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INDUSTRIALIZATION OF a-Si SOLAR CELLS

Y. Kuwano and M. Ohnishi


Abstract.-
The industrialization of amorphous Si (a-Si) solar cells has been made possible by an accumulation of basic physics research in the field of a-Si by a number of researchers. A new fabrication process in which p, i, and n layers are deposited in consecutive, separated reaction chambers has been developed. In this process, high-quality a-Si films are produced, because undesirable mixing of dopants is prevented. An integrated a-Si solar cell module in which several a-Si solar cells are connected in series has also been developed, which can generate a high voltage from one substrate. The mass production of this type of a-Si cell module has already begun for use in consumer applications. The theoretical limit efficiency and the energy payback period of p-i-n a-Si solar cells have been calculated. In order to apply the a-Si solar cell to a power source, experimental a-Si solar cell panels were produced. A 2-kW class demonstration plant consisting of these panels was constructed for the development of a power generating system and for the life test.

1. INTRODUCTION

Research aimed at developing a low-cost solar cell is being conducted in various countries around the world. In the United States, such research and development is now progressing with the goal of producing solar cells at a cost of $.70/W by 1986, and reducing this to $.15~$.40/W by 1990. And in Japan as well, starting with the "Sunshine Project" in 1974, a wide scope of solar cell research is being conducted. The goal is to reduce the cost of solar cell production to 1/100 of what it was in 1974 by approximately 1990. The recent appearance of the amorphous silicon (a-Si) solar cell offers great potential for the realization of this low-cost solar cell.

The a-Si has been gathering attention since Spear et al.1) showed in 1975 that it is possible to control the electrical properties of a-Si deposited by a glow discharge in silane. This was followed in 1976 by a report2) on the a-Si solar cell published by Carlson et al. The conversion efficiency of this first p-i-n type a-Si solar cell was 2.5%3). Through extensive research, however, this has been improved to the level of 6-7%. From this accumulation of basic research on amorphous materials and on their applications, SANYO in 1980 took the first step toward the realization of industrializing the a-Si solar cell for use in consumer products.9)

This report describes the industrialization of solar cells utilizing a-Si, and presents a prospective outlook on the future of this solar cell production.

2. MANUFACTURING PROCESS OF a-Si SOLAR CELLS

2-1. Fabrication method of a-Si solar cells

The conventional method10) for fabricating a-Si solar cells in a laboratory is
shown in Fig.1. In this process, silane (SiH₄) is introduced to a reaction chamber kept at a low degree of vacuum. An external electric field produces a glow discharge, by which a-Si is deposited on a substrate. The p-n junction is formed by mixing an impurity gas such as diborane (B₂H₆) or phosphine (PH₃) in the SiH₄.

This fabrication method is adequate if done in a laboratory, but involves the following problems for mass production.

1. It is not possible to produce high quality a-Si film with good reproducibility by depositing the p and n type layers in a single reaction chamber. The dopant gases which remain on the surface of the electrodes and reaction chamber walls from each deposition deteriorate the quality of the films.

2. The batch system is not efficient for mass production.

3. The inside of the reaction chamber should not be exposed to the open air.

In order to solve these problems, we have developed a new fabrication process for a-Si solar cells. This new process is called the consecutive, separated reaction chamber method, and is shown in Fig.2.

Fig.1 Conventional apparatus for the fabrication of a-Si solar cells.

2-2. The consecutive, separated reaction chamber method

In this method, the p and n type layers are deposited in different reaction chambers, as shown in Fig. 2. The substrates are set on substrate holders in the preparation chamber. The substrate holders are then carried to the first reaction chamber, and p type a-Si layers are deposited on the substrates. Next, the substrate holders are carried to the second chamber, and n type a-Si layers are deposited. Following this, the substrate holders are carried to the third chamber, and n-type a-Si layers are deposited. Finally, the substrate holders are carried to the fourth chamber to be removed.

The features of this method are as follows.

1. It is possible to avoid the influence of the residual gaseous dopants which remain on the surface of the electrodes and reaction chamber walls.
2. It is possible to sufficiently control the amount of the dopant in each layer.
3. a-Si solar cells can be produced consecutively.
4. It is possible to prevent the inside of the reaction chamber from being exposed to the open air.
These features indicate a significant improvement over the single chamber method.

3. CHARACTERISTICS OF THE a-Si SOLAR CELL

3-1. Structure

Typical structures of a-Si solar cells for industrialization are shown in Fig. 3. The present photovoltaic performance values for each structure are shown in Table 1. The conversion efficiency of the Glass/SnO2/p-SiC/in/Al type is 7.55%\(^4\), that of the ITO (Indium Tin Oxide)/n/p/S.S. type is 6.1~6.9%\(^5\),\(^7\),\(^8\) and that of the ZnS/AuPd/Nb2O5/in(F)-n(F)/Mo type is 6.6%\(^6\).

