Characterization of $\mu\text{c-Si:H/a-Si:H}$ tandem solar cell structures by spectroscopic ellipsometry

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Abstract

In order to perform the structural characterization of Si thin-film solar cells having submicron-size rough textured surfaces, we have developed an optical model that can be utilized for the spectroscopic ellipsometry (SE) analysis of a multilayer solar cell structure consisting of hydrogenated amorphous silicon (a-Si:H) and microcrystalline silicon ($\mu\text{c-Si:H}$) layers fabricated on textured $\text{SnO}_2\text{:F}$ substrates. To represent the structural non-uniformity in the textured structure, the optical response has been calculated from two regions with different thicknesses of the Si layers. Moreover, in the optical model, the interface layers are modeled by multilayer structures assuming two-phase composites and the volume fractions of the phases in the layers are controlled by the structural curvature factor. The polarized reflection from the $\mu\text{c-Si:H}$ layer that

shows extensive surface roughening during the growth has also been modeled. In this study, a state-of-the-art solar cell structure with the textured $\mu\text{c-Si:H}$ (2000 nm)/ZnO (100 nm)/a-Si:H (200 nm)/SnO₂:F/glass substrate structure has been characterized. The $\mu\text{c-Si:H/a-Si:H}$ textured structure deduced from our SE analysis shows remarkable agreement with that observed by transmission electron microscopy. From the above results, we have demonstrated the high-precision characterization of highly-textured $\mu\text{c-Si:H/a-Si:H}$ solar cell structures.

Keywords:

spectroscopic ellipsometry, solar cell, a-Si:H, $\mu\text{c-Si:H}$, ZnO, tandem structure

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1. Introduction

In tandem-type Si thin-film solar cells, hydrogenated amorphous silicon (a-Si:H) and microcrystalline silicon ($\mu\text{c-Si:H}$) p-i-n structures are stacked perpendicularly to enhance the performance of the solar cells [1-5]. In the $\mu\text{c-Si:H/a-Si:H}$ tandem solar cells, however, the thickness ratio between the a-Si:H and $\mu\text{c-Si:H}$ i layers (light absorber layers) is quite important, as a total current in the tandem solar cell is limited by a cell that shows a minimum current. Accordingly, to maximize the performance of $\mu\text{c-Si:H/a-Si:H}$ tandem solar cells, the accurate structural characterization of each solar-cell component layer is essential.

Nevertheless, the evaluation of $\mu\text{c-Si:H/a-Si:H}$ solar cell structures has been rather difficult since the submicron-range textured structures have been incorporated into the solar cells to reduce the front light reflection and to enhance the light-trapping properties of the solar cells [2]. In the case of the conventional transmission/reflection measurements, the light scattering by the rough surface textures complicates the data analysis significantly [6].

On the other hand, Rovira et al. has reported that a spectroscopic ellipsometry (SE) technique can be utilized to characterize the submicron-size textured structure of $\text{SnO}_2\text{:F}$ transparent conductive oxide (TCO) layers [7]. In particular, in the normal SE

measurement configuration, only the specular light reflection is measured, whereas the diffused light generated by surface scattering is not detected as the reflection angle of the scattered light is different from that of the specular light. In our previous study [8], we have further established an optical model that allows the complete evaluation of a-Si:H/SnO₂:F textured structures. In this analysis, to express the optical response of the microscopically non-uniform textured structure, we have employed (i) a Bruggeman effective-medium-approximation (EMA) multilayer model developed for the rough surface and interface structures and (ii) an optical model divided into two regions with different layer thicknesses. From the above analysis, we have demonstrated that the textured a-Si:H/SnO₂:F structure deduced by SE almost perfectly matches with the actual structure observed in transmission electron microscopy (TEM) [8].

In this study, our optical model developed for the analysis of the textured solar cell structure has been extended to characterize the state-of-the-art solar cell with textured $\mu\text{c-Si:H/ZnO/a-Si:H/SnO}_2\text{:F/glass}$ substrate structures. In this solar cell, the ZnO intermediate layer is incorporated between $\mu\text{c-Si:H}$ and a-Si:H layers to increase the light absorption in the a-Si:H layers [4]. From the SE analysis of this structure, we have confirmed that our optical model can be utilized to perform the structural analysis in the real solar-cell device configuration and enables us to deduce the layer structure in the

solar cell accurately.

