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Effect of self-orderly textured back reflectors on light trapping in thin-film microcrystalline silicon solar cells

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Light trapping is a key issue to boost the efficiency of thin-film Si solar cells including $\mu\text{c-Si:H}$. In this work, effect of textured back reflectors on light trapping in $\mu\text{c-Si:H}$ cells has been investigated with self-orderly patterned Al substrates obtained by anodic oxidation. By increasing the period of the patterned substrates from 0 to 1.1 μm , the short circuit current densities of 1- μm -thick $\mu\text{c-Si:H}$ cells on the patterned substrates significantly increase from 18 to over 24 mA/cm^2 , which is attributed to the improved light trapping in the near infrared region. The optimum period for light trapping is determined to be around 1 μm for 1- μm -thick $\mu\text{c-Si:H}$ cells. In addition, it has been demonstrated that the optimized patterned substrate enhances light trapping effect in a wide range of cell thicknesses of 0.5–4 μm . It is also confirmed that natural surface texturing during $\mu\text{c-Si:H}$ film growth improves light scattering for flat substrates but deteriorates the superior light scattering property of the well-designed substrates. © 2009 American Institute of Physics.
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I. INTRODUCTION

Thin-film Si solar cells with tandem structures using hydrogenated amorphous Si ($a\text{-Si:H}$) and hydrogenated microcrystalline Si ($\mu\text{c-Si:H}$) are promising candidates for future low-cost and high-efficiency solar cells.^{1,2} In the high-efficiency tandem cells, $\mu\text{c-Si:H}$ plays a key role as an absorber material in the bottom or middle cell. For $\mu\text{c-Si:H}$ cells, light trapping is crucial to obtain a high current density, as the absorption coefficient of $\mu\text{c-Si:H}$ is small in the near infrared (NIR) region. Theoretically, by ideal light trapping, the optical path length in a material with a refractive index of n is enhanced by a factor of $4n^2$ (Ref. 3), and the amount of photons absorbed in the material can be increased drastically.

To date, various light trapping structures have been researched and developed by many researchers to enhance light trapping in thin-film Si solar cells.^{4–27} Randomly textured substrates have been realized by using SnO_2 ,^{7,8} ZnO ,^{9–14,18} glass,^{15,16} Ag,¹⁷ and plastic films.¹⁸ In fact, they can improve the spectral response in longer wavelengths, and some of them have been already applied in commercial solar cells. When incorporated into $\mu\text{c-Si:H}$ solar cells, such textured surfaces significantly increase the optical path length of the incident light, due to (i) light scattering on textured surface at oblique angles and (ii) enhanced total internal reflection at the interface within the cells. In addition to random textures, periodically textured substrates like surface gratings have also been investigated for light trapping in thin-film Si solar cells.^{20–27} In some cases, surface gratings are combined with distributed Bragg reflector or photonic crystals.^{25–27} Calculated results have shown that a significant enhancement in the photon absorption in thin-film Si cells is expected by applying optically functional periodic structures.^{23–27} Actually, the effectiveness of surface gratings on light trapping

has been demonstrated in $\mu\text{c-Si:H}$ cells,^{21,22} although the current gain by the gratings has not exceed the gain obtained by random textures.

In general, $\mu\text{c-Si:H}$ cells require a light trapping structure with a larger feature size compared with $a\text{-Si:H}$ cells, because $\mu\text{c-Si:H}$ can absorb photons with longer wavelengths than $a\text{-Si:H}$. In superstrate-type $p\text{-i-n}$ $\mu\text{c-Si:H}$ cells, it has been reported that textured ZnO films with craterlike textures with a typical diameter of 0.5–2 μm , which are fabricated by sputtering and post wet etching, show a better light trapping effect.^{9–11} On the other hand, in substrate-type $n\text{-i-p}$ $\mu\text{c-Si:H}$ cells, textured SnO_2 with a typical lateral size of 0.2–0.3 μm show a significant increase in the spectral response in the NIR region.⁸ As another approach, textured ZnO films with a grain size of 1.3 μm , which was fabricated by electroplating, has been applied for $n\text{-i-p}$ $\mu\text{c-Si:H}$ cells and given a high NIR response.¹⁴

As mentioned above, light trapping in $\mu\text{c-Si:H}$ solar cells has been extensively researched by many groups. Nevertheless, the best light-trapping structure for thin-film $\mu\text{c-Si:H}$ cells is still ambiguous. One big problem is that, in the previous reports, each textured substrate is fabricated by a totally different approach including chemical vapor deposition (CVD), sputtering, wet etching, electroplating, and reactive ion etching. This means that the morphology and the feature size of these textured substrates are quite different. Therefore, it is quite difficult to systematically compare the light-trapping effect of the textured substrates previously reported, and to deduce the optimized parameter in realizing better light trapping.

