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A high efficiency thin film silicon solar cell and module

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Abstract

A photoelectric conversion efficiency of over 10% has been achieved in thin-film microcrystalline silicon solar cells which consist of a 2 μm thick layer of polycrystalline silicon. It was found that an adequate current can be extracted even from a thin film due to the very effective light trapping effect of silicon with a low absorption coefficient. As a result, this technology may eventually lead to the development of low-cost solar cells. Also, an initial aperture efficiency as high as 13.5% has been achieved with a large area (91 cm $\times$ 45 cm) tandem solar cell module of microcrystalline silicon and amorphous silicon (thin film Si hybrid solar cell). An even greater initial efficiency of 14.7% has been achieved in devices with a small size (area of 1 cm²), and further increases of efficiency can be expected.

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Keywords: Solar cell; Amorphous silicon; Microcrystalline silicon; Light trapping; Plasma chemical vapor; Deposition

1. Thin-film crystalline (microcrystalline) silicon solar cells

The use of thin-film silicon for solar cells is one of the most promising approaches to realize both high performance and low cost due to its low material cost and ease of manufacturing. Part of the motivation behind these studies comes from the theoretical finding that if these devices can be constructed so that they trap sufficient

light, it should ideally be possible to achieve photoelectric conversion efficiencies in excess of 20%, even with solar cells in which the photoelectric layer is just a few μm thick (Spitzer et al., 1980).

Attention has recently been focused on thin-film solar cells made with crystalline silicon having a small grain size formed by plasma CVD using inexpensive substrate materials such as glass (Meier et al., 1994, 1996; Yamamoto et al., 1994, 1998, 1999; Yamamoto, 1999) and by using low temperatures regardless of the type of substrate instead of these high-temperature processes.

Fig. 1 shows the relationship between grain size and V_{oc} (open circuit voltage) as summarized by Werner of

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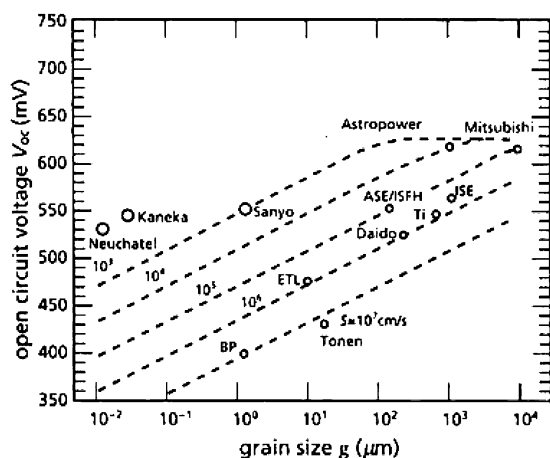


Fig. 1. The relationship between grain size and open circuit voltage (V_{oc}) in solar cells. V_{oc} is correlated to the carrier lifetime (diffusion length). In the figure, S indicates the recombination velocity at the grain boundaries. In this paper, microcrystalline silicon cells correspond to a grain size of $0.1\ \mu\text{m}$ or less. In the figure, Ti, BP, ASE and ISE are abbreviations of the research facilities from which the associated data came.

Stuttgart University (Werner and Bergmann, 1999). Here, V_{oc} can be regarded as a parameter reflecting the cell characteristics and crystalline properties. As the figure shows, superior characteristics are obtained with a grain size of $100\ \mu\text{m}$, but the characteristics are worse with a grain size of a few tens of μm . Conversely, favorable characteristics have been obtained experimentally both at Neuchâtel University (Meier et al., 1994, 1996) and at Kaneka Corporation (Yamamoto et al., 1994, 1998, 1999; Yamamoto, 1999) by using thin-film crystalline silicon formed at low temperatures by plasma CVD with a submicron grain size (this is generally referred to as microcrystalline silicon due to the small grain size). This is an interesting discovery which has caused recent research to shift toward both extremes (one is small grain size, the other is mono-crystalline such as layer transfer method).

1.1. Microcrystalline silicon thin-film solar cells formed at low temperature

Microcrystalline silicon solar cells formed by plasma CVD at low temperature are assumed to have a shorter carrier lifetime than single-crystal cells, and it is common to employ a p-i-n structure including an internal electric field in the same way as an amorphous solar cell. A p-i-n type microcrystalline silicon solar cell is formed by a process fairly similar to that of an amorphous solar cell. Strictly speaking, these cells can be divided into p-i-n and n-i-p types according to the film deposition order, although the window layer of the solar cell is the p-type layer in both cases.

The characteristics of a cell having a p-i-n structure were first reported by Neuchâtel University (Meier et al., 1994, 1996). Unlike an amorphous solar cell, this cell does not deteriorate when exposed to light. The very first reports on the characteristics of an n-p cell were made by our group using the light trapping structure described below. These cells had an intrinsic conversion efficiency of 10.7% and an apparent efficiency of 10.1% for a film thickness of $2\ \mu\text{m}$ (surface area $1\ \text{cm}^2$, measured by the JQA (Japan Quality Assurance Organization) (Fig. 2) (Yamamoto et al., 1998, 1999; Yamamoto, 1999). Also, by subjecting the silicon film in the photoelectric layer of this cell to XRD (X-ray diffraction) measurements, it was found to have a preferential (110) orientation. The p-i-n and n-i-p cells have different characteristics due to their different fabrication sequences. A large difference is that the underlying layer of a p-i-n cell is the transparent p-type electrode, whereas the underlying layer of a n-i-p cell is the n-type back electrode.

