# Solar Cell Development Trends and Future Prospects

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## 1. Introduction

The development of solar cells began with the invention of single crystal silicon solar cells in 1954 at Bell Labs. Thereafter, research continued to make progress, and during the era spanning the latter half of the 1950s through the beginning of the 1960s, this technology began to be utilized in high value added applications such as the power supply for a man-made satellite.

With the 1974 oil crisis as an impetus, major research projects in Japan [including the Sunshine Program sponsored by the Ministry of International Trade and Industry (now the Ministry of Economy, Trade and Industry)] were initiated for power applications.

In the latter half of the 1980s, concern heightened for environmental issues such as global warming. It is thought that approximately 60 % of the greenhouse effect is attributable to $CO_2$ and of that amount, 80 % is attributable to the consumption of fossil fuels. Solar cells are promising not only because they represent a new energy resource that is maintenance-free and does not generate $CO_2$, but also because they will potentially provide a solution to global environmental problems.

The Kyoto Protocol intended to curb global warming was adopted at The 3rd Session of the Conference of the Parties to the United Nations Framework Convention on Climate Change (COP3) held in Kyoto, Japan in December 1997. This protocol sets forth compulsory numerical targets for the reduction of greenhouse gas emissions by each advanced nation by the year 2010. Subsequently, at COP6, basic agreement was also reached regarding the year 2002 enactment of the Kyoto Protocol. Hereafter, momentum is expected to increase for the introduction of new energy, which does not have a deleterious effect on the environment.

The majority of solar cells currently in use are crystal silicon solar cells. Under standard test conditions (in the vicinity of room temperature), these solar cells have a high conversion efficiency of 14 % to 16 %. However, because they have a thick substrate of several hundred micrometers, procurement of a sufficient supply of high-purity silicon material is a problem.

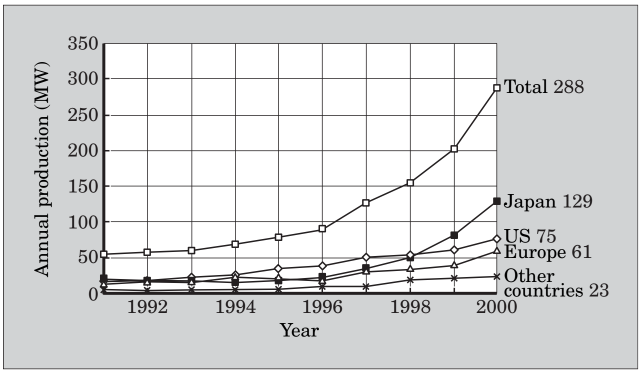
Fuji Electric is working to develop amorphous silicon solar cells, which are fabricated on a plastic film substrate and are formed from 1 µm or thinner semiconductor material. Amorphous silicon solar cells have the advantages of a relatively trouble-free supply of raw material because each cell only uses a small quantity of material; they are well suited for mass production, and cost reductions are expected. The large-scale, widespread use of amorphous silicon solar cells is anticipated, and it is believed that in the future the majority of solar cells will be amorphous silicon solar cells.

## 2. Market Trends

### 2.1 Production history

Solar cell production has continued to expand rapidly since 1997, and solar cell production in the year 2000 was approximately 300 MW. (See Fig. 1). As solar cells began to achieve widespread use, their annual production reached 100 MW in 1997. The rapid growth of today's market can be understood by considering the fact that it took 20 years to surpass the 100 MW level of annual production. With annual solar cell production of 128 MW in year 2000, Japan remained the global leader in solar cell production. (Japan was also the global leader in 1999.) Supporting this rapid expansion are lower costs enabled by

Fig.1 Global market for solar cell production



advances in manufacturing technology and the implementation of Japanese, U.S. and European governmental policies for the promotion of solar cell use. Leading the way is Japan's policy for the promotion of solar cells, and this is followed by other programs including the million solar roofs initiative (MSRI) in the US, the federal 100,000 roof program in Germany, and the 10,000 home solar power generation system initiative in Italy. Acting as a catalyst, this worldwide trend for solar cell use has boosted demand for solar cell modules by a large amount in 2001, and solar cell manufacturers worldwide have begun to increase their large-scale production equipment.

