11.0%-Efficient Thin-Film Microcrystalline Silicon Solar Cells With Honeycomb Textured Substrates

Hitoshi Sai, Takuya Matsui, Koji Matsubara, Michio Kondo, and Isao Yoshida

***Abstract*—In this paper, we present our latest results toward high-efficiency thin-film silicon solar cells. Owing to the superior light trapping capability of periodic textures combined with other technologies, a new world record was achieved for the efficiency of single-junction microcrystalline silicon solar cells, with a conversion efficiency of 11.0%, independently confirmed by the Advanced Industrial Science and Technology (AIST) Characterization, Standards, and Measurement (CSM) team.**

***Index Terms*—Light trapping, periodic structures, photovoltaic cells, silicon, thin-film devices.**

I. Introduction

THIN-FILM silicon solar cells (TFSSC) are promising candidates for future large-area photovoltaic systems operating in the gigawatt scale because of the abundance and nontoxicity of the source materials [1], [2]. Their superior temperature coefficient and blue response are also suitable for warm low-altitude regions with considerable sunlight. To date, an initial efficiency [3] of 16.3% and a stabilized efficiency [4] of 13.4% have been realized in triple-junction TFSSCs using hydrogenated amorphous silicon (a-Si:H), amorphous silicon germanium (a-SiGe:H), and microcrystalline silicon (μc-Si:H) materials with bandgap energies of 1.1–1.8 eV. All of these materials can be grown by plasma-enhanced chemical vapor deposition (PECVD) over a large substrate size. However, a further conversion efficiency improvement is crucial to increase the cost-effectiveness of the TFSSCs.

It is well known that light trapping technology is crucial to absorb photons in thin-Si films to compensate for such films' insufficient carrier transport properties and relatively high film deposition cost. In this study, we focus on μc-Si:H with a bandgap energy of 1.1 eV, which is mainly used in the middle or bottom cells of multijunction TFSSCs. In most cases, the μc-Si:H bottom cell limits the total photocurrent in the devices because its absorption coefficients are rather small in the near-infrared region owing to the nature of the indirect bandgap. Thus, better light trapping is essential in μc-Si:H cells. For this purpose, textured substrates have been developed to scatter the incident light and increase the optical path length inside the cells [5]–[10]. However, it is well known that the use of excessively steep textures with V-shaped valleys often induces defective porous areas during the μc-Si:H growth, resulting in a poor photovoltaic performance [11], [12]. That is, a tradeoff occurs between the absorption enhancement by the textures and the quality of the μc-Si:H films grown on them.

Keeping this in mind, our group developed periodically textured substrates with hexagonal dimple arrays (hereafter, "honeycomb texture") and applied them to μc-Si:H cells with the substrate configuration in order to mitigate the tradeoff as much as possible [13]–[15]. Because of their simplicity and uniformity in texture morphology, periodic structures have the advantage of far clearer correlations between texture structures and the photovoltaic performance in solar cells. In addition, periodic textures have the potential to overcome the limitations of the optical path enhancement with randomly textured substrates [16]–[19]. Furthermore, the periodicity allows for the use of periodic boundary conditions in optical calculations, which reduces the calculation cost substantially. By choosing a proper period and an aspect ratio of honeycomb textures with respect to the cell thickness, a certified efficiency of 10.5% was attained in a single-junction μc-Si:H cell with a thickness of 1.8 μm [15], demonstrating the effectiveness of our approach. In addition, a high short-circuit current density (J_{SC}) of 30.8 mA/cm^2 was realized in a 3-μm-thick μc-Si:H cell [15]. However, despite the superior J_{SC}, the efficiency did not reach the world-record efficiency of 10.7% that was reported by Hänni *et al.* [10], owing to the limited open-circuit voltage (V_{OC}) and fill factor (FF).

In this paper, we report our latest results toward high-efficiency μc-Si:H cells with honeycomb textures, mainly focusing on improving the V_{OC} and FF.

