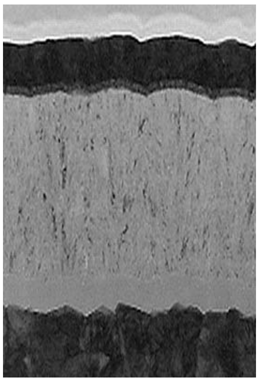

Development of a-Si/Microcrystalline-Si Tandem-type Photovoltaic Solar Cell

YASUHIRO YAMAUCHI*1
KEISUKE KAWAMURA*2
MASAYUKI FUKAGAWA*2
HIROMU TAKATSUKA*1
NOBUKI YAMASHITA*3
YOSHIAKI TAKEUCHI*2

Mitsubishi Heavy Industries, Ltd. (MHI) has been carrying out work to develop thin film type photovoltaic solar cells as a part of efforts to develop and realize clean, "green" sources of energy. MHI has been actively working on developing very high frequency (VHF) large area, high-speed deposition plasma enhanced chemical vapor deposition (CVD) technology with the aim of realizing reduced fabrication costs. As a result of these efforts, we have already put into practical use the world's largest sized amorphous silicon photovoltaic cell (1.4 m x 1.1 m) with a power generating efficiency of 8%, which is currently being sold mainly in markets outside Japan. MHI is currently in the process of developing a high-efficiency amorphous-silicon /microcrystalline-silicon tandem thin film photovoltaic module (a-Si/microcrystalline-Si tandem thin film PV module) with a power conversion efficiency of a 12% targeted for the Japanese domestic market based on this technology. In basic tests, an initial efficiency of 13.1% (stabilized efficiency of 12%) could be attained with small area cells (32 mm^2), and a conversion efficiency of 11% could be attained with a medium sized module (50 cm x 40 cm). We are currently developing cells with a large area substrate that $1m^2$ or more is wide in actual size or greater with a target power efficiency of 12% by combining the above technology with VHF plasma deposition technology. (The image shows a section transmission electron microscope photograph of the cross section of a-Si/microcrystalline-Si tandem PV modules.)

1. Introduction

With the coming into effect of the Kyoto Protocol in February of 2005, more attention than ever is being given to the development and application of clean, "green" sources of energy such as solar power systems and wind power generation systems due to serious concerns regarding the prevention of global warming. Much of this interest has grown rapidly under government guidance in cooperation with industry. One such energy source of interest is PV solar cell. The New Energy and Industrial Technology Development Organization (NEDO) in Japan has been vigorously pursuing the development of cost reducing technologies crucial to spurring the spread and rapid adoption of PV systems in society[1]. Thin-film silicon PV modules are considered to be particularly promising for reducing production costs, because there are essentially no constraints on the availability of the raw materials used in their production, and they offer great benefits in terms of scalability for increased production. As a result, NEDO has also come to support the development of technologies for thin-film Si PV modules as the next generation of solar cells beyond the current mainstream of crystalline Si solar cells.

In order to realize lower production costs, conversion efficiency and productivity must be increased. With regards to raising productivity in particular, it is important to develop a large-area, high-speed, film deposition technology for plasma enhanced CVD, which is the core technology in the thin film Si PV module fabrication process. MHI believes that VHF plasma enhanced CVD is quite advantageous as a high-speed, film deposition technology, and has been concerting its efforts to realize its practical application as early as possible[2]. VHF plasma enhanced CVD is a method by which the gas decomposition rate is increased through the use of a high frequency electric charge that is tens of MHz to one hundred and several tens of MHz instead of the conventional 13 MHz used to generate plasma. This method makes high-speed, high quality film forming with low ion damage possible[3]. However, as the wavelength of the electric charge supplied becomes shorter, it becomes more difficult to apply it to a large area PV module. As a countermeasure to this problem, MHI has invented a unique ladder shaped electrode as well as a new technique called a phase modulation method which controls the phase of the VHF electric charge supplied to the electrode (**Fig. 1**), thereby making it possible for MHI to succeed in realizing large-area VHF plasma enhanced CVD[4][5]. MHI now utilizes the above results to produce 1.4 m x 1.1 m a-Si PV modules, which are the largest size solar cells of their type in the world.

