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Theoretical enhancement of solar cell efficiency by the application of an ideal 'down-shifting' thin film

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ABSTRACT

Poor ultraviolet (UV) quantum conversion efficiency contributes to a reduction in the efficiency of silicon based photovoltaic cells. In the UV, the main loss mechanism is through surface recombination of photo-generated carriers due to the shallow absorption depth of high energy photons. One method for greater utilisation of the UV region is by down-shifting UV photons to lower energies where the quantum efficiency of silicon is higher. This work determines the potential enhancement in efficiency that can be obtained by a luminescent down-shifting layer applied to silicon based solar cells. The efficiency is determined through detailed balance arguments. The maximum calculated efficiency enhancement due to an ideal down shifting process is 0.6% absolute using the AM1.5G standard spectra. Applying a similar analysis to a multicrystalline silicon solar cell results in an efficiency enhancement due to the down-shifting process of 0.17% absolute.

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1. Introduction

One way of overcoming the spectral losses in conventional single junction solar cells is through the manipulation of the incident spectrum before absorption by the solar cell. The subject of this work focuses on the poor UV response of silicon based photovoltaic devices. The shallow absorption depth of UV photons increases the probability that the generated carriers will recombine via surface defect states, thereby reducing the UV response. The refractive index of silicon is comparatively higher in the UV/blue region, which further reduces the UV response due to an increased reflection of UV photons. The high dispersivity of the refractive index in the UV region also introduces complications in optimising anti-reflection (AR) coatings. A method of increasing the efficiency of solar cells with poor UV response, which was first proposed by Hovel et al. [1] is through the down-shifting of UV photons to longer wavelengths where silicon has greater quantum efficiency.

A common method of increasing the UV quantum efficiency of silicon based photovoltaic devices is via thermally grown oxide and PECVD SiN layers to passivate surface defects in order to reduce the front surface recombination velocity [2]. However, to provide further enhancements on the efficiency to cost ratio of silicon based photovoltaic devices, a suitable method, which adds little to the cost and complexity of such devices is required. An approach that has attracted interest is via the application of an organic luminescent down-shifting (LDS) layer on the front face of a photovoltaic device [3,4]. Such organic dyes or pigments are low cost and add little to device complexity and production energy consumption; for example, it has been estimated that the addition of an organic dye material in an encapsulation layer for a 1 m^2 module will add an additional cost of less than US$1¢ [3].

The focus of this work is to determine the potential enhancement in efficiency that can be obtained from an ideal down-shifting thin film. The approach taken has involved an adaption of the Shockley–Queisser detailed balance limit [5], with further incorporations of the work presented by Trupke et al. and Badescu et al. [6,7]. Several models have been published, which extend the detailed balance method of Shockley and Queisser beyond the 30.9% efficiency limit [8–10]. The first theoretical model based on detailed balance to implement multiple carrier generation through the down-conversion of photons however, was described by Trupke et al. [6]. It has been noted that this model involved a combination of down-conversion and down-shifting where the modelled solar cell had zero quantum efficiency and was completely transparent to photons with energies greater than twice the bandgap of the material [7].

In this work, the model developed by Trupke et al. [6] is adapted so that only down-shifting is considered. A further modification that is implemented in this work is to consider the

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internal quantum efficiency of silicon solar cells corresponding to both mono-crystalline and multi-crystalline silicon solar cells (as outlined in Sections 5 and 6). The ideal case of a top hat response is considered first and is discussed in Section 2. The results obtained from this model and presented here include an analysis of the enhancement in efficiency of a down-shifter under the AM1.5 standard spectra as opposed to the theoretical black body spectrum at 6000 K.

2. Description of model

There are several important characteristics that a LDS layer should contain in order to be effective. Obviously, the luminescent quantum efficiency (LQE), defined as the ratio of emitted photons to the number absorbed by a luminescent material needs to be high and ideally greater than or equal to unity. Less than unity LQE will result in an additional loss mechanism. This effect is compounded further if the absorption spectrum of the down-shifter overlaps with the spectral response of the cell. The absorption coefficient and film thickness should enable 100% absorption of short-wavelength light and be completely transparent to all wavelengths within the responsivity range of the cell. The LDS layer should also show a strong red shift to minimise any overlap between the absorption and emission spectra. Reabsorption of luminescent light by the LDS layer will provide a further loss mechanism if the LQE is less than unity. As the luminescent light is emitted isotropically, there are spectral losses that result from luminescence escaping through the front surface of the device. This is again further compounded if the LDS layer's absorption spectrum overlaps with the spectral response of the cell. Optimally, the emission spectrum should be narrow and occur at the peak of the IQE of the cell; this however is not considered initially as it is assumed that the cell has unity quantum efficiency within its responsivity range. The LDS layer also requires a suitable refractive index to minimise device reflections and maximise the forward coupling of luminescent light into the cell. This establishes the conditions required for an idealised LDS layer, which provides the basis of the model analysed in this work. For a more detailed discussion of these characteristics, the review of Klampaftis et al. [3] is recommended.

