Development of high efficiency flexible solar cells

— Management of “Flexible Solar Cell Substrates Consortium” and its achievements —

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Elemental technological challenges required for the development of flexible solar cells have been clarified and a consortium system to solve the problems has been established based on industry-academia-government collaboration. The technology to form texture on polymer base materials indispensable for high efficiency has been developed, and we have succeeded in preparation of thin-film silicon solar cells on polymer base materials whose efficiency is comparable with that of cells prepared on glass substrates. The stage has already moved from research within the consortium to practical realization research in individual enterprises. Establishment process, management policy, patent strategy and training of young researchers of the consortium are described in this paper.

Keywords : Flexible thin-film solar cells, consortium study, polymer base materials, texture, training of young researchers

1 Objectives for the development of flexible solar cells

Recently, the market for photovoltaics is expanding dramatically, and the growth rate is kept at about 40~50 % compared to the previous year. The annual world production volume surpassed 23 GW in 2010. This figure is equivalent to 23 nuclear power plants at peak power. The market is expected to grow steadily, and the annual production volume will reach at least 100 GW by 2030. For the diffusion and expansion of photovoltaics, the lowering of installation cost through weight reduction and the expansion of installation space are important. Since cover glass is used for the light-receiving surface in ordinary solar cell panels, in many cases, the panels cannot be installed on roofs with low withstand load, and the installation may incur considerable cost due to the additional reinforcement of the roof. On the other hand, the flexible solar cells using polymer or metal sheet as base material do not use glass, and weight reduction to about a fraction or 1/10 of the conventional solar cell panel may be possible. This also contributes to increasing the installable space. Other advantages of the flexible solar cell include: it can be applied to curved surfaces, will not break like glass and therefore is safe, has excellent productivity since the roll-to-roll process can be used in manufacturing, and it is easy to transport and store.

2 Strategy and scenario for the development of flexible solar cells

Of the various flexible solar cells, the flexible thin-film silicon solar cell is already being mass-produced in Japan, and is diffusing gradually. It is known that the thin-film silicon does not have high photoabsorption coefficient, and the photoabsorption layer cannot be thickened to suppress the decreased performance due to light irradiation. Therefore, to increase efficiency, it is important to find some way of confining the light in the photoabsorption layer. In general thin-film silicon solar cells, the sunlight is utilized efficiently by using the texture formed on the transparent conductive oxide surface for confinement. For example, in the superstrate thin-film silicon solar cell, where the layers are formed from the front side in the order of transparent conductive oxide, p-type silicon doped layer, i-type silicon photoabsorption layer, n-type silicon doped layer, transparent conductive oxide, and back-side metal electrode, the light is irradiated from the glass substrate side as shown in Fig. 1. Therefore, to achieve increased efficiency, the texture is formed on the transparent conductive oxide surface in the front side to scatter the light and confine it to the photoabsorption layer.

Asahi-U manufactured by Asahi Glass Co., Ltd. is a glass substrate on which fluorine doped tin oxide (FTO) transparent electrode is formed, and it is known that the FTO surface with texture optimal for amorphous silicon solar cells can be obtained. In Asahi-U, substrate temperature of about 500 ºC is necessary in the coating process for FTO to form the optimal texture. However, there is no general-use polymer base material with heat resistance of 500 ºC, and higher performance of the flexible thin-film silicon solar cells cannot be achieved by using the same method as in the glass substrate.

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To solve this issue, the strategy of increasing the heat resistance of the polymer base material can be considered, but in this research, we investigated the way to produce the equivalent characteristic as the texture formed on the transparent conductive oxide, by developing a new technology of forming the texture on the polymer base material itself. By doing so, the transparent conductive oxide itself does not have to be prepared at high substrate temperature necessary for the texture formation, and the film preparation condition can be eased greatly.

