Simulation Standard

Engineered Excellence

A Journal for Process and Device Engineers

Plasmonic Light Trapping Transforming Thin-Film Photovoltaics

Keyur Gandhi and Professor S. Ravi P. Silva, Advanced Technology Institute, Department of Electronic Engineering, University of Surrey, Guildford GU2 7XH, United Kingdom

The photovoltaics (PV) market represents the fastest growing renewable energy technology, with a 35% annual growth rate, which is projected to be worth $150B by 2018.[1] The global cumulative installed PV capacity has exceeded 140 GW in 2013 and is generating 160 TWh/year of electricity, representing 0.85% of worldwide electricity demand. At the present growth rate, it is projected that over 20% of all electricity could be supplied by PV by 2050 [1].

PV has evolved through three generations of device technology, where each subsequent generation has focused on achieving a lower power generation cost per watt through the use of thinner semiconducting materials on low cost substrates.[2] The 1st generation (1G) of mono- and multi-crystalline silicon technology was followed by 2nd generation (2G) thin-film PV cells, such as amorphous and poly-crystalline silicon, a technology sector growing steadily due to its lower cost and material usage. The majority of the cost associated with fabricating PV modules is due to the semiconducting material, with another significant fraction associated with mounting onto structures. Reducing the volume of the semiconducting layer in PV devices will lower the module cost for 2G PVs, but they are less efficient in converting incident light to electricity. The 3rd generation (3G) PV technology is targeting further reductions in manufacturing cost while maintaining the power conversion efficiency of the modules through the integration of nanotechnology.

This article demonstrates the use of ATLAS device simulation framework, along with the structure and mesh editor, DevEdit, to develop an optoelectronic model to design and simulate thin-film amorphous silicon PV cells integrated with plasmon nanomaterial technology. This work was conducted via a research collaboration between the Advanced Technology Institute, University of Surrey, and Silvaco Europe Ltd, supported by the Engineering and Physical Science Research Council (EPSRC) and the European Union through the EU 7th Framework project SMARTONICS (Grant Agreement Number 310229). The work has been reported in a recent issue of the International Society for Optics and Photonics (SPIE) Journal of Photonics for Energy (*KK Gandhi, et al.; "Simultaneous optical and electrical modeling of plasmonic light trapping in thin-film amorphous silicon photovoltaic devices," J. Photon. Energy, 5(1), 057007 (2015).* DOI: http://dx.doi.org/10.1117/1.JPE.5.057007) in their special section on "Nanophotonics and Plasmonics for Solar Energy Harvesting and Conversion").

Plasmonic nanomaterials are metal nanoparticles, typically of gold or silver, which scatter light in the semiconductor layer and can significantly increase light absorption in the PV cell. The new design approach allows PV manufacturers to simulate these plasmonic-enhanced thin-film PV cells prior to fabrication, and allows them to examine the optimum design architecture. Finite Difference Time Domain (FDTD) method in the Atlas Luminous framework was used to examine the plasmonic effects on the performance of PV devices. The plasmonic nanomaterial, due to their optical properties, also acts as a broadband anti-reflection coating to increase light coupling to PV cells.

Continued on page 2 ...

INSIDE

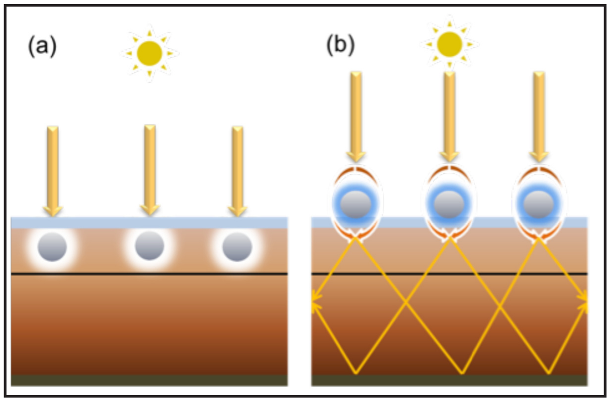

Figure 1. (a) Light concentration by the excitation of localised surface plasmons resonance around metal nanoparticles embedded in the semiconductor of PV device. (b) Light scattering by the metal nanoparticles at the surface of the PV device. The position of the P/N junction is indicated by the solid black line in the active layer of the PV device.