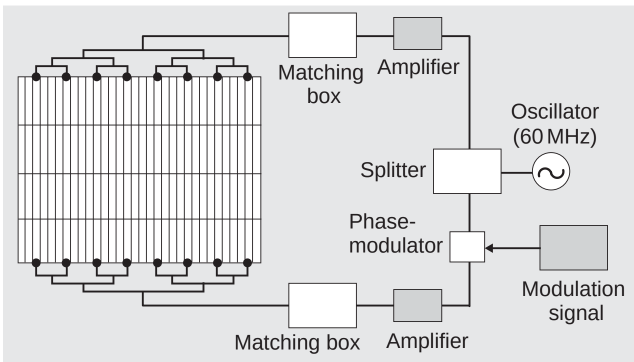

Fig. 1 Conceptual principle of ladder shaped electrode and phase modulation method

*1 Nagasaki Shipyard & Machinery Works
*2 Nagasaki Research & Development Center, Technical Headquarters
*3 Advanced Technology Research Center, Technical Headquarters

At the same time, MHI also has been developing high efficiency technologies for the production of tandem-type PV solar cells utilizing the characteristics of VHF plasma enhanced CVD, and has succeeded in achieving an initial efficiency of 13.1% as a result of basic experiments incorporating MHI's 5 cm^2 glass substrate. The company is now proceeding to research and develop a technology for fabricating larger area tandem-type PV modules based on the basic technologies and techniques acquired from these experiments under a commission by NEDO.

So far, a 40 cm x 50 cm module has been successfully produced with a conversion efficiency of 11%[6][7]. A report is presented here of the current state of progress being made in the development of large area, high-speed film forming technology with a film deposition rate faster than 2.0 nm/s for practical application in the fabrication of PV cells having an area of 1 m^2 or larger that are expected to achieve generation efficiencies of 12% or more.

2. Objective of developing a-Si/microcrystalline-Si tandem solar cell modules

Figures 2 and **3** show the cross sectional structure of a tandem PV module and the usable spectrum of solar light, respectively. A tandem type solar cell module consists of an a-Si cell and microcrystalline-Si cell arranged in a two-level stacked structure. Since short wavelength light is absorbed in the a-Si top cell, and long wavelength light is absorbed in microcrystalline-Si bottom cell, respectively, this type of tandem structure can generate electricity across a broader spectrum of light than a single junction a-Si cell. MHI is aiming to develop a PV module capable of producing electric power with an efficiency of 12% using this structure. Through these efforts, it was possible to develop amorphous type cells that could be installed in an area equivalent to that used for crystalline silicon systems, thereby overcoming a notable shortcoming of amorphous cells in which they require a large installation area.

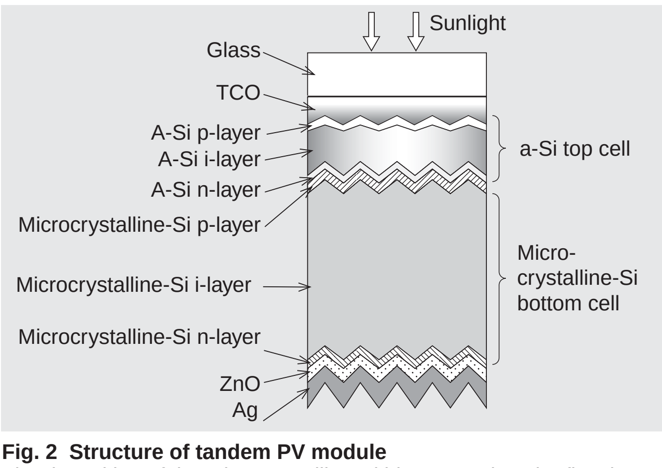

Fig. 2 Structure of tandem PV module
The deposition of the microcrystalline-Si i-layer needs to be five times thicker than that of the a-Si i-layer.