With the guarantee of economic efficiency due to policies that promote widespread use, solar cells have become familiar to users throughout the world.

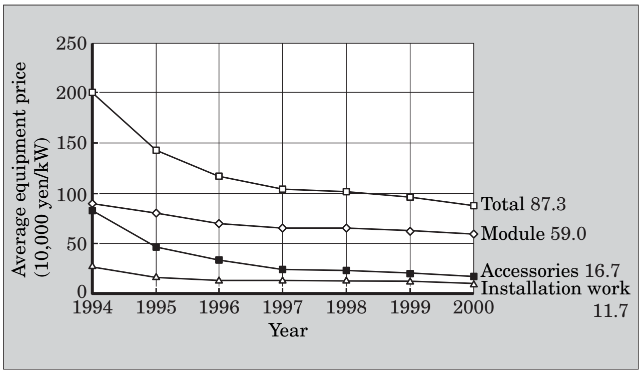
### 2.2 Policy to accelerate introduction in Japan

In Japan, the aggressive measures over the past 5 years to promote widespread usage of solar cells have been effective and, as a result, the market is growing. Against the backdrop of austere budgeting mandated by fiscal belt tightening, the budget for development and promotion of solar power generation systems grew by 10 % to 35.9 billion yen in 2002. This demonstrates the vigor of Japan's efforts to promote solar cell technology. A breakdown of this budget reveals 23.2 billion yen budgeted to promote usage by homeowners through subsidizing the foundation and maintenance work for installation of residential PV (photovoltaic) systems, and 4.5 billion yen budgeted to promote usage by companies through subsidizing industrial field test work. Together, these two items account for 77 % of the budget for promoting solar cells technology. The size of the subsidy per residential PV system was initially 1/2 the cost of the entire system. The subsidy was subsequently reduced to 1/3 of the system cost and then cut further in 2001 to 120,000 yen per 1 kW system so that more applicants could be recruited. A new phase was entered in 2002 with the inception of an experimental study of a centralized linked-type PV system that targets large-scale adoption in a specific region. Hereafter, the implementation may differ, but national and regional governments are expected to continue their policies of aggressive promotion of solar cell technology.

### 2.3 Technical trends

Historical average market prices per kW for a 3 kW PV system are shown in Fig. 2. In 2000, the average market price of PV system was 870,000 yen/kW, the market price of a PV module was 590,000 yen/kW or approximately 77 % of the total cost, and the remaining 23 % was attributable to the cost of the power conditioner, equipment installation, and other costs. Even though the price of residential electrical power may be considered expensive, without the subsidy, more than 20 years would be required to write off the initial cost of a PV system. The primary requirement for promoting widespread usage of solar cells is that the cost of a PV system be reduced to 1/2 or less of its present amount.

Fig.2 Historical market price for residential PV systems




The adoption of solar cell technology is most prevalent in residential applications, where the price of electrical power is relatively high. As the cost of power generation decreases, applications to large-scale buildings and the utilization of idle land are expected to increase. In the present Japanese market, the majority of PV system installations are for residential applications, and this trend is forecast to continue for the time being.

Residential solar cells can be classified as either existing type solar cells that are installed on the roof of an existing house, or as integrated building material that combines roof functionality with building material. In solar cell installations in new buildings or replacement roofs, because the equipment cost is low, applications of solar cell integrated building material are gradually increasing, and these applications are expected to become a key driver of future market growth.

## 3. Fuji Electric's Development of Amorphous Silicon Solar Cells on Plastic Film Substrate

### 3.1 Development history

Fuji Electric's efforts to develop amorphous solar cell technology began in 1978, only 2 years after the discovery in 1976 that p-n control can be applied to amorphous silicon (a-Si). In 1980, Fuji Electric was the first in the world to successfully develop and commercialize an amorphous silicon solar cell for use in calculators. During that same time, Fuji Electric also joined the Sunshine Project, and since then has advanced the research and development of amorphous silicon solar cells for the generation of electrical power. Over the years, Fuji Electric has developed a two-stacked tandem solar cell (30 cm × 40 cm), has demonstrated a stabilized efficiency of greater than 8 %, and was the first in the world to prove that amorphous silicon solar cells could be used to generate electrical power. Problems that surfaced during development included the long heating time due to the high thermal capacity of glass and the long time required for vacuum pumping due to the large size of the conveyer jig for the glass substrate. Without a solution to these problems, it would be difficult to manufacture large quantities of solar cells in a cycle time of several minutes.

