



Performance of Hydrogenated a-Si:H Solar Cells with Downshifting Coating

Preprint

Bill Nemeth, Yueqin Xu, Haorong Wang,
Ted Sun, Benjamin G. Lee, Anna Duda,
and Qi Wang

*Presented at the 2011 Materials Research Society Spring Meeting
San Francisco, California
April 25–29, 2011*

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Conference Paper
NREL/CP-5200-51824
May 2011

Contract No. DE-AC36-08GO28308

NOTICE

The submitted manuscript has been offered by an employee of the Alliance for Sustainable Energy, LLC (Alliance), a contractor of the US Government under Contract No. DE-AC36-08GO28308. Accordingly, the US Government and Alliance retain a nonexclusive royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for US Government purposes.

This report was prepared as an account of work sponsored by an agency of the United States government. Neither the United States government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or any agency thereof.

Available electronically at <http://www.osti.gov/bridge>

Available for a processing fee to U.S. Department of Energy and its contractors, in paper, from:

U.S. Department of Energy
Office of Scientific and Technical Information

P.O. Box 62
Oak Ridge, TN 37831-0062
phone: 865.576.8401
fax: 865.576.5728
email: <mailto:reports@adonis.osti.gov>

Available for sale to the public, in paper, from:

U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
phone: 800.553.6847
fax: 703.605.6900
email: orders@ntis.fedworld.gov
online ordering: <http://www.ntis.gov/help/ordermethods.aspx>

Cover Photos: (left to right) PIX 16416, PIX 17423, PIX 16560, PIX 17613, PIX 17436, PIX 17721



Printed on paper containing at least 50% wastepaper, including 10% post consumer waste.

PERFORMANCE of HYDROGENATED a-Si:H SOLAR CELLS with DOWNSHIFTING COATING

Bill Nemeth¹, Yueqin Xu¹, Haorong Wang², Ted Sun²,
Benjamin G. Lee¹, Anna Duda¹, and Qi Wang¹
¹ National Renewable Energy Laboratory, Golden, CO, 80401
² Sun Innovations, Inc, Fremont, CA 94539

ABSTRACT

We apply a thin luminescent downshifting (LDS) coating to a hydrogenated amorphous Si (a-Si:H) solar cell and study the mechanism of possible current enhancement. The conversion material used in this study converts wavelengths below 400 nm to a narrow line around 615 nm. This material is coated on the front of the glass of the a-Si:H solar cell with a glass/TCO/p/i/n/Ag superstrate configuration. The initial efficiency of the solar cell without the LDS coating is above 9.0 % with open circuit voltage of 0.84 V. Typically, the spectral response below 400 nm of an a-Si:H solar cell is weaker than that at 615 nm. By converting ultraviolet (UV) light to red light, the solar cell will receive more red photons; therefore, solar cell performance is expected to improve. We observe evidence of downshifting in reflectance spectra. The cell J_{sc} decreases by 0.13 mA/cm², and loss mechanisms are identified.

INTRODUCTION

Researchers continue to develop novel approaches to drive the economics of solar cells to be more competitive with traditional fossil fuel power generation. One of the primary limitations of performance for all solar cells is the response to the spectral output of the sun, and many tactics have been utilized or theorized in an effort to circumvent this. Multi-junction cells are tailored to absorb specific wavelength ranges of sunlight, whereas wavelength conversion layers can be used to tailor the sunlight to the particular device. By doing so, lattice thermalization and material transmission losses can be minimized [1].

Light conversion techniques can utilize quantum dots, rare earth ions, as well as various organic dye materials [2], and can be broadly placed into downconversion (high energy to lower energy) and upconversion (vice versa) processes. A subcategory of downconversion is downshifting (or photoluminescence [3]), which occurs at sub-unity quantum efficiencies. The narrow emission lines of rare earth ion light converters [4] lend their utility to single junction solar cells; however, narrow absorption bands limit the likelihood that broadband conversion is likely to occur for a single rare earth ion type. Many solutions have been implemented to films and phosphors with a few applications to solar cells giving mixed results in device performance [5]. Amorphous silicon (a-Si:H) solar cells show peak quantum efficiencies in wavelengths between 500 and 600 nm with sharp declines approaching 350 and 750 nm. The highest laboratory scale stable amorphous silicon (a-Si:H) single junction cell efficiency is in excess of 10% [6] with a theoretical efficiency limit between 15% [7] to 22% [8]. In this paper, we address a luminescent downshifting (LDS) layer applied to a single junction amorphous silicon solar cell to determine performance changes.