II. Experimental Details

Honeycomb textures were fabricated on a Si wafer by the wet chemical etching of a thermally grown SiO_2 film through a resist mask with a honeycomb pattern. In this experiment, the honeycomb pattern was formed by photolithography. The Si wafer itself was used simply as a supporting substrate, as our photolithography equipment was designed for the use of Si wafers. Therefore, in principle, the Si wafer can be replaced with other materials, such as glass. Other pattering techniques

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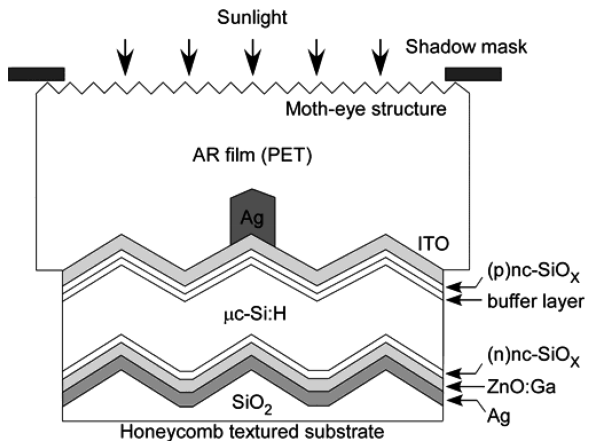

Fig. 1. Schematic illustration of the μc-Si:H cell fabricated in this study.

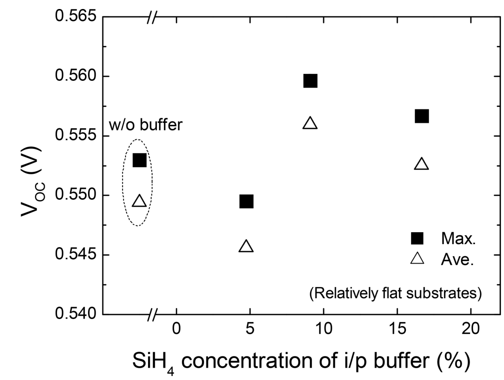

Fig. 2. Relationship between the SiH_4 concentration of i/p buffer layers and V_{OC} in μc-Si:H cells. The cell thickness is fixed at 1 μm.

such as nanoimprinting are also applicable for low-cost and large-area applications [20]–[22]. The textured SiO_2 layer was then coated with a Ag/ZnO:Ga stacked film (200 nm $\times$100 nm) using sputtering to obtain a highly reflective and conductive surface. Details of the fabrication procedure are reported elsewhere [13]. In this paper, we fabricated honeycomb substrates with periods of P = 1.5–2.5 μm and aspect ratios of H/P = 0.1–0.25, where H denotes the peak height of the texture. A commercially available textured SnO_2:F glass substrate and a flat glass substrate were also used with the same Ag/ZnO:Ga film stack as reference substrates.

Substrate-type n-i-p μc-Si:H cells with an active area of 1 cm^2 were fabricated on these substrates. The structure of the μc-Si:H cell fabricated in this study is schematically illustrated in Fig. 1. The bulk μc-Si:H layer, buffer layer, and doped nanocrystalline silicon oxide (nc-SiO_X:H) layer were deposited using a conventional multichamber PECVD tool. Further, an In_2O_3:Sn (ITO) front transparent electrode layer and a Ag finger-grid electrode were deposited using magnetron sputtering at room temperature through shadow masks. Finally, the cell was isolated using reactive ion etching and annealed at 175 °C. The completed solar cell comprises a honeycomb-textured substrate/Ag/ZnO:Ga/(n)nc-SiO_X:H/(i) μc-Si:H /buffer/(p)nc-SiO_X:H /ITO (70 nm)/Ag grid. For some samples, a commercially available antireflection (AR) film (InnoX Co., Ltd.) with a moth-eye structure comprising a UV-curable polymer, a polyethylene telephthalate substrate, and an acrylic adhesive film was applied to minimize the reflection loss at the front surface.