As a general rule, transparent electrodes are made of oxides, and since there is a risk of these oxides being reduced by the hydrogen atoms that are needed to form microcrystalline cells, there is a smaller process window in the cell formation conditions for the p-i-n type. From the viewpoint of the ease with which integrated structures can be formed, which is a characteristic of thin-film solar cells, an advantage of p-i-n cells is that they can be formed as super straight modules using integration techniques similar to those used for amorphous silicon as described below. On the other hand, it should be possible to make integrated structures of n-i-p cells by methods equivalent to those used for Cu(InGa)Se₂-based solar

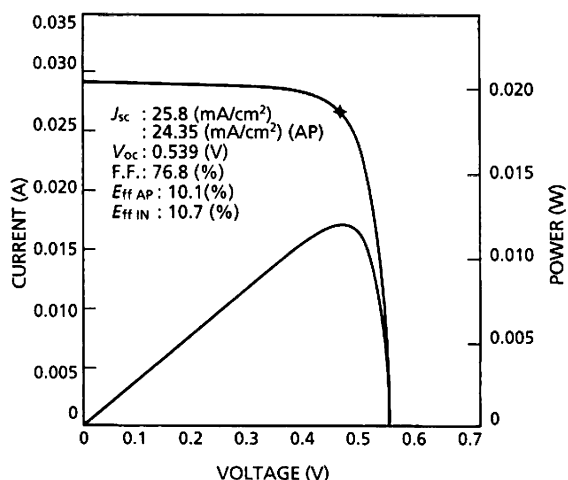


Fig. 2. Current-voltage characteristics of an n-i-p type microcrystalline silicon cell (film thickness $2\ \mu\text{m}$, area $1\ \text{cm}^2$, measured by JQA). In this figure, Eff_{AP} is the characteristic for the area including the grid electrode, and Eff_{IN} is the characteristic of the effective area not including the grid.

cells (Wieting et al., 1995). At the present time it is difficult to determine which is better, but it should become possible to arrive at a conclusion in terms of cost, performance and applications through the production of sub-modules in the future.

1.2. The light trapping effect of microcrystalline silicon cells

Light-trapping techniques are a way of increasing the performance of microcrystalline solar cells. This is a core technique for cells made from microcrystalline silicon because—unlike amorphous silicon—it is essentially an indirect absorber with a low absorption coefficient. That is, the thickness of the Si film that forms the active layer in a microcrystalline silicon solar cell is just a few μm , so it is not able to absorb enough incident light compared with solar cells using ordinary crystalline substrates. As a result, it is difficult to obtain a high photoelectric current. Light-trapping technology provides a means of extending the optical path of the incident light inside the solar cell by causing multiple reflections, thereby improving the light absorption in the active layer.

Light trapping can be achieved in two ways: (1) by introducing a highly reflective layer at the back surface to reflect the incident light without absorption loss, and (2) by introducing a textured structure at the back surface of the thin-film Si solar cell. Of course, the carrier lifetime is also important, and it goes without saying that the diffusion length must be at least as long as the film thickness. Moreover, internal light trapping for amorphous Si and microcrystalline Si tandem cell (stacked cell) by transparent interlayer will be introduced as a new light trapping of tandem cell described below.

As a effective example of light trapping, Fig. 3(a) shows a cell that uses a flat highly reflective layer at the back surface, and Fig. 3(b) shows a cell that uses a textured type of highly reflective layer. This highly reflective back layer also acts as the solar cell's back electrode. Thin-film microcrystalline silicon forms naturally with a textured structure on its surface, and the size of this texture is strongly dependent on the film thickness. When the film is relatively thick ($4\mu\text{m}$ or more), the surface texture is suitable for light trapping, but when the film is relatively thin ($1.5\mu\text{m}$ or less), an adequate surface texture does not form (Yamamoto et al., 1999; Yamamoto, 1999). It is this necessary to use a textured reflective layer at the back surface. Of course, to be precise the texture characteristics depend on the fabrication conditions as well as the film thickness.

The light trapping effect of a thin film microcrystalline silicon layer with a thickness of $1.5\mu\text{m}$ is investigated. Fig. 4(a) shows the reflection spectra of samples corresponding to two types of $1.5\mu\text{m}$ thick cell (one with a flat back reflector and one with a textured back reflector), and Fig. 4(b) shows the corresponding collection efficiency spectra.

In Fig. 4(a), the minimum that appears in the spectra at around 550 nm arises because the ITO film was deposited under anti-reflective conditions. The oscillation seen at wavelengths above 600 nm is caused by interference with the silicon film in the active layer. The reflectivity of the sample with the textured back surface is significantly lower in the infrared region. Fig. 4(b) shows the spectral sensitivity spectra corresponding to the flat and textured samples. In the case of the textured sample, it can be seen that the sensitivity is higher at wavelengths above 600 nm , which corresponds to the reduction of the reflectivity spectrum at longer wavelengths.