Such technological development could not be done by the Research Center for Photovoltaics (RCPV; currently, Research Center for Photovoltaic Technologies), AIST alone. While RCPV had abundant experiences and know-how for the fabrication of solar cells, it did not have the technology for the polymer base material or roll-to-roll apparatus necessary to fabricate the flexible solar cells. Therefore, for the smooth and quick execution of research, we conducted a joint research in the industry-academia-government collaborative consortium style, where the findings of industry, academia and government could be accumulated. This was led by the material and apparatus manufacturers that possessed the technologies.

There are roughly two objectives of the consortium style joint research. One is to accelerate the development by rapid accumulation of technologies, where multiple private companies engage in concentrated research on a topic, and this may also accelerate the transfer of the results to industry. Second is to conduct on-the-job training of the joint researchers dispatched from the private companies to AIST, and the building of human network as well as the sharing of research results can be expected through the collaborative research by multiple companies. The following account depicts the activities of the "Flexible Solar Cell Substrates Consortium" that was established to execute the R&D according to the above scenario.

The first phase of the "Flexible Solar Cell Substrates Consortium" was from June 2006 to March 2008. Eight companies participated: Ishikawajima-Harima Heavy Industries Co., Ltd. (changed its name to IHI Corporation), Ishikawa Seisakusho, Ltd., Kimoto Co., Ltd., Tsutsunaka Plastic Industry Co., Ltd. (merged with Sumitomo Bakelite and changed its name to Sumitomo Bakelite Co., Ltd.), Teijin DuPont Films Japan Ltd., The Nippon Synthetic Chemical Industry Co., Ltd., Mitsubishi Gas Chemical Company, Inc., and Reiko Co., Ltd. The Industrial Research Institute of Ishikawa and a solar cell company served as observers. Figure 2 shows the organization of the first phase of the consortium.

The second phase was from April 2008 to March 2010. Seven companies participated: Arisawa Manufacturing Co., Ltd., Kimoto Co., Ltd., Sumitomo Bakelite Co., Ltd., Teijin DuPont Films Japan Ltd., Toshiba Machine Co., Ltd., The Nippon Synthetic Chemical Industry Co., Ltd., and Mitsubishi Gas Chemical Company, Inc. The same solar cell company from the first phase participated as the observer. The third phase is in progress since April 2010, with the participation by five companies: Kimoto Co., Ltd., Teijin DuPont Films Japan Ltd., Toshiba Machine Co., Ltd., The Nippon Synthetic Chemical Industry Co., Ltd., and Mitsubishi Gas Chemical Company, Inc. Currently, the research has entered the phase of realization. Figure 3 shows the realization scenario of this consortium, limited to the content described in this paper, and indicates the members involved in this research topic and their role divisions.

