Photonics Crystals on high efficiency III-V Solar Cells

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Applicable topic: 1.2 MATERIALS STUDIES, NEW CONCEPTS AND ULTRA HIGH EFFICIENCY: New materials and concepts for cells

Summary

We have explored the following photon management options for increasing the efficiency of concentrator solar cells: increasing the voltage by recycling the luminescence, increasing the current reducing reflection and increasing the optical path. We find that a 1 μm thick GaAs solar cell with optimized nanostructured front and back surfaces has significantly higher efficiency than a similar cell with a perfect back side mirror and a state of the art bilayer antireflective coating. We have also designed a multilayer coating with high reflectivity at angles away from the surface normal that results in luminescence trapping, and thus increases the open circuit voltage and the cell efficiency.

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Abstract

We have explored the following photon management options for increasing the efficiency of concentrator solar cells: increasing the voltage by recycling the luminescence, increasing the current reducing reflection and increasing the optical path. We find that a 1 μm thick GaAs solar cell with optimized nanostructured front and back surfaces has significantly higher efficiency than a similar cell with a perfect back side mirror and a state of the art bilayer antireflective coating. We have also designed a multilayer coating with high reflectivity at angles away from the surface normal that results in luminescence trapping, and thus increases the open circuit voltage and the cell efficiency.

Introduction

Solar cells made of III-V compounds are the most efficient [1] but still far below the Shockley-Queiser limit [2]. In the last 40 years most of the research on high efficiency has been focused on increasing the quality of the semiconductor material and improving the coupling of the band gaps with the solar spectrum in multijunction tandems. Efficiency limitations related to photon management are: reflection losses, the limited absorptivity of the semiconductors and photon reemission. A single junction gallium arsenide (GaAs) device is modeled. The results are applicable to most PV technologies, however the added cost of nanostructuring the photonic crystals only makes sense in high concentration devices, where the cost per solar cell unit area has a small impact on the cost of the produced electricity. We have used the well known detailed balance theory [2], for calculating the voltage, current and efficiency, but taking in account the angle in remission of the device [3]. The theoretical limit without photon management is approximately 31% for a GaAs solar cell at one sun, but with photon management it is approximately 38% [4] independently of the concentration. The objective of this work is to design optimal photon management structures for concentrator solar cells: minimizing reflection [5] (within the acceptance angle), maximizing the absorption [6, 7], and minimizing the emission from the semiconductor out of the acceptance angle [4]. We have attempted this using two nanostructured layers, Fig. 1, on the solar cell: 1 A dielectric photonic crystal (PC) at the top of the semiconductor to act as antireflection layer, to improve J_{sc}, while also acting as an angular filter to improve V_{oc}. 2 A PC in the rear contact acting as a Lambertian light trapping system, to improve J_{sc}. To further limit luminescence

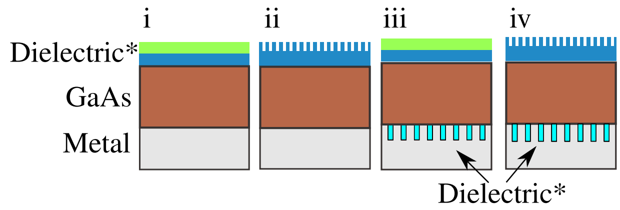

Figure 1: i) Bilayer ARC made of ZnS and MgF_2, (Reference System) ii) Front ZnS PC iii) A bilayer as antireflection coating and a back nanostructure iv) Front and back nanostructures on the same device. Dielectric*: MgF_2, ZnS or SiO_2.

losses and increase the open circuit voltage, we propose a multilayer filter to be integrated on top of the antireflective structure.

Theory and Numerical Methods

The system evaluated has a lossless concentrator at X = 500 suns, and a back metal reflector with no absorption. We have neglected the non-radiative recombination. GaAs has almost 99% [8] internal quantum efficiency, which allows for photon recycling schemes with small loses on non radiative recombination. The Sun and the semiconductor irradiance are modeled as blackbody emitters at $T_s = 6000$ K and $T_c = 300$ K, respectively. The charge created by the photons from the sun is described as qf_s, and the charge lost by the photons emitted from the semiconductor as $qf_{c0}\exp(qV/kT_c)$. In order to achieve high efficiency f_s should be maximized and f_{c0} should be minimized. This can be achieved minimizing reflection and emission from the solar cell without compromising absorption.

