Demonstration of enhanced absorption in thin film Si solar cells with textured photonic crystal back reflector

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Herein the authors report the experimental application of a powerful light trapping scheme, the textured photonic crystal (TPC) backside reflector, to thin film Si solar cells. TPC combines a one-dimensional photonic crystal as a distributed Bragg reflector with a diffraction grating. Light absorption is strongly enhanced by high reflectivity and large angle diffraction, as designed with scattering matrix analysis. 5 μm thick monocrystalline thin film Si solar cells integrated with TPC were fabricated through an active layer transfer technique. Measured short circuit current density J_{sc} was increased by 19%, compared to a theoretical prediction of 28%. © *2008 American Institute of Physics*. [DOI: 10.1063/1.3039787]

Despite their potential for significantly lower cost, thin film Si solar cells suffer from low efficiency ($\sim$10%) (Ref. 1) because of the weak absorption of long wavelength photons. Powerful light trapping technique is essential for absorption enhancement. Traditional light trapping schemes are based on geometrical optics elongating optical path length by scattering at roughened front surface[2] and reflecting at the back surface with an up to 80% efficient aluminum reflector. In thin film Si cells, a random front surface texture is typically created by sputtering transparent conducting oxide on glass substrate followed by texture etching,[3] or substrate treatments such as sandblasting[4] or embossing.[5] One advance is to use Bragg reflector rear mirror to double the optical path length.[6,7] Even combining an ideally roughened front surface and a lossless rear reflector theoretically cannot enhance path length by more than 50 times the cell thickness,[8] while the best experimental result is around 10 times.[9] Separately, periodic gratings were utilized[10–12] to form large angle diffraction, but there were huge transmission losses.

Recently we demonstrated efficiency enhancement in thick Si solar cells using a new light trapping structure, the textured photonic crystal (TPC) backside reflector,[13] which combines a one-dimensional photonic crystal as a distributed Bragg reflector (DBR) and a reflection grating. Design was optimized using coupled wave theory[14] and scattering matrix method[15] (SMM), and there were broad theoretical studies on the light trapping properties of photonic crystals.[16,17] Here we reveal the light trapping principle of TPC using SMM and report the first experimental integration of optimized TPC onto monocrystalline thin film Si solar cells. TPC, based on wave optics theory, allows us to effectively target the longer wavelengths requiring trapping by the combination of nearly 100% omnidirectional wide-band reflectivity of the DBR and the grating's large angle diffraction,[13] achieved by careful selection of DBR stack materials and TPC parameters.[15] The TPC effectively increases the optical path length from the thickness of the cell to its width, leading to significantly enhanced absorption.

Besides thin film Si solar cells integrated with TPC, we also study three types of control cells: reference cells without back structure, "DBR-only," and "grating-only" cells (see schematics in Fig. 1). To quantify the light trapping capability of TPC, scattering matrix method,[18] a particular numerically stable transfer matrix method, is used to simulate the absorption spectrum and calculate the J_{sc}. For the simulation comparison, we assume no shadowing and 100% carrier collection.

The simulated absorption spectra[19] for solar cells with a 5 μm thick device layer and the differing back structures reveal the TPC light trapping mechanisms. Compared to the reference cell, at $\lambda > 500$ nm, the DBR heightens the periodic interference peaks, the grating introduces extra diffraction peaks, and the TPC cell displays increased peak numbers and heights, enabling nearly 100% absorption at long resonant peak wavelengths where the reference cell has very weak absorption. See EPAPS (Ref. 19) for detailed theoretical analysis on the mechanism of efficiency enhancement with backside structures.