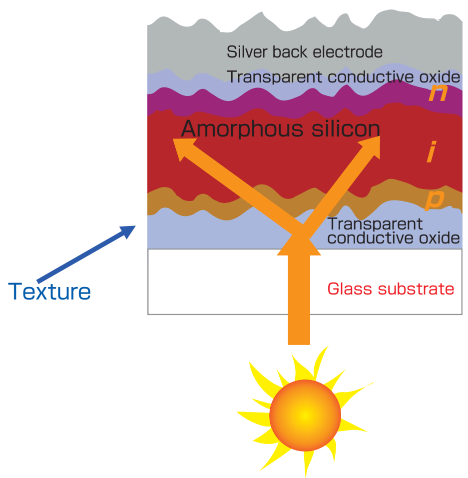

Fig. 1 Principle of light confinement in amorphous silicon solar cells

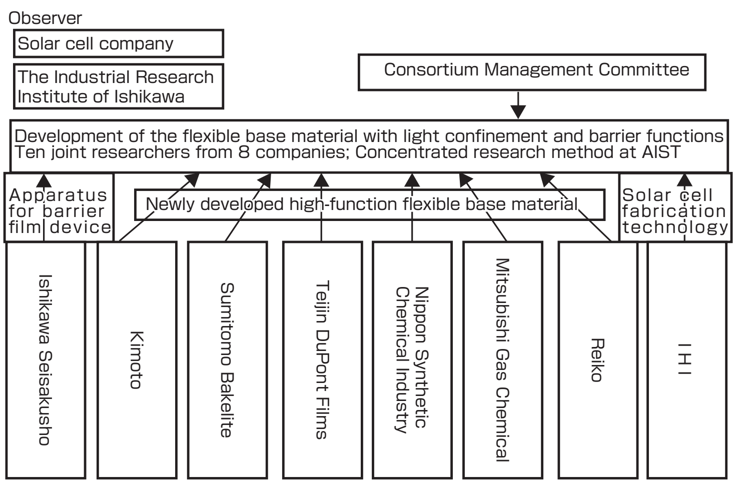

Fig. 2 Organization of the "Flexible Solar Cell Substrates Consortium" (Phase 1)

3 Elemental technology topics needed for the development of flexible solar cells

The "Flexible Solar Cell Substrates Consortium" designated the basic elemental technology to be the technology for forming the texture suitable for light confinement in the thin-film silicon solar cells, onto the polymer base material itself. By doing this, the transparent conductive oxide does not have to have the texture added, and this will ease the conditions for film preparation of the transparent conductive oxide such as the substrate temperature, and the process will be applicable to the polymer base materials with low heat resistance. The idea of forming the texture onto the polymer base material itself was not obtained for the first time in this consortium, but several prior reports had been published[1][2]. For example, the transfer method by stamp with the texture, or the method using lithography had been suggested. However, the transfer by stamping is limited to thermoplastic polymer material only, and the printed texture does not have sufficient precision or reproducibility. In the method using lithography, it is difficult to obtain the ideal texture, and the lithography apparatus is expensive. In this research, the requirements were set that the technology should be universal where any polymer base material could be used and the texture suitable for light confinement could be transferred accurately. We investigated the new method for forming the texture onto the polymer base material. As a result, we concluded that the desirable results could be achieved with the substrate laminated with UV curable acrylic resin onto which the texture had been transferred from a mold. In this paper, we present the results of the comparison of the base material to which the texture of the Asahi-U had been transferred and the base material to which the texture of the moth-eye structure, which is known as a non-reflecting structure, had been transferred.

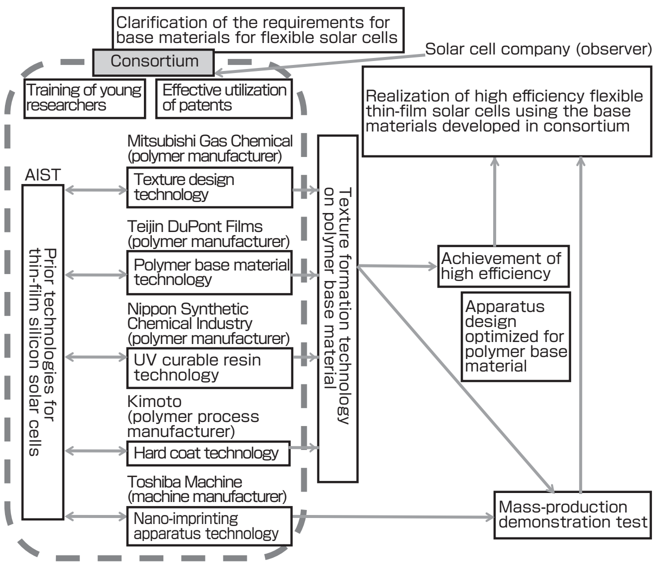

Fig. 3 Scenario for the realization of flexible thin-film silicon solar cells in a consortium style

The examples using the polyethylene naphthalate (PEN) film and polyimide (PI) film as the polymer base materials will be presented in this paper. However, the base materials that can be used in this method are not limited to those films, and the method has been shown to be effective in other polymer base materials such as polyethylene terephthalate (PET) and polycarbonate (PC). It has also been found to be usable on glass substrates.

