Periodic and Psuedo-Random Back-Reflector Nanoparticle Enhanced Light-Trapping in a Silicon Photovoltaic

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ABSTRACT

We consider the light-trapping enhancement of a silicon photovoltaic (PV) with conductive nanoparticles of various shapes, sizes and spacing as top-reflectors; used in conjunction with a periodic and a pseudo-random back-reflectors. The nanoparticles in the top-reflector are silver (with the appropriate Drude model) and the back-reflectors are perfect electric conductors. The power spectral density then multiplied by the responsivity of crystalline-Si and by the input spectral density (blackbody solar radiation herein, normalized to one) to form Jsc. We see that for a given top-reflector the choice of a periodic back-reflector can yield a higher Jsc for a crystalline-Si PV than the choice of a pseudo-random one. This (perhaps initially surprising) result: that a periodic structure can outperform a pseudo-randomly rough surface as a back-reflector is due to resonances that can be setup between it and the top-reflector (although Lambertian probably is still optimal for the infinitely broadband case).

Keywords: Solar energy; Optical communications; Plasmonics; Photonic crystals

1 INTRODUCTION

Light trapping refers to means by which light not converted to electricity in a single pass through the PN junction of a photodetector or a photovoltaic (PV) is reflected back into the junction. Preferably any such non-converted light is trapped within the device, e.g., by total internal reflection or via some Bragg-type of resonant mode confinement. Many techniques exist and some of the most promising include: the use of plasmonics [1-3]; the use of photonic crystal (PC) structures [4, 5]; and the use of quantum dots [6, 7] .

Simple bandgap models don't accurately match experimentally determined responsivities (R) and many studies focus on material absorption (rather than the photo-carrier events, which are characterized by R). At the other extreme: definitive full-model calculations, including electron/hole dynamics in a PN junction, can take hours to run on a supercomputer. Herein we employ new simulation tools (utilizing experimental R data) which facilitate quick but accurate simulations for understanding and optimization. These are described in [8] but briefly we use a mapping of R to an effective exponential decay constant which can then be incorporated into existing software packages as if it were an actual material loss, although it is actually a responsivity based loss.

It's important to distinguish between the actual material based "bad" absorptions; from the responsivity based "good" absorptions which generate photo-carrier current. For the material based absorptions in silicon we utilize a three-Lorentzian model [9]. Figures 1 and 2 compare these for TE and TM polarization respectively.

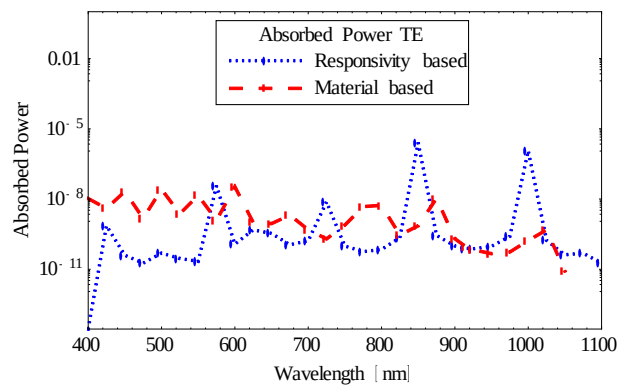

Figure-1: Absorbed Power spectrum for TE polarization.

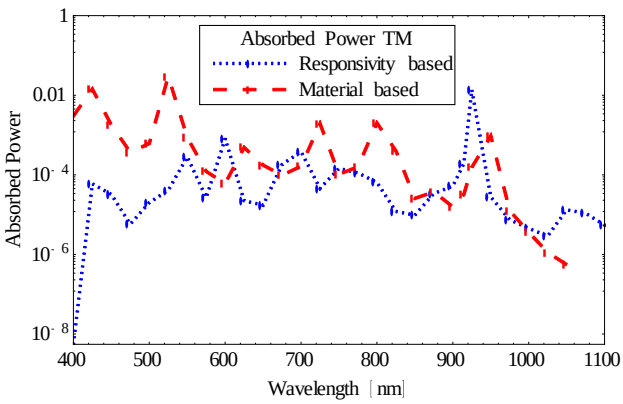

Figure-2: Absorbed Power spectrum for TM polarization.

Although the material losses are larger in the shorter wavelength part of these curves these are surprizingly similar over the 400 to 1100 nm bandwith of this c-Si PV, for this particular light trap (detailed in the next section). Further into the ultra-violet however material losses grow dramatically (and Rayleigh scattering will begin to dominate) whereas the PV has negligible responsivity below 400nm.

