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Research and Development Trends of Solar Cell for Highly Efficiency

DAISUKE KANAMA, HIROSHI KAWAMOTO
Nanotechnology and Materials Research Unit

1 Introduction

The most notable feature of the solar photovoltaic system is the conversion of the solar energy, which is usually unused, into useful electric energy. Also, it is possible to convert it directly into the electric energy without converting the photon energy into the thermal and chemical bond energy during the electric power generation process, which is unlike many other power generation methods. This process requires little maintenance because of its simplicity, and there is no need to use other energy to maintain power generation for circulation of the coolant water etc. Another benefit is that there is no noise generated. Most importantly, there is the advantage of having very little carbon dioxide emission for each unit of electric power generated, which includes the manufacturing process and the purification of the raw materials.

Figure 1 shows the production flow of the solar photovoltaic system. Although the solar photovoltaic system generates no carbon dioxide during its operation after installation, fossil fuels and other energy sources are needed in the production process for the refinement of materials and other purposes. In general, energy payback time (EPT) is used as one of the indicators to measure the total energy efficiency as a power generation system. EPT is the time it takes for the system to generate energy in the amount equivalent to that required for manufacturing the system. According to the estimate of Photovoltaic Power Generation Technology Research Association and National Institute of Advanced Industrial Science and Technology, EPT is about 1.5 - 2 years for the poly-silicon solar cells, which are the most popular product in the market. [1] The solar photovoltaic system is very effective in terms of energy efficiency, as the average life of the poly-silicon solar cells is about 20-30 years.

As a result of such advantages, the photovoltaic power generation market lead by Japan and Germany, who are far more advanced than other countries, is expected to expand all over the world. [2]

This report will delineate the trend by focusing

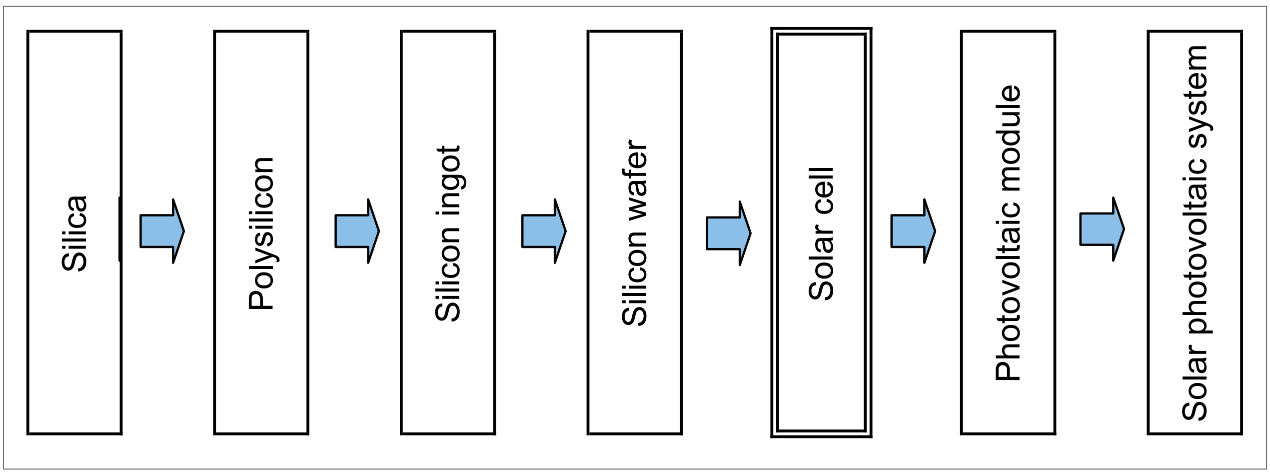

Figure 1 : Production flow of one diagram solar photovoltaic system

Prepared by the STFC based on Reference[3] on the solar cell research and development during the production process shown in Figure 1. Much of the information about the research trend of individual solar cells, such as silicon, organic systems, and compound semiconductors, has already been available. This report will begin from the crystal type, which is most popular in the market, followed by thin films and then the tandem type, which are expected to be ready for mass production within 5 years. This will be followed by the introduction of research and development trends of the solar cell using the quantum dot, which is expected to have an extremely high conversion efficiency, in order to forecast its potential, by summarizing the expected trends of the market. Finally, the implications to the science and technology policy concerning this area are described based on these trends.

2 Current status of solar cell and diversified research and development

2-1 *Current status of crystalline silicon solar cell known as the first generation solar cell – the globalized photovoltaic power generation market and its economic rationality*

The solar photovoltaic system is mostly limited to the markets of Japan and Germany as shown in Figure 2. In the United States however, the solar photovoltaic power generation market has grown, and the expansion into China in recent years shows that this is expected to be extended to other regions and countries in the future. Meanwhile, the photovoltaic power generation lives up to high expectations of the market, but the biggest issue is the cost of power generation. The power generation cost of the current photovoltaic power generation is 40-50 yen/kWh, which is about twice as much as the electricity fee for homes in Japan.

The production turnover of the present solar cell is: about 60% for single-crystal silicon, about 30% for poly-silicon. Therefore bulk crystal silicon makes up 90% of all the used material. As a result, the cost reduction of both crystalline silicon solar cells is the key for the short-term spreading of photovoltaic power generation.

Unfortunately, it is difficult to expect further price decrease of these crystalline silicon solar cells (Figure 3). First, the power generation conversion efficiency of the material is approaching the theoretical value as described below in the next chapter. Therefore, the improvement of the conversion efficiency of the solar cells available in the market has been slight in recent years. Secondly, the price of the materials has soared. The degree of price decreases for solar cells has been declining compared with the price decreases of its auxiliary equipments, as shown in Figure 3. In the

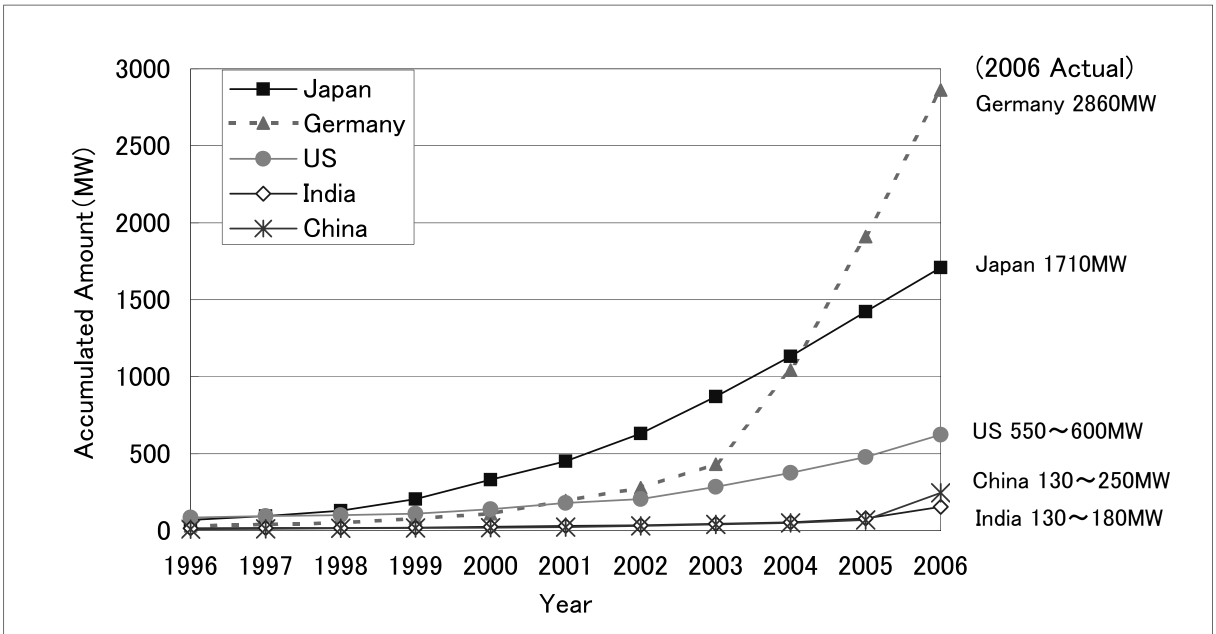

Figure 2 : Amount of solar photovoltaic system of accumulation introduction

Prepared by the STFC based on Reference[3,5]