The p-i-n structure has many advantages for solar cell applications, such as stability, mass-production ease and low fabrication cost. Structures which appear attractive for industrialization are Glass/ITO/p-n-p/S.S., and, particularly, Glass/SnO2/p-SiC/in/Al, which has recently been developed by Hamakawa et al\(^9\).

Table 1 Photovoltaic performance of a-Si solar cells

<table>
<thead>
<tr>
<th>Cell structure</th>
<th>Voc (mV)</th>
<th>Jsc (mA/cm(^2))</th>
<th>F.F.</th>
<th>(\eta(%))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass/ITO/n/p(SiC)/in/Al</td>
<td>909</td>
<td>13.45</td>
<td>0.619</td>
<td>7.55</td>
</tr>
<tr>
<td>ITO/n/p/S.S.</td>
<td>857</td>
<td>11.8</td>
<td>0.72</td>
<td>6.91</td>
</tr>
<tr>
<td>ITO/p/n/S.S.</td>
<td>876</td>
<td>11.1</td>
<td>0.65</td>
<td>6.4</td>
</tr>
<tr>
<td>Glass/SnO2/p/Al</td>
<td>860</td>
<td>12.5</td>
<td>0.58</td>
<td>6.1</td>
</tr>
<tr>
<td>Pt/In/S.S.</td>
<td>800</td>
<td>11.3</td>
<td>0.66</td>
<td>5.52</td>
</tr>
<tr>
<td>Glass/ITO/p/In</td>
<td>830</td>
<td>12.0</td>
<td>0.58</td>
<td>5.5</td>
</tr>
<tr>
<td>ZnS/AuPd/Nb2O5/in(F)-n(F)/Mo</td>
<td>880</td>
<td>13.1</td>
<td>0.57</td>
<td>6.6</td>
</tr>
<tr>
<td>ITO/n(F)-i(F)-p/p/S.S.</td>
<td>840</td>
<td>8.1</td>
<td>0.55</td>
<td>3.7</td>
</tr>
</tbody>
</table>

3-2. Theoretical limit efficiency of the a-Si solar cell

We have calculated the theoretical limit efficiency of the p-i-n a-Si solar cell. This is an important factor in the industrialization.

The photovoltaic characteristics of the a-Si solar cell are strongly influenced by the gap states in the a-Si film. It is therefore important to use precision in dealing with the gap states. As for the distribution function of the gap states, Shur proposed a "V-shape" distribution\(^11\), and Konagai proposed a "U-shape" distribution\(^12\), which is shown in Fig. 4 (2). These distributions, however, are considerably different from actually observed gap state distributions. An example of the observed distribution, as reported by Spear et al.\(^13\), is shown in Fig. 4 (1). The Fermi level of the V-shape and U-shape distributions is also different from that of the actually observed distributions.

We have therefore proposed a new distribution function called the "Shifted U" distribution\(^14\), as shown in Fig. 4 (3). After calculating the Fermi integral, we confirmed that the Fermi level of the shifted U distribution was equal to the observed Fermi level. Accordingly, we will use the shifted U distribution hereafter.

Next, we calculated the potential energy and
the electric field distribution of the p-i-n a-Si solar cell by solving Poisson's equation. It is impossible to solve it analytically. Some researchers use the "step-by-step" method\(^1\), but there is some ambiguity in this method. We therefore dealt with Poisson's equation as a "boundary condition problem", and solved it directly by computer\(^2\).

This integral form of Poisson's equation can be written as follows.

\[
\frac{d\phi}{dx} = -e\sqrt{\frac{2}{\varepsilon K}} \int_{\phi_0}^{\phi} \rho(\xi) d\xi + C^2
\]

(1)

In Eq.(1), the integral constant \(C\) can be determined by the following equation.

\[
W = \frac{1}{e} \int_{\phi_n}^{\phi_p} \sqrt{\frac{2}{\varepsilon K}} \rho(\xi) d\xi + C^2
\]

(2)

\(W, \phi_p\) and \(\phi_n\) represent the thickness of the i-layer, the potential energy of the p-layer, and the potential energy of the n-layer, respectively. We calculated the potential energy and the electric field distribution by the previously mentioned procedure. An example of the result is shown in Fig.5.

We solved the continuity equation with the above results, and calculated the theoretical output characteristics of the a-Si solar cell using present values of the a-Si film's fundamental properties. Consequently, we calculated the theoretical limit efficiency to be 12.5%.