The collective effect of the enhancement in absorption of long wavelength photons due to DBR and grating can be quantified by the improvement in short circuit current density J_{sc}, calculated from $J_{sc}=q\int_{\lambda=300\text{ nm}}^{1100\text{ nm}} A(\lambda)s(\lambda)d\lambda$, where q is the electronic charge, $A(\lambda)$ is the absorption, and $s(\lambda)$ is

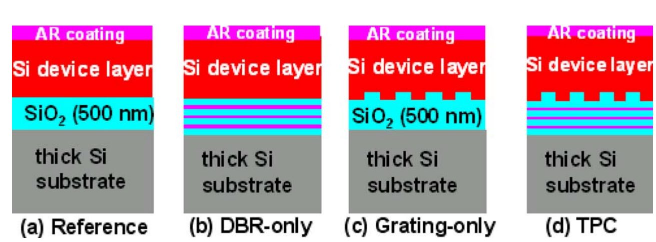

FIG. 1. (Color online) Schematic of thin film Si solar cells with different back structures.

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the incident solar photon flux density from AM1.5 spectrum. For 5 μm thick reference cell, the calculated J_{sc} is 19.82 mA/cm^2, and the J_{sc} for grating-only, DBR-only, and TPC cells are 21.62, 21.80, and 25.43 mA/cm^2, respectively, corresponding to relative enhancement of 9.1%, 10.0%, and 28.3%.

Both absolute and relative J_{sc} enhancement increase for thinner cells as a wider wavelength range is available for absorption enhancement. The calculated J_{sc} for the 2 μm thick TPC cell is 20.6 mA/cm^2, and the corresponding relative enhancement is 45.2%. The relative power conversion efficiency enhancement is similar to the relative J_{sc} enhancement from ideal diodes and 100% carrier collection assumptions.

To prove the theory on the intended application, top-contacted monocrystalline thin film Si solar cells integrated with TPC were successfully fabricated using Si-on-insulator (SOI) material through an active layer transfer technique. Monocrystalline Si was used to eliminate the complication of quality issues of materials associated with deposited thin films and to make the optical effect obvious. It should be noted that the relative efficiency enhancement should not change if the active layer is changed to polycrystalline Si since the optical properties will remain virtually the same. The active layer thickness was 5 μm, and four different back structures were tested: no back reflectors (reference structure), DBR-only, grating plus wavy DBR (TPC), and grating plus flat DBR (TPC). The grating (period ~300 nm), DBR, and antireflection coating (ARC) parameters adopted were those used in simulation.[15,19] Processing of the SOI active layer included grating formation with interference lithography, followed by reactive ion etching, DBR deposition using plasma enhanced chemical vapor deposition, bonding the active layer to a new handle wafer, removal of original handle wafer, ARC formation on the newly exposed Si surface, lateral *p-i-n* junction creation by ion implantation, and metallization with interdigitated top contacts. The cell size was 4.3 mm^2, with 20.4% shadowing due to metallization. Electrode optimization was not undertaken to simplify processing.

If DBR is deposited after grating etching, the stack film will adopt the waviness of the underlying grating, as shown by the transmission electron microscopy image in Ref. 20, which seemed beneficial to light trapping by causing more diffraction than flat stack film. To verify this, control samples with grating plus flat DBR were made by chemical mechanical polishing flat the first layer of DBR stack film.

Dark *I-V* measurements showed good rectifying behavior for all the solar cells, with leakage current at a few nA/cm^2. External quantum efficiency (EQE) measurements were carried out with a monochromator coupled to a semiconductor analyzer. Figure 2(a) depicts the measured EQE spectra. At short wavelengths, the EQE spectra significantly overlap but diverge as λ increases past 640 nm. The reference sample displays the lowest curve; the introduction of DBR back reflector makes the curve higher in the longer wavelengths; and the wavy DBR plus grating sample displays several shoulders and the largest area, corresponding to strongly enhanced absorption.

For comparison, the simulated absorption spectra are shown in Fig. 2(b), corrected for shadowing. The closely spaced sharp peaks like those shown in Ref. 19 were smoothed out with a moving average method which preserves the area under the curve. Experimentally, the spectral resolution of our monochromator is only ~10 nm so the peaks should not be observed. An inspection of Figs. 2(a) and 2(b) confirms that the measured EQE closely matches simulation in trend and magnitude.

