Mass Production Start-up Activities on High Efficiency-microcrystalline Tandem Solar Cells

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The solar cell has attracted attention as a 'trump card' in the struggle to reduce burdens on the global environment. Mitsubishi Heavy Industries, Ltd. (MHI) is already selling an amorphous solar cell for practical use. More recently, MHI has researched and developed a thin film type silicon solar cell for mass production. These new cells can obtain outputs up to 1.5 times higher than conventional amorphous solar cells, and at lower cost. In October 2007, MHI began producing the cells at a newly constructed factory with an annual production capacity of 40 MW.

1. Features of the microcrystalline tandem solar cell

MHI has been producing and selling[1] amorphous solar cells for many years. In October 2007, MHI started to produce a microcrystalline tandem type solar cell with a far higher efficiency than the amorphous cell. MHI plans to produce three kinds of products, with generation outputs of 130 W, 140 W, and 150 W. These cells use a substrate of the same size as the amorphous cell.

In a microcrystalline tandem type solar cell, films of microcrystalline cells are laminated in series over the film of a conventional amorphous cell (**Fig. 1**). **Figure 2** shows an example of spectral sensitivities of the microcrystalline tandem type solar cells. The microcrystalline cell film absorbs long-wavelength light, a type of light unabsorbable by the amorphous cell film, for higher energy efficiency. But because the microcrystalline Si film has an optical absorption coefficient smaller than that of amorphous Si film, the film thickness of the i layer of the microcrystalline tandem type solar cell must be at least fivefold greater than that of the amorphous solar cell. To ensure the same production capacity as that of amorphous cell without increasing the number of film deposition chambers, the film deposition rate must be fivefold faster, with simple calculation. To meet these demands, MHI developed a super-high-rate film deposition technology for fabricating the microcrystalline Si film. The functionality of this new technology is superior to that of the VHF plasma-enhanced CVD film deposition technology developed earlier for the amorphous solar cell.[2]

2. High-rate film deposition

If the film deposition rate is increased, a performance decrement usually results. To prevent this, the National Institute of Advanced Industrial Science and Technology,

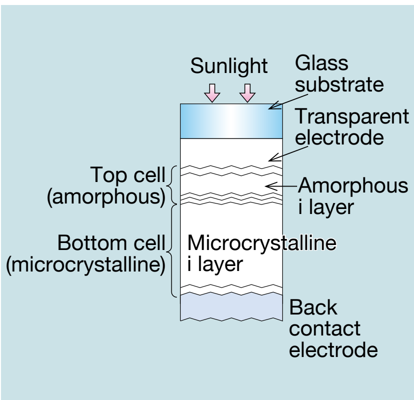

Fig. 1 Structure of microcrystalline tandem type solar cell
The cross-sectional structure of the microcrystalline tandem type solar cell.

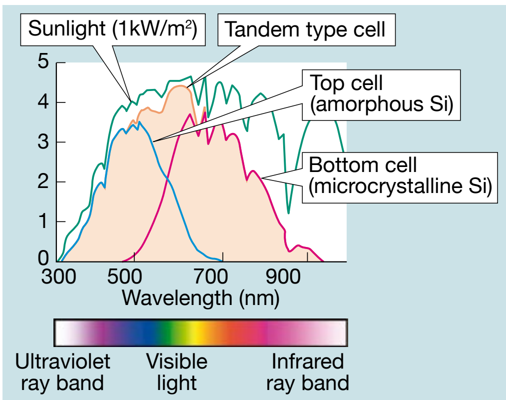

Fig. 2 Spectral sensitivity characteristics of microcrystalline tandem type solar cell
The density of photons converted into electricity for each wavelength of sunlight.

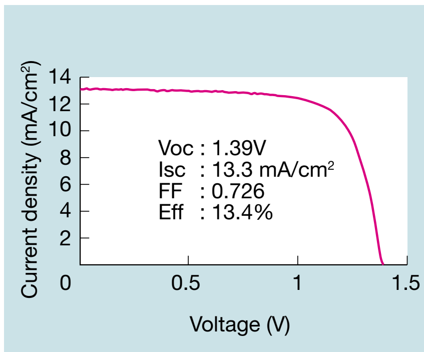

Fig. 3 Power generation characteristics of microcrystalline tandem type cell
The characteristics of the current and voltage of the power generated by a small microcrystalline tandem type cell (area: 12 cm^2).