2. Experiment

To develop the SE analysis method for $\mu\text{c-Si:H/ZnO/a-Si:H/SnO}_2\text{:F}$ textured structures, we prepared a-Si:H and $\mu\text{c-Si:H}$ layers on a textured $\text{SnO}_2\text{:F}$ -coated glass substrate (Asahi-U substrate) using plasma-enhanced chemical vapor deposition, whereas a ZnO:Al intermediate layer was deposited by rf magnetron sputtering. Although a-Si:H and $\mu\text{c-Si:H}$ solar cells generally consist of p-i-n structures [1-5], only the a-Si:H and $\mu\text{c-Si:H}$ i layers were deposited in this study to verify the feasibility of the SE analysis for the $\mu\text{c-Si:H/a-Si:H}$ tandem structure.

Fig. 1 shows a scanning electron microscope (SEM) image obtained from the $\mu\text{c-Si:H}$ (~ 2000 nm)/ZnO:Al (~ 100 nm)/a-Si:H (~ 200 nm) structure deposited on the textured $\text{SnO}_2\text{:F}$ substrate (Sample A). The SEM measurement was performed at an acceleration voltage of 5 kV (HITACHI S-4800). Since $\mu\text{c-Si:H}$ has low absorption coefficients, compared with a-Si:H, the thickness of the $\mu\text{c-Si:H}$ layer is significantly thicker than that of the a-Si:H in the cell structure [1]. As shown in Fig. 1, the textured structure has submicron dimensions and is microscopically quite inhomogeneous. It should be noted that the surface morphology becomes quite rough after the $\mu\text{c-Si:H}$ deposition by the

columnar growth of $\mu\text{c-Si:H}$ grains [1,9]. In order to investigate the effect of the ZnO intermediate layer on the SE analysis, we also prepared a $\mu\text{c-Si:H/a-Si:H/SnO}_2\text{:F}$ structure without introducing the ZnO intermediate layer using identical growth conditions (Sample B).

The a-Si:H layers were fabricated using a substrate temperature of 190 °C, a SiH_4 flow rate of 5 sccm, an rf power of 13 mW/cm^2 , and a pressure of 6.7 Pa [10]. For the $\mu\text{c-Si:H}$ deposition, we employed a two-step deposition process. Specifically, a highly-crystallized $\mu\text{c-Si:H}$ seed layer (~ 50 nm) was first deposited on the ZnO layer (or a-Si:H layer) using a high hydrogen dilution ratio of $R=[\text{H}_2]/[\text{SiH}_4]=100$, and then a thick $\mu\text{c-Si:H}$ bulk layer (~ 2 μm) was prepared using $R=50$. The $\mu\text{c-Si:H}$ seed layer corresponds to the highly-crystallized $\mu\text{c-Si:H}$ p layer in actual $\mu\text{c-Si:H/a-Si:H}$ solar cells. The $\mu\text{c-Si:H}$ layers were fabricated using a substrate temperature of 190 °C, a SiH_4 flow rate of 5 sccm, and a pressure of 40 Pa [11]. For the $\mu\text{c-Si:H}$ seed layer ($R=100$), an rf power of 65 mW/cm^2 was used, whereas the $\mu\text{c-Si:H}$ bulk layer was prepared using a very-high-frequency plasma (30 MHz) with a power of 260 mW/cm^2 to obtain a high deposition rate of 2 $\text{\AA/s}$ [11]. The ZnO:Al layer was fabricated at room temperature with a ZnO target (Al_2O_3 : 2 wt.%) using a pressure of 0.6 Pa, an rf power of 50 W, and an Ar flow rate of 9 sccm.

The (ψ , Δ) ellipsometry spectra of the samples were measured using a rotating compensator instrument (J. A. Woollam M-2000). The SE measurements were performed at room temperature using an incident angle of 55° , which corresponds to the Brewster angle of glass substrates. The spot size of the SE light probe was 7 mm. To confirm SE results, transmission electron microscope (TEM) measurements were also performed using an acceleration voltage of 200 kV (JEOL JEM-2100F). The TEM samples were prepared by a focused-ion-beam technique (HITACHI FB-2100).