The initial device configuration, which is analysed here consists of a conventional single junction silicon solar cell with a physically deposited solid film of an LDS material on the front surface (Fig. 1(a)). It is assumed that the LDS layer and the solar cell surfaces are spectrally flat; however for a solid film of an organic LDS layer, this assumption may be unrealistic [11]. The LDS layer is modelled to have complete absorption of all incident light with wavelength shorter than 400 nm and is otherwise transparent. It is assumed that the LDS layer has unit LQE and exhibits luminescence at wavelengths longer than 400 nm to ensure that there is no overlap of its absorption and emission spectra. It is also assumed that the LDS layer is a perfect insulator.

The LDS layer modelled here is considered as a crystalline thin film of an organic dye molecule. The following discussion presents a qualitative description of the luminescence processes of organic species in the gas and crystal phases. The spectral properties of such materials introduce a restriction on the characteristics of an ideal LDS layer. It was mentioned previously that an ideal LDS layer should contain an emission spectrum with its peak located at the maximum of the IQE of the cell. This ideality is unrealistic for an organic LDS layer and is later relaxed where it is assumed that the red shift is just enough to consider the effects of any reabsorption processes as negligible. The ideal case is presented and discussed first.

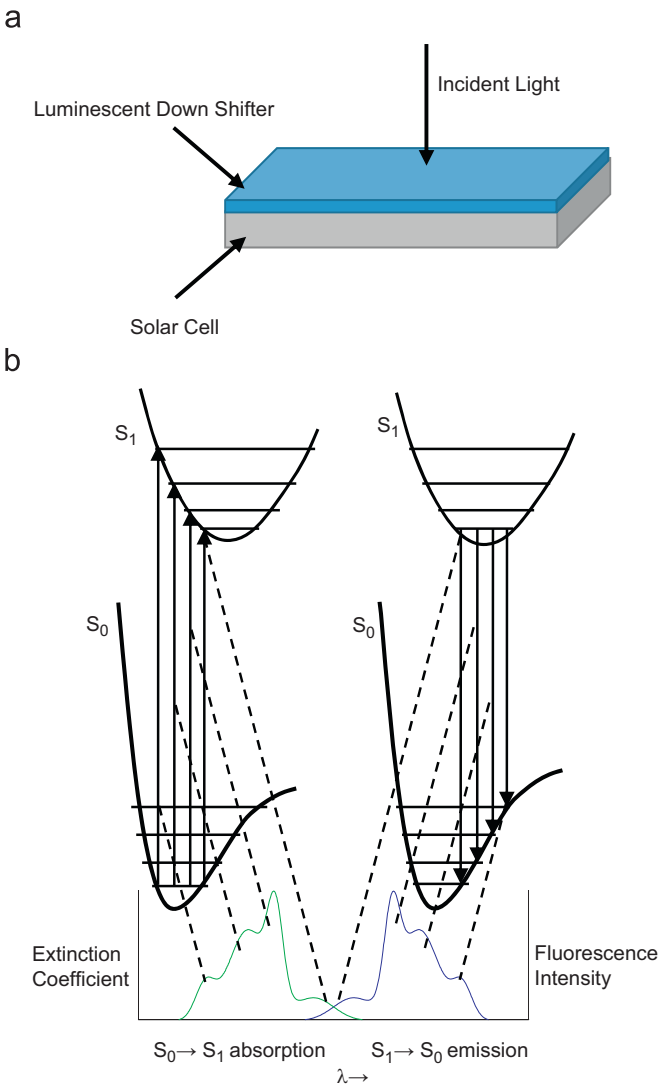

Fig. 1. (a) Schematic representation of the solar cell and LDS layer. (b) Potential energy level diagram of the LDS layer [12].

The electronic structure of isolated organic molecules consists of energetic states comprised of electronic, vibrational and rotational components. Electronic transitions correspond to excitation energies in the order of ultra-violet and visible photons. Vibrational and rotational transition energies are in the near infra-red and far infra-red, respectively. Electronic states are coupled to a manifold of vibrational states as well as other electronic states. Upon optical excitation of an electron from the ground to an excited electronic state, the nuclear configuration of the molecule is no longer in a steady equilibrium allowing the electron to relax non-radiatively to lower vibrational states within the vibrational manifold. Non-radiative vibronic relaxation occurs much faster than radiative relaxation to the ground state meaning that radiative relaxation to the ground state generally occurs from a lower energetic state. The energy lost through vibrational relaxation results in an emitted photon of less energy than the excitation photon. The frequency shift of the transitions associated with the 0-0 vibrational energy levels (lowest vibrational energy levels of the electronic states) of the ground and excited electronic states is termed the Stoke's shift. The excited electronic state is also coupled to other electronic manifolds of different spin multiplicity. Radiative relaxation from these states (triplet states) is termed phosphorescence whereas the previous process

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