Recently, we have reported unique periodically textured back surface reflectors (BSR) fabricated by using anodic oxidation of Al.²⁸ In that report, we have shown that BSR with an appropriate dimple size of ~ 0.9 μm significantly improves the spectral response of substrate-type $\mu\text{c-Si:H}$ cells

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in the NIR region. An advantage of our approach is the availability of systematic control of the dimple size, namely, period, by simply changing the applied voltage and electrolytes during anodic oxidation.^{29–31} Using this approach, self-ordered dimple patterns with a wide range of periods can be prepared on Al substrates with high uniformity as well as large substrate sizes. In this paper, we report the structural and optical properties of patterned Al substrates with a wide range of periods, and their effects on the light trapping in substrate-type *n-i-p* $\mu\text{c-Si:H}$ single cells. The relationship between the period of substrates and the light-trapping effect in $\mu\text{c-Si:H}$ cells is presented, and the optimum size is determined. In addition, it is shown that angular reflection property of substrates is well correlated with the light-trapping effect in the cells. Light-trapping effect by natural textures grown during $\mu\text{c-Si:H}$ deposition is also discussed.

Generally, efficiency of solar cells is given by multiplying the open circuit voltage V_{OC} , the short circuit current density J_{SC} , and the fill factor (FF). To boost the cell efficiency, all the parameters should be improved. However, light trapping textures for increasing J_{SC} often induce the defects in $\mu\text{c-Si:H}$ layers and deteriorate V_{OC} and FF of the cells.^{8,12} In fact, we have experienced a decrease in V_{OC} and FF by applying textured substrates. However, the purpose of this work is to examine the light-trapping effect of textured substrates. Therefore, in this paper, we will focus only on J_{SC} and spectral response of solar cells, and not discuss the other cell parameters. The other cell parameters can be referred in our previous paper, and in some cases, our patterned substrates give a rise of efficiency as well as J_{SC} , compared with conventional textured substrates.²⁸

II. EXPERIMENT

A. Substrate preparation

BSRs with a periodic dimple pattern were fabricated by the following procedure. Electrochemically polished Al sheets are first anodically oxidized at a constant voltage in an electrolyte solution.^{28–31} By the anodization, an Al_2O_3 film with pore arrays is formed on the Al surfaces. During the oxidation, a self-ordered dimple pattern is simultaneously formed on the Al surface beneath the Al_2O_3 film. The Al_2O_3 film is easily etched off with a mixture of chromium and phosphoric acid solutions, leaving a bare patterned Al substrate.

A unique feature of self-ordered porous alumina films is that the period Λ is roughly proportional to the applied voltage during the anodic oxidation. To control Λ from 0.1 to over 1 μm , anodic oxidations were performed using three different acid solutions, namely, oxalic acid $[(\text{COOH})_2]$, phosphoric acid (H_3PO_4), and citric acid ($\text{C}_6\text{H}_5\text{O}_7$) under the different applied voltages from 40 to 450 V, as listed in Table I.

B. Solar cell fabrication

Substrate-type *n-i-p* $\mu\text{c-Si:H}$ cells with an active area of 1 cm^2 were fabricated on the patterned Al substrates coated with a Ag/ZnO stacked film, by conventional plasma-enhanced chemical vapor deposition (PECVD). The structure

TABLE I. Anodic oxidation conditions for preparing patterned Al substrates.

Period Λ (μm)	Electrolyte	Voltage (V)	Temperature ($^\circ\text{C}$)
0.1	3.6 wt % oxalic acid	40	25
0.3	3.6 wt % oxalic acid	120	2
0.45	3.8 wt % phosphoric acid	195	2
0.6	4 wt % citric acid	270	25
0.9	4 wt % citric acid	370	25
1.1	4 wt % citric acid	450	25

of the solar cell consists of Al substrate/Ag(200 nm)/ZnO(40 nm)/ $\mu\text{c-Si:H}$ *n-i-p* layers/ In_2O_3 :Sn(ITO, 75 nm)/Ag grid. The $\mu\text{c-Si:H}$ *i*-layers with thicknesses of $t_i = 0.5\text{--}4$ μm were deposited on the substrates using a SiH_4 and H_2 gas mixture ($\text{SiH}_4/\text{H}_2 = 10.5/380$ SCCM) (SCCM denotes standard cubic centimeter per minute at STP) at a substrate temperature of 170 $^\circ\text{C}$, a pressure of 1.5 torr, and a rf power density of 0.04 W/cm^2 . For comparison, *n-i-p* $\mu\text{c-Si:H}$ cells were also fabricated on flat-glass/Ag/ZnO and textured- SnO_2 (Asahi Glass, Asahi-U)/Ag/ZnO substrates⁷ in the same manner.

C. Characterization

Surface morphology of Al substrates and solar cells was observed with a scanning electron microscope (SEM) and an atomic force microscope (AFM). Total and diffuse reflectivity of the samples was measured by using a spectrometer (PerkinElmer, Lambda950) with an integral sphere (Lab-sphere, 150 mm RSA ASSY). Angle-dependent reflectivity of the substrates was characterized by using a photodiode which can rotate around the samples illuminated by a laser beam. The performance of the cells was evaluated by measuring current-voltage characteristics and quantum efficiency spectra under AM 1.5 G 100 mW/cm^2 illumination.

III. RESULTS AND DISCUSSION

A. Structural and optical properties of patterned substrates

Figure 1 shows SEM images of Al surfaces obtained after the anodic oxidation process at (a) 40 V, (b) 120 V, (c) 195 V, (d) 270 V, and (e) 370 V. Also, Fig. 1(f) shows a SEM image of a commercially available Asahi-U type textured SnO_2 substrate, which is used as a reference textured substrate in this study. It can be seen in Figs. 1(a)–1(e) that self-ordered dimple patterns with different periods are uniformly formed on Al substrates. The patterns are almost arranged in a hexagonal array, and each dimple has a smooth concave shape. The obtained average periods for Figs. 1(a)–1(e) are $\Lambda \sim 0.1, 0.3, 0.45, 0.6$, and 0.9 μm , respectively. The aspect ratio of these dimples, namely, the ratio of the peak height to Λ is about 0.2.