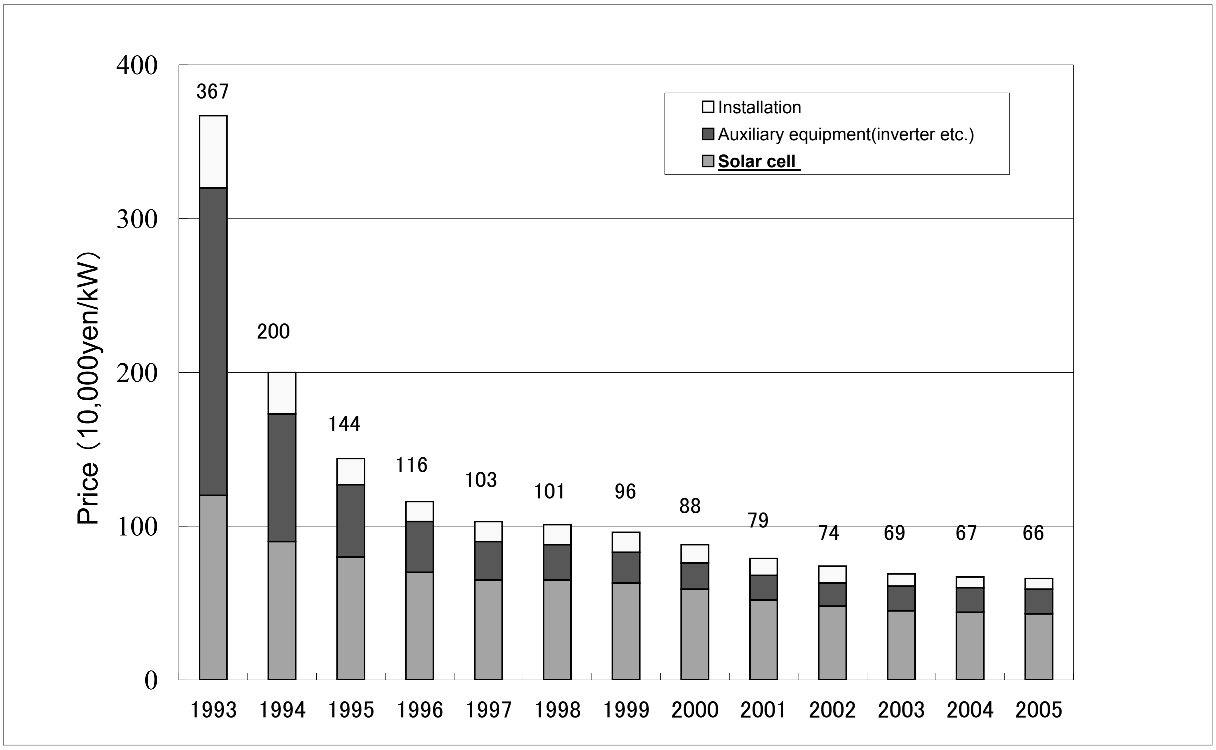

Figure 3 : Solar cell system price for residence

Prepared by the STFC based on Reference[1,3,5]

Table 1 : Production plan of polysilicon of Japan

	Production capacity	..production increase..	Time	Investment	
Tokuyama	8,200ton	3,000ton	2009	45 billion yen	It increases production of 2,500 tons for the semiconductor and 500 tons for the solar cell.
Mitsubishi Material	3,300ton	450ton	2009	5.5 billion yen	The upper load of +1,000 tons is planned by an additional investment of 20 billion yen or less.
Sumitomo Titanium	1,400ton	500ton	2008	6.6 billion yen	+400 tons of 1st step are completed in July, '07.
Nippon Steel Corporation	480ton	480ton	2007	3billion yen	The new factory of 2,000-ton scale is being examined in 2010.
JFE Steel	400ton	300ton	2007	5billion yen	The incremental capacity of the wafer step is examined.

Prepared by the STFC based on Reference[3]

industrial structure of the crystalline silicon solar cell, the price for production greatly depends on the upstream process. In is the so-called material added-value type structure, most of the sales of the finished products only covers the process up to the silicon wafer process [3] [note 1]. Consequentially, material manufacturing companies have come out with production increase plans for the silicon crystal (Table 1). Production of the silicon crystal strongly depends on the supply of the silica at the most upstream process, and therefore the scale merit of investing facilities is not effective. For that reason, there will be a severe competition in cost for production of the silicon crystal, unless an innovative silicon crystal material process technology is developed in the future. The details of the supply shortage of the material and its countermeasures are presented in the main body of

[NOTE 1]

For reference, the wafer cost composition during the upstream process, in the semiconductor device market, is said to be 3-4%.

[NOTE 2]

As a quantitative standard for the amount of power generation systems to be installed. the Kashiwazaki Kariya Nuclear Plant for example, has the power supply ability of 1.1GW(1,100MW) per reactor system.

January 2007 issue of this magazine.[6]

The accumulated amount of the solar photovoltaic systems in Japan was exceeded by Germany in 2004-2005(Figure 2) [NOTE 2]. This is due to Germany placing an energy policy with strong incentives for the purchase of the photovoltaic power. [7-9] However, the power generation markets of only Japan and Germany are too small of a scale for obtaining the actual results of the solar photovoltaic system. In the future, it is necessary to take cost measures while observing the power generation market worldwide to steadily increase the production turnover (Figure 4).

2-2 Added-value with thin film - development competition of the second generation solar cell

As mentioned earlier, the shift from the crystalline silicon solar cell to the thin film silicon solar cell has rapidly advanced as a countermeasure for industrial structure's strong dependency on the supply and refinement of the material.

Thin film silicon solar cell is mainly comprised of amorphous silicon [NOTE 3] and microcrystalline silicon [NOTE 4]. These thin films are very thin, only a few µm in thickness, which significantly saves the silicon raw material compared to the crystalline

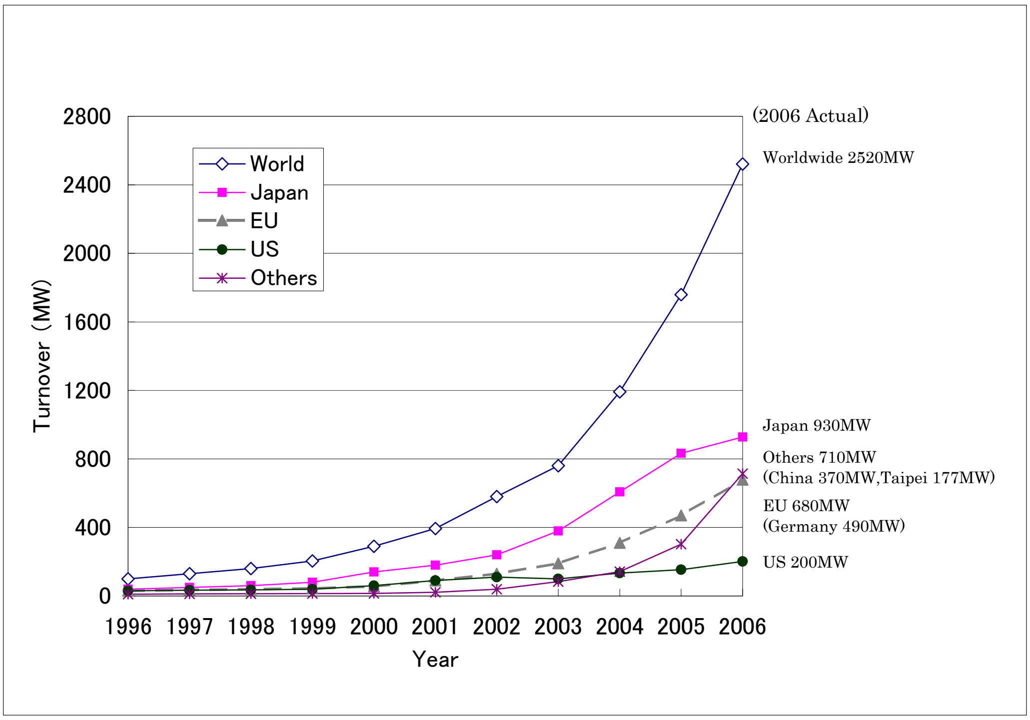

Figure 4 : Turnover of solar photovoltaic system in the world (single year's total)

Prepared by the STFC based on Reference[4,5]

[NOTE 3]
Silicon semiconductor of amorphousness. The energy gap is larger than that of the crystalline silicon, has a High optical-absorption coefficient, and is advantageous because its deposition of film is simple, but it is difficult to increase the conversion efficiency.

[NOTE 4]
It is called a film polycrystalline silicon, and has the structure consisting of the mixture of the crystal phase for several ten nm and the amorphous phase P-i-n junction which places an optical absorption layer (i layer). p type and n-type semiconductor layers are the fundamental structures. It has been used mainly for indoor-use, such as calculators, due to the high efficiency under a low lighting intensity and sensitivity of the short wave light due to its high band-gap energy. Its weak point is that the dangling-bond (uncombined hand in atom) increases due to exposure to strong sunlight to degrade the conductivity, though this issue has began to be solved as a result of new technology to control impurities such as hydrogen.

silicon, which is about 200 μm. Furthermore, the energy required for manufacturing can be saved, because the thin films can be formed at a low temperature, and thus possibly enable mass production at a low-cost. The current power generation efficiency is only a little more than 10%, which is far below that of the poly-silicon as 13-17%. However, it is still possible to improve the efficiency by making the amorphous and microcrystalline silicon to a Lamination type (tandem type). Moreover, selecting a flexible substrate will enable the creation of a flexible solar cell.

