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## Innovative dual function nc-SiO<sub>x</sub>:H layer leading to a >16% efficient multi-junction thin-film silicon solar cell

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We present our development of *n*-type nano-structured hydrogenated silicon oxide (nc-SiO<sub>x</sub>:H) as a **dual-function layer in multi-junction solar cells**. We optimized nc-SiO<sub>x</sub>:H and attained a conductivity suitable for a doped layer and optical property suitable for an inter-reflection layer. We tested the effectiveness of the dual-function nc-SiO<sub>x</sub>:H layer **by replacing the normal *n* layer between the middle and the bottom cells** in an a-Si:H/a-SiGe:H/nc-Si:H triple-junction structure. A significant gain in the middle cell current density of  $\sim 1.0$  mA/cm<sup>2</sup> is achieved. We further optimized the component cells and the triple-junction structures and attained an initial active-area cell efficiency of 16.3%. © 2011 American Institute of Physics. [doi:10.1063/1.3638068]

Hydrogenated amorphous silicon (a-Si:H) and hydrogenated nanocrystalline silicon (nc-Si:H) based multi-junction solar cells offer high efficiency and good stability.<sup>1–6</sup> Compared to hydrogenated amorphous silicon-germanium alloy (a-SiGe:H), **nc-Si:H has a broader spectral response and higher photocurrent**. High efficiencies have been reported for nc-Si:H based multi-junction structures<sup>7,8</sup> and exceeded the efficiency previously achieved using a-Si:H/a-SiGe:H/a-SiGe:H triple-junction structures.<sup>9</sup> However, in a multi-junction configuration, the use of a nc-Si:H bottom cell leads to a high short-circuit current density ( $J_{sc}$ ); thus, thick a-Si:H top cell and a-SiGe:H middle cell are needed to match the bottom cell current. **It is well-known that thick a-Si:H and a-SiGe:H cells result in low fill factor (FF) and large light-induced degradation**. To mitigate these issues, inter-reflection layers have been proposed to partially reflect incident light back to the top cell in a-Si:H/nc-Si:H double-junction structures, so a thinner top cell may be used.<sup>10–14</sup> An initially proposed inter-reflection layer was ZnO.<sup>10</sup> Subsequently, nano-structured hydrogenated silicon oxide (nc-SiO<sub>x</sub>:H)<sup>12,13</sup> and silicon nitride (nc-SiN<sub>x</sub>:H)<sup>14</sup> films were used as the inter-reflection layer in a-Si:H/nc-Si:H double-junction structures. In this paper, we use a highly conductive *n*-type nc-SiO<sub>x</sub>:H layer to replace the normal *n* layer in the tunnel-junction of multi-junction solar cells. In this case, the *n*-type nc-SiO<sub>x</sub>:H layer serves two functions: first, it acts as an *n* layer for junction formation in the a-Si:H top or a-SiGe:H middle cell, and second, as an inter-reflection layer to enhance top and/or middle cell current. Thus, we refer to it as a “dual-function” layer. **We deposited nc-SiO<sub>x</sub>:H films using a very high frequency glow discharge technique from a gas mixture of Si<sub>2</sub>H<sub>6</sub>, CO<sub>2</sub>, H<sub>2</sub>, and PH<sub>3</sub>**. The details of the deposition and characterization of nc-SiO<sub>x</sub>:H were reported elsewhere.<sup>15</sup> We previously tested the dual-function nc-SiO<sub>x</sub>:H layers in a-Si:H/nc-Si:H double-junction solar cells.<sup>15</sup> In this paper, we mainly used the dual-function nc-SiO<sub>x</sub>:H layer in a-Si:H/a-SiGe:H/nc-Si:H

triple-junction structures on Ag/ZnO back reflectors (BRs) to increase the photocurrent in the a-SiGe:H middle cell.