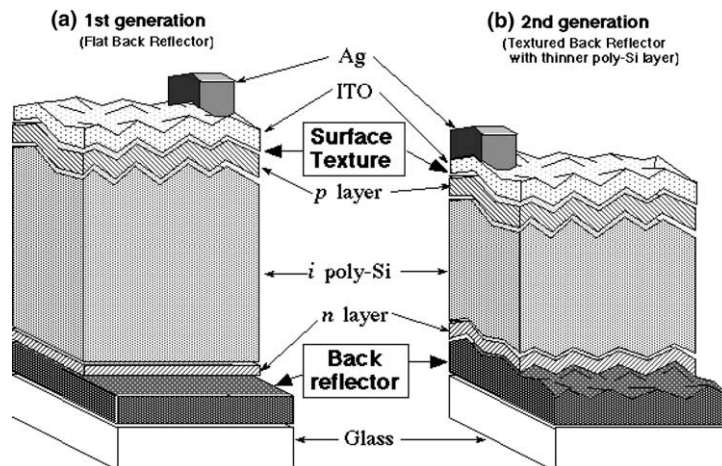


Fig. 3. Cross-sections through light-trapping microcrystalline silicon solar cell devices: (a) first generation (flat back reflector); (b) second generation (textured back reflector, thinner polycrystalline silicon layer).

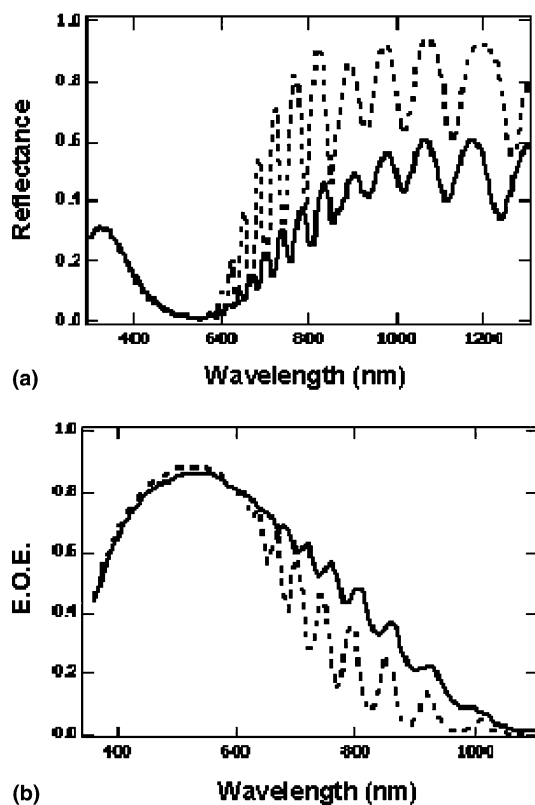


Fig. 4. The characteristics of microcrystalline solar cells on glass substrates having flat and textured back reflectors: (a) reflectivity, and (b) collection efficiency characteristics (quantum efficiency).

This result provides experimental verification of the contribution made by minute textured structures to light trapping. In the future, it will be necessary to aim at increasing the efficiency by obtaining larger currents in the thin film through the formation of better light trapping structures by controlling the profile of the microcrystalline silicon surface and the underlying reflective layer.

2. Amorphous Si/microcrystalline Si stacked solar cells

Although the microcrystalline silicon cells formed at low temperature as described above have a potential for high efficiency, their efficiency in single-cell structures is currently only about 10%, which is much lower than that of bulk polycrystalline cells. To achieve a substantial improvement of efficiency there needs to be some kind of breakthrough, such as a substantial reduction in the abovementioned grain boundary recombination or the establishment of more advanced light trapping techniques. In an attempt to achieve this, we have investi-

gated the use of two- and three-stacked (hybrid) structures in which multiple cells with different light absorption characteristics are stacked together. This approach allows better characteristics to be obtained with existing materials and processes. The advantages of using a layered structure include the following: (1) it is possible to receive light by partitioning it over a wider spectral region, thereby using the light more effectively; (2) it is possible to obtain a higher open-circuit voltage; and (3) it is possible to suppress to some extent the rate of reduction in cell performances caused by photo-degradation phenomena that are observed when using amorphous silicon based materials.

Based upon above reasons, we have engaged in thin film amorphous and microcrystalline (a-Si/μc-Si) stacked solar cell. In this kind of stacked cell of a-Si/μc-Si, pioneer work had been done by Professor Hamakawa in 1983 (Okuda et al., 1983; Hamakawa, 1984). The last few years have witnessed significant development in this area. One of them is that Dr. Meier of University of Neuchatel reported 13% initial efficiency of a-Si/μc-Si stacked cell in 1996 (Meier et al., 1996). In the FY of 1998, a-Si/crystalline stacked solar cell reached the stabilized efficiency of 11.5% by our Kaneka Corporation (Yamamoto et al., 1998).

The advantage of a high J_{sc} for our μc-Si solar cell shown in previous chapter was applied to the stacked cell with the combination of a-Si cell. In applying the a-Si cell to the stacked cell we must pay attention to the stabilized efficiency as mentioned, since a-Si has a photo-degradation, while a μc-Si cell is stable. We have also prepared three stacked cell of a-Si:H/μc-Si/c-Si (triple), which will be less sensitive to degradation by using the thinner a-Si. We have investigated the stability of a-Si:H/μc-Si/μc-Si (triple) cell. These devices were then subjected to indoor light soaking under AM 1.5, 100 mW/cm², 48 °C, and open-circuit conditions. The triple cell showed a stabilized efficiency of 12% as shown in Fig. 5(a). Note that a high stabilized FF of 76.2% was also obtained. Fig. 5(b) shows the change in the device efficiency during light soaking under the above conditions, where very little photo-degradation is observed for our 3-stacked cell.