3. SE analysis

3.1 Optical model for tandem solar cell structures

Fig. 2 shows (a) an optical model constructed for the analysis of the $\mu\text{c-Si:H/ZnO/a-Si:H/SnO}_2\text{:F}$ textured structure and (b) the schematic structure of the Bruggeman EMA multilayer model used to calculate the optical response of the interface regions. For the optical model in Fig. 2(a), we have applied the surface area model in which the light reflection is calculated from multiple optical models with different thicknesses of component layers. In this case, the total amplitude-reflection coefficient of the optical model is obtained simply as the weighted average of the reflection coefficients using surface area fractions. We confirmed previously that the

surface area model applying two different thickness responses is sufficient for the optical modeling of textured a-Si:H/SnO₂:F structures [8]. Thus, the optical model of Fig. 2(a) is also divided into the two regions (Region A and B). In the optical model, the SnO₂ TCO layer is divided into three layers to model the free carrier absorption in the SnO₂ layer accurately [12,13]. For the SnO₂ layers, however, the surface area model is not utilized as the optical reflection from these layers is rather weak.

In the multilayer structure of Fig. 2(a), three interface layers with two-phase composites of $\mu\text{c-Si:H/ZnO:Al}$ (Interface layer 1), ZnO:Al/a-Si:H (Interface layer 2) and $\text{a-Si:H/SnO}_2\text{:F}$ (Interface layer 3) are introduced. For the calculation of the optical response in these regions, the EMA multilayer model shown in Fig. 2(b) is applied. This model assumes a two-phase mixture in a cylindrical geometry with a radius of $r=1$, and the variation of the composite is modeled by $d(r)=d_0(1-r^\alpha)$, where d_0 is the thickness of the interface layers and α is the curvature factor at the cylinder cross-section [8]. From this model, the volume fractions of the two-phase mixture in divided layers (total 10 layers) are calculated. For the interface layer 2, we employed an additional parameter β , which represents the ZnO volume fraction in the top EMA layer [8]. The parameter κ for the $\mu\text{c-Si:H}$ layer in Fig. 2(a) will be explained in the next section.

As confirmed from Fig. 1, on the other hand, the $\mu\text{c-Si:H}$ layer shows extensive

surface roughening. Thus, the optical modeling for the $\mu\text{c-Si:H}$ surface region is quite important [11]. In this study, we have also developed the optical layers that can reproduce the polarized light reflection on rough $\mu\text{c-Si:H}$ layers.

3.2 Dielectric functions of Si:H and TCO layers

For the SE analysis of the $\mu\text{c-Si:H}$ layer, we have applied a $\mu\text{c-Si:H}$ optical database established in our previous study [11]. In this database, the dielectric function of $\mu\text{c-Si:H}$ in the visible/ultraviolet region is parameterized completely using only one parameter, the $\mu\text{c-Si:H}$ structural factor κ . This κ value is defined based on the amplitude of the optical transition in the crystalline Si (c-Si) component at a photon energy of $E=4.3$ eV and a variety of Si microstructures from a complete a-Si:H phase ($\kappa=0$) to highly crystallized $\mu\text{c-Si:H}$ ($\kappa=1$) can be expressed by the value of κ . In this study, we have also characterized the microstructure of the $\mu\text{c-Si:H}$ bulk layer from the κ value deduced by the SE analysis.

For the a-Si:H layer, on the other hand, we employed the a-Si:H dielectric function extracted from an a-Si:H layer deposited on a flat c-Si substrate covered with native oxide. To determine the dielectric function of this a-Si:H layer, the global error minimization scheme [14] has been applied and the a-Si:H dielectric function obtained

from this analysis was further parameterized by applying the Tauc-Lorentz (TL) model

[15]. In this TL model, ε_2 spectra are calculated by

$$\varepsilon_2(E) = \frac{A_{TL} C E_0 (E - E_g)^2}{(E^2 - E_0^2)^2 + C^2 E^2} \frac{1}{E} \quad (E > E_g), \quad (1)$$

$$= 0 \quad (E \leq E_g), \quad (2)$$

where A_{TL} , C , E_0 , and E_g represent the amplitude parameter, broadening parameter, peak transition energy, and Tauc optical gap. The $\varepsilon_1(E)$ of the TL model has been obtained using the Kramers-Kronig relations by incorporating an additional parameter $\varepsilon_1(\infty)$ that shows the energy-independent contribution to ε_1 at high energies. For the a-Si:H layer in this study, the five independent parameters of the TL model are $A_{TL}=212.77$ eV, $C=2.32$ eV, $E_0=3.635$ eV, $E_g=1.668$ eV, and $\varepsilon_1(\infty)=0.2$.

