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Efficiency enhancement in Si solar cells by textured photonic crystal back reflector

L. Zeng,[a] Y. Yi, C. Hong, J. Liu, N. Feng, X. Duan,[b] and L. C. Kimerling
Department of Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

B. A. Alamariu
Microsystems Technology Laboratories, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

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An efficient light-trapping scheme is developed for solar cells that can enhance the optical path length by several orders of magnitude using a textured photonic crystal as a backside reflector. It comprises a reflection grating etched on the backside of the substrate and a one-dimensional photonic crystal deposited on the grating. Top-contacted crystalline Si solar cells integrated with the textured photonic crystal back reflector were designed and fabricated. External quantum efficiency was significantly improved between the wavelengths of 1000 and 1200 nm (enhancement up to 135 times), and the overall power conversion efficiency was considerably increased. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2349845]

One major challenge in achieving high efficiency thin film solar cells is the insufficient absorption of long wavelength photons because of the low absorption coefficient and short optical path length imposed by the small film thickness ($\sim 1\ \mu$m). This problem is especially severe in thin film Si solar cells due to relatively low absorption of the indirect band gap, leading to long absorption length (L) for the infrared light. For example, $L \approx 10\ \mu$m at $\lambda = 800$ nm and 3 mm at $\lambda = 1100$ nm. The key solution is to enhance the optical path length by strongly trapping light within the cell. Various light trapping techniques have been proposed and explored, but each has its own limitations. Randomly roughened surfaces boast a path length enhancement limit of 50 times,[1] but the best realized result is around ten times.[2] Periodic gratings[3–5] can form oblique angle diffractions, but are ineffective in preventing big reflection losses, and Bragg reflectors,[6–8] while having high reflectivity, can only double the path length. We developed a light trapping scheme that can enhance the optical path length by more than 10^4 times via a textured photonic crystal back reflector.

Our back reflector is a combination of a reflection grating and a one-dimensional (1D) photonic crystal as a distributed Bragg reflector (DBR). Figure 1 is a schematic diagram of this design. The grating equation states that

$$m\lambda = np(\sin \alpha + \sin \theta), \tag{1}$$

where m is the diffraction order in integers, λ is the incident wavelength, n is the refractive index of the material, p is the period of grating, α and θ are the incidence and diffraction angles, respectively. When $p = \lambda / n$, for normal incidence, m can take values of 0, ±1. For rectangular gratings, if the grating etch depth $t = \lambda / 4n_{\mathrm{Si}}$, where n_{Si} is the refractive index of Si, the zeroth-order reflection will be strongly suppressed, so that ±1-order diffractions are left and bent by 90°. Consequently, the optical path length can be greatly increased. In our design, $p = \lambda_g / n_{\mathrm{Si}}$, where $\lambda_g = 1107$ nm is the band gap wavelength of Si and $n_{\mathrm{Si}} = 3.5$ at this wavelength. According to Eq. (1), under normal incidence, the first order reflection at the backside grating can be bent by 45° (at $\lambda = 800$ nm) to 90° (at $\lambda = \lambda_g$), far exceeding the critical angle of total internal reflection of Si (16.6°). Therefore, the total internal reflection will occur at the front surface of the cell and the light is reflected back to the active region of the solar cell for further absorption.

The DBR structure we generated is a one-dimensional photonic crystal with high index contrast. Superior to any other high quality mirrors, DBR has a wide stop band[9] expanding several hundred nanometers with nearly 100% reflectivity. Our DBR stacks $\mathrm{Si/Si_3N_4}$ ($n_1/n_2 = 3.5/2.0$) or $\mathrm{Si/SiO_2}$ ($n_1/n_2 = 3.5/1.46$) achieved reflectivity of $>99.8\%$ for λ between 800 and 1100 nm with just a few quarter-wave pairs. In contrast, when light is incident from Si to an Al backside reflector commonly used in solar cells, the reflectivity is $<80\%$. The high reflectivity of DBR guarantees that almost no light can transmit through the backside. By the unique combination of grating and DBR, light is tightly trapped within the solar cell, effectively changing the optical path length from the thickness of the cell to its lateral dimension. Assuming a 2×2 cm^2 solar cell with a thickness of

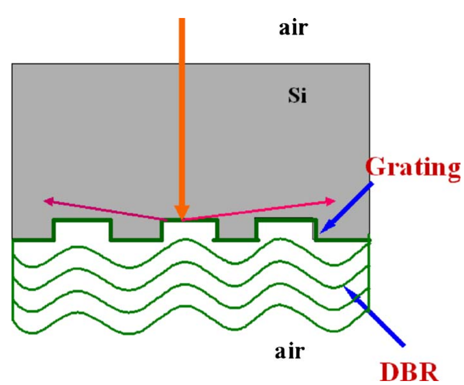

FIG. 1. (Color online) Schematic of the back reflector combining reflection grating and DBR.