This is particularly important in being able to introduce such systems in the Japanese domestic market where a-Si PV systems have been at a disadvantage until now vis-a-vis crystalline silicon systems due to the constraints on installation space in Japan. In addition, a-Si PV systems can be supplied at a cost less than that of crystalline silicon systems due to the adoption of MHI's original large-area, high-speed film deposition technology. Furthermore, since the actual amount of power produced annually by a-Si PV systems outdoors is about 5-10% more than crystalline systems, they have become an increasingly competitive product for manufacturers of solar cell systems.

3. Development of high efficiency microcrystalline i-layer deposition technology

Although a microcrystalline-Si film can absorb a broader range of wavelengths than an a-Si film, it has a smaller optical absorption coefficient than a-Si. Consequently, the i-layer of a microcrystalline PV cell that forms the bottom cell of a tandem PV module needs to be at least five times thicker than the a-Si i-layer, as shown in Fig. 2. As a result, a film deposition rate that is five times faster is necessary in order to realize the level of productivity as that for amorphous silicon.

Normally, an increase in the deposition rate results in a decline in performance. As a countermeasure to this, the National Institute of Advanced Industrial Science and Technology (AIST), which conducts joint research with MHI, developed a method of producing plasma (used in the plasma enhanced CVD method) in which the deposition pressure was increased to a level higher than that previously used (to several hundred Pa) and in which the distance between the discharge electrode and the substrate was reduced to less than 10 mm.

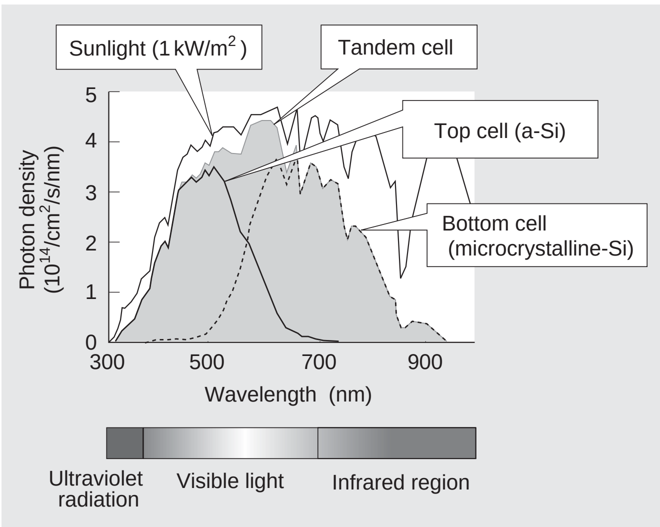

Fig. 3 Wavelength regions utilized in a tandem PV module
Conversion efficiency is enhanced by stacking the a-Si top cell and microcrystalline-Si bottom cell in order to expand the utilized wavelength region from 300 nm to 1 μm.

This newly developed plasma production method made it possible to increase the deposition rate to 2.0 - 3.0 nm/s, a five-fold increase over former rates, while achieving an efficiency in excess of 9% in microcrystalline single junction cells produced with this method[8].

On the other hand, since plasma formation becomes increasingly localized as the deposition pressure rises, it becomes all the more difficult to achieve uniform film deposition over a large area. In order to extend the application of the above results into technology for developing units of larger size for practical use, MHI developed a new type of electrode that can better accommodate higher pressures and closer electrode gaps. This electrode shortens the distance between the electrodes in the conventional ladder type electrode and improves the cross sectional configuration of the electrode rods.