The dielectric functions of the TCO layers ($\text{SnO}_2:\text{F}$ and $\text{ZnO}:\text{Al}$) have been modeled by combining the TL model with the Drude model, as reported previously [7,16]. In this TCO modeling, the TL model is applied to express the interband transition, while the Drude model is used to show the free carrier absorption in the TCO layers. Although the TL model has been developed for the dielectric function modeling of amorphous materials, the TL model is also suitable to express the TCO light absorption near the band-edge region, where the optical transition due to the tail state also occurs. When compared with a more conventional Lorentz model, the TL model provides better fitting

to the TCO dielectric functions, as the Lorentzian peak shows tail absorption in a rather wide energy range.

Since the Drude model is expressed by using amplitude (A_D) and broadening (Γ) parameters, each TCO dielectric function is parameterized by a total of seven parameters $\{A_{TL}, C, E_0, E_g, \epsilon_1(\infty), A_D, \Gamma\}$. In the analysis of three SnO_2 layers shown in Fig. 2(a), parameter values similar to those reported previously [12] were employed. We determined these parameter values by characterizing the textured SnO_2 :F substrate prior to the a-Si:H deposition. In the case of the ZnO:Al, the dielectric function was estimated from a ZnO:Al layer deposited on a flat glass substrate, and the optical parameters obtained from the analysis are $A_{TL}=107.75$ eV, $C=12$ eV, $E_0=7$ eV, $E_g=2.749$ eV, $\epsilon_1(\infty)=1.0$, $A_D=0.13$ eV, and $\Gamma=0.19$ eV.

The optical constants of the glass substrates were modeled by the modified Cauchy model ($n=A+B/\lambda^2+C/\lambda^4-D\lambda^2$) with $A=1.498$, $B=2844$ nm², $C=1.181\times 10^8$ nm⁴, and $D=4.937\times 10^{-9}$ nm⁻². In this model, the term $-D\lambda^2$ is added to express the rapid reduction of the refractive index n below 1.0 eV [17]. In the SE analysis of Fig. 2(a), therefore, only the $\mu\text{c-Si:H}$ dielectric function was varied to determine the value of κ , whereas we employed the fixed dielectric functions for the a-Si:H layer, the SnO_2 layers, the ZnO layer and the glass substrate.

4. Results and discussion

4.1 Optical model for $\mu\text{c-Si:H}$ surface

In order to establish the SE analysis method for $\mu\text{c-Si:H/ZnO/a-Si:H/SnO}_2\text{:F}$ textured structures, we have performed the fitting analysis of ellipsometry (ψ , Δ) spectra using optical models having different surface roughness layers. Fig. 3 shows the ψ spectrum obtained experimentally from Sample A (open circles) and fitting results (solid lines) when the number of surface roughness layers is (a) one, (b) two, and (c) three. The corresponding optical models are shown in the inset of Fig. 3. The two small peaks that appear in the ψ spectrum show the optical transitions of E_1 (3.4 eV) and E_2 (4.3 eV) [18] and, in our analysis, the κ value of the $\mu\text{c-Si:H}$ is determined from the analysis in this region [11]. It should be noted that, in a high energy region ($E > 2.5$ eV), the (ψ , Δ) spectra are determined by the near-surface optical response, because the penetration depth of light is small due to the high absorption coefficients of the $\mu\text{c-Si:H}$ in this region. In Fig. 3, therefore, to optimize the surface roughness model, only the high energy region is analyzed assuming the infinite thickness of the $\mu\text{c-Si:H}$.

The surface roughness layers were modeled by incorporating voids into the $\mu\text{c-Si:H}$ layer. To express the surface oxidation of $\mu\text{c-Si:H}$ layers, the SiO_2 component is also included [19,20]. However, the SiO_2 contribution is neglected in the second and third

roughness layers to reduce the number of free parameters in the SE analysis. The optical constants of each roughness layer are calculated simply from the volume fractions of voids (f_{void}), SiO_2 (f_{SiO_2}) and $\mu\text{c-Si:H}$ ($f_{\text{Si}}=1-f_{\text{void}}-f_{\text{SiO}_2}$) using the Bruggeman EMA.