[a]Electronic mail: lrzengcn@mit.edu
[b]Electronic mail: xduan@mit.edu

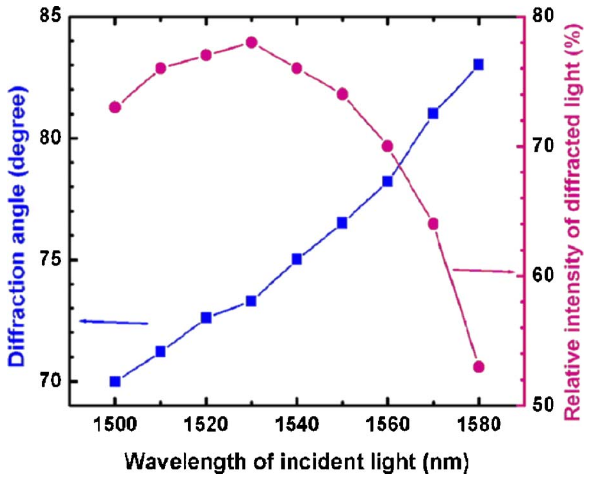

FIG. 2. (Color online) Diffraction by a Si grating with 1.5 μm period when light is incident from the air. The designed grating period is scaled from 1.1 $\mu m/n_{Si}$ to 1.5 μm due to air incidence and light source limitations. Reflection intensity is normalized to the case without grating.

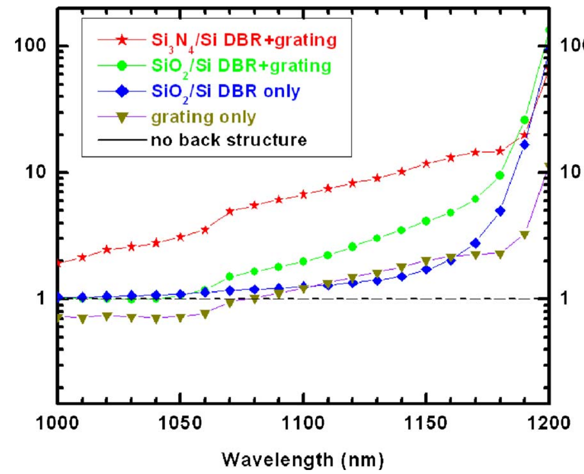

FIG. 3. (Color online) External quantum efficiency enhancement factor for solar cells with different back structures.

1 μm, the path length enhancement can be as huge as 10^4 times the cell thickness. Therefore, almost complete absorption can be realized.

To demonstrate the physics of light bending by grating, Fig. 2 shows the measured light bending angle and relative reflection intensity as a function of wavelength. For easier measurements and due to light source limitations, air incidence was used and the grating period was scaled from 1107 to 1550 nm. It is clear that strong light bending was achieved in a broad wavelength range from 1500 to 1580 nm.

Although the aforementioned modeling and experiments were done at normal incidence, the back reflector also works well for oblique incidence. On average, around 15% of the sunlight is diffuse[10] and incident onto the solar cell from all angles. However, because of refraction at the top surface of Si, all the light entering the Si is directed to within a small cone of 16.6° around the normal. When it impinges onto the backside grating, for λ between 800 and 1100 nm, only 0 and ±1 order reflections can occur, and all the ±1 orders are diffracted at angles between 27.2° and 90°, again exceeding the critical angles for the respective λ's. As for DBR, angled incidence renders a wider stop band with even higher reflectivity and slight blueshift. Therefore, the textured photonic crystal back reflector can elongate the optical path length significantly at all incidence angles from the sun. According to simulation using coupled wave theory, the enhancement of solar cell quantum efficiency will drop only slightly as the incidence angle increases; for a 10 μm thick cell, at 45° incidence from the air, the enhancement of power conversion efficiency is still 80% that of the normal incidence.

Prospective solar cell efficiency increase, $\Delta\eta$, due to light trapping is calculated. Optical path length enhancement is equivalent to increasing the cell thickness, but with the extra benefit of reduced bulk recombination losses, because the minority carriers need to diffuse over a much shorter distance to reach the electrodes. Assuming 100% carrier collection efficiency, 86% fill factor as for the ideal diode,[11] and 29% maximum efficiency of Si solar cells as predicted by Henry,[12] integration over the solar spectrum (AM1.5) up to λ_g of Si will provide the absolute $\Delta\eta$ corresponding to a certain effective cell thickness (d) increase. Obviously $\Delta\eta$ is more pronounced for thinner cells. For a 1 μm thick cell, when d is enhanced to 1 cm, $\Delta\eta$ is as high as 21.7%, whereas for a 675 μm thick cell, when d is increased even to 10 cm, $\Delta\eta$ is less than 2.6%.