Manufacturers with various backgrounds are now considering about entering the thin-film solar cell market (Table 2). If many market players from various fields take part, there will be a need for each maker to have a technical variations and/or manufacturing process for the product.. The key in the market is how they can establish a production process at a low cost and high efficiency for the tandem type cells. The research and development trends of the tandem type will be explained in the next chapter.

3 Basic characteristics of the solar cell and tandem type solar cell

While the preceding chapters introduced the current status and the trends of various manufacturing process of the crystalline silicon solar cell and thin film silicon solar cell, this chapter provides a general view of the basic characteristic concerning the conversion efficiency of the solar cell, and describes in detail the technology of the tandem type.

3-1 Characteristic of sunlight and theoretical efficiency of solar cell materials

Sunlight, which is the energy source of the photovoltaic power generation, may be approximated to the radiation of black body of the sun at almost 6000 C. Sunlight is a light ray of a wide wavelength peaking in the visible spectral range. However, sunlight reaches the earth ground after it is reflected, scattered and absorbed by the atmosphere because the atmosphere exists in the vicinity of the surface of the earth[10][11] (Figure 5). The amount of the sunlight which reaches a certain point on the surface of the earth may vary depending on the latitude of the area. The difference of this radiation total is shown by the indicator of the atmosphere air mass (Air Mass: AM). The air flow from above vertically is called AM-1. In Tokyo during spring or autumn at about noon, it is about AM-1.5, while it is AM-0 in the exo-atmosphere. Naturally, it is necessary to consider the wavelength distribution and strength of the sunlight when designing the solar cell. In the cell design, it is essential to select a material which will absorb the light of the peak wave length zone.

Figure 6 shows calculation results of band-gap energy (Eg) of a major solar cell material, the conversion efficiency achieved to date and theory

Table 2 : Production planning of thin-film solar cell

Firm name	Country	Type	Production capacity	When	Background
< amorphous system >					
Moser Baer India	India	Amorphous Si	Initial: 40MW、200MW, 2009	2007	Optical media manufacturer
Kaneka	Japan	A-Si/film polycrystalline	Increase from 30MW to 55MW	Spring, 2007	Chemical manufacturer
Mitsubishi Heavy Industries	Japan	Microcrystal tandem type	40MW(+Amorphous 10MW)	April 2007	Total heavy machine manufacturer
NexPower Technology	Taiwan	Amorphous Si	12.5MW, early 100M	2008 1Q	Subsidiary company of UMC
Schott Solar	Germany	Amorphous Si	3MW→30MW	2008	Crystal system solar cell
Fuji Electric Systems	Japan	Amorphous Si	40MW (in the future: 150MW)	2009(2011)	Total heavy machine manufacturer
Sharp	Japan	Microcrystal triple type	1,000MW	2010	Consumer electronic manufacturer
< Chemical compound semiconductor >					
Nanosolar	US	CIGS	430MW	2008	Venture company
Miasole	US	CIGS	50MW		Venture company
HONDA	Japan	CIGS	27.5MW	Autumn,2007	Car manufacturer
Showa Shell Sekiyu	Japan	CIS	60MW	2009	Oil refinery

CIGS: $CuInGaSe_2$
CIS: $CuInSe_2$

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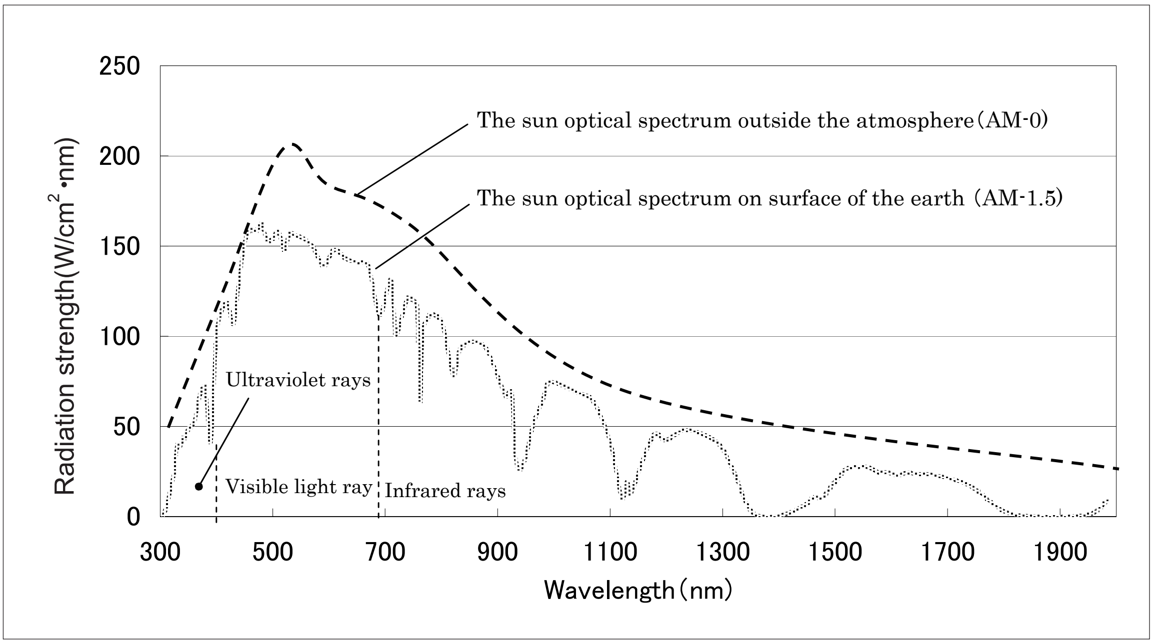


(AM (Air Mass): Air amount where sunshine passes. The air flow from the vertical top is called AM-1)

Figure 5 : Energy spectrum of sunshine in the atmosphere (AM-0) and on surface of the earth (AM-1.5)

Prepared by the STFC based on Reference[10,11]

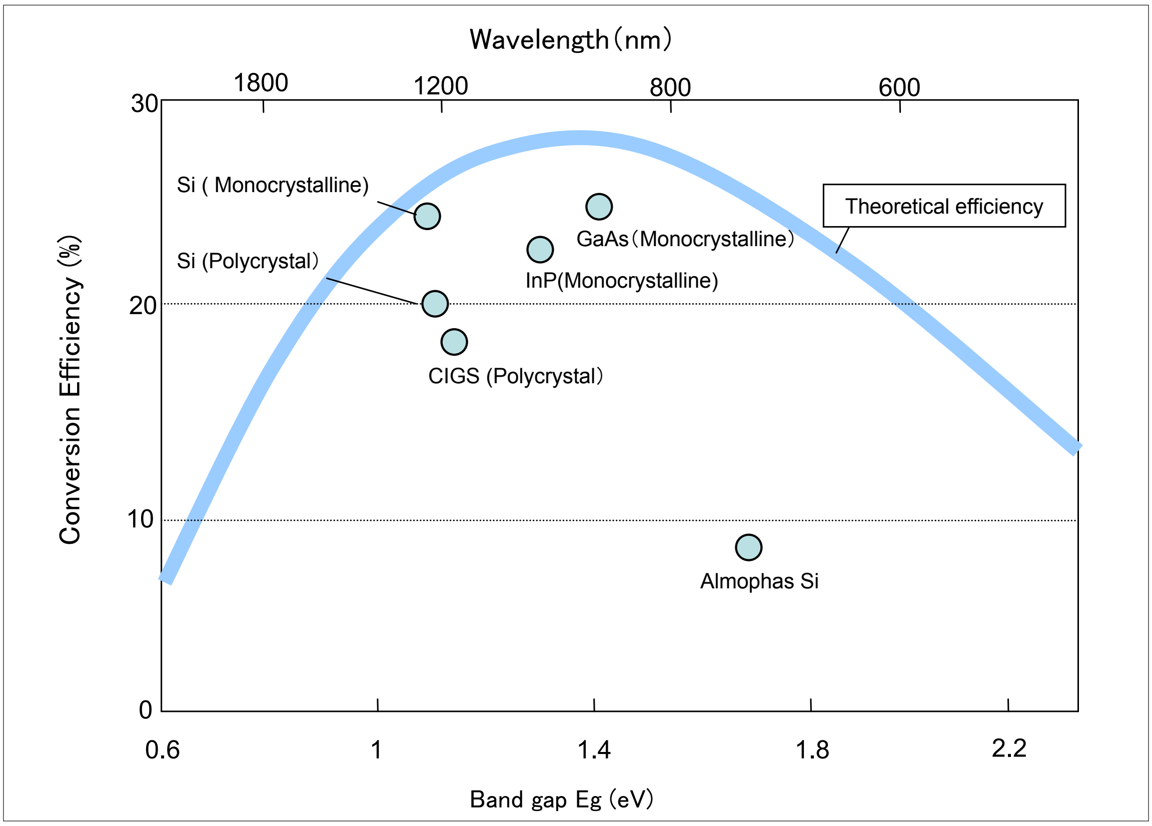


Figure 6 : Band gaps (Eg) of various solar cell materials and conversion efficiencies

Prepared by tne STFC based on Reference[12,13]

marginal efficiency. As shown in Figure 5, the radiant intensity of sunlight becomes the strongest at about 500-700 nm. The sunlight of less energy than Eg, explained in the next paragraph and Figure 7 is not absorbed by the solar cell but simply goes through. Therefore, the material with a Eg of no more than 1.6-1.2eV, which is a slightly thinner wavelength compared to 500-700nm (2.5-1.8eV). Accordingly, the theoretical marginal -efficiency becomes the greatest at this proximity.