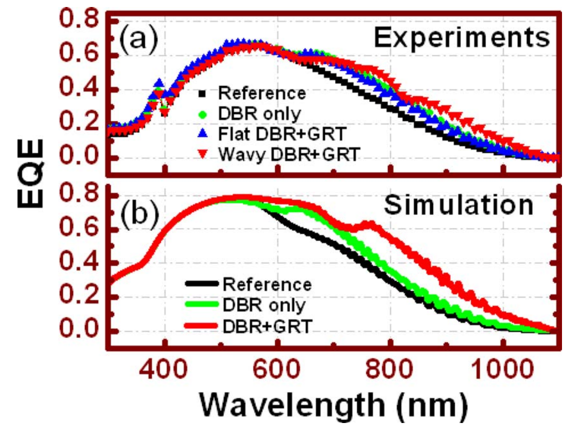

FIG. 2. (Color online) EQE for 5 μm thick Si solar cells with differing back structures. (a) Measured EQE. The discontinuity at $\lambda=400$ nm is due to the introduction of a filter to remove the second harmonic from the monochromator light source. (b) Simulated absorption spectra after moving average. 100% carrier collection is assumed. To compare with experimental results, 20.4% shadowing is taken into account.

Figure 3 illustrates the *J-V* characteristics of solar cells with different back structures measured under AM1.5 conditions. Each back structure improves absorption and cell efficiency, with the wavy DBR+grating cell achieved the highest J_{sc} of 17.45 mA/cm^2, corresponding to 18.9% enhancement over the reference cell versus 28.3% theoretically. The higher J_{sc} of wavy DBR+grating compared to flat DBR+grating verifies our previous assumption of improved efficiencies with the wavy DBR stack.

The V_{oc} is almost the same for all cells with back structures, at around 0.62 V, compared to 0.65 V for the reference cell. The bigger V_{oc} of the reference cell is probably due to a smaller reverse bias saturation current. All cells have almost the same fill factor of 0.81. This makes the power conversion efficiency η vary from 7.68% for the reference cell to 8.82% for the wavy DBR+grating cell, corresponding to a relative efficiency enhancement of 14.8%. Better surface passivation should render efficiency enhancement close to the theoretical prediction of 28%.

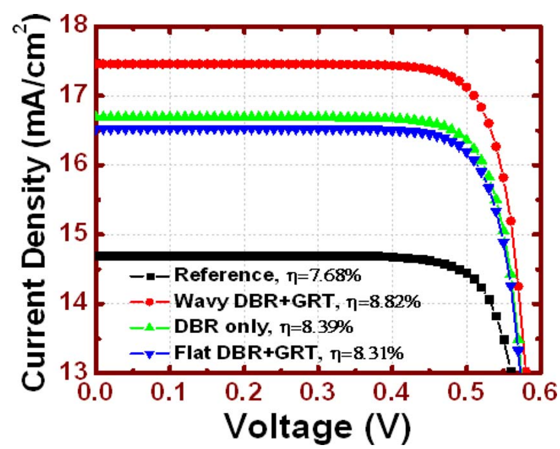

FIG. 3. (Color online) *J-V* curves of 5 μm thick Si solar cells with differing back structures under AM1.5 spectrum.

It is noteworthy that experimentally the flat DBR +grating cell does not show higher J_{sc} than the DBR-only cell, which might be attributable to the surface damage caused by plasma etching of the grating. For the wavy DBR+grating cell, the increase in surface recombination velocity due to grating etching is overcompensated by the deflection caused by the wavy stack films. Better surface passivation can be achieved by a short wet etching following plasma etching[21] and forming the first layer of DBR film (SiO_2) by thermal oxidation or rapid thermal annealing.

In conclusion, we have experimentally demonstrated that TPC backside reflector, combining reflection grating and distributed Bragg reflector, can significantly enhance absorption in the red and near infrared spectral regime in thin film Si solar cells, as predicted by simulation. We report a 19% increase in J_{sc} in 5 μm thick monocrystalline Si solar cells made from SOI wafers through an active layer transfer technique. The TPC back reflector we developed can be applied to any thin film solar cells. With grating fabrication methods suitable for large scale production, such as nanoimprint lithography,[22] and better surface passivation, the potential for TPC to significantly boost thin film solar cell efficiency can be exploited.

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