

Combining front and back grating structures for broadband absorption enhancement in thin-film silicon solar cells

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Abstract: We investigate the possibilities of enhancing absorption in thin-film silicon solar cells with grating structures on the front ITO and back Ag contacts simultaneously. Broadband enhancement from complementary effects of each grating is demonstrated.

OCIS codes: (040.0040) Detectors : Detectors; (040.5350) Detectors : Photovoltaic; (240.0240) Optics at surfaces : Optics at surfaces; (240.6680) Optics at surfaces : Surface plasmons

1. Introduction

Driven by the increasing demand for clean energy, much research has been performed to develop low-cost and efficient solar cells (SCs). However, the use of low-cost silicon based materials for SCs tends to give rise to severe limitations in active material thickness, due to electrical reasons. For example in amorphous silicon (a-Si) SCs, due to high defect-related carrier recombination, the a-Si thickness is limited to a few hundred nanometers to keep the charge collection optimal. Similarly, in polycrystalline silicon (p-Si) SCs there is high carrier recombination at grain boundaries. This thickness limitation leaves the photon absorption to be inefficient when no proper light trapping techniques are utilized.

In the past few years, several techniques have been introduced to enhance absorption in thin film SCs [1-4]. One of the most widely used techniques is light-trapping caused by scattering surface textures [4]. This is done by tailoring the top contact of the cell, making it an efficient antireflection and scattering layer. Absorption enhancement has also been demonstrated by utilizing strong near field enhancement in plasmonic modes and by employing structures with resonantly enhanced scattering cross section [1-3].

In this work, we introduce triangular gratings both in the transparent conducting oxide (TCO) layer front contact and on the silver (Ag) back contact. We demonstrate a complementary absorption enhancement effect by the TCO grating in the shorter wavelength range via scattering and by the metal grating in the longer wavelength range via plasmonic mode excitation. Also, enhancement from cross interaction between the two gratings is observed.

Only results for amorphous silicon SCs are shown here, but the application of this double grating structure in polycrystalline silicon SCs will be investigated as well.

2. Simulation Results

The analysis is done using electromagnetic-wave simulations with COMSOL Multiphysics which employs the finite-element method. We model the light illumination on our structure as an incoming plane wave with wavelengths in the range 400-850 nm. The sketch of the proposed device structure is depicted in Fig. 1(a). The TCO layer is made by indium tin oxide (ITO). The absorbing material is amorphous silicon (a-Si). The back contact is silver (Ag). Triangular grating structures are introduced on the top ITO and bottom Ag layer. Here we show the optimal design for the case of single periodicity without any phase offset between the front and back contact gratings (the ITO triangles will always be directly on top of the Ag triangles). Fig. 1(b) shows the integrated absorption efficiency of the AM 1.5G spectrum in the 400-850 nm wavelength region

for flat structures with different ITO and a-Si thickness. The oscillation seen is due to Fabry-Perot effects. We see that without any grating structure, even with a relatively thick a-Si layer of 820 nm, we cannot obtain 90% absorption efficiency. The thickness values indicated in Fig. 1(a) are the values for a planar SC structure which give a Fabry-Perot optimum absorption point with an electrically favorable a-Si thickness of 200nm.

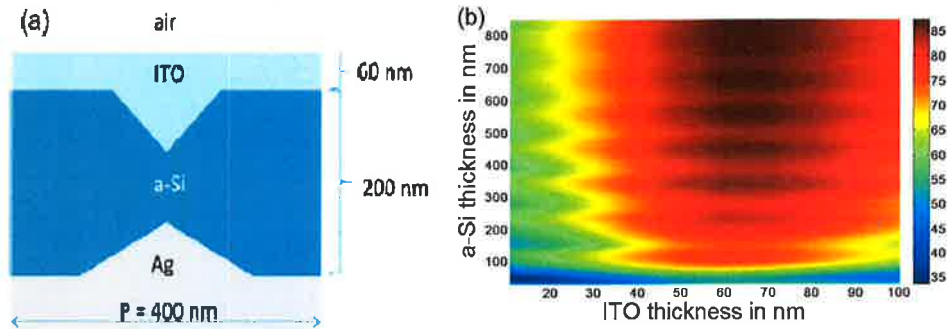


Figure 1. (a) The studied geometry. (b) Integrated absorption efficiency for flat structures in the 400-850 nm wavelength range.