For the single-crystal silicon (Eg=1.1eV), a typical solar cell material, 26-28% is the maximum

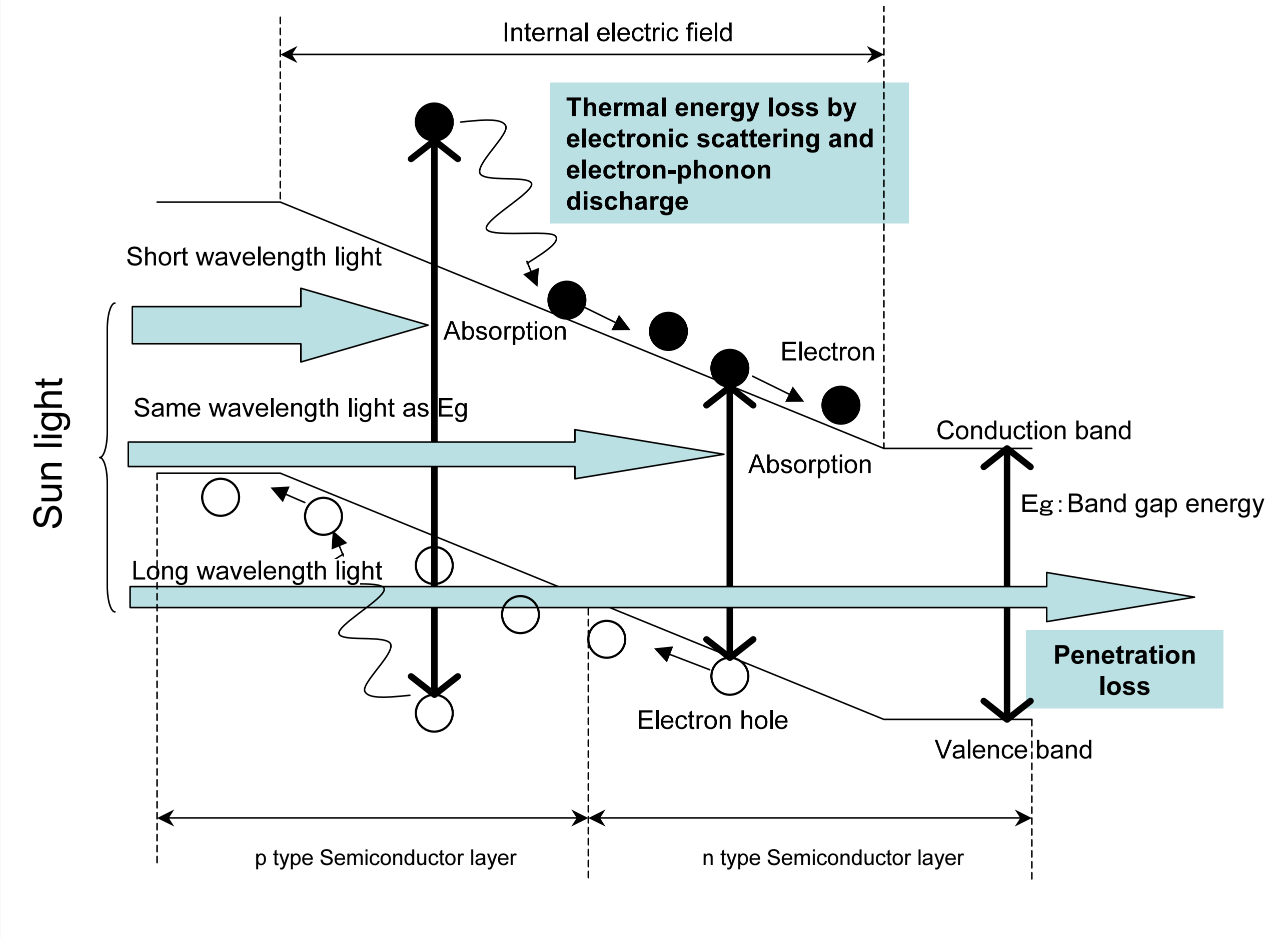


Figure 7 : Energy band structure of a single joint type solar cell and the main energy loss factor

Prepared by the STFC

value of theoretical marginal-efficiency.[14] Chemical compounds such as GaAs and InP are expected to achieve the higher efficiency than that of the single-crystal silicon because it has Eg around the range 1.4-1.5eV, in which the theoretical marginal-efficiency becomes the highest. On the other hand, because of a huge loss of electric current due to defects of the inner grid, the amorphous silicon has not yet achieved the conversion efficiency near that theoretical marginal efficiency.

[NOTE 5]
A solar cell with a pn-connected semiconductor layer structure.

[NOTE 6]
It is the quantum resulting from grid vibration in a crystal. The frequency of the phonon will be limited to be discrete within the frequency structure such as crystal grid. If the crystallizing temperature is increased, the vibration range of the photons will increase.

3-2 Energy loss factor of solar cell

The solar cells aforementioned are called single junction type solar cells, [NOTE 5] as they are formed with a layer of semiconductor connected by pn. Figure 7 shows the energy band structure of a single junction type solar cell and its main energy loss factor. Light rays with various wavelengths come from the sun as shown in Figure 5. An incident light with energy in or around Eg would excite electrons which are at the top of the valence band to a conducting zone. Other incident lights with wider wavelengths would go through the zone, not being absorbed by the semiconductor, or they can be converted into heat by transforming them into phonon energy. [NOTE 6] On the other hand, incident light with much more energy than Eg sends the high-energy electrons to the contracting zone. Afterwards, it would lose the energy in a very short time, and mitigate the energy to the lower end of the band of the conducting zone. In such a highspeed energy relaxation process in a semiconductor with high electron concentration, the electrons reach equilibrium after scattering, and this is followed by photon emission, eventually leading to a loss of heat energy. The energy loss at the short wavelengths makes up about 30% of all solar energy, which is the biggest cause of conversion efficiency loss in the single junction type solar cell.[11]

3-3 The challenge for high conversion efficiency by tandem solar cell

The tandem type solar cell is gaining attention as a new material to achieve high efficiency far beyond the theoretical marginal-efficiency of the single junction type solar cell. Since the thin-film solar cell is made by a chemical vapor deposition (CVD) at a low temperature, the tandem type also becomes possible. For instance, a three joint tandem solar cell that consists of compound semiconductors of GaInP/GaAs/InGaAs achieved a high conversion efficiency of about 33%.[15] With such a tandem solar cell, the transmission loss of long-wavelengths and the thermal energy loss of shorter wavelengths can be mitigated by laminating a semiconductor with a wide band gap to those which narrow band gaps on the light incident light side, which will achieve consistency with the sunlight spectrum as a whole.

Even for the tandem solar cell that enables high conversion efficiency, there are still many issues to be solved. As shown in Figure 8, the tandem type is basically constructed as a series of stripes connected in a straight line. The total voltage would be the total of voltage of each layer, while the electric current is constant within a circuit. Therefore, if the effectiveness of power generation falls even within just a single layer at any level, it would cause a bottle-neck effect, and decrease the amount of the electric current flow for the entire line. For instance, even if an optimized tandem-type is based on the ideal sunlight of AM-1.5, the layer aiming the wavelength around the red zone would have a significant power loss, since the red light would be weakened on a cloudy day. As a result, the tandem type only shows its advantages on sunny days, and it is limited to areas which are advantageous in terms of the geographical condition. For further development of the tandem type, a better-suited design should be planned, one which takes into consideration the climate conditions of all parts of the world. On the other hand, researchers at the Delaware University proposed a new and drastic design idea, to extract electric currents per layer without an in-line structure. It has achieved a maximum conversion efficiency of 42.8% as of July, 2007.[16] However, there is a production cost issue for this method, as the structure is more complicated than other simple in-line lamination layers.