2 THE PERFORMANCE OF PERIODIC VERSUS PSEUDO-RANDOM BACK-REFLECTORS

Throughout this section we will include a layer of air on top of the glass cover so that we include the losses from reflection off of the entire light-trap enhanced device. The nanoparticles in the top-reflector are silver (with the appropriate Drude model: plasma frequency = 9.176 eV and damping factor = 0.021 eV) and the back-reflectors are perfect electric conductors (PECs).

The short-circuit current is calculated from the resposivity based absorption spectra for a given trap and for "no trap" (i.e., the same geometry with the top reflectors removed and the back reflector replaced by a flat PEC) and the ratio defines an improvement factor – values of which are summarized in Table 1 for various top-reflector nanoparticle shapes (ellipse, triangle, and cone) and spacing Λ (in microns). The nanoparticle size parameter D (in microns) is the length of the base of the triangles and and the diameter of the circles; and is the length of the minor axis of the ellipses, which have an aspect ratio of two. We see that for a given top-reflector (i.e., a specific shape, Λ and D) the choice of a periodic back-reflector (P) can often yield a better improvement factor than the choice of a pseudo-random one. Cases in which this happened within the grid of our parameter space are highlighted in yellow (and purple which will be discussed via Figure 3).

This (perhaps initially surprising) result: that a periodic structure can outperform a pseudorandomly rough surface as a back-reflector is due to resonances that can be setup between it and the top-reflector. At a single (resonant) frequency it's easy to see how this can happen. The surprise is that we can sometimes produce enough resonances (perhaps manifesting as a sufficiently broad one) to provide sufficient enhancement across the 700nm broad band of silicon's responsivity to surpass Lambertian (although Lambertian probably is still optimal for the infinitely broadband case).

This is initially surprising since in the *ray optics* limit: randomly rough is optimal. There are mathematical issues of the fact that structures of finite extent can only be pseudo-random (rather than perfectly Lambertian) and we are concerned with a finite, albeit very broad, bandwidth, yet it might be that this provides another example of how wave optics results can differ from the predictions of ray optics in light trapping.

Wave optics however describes the complete physics (which must be utilized when scattering from nanoparticles) and this is already known [10] to enable trapping beyond the "$4n^2$ limit" in path length enhancement predicted by ray optics [11] (where n is the index of refraction). Rather than path length enhancements, our metrics are the power spectral density and/or its integral after weighting by the responsivity of the PN junction considered. Thus, in this methodology one can also optimize the trapping to match the spectral response of the PV or photodectector used.

Λ	D	TE/TM	P / PR	Improvement Facor		
.75	.3	TE	P	7.5	14.7	5.3
			PR	4.7	2.5	3.5
		TM	P	0.8	0.7	1.9
			PR	1.1	0.6	1.5
1.5	.3	TE	P	6.2	3.8	4.2
			PR	3.6	3.1	3.4
		TM	P	0.9	1.0	0.9
			PR	0.8	3.2	0.7

Table 1: Trapping improvement factors for elliptical, trianular and circular top reflectors; where Λ is the distance between nanoparticles of size D (both in microns).

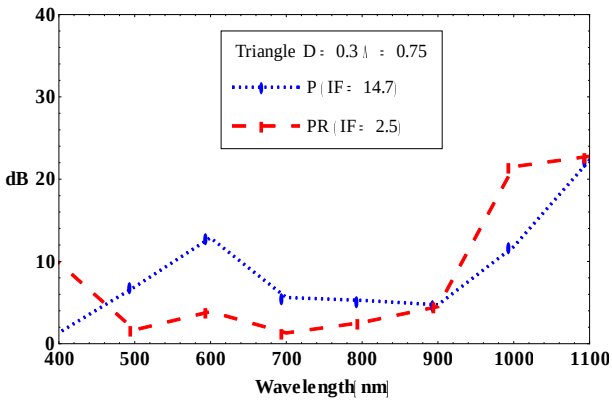

Figure-3: Single-frequency improvement factor (in dB) vs wavelength (in nm) for purple case of Table 1.

Note we could also define an improvement factor at a single frequency which we present in Figure 3 for one of the cases in which the overall improvement factor has P surpasing PR. Therein the large resonance for PR near 1 micron is due to an "accidental" resonance occurring because the surfaces are pseudo-random rather than perfectly random. This can be seen in this "dB-plot" (power enhancement spectral density plot) since a perfectly Lambertian surface would have a flat (i.e., constant valued) dB-plot. Such large resonances can be excited when the shape, spacing and size of the nanoparticles in the top-reflector is matched to it. It is this "accidental" or potential resonance, due to the *pseudo*randomness which creates such a large value of Jsc – whereas, again, a perfectly Lambertian surface would have a flat dB-plot.

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