Our optimization goal is to attain *n*-type nc-SiO<sub>x</sub>:H materials with high conductivity for use as an *n* layer in the tunnel-junction and suitable optical properties for use as an inter-reflection layer. From the transmission and reflection spectra of a nc-SiO<sub>x</sub>:H film deposited on a glass substrate, we measured a refractive index of  $\sim 2.0$ , an optical bandgap of 2.3 eV, and a conductivity of  $\sim 10^{-5}$  ( $\Omega$  cm)<sup>-1</sup>. We previously reported that conductive atomic force microscopy (C-AFM) is a useful tool to characterize the microscopic current flow in the vertical direction<sup>16</sup> in nano-structured materials, where nanometer sized crystallites form clusters and provide a path for high current flow. In this study, we used C-AFM to measure the current flow in the vertical direction on *n*-type nc-SiO<sub>x</sub>:H films deposited on stainless steel (SS) substrates. Figure 1 shows two C-AFM images, the top image from a sample made using lower hydrogen dilution and higher CO<sub>2</sub>/Si<sub>2</sub>H<sub>6</sub> ratio and the bottom image from a sample made using higher hydrogen dilution and lower CO<sub>2</sub>/Si<sub>2</sub>H<sub>6</sub> ratio. One can see the top image has very low surface current over the entire scanned area, while the bottom image exhibits high current and significant non-uniformity. From our previous study on mixed-phase Si:H films,<sup>16</sup> we learned about the high current flows in the nanocrystallites clusters. Therefore, we speculate that the current spikes correspond to areas of nanocrystallite clusters, while the low current regions are amorphous SiO<sub>x</sub>:H tissues.

We previously used the dual-function *n*-type nc-SiO<sub>x</sub>:H in a-Si:H/nc-Si:H double-junction and a-Si:H/a-SiGe:H/nc-Si:H triple-junction solar cells deposited on Ag/ZnO coated SS substrates.<sup>15</sup> **We found the *n*-type nc-SiO<sub>x</sub>:H and *p*-type nc-Si:H can form a good tunnel-junction without noticeable impact on series resistance and FF**. Therefore, we can use the *n*-type nc-SiO<sub>x</sub>:H to replace the *n* layer of the top cell in a-Si:H/nc-Si:H double-junction solar cells and the *n* layer of the middle cell in a-Si:H/a-SiGe:H/nc-Si:H triple-junction structures. Figure 2 shows the quantum efficiency (QE) spectra of two a-Si:H/a-SiGe:H/nc-Si:H triple-junction solar

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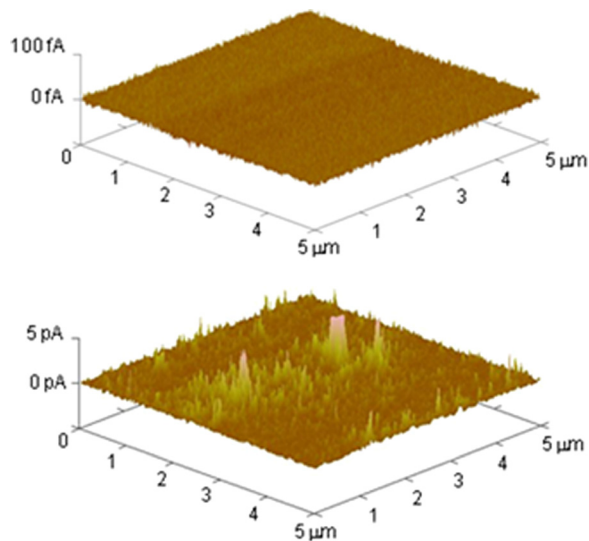


FIG. 1. (Color online) C-AFM images from  $n$ -type  $\text{SiO}_x\text{:H}$  films made with (top) low hydrogen dilution and high  $\text{CO}_2/\text{Si}_2\text{H}_6$  ratio and (bottom) high hydrogen dilution and low  $\text{CO}_2/\text{Si}_2\text{H}_6$  ratio.