As a next generation of further high efficiency of solar cell, we have developed the new stacked thin film Si solar cell, where the transparent inter-layer was inserted between a-Si and μc-Si layer to enhance a partial reflection of light back into the a-Si top cell. We call this structure as internal light trapping. This structure enables the increase of current of top cell without increasing the thickness of top cell, which leads less photo-degradation of stacked cell.

Fig. 6 shows the schematic view of a-Si/μc-Si stacked pin cell with interlayer, where the transparent intermediate layer between a-Si top and μc-Si bottom cells is inserted. By introduction of this interlayer, a par-

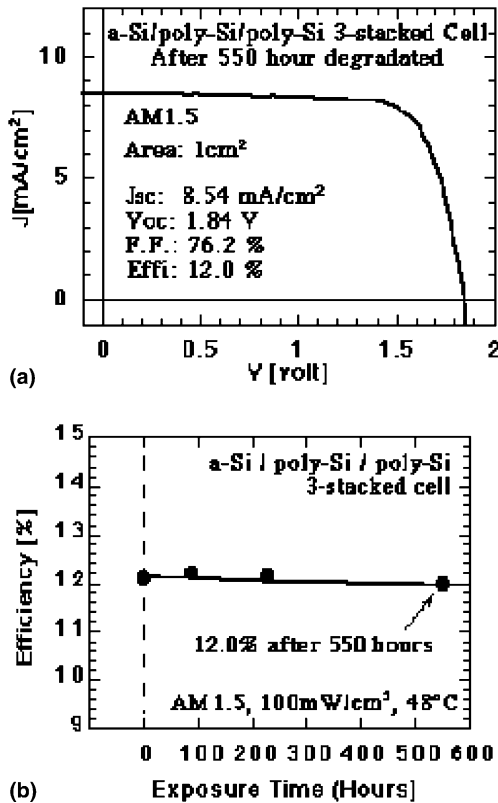


Fig. 5. (a) The established performance of the a-Si/poly-Si/poly-Si 3-stacked hybrid solar cell after 550h indoor light soaking; (b) Light-induced changes in efficiency for a-Si/poly-Si/poly-Si 3-stacked hybrid solar cell under AM 1.5, 100mW/cm², 48°C, and open-circuit conditions.

tial reflection of light back into the a-Si top cell can be achieved. The reflection effect results from the difference in index of refraction between the interlayer and the surrounding silicon layers. Table 1 shows the internal light trapping effect for different refractive index (n) and thickness (d) of inter-layer. The product of $\Delta n \times d$ deter-

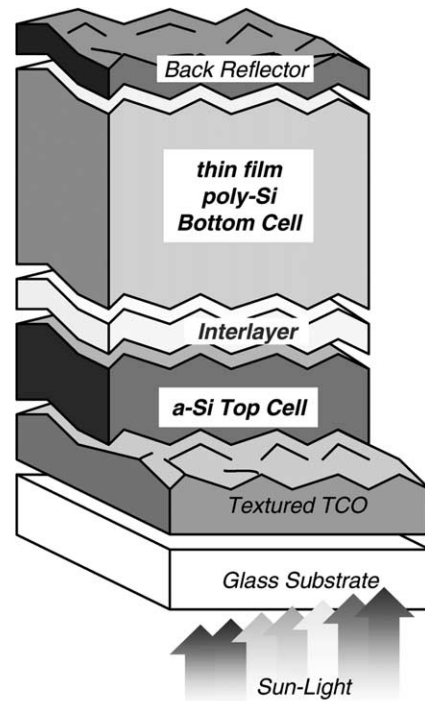


Fig. 6. Schematic view of a-Si/poly-Si (μ c-Si) stacked cells with an interlayer.

mine the ability of partial reflection. Another important aspect is that total current, in another word bottom current, is affected by the interlayer its-self such as a thickness, kind of material, fabrication method. This effect is more cleared by the observation of spectral response as shown in Fig. 7. The photo-response of top cell is enhanced in the wavelength region of more than 500nm due to the partial reflection effect by the introduction of interlayer, at the same time the total current of the stacked cell is enhanced the wavelength region of 600–900nm. This increase in photosensitivity is thought to be caused by the effective light trapping of red light

Table 1
Internal light trapping effect refractive index (n) and thickness (d) of inter-layer

Cell structure	Thickness of intermediate layer (relative)	Normalized photo current		
		a-Si	poly-Si	Total
Without intermediate layer	0	1.00	1.00	1.00
With intermediate layer (A)	1	1.02	1.04	1.03
	2	0.94	0.96	0.95
With intermediate layer (B1)	4	1.04	0.95	1.00
With intermediate layer (B2)	4	1.05	1.02	1.03

Note that total current (bottom current) is increased by the introduction of inter layer B2, while the total current is decreased by the inter-layer B1.

Refractive index: interlayer (A) < interlayer (B) different fabrication process between B1 and B2.

Refractive index (n), thickness (d) $\Delta n \times d$.