A new method of supplying power and new electrode configuration were developed that could accommodate an increase in VHF power levels in the microcrystalline-Si deposition process. Traditionally, electric power has been branched off from two power sources to supply power to multiple electrical feeds surrounding an electrode using one large area ladder electrode, as shown in Fig. 1. In the case of microcrystalline-Si deposition, the electrodes are divided and arranged into an eight parallel segmented electrode configuration, in which power is supplied to each respective electrode from multiple, independent VHF power sources (**Fig. 4**). This arrangement has made it possible to control each individual electrode independently, thereby improving the ability to control the amount of power input and the phase shift of each electrode to a much finer and greater degree.

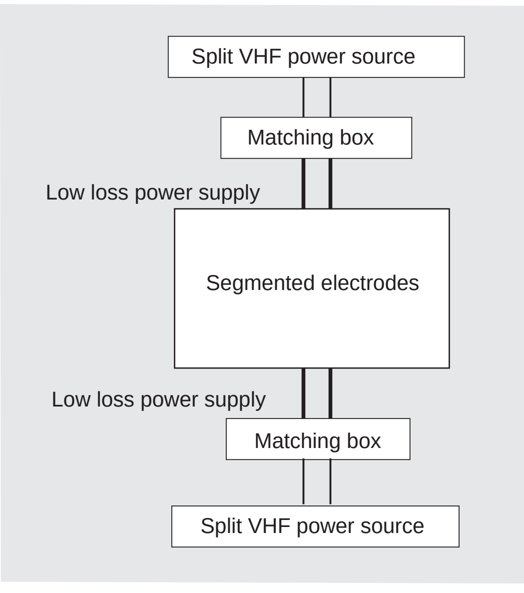

Fig. 4 Schematic of the electrodes in the large area plasma enhanced CVD apparatus used for deposition of microcrystalline-Si
Control is enhanced through the adoption of segmented electrodes and multiple power source method.

In order to achieve a film deposition rate for amorphous silicon that is several times faster, it is necessary to apply a comparably greater amount of electric power. As a result, it is no longer possible to ignore the power loss that occurs in the power feed to the electrodes from the VHF power source that previously had not been a problem in the a-Si deposition process. Consequently, a low-loss, coaxial straight cable power supply structure was newly designed, which made it possible to reduce power loss from the power feed from the previous 10% to just 3%.

Heat input from the plasma to the substrate becomes a problem as more power is introduced into the process. In other words, since the VHF power added in to enhance the deposition process eventually converts into heat, it becomes increasingly difficult to control the temperature of the substrate, unless the something is done to eliminate the additional heat generated in the process. The desired level of device performance would then no longer be achievable. In the worst case, the substrate may undergo warping deformation and heat cracks will appear. Furthermore, the distance between the electrodes can no longer be maintained evenly due to structural heat deformation of the electrodes and other parts of the CVD apparatus.

In order to solve these heat related problems, calculations were carried out to predict substrate deformation during the deposition process based on thermal strength coupled analysis. The results were then used in the thermal design of the CVD apparatus. As a result, a structure was adopted by which heat generated during the deposition process is removed from the electrodes by circulating coolant through the electrodes, thereby making it possible to better limit and prevent deformation and cracking of the substrate.

Figure 5 shows the results of this analysis. It was predicted that when there is no electrode cooling, the temperature of the substrate would rise during film deposition to more than 40°C and that about 1 substrate sheet in 1000 would crack due to differences in temperature between the front and back surfaces and the interior of the substrate. The application of electrode cooling would significantly reduce the rate of such defects by limiting the temperature to less than 10°C and hence, reduce the probability of substrate cracking to approximately one sheet in 100 000 during film deposition.

Based on these results, stable film deposition has become possible under conditions which allow for the introduction of the large power input needed for the high-speed deposition of microcrystalline-Si. Hence, a high-speed deposition rate of 1.6 nm/s with a uniform film forming distribution of +/–15% (**Fig. 6**) or even a rate of 2.0 nm/s with a uniform film forming distribution of +/– 20% on a 1.4 m x 1.1 m substrate could be demonstrated and verified. Development efforts are currently continuing to realize even further improvements in high speed deposition rates and film uniformity.