To solve these problems, in 1994, Fuji Electric developed an amorphous silicon solar cell that has a substrate of 50 μm thick plastic film (See Fig. 3).

### 3.2 Advances in production technology and electricity generation performance

In contrast to a glass substrate, the film substrate has low thermal capacity and therefore only requires several seconds for heating. With a film substrate, it is possible to construct a roll-to-roll system that allows a 1,000 m long roll of film to be placed all at once into vacuum equipment and then automatically conveys the film from one roll to another. Additionally, the factor having the greatest effect on production capacity, the deposition rate of amorphous silicon film, has been greatly improved. Figure 4 shows the progress of the past several years in increasing the deposition rate of amorphous silicon. At present, the amorphous silicon film deposition rate for fabricating a good quality device is greater than 20 nm/min, and this is approximately 10 times the deposition rate in 1997 of several nm/min. In addition to this increase in deposition rate, the active area has been increased due to Fuji Electric's proprietary series-connection through apertures formed on film (SCAF) technology and the speed of laser patterning technology has been boosted. We are coming closer to the goal of constructing a 5-minute mass production system, in which each process is completed in a cycle time of several minutes.

In addition to these improvements in production technology, device structures have also made progress. Figure 5 shows the two-stacked tandem solar cell device configuration developed by Fuji Electric, using a silicon-germanium alloy in the bottom cell. Because longer light wavelengths can be used with silicon-germanium than with amorphous silicon, the electrical current generated per unit area is approximately 20 %