4 Organization and management of the consortium

4.1 Role division in the consortium

While the topics of elemental technologies necessary for the development of flexible solar cells became clear, it was necessary to combine the material technologies for polymer base material and UV curable acrylic resin, process technology for laminating the layers, simulation technology for optimal texture, roll-to-roll apparatus technology needed for mass-production, and process and device technologies for thin-film silicon solar cell fabrication. The RCPV did not have all such technologies, and as mentioned in chapter 2, it was determined that the research should be carried out as a joint research in the industry-academia-government collaboration consortium. In this chapter, we present the specific management policy applied to the consortium.

In the "Flexible Solar Cell Substrates Consortium", AIST organized the research and was in charge of the investigation of the conditions for fabricating the solar cells and the transparent conductive oxide on the polymer base material, while the participating companies were in charge of the development of the polymer base material. As shown in Fig. 3, the role division of the participating companies was as follows: Mitsubishi Gas Chemical Company, Inc. designed the texture by simulation, Teijin DuPont Films Japan Ltd. developed and supplied the PEN film (Teonex®), The Nippon Synthetic Chemical Industry Co., Ltd. developed and supplied the UV curable acrylic resin, Kimoto Co., Ltd. applied the hard coat to the polymer base material surface, and Toshiba Machine Co., Ltd. was in charge of the transfer of the texture to the acrylic resin by nano-imprinting technology using the single substrate method or the roll-to-roll method. The texture design is currently under development, and in this paper, only the results of the transfer of the moth-eye structure and the Asahi-U texture will be described. While Asahi-U uses the texture obtained by self-formation, the base material developed in this consortium has the texture formed by transfer, and the textures can be varied arbitrarily. Therefore, through the precise design of the texture, a solar cell with performance surpassing that using the Asahi-U substrate may be achieved. This implies that high efficiency solar cells can be achieved on polymer instead of the current thin-film silicon solar cells formed on a glass substrate. Therefore, the design of the texture is an extremely important research topic.

4.2 Management of the monthly research meeting

This consortium employed the concentrated research method in which the researchers were dispatched from the participating companies to AIST. A monthly research meeting in which the researchers of all companies participated was held to share the results. Through the discussions at the meetings, the setting of the collaborative topic among the participants and the review of the direction of the research topic were done flexibly. Through such activities, derivative results that were not expected at the start of the research were obtained. Therefore, comments at the monthly research meetings were considered extremely important, and the minutes of the meetings were kept carefully, since they might become evidences for recognizing a patent.

Since the companies that may be mutual competitors participated in this consortium, we set the following rules for the joint monthly research meetings. The synthesis methods and know-how that were regarded as the most important factors by the materials manufacturers that were the main members of the consortium did not have to be disclosed. The synthesis of the materials would be basically done within the participating company, and in principle, the findings should not be shared. On the other hand, the results concerning the fabrication of solar cells were considered as common knowledge among the participating companies, and in principle, disclosure was required for the characteristics of the materials that may affect the solar cell performance. Also, when combining the materials, it might be necessary to know the synthesis method for the component materials, and in such cases, separate non-disclosure agreements were signed among limited members. We believe one factor of the success of this consortium was to clearly separate the technologies that should be shared by the participants and the technologies that would be developed individually. By doing so, the advantages of consortium participation were maximized and the individual interests of the companies were protected.

4.3 Management committee and patent strategy

We set the Consortium Management Committee composed of the representatives of the participating companies and AIST to be the highest decision-making body. The Management Committee determined the handling of the results, recognized the inventor when a patent was made, and adjusted the conflicting interests. By having the participants follow its decisions, fair and transparent management of the consortium became possible and smooth management was realized. For the patents created in the consortium, the organization to which the inventor belonged became the applicant, and the share was divided according to the degree of contribution. However, participants who were not applicants may be licensed to use the patent upon payment of the appropriate licensing fee. This meant that one of the motivations to participate in the consortium was that there would be no domination by a single company. The handling of the patents became possible by setting the two basic principles: the results pertaining to solar cells were common assets of the consortium, and the findings and know-how pertaining to the materials that came from the R&D within the participating companies should not be brought into the consortium. Moreover, the results obtained at the consortium would be basically published after the patent application was filed.