Figure 2 shows the root-mean-square roughness σ_{rms} of the patterned Al substrates determined by AFM. As can be seen in Fig. 2, σ_{rms} increases linearly from 0 to 70 nm with increasing Λ from 0 to 1.1 μm . This result indicates that the

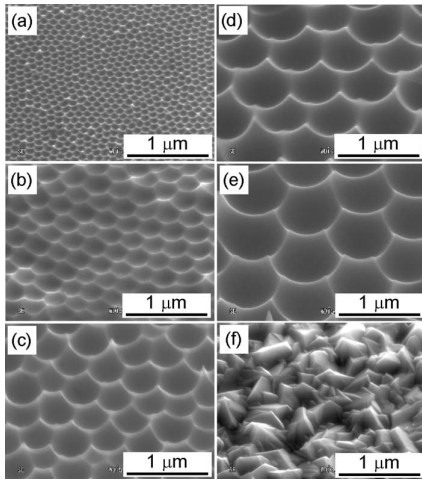


FIG. 1. SEM images of patterned Al substrates fabricated by anodic oxidation process under the applied voltages of (a) 40 V, (b) 120 V, (c) 195 V, (d) 270 V, (e) 370 V, and (f) Asahi-U type textured SnO_2 on glass. The average periods of the patterned Al substrates [(a)–(e)] are $\Lambda=0.1, 0.3, 0.45, 0.6$, and $0.9 \mu\text{m}$, respectively.

size of the dimple patterns on Al substrates is enlarged by increasing the applied voltage with a constant aspect ratio.

Figure 3 shows (a) total reflectivity R_{total} and (b) diffuse reflectivity R_{diffuse} spectra of the patterned Al substrates with a Ag coating. As can be seen in Fig. 3(a), all the samples show high R_{total} over 96% in the NIR region. However, an absorption peak at a wavelength of $\lambda \sim 0.35 \mu\text{m}$ and its absorption tail are also observed in Fig. 3(a). The intensity of this peak is sharply increased by increasing Λ from 0.1 to $0.3 \mu\text{m}$, and then decreased by increasing $\Lambda > 0.3 \mu\text{m}$. This tendency is also valid for the absorption tail in the visible and NIR regions. As a result, the R_{total} of the Al substrates is slightly increased in the visible and NIR regions with increasing Λ from 0.3 to $0.9 \mu\text{m}$. For the substrates with $\Lambda = 0.9$ and $1.1 \mu\text{m}$, R_{total} is almost identical. This absorption is attributed to localized surface plasmon (LSP) excited in Ag nanostructures, which is often observed in Ag surface with roughness.^{5,32} In other words, the intensity of LSP is related to a degree of nanoroughness. Therefore, the results in Fig. 3(a) indicate that the higher reflectivity of the Al

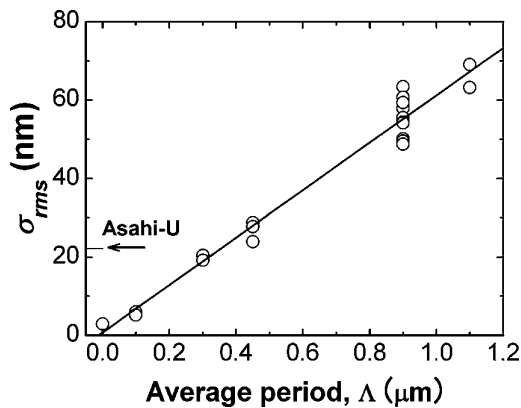


FIG. 2. RMS roughness of patterned Al substrates as a function of average period Λ .

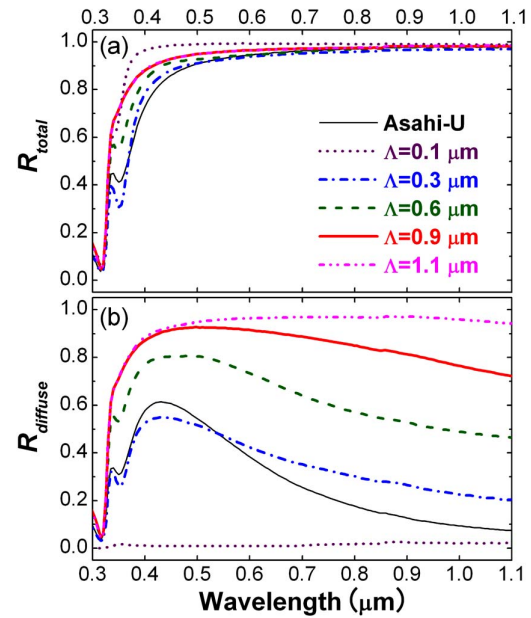


FIG. 3. (Color online) (a) Total reflectivity R_{total} and (b) diffuse reflectivity R_{diffuse} spectra of the patterned Al substrates and Asahi-U type textured SnO_2 on glass. All samples are coated with a Ag film.

substrates with larger Λ is attributed to the less nanoroughness resulting in the weaker LSP absorption. It should be remarked that absorption by surface plasmon polariton supported by periodic structures as observed in perfect surface gratings³³ is not observed in our substrates. This is attributed to insufficient long-range periodicity in our substrates, as often observed in self-ordered structures fabricated by anodic oxidation. On the other hand, it is clearly shown in Fig. 3(b) that the R_{diffuse} increases monotonically with increasing Λ from 0.1 to $1.1 \mu\text{m}$ in the visible and NIR regions. For the substrates with $\Lambda > 0.9 \mu\text{m}$, more than 90% of visible light is reflected diffusely. This property is preferable to increase the optical path length in thin $\mu\text{c-Si:H}$ layers.