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a research collaborator with MHI, developed a film deposition method (high pressure depletion method) for the input of high power. This new method applies a film deposition pressure (several hundred Pa) higher than the pressure applied by the conventional method, and works with a narrower gap between the electrode and substrate. Overall, the new method achieves a microcrystalline Si single cell efficiency of 9% at a film deposition rate of 2 to 3 nm/s.[3] MHI, meanwhile developed a more efficient microcrystalline tandem type solar cell using a small plasma CVD device designed to respond to a substrate of 5 cm × 5 cm. This new cell achieves a 13.4% initial efficiency with the tandem type cell, as shown in **Fig. 3**.[4] By amalgamating these technologies and applying a new type of electrode for depositing microcrystalline Si film with reduced plasma localization under the high-pressure conditions described above, MHI obtained a bottom cell (microcrystalline Si type) efficiency of 8.8% at a high film deposition rate of about 2 nm/s. And by applying the electrode cooling structure based on the results of the technological development of the large-area high-rate uniform film deposition, MHI achieved an efficiency of 8.6% at a film deposition rate of 2.5 nm/s, as shown in **Fig. 4**.

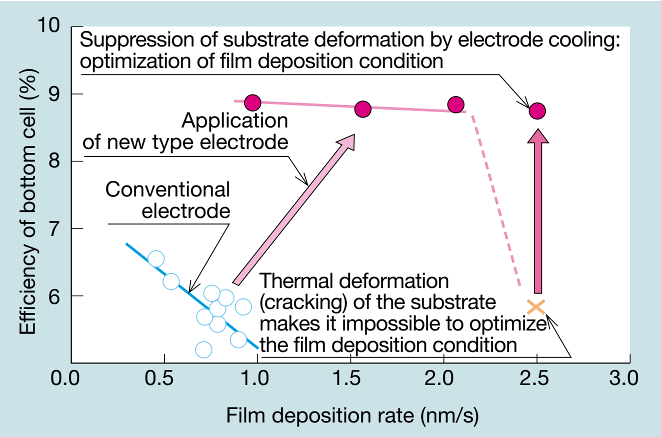

Fig. 4 Relation between the film-deposition rate of the microcrystalline bottom cell and efficiency
As the figure shows, the new electrode is more efficient than the conventional electrode. The efficiency does not decrease at the film-deposition rate of 2.5 nm/s, the rate at which the glass substrate deformation is suppressed by electrode cooling.

3. Improvement of availability factor of CVD equipment

The production capacity of the cell film in the plasma CVD equipment is not determined solely by the film deposition rate. Instead, it is calculated by multiplying five parameters: the substrate size, film deposition rate, availability factor, efficiency, and yield. For plasma CVD equipment, the film is generally stuck onto the electrodes and heaters in the film deposition chamber when the film deposition is continued. It thus becomes necessary to periodically open the film deposition chamber, remove the components, and exchange these components with clean replacements. After the reassembly in this operation, the film deposition distribution must be adjusted and the film deposition chamber must be baked. These steps reduce the availability factor. To address this problem, MHI has developed a new way to clean solar cell production equipment using a plasma-