4.4 Policy for training young researchers

Although this consortium was operated by private funds without public money, majority of the apparatuses used in the research were purchased by AIST's research funds before the establishment of the consortium, and much know-how applied to the research was developed by AIST. Also, AIST provided matching funds where the upper limit was the total of joint research fundings from the private companies. Considering these situations, the research results are actively published to fulfill the mission as a public research institute. In the publication of research results, we believe it was beneficial in training the young researchers dispatched from the participating companies, to do presentations at international academic conferences and to write papers in English. There were cases where the research greatly advanced from the comments provided at the academic conferences, and cases where business opportunities expanded for the participating company through newly formed human networks. Many seminars were held as part of the consortium activities for the joint researchers dispatched to AIST for the purpose of acquiring a wide-range of knowledge about solar cells, so they would be able to act as experts on solar cells at their respective companies after the completion of the joint research.

5 Results of the consortium research

The result of the consortium research was the development of the base material consisting of UV curable acrylic resin onto which the surface texture of Asahi-U, the glass with

Fig. 4 Photograph of PEN film onto which the texture of Asahi-U has been transferred

transparent conductive oxide manufactured by Asahi Glass, was transferred and then laminated onto the PEN or PI films. Figure 4 shows the photograph of the developed base material. The base film of this material is PEN. The light scattering is reinforced by the transferred texture, and the film appears white to the naked eyes.

Figure 5 shows the outline of the fabrication method of the base material. Since the texture became reversed if the Asahi-U or the moth-eye structure was transferred directly, as shown in the scanning electron microscope photograph in Fig. 5, the mold to which the desired structure was initially transferred was used. The UV curable acrylic resin monomer was coated to the mold, and then the general-use PEN or PI film was laminated on top. By irradiating with ultraviolet light after laminating, the monomer changed into polymer. When the film was peeled off from the mold, the polymer material laminated with acrylic resin onto which the texture was transferred was obtained. As shown in the atomic force microscope photograph in Fig. 5, it can be seen that the texture is present on the base material surface. This method can be used not only for the single substrate method shown in Fig. 5, but it has been proven applicable to the roll-to-roll method as shown in Fig. 6, and there seems to be no barrier to mass production.

The current-density and voltage characteristics of the amorphous silicon solar cells fabricated on the PI and PEN films are shown in Fig. 7, and the quantum efficiency spectra are shown in Fig. 8. The amorphous silicon solar cell has a substrate structure with the following structure: polymer base material, acrylic resin layer with texture, gallium doped zinc oxide layer, silver back surface electrode layer, gallium doped zinc oxide layer, n-type amorphous silicon doped layer, i-type amorphous silicon photoabsorption layer, p-type amorphous silicon doped layer, indium tin oxide transparent electrode, and silver collector electrode. It is shown in Fig. 7 that sufficient light confinement is obtained on the polymer base material, and the current density increases by using the base material with the texture. From Fig. 7, it also becomes clear that there is