EXPERIMENTAL

Solar cells with a *p-i-n* structure were grown on Asahi U-type SnO:F substrates. Substrates were ultrasonically cleaned in DI water, rinsed with acetone and isopropanol, and dried with N₂. All a-Si:H layers were grown by PECVD in a multi-chamber cluster tool manufactured by MVSsystems, Inc. at a substrate temperature of approximately 200 °C. The 5000 Å intrinsic layer was grown using SiH₄ without hydrogen dilution with E_{Tauc} = 1.78 eV and $\sigma_{\text{dark}} \sim 2 \times 10^{-10}$ S/cm. The *n*-layer was grown using SiH₄ and PH₃/H₂ with E_{Tauc} = 1.75 eV and $\sigma_{\text{dark}} \sim 2 \times 10^{-2}$ S/cm. Two *p*-layers were grown using SiH₄, CH₄, and TMB/He with E_{Tauc} = 2.0 eV and $\sigma_{\text{dark}} \sim 4 \times 10^{-8}$ S/cm and E_{Tauc} = 1.8 eV and $\sigma_{\text{dark}} \sim 2 \times 10^{-5}$ S/cm. All layers were deposited with 9.5 mW/cm² 13.56 MHz RF power, and 1 cm² 3000 Å thick Ag back contacts were deposited by electron beam evaporation [9]. The LDS layer was synthesized and applied on the glass front surface of the device as well as on a standard microscope slide by Sun Innovations, Inc. It consists of dissolving 30 mg Eu phosphor material (Red1) and Lucite Elvacite 2042 resin in methyl ethyl ketone, and applying a 100 μm thick layer using a scraper, allowing the film to dry naturally.

Indium lines were soldered to the front TCO and used as the front contact for current density voltage (J-V) measurements. The J-V measurements via a Keithley model 2400 were made using an ELH projector lamp light source calibrated with an AM1.5 standard reference solar cell. The resulting measurements reported are averaged over device areas of 1 cm². Layer thicknesses, reflection, and transmission measurements were measured using an n&k 1700 R-T analyzer from n&k Technology, Inc. Photoconductivity measurements were made using standard current-voltage (I-V) measurement under illumination utilizing 1 cm bars spaced 1 mm apart under a 100 V bias. Global reflectance measurements were taken with a Cary-6 spectrometer in an integrating sphere. Device external quantum efficiency (EQE) measurements were made using an inhouse QE measurement system calibrated with a reference cell. Photoluminescence (PL) quantum efficiency is measured in a LabSphere integrating sphere, with excitation of 365 nm (selected from a xenon lamp passed through a monochromator). The excitation and emission spectra are fiber coupled to an LN₂-cooled silicon CCD spectrometer. All spectra are corrected for grating, fiber, sphere, and detector efficiencies using a calibrated lamp.

RESULTS AND DISCUSSIONS

We calculated J_{sc} values to determine prospective enhancement due to the LDS coating by integrating the AM1.5 flux values (Figure 1) with respect to weighting factors in wavelengths between 350 and 400nm. An ideal solar cell with 100% EQE would yield 1.02 mA. Our cell shows a 75% EQE at 615nm, which is the emission wavelength of the conversion. The J_{sc} resulting from a 75% EQE would be 0.77 mA, and our cell would yield 0.49 mA. Since this is the light that is being converted, this represents a loss. Therefore, the maximum theoretical gain that we could expect from our device with this LDS coating is 0.28 mA/cm².