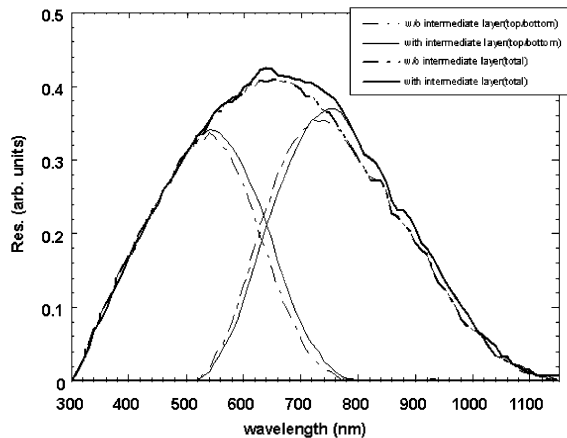


Fig. 7. Spectral-response of the cell with and without inter-layer. Bold and normal line shows the spectral-response of the cell with and without inter-layer.

(600–900) in the bottom cell as shown in Fig. 7. Namely, the light trapping is occurred between the front and back electrode without inter-layer, while with inter-layer, it is also occurred between inter-layer and back electrode. This could reduce the absorption loss of TCO and a-Si:H. As another possibility, it is noted that the quality of p and p-n interface is improved by the introduction of interlayer, which leads the reduction of absorption loss. This concept of internal light trapping is shown in Fig. 8.

By optimizing the deposition conditions including a interlayer, initial efficiency of 14.7% have been achieved for 1 cm² a-Si/interlayer/poly-Si stacked cell as shown in Fig. 9 (Yamamoto et al., 2002, 2003). The highest J_{sc} of

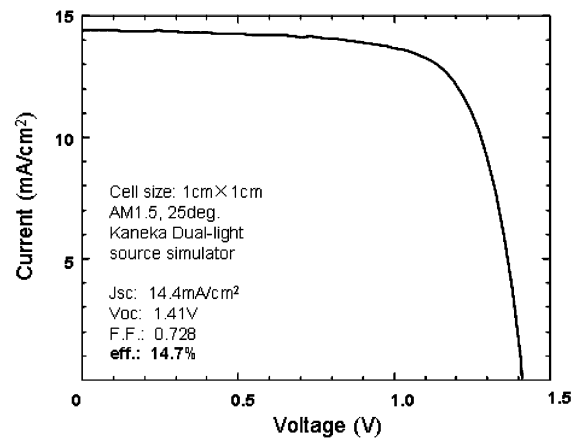


Fig. 9. I - V characteristics of Si thin film hybrid solar cell with inter-layer.

15.0 mA/m² with interlayer is obtained, which will lead the higher efficiency in near future.

2.1. Large area thin film silicon HYBRID (amorphous silicon and microcrystalline silicon stacked) module

We have been developing techniques for depositing microcrystalline silicon films on large area substrates, and for the production of silicon hybrid modules based on tandem cells of amorphous silicon and microcrystalline silicon (Yamamoto et al., 2002; Yoshimi et al., 2003). These hybrid modules employ a super-straight structure in which light is incident through a glass substrate on which a transparent electrode is formed, and are integrated by laser scribe processing as shown in

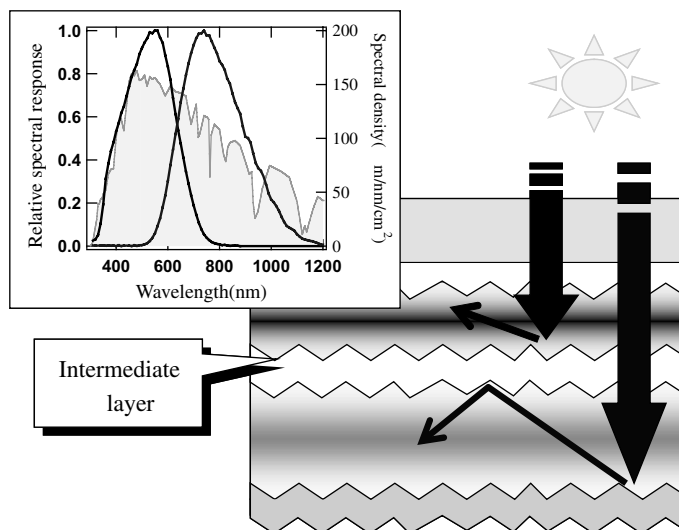


Fig. 8. Schematically drawn concept of inter-layer.

Fig. 10. We have also been developing mass production techniques, which were put into commercial operation in 2001.

Since the required thickness of $\mu\text{-Si}$ active layer is around several times thicker than that of a-Si , increasing the deposition rate of $\mu\text{-Si}$ is one of the key issues for a mass production of the HYBRID modules. We have developed large area plasma CVD apparatus for high throughput deposition of $\mu\text{-Si}$ bottom cell. The technical points are summarized as; (1) improving an ability of gas supply or an exhausting system, (2) increasing RF power into the electrode as well as reducing the power-loss, (3) effective film deposition on substrate by plasma confinement. The item (2) and (3) directly contribute to improving the deposition rate. Fig. 11 shows a relation between normalized RF power and deposition rate of $\mu\text{-Si}$. In the entire RF power region shown in this figure, each maximum initial efficiency of the HYBRID modules were kept more than 11%, representing the quality of $\mu\text{-Si}$ layer deposited at high power is not so inferior. Reasonably high deposition rate of 11 A/s for $\mu\text{-Si}$ at the area of $910 \times 910\text{mm}$ has been achieved with its good uniformity of the thickness.