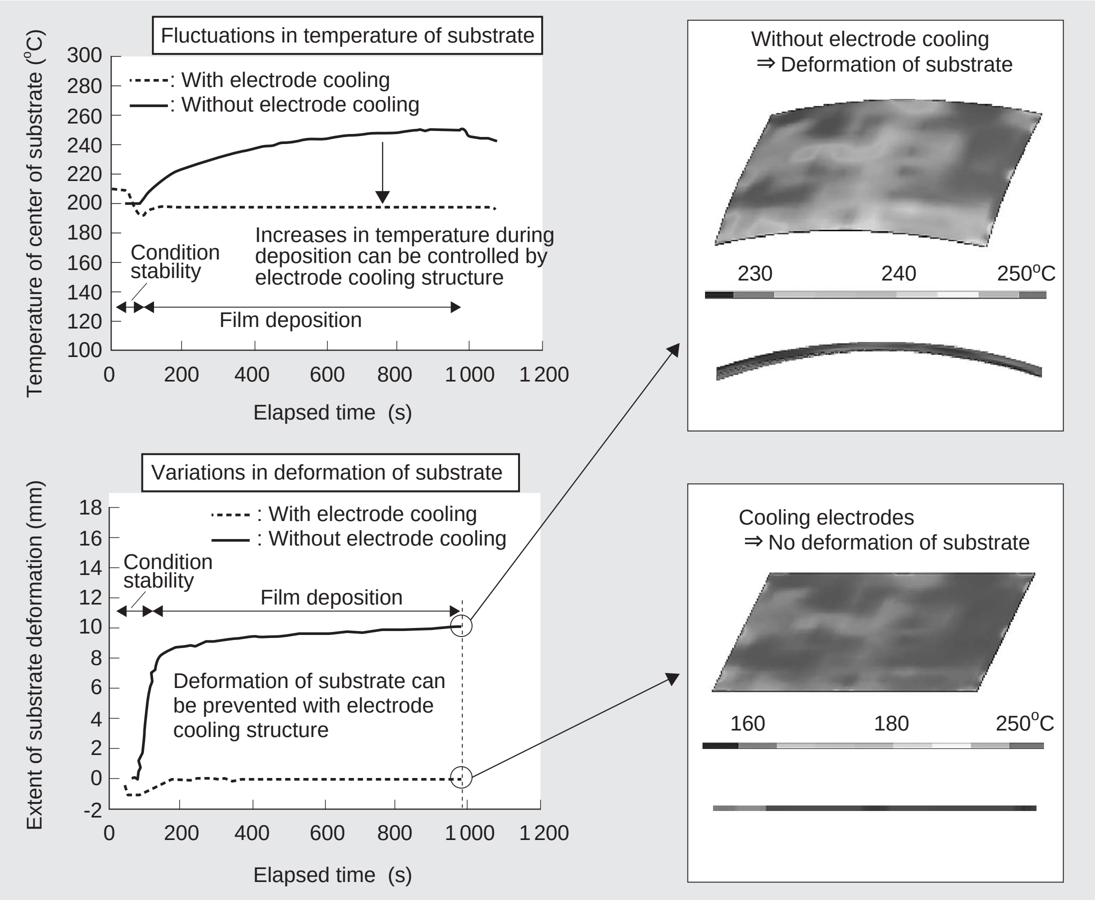

Fig. 5 Results of analysis of fluctuations in the temperature of the substrate and deformation of the substrate during deposition based on thermal strength coupled analysis
Temperature distribution and deformation within the substrate are controlled and contained through electrode cooling.