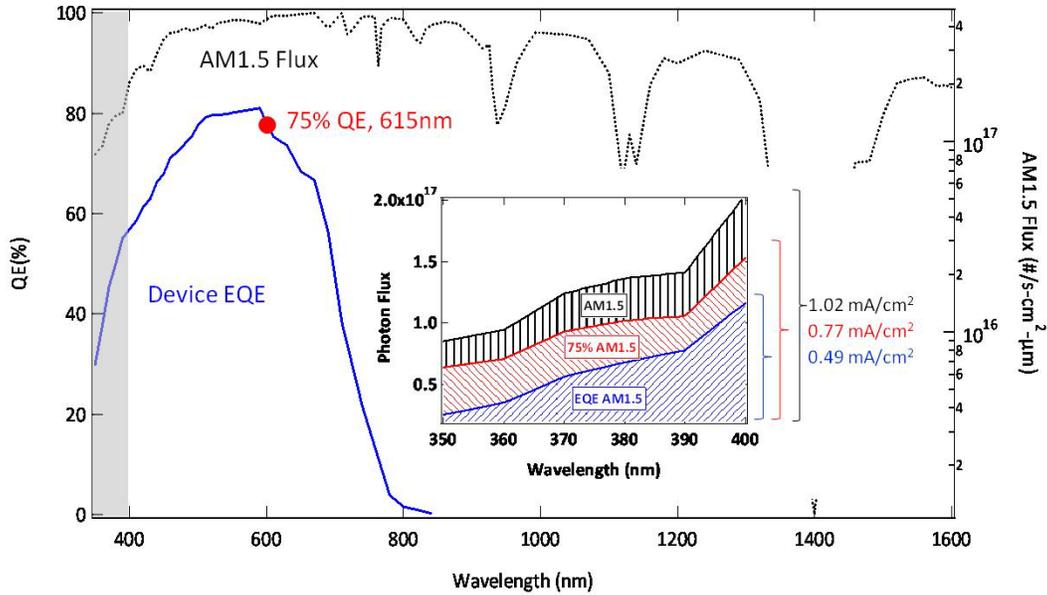


Figure 1. AM1.5 spectrum (log scale) and EQE measurement of a-Si:H device without LDS coating. Inset shows photon flux with weighting factors to calculate theoretical J_{sc} values.

To characterize the LDS coating on glass, we extracted the quantum yield of the conversion using PL data (Figure 2). The spectrum on the left shows the amount of excitation light absorbed by the LDS coating. The spectrum on the right shows the amount of light emitted by the LDS coating. The ratio of the emission integral (emitted photon flux) to the excitation integral (absorbed photon flux) results in a quantum yield of 88% for the LDS coating. We take the approach that the LDS coating is not part of the device, but a separate component to the system. As such, it can be conceptualized that the AM1.5 spectrum has been altered by the LDS coating incident to the device as depicted in the figure inset.

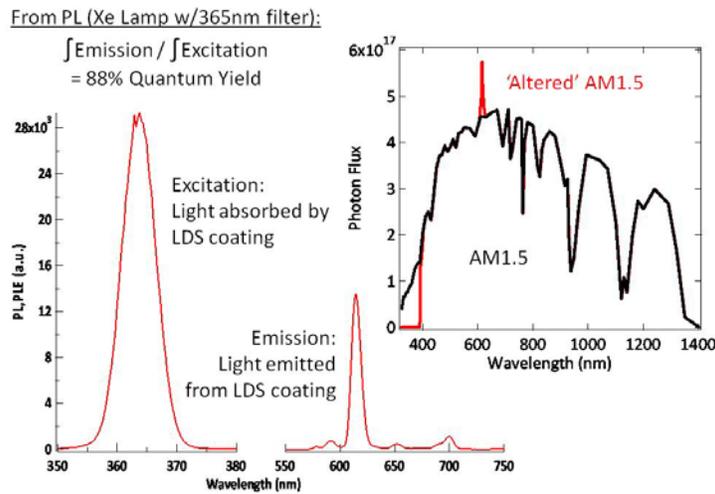


Figure 2. PL spectra of the LDS coating and depiction of altered AM1.5 spectrum.

Figure 3 shows devices with (left) and without (right) LDS coating illuminated with a 400 nm filter on a Xe lamp. The reflectance data on the right shows an additional 2% in reflectance. This is presumably the 10% UV reflectance and additionally the extra 2% of converted red light that has met the escape cone criteria for incident surface. This is designated in the UV, but is actually red due to the nature of the measurement, where discrete steps in excitation source coupled with a solid state detector are used.

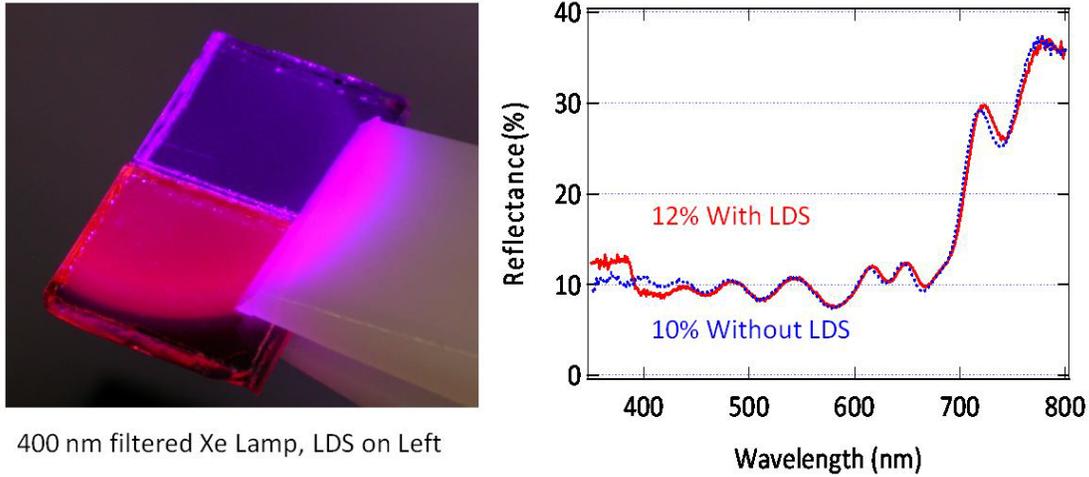


Figure 3. Device with and without LDS coating under Xe illumination and reflectance data of these devices.