Based on the large amount of experimental data gained by our group, the guidelines for forming high-quality microcrystalline silicon by plasma CVD are very

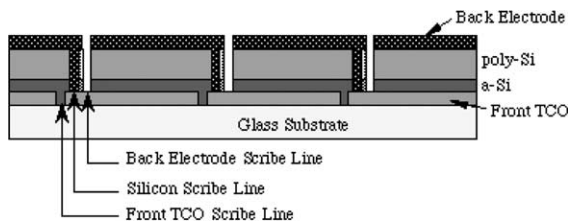


Fig. 10. Cross-sectional structure of the silicon hybrid module (amorphous microcrystalline silicon tandem solar cell module; series-connected).

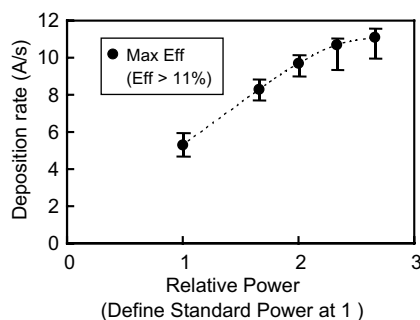


Fig. 11. Deposition rate of poly-Si as a function of relative RF power in 1m^2 class plasma CVD. Closed circles indicate the points of maximum initial efficiency obtained for each RF power.

simple as long as it is possible to supply a sufficient quantity of hydrogen atoms to the substrate during crystallization without causing any damage (most of it is ion damage), then the film fabrication speed can be improved without deteriorating the cell characteristics.

The result of long-run production of more than 4000 HYBRID modules (sized $910 \times 455\text{mm}$) in our plant exhibits the initial average efficiency of around 11% by using high deposition rate $\mu\text{-Si}$ as the bottom cell, as shown in Fig. 12. It was confirmed that the HYBRID modules could be fabricated with high throughput and stable production. For further R&D, it will be necessary to establish much higher throughput processes of $\mu\text{-Si}$ deposition including the reduction of downtime for plasma CVD apparatus. The highest module initial aperture efficiency of 12.5% confirmed by independent laboratories (AIST) is shown in Fig. 13.

Internal light trapping technology transfer from small size device as shown in Fig. 6 to large area module has been performed. A fabrication technology of transparent interlayer onto $910 \times 455\text{mm}$ sized large area has been prepared. We call this new HYBRID module (a-Si and $\mu\text{-Si}$) with transparent interlayer as a HYBRID PLUS.

The design of multi-junction device structure as well as the optimization of fabrication process have been promoted under the concept of realizing high annual output power at outdoor as the “high performance module”. We have applied a large area dual light source solar simulator not only to obtain an approximate AM 1.5 spectrum but also to demonstrate quasi-summer or winter spectra by changing the ratio of halogen/xenon light intensity. The measurement of dual light source simulator under various irradiation spectra have been performed to optimize the kind of transparent interlayer. Fig. 14 shows the results for three modules with different kind of interlayer A, B and C while keeping the thickness of each top a-Si and bottom $\mu\text{-Si}$ layer the same.

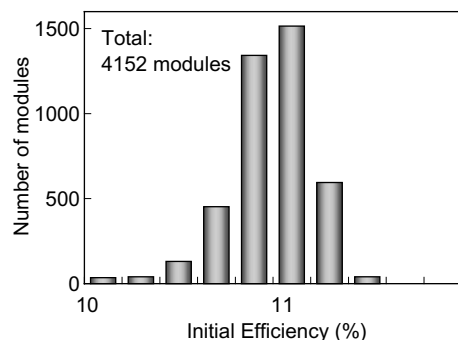


Fig. 12. Distribution of initial efficiency for $910 \times 455\text{mm}$ $\text{a-Si}/\text{poly-Si}$ HYBRID modules fabricated with high throughput production line. The total amount of modules in this long test run is 4152.

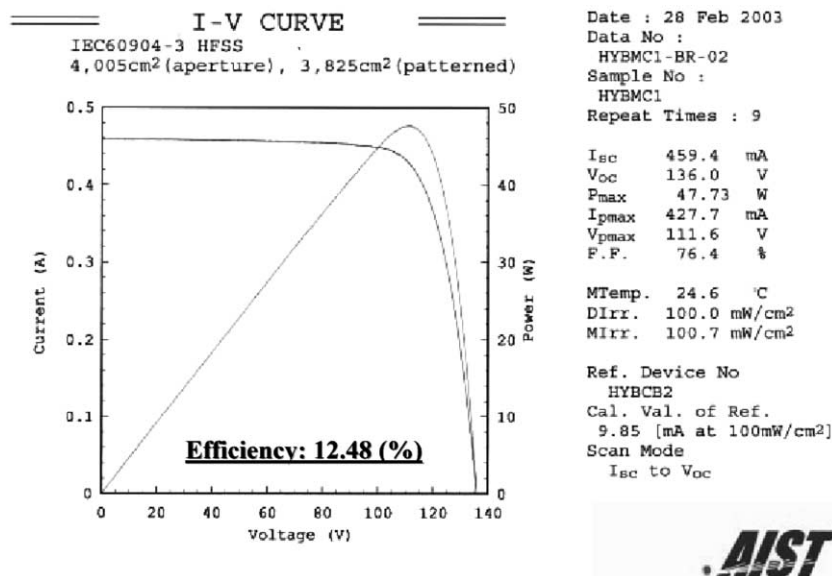


Fig. 13. The performance of HYBRID module confirmed by AIST (National Institute of Advanced Industrial Science and Technology). The scribed area's efficiency are shown in this figure.