cells: one baseline cell (solid lines) without  $n\text{-SiO}_x\text{:H}$  and one (dashed lines) with an  $n$ -type  $n\text{-SiO}_x\text{:H}$  as the dual-function layer replacing the  $n$  layer of the  $a\text{-SiGe:H}$  middle cell, while other components in the two cells are the same. One can see that the triple-junction cell made with the dual-function layer exhibits two types of interference patterns as indicated by the arrows: one with narrow peaks from the interference of reflected light by the substrate and one with broad peaks from the interference of reflected light by the  $n\text{-SiO}_x\text{:H}$  layer. We also observe the dual-function layer indeed functions as an inter-reflection layer, because it increases the middle cell current density by  $\sim 1 \text{ mA/cm}^2$ ; more importantly, it does not decrease the total current density (the sum of current densities of the three component cells). This is a remarkable advantage over the conventional structure having the inter-reflection layer inserted between the  $n$  layer and  $p$  layer of a tunnel junction. Typically, the bottom cell current is reduced when an inter-reflection layer was used. The reflected long-wavelength light escapes from the solar cell and any absorp-

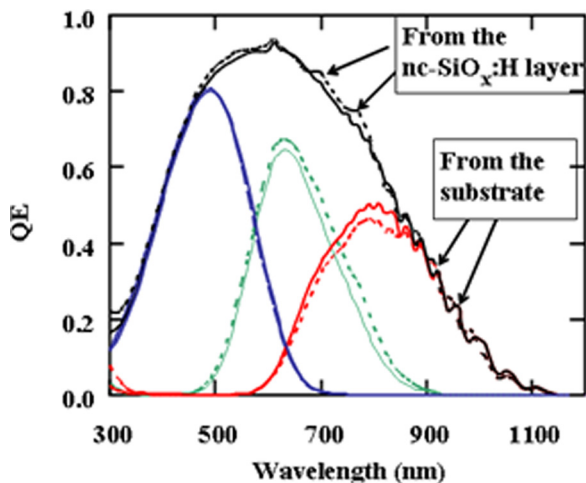


FIG. 2. (Color online) QE curves of two  $a\text{-Si:H/a-SiGe:H/nc-Si:H}$  triple-junction solar cells: baseline cell (solid lines) without  $n\text{-SiO}_x\text{:H}$  and (dashed lines) improved cell with an  $n$ -type  $n\text{-SiO}_x\text{:H}$  as the dual-function layer replacing the  $n$  layer of the  $a\text{-SiGe:H}$  middle cell.

TABLE I. Characteristics of  $a\text{-Si:H/a-SiGe:H/nc-Si:H}$  triple-junction structures, where A is a baseline cell without the  $n$ -type  $n\text{-SiO}_x\text{:H}$  layer, and B is with the  $n$ -type  $n\text{-SiO}_x\text{:H}$  dual-function layer between the  $a\text{-SiGe:H}$  middle and  $nc\text{-Si:H}$  bottom cells. The QE current densities were calculated from the integral of QE curves and AM1.5 solar spectrum. The bolded current density was used as  $J_{sc}$  for the efficiency calculation.

| Sample | $V_{oc}$ (V) | FF    | QE current density ( $\text{mA cm}^{-2}$ ) |             |             |       | Eff. (%) | Comment                 |
|--------|--------------|-------|--------------------------------------------|-------------|-------------|-------|----------|-------------------------|
|        |              |       | Top                                        | Middle      | Bottom      | Total |          |                         |
| A      | 2.201        | 0.692 | 8.88                                       | <b>8.62</b> | 8.67        | 26.17 | 13.13    | Baseline                |
| B      | 2.237        | 0.760 | 8.81                                       | 9.60        | <b>8.04</b> | 26.45 | 13.67    | $\text{SiO}_x\text{:H}$ |