$$f_s(E,\theta,T_s) = \int_{E_g}^{\infty} dE \int d\Omega/\pi B_{sun}(E,T_s)a(E,\theta)\cos(\theta)$$
$$f_{c0}(E,\theta,T_c) = \int_{E_g}^{\infty} dE \int d\Omega/\pi B_{sc}(E,T_c)e(E,\theta)\cos(\theta) \quad (1)$$

The current increases with the absorption, $a(E,\theta)$, while the voltage decreases with the emission, $e(E,\theta)$. This can be seen in the classical expression Eq. 2 of open circuit voltage, V_{oc}. The only possibility to increase the voltage in an ideal cell without non-radiative recombination is to control the emission. The ideal is to absorb all the photon flux from the sun and to avoid emission at angles out of the cone of incidence from the sunlight. These two premises are compatible as it is described in [3]. Having a more directional remission does not significantly affect the current as f_{c0} is orders of magnitude smaller than f_s.

$$V_{oc} = \frac{kT_c}{q}\log\left(\frac{f_s - f_{c0}}{f_{c0}}\right) \tag{2}$$
$$J_{sc} = q(f_s - f_{c0})$$

A solar cell that only uses a light trapping scheme to maximize absorption, such as a Lambertian scatterer [9] and/or an antireflective coating, pays a voltage penalty due to luminescence at angles outside the incoming light cone. Thus angular filters are needed in conjunction with schemes that maximize absorption.

Results

The simulations have been done using scattering matrix method [10, 11] and transfer matrix methods [12]. The refractive index of the materials are taken from [13]. The optimizations have been done using a local algorithm [14].

Nanoestructured devices

The systems calculated (Fig. 1) are formed by a 1 μm thick GaAs layer with a perfect mirror at the back. The top surface is a square lattice PC made of ZnS nanopillars and a thin film made also of ZnS between the PC and the semiconductor. The back nanostructure is a square lattice PC made of nanopillars of silicon dioxide (SiO_2) in between the semiconductor and the absorption-free back side mirror. Nanoholes, in square and triangular lattice, and nanopillars in triangular lattice were calculated in the front layer showing worse efficiencies, because of higher reflection. The reference system has an optimized bilayer MgF_2/ZnS as antireflection coating on the front side (which is very common on III-V solar cells) and a perfect mirror at the back. The four types of solar cells that have been tested are shown in Fig. 1.

The thicknesses of the front nanostructure were optimized first (PC and the thin film between PC and the semiconductor), keeping the lattice parameter (a) and radius (r) fixed, $a = 350$ nm, $r = 110$ nm, (as a first guess we used an effective index theory to choose the filling factor, and a lattice parameter smaller than the working wavelength). Once the thicknesses were optimized, we kept its value fixed and proceed to look for the optimal lattice parameter and filling factor. A final optimization is done using these four parameters, using as seed the result from the earlier optimizations. When the back contact is assumed to be nanostructured, it is represented as a square lattice of nanopillars, starting with $a = 500$ nm, $r = 125$ nm, and also optimized in efficiency. The cell with optimized photonic crystals on both, the front and the back side, shows an increase in absolute efficiency of 1.2%, as can be seen in Table 1. The front nanostructured system (ii), minimizes reflection, increasing J_{sc} more than the back nanostructured system (iii). Despite this increase in absorption the voltage is higher in (ii) than in (iii).

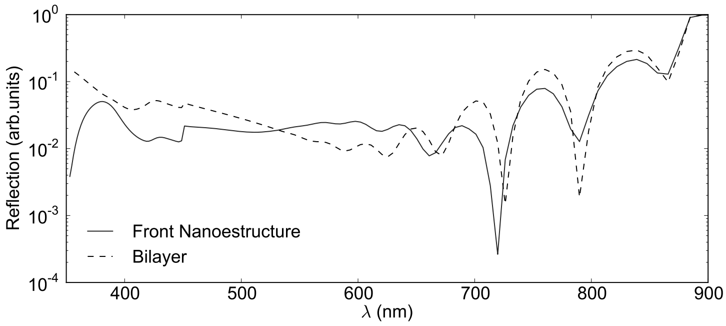

Figure 2: Reflection at 0 angle of incidence for (i) and (ii) systems

		η	V_{oc}(V)	J_{sc}(A/cm^2)
i	Bilayer	0.325	1.331	20.42
ii	Front PC	0.333	1.330	20.93
iii	Back PC	0.331	1.329	20.80
iv	Front and Back PC	**0.337**	1.329	21.20

Table 1: Summary of efficiencies currents and voltage calculated for X=500 for nanostructured devices with 1 μm thickness.