In Fig. 3(a), the large deviation can be seen between the experimental and calculated spectra, indicating that the surface roughness layer cannot be represented by a single layer with uniform optical constants. When the number of the surface roughness layers increases, the fitting improves drastically. This shows clearly that the rough textured surface of the $\mu\text{c-Si:H}$ layer can be modeled by simply increasing the number of the roughness layers having different f_{void} . From the analysis of Fig. 3(c), we obtained a κ value of 0.60 ± 0.02 . This κ value shows reasonable agreement with the value reported previously [11], indicating that the $\mu\text{c-Si:H}$ microstructure can be deduced accurately from the SE analysis.

4.2 SE analysis of solar cell structures

Fig. 4 shows the SE spectra obtained from the measurement of Sample A (open circles) and the fitting result (solid lines) using the optical model shown in Fig. 2(a). For the roughness layer in Fig. 2(a), we have applied the model consisting of the three layers shown in Fig. 3(c) and used the same roughness parameters for Region A and B

to reduce the number of free parameters. In this analysis, we assumed $d_{i2A}=d_{i2B}$ and $A=B=0.5$, where A and B show the surface area fractions of the two regions in Fig. 2(a). In addition, fixed values of $d_t=141$ nm and $d_{F2}=408$ nm, estimated in advance from the characterization of the textured SnO₂:F sample, were used for the analysis. As a result, the total number of analytical parameters in Fig. 2(a) becomes 21. The fitting analyses were also performed using a fitting error function [11] in which the fitting error at lower energies is suppressed, since the number of the data points in the (ψ, Δ) spectra increases in a low energy region and the fitting error in this region is weighted heavily if no correction is made. This is particularly important to determine κ values accurately using the high-energy spectral region [11]. As confirmed from Fig. 4, the (ψ, Δ) spectra calculated from our model show good agreement with the experimental spectra.

Fig. 5 shows the SE characterization result obtained from Sample B that incorporates no ZnO intermediate layer. In this SE analysis, the contribution of the ZnO intermediate layer was removed from the optical model in Fig. 2(a) and the $\mu\text{c-Si:H/a-Si:H}$ interface layer was provided between the a-Si:H and $\mu\text{c-Si:H}$ bulk layers. For this interface layer, three analytical parameters (d_{i2A} , α_{i2} , β_{i2}) have been used. Other than this interface layer, the analysis procedure is identical to that of Sample A. As confirmed from Fig. 5, good fitting to the experimental spectra can also be seen for Sample B.

Table 1 summarizes the parameter values extracted from the fitting analyses of Sample A and B. The number of the subscript for d_s and f_{void} in Table 1 corresponds to the layer number shown in Fig. 3(c). We find that the layer thicknesses obtained from Region A and B of the surface area model are rather similar. In the case of Sample B, however, the 90 % confidence limits for the structural parameters of the $\mu\text{c-Si:H/a-Si:H}$ interface layer ($d_{i2A}=d_{i2B}$) and a-Si:H bulk layers (d_{aA} , d_{aB}) become quite large. These results indicate that the measurement accuracy degrades seriously when there is no ZnO layer between the $\mu\text{c-Si:H}$ and a-Si:H layers. This is essentially caused by the similarity between the optical constants of $\mu\text{c-Si:H}$ and a-Si:H layers [11]. At $E=1.0$ eV, for example, n of $\mu\text{c-Si:H}$ is 3.47 and is quite similar to that of a-Si:H ($n=3.59$). In addition, the a-Si:H layer is located in a deep position from the surface and the characterization of the a-Si:H layer having the similar optical properties with $\mu\text{c-Si:H}$ becomes difficult. In contrast, when the ZnO intermediate layer is inserted (Sample A), the high-precision characterization of the a-Si:H layer becomes possible since the optical constants of the ZnO layer ($n=1.88$ at 1.0 eV) are quite different from those of the $\mu\text{c-Si:H}$ and a-Si:H layers and these layers can be distinguished quite easily from the interference effect in the $\mu\text{c-Si:H/ZnO/a-Si:H}$ multilayer. Accordingly, for the characterization of textured $\mu\text{c-Si:H/a-Si:H}$ solar cells, the introduction of a ZnO intermediate layer is more

preferable.