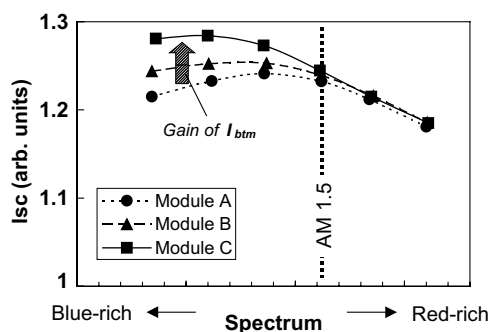


Fig. 14. Short circuit current I_{sc} comparison for three HYBRID modules (three modules with different kind of interlayer A, B and C while keeping the thickness of each top a-Si and bottom poly-Si layer the same) measured by under various irradiation light spectrum. The spectrum was controlled by changing the light intensity ratio of halogen/xenon dual light source simulator. Total irradiation intensity was approximately equivalent in the entire spectrum region. A dashed vertical line indicates nearly AM 1.5 spectrum condition in this measurement.

The spectrum was controlled by changing the light intensity ratio of halogen/xenon dual light source simulator. Total irradiation intensity was approximately equivalent in the entire spectrum region. A dashed vertical line indicates nearly AM 1.5 spectrum condition in this measurement. With increasing the transmittance of interlayer (from A to B to C), the I_{sc} of Blue-rich region of these module increases. Namely, C is the highest I_{sc} at Blue-rich conditions among these modules, which is

introduced as a inter-layer of most transparent among these inter-layers. This implies that bottom cell current is very much affected by the transmittance of inter-layer.

By applying these measurement's technology to optimize the each thickness of top a-Si, interlayer, bottom μ c-Si layer. We have succeeded in fabricating the large area series integrated monolithic a-Si/transparent interlayer/ μ c-Si module. It is confirmed that the J_{sc} as well as efficiency of module increase by inserting a transparent interlayer as shown in Table 2. Here module D & E have same thickness of top a-Si layer without interlayer (D) and with improved interlayer (E). The remarkable 19% increase of short circuit current (I_{sc}) of this module was obtained by the introduction of transparent interlayer, namely internal light trapping. A serious shunting problem for the integration structure in the module having conductive interlayer has been suppressed. However, a little problem still remains because the FF of module D is relatively lower.

Table 2

I - V characteristics of two types of HYBRID module without and with "improved" transparent interlayer

	V_{oc}	J_{sc}	FF	Efficiency
Module D (w/o interlayer)	1.00	1.00	1.00	1.00
Module E (with interlayer)	1.00	1.19	0.963	1.15

The parameters were normalized by those of Module D (without interlayer).

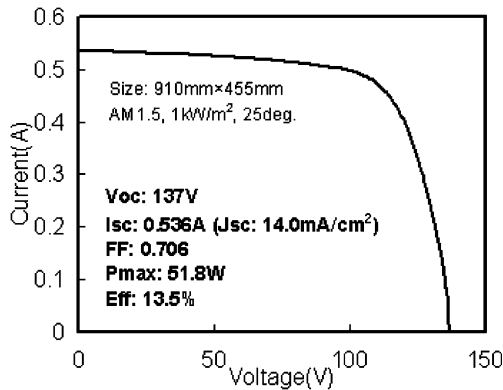


Fig. 15. Initial I - V performance of 910×455 mm HYBRID solar module measured under AM 1.5, 1 kW/cm^2 conditions.

Up to now, an initial aperture efficiency of 13.5% (V_{oc} : 137V, I_{sc} : 0.536 A (J_{sc} : 14.0 mA/cm^2), FF: 0.706) has been achieved for 910×455 mm size HYBRID solar cell module as shown in Fig. 15. Remarkably high intrinsic J_{sc} reaches to 14.5 mA/cm^2 in taking into account the inter-connection losses of this module (Yamamoto et al., 2004).

2.2. Outdoor performance of thin film Si Hybrid module

Outdoor performance of our thin film Si hybrid modules have been systematically investigated, which are published elsewhere (Nakajima et al., 2003, in press). We have achieved the actual output current corresponding to the J_{sc} of 13 mA/cm^2 at the irradiance of 1.0 kW/m^2 in natural sunlight as shown in Fig. 16. The irradiance was measured with the pyranometer (Eko MS801) located on the co-planar plane with modules.

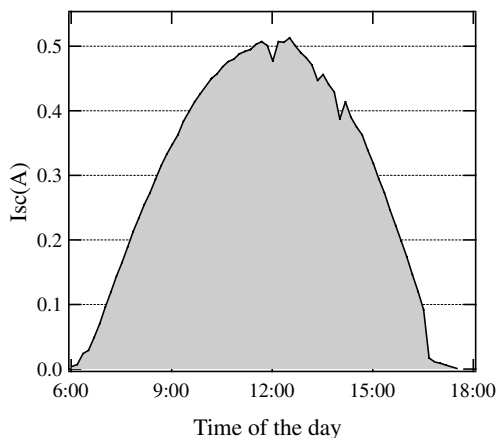


Fig. 16. Actual short circuit current of HYBRID module exposed after a month measured under clear sky condition. The I_{sc} was 0.506 A by the initial measurement at STC.