In addition, there have been advances in new technology as well, such as the forming of the surface structure (texture structure) with micro- and nanometer-sized convex/concave shapes to reduce the amount of reflected light, and the improvement

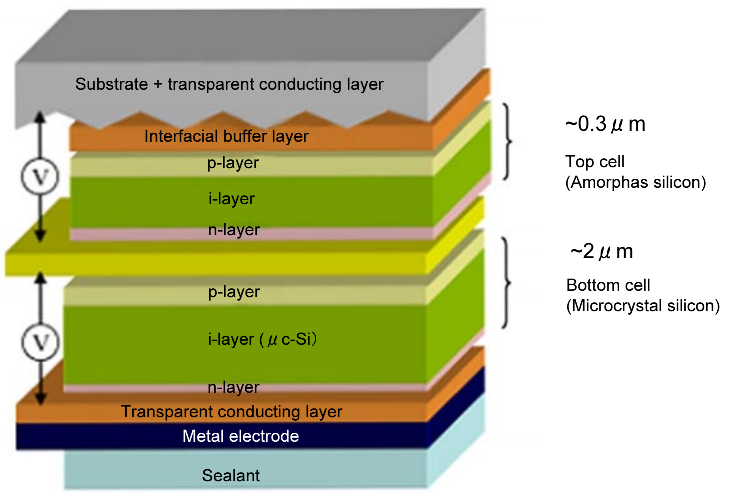


Figure 8 : Concept drawing of a tandem (two layers) type solar battery

Souce:Reference [17]

of the optical absorption ratio by the effect of an optical confinement in a crystal. The development of a passivation processing using impurities such as hydrogen has also gone forward to deal with the issue of bonding of atoms at the grain boundary of the crystal particle often becoming defective, which could lead to structural defects, and a lower conversion efficiency of the solar cell. Likewise, more advanced surface treatment technologies are required for the development of the tandem type, which should be more refined than that of the single junction type solar cell.

4 Solar cells other than silicon-current status of research and development of chemical compound semiconductor and organic system materials

While this report mainly focuses on the silicon solar cell, the research and development activities concerning a variety of solar cells not made of silicon have been in progress. (Table 3) The following briefly introduces the research and development trends of chemical compounds for achieving higher conversion efficiency than silicon, and organic materials which enable a low-cost manufacturing process. The main focus is to save raw materials for each unit of electric power generated, to develop a material with higher power

Table 3 : Type of solar battery cell measured under the condition complied with the standard (Environment AM-1.5 and 25℃)

Type			Conversion efficiency(%)	Area 1*(cm^2)	Open circuit voltage Voc(V)	Short-circuit current density Jsc(mA/cm^2)	FF*2(%)	Place and date (month/year)	Institution *3
Silicon	Bulk type	Si(crystalline)	24.7±0.5	4.00(da)	0.706	42.2	82.8	Sandia(3/99)	UNSW PERL
		Si(multicrystalline)	20.3±0.5	1.002(ap)	0.664	37.7	80.9	NREL(5/04)	FhG-ISE
	Thin film type	Si(thin-film transfer)	16.6±0.4	4.017(ap)	0.645	32.8	78.2	FhG-ISE(7/01)	U.Stuttgart
		Si(thin-film submodule)	9.4±0.3	94.9(ap)	0.493	26/0	73.1	Sandia(4/06)	CSG Solar
		Si(amorphous)	9.5±0.3	1.070(ap)	0.859	17.5	63.0	NREL(4/03)	U.Neuchatel
		Si(nanocrystalline)	10.1±0.2	1.199(ap)	0.539	24.4	76.6	JQA(12/97)	Kaneka
Chemical compound	Bulk type	GaAs(crystalline)	25.1±0.8	3.91(t)	1.022	28.2	87.1	NREL(3/90)	Kopin
		GaAs(multicrystalline)	18.2±0.5	4.011(t)	0.994	23	79.7	NREL(11/95)	RTI
		InP(crystalline)	21.9±0.7	4.02(t)	0.878	29.3	85.4	NREL(4/90)	Spire
	Thin film type	CIGS(cell)	18.4±0.5	1.04(t)	0.669	35.7	77	NREL(2/01)	NREL
		CIGS(submodule)	16.6±0.4	16.0(ap)	2.643	8.35	75.1	FhG-ISE(3/00)	U.Uppsala
		CdTe(cell)	16.5±0.5	1.132(ap)	0.845	26.7	75.5	NREL(9/01)	NREL
		GaAs(thin film)	24.5±0.5	1.002(t)	1.029	28.8	82.5	FhG-ISE(5/05)	Radboud U.
Organic	Dye-sensitization	Dye sensitized	10.4±0.3	1.004(ap)	0.729	21.8	65.2	AIST(8/05)	Sharp
		Dye sensitized(submodule)	6.3±0.2	26.5(ap)	6.145	1.7	60.4	AIST(8/05)	Sharp
	Organic semiconductor	Organic polymer	3.0±0.1	1.001(ap)	0.538	9.68	52.4	ASIT(3/06)	Sharp
Tandem type		GaInP/GaAs	30.3	4.0(t)	2.488	14.22	85.6	JQA(4/96)	Japan Energy
		GaInP/GaAs/Ge	32.0±1.5	3.989(t)	2.622	14.37	85	NREL(1/03)	Spectrolab
		GaAs/CIS(thin film)	25.8±1.3	4.00(t)				NREL(11/89)	Kopin/Boeing
		a-Si/CIGS(thin film)	14.6±0.7	2.40(ap)				NREL(6/88)	ARCO
		a-Si/Si(crystaline)	21.3	100(t)	0.717	38.6	77		Sanyo
		a-Si/μc-Si(thin submodule)	11.7±0.4	14.23(ap)	5.462	2.99	71.3	AIST(9/04)	Kaneka

*1
da=designated illumination area
ap=aperture area
t=total area

*2
FF:Fill Factor

*3
NREL:National Renewable Energy Laboratory
Sandia:Sandia National Laboratories
AIST:National Institute of Advanced Industrial Science and Technology
JQA:Japan Quality Assurance Association
UNSW:The University of New South Wales, Australia
U.Stuttgart:University of Stuttgart, Germany
Kopin:Kopin, US
Radboud U.:Radboud University, Holland
U. Uppsala:University of Uppsala, Sweden
U.Neuchatel:University of Neuchatel, Switzerland
Spectrolab:Spectrolab, US

Prepared by the STFC based on Reference[12] and data provided by Professor Konagai, Tokyo Institute of Technology.

generation efficiency, and to establish a production process to supply them at a low price and on a constant basis.

4-1 Chemical compound semiconductor

Bulk-type chemical compound semiconductors have the potential to achieve high power generation efficiency at a level equivalent to, or higher than single-crystal silicon.(Table 3) As mentioned earlier, the theoretical conversion efficiency of the solar cell is subject to the band-gap energy (Eg) of the semiconductor. In terms of consistency with the solar spectrum, a semiconductor with a band gap of about 1.4-1.5eV is suitable as a solar cell with high efficiency.[18] High efficiency can be expected for GaAs of 1.42eV and InP of 1.35eV, compared with the silicon of about 1.1eV.

Silicon has a small optical-absorption coefficient due to indirect transition type and may require a thickness more than 100μm to sufficiently absorb sunlight, but most of the chemical compound semiconductors such as CIGS ($CuInGaSe_2$) of thin film, are direct transition types and have a high optical-absorption coefficient and a thickness of just a few μm is sufficient. Yet still, the prices are also higher than silicon because it is necessary to use scarce and highly toxic materials such as indium and cadmium respectively. The key for mass production is finding a way to establish a recycling technology for such raw materials and to find techniques using alternative material.

SHARP Corporation has developed a concentrating solar photovoltaic system, which collects sunlight into a small solar cell using a lens as a solution to the issue above.[19] They achieved a conversion efficiency of about 37% by condensing the light to about 700 times with a Fresnel lens. It is then irradiated to the 3 layer solar cell based on the chemical compound semiconductor. The solar cell reaches a high temperature by the concentration, but the solar cells using GaAs remain stable with almost no change in conversion efficiency, even at the temperature of 200C or more[NOTE 7]. For that reason, the collimation technique of today is expected to be the technique for efficiency improvements in the solar cell of the compound semiconductor.

4-2 Organic materials

Research is underway for organic semiconductors as solar cells that can be made at a low cost with simple production, due to the low price of the raw material. It has a simple structure which can be made onto a polymer board, and it is flexible and able to be designed. Although the power generation efficiency is low as only a few%, but because there are many candidate materials for the organic semiconductor, it could leap to significant a status if an optimal material is found. It can be expected that many researchers will start the research in the same area.

While dye-sensitization type also has a low power generation efficiency, it receives high expectation for its price and design. By choosing a type with organic pigments, it may be possible to create colorful solar cells. At present, its system durability is an issue to consider because it uses an electrolyte solution with volatility to transmit the ion. Therefore, it is currently necessary to conduct research on the solidification of the electrolyte solution.

As mentioned before, the power generation efficiency is still low for both the organic semiconductors and the dye-sensitization type solar cells, and so there are slightly different types of developmental activities underway compared to the solar cells aiming for high efficiency.

5 New trends for the development of solar cells – the possibilities of quantum dot solar cell also known as the third generation solar cell

In recent years, the quantum dot solar cell has gained attention as a solar cell which may exceed the theoretical limitations of the conversion efficiency as shown in Figure 6. In the following,

[NOTE 7]
The concentrating solar photovoltaic system by SHARP was announced in the 2nd New Energy World Exhibition held in October, 2007. This company plans to launch sales by the end of 2008.

the application potential of the technology to solar cells is described, based on the basic physical properties of the quantum dot.