tion in the inter-reflection layer causes the additional loss. When the dual-function  $n\text{-SiO}_x\text{:H}$  layer is used, while the reflection loss may still exist, the absorption loss is greatly suppressed, because the  $n\text{-SiO}_x\text{:H}$  layer is designed to have much lower absorption than the  $n$ -type  $a\text{-Si:H}$  layer. Therefore, the dual-function  $n\text{-SiO}_x\text{:H}$  layer can be engineered to reduce optical losses and achieve high efficiencies. Table I lists the current-voltage ( $J$ - $V$ ) characteristics of the two  $a\text{-Si:H/a-SiGe:H/nc-Si:H}$  triple-junction solar cells. The  $n\text{-SiO}_x\text{:H}$  dual-function layer shifts the current from the bottom cell to the middle cell. In the control cell (A), the current limiting cell is the middle cell, where the current density is  $8.62 \text{ mA/cm}^2$ , while in the testing cell (B), the middle cell current density becomes  $9.60 \text{ mA/cm}^2$ , resulting in a reduction of bottom cell current density to  $8.04 \text{ mA/cm}^2$ . In the latter case, the bottom cell is the limiting cell and determines the  $J_{sc}$ . One may also observe that except for light management, the  $n\text{-SiO}_x\text{:H}$  dual-function layer improves the open-circuit voltage ( $V_{oc}$ ) and FF. The increase in  $V_{oc}$  could come from the improved tunnel-junction between the  $a\text{-SiGe:H}$  middle and  $nc\text{-Si:H}$  bottom cells, because the nanostructures present in  $n$ -type  $n\text{-SiO}_x\text{:H}$  may reduce the voltage loss in the tunnel-junction. The increase in FF mainly comes from current mismatch. In the baseline cell, the current is roughly matched among the three component cells. It is well-known that  $a\text{-SiGe:H}$  middle cells generally have poorer performance than  $a\text{-Si:H}$  top and  $nc\text{-Si:H}$  bottom cells. The low performance of the  $a\text{-SiGe:H}$  middle cell has more impact on the FF in a triple-junction cell for matched or middle cell limited current than for  $a\text{-Si:H}$  top cell or  $nc\text{-Si:H}$  bottom cell limited current. The shift of current from the  $nc\text{-Si:H}$  bottom cell to the  $a\text{-SiGe:H}$  middle cell gives us remarkable flexibility in the design of multi-junction solar cells, which allows us to use either a thinner  $a\text{-SiGe:H}$  cell or a wider bandgap  $a\text{-SiGe:H}$  intrinsic layer.

TABLE II. Characteristics of component cells used in  $a\text{-Si:H/a-SiGe:H/nc-Si:H}$  triple-junction structures, where in each type, a baseline cell and an improved cell are listed.

| Sample type       | $J_{sc}$ ( $\text{mA/cm}^2$ ) | $V_{oc}$ (V) | FF    | $P_{max}$ ( $\text{mW/cm}^2$ ) | Comment  |
|-------------------|-------------------------------|--------------|-------|--------------------------------|----------|
| $a\text{-Si:H}$   | 9.71                          | 1.026        | 0.727 | 7.24                           | Baseline |
| top               | 9.73                          | 1.024        | 0.746 | 7.43                           | Improved |
| $a\text{-SiGe:H}$ | 11.51                         | 0.716        | 0.633 | 5.22                           | Baseline |
| middle            | 11.06                         | 0.743        | 0.663 | 5.45                           | Improved |
| $nc\text{-Si:H}$  | 16.88                         | 0.489        | 0.628 | 5.18                           | Baseline |
| bottom            | 16.47                         | 0.505        | 0.690 | 5.74                           | Improved |