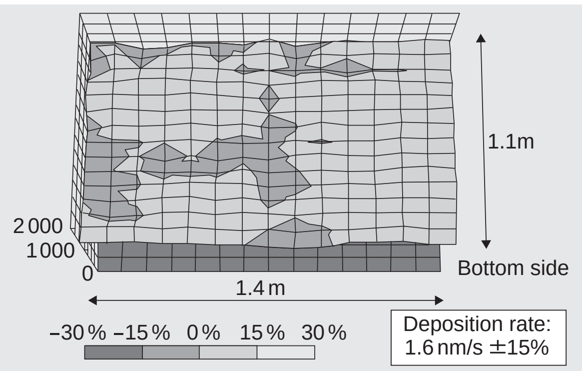

Fig. 6 Results of deposition of microcrystalline-Si film on 1.4 m x 1.1 m large area substrate
Deposition rate distribution depicted on a two-dimensional graph. The microcrystalline-Si film can be deposited on the large area substrate to a distribution of ±15%.

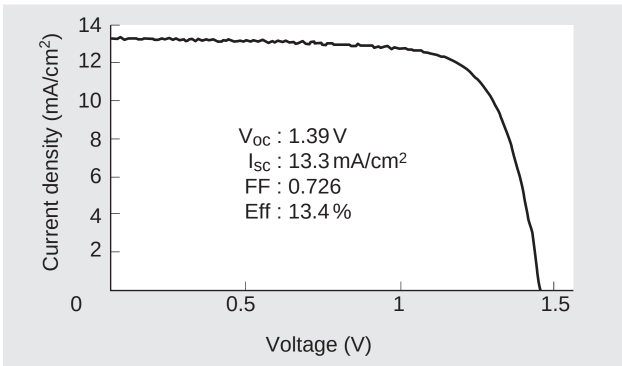

Fig. 7 Characteristic initial power generation curve for a small area tandem thin film solar cell fabricated with a small area plasma enhanced CVD apparatus
A world top level initial conversion efficiency of 13.1% could be attained.

4. Development of a-Si/microcrystalline-Si tandem-type PV solar cell

MHI has been developing technologies to increase the efficiency of a-Si/microcrystalline-Si tandem PV modules using small-scale VHF plasma enhanced CVD apparatus provided for a 5 cm^2 area substrate. Thus far, an initial tandem-cell conversion efficiency of 13.1% has been achieved (**Fig. 7**)[9]. MHI has established tandem module fabrication technology that reflects the high efficiency technologies and techniques established with this small-scale apparatus in the VHF plasma enhanced CVD apparatus used for the fabrication of 40 cm x 50 cm medium sized substrates. We have also established tandem modularization technology based on the development of stable film forming technology that applies a new type of cooled electrode structure and laser scribing technology for use in the fabrication of tandem PV modules, described above, in which a conversion efficiency exceeding 11% could be obtained in a tandem module of the above size[10].

In order to integrate these technologies, productivity and performance verification tests were carried out on a tandem a-Si/microcrystalline-Si PV module using a VHF plasma enhanced CVD apparatus capable of forming a film on a 1.4 m x 1.1 m substrate for practical use. The performance of the microcrystalline single cell using this equipment was confirmed to be already equivalent to that of the small-scale apparatus used for 5 cm^2 substrates, namely a deposition rate of 2.0 nm/s and an efficiency of approximately 8.5% (**Fig. 8**). The power capacity of the new system will be increased to achieve the same level of performance as that described above even at film forming speeds of 2.5 nm/s or faster, and an efficiency of 12 % is planned to be demonstrated for tandem type modules of this size.

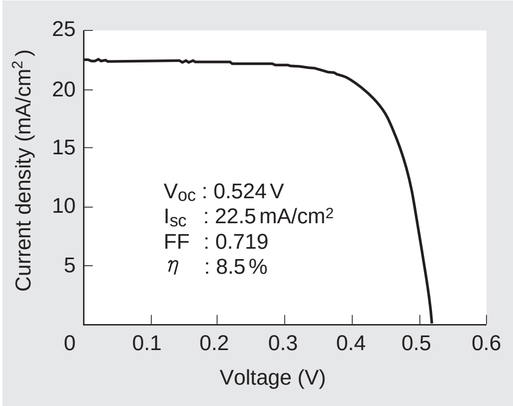

Fig. 8 Initial power generation characteristics of microcrystalline-Si single junction solar cell on a large area substrate
It has become possible to achieve the same level of performance for a large area system as the results of factor tests achieved with a small scale plasma enhanced CVD apparatus.