5-1 Basic physical properties of the quantum dot - why the quantum dot can achieve high efficiency

The quantum dot is a nanocrystalline structure ranging from several nm to about 10 nm in size. It is made by the method of epitaxial growing on a substrate crystal. The quantum dots are surrounded by high potential barriers in a three-dimensional shape, and the electrons and electron holes in the quantum dot become a discrete energy as it is confined in a small space. Consequentially, the energy state of the ground-state energy of the electrons and electron holes in the quantum dot would be subject to the size of the quantum dot. [20,21]

As physical characteristics of the quantum dot, three items are expected to be available from the point of application to the solar cell.[20,21] By achieving these items, it is expected to accomplish a theoretical efficiency exceeding 60%.[22,23] The items (1) and (2) below are expected to be the key to overcome the two factors of loss, as shown in Figure 7 (transmission loss of light and loss of thermal energy by phonon emission) .

(1) The quantum size effect: By adjusting the size of the quantum dot, the optical absorption wavelength can be selected, which can make it be more consistent with the sunlight spectrum. [20,24]

(2) The increase of the energy relaxation time: It is known that the energy relaxation time of the electron slows down in the quantum dot. Therefore, there is a possibility to remove the electrons in a state of high energy by phonon emissions, before energy relaxing occurs.

(3) Formation of the miniband: When there is a bonding of the quantum dots, a miniband is formed at the superconductor and the valence band. [25] For example, if the middle layer between the quantum dots is very thick, a quantum dot solar cell with a structure of multiple layers of quantum dots between pn bonding, as shown in Figure 9, becomes like the energy band structure shown in Figure 10(a). In this case, the electrons excited by sunlight slip out the well of the quantum dots by further optical excitation or thermal excitation, which can be removed as an electric current. Meanwhile, if the middle layer is several nm thin, a miniband is formed between quantum dots, and the electrons and the electron holes can move with little energy loss (Figure 10(b)).[20,21]

Of course, there are many research topics remaining. Especially for arranging the quantum dots in a regular and stable manner, which need to be achieved with general materials. The next paragraph explains the applicability of the quantum dots to solar cells, mainly from the viewpoint of the

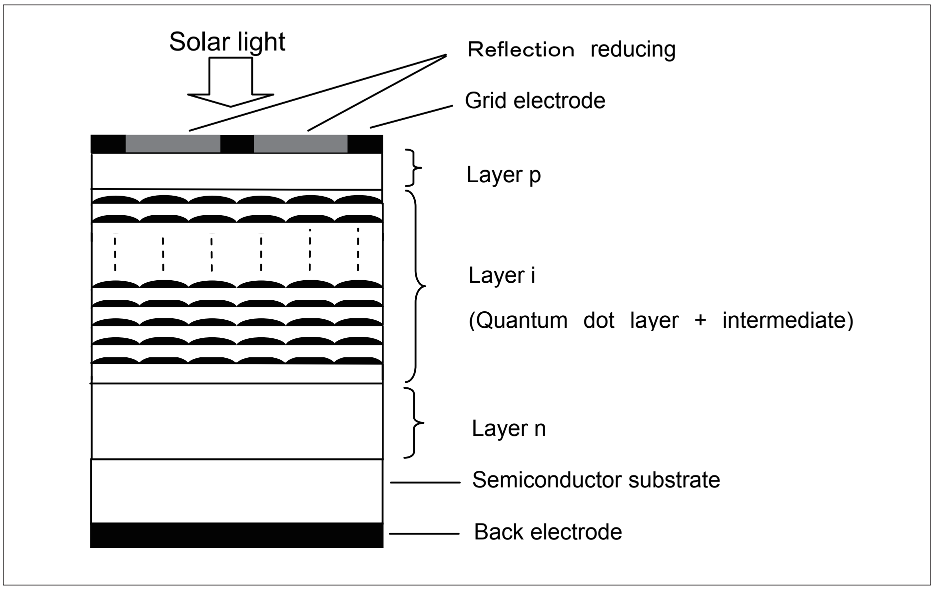


Figure 9 : Concept drawing of quantum dot solar battery structure

Prepared the STFC based on Reference[20,21]

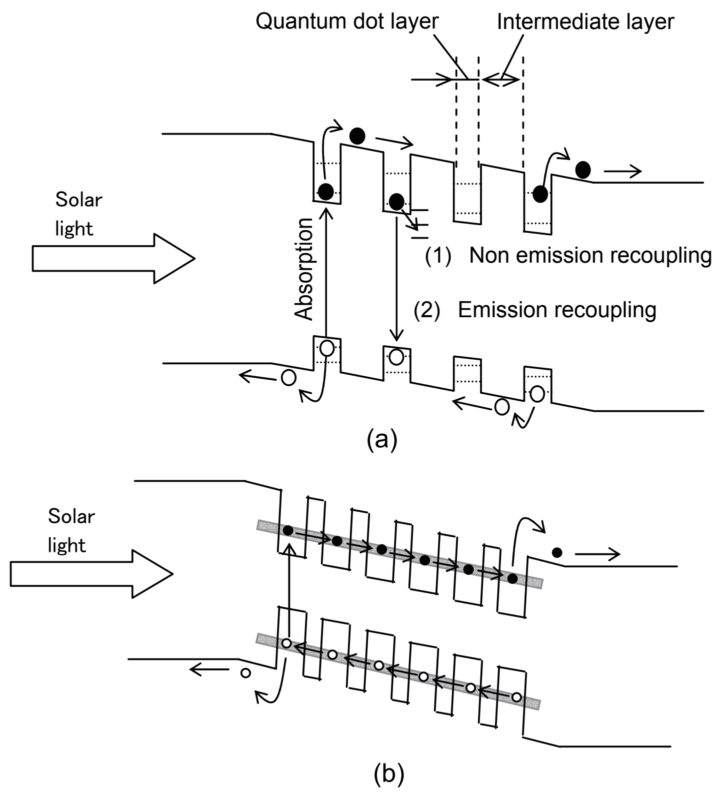


Figure 10 : Quantum dot solar battery energy band (a) and mini band (b)

Prepared by the STFC based on Reference[20,21]

manufacturing process technology of the quantum dot.

5-2 *Quantum dot manufacturing process technology aimed for application to solar cells*

In past research of quantum dot solar cells, the chemical compound semiconductor was the main focus. In the case of production methods, producing the quantum dots by self-organization using the difference of the grid parameter and the high-index plane substrate are thought to be the most probable process. For example, if a material with a higher grid parameter than that of the substrate crystal needs to be grown epitaxially, the quantum dot will grow on a regular basis to be an island shape, in order to reduce the strain energy which accompanies the growth process. Typical examples include InAs/GaAs, with a grid parameter of InAs of7.2% which is larger than that of GaAs. Mr. Okada, Associate Professor of Tsukuba University achieved the conversion efficiency of 8.54% by using this system.[26] It is now under consideration for the concentrating solar photovoltaic system, as shown in 4.1, because it is difficult to apply to a large area.

It should be noted, however, that these phenomenon are enabled mainly with chemical compound semiconductors. By taking into consideration the cost of raw materials and future mass production, it is most desirable to use silicon. Under the current condition, the quantum dot cannot be arranged by silicon material to achieve a regular and stable layout. In particular, it is quite difficult to achieve less than the allowed range of 10% for the size fluctuation

However, the recent study of the silicon quantum dot solar cells also shows a certain gradual development. As one of the methods gaining attention, there is a technique of heat treatment for silicon carbide with a silicon excess composition. Applying the plasma CVD technique, as shown in Figure 11, a silicon quantum dot super grid is made in a self-organizing manner, by making an amorphous super grid consisting of amorphous silicon carbide with the stoichiometry and silicon excess composition. [27] This is a method for forming a quantum dot voluntarily during the process of crystallization by making use of the phenomenon in which grid distortion is caused

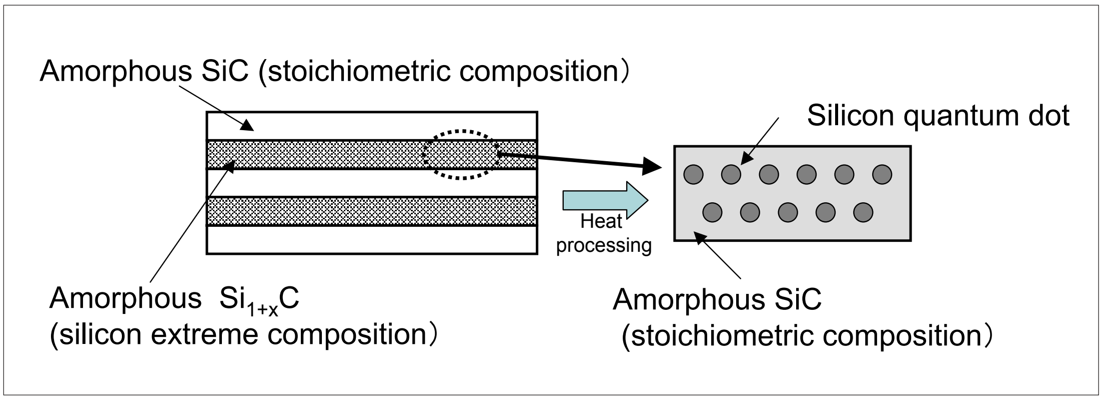


Figure 11 : Heat - processed silicon quantom dot structure

Prepared by the STFC based on Reference[27]