The performance of the cells was evaluated by measuring the current–voltage (*J*–*V*) characteristics using a dual-light solar simulator under AM 1.5 G 100 mW/cm^2 and external quantum efficiency (EQE) spectra. A black shadow mask with a square aperture was used to determine the illumination area (a designated area of $\sim$1.0 cm^2) in the measurements. The *J*–*V* properties of the μc-Si:H cell that exhibited the highest efficiency in this study were independently confirmed by the characterization, standards, and measurement (CSM) Team of the Research Center for Photovoltaic Technologies, National Institute of Advanced Industrial Science and Technology, Japan.

III. Results and Discussion

A. i/p Buffer Layers

The insertion of a buffer layer at the p/i interface improves the open-circuit voltage (V_{OC}) in μc-Si:H cells. In Fig. 2, the V_{OC} is plotted as a function of the SiH_4 concentration (SC) used for the buffer-layer deposition. In this experiment, 8 μc-Si:H cells were fabricated for each buffer layer; the best and the average V_{OC} are plotted in the figure. Relatively flat honeycomb textures with an aspect ratio of $\sim$0.1 were used as substrates to minimize the experimental variations that could be caused by texture-induced defects and insufficient film coverage. The thicknesses of the buffer layer and μc-Si:H layer were fixed at 10 nm and 1 μm, respectively. The maximum V_{OC} was obtained at SC $\sim$10% ($SiH_4 : H_2 = 1:10$), and the use of improper buffer layers resulted in a reduction in the V_{OC}. An increase in the buffer-layer thickness does not yield an improvement in the V_{OC} (not shown). The best V_{OC} of 0.562 V was obtained using the optimized buffer layer. The V_{OC} was improved to 0.570 V by adopting a thinner μc-Si:H layer ($\sim$0.6 μm). The optimal SC obtained here is roughly four times higher than that for the deposition of the bulk μc-Si:H layer ($\sim$2.7%), indicating that it contains a greater amorphous component. It is well known that a-Si:H can passivate the surface of crystalline Si wafers very well [23]. We expect that a similar mechanism occurs in our devices and that the recombination at the p/i interface is reduced. The effectiveness of a buffer layer at the p/i interface for improving the V_{OC} was also reported by van den Donker *et al*. [24].

Next, we apply the optimized i/p buffer layer to the μc-Si:H cells on an optimized honeycomb texture. The honeycomb texture has P = 1.5 μm and H/P = 0.2, which is a typical ideal combination for 1-μm-thick μc-Si:H cells [13]. Fig. 3(a)–(d) shows the impact of the textures and the buffer layer on the photovoltaic parameters: V_{OC}, J_{SC}, FF, and conversion efficiencies. As shown in Fig. 3(a), the V_{OC} is improved in comparison with the reference voltage by using the honeycomb texture. This can

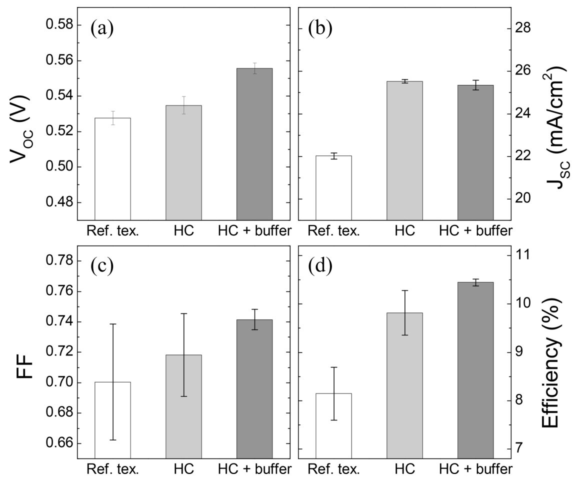

Fig. 3. Impact of the substrate morphology and buffer layer in μc-Si:H solar cells with a thickness of 1 μm. J_{SC} and efficiencies were characterized using an active area of 1.06 cm^2. Here, "Ref. tex." and "HC" denote "reference texture using a commercial textured SnO_2:F film" and "honeycomb textured substrate," respectively.