Multilayer

The multilayer it is formed by a multistack of Si_3N_4 and SiO_2 with gradual refractive index (sinusoidal), Fig. 3. The filter is embedded in SiO_2 . The system is optimized to have high transmission at normal incidence and high reflection out of the normal. The reflection has an strong dependency as a function of the angle as can be seen in Fig. 3. This is achieved using 7 periods in the stack. For an ideal GaAs cell with 100% external quantum efficiency the energy efficiency increases from 35.1% to 35.3% with the multilayer filter. This is due to avoltage increase from 1.325 V to 1.338 V. The J_{sc} current decreases from 22.10 A/cm^2 to 22.06 A/cm^2 due to incomplete transmission through the multilayer and 22.06 A/cm^2 of Jsc at X = 500 suns. Compared to perfect transmission (absence of filter with zero reflection at all angles) the multilayer shows an increase of 13 mV and 0.2% of efficiency.

Conclusions

In this work we have explored 1D and 2D photonic crystal solutions for high efficiency solar cells. We achieve efficiencies above the reference systems, a bilayer and a perfect transmission filter.

The solar cell with optimized 2D photonic crystals on the front and at the back side shows an increase in absolute efficiency of **1.2%**. The 2D PC exhibits more angular selection than the bilayer, increasing the voltage.

A multilayer (1D PC) as angular filter made of SiO_2 and Si_3N_4 was simulated. Using this angular filter the efficiency could be increased above the limit of 35.1% for X = 500 suns. This enhancement is directly related to an increase in voltage.

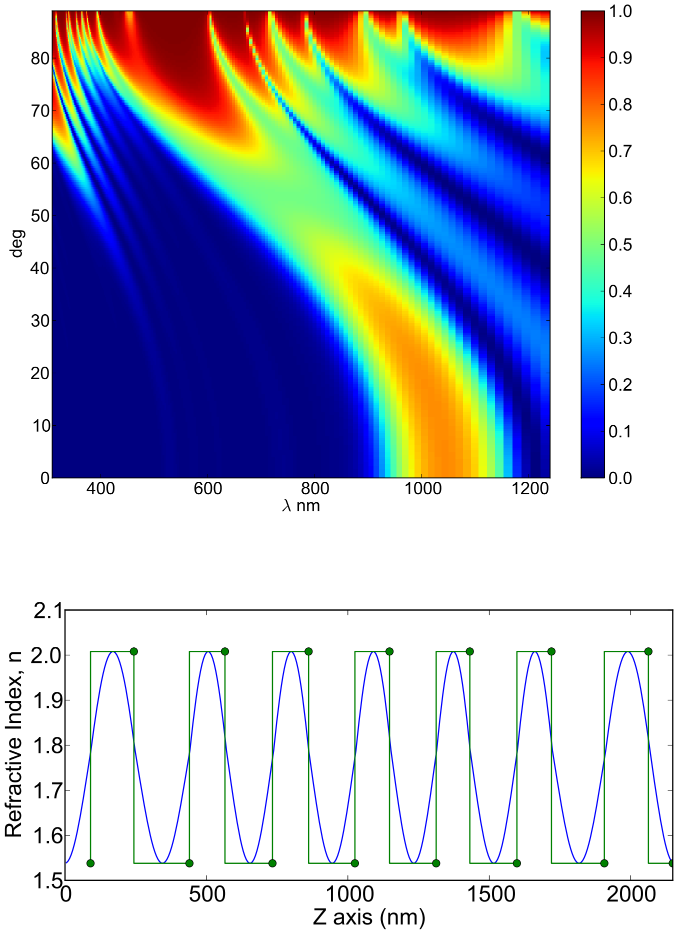

Figure 3: Top: Reflection for a multilayer showing angle selection: high transmission for energies above the gap at normal incidence and high reflection for angles out of the cone of incidence Bottom: Refractive index profile for the optimized multilayer made of SiO_2 and Si_3N_4

The photonic structures put to test increase the efficiency limit of the solar cell with respect to solutions based on dielectric layers for antireflective purposes.

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