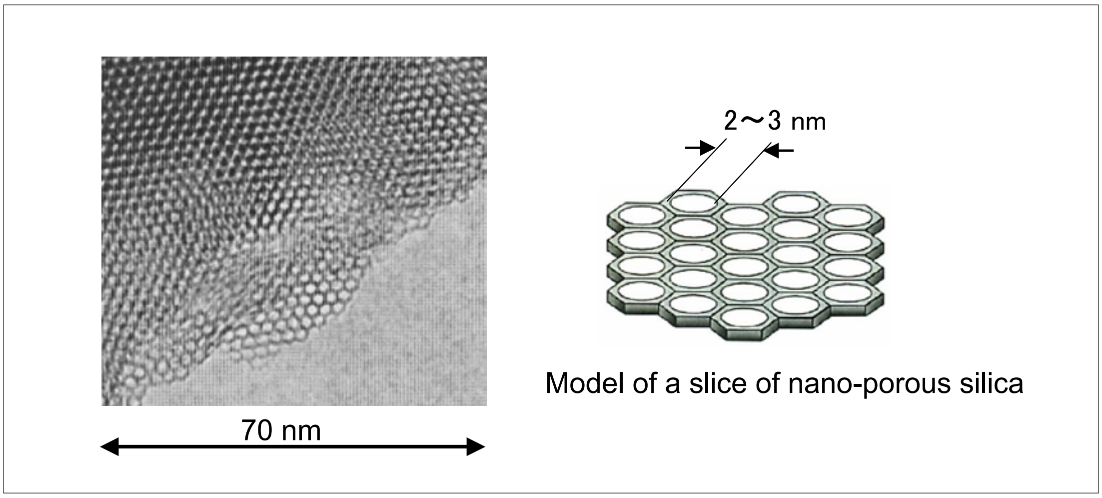


Figure 12 : High resolution transmission electro microscope imaging of nanoporous silica

Source:Reference[28]

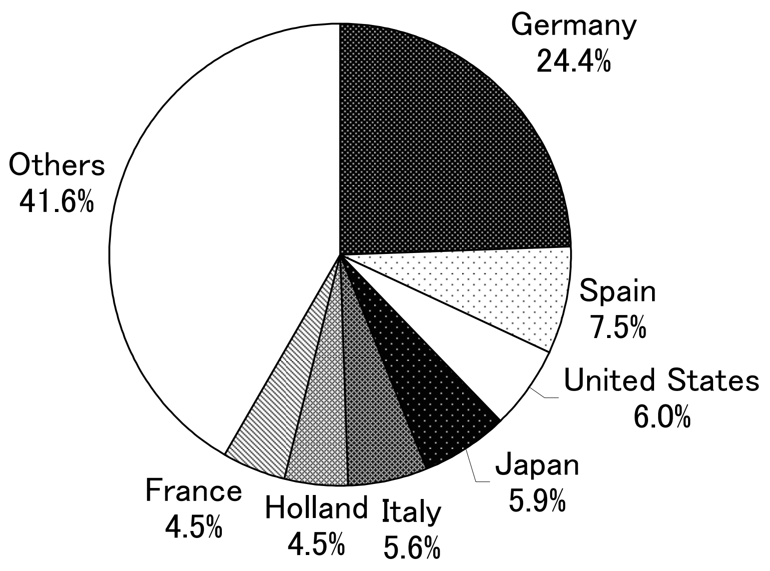
because of a difference in the grid parameter between the material used as a quantum dot and another material used as an energy barrier layer.

Another technique which may be applicable to the quantum dot structure is the synthesis process of nano porous silica (SiO_2), which contains a laminar silica salt precursor. [28] At present, this is not for the production quantum dots super-grid. As seen in Figure 12, the high-resolution transmission electron's mirroring image, there is a structure of silica pore controlled by a nano scale. If a technology to enclose the semiconductor nanoparticle in each nano holes is developed, it is possible to use the silica itself as the interlayer. It may even enable the creation of a three dimensional quantum-dot structure containing thin films with regular layouts of the semi-conductor nano particles.

The above-mentioned quantum-dot structure fabrication methods are all in the process of research, and have only been able to produce small-scale samples. There are still a lot of existing problems for arranging the quantum dots to a uniform nominal size in a three dimension orderly manner, all the while achieving highly dense and thin inter layer. In particular, the key is how to control the quantum dot size fluctuation. In order for practical applications in the future, it may also be important to develop a method without the need to utilize an ultra-air-tight-vacuum.

6 Enhancement of basic research from a long-term view and the necessity of human development

As summarized above, solar cell research has been proceeding, to discover solutions for higher conversion efficiency and lower costs, in a range from crystal, thin film, chemical compound, organic materials, tandem type, to quantum dots.



Number of papers at Europe Solar Power Conference (The 20th-22nd in Total)

Figure 13 : The total number of academic papers for each country

Prepared by the STFC

Table 3 shows the current development status for various solar cells. In turn, such a number of different types of products may represent the current condition that no specific solar cell is found for the market.

The most popular solar photovoltaic system of the crystalline silicon has established the industrial structure for generating more profits from the upstream process, including refinement of the silicon material and silicon wafers. Therefore, the main focus of research and development for the technologically aggressive companies has shifted to the thin film or tandem type, which has a potential to create added-value to the downstream process.

For the development of the solar cell, the key is to improve the conversion efficiency and to create a large-scale manufacturing process. The Japanese industry has led the technology development for the manufacturing processes in the past. At present, as thin or tandem type products are shifted to the mass production phase, enterprises should assign more researchers and engineers to be engaged in development and start-up mass production processes. The international competition is getting fiercer due to rapid business and the differentiation of products, and researchers and engineers have been tied up with finding solutions. In addition, due to the fact that research of this technical area had not been so active in the past, there is concern, by the academia in Japan, towards development of advanced research for this area.

Figure 13 shows the total number of academic papers for each country, announced from the 20th (2005) to the 22nd (2007) European Photovoltaic Solar Energy Conference and Exhibition. This conference receives the largest number of participants and academic paper publications among all the world conferences concerning the photovoltaic power generation, and its scale has been expanded every year. [29,30] Europe has an especially high awareness for the development and introduction of the solar cells. This is one of the most important conferences to in the future. The 22nd conference received about 3000 people from 83 countries, with about 1100 publications of articles. As this is a conference hosted by EU countries, the number of papers from European countries is high. Meanwhile, Japan has only about 6% of the share, which is very notable, as shown in Figure 4. Although Japan is the world largest producer of solar cells, the share of the academic papers submitted is quite small. Of course, it is difficult to compare the level of researches only with the number of academic papers, but Japan is still concerned about its lack of depth on the solar cell research, as the development of future solar cells will be more advanced and complicated.

Under these circumstances, Japan should

strengthen their basic research, centering more on universities and public research institutes. Up to now, public research development products from institutes such as The New Energy and Industrial Technology Development Organization (NEDO) have been supporting the industry, and have achieved fruitful solutions in various ways. It is expected that the industries with advanced technology will also achieve successful short term solutions by the support and contribution of the public institutes. However, the industry is now seeking rather long-term views for such public service, and therefore it is in high need of enhancing the basic research and human development required for the research activities. [NOTE 8] Development of personnel who are strongly committed to basic research will have a significant meaning for Japanese competitiveness in the future.

Above all, this report emphasizes the need to enhance basic research with the following three criteria:

1) Clarification of basic visible and interfacial physical properties, and the search for raw materials, concerning the layered structure of the tandem type (section 3-3)
2) Research of the quantum dot manufacturing process that enables an orderly arrangement of the quantum dot, in three dimensions and with high density (section 5-2)
3) The pursuit of possibilities by brand-new ideas for high efficiency solar cells.

1) is a research topic we expect to face within the next several years. There are already many demands from the industry. 2) is a more innovative research topic, which may lead ripple effects to other technological developments by fundamental research of process technology. 3) is a more challenging topic. For example, there is some interesting research on MEG:Multiple Exciton Generation published by The National Renewable Energy Laboratory NREL in the United States in July, 2007 [31].It is about the generation of one more electron per photon of sunlight. It is worth noting, in terms of the subject, that the energy loss factors of photovoltaic power generation shown in Figure 7 could be significantly reduced to increase the conversion efficiency.