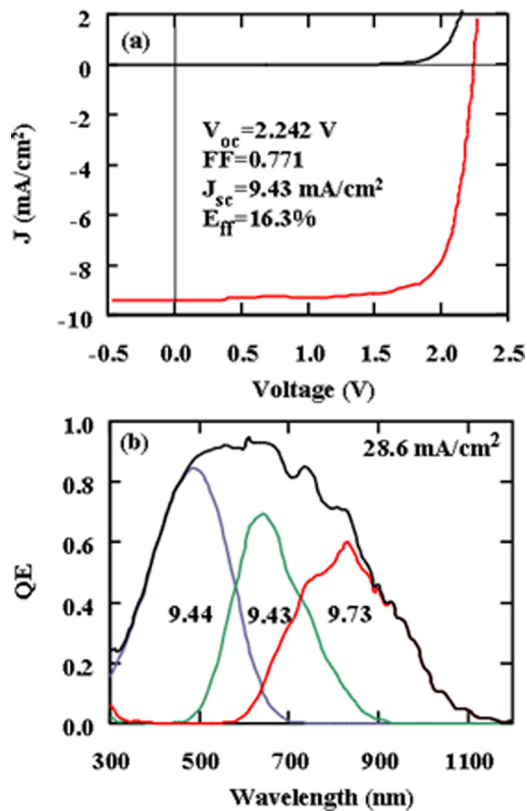


FIG. 3. (Color online) (a) J-V characteristics and (b) QE curves of the 16.3% a-Si:H/a-SiGe:H/nc-Si:H triple-junction solar cell.

In order to achieve higher efficiency than previously attained, we further optimized the component cells and used improved BRs for effective light trapping.<sup>7</sup> Table II compares the component cell performance for a baseline cell and an improved cell. To simulate the component cell performance in a triple-junction structure, the a-Si:H top cell was deposited on specular SS substrates and measured under an AM1.5 solar simulator, the a-SiGe:H middle cell was also deposited on flat SS substrates and measured under an AM1.5 solar simulator with a 530-nm long-pass filter, and the nc-Si:H bottom cell was deposited on Ag/ZnO BR coated SS substrates and measured under an AM1.5 solar simulator with a 610-nm long-pass filter. The reason for the different substrates and different filter measurements is that not much light is reflected from the substrates to the a-Si:H top and a-SiGe:H middle cells. One may note that the FF of the component cells is improved, indicating better material quality obtained by optimizing deposition conditions and device design.

By the combination of the improved component cells and incorporation of the *n*-type nc-SiO<sub>x</sub>:H dual-function layer in a-Si:H/a-SiGe:H/nc-Si:H triple-junction structures, we have significantly improved the triple-junction cell efficiency. An initial active-area efficiency of 16.3% is attained. The J-V characteristics and QE curves of the a-Si:H/a-SiGe:H/nc-Si:H triple-junction solar cell are shown in Fig. 3. The use of

nc-SiO<sub>x</sub>:H dual-function layer enables the use of a thinner a-SiGe:H middle cell, which can reduce the light-induced degradation of the triple-junction structure. Improved stability observed for a-Si:H/nc-Si:H double-junction solar cells by incorporating the nc-SiO<sub>x</sub>:H dual-function layer has been reported in our previous paper.<sup>15</sup>

In summary, we demonstrate a cell structure using a highly conductive nc-SiO<sub>x</sub>:H layer replacing the *n* layer of a-SiGe:H middle cell in an a-Si:H/a-SiGe:H/nc-Si:H triple-junction structure. The advantages of this innovative structure are (1) an increase in middle cell current, as the nc-SiO<sub>x</sub>:H layer serves as an inter-reflection layer; (2) an overall gain in short-circuit current; i.e., the gain in the middle cell current is not less than the loss in the bottom cell current; and (3) a simplified and manufacturable cell structure. Combining the high quality component cells and incorporating the *n*-type nc-SiO<sub>x</sub>:H dual-function layer in an a-Si:H/a-SiGe:H/nc-Si:H triple-junction structure, we attain an initial active-area (0.25 cm<sup>2</sup>) cell efficiency of 16.3%.

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<sup>1</sup>For a review, see *Thin-Film Silicon Solar Cells*, edited by A. Shah (EPFL, Lausanne, Switzerland, 2010).

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