Figure 1 shows a graphical representation of the plasmonic effect of the metal nanoparticles in the PV device under illumination. Such nanoparticles can be easily integrated in the PV device architecture during the fabrication process.[3] Light interaction with the plasmonic structures induces plasmons, i.e. collective surface oscillations of conduction electrons in the metal nanoparticles, which traps light by either exciting localised surface plasmon resonance (LSPR) (Figure 1a) or light scattering (Figure 1b).

Coupled opto-electronic simulations were performed on thin-film amorphous silicon PV devices with gold metal nanoparticles of 30 nm radii used to demonstrate the plasmonic effects in different positions in the device structure (Figure 2). More detailed information on the simulation and parameters used can be found in the published article.[4] Incident light (AM1.5G solar spectrum) was used to perform opto-electronic simulations and to calculate current density-voltage (J-V) curves,

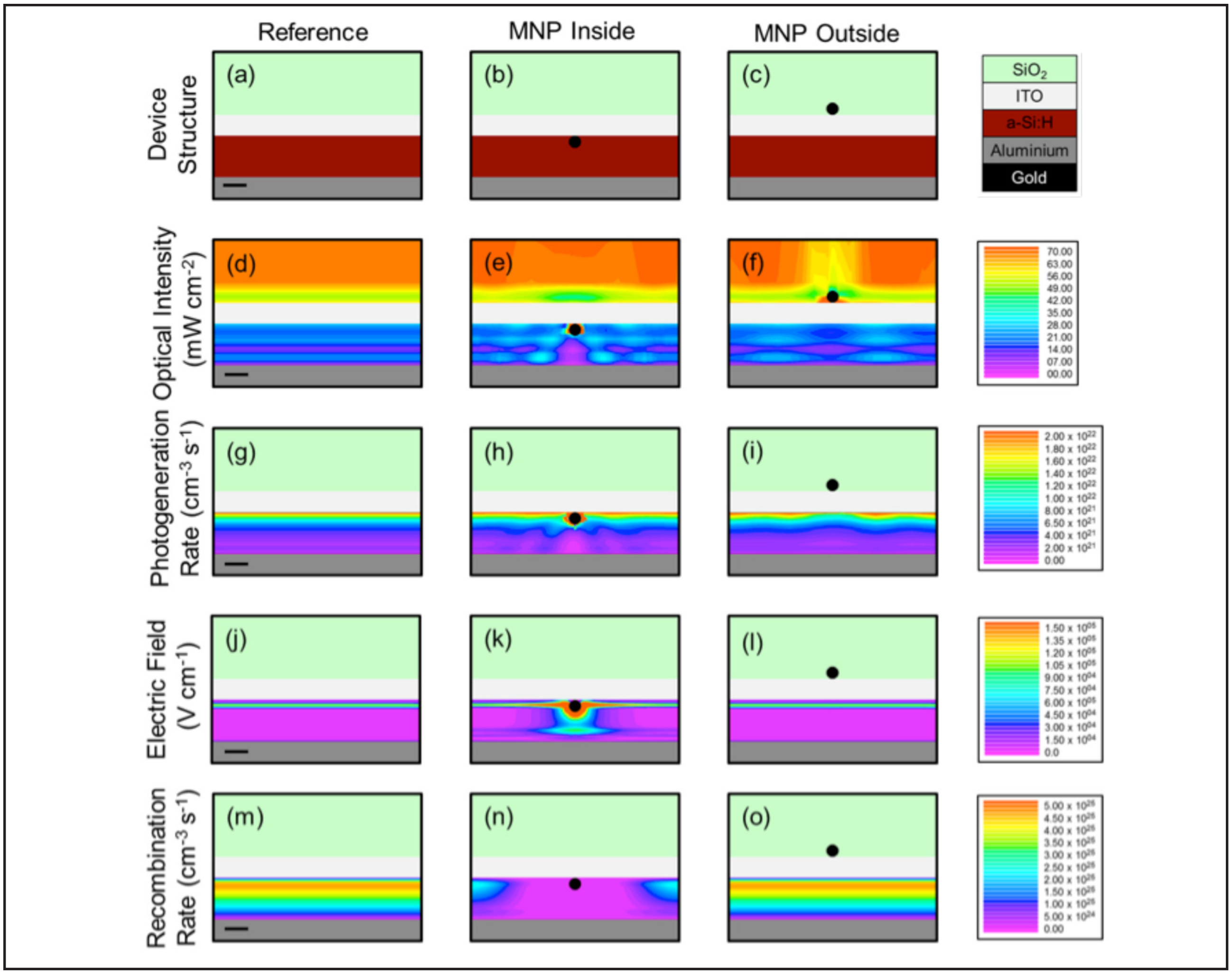

Figure 2. (a-c) PV cell device structures with a 200 nm thick a-Si:H active layer: (a) reference and plasmonic device structures incorporating 30 nm radii gold nanoparticles embedded between the (b) ITO/a-Si:H and (c) ITO/SiO2 layers respectively. (d-f) Optical Intensity profile calculated from FDTD analysis under AM1.5G illumination. (g-i) Photogeneration rate calculated from the optical intensity profile plotted in the a-Si:H layer. (j-l) Electric field intensity calculated from the optical intensity and the built-in field in the a-Si:H layer. (m-o) Recombination rate profile in the a-Si:H layer. The scale bar in each case = 100 nm.

photogeneration and recombination rates, as well as providing spectral response data such as surface reflection, absorption and transmission. The syntax used for the definition of the incoming beam is defined as:

```
Beam num=1 x.o=0.0 y.o=-25.0 angle=90.0
AM1.5 wavel.start=0.295 wavel.end=0.805
wavel.num=51 FDTD fd.auto td.srate=5
prop.leng=150.0 s.top big.index te cos
phase=0.0 td.errmax=0.01 dt=5.0E-18
td.end periodic verbose
```

Whereas, the syntax used to define the phase matched layers is described as:

```
pml top    degree=1 width=25.0 r90=0.01
pml bottom degree=1 width=25.0 r90=0.01
```

The material parameters of the amorphous silicon are defined as follows:

```
