Light trapping in thin film silicon solar cells with mono and bidimensional photonic patterns

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Abstract: 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.

OCIS codes: (040.5350) Photovoltaic, (050.5298) Photonic crystals.

1. Photonic light trapping and PV structures under investigation

Light trapping has been suggested as a way to increase absorption of sunlight in PV cells since the '80's. It was first investigated by E. Yablonovitch, who derived an upper limit for light path enhancement for lambertian light trapping in *bulk* PV cells, where thickness is much larger than wavelength of solar radiation and absorption is sufficient weak [1]. In this case a maximum light path enhancement of $4n^2$ with respect to single pass (with n real part of refractive index of the active material) can be derived using a Ray-Optics approach (hereafter it will be denoted as LL1 limit). In more recent years M.A. Green extended this result [2], giving analytical expressions (hereafter denoted as LL2 limit) for light path enhancement in the case of arbitrary absorbing active material.
When thickness of active material is comparable with wavalength of incident light, these appoaches are no more applicable and absorbance has to be calculated solving Maxwell equation in a rigorous way. In the literature this case is often referred to as *photonic light trapping* [3]- [8]. In this work we evaluate its benefits in the thin film PV cells shown in Figs. 1a and 1b. The first (Fig 1a) is c-Si or a-Si PV cell of thickness d with a 1D pattern etched on the front surface (optical data for c-Si and a-Si are taken from Ref. [9]). The etching depth is denoted with h, the etching width with b, and the period of the 1D pattern is denoted with a. The etched grooves are filled with a transparent dielectric medium whose refractive index is taken to be 1.65. This upper layer serves both as anti reflection coating (ARC) and as passivating structure, and has fixed thickness equal to 70 nm. PV cells patterned with 2D square lattice are shown in Fig. 1b. The symbols are analogous to those of PV cells with 1D pattern, but now grooves are replaced with circular rods of radius r. As reference PV cell, a planar cell of the same thickness d, with an optimized, trasparent single-layer ARC with constrant refractive index is considered, and it is shown in Fig. 1c.

2. Theory and Numerical Methods

We analyze the effects of photonic patterning on the absorbance $A(E)$ of the active material and on the short-circuit current density J_{sc} of the PV cell, which are assumed as figures of merit. Assuming unit internal quantum efficiency for the processes of separation and collection of the photogenerated electron-hole pairs, J_{sc} can be expressed as:

$$J_{sc} = e\int_{E_g}^{\infty} A(E)\frac{dN}{dE}dE = \int_{E_g}^{\infty}\frac{dJ_{sc}}{dE}dE, \tag{1}$$

where e is the electron charge, E_g the energy gap of the active material (equal to 1.12 eV for c-Si and 1.25 eV for a-Si), $\frac{dN}{dE}$ is the incident solar photon flux, which has been modelized as a blackbody spectrum with temperature 5800 K and standard irradiance 100 mW/cm^2, and dJ_{sc}/dE are spectral contributions to short-circuit current density. The upper limit for integration in Eq. 1 has been set to 3.5 eV. The absorbance $A(E)$ of the active material is calculated solving Maxwell equations by means of rigorous coupled wave analysis and scattering matrix formalism [10].

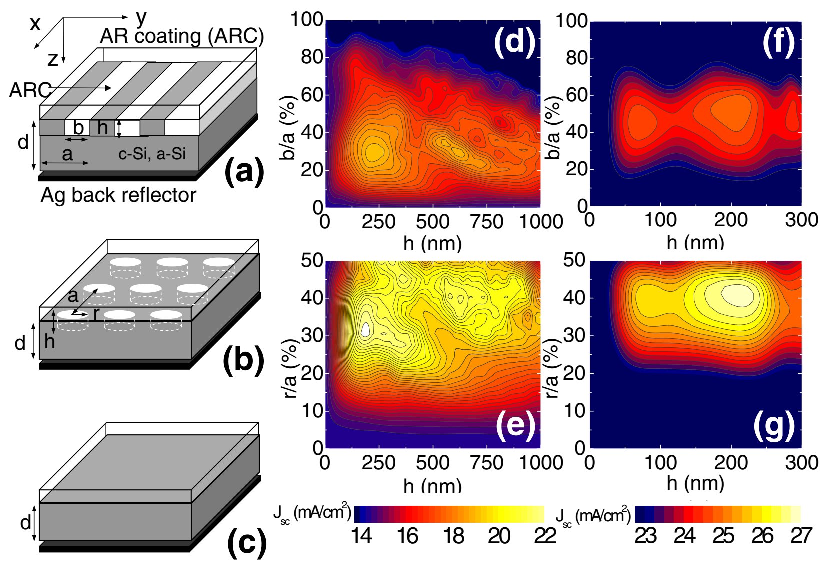

Fig. 1. Investigated PV cells' strctures: PV cell with 1D pattern (**a**), PV cell with 2D square pattern (**b**) and reference planar cell (**c**). Countour plot of short-circuit current density J_{sc} for c-Si PV cells (thickness d=1 μm, period a=600 nm) with 1D pattern (**d**) and 2D square pattern (**e**). Countour plot of short-circuit current density J_{sc} for a-Si PV cells (thickness d=300 nm, period a=300 nm) with 1D pattern (**f**) and 2D square pattern (**g**)