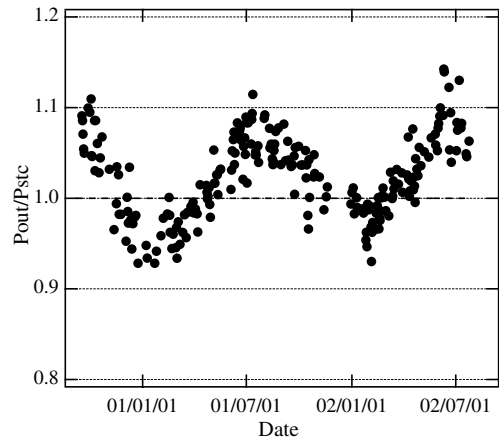


Fig. 17. Performance change of the HYBRID module optimized at noon output in the field. In summer, P_{out} was 10% greater than the P_{stc} measured at STC in May 2002.

The above module exhibited the J_{sc} of 13.2 mA/cm^2 and the efficiency of 13% at STC initially.

Performance change of the HYBRID module optimized at noon output in the field had been investigated through 2000 to 2002 in Japan as shown in Fig. 17. The P_{out} was the output power corrected to the standard conditions (25°C and 1 kW/m^2). All observed points in the figure were normalized by P_{stc} , which was the P_{max} measured at STC in May 2002. P_{out} was 10% greater than P_{stc} when the spectral irradiance was close to AM 1.0 in summer. Note that P_{out} was 10% greater than the P_{stc} measured at STC in May 2002.

Fig. 18 shows the performance normalized by the irradiance of sunlight and the nominal power as the function of the irradiance. T_{mod} shows the module temperature at each observed point. Solid line was evaluated from the empirical model of c-Si module (Nakajima et al., in press). The performance of c-Si module decreased as the irradiance of sunlight is close to 1.0 kW/m^2 . On the other hand, the HYBRID module kept its performance at the irradiance close to 1.0 kW/m^2 , and which behavior was well explained by both the low temperature coefficient of Si hybrid module and spectral effect.

2.3. Application to the roofing materials and grid connected systems for thin film Si module

One of the advantage of thin film Si solar module is characterized to the low temperature coefficient. This advantage was applied for the low angle (5 degree off from horizontal) and simple installation of module as shown in Figs. 19–21. Figs. 19 and 20 show the 40KW system of North Daito Island and 20KW system at the top of the building Osaka, respectively. Fig. 21 shows another application of the roof top of the building with combination of plant for reduction of heating the roof.

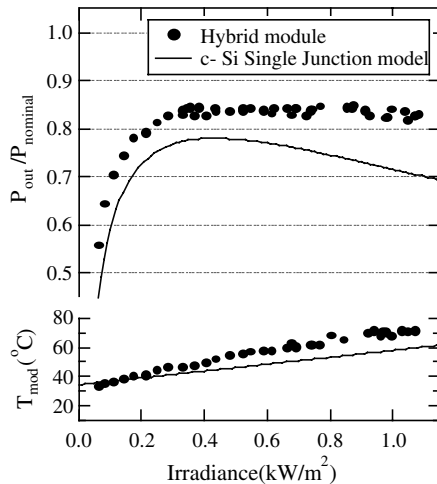


Fig. 18. Performance of HYBRID module as a function of the irradiance a day. P_{out} is actual output normalized by the irradiance. T_{mod} is module temperature. Solid line indicates the typical c-Si module model.

The other advantages of the thin film PV modules are the design flexibility with a variety of voltage and the cost potential. As the modules are prepared to be cut from the maximum module with $980\text{ mm} \times 950\text{ mm}$ in our manufacturing plant, any size of modules can be applied to the roofing tiles. $910\text{ mm} \times 910\text{ mm}$, $910\text{ mm} \times 455\text{ mm}$, $910\text{ mm} \times 227\text{ mm}$ and $455\text{ mm} \times 227\text{ mm}$ are the typical sizes now. Figs. 21 shows the private house with these PV roofing tiles. In case the PV roofing tiles act as ordinary roofing tiles, so that the construction cost for PV system can be saved. Through the detailed designing, the actual installation and the performance evaluation, we confirmed the availability of proposed

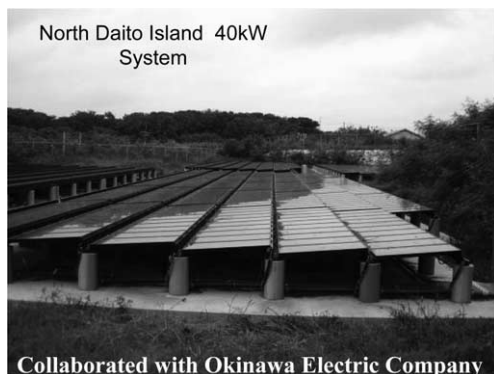


Fig. 19. KW system of North Daito Island (a-Si modules). Note that modules are installed at low angle (5 degree off from horizontal).



Fig. 20. KW system at the top of the building Osaka (HYBRID modules). Note that modules are installed at low angle (5 degree off from horizontal).



Fig. 21. A private house with these PV roofing.

modules as roofing materials. It is said that the thin film Si solar cells can be practically used for the PV systems on the roof of private houses.

3. Conclusion

An initial aperture efficiency of 13.5% ($J_{\text{sc}} = 14\text{ mA/cm}^2$) has been achieved for $910 \times 455\text{ mm}^2$ a-Si:H/transparent inter-layer/microcrystalline Si thin film integrated large area solar cell module. We conclude that further investigation and optimization should be required for the new type of HYBRID PLUS module towards higher efficiency.

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