Fig.3 a-Si solar cell on plastic film substrate

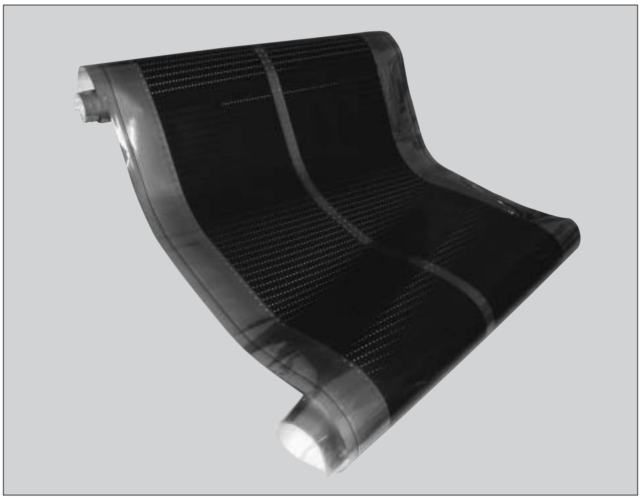


Fig.4 Progress toward faster deposition rates of a-Si

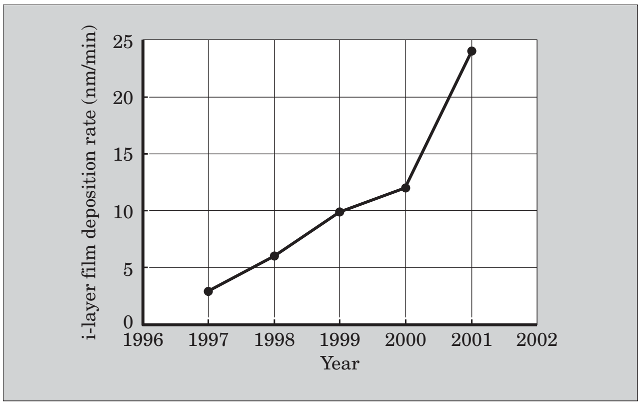



Fig.5 Device structure of two-stacked tandem solar cell

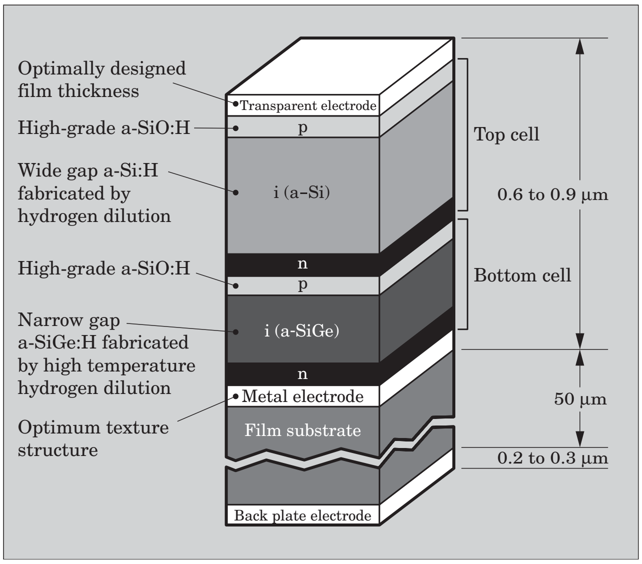
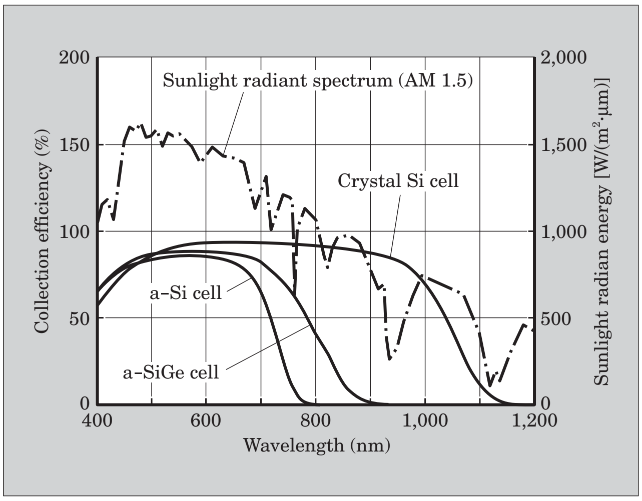



Fig.6 Solar spectrum and quantum efficiency of various solar cells



higher than that of amorphous silicon, and the power generation efficiency is improved proportionately.

Figure 6 shows the solar spectrum and light wavelengths that can be used effectively with solar cells. It can be seen that amorphous silicon solar cells use wavelengths approximately in the visible light range and that crystal silicon solar cells use longer light wavelengths. The reason for this difference in wavelength ranges of the utilized light is due to the different semiconductor energy gaps. Crystal silicon solar cells have a small energy gap and their performance is strongly temperature dependent. This is disadvantageous because when a module operates at high temperatures above 50 °C, its conversion efficiency will be less than when at room temperature. The results of a field test, standardized to the measurement of module power generation at room temperature, demonstrated that the annual quantity of power generated per unit capacity is at least 10 % higher for amorphous silicon solar cells than for crystal silicon solar cells.

### 3.3 Outdoors applications and verification of reliability

At Fuji Electric's Corporate Research and Development facility in Yokosuka City, Kanagawa Prefecture, 3 kW solar cells of both the glassless PV module-type that is encapsulated with plastic and was developed jointly with a building material manufacturer, and the conventional PV module-type with cover glass, have been installed on the rooftop of the facility's health promotion center. Field verification tests are ongoing to investigate the characteristics of outdoor power generation. Three years have passed since the solar cells were installed and both types of cells have continued to generate electricity stably. No difference in power generation characteristics has been found for different encapsulation structures of the modules.

In addition to the field test results, various reliability testing was performed and the goal of using glassless PV modules with more than 8 % of conversion efficiency outdoors has been clarified. By leveraging Fuji Electric's proprietary SCAF construction that makes it easier to implement high-voltage wiring and easy-to-fabricate integrated type solar cells formed from lightweight cells that are attached to building material for the roof or walls of a building, applications are expected to advance into various fields.

## 4. Conclusion

The history of solar cell development has been retraced from several perspectives and an overview the current status has been presented. For the ultimate objective of power generation, cost is the most important factor. The film substrate developed by Fuji Electric is well suited for the automation of production processes. By advancing well-timed applications and development, a new mode of solar cells that rejuvenate the old stately image will be transmit into the world as the standard-bearer for the next generation of mass-produced solar cells.

The very act of putting solar cells into practical use is in itself a contribution to the global environment. Fuji Electric, which has adopted the concept of "harmony with nature" as a basic philosophy, is on a mission to develop this technology.

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