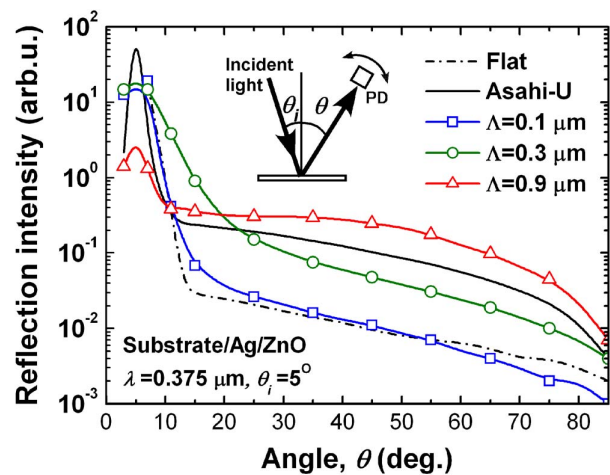


FIG. 4. (Color online) Angular distribution of the reflected light from the patterned Al and Asahi-U substrates coated with a Ag/ZnO film stack at $\theta_i = 5^\circ$ and $\lambda = 0.375 \mu\text{m}$.

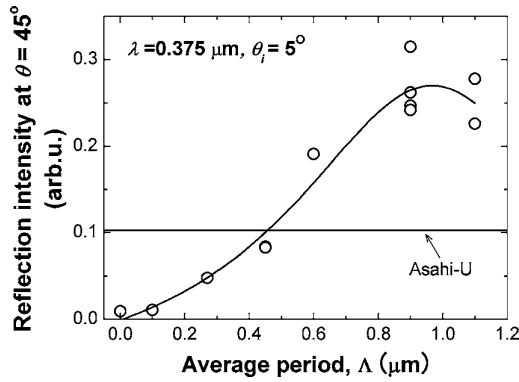


FIG. 5. Angular reflection intensity of the patterned Al substrates coated with a Ag/ZnO film stack measured at 45°. The line is the guide to the eyes.

Figure 4 shows the angular distribution of the reflected light intensities from the patterned Al and Asahi-U substrates with a Ag/ZnO coating. In this experiment, a laser beam with $\lambda = 0.375 \mu\text{m}$ was used as a light source and the incident angle was set near the normal ($\theta_i = 5^\circ$). It should be noted that the wavelength of $\lambda = 0.375 \mu\text{m}$ corresponds to NIR light ($\lambda \sim 1.3 \mu\text{m}$) when propagating in $\mu\text{c-Si:H}$ films with a refractive index of ~ 3.5 . Thus, by this configuration, we can estimate the optical behavior at the rear side of $\mu\text{c-Si:H}$ solar cells in the NIR region, where light trapping is crucial. It can be seen from Fig. 4 that the patterned Al substrate reflects the incident light at larger angles over 20° more effectively with increasing Λ from 0.1 to $0.9 \mu\text{m}$. At the same time, the intensity of specular reflection decreases significantly. The patterned Al substrate with $\Lambda = 0.9 \mu\text{m}$ exhibits stronger reflection at larger angles compared with the Asahi-U substrate. From this result, it is confirmed that the patterned substrates with larger Λ reflect the incident light at oblique angles quite effectively. This property is useful to increase the optical path length within the i layer of $\mu\text{c-Si:H}$ solar cells and enhance the total internal reflection at the interface between the $\mu\text{c-Si:H}$ film and the transparent conducting oxide (TCO) top electrode.

Figure 5 shows the angular reflection intensities of the patterned Al substrates coated with a Ag/ZnO film stack measured at 45° . The incident angle and wavelength are the same, as used in Fig. 4. It is found that the intensity increases monotonically with increasing Λ from 0.1 to $0.9 \mu\text{m}$ by a factor of ~ 30 . However, it appears to be saturated for Λ longer than $0.9 \mu\text{m}$.

B. Solar cells

1. Effect of the period of patterned substrates

Figure 6 shows the external quantum efficiency (EQE) spectra of the $\mu\text{c-Si:H}$ cells with an i -layer thickness of $t_i = 1.0 \mu\text{m}$ fabricated on the flat, Asahi-U, and patterned Al substrates with $\Lambda = 0.1$ – $0.9 \mu\text{m}$ measured under AM 1.5 white bias light. It can be seen in Fig. 6 that the patterned Al substrates enhance the EQE in the wavelength range from 0.6 to $1.1 \mu\text{m}$ compared with the flat substrate. In addition, this EQE gain is significantly improved by increasing Λ , as expected from Fig. 5. The patterned Al substrate with Λ