7 Conclusion

The promotion policy of the photovoltaic power generation in Japan has received a good reputation by foreign countries as one of the successful examples, through introductions of Sunlight Program, Electric Power Development Promotion Measures Special Accounting, Petroleum Oil and Energy Supply Structure Advancement Measures Special Accounting System, etc., after the inauguration of Agency of National Resources and Energy in 1973. [32,33] In the future, one idea from the viewpoint of the market introduction, would be providing a strong incentive for the development of a more highly effective solar cell,. For example, having a subsidy for the development of tandem type solar cells, which requires higher costs, be the equivalent amount of a subsidy for crystalline silicon, in order to promote its introduction to the market. The residential environment of Japan in particular, offers high efficiency solar cell development. It is much more advantageous for Japan to continue its research, when compared to other countries, as the area of land for collecting sunlight is smaller. Such incentives for photovoltaic power generation introduction have been discussed mainly from the views of the environment and energy, including reduction of CO_2 emissions and alternative products of fossil fuel. Now, by promoting a more advanced research and developmental activities with added value, Japan's global competitiveness should improve, and eventually achieve another successful result.

This report only showed the overview of the trends of the solar cell, and did not refer to the topics such as solar photovoltaic power generation module and system, the field test, and the resource recycling, etc. For the promotion of the renewable energy, including the photovoltaic power generation, please see the past issues of

[NOTE 8]
From the hearing and survey of photovoltaic power generation related project researchers from NEDO, specialists of universities and corporate technical institutes.

Science and Technology Trends [34] and reports by international institutions.

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References

[1] "Taiyoko Hatsuden Hyoka no Chosa Kenkyu" Research on photovoltaic generation evaluation" Photovoltaic Power Generation Technology Research Association, committed by NEDO (2001) (Japanese)

[2] "Photovoltaic Energy Barometer: GWp Installed in European Union", EurObserv' ER 2007

[3] Koichi Choya, "Taiyo Denchi Sangyo ha Uri ka Kai ka – Analyst no Shiten Kara, "Sell or buy? - the solar battery industry from analyst's aspects" Solar battery seminar 2007 NIKKEI MICRODEVICES Nikkei Electronics (2007) (Japanese)

[4] PV News March 2007 issue (2006) (Japanese)

[5] "General Resource Energy Survey Committ ee, 15th New Energy Conference, Reference (2006) (Japanese)

[6] Hiroshi Kawamoto, Kumi Okuwada , "Development Trend for High Purity Silicon Raw Material Technologies - Expecting Innovative Silicon Manufacturing Processes for Solar Cell Applications - "Science and Technology Trends—Quarterly Review, No.24, July,2007

[7] Taiyo Ko Hatsuden Sangyo Jiritsu ni Muke ta Vision, Vision for photovoltaic generation industry independence revision, 2006, Japan Photovoltaic Energy Association 2006 (Japanese)

[8] "Environmental Policy, Renewable energy sources in figures -national and international development, Status: May 2006"Federal Ministry for the Environment, Nature Conservation and Nuclear Safety BMU Public Relation Division -D-11055 Berlin

[9] Tatsuya OHIRA, Measures to Promote Renewable Energy and the Technical Challenges Involved Science and Technology Trends - Quarterly Review, No.18, January 2006

[10] "Solar Spectra: Air Mass Zero" National Renewable Energy Laboratory, website: http:// rredc.nrel.gov/solar/spectra/ am0/

[11] Takahiro Hamakawa, Kotsoku Kuwano, Taiyo Energy Kogaku, Solar energy engineering: Solar battery, Baifukan (1994) (Japanese)

[12] Green, M. A. , Emery, K., Hisikawa, Y. and Warta, W. "Short communication; Solar cell efficiency tables (virsion30)" Progress in Photovoltaics: Research and Applications, Vol.15, Issue 5, pp.425

[13] Taiyo Denchi no Hon, Solar Battery Book, National Institute of Advanced Industrial Science and Technology, Solar Photovoltaic Generation Research Center (2007) (Japanese)

[14] Shockley, W. and Queisser, H. J. "Detailed Balance Limit of Efficiency of p-n Junction Solar Cells" J. Appl. Phys., Vol.32, Issue 3, pp. 510-519 (1961)

[15] Yamaguchi, M."Multi junction solar cells and novel structures for solar cell applications" Physica E, Vol. 14, Issues 1-2, pp. 84-90 (2002)

[16] Delaware University, US, HP http://www.udel.edu/PR/ UDaily/2008/jul/solar072307.html

[17] National Institute of Advanced Industrial Science and Technology, Solar Photovoltaic Generation Research Center http://unit.aist.go.jp/rcpv/ index.html (Japanese)

[18] Takahiro Hamakawa, Photonics Series 3 Solar Cells, Korona Sha (2004) (Japanese)
[19] Tatsuya Takagi,Minoru Kaneiwa,Converging type compound solar battery, SHARP Technical Report No. 93 (2005) (Japanese)
[20] Yoshitaka Okada, Jiko Soshiki ka Ryoshi Dotto Cho Koshi to Kokuritsu Taiyo Denchiheno Oyo, Application to self-assembler quantum dot super-grid and highly effective solar batterythe Japanese Association for Crystal Growth Cooperation (JACG) Magazine Vol. 33 No. 2 (2006) (Japanese)
[21] Yoshitaka Okada, Ryuji Oshima, Ryoshi, Nano Kozo wo Donyu Shita Jisedai Taiyo Denchi, The next generation solar battery that introduces quantum nano structure, Applied physics Vol.76, No.1 (2007) (Japanese)
[22] Luque, A. and Marti, A. “Increasing the Efficiency of Ideal Solar Cells by Photon Induced Transitions at Intermediate Levels”, PRL. Vol.78, pp.5014-5017 (1997)
[23] Green,M.A.“Third Generation Photovoltaics: Advanced Solar Energy Conversion”, Springer (2003)
[24] Barnham, K. W. J. and Duggan, G. “A new approach to high-efficiency multi-band-gap solar cells”, J. Appl. Phys. Vol. 67, pp.3490-3493 (1990)
[25] Reona Ezaki, Hiroyuki Sakaki, Super-grid heterostructure device, Japan Industrial Standard Committee (1988) (Japanese)
[26] Oshima, R., Nakamura, Y., Takata, A. and Okada, Y. ”Multi-stacked InAs/GaNAs Strain-compensated Quantum Dot Solar Cells” 22nd EU-PVSEC, Milan (2007)
[27] Shinsuke Miyajima,Tokyo Technical Institute Graduate School,website - Research on making silicon quantum dot array in which it aimed at application to solar battery: http://www.eng.titech.ac.jp/ jyosei/h17/s_miyajima.html (Japanese)
[28] Yukichi Sasaki, Na2SiO5 Politype wo Zenkutai Tohsita Mesopo-rasu Shirika no Haiko Seigy, Control for distribution of meth-pollous silica Zeolight Conference, Draft (2007) (Japanese)
[29] 22nd European Photovoltaic Solar Energy Conference and Exhibition website: http://www.photovoltaicconference.com/conference.0.html
[30] Participants with the highest number of attendance at European Photovoltaic Solar Energy Conference and Exhibition, Science and Technology Trends, Topics September 2005 National Institute of Science and Technology Policy (2005) (Japanese)
[31] Beard, M. C., Knutsen, K. P., Yu, P., Luther, J. M., Song, Q., Metzger, W. K. , Ellingson, R. J. and Nozik, A. J. “Multiple Exciton Generation in Colloidal Silicon Nanocrystals” Nano Lett., Vol.7, No.8, pp. 2506-2512 (2007)
[32] “Creating Markets for Energy Technologies”, OECD/IEA (2003)
[33] Tatsujiro Suzuki, Hideaki Shiroyama, Miwao Matsumoto, Energy Gijutsu no Shakai Ishi Kettei, Social decision making of energy technology, Nihon Hyoron Sha (2007) (Japanese)
[34] “Trends in Photovoltaic Applications: Survey report of selected IEA countries between 1992 and 2006” IEA (2007)

Daisuke KANAMA, PhD
Nanotechnology and Materials Research Unit
Research Fellow
kanama@nistep.go.jp

He is interested in the relationships among the science and technology, the economic society, and the innovation, and is especially specialized in researching and surveying the roles of university and government institutions, concerning the national innovation system, and intellectual property rights. He is also interested in the research trends of nanotechnology and carries out survey activities.

Hiroshi KAWAMOTO, Dr. Eng.
Head, Nanotechnology and Materials Research Unit
Visiting Researcher

Doctor of Engineering and a Fellow of The Japan Society of Mechanical Engineers. In the past Dr. Kawamoto has done R&D on strength design and evaluation of automobiles materials and components at Toyota Motor Corporation, thereafter working at the Japan Fine Ceramics Center becoming engaged in projects (such as the research and development on fine ceramics, etc.) sponsored by the Ministry of Economy, Trade and Industry. Special fields of interest include strength design and reliability evaluation technology on structural materials and components.

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