In order to confirm the SE result shown in Fig. 4, the same sample (Sample A) was characterized further using TEM. Fig. 6 shows (a) the cross-sectional TEM image of Sample A and (b) the enlarged image of (a). The white and black lines in Fig. 6 represent the thicknesses of each layer as estimated from the SE analysis of Fig. 4 and they correspond to the average thicknesses of Region A and B in Table 1. It can be seen from Fig. 6 that the structure estimated from SE shows excellent agreement with that of TEM. The layer thicknesses estimated from the SE analysis in Fig. 4 and the TEM image in Fig. 6 are compared in Table 2 and these values indicate good agreement. The above results show clearly that the $\mu\text{c-Si:H/ZnO/a-Si:H/SnO}_2\text{:F}$ textured structure is expressed almost perfectly by combining the surface area model with the EMA multilayer model and the roughness model shown in Fig. 3(c), and our analysis allows the quantitative and high-precision characterization of the textured structure.

In our SE analysis, the calculation of the (ψ, Δ) spectra has been performed using conventional Fresnel equations and the effect of light scattering on textured surfaces has been neglected completely. The quite good agreement between the experimental and calculated spectra in Figs. 4 and 5 confirms that the contribution of the light scattering is indeed negligible in a conventional measurement configuration that uses no focusing

optics. The complicated layered structure deduced from SE shows excellent agreement with that observed in TEM, which provides further support for the validity of our analysis. Nevertheless, when the texture size is larger than a few micrometers, the specular light reflection reduces drastically and the measurement of the ellipsometry spectra itself becomes difficult, although this effect depends totally on the amplitude of the roughness modulation. For pyramid-shaped c-Si textures (size $\sim 10\text{ }\mu\text{m}$), which have been employed commonly in c-Si solar cells, conventional ellipsometry measurements cannot be performed due to significant light scattering [21]. In the case of c-Si textures fabricated by wet chemical etching of the single crystals, accurate ellipsometry measurements are still possible by using a tilt angle measurement configuration, in which textured c-Si samples are tilted so that the specular light reflection on the texture facets is measured [21-23]. For the precise calculation of the light reflection on textured surfaces, on the other hand, other approaches including rigorous coupled-wave analysis (RCWA) could be used [24]. In the case of RCWA, however, detailed geometrical parameters are required for all the interfaces in a multilayered structure. Accordingly, our analysis method is suitable particularly for the characterization of multilayer structures with random textured interfaces.

5. Conclusion

We have established a SE analysis method that can be employed for the high-precision structural characterization of $\mu\text{c-Si:H/ZnO:Al/a-Si:H/SnO}_2\text{:F}$ textured structures. To express the microscopic structural inhomogeneity of the $\mu\text{c-Si:H/ZnO:Al/a-Si:H/SnO}_2\text{:F}$ texture, we used a surface area model in which the total amplitude reflection coefficient is calculated from the surface area fractions of optical models with different thicknesses. Moreover, in order to model rough surfaces of $\mu\text{c-Si:H}$ layers, we have developed a model with three optical layers. The optical response in the interface regions was further modeled using a Bruggeman EMA multilayer model. By applying the developed optical model, the ellipsometry spectra obtained from the $\mu\text{c-Si:H/ZnO:Al/a-Si:H/SnO}_2\text{:F}$ textured structure are reproduced quite well, and the structure determined by TEM shows excellent agreement with that deduced from the SE analysis, supporting the validity of our analysis. Finally, we note that the SE technique provides a promising way of determining the detailed layered structures in large-area $\mu\text{c-Si:H/ZnO:Al/a-Si:H}$ solar cell modules.

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Figure Captions

Fig. 1. SEM image of the $\mu\text{c-Si:H/ZnO:Al/a-Si:H}$ structure deposited on a textured $\text{SnO}_2\text{:F}$ (Asahi-U) substrate.

Fig. 2. (a) Optical model used for the SE analysis of the $\mu\text{c-Si:H/ZnO:Al/a-Si:H/SnO}_2\text{:F}$ textured structure and (b) Bruggeman EMA multilayer model used for the calculation of the interface layers.

Fig. 3. ψ spectrum obtained experimentally from Sample A (open circles) and fitting results (solid lines) when the number of surface roughness layers is (a) one, (b) two, and (c) three.

