LETTER

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Enhanced efficiency of ultrathin (~500 nm)-film microcrystalline silicon photonic crystal solar cells

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Enhancing the absorption of thin-film microcrystalline silicon solar cells at 600–1000 nm wavelengths is very important to the improvement of the energy conversion efficiency. This can be achieved by creating a large number of resonant modes utilizing two-dimensional photonic crystal band edges, which exceeds the Lambertian limit of absorption in random textures. We focus on suppressing the parasitic absorption of back-reflector metal and doped layers in photonic crystal microcrystalline silicon solar cells. We achieve a high active-area current density of 22.6 mA cm⁻² for an ultrathin (~500 nm)-film silicon layer and obtain an active-area efficiency of ~9.1%, as independently confirmed by the CSMT of AIST.

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Thin-film solar cells based on microcrystalline silicon (μc-Si) have recently drawn attention because of their nontoxicity, low fabrication cost, and high stability. However, thin-film μc-Si has low optical absorption at wavelengths near the electronic band edge (i.e., 600–1000 nm) because of its indirect bandgap nature. Many studies have focused on enhancing the optical absorption of thin films in this wavelength region to increase the energy conversion efficiency of solar cells.1–11,15,19 Randomly textured structures are generally used,1–5 where photons are scattered into the Si layer by the texture. However, the randomness makes it difficult to control crack formation in μc-Si fabricated on such texture. In addition, the maximum absorption level is limited to the Lambertian limit.12 In contrast, for the light absorption in μc-Si solar cells, photonic crystal (PC) structures give a promising way to trap light by using large-area resonant modes over a broad band.13–19 PC structures may exceed the absorption limit of randomly textured structures.15 In addition, even in ultrathin films, large light absorption enhancement can be created by the strong light trapping of resonant modes of PCs. Ultrathin films are much attractive for reducing the deposition time, which results in low production cost.

In this Letter, first, we discuss the guidelines for enhancing broadband light absorption in the wavelength range of 600–1000 nm by utilizing multiple large-area resonant modes at the band edge of a PC.13–19 Higher-order modes perpendicular to the Si layer and band-folding effects in photonic superlattice structures are used to create a large number of resonant modes. Next, we present our previous experimental results16,19 for PC-introduced solar cells, which clearly showed enhanced absorption and conversion efficiency. Here, we evaluated our experimental results by performing a detailed analysis of the absorption; we considered the parasitic absorptions of the metal reflector, transparent conductive oxide (TCO), and doped layers in addition to that of the μc-Si layer. We discuss the existence of prominent unwanted absorption due to the back-reflector metal and doped layers. Such metallic plasmonic absorption can be suppressed by tuning the thickness of the TCO layer inserted between the silicon and the metal. The absorption of the doped layer can also be suppressed by introducing wide-bandgap nanocrystalline SiOₓ-based doped layers. Such improvements led us to achieve a higher active-area short-circuit current density of 22.6 mA cm⁻² and consequently obtain an active-area conversion efficiency of ~9.1% for ultrathin (~500 nm)-film solar cells, the performance of which was confirmed by the Calibration, Standards and Measurement Team (CSMT) of the National Institute of Advanced Industrial Science and Technology (AIST).

Here, we briefly describe the method of light absorption enhancement by using PCs. Large-area broadband resonant modes are created at the Γ point of PCs and used to trap light in solar cells.13 Figure 1(a)15,16 shows a schematic illustration of a solar-cell structure in which such band-edge resonant effects can be applied. Here, we utilized a square-lattice PC. It is important to create as many resonant modes as possible in order to trap light over a broad range of wavelengths and be compatible with the solar spectrum. We utilized the multi-

Fig. 1. (a) Schematic diagram of photonic-crystal-introduced solar cell. (b) Real-space image of PC structure and photonic band diagram. (c) Schematic view of 4 × 4 period superlattice PC and band diagram.
mode nature of light confined in the vertical direction and the band-folding effect by employing a superlattice.\textsuperscript{5,16} Figure 1(b) shows a photonic band diagram of a square-lattice PC having a lattice constant of 275 nm, assuming an approximately 400-nm-thick Si layer, where the black line corresponds to the fundamental mode and the colored lines correspond to higher-order modes of light confined in the vertical direction. This creates several resonant modes at the \textGamma point.\textsuperscript{15-19} By coupling incident light into these resonant modes, the light absorption should be increased at the resonant frequency. Figure 1(c) shows a 4 \times 4 superlattice structure, which provides further band edges at the \textGamma point owing to the reduced size of the fundamental Brillouin zone.