In Fig. 2 we show several absorption spectra for different structures to demonstrate the enhancement provided by our double-grating structure. All the absorption spectra shown are for normal incidence case. The red line shows the absorption spectrum for an optimized flat cell. The peak we see at 725 nm wavelength for this flat case is due to a Fabry-Perot resonance. From this optimized flat structure, we introduce optimized triangular gratings on the ITO and Ag contacts with an optimized period of 400nm. For the Ag grating, the triangle height is 75 nm with a fill factor of 0.6 while, for the ITO grating, the triangle depth is also 75 nm with a fill factor of 0.4. The effect of using only the Ag back grating can be seen in the green curve in Fig. 2. Additional surface plasmon polariton (SPP) and waveguide mode resonances arise in the 760-850 nm wavelength range, due to the periodicity on the metal surface, which enhances the absorption efficiency. The absorption performance for smaller wavelengths stays practically the same. By using only the front ITO grating structure (black curve), we see a broad enhancement nearly throughout the 400-720 nm wavelength region with only a relatively small weakening of absorption strength in the 720-770 nm wavelength region and little improvement beyond that. The ITO grating improves the absorption performance in the lower wavelength region by efficient light scattering.

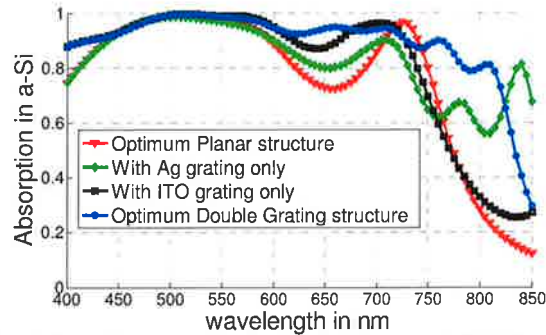


Figure 2. Absorption spectra of optimized SC structures for flat case (red line: with ITO thickness of 60 nm and a-Si thickness of 200 nm), with ITO front grating only (black line: the structure is based on the same ITO and a-Si thickness with ITO grating depth of 75 nm and fill factor of 0.4), with Ag back grating only (green line: Ag grating height of 75 nm and fill factor of 0.6), and for double grating case (blue line).

Introducing both grating structures at once basically combines the best of both worlds, as it can be seen by inspecting the blue line in Fig. 2. It leads to a remarkable enhancement occurring nearly throughout the whole wavelength range of 400-850 nm. Both gratings work together in a complementary manner. The back Ag grating again provides enhancement for the longer wavelength region while the ITO grating enhances the absorption performance at shorter wavelengths. 91.2 % absorption of the AM 1.5G spectrum in the 400-850 nm wavelength region is achieved. This is 11.2% more compared to a flat cell with a thin a-Si thickness of 200nm with optimized ITO thickness of 60 nm.

There are four peaks of interest in the absorption spectrum for the combined grating structure, with maximum at wavelengths of 660 nm, 705 nm, 760 nm, and 805 nm. Fig. 3 shows the spatial absorption

profile and the power propagation of the light in the structure. The spatial absorption profile at 600 nm and 660 nm wavelength shows how the ITO triangle scatters the light to increase absorption at shorter wavelengths. The ITO triangle first focuses the incoming light and then scatters it in the active material. The absorption peak at 660 nm is due to optimum interference effects in this scattering process. There is significant concentration of light absorption around the sharp metal back contact tip due to the lightning rod effect commonly seen in such sharp geometries. The spatial absorption profile at 705 nm shows a more distributed absorption throughout the active material, with maximum positions that are not directly between the bottom and top triangles. This indicates that the absorption peak is due to a standing-wave Fabry-Perot type mode. The spatial absorption profile at 760 nm and 805 nm wavelength is concentrated near the metal surface, but not only at the triangular metal tip, indicating that they are connected to SPP. While the peak at 805 nm is predominantly plasmonic, the peak at 760 nm is more mixed with a (standard) waveguide mode. This is seen from the field profile at those resonances (not shown) and from the pattern of the absorption in the active layer.