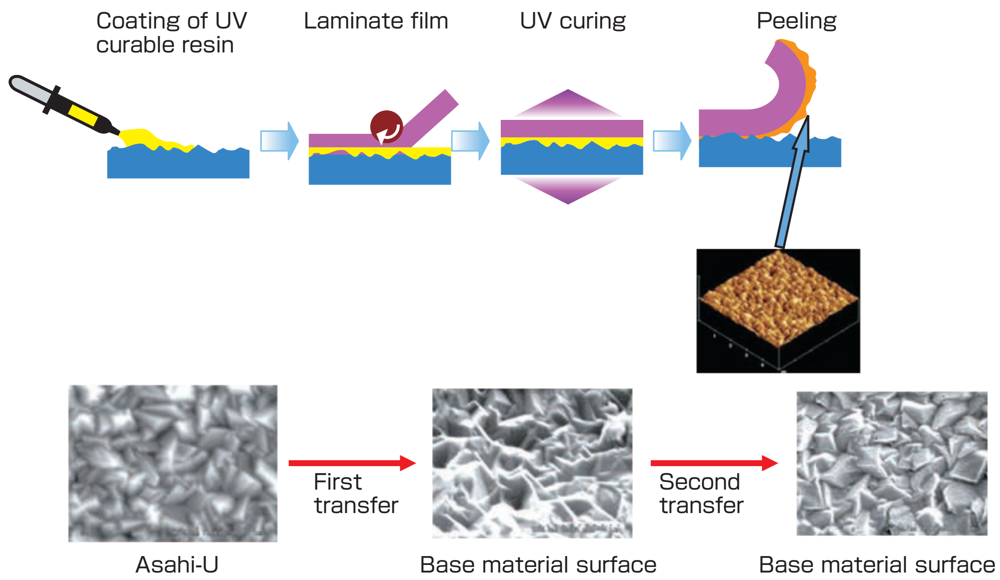

Fig. 5 Outline of the base material fabrication by single-substrate method and the microscope photograph of Asahi-U and base material surfaces

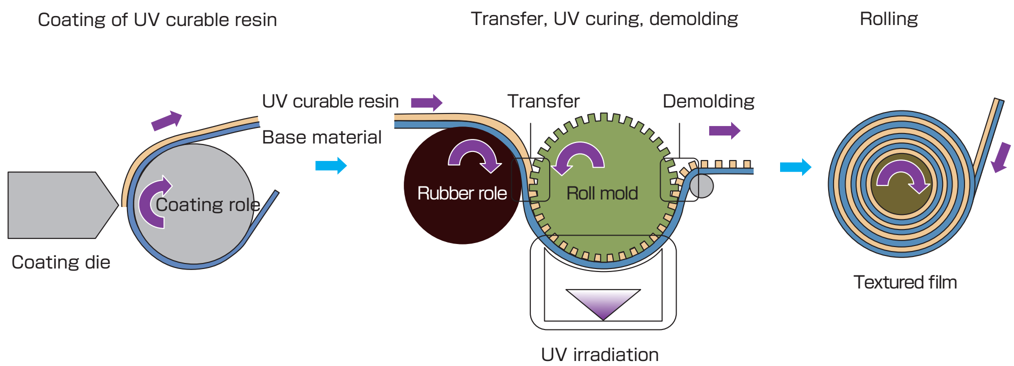

Fig. 6 Outline of base material fabrication method by roll-to-roll method

Table 1. Characteristics of the solar cells fabricated on various base materials

Base material	Short-circuit current density (mA/cm^2)	Open-circuit voltage (V)	Fill factor	Efficiency (%)
Asahi-U	15.7	0.88	0.59	8.2
Asahi-U transferred PI	15.0	0.84	0.65	8.3
Non-textured PI	11.7	0.83	0.68	6.5
Asahi-U transferred PEN	15.6	0.87	0.60	8.1
Moth-eye transferred PEN	14.1	0.87	0.62	7.7

an optimal shape of the texture, and the current density of the texture of the transferred moth-eye structure does not come close to the current density of the texture of the transferred surface structure of Asahi-U. Also, from Fig. 8, when the base material on which the texture is formed is used, it is shown that the quantum efficiency in the long-wavelength region increases due to light confinement. As shown in Table 1, in the case where the polymer base material was used, solar cell properties equivalent to the one fabricated on Asahi-U were obtained. This means that we succeeded in fabricating the amorphous silicon solar cell on the polymer base material, with equivalent performance to the one fabricated on a glass substrate. With the research result from this consortium, one of the participating companies, Toshiba Machine Co., Ltd., won the Nanotech Award in the Nano-fabrication Technology Category of the 2009 International Nanotechnology Exhibition and Conference (nano tech 2009). Also, although the details will not be discussed in this paper, a participant of the consortium, Sumitomo Bakelite Co., Ltd. fabricated the amorphous silicon solar cell with superstrate structure using this transfer technology, on SUMILITE® that is its organic-inorganic hybrid film, and demonstrated its effectiveness[3].