We calculated the optical absorption of \textmu c-Si solar cells incorporating the PCs shown in Fig. 1, which have steep TCO rods embedded in the \textmu c-Si layer, by using the three-dimensional (3D) finite-difference time-domain (FDTD) method. The average thickness of the \textmu c-Si layer was set to \textapprox 400 nm, and the parasitic optical absorption of the TCO, metal reflector, and doped layers was ignored at this stage. Later, we will discuss the detailed calculation that incorporates all parasitic absorptions. The absorption spectra of solar cells with PCs were calculated for the irradiance of white light on top of the solar cell. The calculated absorption spectrum was multiplied by the spectrum of the solar photon flux (AM 1.5) to obtain the short-circuit current density.\textsuperscript{15} We found that introducing PCs significantly enhanced the optical absorption by 1.8-fold compared with that of the solar cell without PCs in the wavelength rage of 500–1000 nm. We also calculated the absorption enhancement by a Lambertian-textured structure,\textsuperscript{15} which ideally induces light scattering that depends on Lambert’s cosine law. This law is known to be the upper limit for the scattering effect of a randomly textured structure. It was previously found that the absorptivity of 4 \times 4 superlattice photonic structures can exceed that of the Lambertian-textured structure owing to the resonant light trapping that occurs in PC structures.\textsuperscript{15}

Next, we discuss previous experimental results for PC-introduced solar cells. We used round shapes for the PC pattern, which helps to suppress grain collisions of \textmu c-Si grown on PCs and leads to better performance.\textsuperscript{19} Such PCs with round surface geometry were prepared by utilizing the isotropic etching mechanism of silicon with reactive-ion etching (RIE). By properly adjusting the shape of the etching mask and etching conditions, we were able to fabricate PC patterns having a lattice constant of 600 nm, as shown in Fig. 2(a). The height of the pointed region of the pattern was set to \textapprox 150 nm, which helps to avoid grain collisions for \textmu c-Si with a thickness of \textapprox 540 nm (thickness with doped layers). Then, the surface was coated by 100-nm-thick Ag and 50-nm-thick gallium-doped zinc oxide (GZO) layers. Next, we deposited an n–i–p \textmu c-Si photovoltaic layer. We used plasma-enhanced chemical vapor deposition (PE-CVD) at a very high frequency to fabricate \textmu c-Si. The fabrication conditions are discussed in detail in our previous report.\textsuperscript{19} The crystalline fraction of the i-\textmu c-Si layers was set to \textapprox 50%. Note that the designated area of the solar cell was set to be \textapprox 8 mm$^2$ for the lab test. Figure 2(b) shows the scanning electron microscopy (SEM) image of the fabricated structure. It can be seen that solar cells with PCs were formed well. The top of the solar cell showed a unique dome shape, which enables an enhancement of absorption comparable to that of the 4 \times 4 superlattice [Fig. 1(c)] owing to the 3D periodic structures on both front and rear surfaces,\textsuperscript{20} even when the lattice constant is equivalent to a 2 \times 2 superlattice. We found that the photocurrent response of the solar cell with PCs was greatly enhanced in the wavelength range of 600–1000 nm compared with that of the reference cell without PCs. As a result, very promising cell performance characteristics were realized: short-circuit current density ($J_{sc}$) = 20.6 mA cm$^{-2}$, open-circuit voltage ($V_{oc}$) = 0.555 V, fill factor ($FF$) = 0.758, and active-area conversion efficiency ($\eta$) = 8.7%.\textsuperscript{19}

We now present an analysis of the absorption of the PC-introduced solar cell based on detailed numerical simulations. As discussed above, we used the FDTD method to calculate the absorption of the \textmu c-Si layer while ignoring the parasitic absorptions of the GZO, indium–tin oxide (ITO), and Ag of the PCs. However, for accurate calculations, these absorptions must be considered in addition to that of \textmu c-Si. The FDTD method takes a long calculation time when employing the real optical parameters of Ag because the mesh size should be reduced for accurate calculations. Hence, we developed a code based on rigorous coupled wave analysis (RCWA) that includes the optical parameters of \textmu c-Si,\textsuperscript{21} ITO (in-house data), GZO,\textsuperscript{22} and Ag. The geometry of the solar cells was modeled by considering the SEM images shown in Fig. 2(b); the unique top shape was also included. However, because the penetration depth of Ag is less than 15 nm (wavelength range of 500–1000 nm), we considered a Ag-metallic PC, which is equivalent to a PC structure covered by a Ag layer in this scope. The model consisted of 50-nm-thick GZO, 30-nm-thick n-\textmu c-Si, \textapprox 500-nm-thick i-\textmu c-Si, 10-nm-thick p-\textmu c-Si, and 70-nm-thick ITO layers, just like in the experiments. Figure 3(b) shows the calculated absorption spectrum. The absorptions of the Ag, GZO, n-\textmu c-Si, i-\textmu c-Si, p-\textmu c-Si, and ITO layers are shown separately with different colors (gray: Ag, green: GZO, cyan: n-\textmu c-Si, red: i-\textmu c-Si, yellow: p-\textmu c-Si, and blue: ITO). Note that the white part of the graph indicates the reflection of the solar cell. We supposed that only the electron–hole pairs generated in the i-\textmu c-Si layer are responsible for the short-circuit current. Hence, $J_{sc}$ was calculated to be 20.9 mA cm$^{-2}$ by multiplying...
the absorption spectrum of the i-µc-Si layer and photon flux density of sunlight. These analytical results agreed well with the experimental results presented above (20.6 mA cm$^{-2}$).