The two gratings are not entirely independent with respect to each other when both are present. We can see this from the red shifting of the waveguide and SPP resonance wavelengths. The red shift leads to more favorable resonance wavelength positions in this case. Intuitively, this red shift can be simply explained by noticing that the modes ‘feel’ a different effective refractive index due to the grating geometry. There is also interference between the modes, so a change in one will lead to a change in the wavelength position of both peaks.

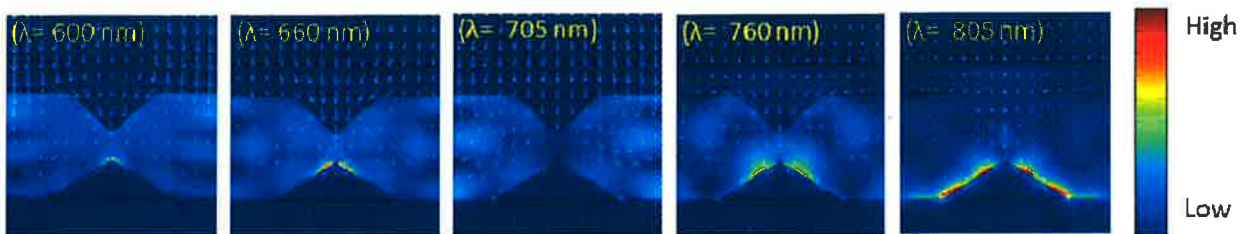


Figure 3. Absorption profiles at specific wavelengths (color scale: same scale in all graphs). The white arrows give the time averaged Poynting vector with normalized scale for each wavelength separately.

3. Conclusions

We show the possibility of achieving complementary absorption enhancement from simultaneous use of periodic gratings on the front and back contact of our cell. The ITO front contact grating is shown to enhance the shorter wavelength absorption performance through effective scattering of incoming light while the metal back contact grating enhances the longer wavelength regions via SPP and waveguide mode excitation. The combined effect of both grating structures leads to a broadband absorption enhancement in nearly the whole 400-850nm wavelength range. The combined structure gives 91.2 % absorption of the AM 1.5G spectrum which is 11.2% more compared to an optimized flat cell with acceptable a-Si thickness of 200nm.

4. Conclusions

This work is part of the Flemish IWT-SBO project SiLaSol (Number: 3E100243).

5. References

1. C. Hägglund and B. Kasemo, "Nanoparticle plasmonics for 2D photovoltaics: mechanisms, optimization and limits," *Opt. Express* **17**, 11944-11957 (2009).
2. H. Shen, P. Bienstman, and B. Maes, "Plasmonic absorption enhancement in organic solar cells with thin active layers," *J. Appl. Phys.* **106**, 073109 (2009).
3. A. Abass, H. Shen, P. Bienstman, and B. Maes, "Angle insensitive enhancement of organic solar cells using metallic gratings," *J. Appl. Phys.* **109**, 023111 (2011).
4. R. Dewan, M. Marinkovic, R. Noriega, S. Phadke, A. Salleo, and D. Knipp, "Light trapping in thin-film silicon solar cells with submicron surface texture," *Opt. Express* **17**, 23058-23065 (2009).



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PROGRAM GUIDE

Wednesday, November 2, 2011

Capital Ballroom A: PV

PWB: Photon Management in Solar Cells: Dielectric Nanostructures I

Wednesday, November 2, 2011 10:30-12:30

Ralf Wehrspohn; *Fraunhofer IWM Halle, Germany, Presider*

PWB1 · 10:30 Invited

Light Trapping in Nano-textured Silicon Thin Film Solar Cells, *Rahul Dewan¹, Vladislav Jovanov¹, Dietmar Knipp¹*; ¹*Jacobs University Bremen, Germany*. The optics of thin-film microcrystalline silicon solar cells with integrated 3-D pyramid-like surface texture was investigated. The influence of the dimensions of the surface texture on the quantum efficiency and short circuit current was evaluated.