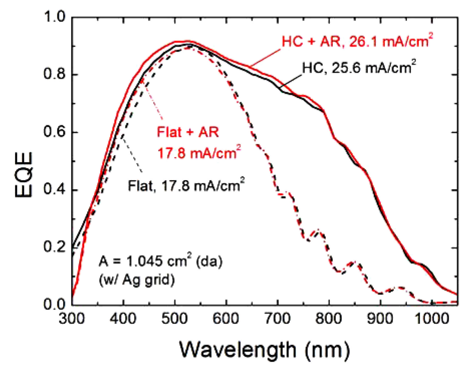

Fig. 4. EQE spectra of μc-Si:H cells deposited on a flat substrate and a honeycomb-textured substrate (HC) with and without an AR film. The numbers in the graph indicate the corresponding J_{SC}.

be attributed to the smooth morphology of the honeycomb texture, which allows the growth of higher quality μc-Si:H films. The V_{OC} is further increased by the application of the buffer layer, as shown in Fig. 2. On the other hand, Fig. 3(b) shows that the J_{SC} is substantially enhanced by using the honeycomb texture, while the buffer layer does not exhibit a negative impact on it, suggesting that the photocarriers generated in the buffer layer can contribute to the photocurrent. The FF exhibits a trend similar to that of the V_{OC}, as shown in Fig. 3(c). The highest efficiencies, ~10.5%, are reproducibly obtained when both the honeycomb texture and the i/p buffer layer are implemented.

B. Antireflection Film

In our μc-Si:H cell design, an ITO antireflection (AR) coating is used to improve the light in-coupling at the front interface. The AR effect can be improved by utilizing a multilayer AR coating with several dielectric materials. However, in our case, such an approach is rather difficult because of the requirement for the sheet resistivity of the ITO layer. Therefore, we apply an AR moth-eye film to improve the light in-coupling. The EQE spectra of the μc-Si:H cells with flat and honeycomb-textured substrates are shown in Fig. 4. In the case of the flat substrate, the AR film slightly enhanced the EQE in the range of 350–500 nm, but no clear gain was obtained at long wavelengths. This is because the incident light is not scattered in the flat cells and the light reflected at the back reflector is easily reemitted from the surface. Consequently, the J_{SC} remains almost constant. In the case of the honeycomb cell, however, the AR film can improve the EQE even at long wavelengths, as shown in Fig. 4. This indicates that the improved light in-coupling due to the AR film can contribute to an EQE gain when a proper light-trapping texture such as the honeycomb texture is introduced in the cell. Accordingly, the J_{SC} is enhanced from 25.6 to 26.1 mA/cm^2. The benefit of the AR film is more pronounced as the cell thickness is increased (not shown). Note that the reduction in the EQE at wavelengths below 330 nm was caused by the absorption loss in the UV-curable polymer used in the AR film.

C. High-Efficiency Cell

We succeeded in enhancing the efficiency of the μc-Si:H cell from 10.5% to 11.0% by using the aforementioned technologies to optimize the cell thickness, crystalline volume fraction in μc-Si:H layer, and honeycomb texture. To date, this is the world-record certified highest efficiency for single-junction μc-Si:H cells [25]. The photovoltaic parameters and the *J–V* curve of the new record cell, which were independently confirmed by the AIST CSM team, are shown in Table I and Fig. 5, respectively. As indicated in Table I, the V_{OC} and FF are improved substantially and are very close to the previous world-record cell developed by Hänni *et al.* [10]. On the other hand, the J_{SC} remains at a high level because of the honeycomb texture and the AR film. However, it is slightly lower than that of our previous cell owing to the thinner absorber layer, lower crystalline volume fraction, and standard ITO front contact. A cross-sectional transmission electron microscope (TEM) image of the record cell is shown in Fig. 6. The thickness and the texture period are 1.7 and 2 μm, respectively. The parasitic absorption loss in the ITO layer can be mitigated by utilizing a highly transparent In_2O_3:H (IOH) layer [26], as was used in our previous cell. No intentional buffer layer has been applied at the n/i interface. Thus, there remains a considerable potential for boosting the efficiency of μc-Si:H cells.