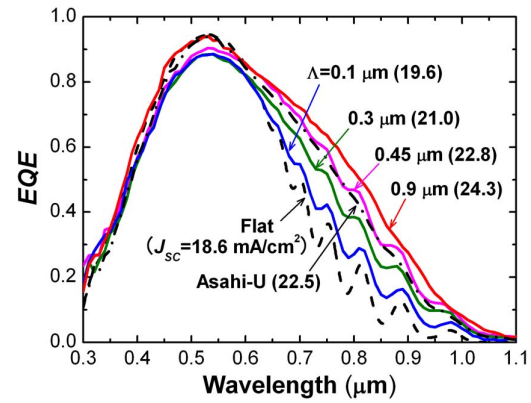


FIG. 6. (Color online) EQE spectra of the n - i - p $\mu\text{c-Si:H}$ solar cells with $t_i = 1 \mu\text{m}$ fabricated on a flat, Asahi-U, and patterned Al substrates with $\Lambda = 0.1, 0.3, 0.45$, and $0.9 \mu\text{m}$ measured under white bias light and zero bias voltage. The values in the brackets show the corresponding short circuit current densities.

$= 0.9 \mu\text{m}$ shows higher EQE than Asahi-U type randomly textured substrate. The corresponding short circuit current densities J_{SC} of the flat, Asahi-U, and patterned Al with $\Lambda = 0.1, 0.3, 0.45$, and $0.9 \mu\text{m}$ are 18.6, 22.5, 19.6, 21.0, 22.8, and 24.3 mA/cm^2 , respectively.

Figure 7 shows the relationship between Λ of the patterned substrate and photo-current densities J_{ph} of the n - i - p $\mu\text{c-Si:H}$ solar cells with $t_i = 1 \mu\text{m}$. In this figure, J_{SC} were calculated from EQE curves measured under bias voltages of $V_b = 0$ and -0.5 V . It is clearly found out that the J_{ph} at $V_b = 0 \text{ V}$, namely J_{SC} , is significantly improved by increasing Λ , having a maximum value at around $\Lambda \sim 1 \mu\text{m}$. This value is quite close to the feature size of the electroplated ZnO back reflector reported by Toyama *et al.*,¹⁴ which gives a significantly high J_{SC} . This tendency is also valid when applying a negative bias of $V_b = -0.5 \text{ V}$ during the measurement. However, the discrepancy between the J_{ph} obtained under $V_b = 0$ and -0.5 V increases with increasing Λ . This result suggests that the increase in Λ induces a higher concentration of defects in $\mu\text{c-Si:H}$ films, and enhances the recombination of photogenerated carriers. By eliminating this negative effect,

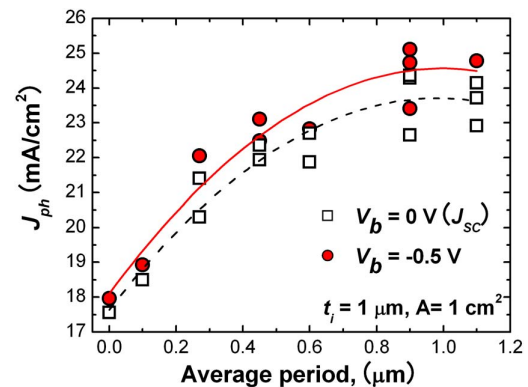


FIG. 7. (Color online) J_{ph} of the n - i - p $\mu\text{c-Si:H}$ solar cells with $t_i = 1 \mu\text{m}$ fabricated on a the patterned Al substrates as a function of Λ . These values were calculated from EQE curves measured under $V_b = 0$ and -0.5 V . The lines are the guides to the eyes.

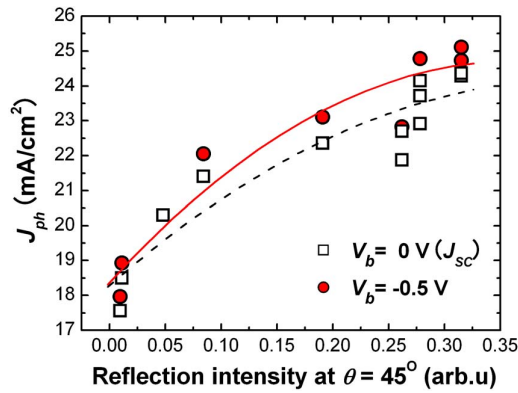


FIG. 8. (Color online) J_{ph} of the n - i - p μc -Si:H solar cells with $t_i=1$ μm fabricated on the patterned Al substrates as a function of the reflected light intensity at 45° and $\lambda=0.375$ nm. The lines are the guides to the eyes.

a high J_{sc} over 25 mA/cm² is expected by using patterned substrates with an appropriate Λ . Unfortunately, we have not succeeded to fabricate uniform patterns with Λ longer than 1.2 μm using the anodic oxidation process, although the behavior of EQE for much longer Λ is of interest.

The light-trapping property of textured substrates is often evaluated with σ_{rms} or a haze ratio, $R_{diffuse}/R_{total}$, in the NIR region. However, in this experiment, both parameters increase monotonically with increasing Λ , as confirmed from Fig. 2 and 3(b), unlike to the J_{ph} shown in Fig. 7. On the other hand, J_{ph} is well correlated with the angular reflection intensity, as shown in Fig. 8. This result indicates that the σ_{rms} and the haze ratio are useful parameters to evaluate the light scattering property of substrates, but that the direct measurement of reflected light at large angles is a more precise way to estimate the light-trapping effect in μc -Si:H cells.