In this consortium, the formation of the barrier film onto the polymer base material was investigated with Ishikawa Seisakusho, Ltd. and the Industrial Research Institute of Ishikawa, for the purpose of realizing a highly weather-resistant flexible solar cell. To facilitate the introduction to material companies, we set the goal of not using monosilane, a special material gas, as the raw material of the silicon nitride barrier film by chemical vapor deposition. When hexamethyldisilane

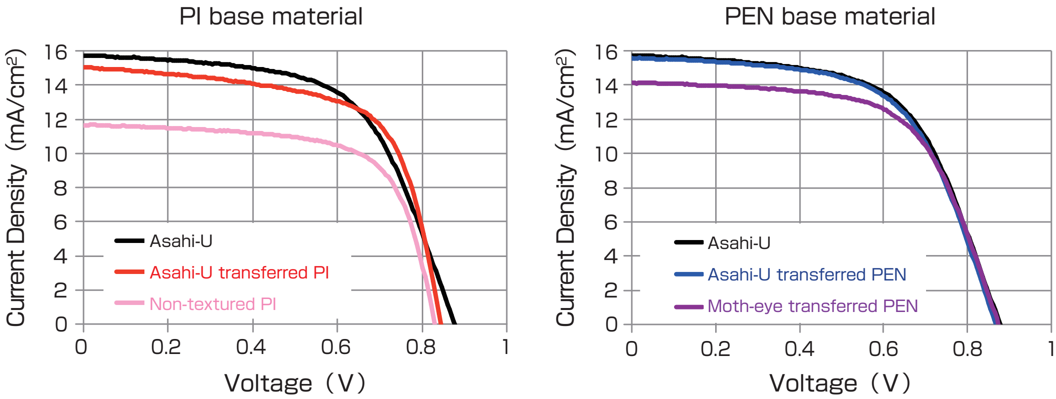

Fig. 7 Current-density – voltage characteristics of the amorphous silicon solar cells fabricated on PI and PEN films

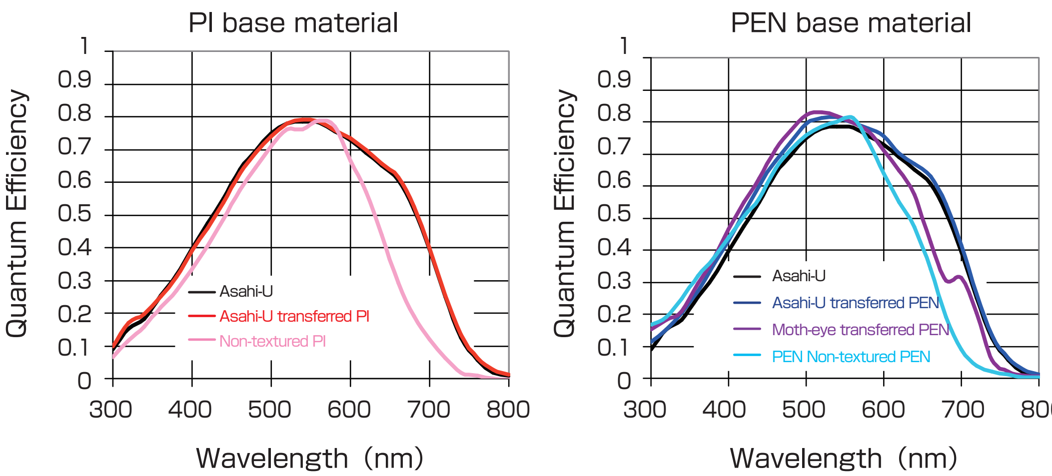

Fig. 8 Quantum efficiency spectra of the amorphous silicon solar cells fabricated on PI and PEN films

was used as raw material gas, the water vapor transmission rate of 0.02 g/m^2day was achieved in the barrier film formed at the deposition rate of 40 nm/min onto the PEN film.