IV. Conclusion

A new record efficiency for thin-film μc-Si single-junction solar cells with a conversion efficiency of 11.0% was obtained and independently confirmed by the AIST CSM team. The key technology in this cell is the carefully designed honeycomb texture that enables us to grow high-quality μc-Si:H layers with a superior light-scattering capability, but several additional technologies further enhance the efficiency. Nevertheless, there remains substantial room for improvement, e.g., improving the

TABLE I
J-V PROPERTIES OF μC-SI:H SOLAR CELLS FABRICATED IN THIS STUDY

ID	Area (cm^2)	Texture period (μm)	Thickness (μm)	V_{OC} (V)	J_{SC} (mA/cm^2)	FF	Eff. (%)	Remarks
1227R3	0.997 (da)	2.5	1.8	0.521	28.17	0.716	10.5	w/ IOH [15]
1551R3	1.045 (da)	2.0	1.7	0.542	27.44	0.738	11.0	w/ AR film

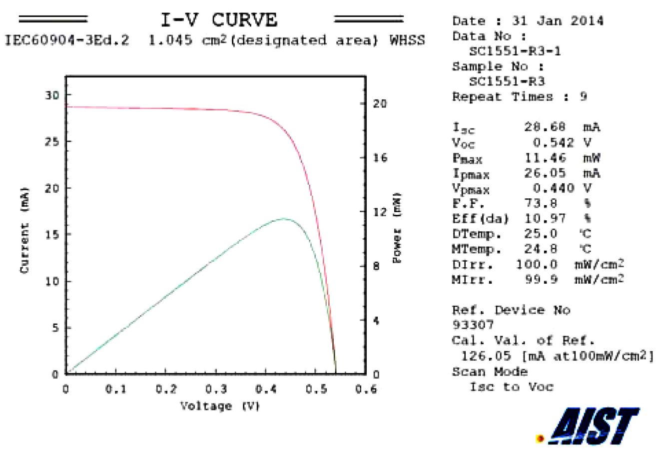

Fig. 5. *J–V* curve of the record μc-Si:H cell measured by AIST CSM team.

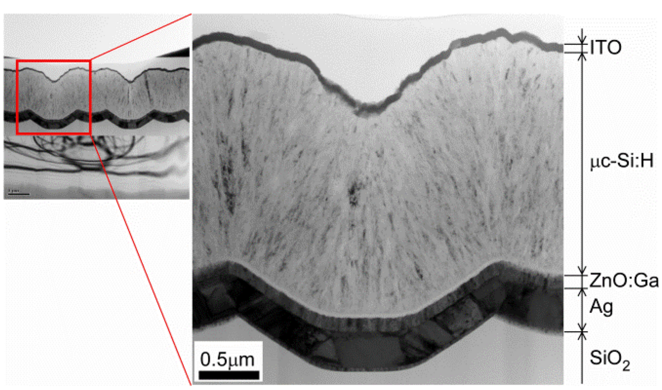

Fig. 6. Cross-sectional TEM image of the record μc-Si:H cell deposited on a honeycomb textured substrate.

transparency of the front contacts, controlling the n/i interfaces, and modifying the shape of the honeycomb textures to improve the light-trapping effect. An improvement in the V_{OC} should be possible, as a notably high V_{OC} of 0.607 V has already been demonstrated [10]. Considering that a $J_{SC} > 30$ mA/cm^2 was also demonstrated separately [15], μc-Si:H cells with efficiencies >12% are feasible in the near future.

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