In Fig. 9, EQE, internal quantum efficiency (IQE), and R_{total} spectra of the μc -Si:H cells fabricated on the patterned Al substrate with $\Lambda=0.9$ μm are compared with those of the cell on the Asahi-U substrate. As a reference, R_{total} of a crystalline Si (c -Si) wafer coated with an ITO film is also plotted in this figure. Interestingly, R_{total} of the both solar cells are

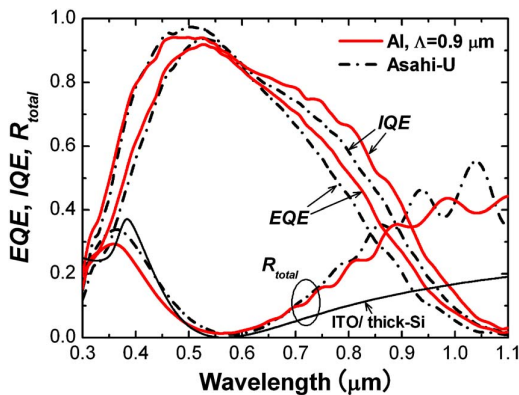


FIG. 9. (Color online) EQE, IQE, and R_{total} spectra of the n - i - p μc -Si:H solar cells with $t_i=1$ μm fabricated on Asahi-U and patterned Al substrate with $\Lambda=0.9$ μm measured under white bias light and zero bias voltage. As a reference, R_{total} of c -Si wafer coated with an ITO film is also plotted.

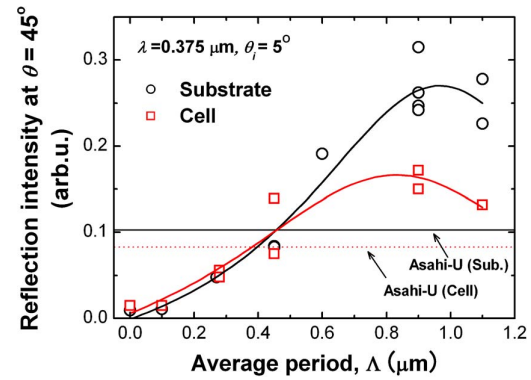


FIG. 10. (Color online) Angular reflection intensity of the patterned Al substrates and the n - i - p μc -Si:H solar cells with $t_i=1$ μm measured at 45° as a function of Λ . The lines are the guides to the eyes.

almost the same, in spite of the clear difference in EQE. As a result, the cell on the patterned Al substrate exhibits a significant increase in IQE in the wavelengths longer than 0.6 μm compared with that of the Asahi-U substrate. A higher IQE means that photons absorbed in the cell are more effectively absorbed within the active layer and contribute to generate photo-current. In other words, this result indicates that the improved light-trapping structure can reduce the parasitic absorption in the cell. However, in the μc -Si:H cells, there remains a large reflection loss in the NIR region, compared with the thick c -Si with an ITO antireflection coating. This reveals that light trapping in μc -Si:H cells can be improved further in this region.

The main factors of the parasitic absorption in our solar cells are the p - and n -layers, the front ITO layer, and the BSR. In this case, only the BSR is different among these factors. Therefore, an increase in reflectivity at the BSR is a possible reason for this IQE gain. In addition, the amount of the parasitic absorption can be varied by changing the optical path length inside the cell. If incident light is effectively scattered at the front side of the cell, it has a higher possibility to be absorbed within the active layer before reaching the absorbing BSR. In the same manner, if the light reflected at the BSR back to the cell is effectively scattered, it has higher possibility to be absorbed within the active layer before reaching the absorbing front TCO. Thus, the improved BSR structure can offer the three beneficial effects: (i) an increase in reflectivity of the BSR, (ii) effective light scattering at the front side, and (iii) effective light scattering at the rear side. The effect (i) can be confirmed in Fig. 3(a), showing that R_{total} of the patterned substrate with $\Lambda=0.9$ μm is slightly higher than that of Ag-coated Asahi-U in the visible-NIR region, although the data were obtained in air atmosphere. The effect (iii) is obvious from Fig. 5. To check the effect (ii), the angular reflection intensity of the cell surfaces was measured.

Figure 10 shows the angular reflection intensity of the n - i - p μc -Si:H solar cells measured by the same experimental configuration used in Fig. 5. The data for the substrate are identical with those shown in Fig. 5. It should be noted that the reflection from the cells is caused only by the front reflection because the incident beam with $\lambda=0.375$ μm cannot

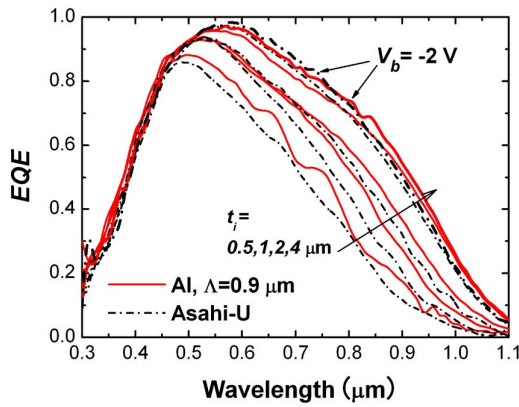


FIG. 11. (Color online) EQE spectra of the *n-i-p* $\mu\text{c-Si:H}$ solar cells with $t_i = 0.5\text{--}4\ \mu\text{m}$ fabricated on Asahi-U and patterned Al substrates with $\Lambda = 0.9\ \mu\text{m}$.

reach the rear surface. Obviously, the reflection of the cells shows the similar behavior with that of the substrates. This result indicates that the light scattering property of substrates is replicated to the cells fabricated on them, and light-trapping effect is enhanced by the textures on the front side as well as on the rear side. However, in the case of longer $\Lambda > 0.5\ \mu\text{m}$, reflection intensity of the cells shows the lower values than those of the substrates. This result reveals that light scattering property at the front side of the cells is decreased as compared with the substrates. It is expected that the results obtained here are valid in the NIR region where light trapping is crucial, although the absolute value must be different.