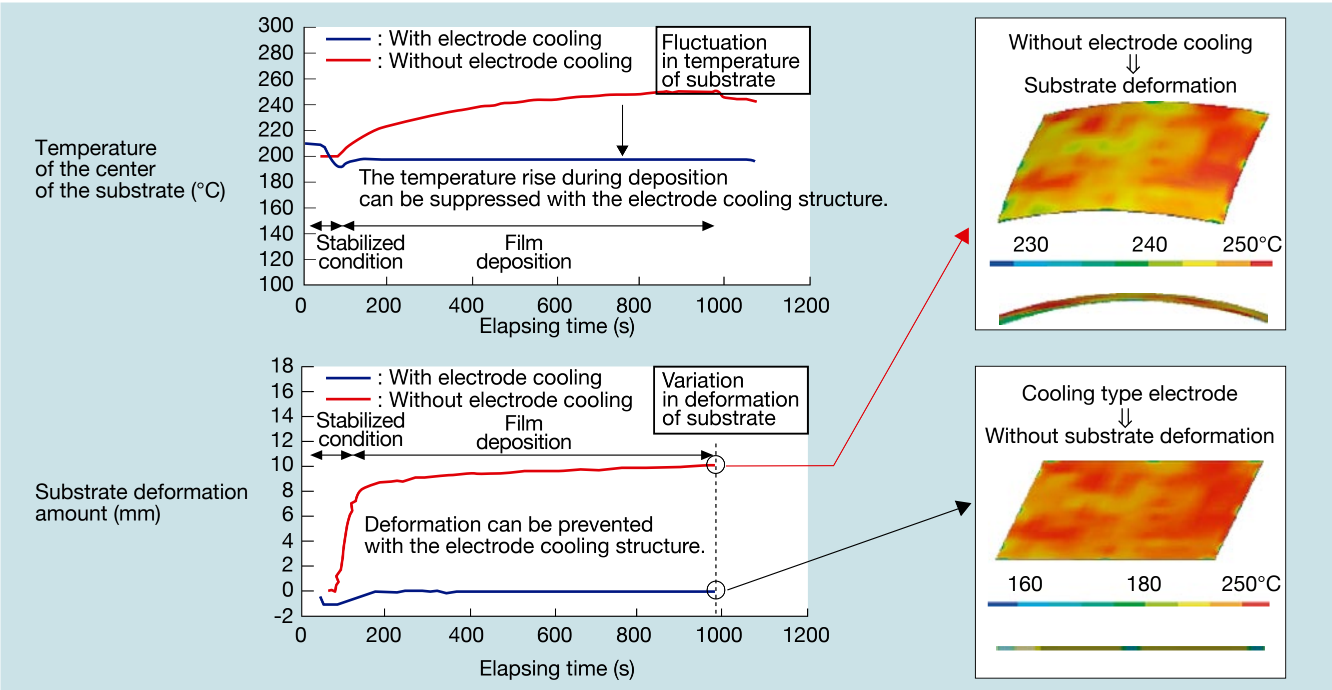

Fig. 5 Results of analysis of the glass substrate temperature and amount of deformation during deposition of the microcrystalline bottom cell
The simulation calculation results of temperature fluctuation and the amount of glass substrate deformation during deposition, according to existence of substrate cooling.

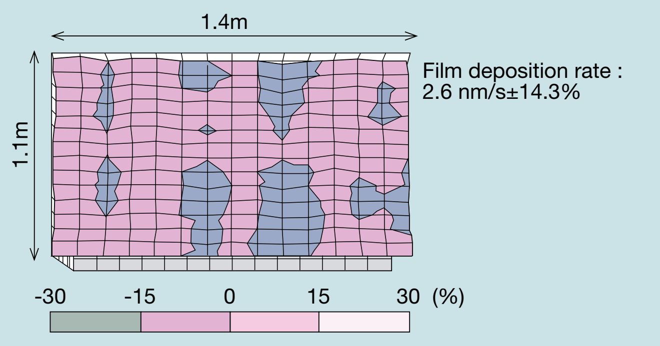

Fig. 6 Distribution of film deposition rate of microcrystalline silicon film
The distribution of the microcrystalline silicon film deposition rate of a large-area substrate (area : 1.1 m × 1.4 m).

Fig. 7 Appearance of microcrystalline tandem production factory
Photograph of a microcrystalline tandem production factory with an annual capacity of 40 MW.

cleaning technology originally applied for the cleaning of semiconductor film deposition equipment with fluorine base gas. With this development, film deposition can be continued for several months without opening the film deposition chamber, and the availability factor is increased by about 20% as a relative value.

For the tandem type solar cell production facility, MHI has used these technologies to develop plasma CVD equipment. The company has developed an electric power source and an electrode capable of supplying the very-high-frequency power required for high-rate film deposition. To control the uniformity of the film distribution, we divided the electrodes and added a function to adjust the film deposition rates of the various divisions of electrodes. We chose not to use a special robot for transfer of the glass substrate. Instead, we adopted a system for transfer with a mechanical mechanism to reduce the mechanical trouble in the vacuum. For the temperature control of the substrates in the plasma CVD equipment, we predict the heat transfer from the load lock room to the unloading room using a heat transfer simulation. To reduce the substrate deformation, we developed an analysis technology by combining the heat transfer simulation and stress analysis. As the stress generated in the glass substrate can be calculated using this technology, the likelihood of substrate cracking can be presumed from the analysis result of the cracking strength of the glass. **Figure 5** shows the analysis results. It has also become possible to suppress the deformation and cracking of the substrate by adopting a structure to remove the heat generated due to the electrical discharge from the electrode, with the electrode cooled. In the absence of electrode cooling, we could predict a rise in the substrate temperature to 40°C or higher during the film deposition, followed by substrate cracking (about 1 substrate per 1,000) due to the temperature difference between the front and back surfaces and interior of the substrate. By cooling the electrode, the rise of substrate temperature during the film deposition can be suppressed to 10°C or less, and the chance of substrate cracking can be suppressed to 1/100 or less, in comparison with the condition without cooling.