PWB2 · 11:00 Invited

Efficient Light-Trapping in Periodic Nanostructured Thin Crystalline Silicon Solar Cells, *Gang Chen¹*; ¹*MIT, USA*. We theoretically and experimentally show that simple periodic pyramid structures on the order of the wavelength can greatly enhance absorption for solar cell applications and potentially reduce silicon mass up to two orders of magnitude.

PWB3 · 11:30 Invited

Use of PLD-grown Moth-eye ZnO Nanostructures as Templates for MOVPE Growth of InGaN-Based Photovoltaics, *Dave Rogers¹, V. E. Sandana^{1,2}, F. Hosseini*

Teherani¹, S. Gautier⁴, G. Orsa¹, T. Moudakir⁵, M. Molinari⁶, M. Troyon⁶, M. Peres⁷, M. J. Soares⁷, A. J. Neves⁷, T. Monteiro⁷, D. McGrouther⁸, J. N. Chapman⁸, H. J.

Drouhin³, M. Razeghi², A. Ougazzaden⁹; ¹*Nanovation, France*; ²*Center for Quantum Devices, Northwestern University, USA*; ³*LSI, Ecole Polytechnique, France*;

⁴*LMOPS, University of Metz & Supelec, France*; ⁵*Supelec/UMI 2958, Georgiatech-CNRS, France*; ⁶*LMEN, University de Reims Champagne Ardennes, France*;

⁷*Departamento De Fisica/13N, Universidade de Aveiro, Portugal*; ⁸*Department of Physics & Astronomy, University of Glasgow, United Kingdom*; ⁹*Georgia Institute of*

Technology, Georgia Tch-CNRS, France. ZnO based thin films and nanostructures are used in many photovoltaic devices. This talk will overview these and present the

potential of moth-eye ZnO nanostructures for use as buffer layers in novel InGaN-based photovoltaics.

PWB4 · 12:00

3D Photonic Crystal as Intermediate Reflector Layers in Micromorph Tandem Cells, *Ralf B. Wehrspohn^{1,2}, Johannes Üpping¹, Andreas Bielawny¹*; ¹*Institute of*

Physics, University of Halle, Germany; ²*Fraunhofer Institute for Mechanics of Materials, Germany*. Unbalanced currents in serial-connected tandem solar cells are a

major limitation of their performance. We will show that an embedded 3D photonic crystal acting as an intermediate reflector can balance the currents.

PWB5 · 12:15

Performance of Large Period Engineered Grating for Solar Cell Applications, *Emiliano R. Martins¹, Juntao Li¹, Yikun Liu^{2,1}, Jianying Zhou², Thomas Krauss¹*;

¹*Physics and Astronomy, University of St. Andrews, United Kingdom*; ²*State Key Laboratory of Optoelectronic Materials and Technologies, Sun Yat-sen University, China*.

We study engineered large period gratings for thin-film silicon solar cells. Numerical calculations indicate that such gratings outperform conventional gratings over a

wide range of wavelengths, incident angles and for both polarizations.

Capital Ballroom A: PV

PWC: Photon Management in Solar Cells: Dielectric Nanostructures II

Wednesday, November 2, 2011 14:00-16:00

Thomas Krauss; *University of St. Andrews, United Kingdom, Presider*

PWC1 · 14:00

Light Trapping in Thin Film Silicon Solar Cells with Mono and Bidimensional Photonic Patterns, *Angelo Bozzola¹, Marco Liscidini¹, Lucio C. Andreani¹*; ¹*University*

of Pavia, Italy. We investigate light trapping in thin film silicon solar cells with 1D and 2D photonic patterns. Absorbance and short-circuit current density are calculated

with scattering matrix formalism and compared with Lambertian limits.

PWC2 · 14:15

Optimization of Silicon Solar Cells using Backside Diffraction Gratings, *Markus Wellenzohn¹, Rainer Hainberger¹*; ¹*Health & Environment Department, Nano*

Systems, AIT Austrian Institute of Technology GmbH, Austria. This numerical study investigates the influence of backside diffraction gratings on the efficiency of silicon

solar cells. In particular, the dependence of the optimum grating period and modulation depth on the silicon thickness is determined.