6 Remaining issues

It has been six years since the start of the “Flexible Solar Cell Substrates Consortium”, and the goals at research phases and laboratory levels were mostly achieved by accumulating the experiences and the findings of AIST and the participating companies. For product realization, the prototype fabrication at the solar cell company will become important. To replace the current base materials with the materials developed at the consortium, the design of the solar cell device structure may have to be changed, and the decisions of the solar cell company will become important. In the future, the stage will move to the development phase with actual application in view, through collaboration with the solar cell company that has participated as an observer from the initial research stage of the consortium. AIST, the participating companies, and the solar cell company started consideration for technological transfer to the solar cell company. Also, utilizing the consortium management method for the “Flexible Solar Cell Substrates Consortium”, the “Consortium Study on Fabrication and Characterization of Solar Cell Modules with Long Life and High Reliability” was established with 44 organizations including 33 private companies and the Photovoltaic Power Generation Technology Research Association, starting October 1, 2009, to engage in research to reduce the cost of photovoltaics through increased lifetime and reliability of the solar cell module, as well as the development of the accurate testing method to ensure reliability. Currently, we engage in R&D with the phase II consortium with 78 organizations including the private companies.

The fusion of knowledge from wide-ranging fields from materials, processes, devices, and systems is necessary for the technological development of photovoltaics. In the field of photovoltaics, it is well known that the close industry-academia-government collaboration was done from the initial Sunshine Project that was started immediately after the First Oil Shock, and this bloomed as the current industry. Needless to say, the technological developments through the collaboration of various fields will become even more important for the further advancement of the photovoltaic industry. Moreover, as much as the technological development, for the continuous development of the industry, training of young people such as the researchers of the private companies, post-doctors, and students is important through on-the-job training in the industry-academia-government collaboration. We are working on the consortium management so the joint researches by the industry-academia-government collaboration in the consortium style conducted by the Research Center for Photovoltaic Technologies of AIST will contribute to the development of new technologies, technology transfer, and training of young researchers.

Acknowledgements

The research results of the “Flexible Solar Cell Substrates Consortium” described in this paper were obtained through the joint research with: Toshikazu Niki of Ishikawa Seisakusho, Ltd.; Joji Nobe and Susumu Kurishima of Kimoto Co., Ltd.; Yusuke Inoue and Hideo Umeda of Sumitomo Bakelite Co., Ltd.; Rei Nishio and Takashi Nakahiro of Teijin DuPont Films Japan Ltd.; Akihiko Hagiwara of Toshiba Machine Co., Ltd., Katsuhiko Katsuma and Seiichiro Hayakawa of The Nippon Synthetic Chemical Industry Co., Ltd.; Terutaka Tokumaru of Mitsubishi Gas Chemical Company, Inc.; and Yukiko Hara, Chizuko Yamamoto, Minoru Karasawa, Yoko Takeyama (currently, Tokyo Institute of Technology), and Nana Hozuki (currently, Photovoltaic Power Generation Technology Research Association) of AIST. For their valuable advice on this research, I am grateful to: Michio Kondo, director; Takashi Koida, senior researcher; and Takuya Matsui, senior researcher, Research Center for Photovoltaic Technologies, AIST.

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Discussion with Reviewers

1 Title

Comment (Yoshiro Owadano, Environment and Energy, AIST)

This is a very valuable paper as it is a report of a large-scale consortium for technological development originally planned and organized by AIST. Please modify the main title and the subtitle of the paper so they will indicate the content of the development and that it was managed in a consortium style.

Answer (Atsushi Masuda)

As you suggested, I modified the title to: Development of high efficiency flexible solar cells - Management of “Flexible Solar Cell Substrates Consortium” and its achievements.

2 Breakdown of the contents and titles for each chapter

Comment (Yoshiro Owadano)

Please use specific titles for each chapter such as shown below and break down the rather long text into paragraphs according to content, to make the paper easier to read. My suggestion is breakdown of contents as follows:

- Background and setting of themes for technological development
- Organization of the consortium and management method
- Results obtained

etc..

Answer (Atsushi Masuda)

I reorganized the structure of each chapter, and changed the chapter titles to reflect the content. For chapter 4, in response to your suggestion, I divided the text into subchapters and added some details.