2. Effect of cell thickness

In the following section, the effect of *i*-layer thickness t_i on the light trapping is examined and discussed. Figure 11 shows EQE spectra of the *n-i-p* $\mu\text{c-Si:H}$ solar cells with $t_i = 0.5\text{--}4\ \mu\text{m}$ fabricated on Asahi-U and the patterned Al substrates with $\Lambda = 0.9\ \mu\text{m}$. The cells on the patterned Al substrates exhibit higher EQE in the NIR region than those on the Asahi-U. This result indicates that the patterned Al substrates confine the incident light effectively in the cells irrespective of the t_i . On the other hand, with increasing t_i , the patterned Al substrates show a decrease in EQE curves in the wavelength range from 0.6 to 0.8 μm compared with the Asahi-U. This EQE drop is partially recovered by applying a negative bias of $V_b/t_i \sim -0.5\ \text{V}/\mu\text{m}$ during EQE measurement, as shown by the dashed lines in Fig. 11. Therefore, this drop is not an optical effect but attributed to defects in $\mu\text{c-Si:H}$ layers deposited on rough substrates. To eliminate this negative effect, further optimization of surface morphology of patterned Al substrates and the $\mu\text{c-Si:H}$ deposition condition are required. In other words, there remains still a room to improve EQE and J_{SC} .

Figure 12 shows the relationship between t_i and J_{ph} of the *n-i-p* $\mu\text{c-Si:H}$ solar cells fabricated on flat, Asahi-U, and patterned Al substrates with $\Lambda = 0.9\ \mu\text{m}$. As expected, J_{ph} monotonically increases with increasing t_i . For all t_i shown in this figure, a highest J_{ph} or J_{SC} is obtained by using pat-

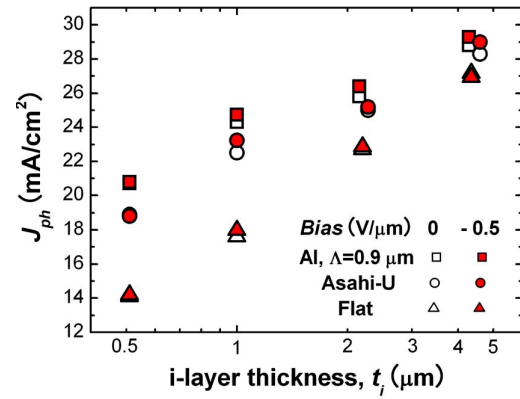


FIG. 12. (Color online) J_{ph} of the *n-i-p* $\mu\text{c-Si:H}$ solar cells fabricated on flat, Asahi-U, and patterned Al substrates with $\Lambda = 0.9\ \mu\text{m}$ as functions of t_i .

terned Al substrate. However, the gain in J_{ph} by using textured substrates becomes smaller with increasing t_i . This result can be explained by the facts that, with increasing t_i , (i) less amount of photons reaches to the back side where the effective light scattering occurs, and (ii) light scattering at the front side becomes pronounced due to the evolution of naturally formed textures during the growth of $\mu\text{c-Si:H}$ layers. To investigate the light scattering effect of the front side of the cells, we have performed SEM and AFM observations of the cell surfaces, and evaluated the light scattering property by measuring the angular reflectivity.

Figure 13 shows SEM images of the *n-i-p* $\mu\text{c-Si:H}$ cells with different t_i fabricated on the flat, Asahi-U, and patterned Al substrates with $\Lambda = 0.9\ \mu\text{m}$. It can be seen from Fig. 13 that the surface morphology of the substrates is replicated to the cell surfaces, especially for thinner cells. However, with increasing t_i , evolution of natural textures hinders this replicated shape, and finally a similar surface morphology is formed for all the substrates.

Figure 14 shows (a) the σ_{rms} and (b) the angular reflection intensities of the *n-i-p* $\mu\text{c-Si:H}$ solar cells measured by the same experimental configuration used in Figs. 5 and 8. It is found in Fig. 14 that, for the flat substrate, both of the σ_{rms} and angular reflection intensity increases monotonically with increasing t_i , as expected from Fig. 13. For the Asahi-U substrates, σ_{rms} increases with increasing t_i , but the angular reflection is almost independent from it. For the patterned Al substrates, σ_{rms} is less dependent on t_i than the other two substrates. Interestingly, the angular reflection intensity decreases with increasing t_i , on the contrary to the flat substrate. It is found in Fig. 14 that σ_{rms} and the angular reflection approaches to constant values asymptotically with increasing t_i , irrespective of substrate morphology. Thus, with increasing t_i , (i) the surface morphology of substrates is replicated to the cell surfaces, then (ii) natural texture evolution of $\mu\text{c-Si:H}$ gradually hinders the replicated shapes, and finally (iii) the cells have a similar surface morphology and light scattering property. The results shown in Fig. 12 can be explained reasonably with this mechanism. From these results, it is confirmed that an additional gain in J_{SC} can be expected by improving the light scattering ability at the front side.