PWC3 · 14:30 Invited

Decreasing the Thickness of Crystalline-Silicon Solar Cells below 40 µm and Increasing their Light Absorption with Surface Nanostructures, *Valérie Depauw¹,*

Ounsi El Daif¹, Dries Van Gestel¹, Kris Van Nieuwenhuysen¹, Christos Trompoukis¹, Frederic Dross¹, Ivan Gordon¹, Jef Poortmans¹; ¹*IMEC, Belgium*. Three methods for

fabricating crystalline-silicon solar cells thinner than 40 µm down to 1 µm are presented, together with the integration of three nanostructuring schemes - texturing,

photonic crystals, plasmons - to boost their light absorption.

PWC4 · 15:00

Combining Front and Back Grating Structures for Broadband Absorption Enhancement in Thin-Film Silicon Solar Cells, *Aimi Abass¹, Khai Q. Le^{2,3}, Peter*

Bienstman², Andrea Alu², Bjorn Maes^{3,4}, Marc Burgelman¹; ¹*Department of Electronics and Information Systems, Ghent University, Belgium*; ²*Department of Electrical*

and Computer Engineering, The University of Texas at Austin, USA; ³*Department of Information Technology, Ghent University-imec, Belgium*; ⁴*Department of Physics,*

Academy of Sciences, China. Hereby we present a few approaches to construct precise morphology towards high-performance device for printable polymer solar cells based mainly on P3HT/PCBM composite, which could be potentially produced by using roll-to-roll technique.

PTd2 · 17:00 Invited

Morphology and Performance of Polymer-Based Solar Cells, Michael E. Mackay¹; ¹*University of Delaware, USA.* Excitons in polymer-based solar cells are short lived placing great emphasis on construction of a nanoscale morphology of electron donor and acceptor. Here we discuss how processing affects the morphology and subsequent performance.

PTd3 · 17:30

Using Localized Plasmon Resonances to Enhance Absorption Efficiency in Thin-film Organic Solar Cells, Khai Q. Le^{1,2}, Aimi Abass², Bjorn Maes³, Peter Bienstman², Andrea Alu¹; ¹*Electrical and Computer Engineering, The University of Texas at Austin, USA*; ²*Ghent University, Belgium*; ³*University of Mons, Belgium.* We propose the use of localized surface plasmon modes excited by square metallic gratings to enhance the optical absorption of thin-film organic solar cells. Broadband absorption enhancement of up to 29% is theoretically demonstrated.

PTd4 · 17:45

Simulation and Optimization of Fluorescent Dyes and 3D Microtextures for Luminescent Solar Concentrators, Günther Hasna¹; ¹*OTPIS, France.* Development of a simulation software taking into account the fluorescent dyes and the shape of the light guide applying 3D virtual textures to reduce reflection.

PTd5 · 18:00

Metal Nanoparticle Enhanced Organic Solar Cells: A Numerical Study of Structure Property Relationships, Michael Salvador¹, David S. Ginger¹, Yong Zhang², Kung-Shih Chen², Hin-Lap Yip², Alex K.-Y. Jen²; ¹*Chemistry, University of Washington, USA*; ²*Materials Science & Engineering, University of Washington, USA.* We conduct systematic FDTD calculations for assessing the impact of size and shape of metal nanoparticles as well as the influence of spectral overlap for given particle/semiconductor pairs in nanoparticle enhanced organic solar cells.

PTd6 · 18:15

Improved Performances in Annealed P3HT-Based Dye Sensitized Solar Cells (DSSC): A Detailed Morphological and Spectroscopic Investigation, Sai Santosh Kumar Raavi¹, Giulia Granchini^{2,3}, Agnese Abruzzi³, Henry Snaith²; ¹*Center for Nano Science and Technology of IIT@PoliMi, Italy*; ²*Dipartimento di Fisica, Politecnico di Milano, Italy*; ³*Oxford University, Department of Physics, Clarendon Laboratory, United Kingdom.* We employ femtosecond transient absorption spectroscopy and atomic force microscopy on operating hybrid solid-state DSSC with P3HT as the hole transporter, to probe the effect of annealing on charge transfer dynamics and nanoscale morphology.

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