From these results, we have been able to deposit film stably with the large electric power inputs required for

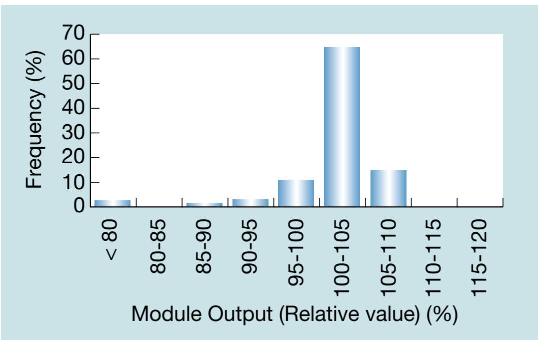

Fig. 8 Output distribution of cell module
The output distribution characteristics of a tandem type solar cell during mass production.

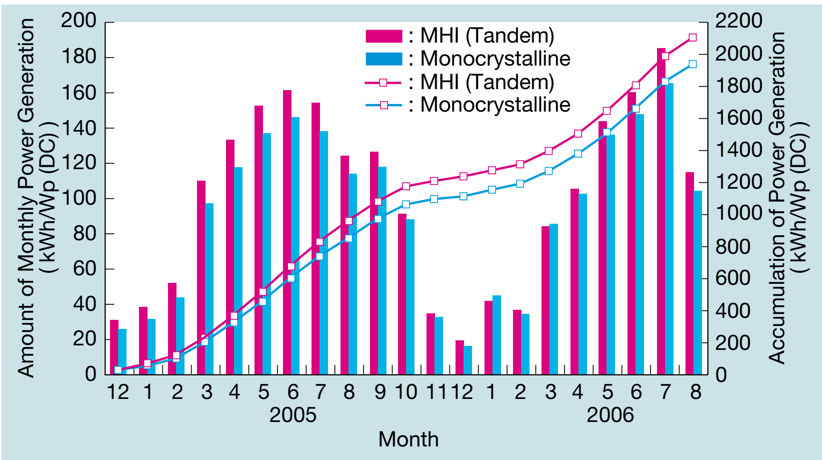

Fig. 9 Annual power generation characteristics of microcrystalline tandem type solar cell
The figure compares the power generation characteristics of a microcrystalline tandem type solar cell with those of a monocrystal silicon solar cell, measured outdoors in the city of Kassel, Germany.

high-rate microcrystalline film deposition. As shown in **Fig. 6**, we confirmed a large-area high-rate uniform film deposition of microcrystalline Si at a film deposition rate of 2.6 nm/s ± 14.3% using a large-area substrate of 1.1 m × 1.4 m. By applying the above-mentioned design technologies, it has become possible to stably transfer the 1.1 m × 1.4 m substrate and to deposit the microcrystalline silicon film at high rate.

The new factory shown in **Fig. 7** began the production from October 2007, and it is scheduled to start the full-scale production of 40 MW from FY 2008. The photograph at the top of this paper shows the appearance of a microcrystalline tandem type solar cell.

The output distribution of the cell module is shown in **Fig. 8**. The outputs of the cell modules fall within the range of average value ± 5%, and we can see that the respective modules have a high repeatability of production. We began selling 130 W products in FY 2007 and plan to sell 150 W products within FY 2008, after improving the module output in parallel with the production. **Figure 9** shows the annual fluctuation of power generation per standard output of microcrystalline tandem type solar cell, as measured by a German performance evaluation organization. The power generation characteristics shown in these data exceed the power generation characteristics of the crystal type. Microcrystalline silicon consists of amorphous silicon filled with columnar crystal grains. The electrical characteristic lies between that of a crystal type and that of an amorphous type. Thus, the temperature coefficient of the output also stands between the coefficients of the crystal and amorphous types. This means that the power produced by the microcrystalline type will exceed that produced by the crystal type during the higher-temperature months of summer.

4. Conclusion

From October 2007, we began producing a microcrystalline tandem type solar cell with a power output far superior to that of our conventional amorphous solar cell. For optimal production, we developed and designed plasma CVD equipment capable of depositing the microcrystalline cell film for the microcrystalline tandem type solar cell using very high frequency, at a film-deposition rate five times faster than the conventional method. In fields test conducted in Germany to assess the performance of this new microcrystalline tandem type solar cell, we confirmed that the cell has higher annual power outputs than the crystal type. In the future we intend to improve the output per cell module and produce products of even higher quality.

The development of the microcrystalline tandem type solar cell and microcrystalline Si high-rate film deposition technology has been commissioned by the New Energy and Industrial Technology Development Organization.

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