To verify the cell efficiency enhancement, solar cells with different back structures were designed and fabricated: grating or DBR only, both, and no back reflector. Unlike the traditional solar cells using top and bottom contacts, we used interdigitated top contacts with lateral *p-i-n* junctions to incorporate the back reflector. Crystalline Si was used to eliminate materials quality issues and make the back reflector effect prominent. Cell size varies from 1 to 36 mm^2, with 15.3% metal coverage. Due to the limitation of standard fabrication facilities, 675 μm thick double-side polished 6 in. Si (100) wafers were used as the starting material just to demonstrate the concept. Projection photolithography and plasma etching were used to form gratings on the backside of the substrate. Eight pairs of DBR stacks were deposited via plasma enhanced chemical vapor deposition. Note that due to the limited resolution of photolithography, the grating period was set as 1.1 μm, instead of 1.1 $\mu m/n_{Si}=314$ nm. Al–2%Si metal contacts were formed on the front side of the wafers.

External quantum efficiency (EQE) was measured using a semiconductor analyzer coupled to a monochromator. The EQE demonstrates significant enhancement for all back reflectors at $\lambda > 1000$ nm, as shown in Fig. 3. The EQE enhancement factor increases with λ, and reaches a maximum of 135 times at $\lambda = 1200$ nm for the cell with Si_3N_4/Si DBR plus grating.

Solar cell power conversion efficiency was measured using a sun simulator under AM1.5 conditions. All back structures improve the cell efficiency appreciably, as evidenced by the *J-V* characteristics of cells with different back structures in Fig. 4. Although all cells have similar V_{oc} of ~620 mV and fill factor around 77%, J_{sc} increases from 23.3 mA/cm^2 for the cell without back structure to 27.5 mA/cm^2 for the one with Si_3N_4/Si DBR plus grating. Correspondingly, the overall efficiency increases from 11.1% to 13.2%, meaning a relative increase ($\Delta\eta/\eta$) of 19%. The absolute efficiency increase ($\Delta\eta$) is 2.1%, in good agreement with the theoretical limit (<2.6%) mentioned earlier. It corresponds to an effective path length of 2 cm for an ideal diode, which is 30 times the cell thickness.

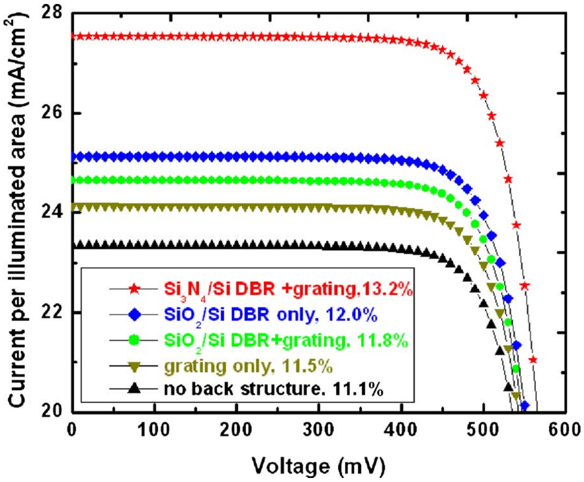

FIG. 4. (Color online) *J-V* characteristics for solar cells with different back structures.

It is interesting to see that in Fig. 3, for $\lambda < 1070$ nm, the "grating only" cell has a lower EQE than the one without any back structure. Also, in Fig. 4, adding a grating to the SiO_2/Si DBR actually decreases the current. These effects could be due to the dangling bonds caused by dry etching of the grating, which increases the surface recombination velocities. Furthermore, compared to standard solar cells, cells with light trapping structures may suffer from higher back surface recombination losses, because more carriers are available there for recombination.[13] Nevertheless, all the back structures still show significant optical enhancement as evidenced by Figs. 3 and 4. Better surface passivation would make the light trapping effect more pronounced.

Note that since the huge cell thickness (675 μm) far exceeds the minority carrier diffusion length (230 μm, based on photoconductance decay measurement), the absolute cell efficiency is severely limited. Electron-hole recombination is especially severe when both *n* and *p* contacts are at the top. The thick cell also limits the EQE enhancement wavelength to a narrow window beyond 1000 nm. Furthermore, the efficacy of the back reflector could not be fully demonstrated because the big grating period, 1.1 μm instead of the preferred 314 nm, makes total internal reflection almost impossible to occur at the front surface of the cell.

In conclusion, solar cells with an efficient light trapping scheme combining reflection grating and 1D photonic crystal were developed. The devices demonstrated significantly improved external quantum efficiency between the wavelengths of 1000 and 1200 nm, with enhancement up to 135 times, as well as considerably increased overall power conversion efficiency. The efficiency enhancement will be much more pronounced for cells with a smaller thickness and finer grating period.

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