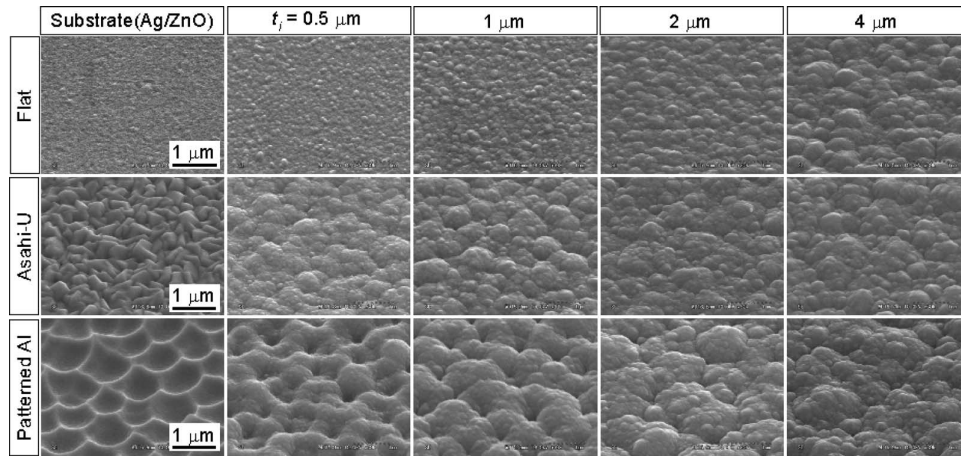


FIG. 13. Surface morphology of the n - i - p μ c-Si:H cells with different t_i fabricated on the flat, Asahi-U, and patterned Al substrates with $\Lambda=0.9$ μ m. All images were taken at the same magnification.

IV. CONCLUSIONS

In this work, effect of patterned back reflectors on light trapping in μ c-Si:H cells has been investigated with self-ordered Al substrates obtained by anodic oxidation. With increasing the period of the patterned substrates from 0 to 1.1 μ m, 1- μ m-thick μ c-Si:H cells on the patterned substrates have shown a significant enhancement in spectral response in the NIR region, giving an increment of J_{SC} from 18 to 24 mA/cm^2 . The optimum period of patterned substrates is determined to be around 1 μ m for 1- μ m-thick μ c-Si:H

cells. This enhanced light-trapping effect is attributed to the improved reflectivity of the rear side and effective light scattering at the front side, as well as light scattering at the rear side. A high J_{SC} more than 25 mA/cm^2 is expected in the cell with the same cell configuration used in this study, if the defect formation in μ c-Si:H layer is sufficiently suppressed. In addition, it has been demonstrated that the optimized patterned substrate enhances light-trapping effect in a wide range of cell thicknesses of 0.5–4 μ m. Compared with rms roughness or haze ratio, angular reflection intensity of textured substrates is well correlated with light-trapping effect in μ c-Si:H cells. It is also confirmed that natural surface texturing during μ c-Si:H film growth improves light scattering for flat substrates, but deteriorates the superior light scattering property of the well-designed substrates.

It is expected that independent control of the surface morphology of the front and the back sides yields an additional gain in the NIR response. Optimization of the texture shape will also improve the NIR response, although we have treated a fixed shape in this study. In addition, there remains a room for optimization of the aspect ratio. Needless to say, development of improved reflector materials including low-absorption TCO has been also a big challenge to enhance the light trapping in thin-film Si solar cells.

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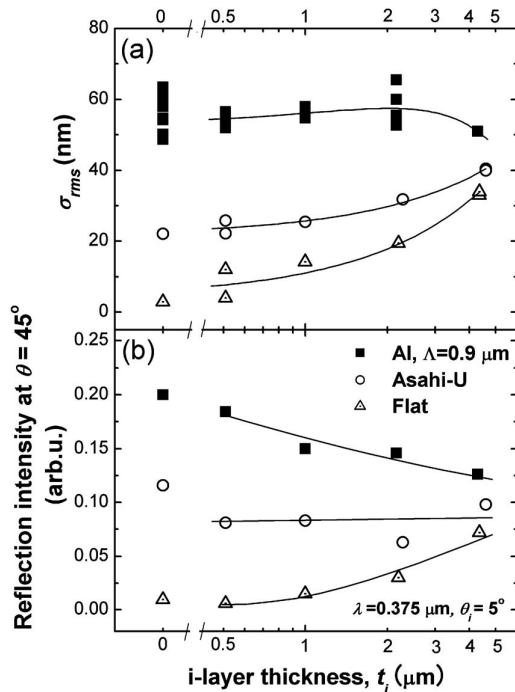


FIG. 14. Thickness dependence of (a) the σ_{rms} and (b) the angular reflection intensities of the n - i - p μ c-Si:H solar cells fabricated on flat, Asahi-U, and patterned Al substrates with $\Lambda=0.9$ μ m as a function of t_i . The angular reflection intensities were determined by the same configuration in Figs. 5 and 8.

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