3. Results and Discussion

The analysis starts with a calculation of short-circuit current density J_{sc} varying at the same time both the etching depth h and the ratio b/a (for 1D patterns) or r/a (for 2D patterns), as it is shown in the contour plots of Figs. 1d-1g for c-Si PV cells (thickness d=1 μm) and a-Si PV cells (thickness d=300 nm). Optimal configurations emerge when both reduction of reflection losses and wave coupling properties of the pattern are optimized. Reflectance $R(E)$, absorbance $A(E)$ and spectral contributions to short-circuit current density dJ_{sc}/dE are then analyzed. For absorbance $A(E)$ the comparison is also made with the single pass (SP in Figs. 2b and 2f) absorbance through a planar slab of active material with the same thickness d, with or without reflection losses, in order to compare with LL1 and LL2 limits.

Starting from reflectance, it is evident from the data of Figs. 2a and 2e that patterning reduces reflection losses over a broader spectral range with respect to simple single-layer ARC. Absorbance is increased due to both better impedance matching conditions and coupling into quasi guided modes (*photonic* light trapping), as it is shown in Figs. 2b and 2f. The second feature is evident at low energy (below 2.75 eV for c-Si and below 2 eV for a-Si), and causes the absorbance of c-Si PV cells with 2D pattern to be higher than both LL1 and LL2 limits when the exact energies for coupling are matched. Furthermore, it is evident that 2D patterns are better than 1D patterns since, at a given energy, there are always more quasi-guided modes available for coupling [3]. The same conclusions hold also for spectral contributions to short-circuit current density dJ_{sc}/dE which are shown in Fig. 2c and 2g. The effects of patterning are summarized in Figs. 2d and 2h where short-circuit current densities for optimal configurations are reported as functions of active material's thickness d for c-Si and a-Si respectively. Patterning improves the PV cells' performance with respect to reference cells and the relative increase is higher for thinner cells. Furthermore 2D photonic patterns are better than simple 1D patterns due to better wave coupling properties.

We have shown that patterned cells have better performance with respect to reference cell over a relatively large range of thicknesses (250 nm - 4 μm for c-Si, and 50-500 nm for a-Si), and this is due to both better optical impedance matching conditions (the effective refractive index of the patterned layer is between that of Si and that of the top ARC) and to coupling of incident radiation into quasi-guided optical modes of the structures. Further strategies to improve light trapping towards lambertian limits are being investigated.

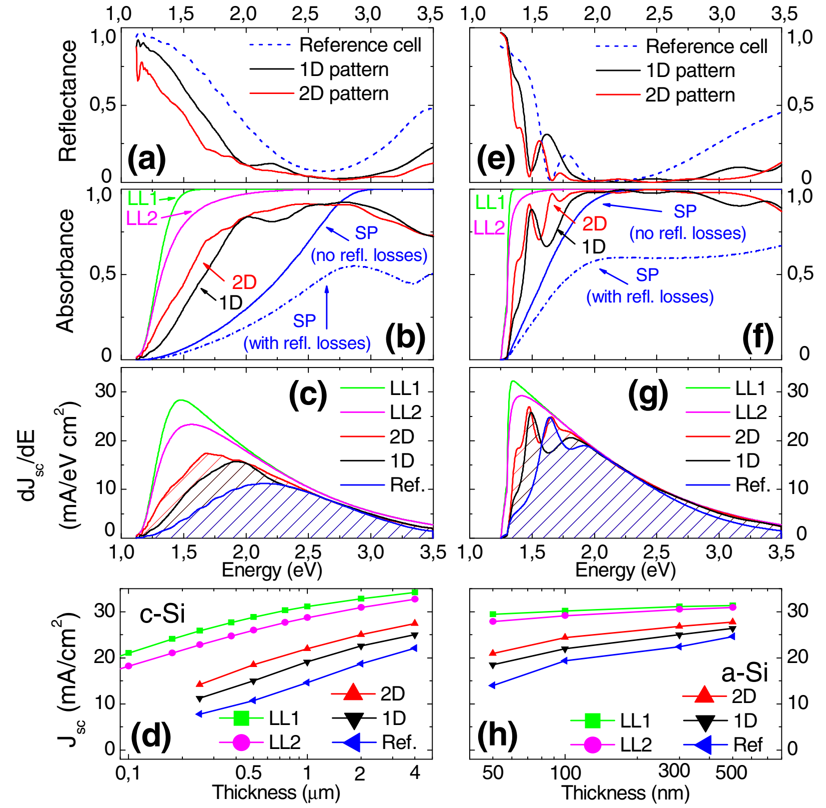

Fig. 2. Calculated optical functions for c-Si PV cells (thickness d=1 μm, period a=600 nm): reflectance R (**a**), absorbance (**b**), spectral contributions dJ_{sc}/dE (**c**) and short-circuit current density J_{sc} at optimal configurations (**d**). Calculated optical functions for a-Si PV cells (thickness d=300 nm, period a=300 nm): reflectance R (**e**), absorbance (**f**), spectral contributions dJ_{sc}/dE (**g**) and short-circuit current density J_{sc} at optimal configurations (**h**). Spectra (**a-g**) are smoothed for better readability.

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