Fig. 4. (ψ, Δ) spectra obtained from the $\mu\text{c-Si:H}$ ($\sim 2\ \mu\text{m}$)/ ZnO:Al ($\sim 100\ \text{nm}$)/ a-Si:H ($\sim 200\ \text{nm}$)/ $\text{SnO}_2\text{:F}$ textured structure (open circles) and the fitting result (solid lines) using the optical model in Fig. 2(a).

Fig. 5. (ψ, Δ) spectra obtained from the $\mu\text{c-Si:H}$ ($\sim 2\ \mu\text{m}$)/ a-Si:H ($\sim 200\ \text{nm}$)/ $\text{SnO}_2\text{:F}$ textured structure without the ZnO intermediate layer (open circles) and the fitting result

(solid lines).

Fig. 6. (a) Cross-sectional TEM image of the $\mu\text{c-Si:H/ZnO:Al/a-Si:H/SnO}_2\text{:F/glass}$ substrate structure and (b) enlarged image of (a). The white and black lines in this figure represent the thicknesses of each layer as estimated from the SE analysis of Fig. 4 and they correspond to the average thicknesses of Region A and B in Table 1.

Table 1

Structural parameters extracted from the SE analyses of the textured structures of $\mu\text{c-Si:H/ZnO:Al/a-Si:H/SnO}_2\text{:F}$ (Sample A) and $\mu\text{c-Si:H/a-Si:H/SnO}_2\text{:F}$ (Sample B). In the SE analyses, fixed values of d_t and d_{F2} were employed.

Parameter	Sample A	Sample B
d_{s1} (nm)	14 $\pm$ 1	14 $\pm$ 1
f_{SiO_2}	0.46 $\pm$ 0.02	0.38 $\pm$ 0.02
f_{void1}	0.08 $\pm$ 0.01	0.13 $\pm$ 0.01
d_{s2} (nm)	27 $\pm$ 1	27 $\pm$ 1
f_{void2}	0.21 $\pm$ 0.01	0.21 $\pm$ 0.01
d_{s3} (nm)	32 $\pm$ 1	32 $\pm$ 1
f_{void3}	0.06 $\pm$ 0.01	0.06 $\pm$ 0.01
$d_{\mu\text{cA}}$ (nm)	1995 $\pm$ 20	2000 $\pm$ 42
$d_{\mu\text{cB}}$ (nm)	1966 $\pm$ 12	1961 $\pm$ 38
κ	0.60 $\pm$ 0.02	0.41 $\pm$ 0.04
d_{i1A} (nm)	151 $\pm$ 11	—
d_{i1B} (nm)	143 $\pm$ 10	—
α_{i1}	1.9 $\pm$ 0.4	—
d_{i2A} (nm)	184 $\pm$ 16	142 $\pm$ 249
α_{i2}	2.1 $\pm$ 0.7	4.9 $\pm$ 53.5
β_{i2}	0.59 $\pm$ 0.11	0.32 $\pm$ 1.78
d_{aA} (nm)	63 $\pm$ 11	63 $\pm$ 260
d_{aB} (nm)	50 $\pm$ 12	58 $\pm$ 261
d_{i3} (nm)	153 $\pm$ 8	149 $\pm$ 4
α_{i3}	3.4 $\pm$ 0.2	3.5 $\pm$ 0.2
d_{F1} (nm)	187 $\pm$ 14	198 $\pm$ 8
d_{F2} (nm)	408 (fixed)	386 (fixed)
d_t (nm)	141 (fixed)	142 (fixed)

Table 2

Layer thicknesses in the $\mu\text{c-Si:H/ZnO:Al/a-Si:H/SnO}_2\text{:F}$ structure (Sample A) obtained from the SE and TEM analyses. For the SE results, the average values of the two layer thicknesses of Region A and B [Fig. 2(a)] in Table 1 are indicated.

Parameter	SE	TEM
d_s (nm)	73 ± 3^a	100 ± 44
$d_{\mu\text{c}}$ (nm)	1981 ± 61	1913 ± 91
d_{i1} (nm)	147 ± 29	123 ± 45
d_{i2} (nm)	184 ± 16	125 ± 48
d_a (nm)	57 ± 36	103 ± 48
d_{i3} (nm)	153 ± 8	129 ± 54
d_{SnO_2} (nm)	736 ± 14^b	783 ± 22

^a $d_s = d_{s1} + d_{s2} + d_{s3}$, ^b $d_{\text{SnO}_2} = d_{F1} + d_{F2} + d_t$

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6