material material=silicon mun=1 mup=0.05
nc300=2.0e21 nv300=1.0e22 eg300=1.75
affinity=4.0 taun0=1.0E-6 taup0=1.0E-6
```

The defects states in the bandgap of amorphous silicon are defined as follows:

```
defects nta=1.e21 ntd=1.e21 wta=0.033
wtd=0.049 nga=1.5e15 ngd=1.5e15
ega=0.62 egd=0.78 wga=0.15 wgd=0.15
sigtae=1.e-17 sigtah=1.e-15 sigtde=1.e-
15 sigtdh=1.e-17  siggae=2.e-16
siggah=2.e-15 siggde=2.e-15 siggdh=2.e-
16  tfile=Defects.log continuous
```

Steady state responses such as optical intensity [Figure 2(d-f)], photogeneration rate [Figure 2(g-i)], electric field [Figure 2(j-l)] and recombination rate [Figure 2(m-o)] were obtained as a result of the simulation. These steady state responses assist in the optimisation of the plasmonic effects, both electrical [Figure 1(a)] and optical [Figure 1(b)], within the thin-film PV cells. The initial results suggest at least a 5% increase in the performance of the PV device can be achieved upon the incorporation of plasmonic structures. Such plasmon nanomaterial technology can also be applicable to other thin-film technologies such as poly-crystalline silicon, cadmium telluride (CdTe) and copper indium gallium selenide (CIGS), as well as organic photovoltaics, with similar gains in efficiency expected. The code produced in the collaboration between the University and Silvaco is expected to become a valuable asset to the future design of nanoparticle enhanced PV technology.

Reference:

1. European Photovoltaic Industry Association (EPIA) - Global Market Outlook for Photovoltaics 2014-2018, June 2014.
2. Jayawardena, KDG Imalka, Lynn J. Rozanski, Chris A. Mills, Michail J. Beliatis, N. Aamina Nismy, and S. Ravi P. Silva. "'Inorganics-in-Organics': recent developments and outlook for 4G polymer solar cells." Nanoscale 5, no. 18 (2013): 8411-8427.
3. Beliatis, Michail J., Simon J. Henley, Seungjin Han, Keyur Gandhi, A. A. D. T. Adikaari, Emmanuel Stratakis, Emmanuel Kymakis, and S. Ravi P. Silva. "Organic solar cells with plasmonic layers formed by laser nanofabrication." Physical Chemistry Chemical Physics 15, no. 21 (2013): 8237-8244.
4. KK Gandhi, A Nejim, MJ Beliatis, CA Mills, SJ Henley, SRP Silva et al.; "Simultaneous optical and electrical modeling of plasmonic light trapping in thin-film amorphous silicon photovoltaic devices," J. Photon. Energy, 5(1), 057007 (2015). doi:10.1117/1.JPE.5.057007.