The following table (Table I) shows the device performance compared with and without LDS coating application. Our results for 1 cm² cells show that 0.13 mA was lost with the LDS coating, while V_{oc} and FF remained the same. Any gain experienced by the cell’s increased quantum efficiency (75% at 615 nm versus 50% at 365 nm) was negated by losses in conversion (88% quantum yield) and scattering (12% reflection and 43% waveguiding). Figure 4 shows the loss mechanisms responsible for the device performance.

Table I. 1cm² Device Characteristics with and without LDS Layer

	V _{oc} (V)	FF	J _{sc} (mA/cm ²)	Eff (%)
Without LDS	0.843	0.607	17.728	9.066
With LDS	0.843	0.606	17.598	8.975

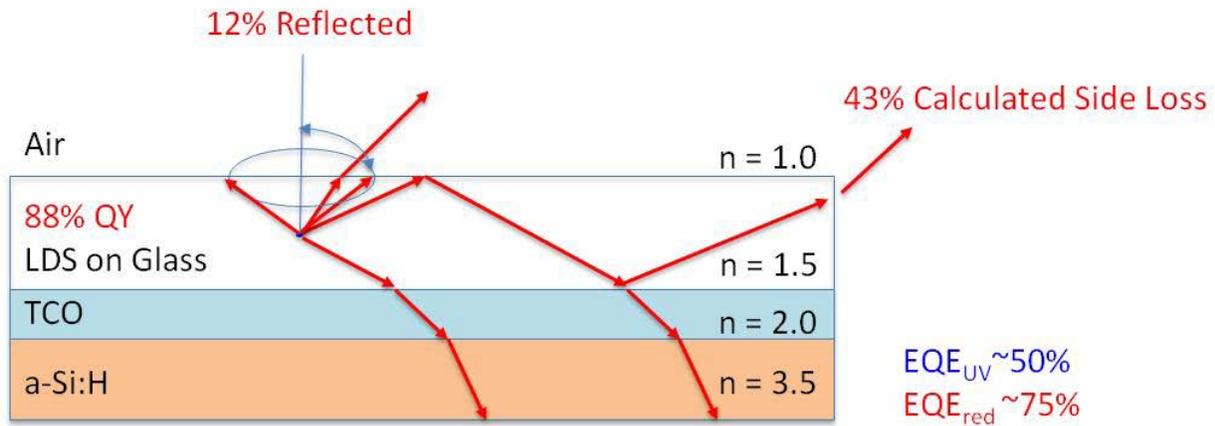


Figure 4. Loss mechanisms of LDS coating on device.

CONCLUSIONS

Light downshifting has marginal application for use in single junction amorphous silicon solar cells as evidenced by theoretical calculation (possible 0.28 mA/cm^2 net gain) as well as by application to solar cells (0.13 mA/cm^2 loss). Downshifting materials may be applied with better results to other materials systems with lower blue response. Downconversion, where quantum yields of greater than 100% occur, shows more promise for application to amorphous silicon.

ACKNOWLEDGEMENTS

The authors would like to thank Pauls Stradins and Eugene Iwaniczko for helpful discussion and dedicated effort to the world of photovoltaics. This work was supported by the U.S. Department of Energy under Contract DE-AC36-08-GO28308 to NREL.

REFERENCES

1. B.S. Richards, *Solar En. Matls. and Sol. Cells* **90**, 2329, 2006.
2. B.M. van der Ende, L. Aarts, A. Meijerink, *Phys. Chem. Chem. Phys.* **11**, 11081, 2009.
3. C. Strumpel, M. McCann, G. Beaucarne, V. Arkhipov, A. Slaoui, V. Svrcek, C. del Canizo, and I. Tobias, *Sol. En. Matls. and Sol. Cells* **91**, 238–249, 2007.
4. G.H. Dieke and H.M. Crosswhite **2**, *Appl. Opt.*, 1963.
5. E. Klampaftis, D. Ross, K.R. McIntosh, B.S. Richards, *Solar En. Matls. and Solar Cells* **93**, 1182, 2009.
6. M.A. Green, K. Emery, Y. Hishikawa, and W. Warta, *Prog. Photovolt: Res. Appl.* **19**, 84, 2009.
7. D.E. Carlson, *IEEE Trans. Elec. Dev.* **24**, 449, 1977.
8. F. Meillaud, A. Shah, C. Droz, E. Vallat-Sauvain and C. Miazza, *Solar En. Matls. and Solar Cells* **90**, 2952, 2006.
9. Y. Xu, B. Nemeth, F. Hasoon, L. Hong, A. Duda, Q. Wang, *MRS Proc. Spring 2010*, 1245-A07-15, 2010.