Plasmonic Light Trapping Transforming Thin-Film Photovoltaics

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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 polycrystalline 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 plasmonic 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).


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.

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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. 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. Incident light (AM1.5G solar spectrum) was used to perform opto-electronic simulations and to calculate current density-voltage (J-V) curves,
phologeneration and recombination rates, as well as pro-
viding 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 de-
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
sigtde=1.e-15 sigtdh=1.e-17 siggde=2.e-16
siggdh=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 re-
ponses 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 appli-
cable to other thin-film technologies such as poly-crystalline 
silicon, cadmium telluride (CdTe) and copper indium gal-
lium 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 ex-
pected to become a valuable asset to the future design of 
nanoparticle enhanced PV technology.

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