embedded in a transparent matrix forming a luminescent solar concentrator (LSC) that allows for additional geometric concentration onto the upconverter that covers only a fraction of the LSC surface, a configuration proposed by Goldschmidt et al. [3,18]. The suggested setup is shown in Fig. 1.

For the simulation of solar cell characteristics, commercial simulation tools exist that achieve high accuracy, such as the Sentaurus TCAD [19] used in this work. Solar cells made on n-type Si have been already simulated successfully. To describe the effects of upconversion, the existing simulation models for n-type Si silicon solar cells [20–25], need to be extended to include rear-side illumination. This was successfully implemented for a different purpose in an earlier work [26,27]. Additionally, the covered spectral range was extended to wavelength beyond 1200 nm, a spectral region that is typically not covered in Si solar cell simulations. This included determining all necessary parameters, especially the optical dispersion curves for the used materials, also for the wavelength range above 1200 nm [27].

The combined simulation model is subsequently used to optimize the optical properties of the solar cell and to calculate the additional current density from UC. This allows for an assessment of the potential efficiency increase due to upconversion, based on realistic solar cell properties and realistic upconverter characteristics in combination with idealized assumptions for the extension of the used spectral range. This extends earlier work [4,28], where realistic solar cell properties were combined with ideal upconverter properties. These optimizations are carried out

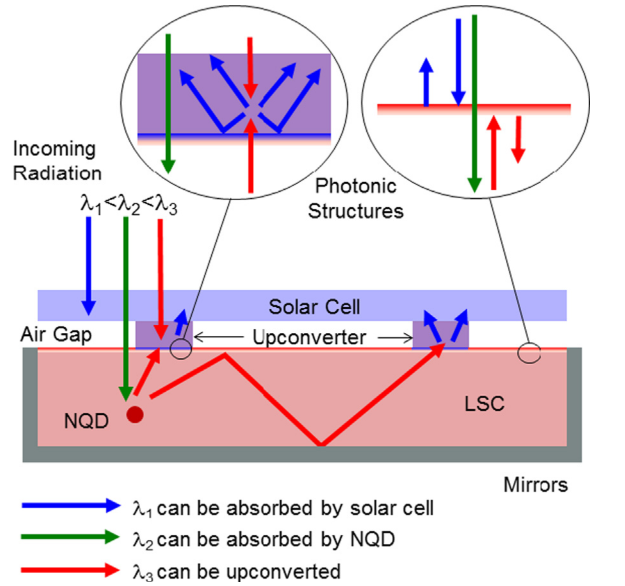

Fig. 1. Concept of an advanced upconverter system [3,18]. It consists of a bifacial solar cell that can utilize higher energy photons (λ_1), and of an upconverter that can convert low energy photons (λ_3) into higher energy photons (λ_1). Photons of the intermediate spectral range (λ_2) are absorbed by luminescent nanocrystalline quantum dots (NQD), which are embedded in a transparent matrix. The luminescent NQD emit photons that can be utilized by the upconverter (λ_3). The emitted photons are guided by total internal reflection and photonic structures to the upconverter elements. Such a configuration increases the photon flux in the absorption range of the upconverter (spectral concentration). Additional geometric (or spatial) concentration occurs because the upconverter does not cover the full solar cell area. Spectrally selectively reflecting photonic structures ensure that the photons are directed to that part of the system, in which they are used most efficiently.

both for planar and both-sides-textured solar cells. Both-sides-textured solar cells were chosen, because the texturing promises advantageous anti-reflection properties. Planar solar cells were included, as all previous experimental results were achieved on planar solar cells, motivated by the higher transmission of upconvertible light in the planar case.

The second part of the paper deals with the fabrication and characterization of optimized, planar solar cells that were prepared based on the findings presented in the first part. Upconverter samples are applied to different kind of solar cells, and the EQE of the whole system of upconverter and solar cell is measured under monochromatic excitation at 1508 nm, showing extremely high performance. The purpose of these measurements is to document the successful optimization carried out in the first part of the paper. Detailed experimental investigations of UC PV devices using our optimized solar cells focusing on the upconverter materials and different illumination conditions (monochromatic, broad-band) have been performed in the mean-time, achieving as well record breaking results [29,30].

2. Optimizing the solar cell structure

2.1. Solar cell simulation model and figures-of-merit

The optical performance of the solar cell was modeled using Sentaurus TCAD [19]. The optical properties of the ARCs were determined via transfer matrix calculations and these data were implemented into the Sentaurus ray-tracing tool. One important effect determining the transmission of sub-band-gap photons is free carrier absorption (FCA). FCA was considered in the simulations based on the parameterization of Green [33]. In the