5. Conclusion

MHI has been developing a-Si/microcrystalline-Si tandem PV modules as one of the technologies for attaining the high efficiency required for low cost thin film Si PV modules. With the success in achieving an initial conversion rate of 13.1% for tandem cells obtained from experiments conducted on small area cells used in small-scale apparatus having a substrate with an area of 5 cm^2, electrodes for microcrystalline-Si film deposition and VHF power supply technologies were newly developed and applied in a new plasma enhanced CVD apparatus. These achievements have made the practical application of technology for large area, high-speed film deposition of areas 1 m^2 in size at a rate of 2.5 nm/s or faster feasible.

In addition, it was confirmed that the microcrystalline-Si single cells produced with this apparatus had a level of performance comparable to that of cells produced with the small-scale apparatus. Further improvements in the quality and uniformity of the film are expected to achieve a target conversion efficiency of 12%, and techniques and technologies for realizing lower costs are scheduled.

Lastly, the authors would like to add that development of the technologies for large area, high-speed film deposition for microcrystalline-Si tandem PV modules described in this report was carried out under a commission by NEDO, as well as with the advice and guidance of various cooperating universities and research institutes. We would like to extend our sincere appreciation to NEDO and each university and research institute that has contributed to this research work for their kind assistance and guidance.

References

(1) http://www.nedo.go.jp/taiyoshitsu/ (2003-7)
(2) Takeuchi et al., Development of Amorphous Silicon Photovoltaic Solar Cell, Mitsubishi Juko Giho Vol. 37 No. 1 (2000) p.26
(3) H. Curtins, N. Wyrsch, M. Favre and A. V. Shah: Plasma Chem. Plasma Process. 7 (1987) 267.
(4) MHI's Photovoltaic Power Generation System, Mitsubishi Juko Giho Vol. 39 No. 3 (2002) p.172
(5) Y. Takeuchi, A. Takano, H. Mashima, K. Kawamura, Y. Yamauchi and H. Takatsuka, "Development of Large Area VHF Plasma CVD and its Application to Si Thin Film Solar Modules", Proceedings of the 19th European Photovoltaic Solar Energy Conference and Exhibition (2004) p1378
(6) Yonekura et al., High Technology Achieving Photovoltaic Solar Cell with High Cost-Performance, Mitsubishi Juko Giho Vol. 40 No. 6 (2003) p.320
(7) Noda et al., Photovoltaic Module as Source of Infinite Energy for the Earth, Mitsubishi Heavy Industries Technical Review Vol. 42 No. 1 (2005)
(8) T. Matsui, M. Kondo and A. Matsuda, "Microcrystalline silicon solar cells grown at 20-30•ð/s by high pressure silane-depletion plasma", Proceedings of 3rd World Conference on Photovoltaic Energy Conversion (Osaka,2003) p.1570
(9) S. Goya, Y. Nakano, N. Yamashita, et al., "Development of amorphous silicon/ microcrystalline silicon tandem solar cells", Proceedings of 3rd World Conference on Photovoltaic Energy Conversion (Osaka,2003) p.1849
(10) H. Takatsuka, M. Noda, Y. Yonekura, Y. Takeuchi and Y. Yamauchi, Solar Energy, Vol.77 (2004) p.951


Yasuhiro Yamauchi


Hiromu Takatsuka


Keisuke Kawamura


Nobuki Yamashita


Masayuki Fukagawa


Yoshiaki Takeuchi