Figure 3(b) shows that, in the longer wavelength region, the back Ag contact (gray) had higher unwanted absorption. Such absorption is due to the plasmonic excitation of Ag. To suppress unnecessary plasmonic excitation in the back Ag layer, we can optically separate the Ag layer from photonic modes confined in the µc-Si layer by increasing the thickness of the GZO layer. Figure 3 also shows the calculated absorption spectra for GZO layer thicknesses of 10, 100, and 150 nm in addition to 50 nm. The calculated current densities were 19.7, 21.6, and 21.6 mA cm$^{-2}$ for the 10-, 100-, and 150-nm-thick GZO layers, respectively (20.6 mA cm$^{-2}$ for the 50-nm-thick GZO layer, as explained above). Introducing a thicker GZO layer clearly suppressed the plasmonic absorption of Ag, which increased the short-circuit current density. However, increasing the thickness of the GZO layer also increased the free carrier absorption of GZO itself as seen in the longer wavelength range of spectra in Fig. 3. We also confirmed that an increase in GZO thickness of more than 150 nm leads to a decrease in current density owing to the increase in the free carrier absorption of GZO. Hence, the short-circuit current density saturated at GZO thicknesses of 100–150 nm.

A close observation of Fig. 3 shows that considerably large absorption also existed owing to p-µc-Si (yellow) and n-µc-Si (cyan). In particular, the p- and n-layers are responsible for absorptions at shorter wavelengths (<600 nm) and longer wavelengths (>500 nm), respectively. To suppress such unwanted absorptions in the doped layer, we utilized wide-bandgap mixed-phase doped nanocrystalline SiO$_x$ (nc-SiO$_x$) layers. Introducing GZO in the SiO$_x$ network is known to show a higher vertical conductivity compared to the lateral directions. Thus, possible shunt paths at the n/i and p/i interfaces may also be suppressed.

For the experimental investigation, we fabricated round PCs, as shown in Fig. 2(a) with a 100-nm-thick GZO layer. On top of that, an n–i–p photovoltaic layer with 30 nm n-SiO$_x$, ~500 nm i-µc-Si, and 10 nm p-SiO$_x$ was deposited. Note that the crystalline fraction of the i-layer was ~70%. We fabricated a solar cell with an area of ~1 cm$^2$. For the front surface electrode, we introduced Ag fingers with a width of 100–150 µm and a period of ~2.6 mm. Figure 4 shows the measured characteristics independently confirmed by the CSMT of AIST. The active-area conversion efficiency is found to be ~9.1%.

**Fig. 3.** Calculated absorption spectra for GZO layers with different thicknesses, which are mainly related to evanescent light coupling with the silver layer.

**Fig. 4.** Solar cell characteristics confirmed by CSMT of AIST. The active-area conversion efficiency is found to be ~9.1%.
and $FF$ were found to be 21.6 mA cm$^{-2}$ (by considering the designated area), 0.562 V, and 0.714, respectively, indicating an efficiency of 8.64%. Correspondingly, the active-area current density was found to be 22.6 mA cm$^{-2}$. Hence, this cell showed an active-area conversion efficiency of 9.08%, which was attributed to a very small film thickness of $\sim$500 nm. These efficiency and short-circuit density are one of the world’s highest values for ultrathin ($\sim$500 nm)-film silicon-based solar cells.

A further increase in short-circuit current density is expected to be realized by increasing the thickness of the $\mu$c-Si layer up to a few micrometers. We should, however, note that, when we simply increase the thickness of the $\mu$c-Si layer on the photonic-crystal-patterned substrate, serious defects are introduced into the cells.$^{16}$ Very recently, we have succeeded in solving this problem and obtaining a short-circuit current density of more than 29 mA cm$^{-2}$ for $\sim$2 $\mu$m cells,$^{27}$ which will lead to the realization of a highly efficient tandem solar cell with a combination of a-Si solar cells.

In summary, we have investigated the improvement of PC solar cells, which use a large number of resonant modes to enhance the absorption over a broad band. After the detailed analysis of the previous works, we have found the importance of suppressing the plasmonic absorption of the Ag layer, and pointed out that the unwanted plasmonic absorption of the Ag layer is expected to be realized by increasing the thickness of the GZO layer on the photonic-crystal-patterned substrate, serious defects are introduced into the cells.$^{16}$ Very recently, we have succeeded in solving this problem and obtaining a short-circuit current density is $\sim$29 mA cm$^{-2}$ for $\sim$2 $\mu$m cells.$^{27}$

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