3-3. Integrated type a-Si solar cell

The voltage obtained under sunlight by one unit (one wafer) of the conventional crystal Si solar cell is less than 1V. From the point of view of practical use, an operating voltage of about 1.5V-12V is required for consumer applications, and several hundred volts is required for electric power applications.

The authors have developed an a-Si solar cell with a new structure by taking advantage of the a-Si characteristics, making it possible to generate a high voltage from one substrate\(^3\). This is an integrated type of solar cell in which cell units are arranged in a cascade fashion on an insulated substrate, as shown in Fig.6 (a), (b). The integrated type a-Si solar cell is manufactured by the following method.

First, separate transparent electrodes (ITO) are formed on an insulated substrate. Then, the a-Si films are formed onto them through a mask pattern. Finally, the metal electrodes are deposited on the a-Si films through an appropriate metal mask. The metal electrode of the first cell is in contact with the ITO electrode of the second cell. In this way, each of the a-Si cell modules can be connected in series, resulting in the generation of the desired high voltage.
The merits of this type are summarized as follows.

(1) A high voltage can be obtained from one substrate.
(2) The manufacturing process can be simplified.
(3) The power loss of a large-area cell can be reduced.

3-4. Life test

Reliability is one of the most important factors in the practical use of a-Si solar cell. The results of a-Si solar cell lifetime tests (under AM-1 illumination, 100 mW/cm²) are shown in Fig. 7. We can now fabricate a-Si cell modules which show no significant change in characteristics over a long period by sufficient controlling the film properties and by the passivation of the cell module.

3-5. Energy payback period

The energy payback period is one of the indexes used to evaluate solar cells. The energy payback period in years (Y) can be written as follows.

\[ Y = \frac{E_0}{E_g} \]  

(3)

\( E_0 \) and \( E_g \) are the energy required for solar cell production and the energy generated by the solar cell in one year, respectively.

The \( E_g \) factor in this formula is expressed by the following.

\[ E_g = \eta \cdot S \times 365 \times H_n \times E_i \]  

(4)

where \( \eta \) is conversion efficiency, \( S \) is cell area, \( H_n \) is average sunlight hours, and \( E_i \) is incident light intensity, substituting the following values,

\[ \eta = 5\%, \quad S = 100 \, \text{cm}^2, \quad H_n = 3.84 \, \text{hrs. (in Japan)} \quad \text{and} \quad E_i = 100 \, \text{mW/cm}^2 \]

The equation becomes as follows:

\[ E_g = 0.05 \times 100 \, \text{cm}^2 \times 365 \, \text{days} \times 3.84 \, \text{hrs} \times 100 \, \text{mW/cm}^2 = 700 \, \text{Wh/year} \]

Based on the present SANYO production process, \( E_0 \) was calculated in units of \( 10^5 - 10^9 \) W/year as shown in Table 2, for a-Si solar cell utilizing glass substrates[17]. This is calculated per 10 cm x 10 cm of the p-i-n type a-Si solar cell.

Table 2 Energy required for the production of 1 Watt a-Si solar cell (\( E_0 \)) and energy payback period in years (Y)

<table>
<thead>
<tr>
<th>Production volume (W/year)</th>
<th>( E_0 ) (Wh)</th>
<th>Y (year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 10^5 )</td>
<td>1470</td>
<td>2.10</td>
</tr>
<tr>
<td>( 10^6 )</td>
<td>1169</td>
<td>1.67</td>
</tr>
<tr>
<td>( 10^7 )</td>
<td>735</td>
<td>1.05</td>
</tr>
<tr>
<td>( 10^8 )</td>
<td>623</td>
<td>0.89</td>
</tr>
<tr>
<td>( 10^9 )</td>
<td>609</td>
<td>0.87</td>
</tr>
</tbody>
</table>

The energy payback periods (Y) can be calculated by the equation (3) from the above mentioned values. The results are shown in Table 2. Although this period varies according to the production volume, it equals 2.1 years at \( 10^5 \) W/year and 0.87 year at \( 10^9 \) W/year.

Again, the energy payback period varies according to the production process and volume. For single-crystal cells, however, this period ranges from 10-20 year[18]. The remarkably short payback period of the a-Si cells is emphasized by this comparison.
4. APPLICATIONS TO CONSUMER PRODUCTS

In recent years, applications of the a-Si solar cell in consumer products have received considerable attention. This is due to the fact that (1) the power consumption of consumer products has been reduced through the use of ICs, and (2) the conservation of resources and energy is now required.

4-1. Characteristics of the a-Si solar cell under fluorescent light

Generally speaking, consumer products need a rather high voltage to drive their circuits. Therefore, when solar cells using single-crystal silicon (c-Si) units are applied to them, the units must be arranged in the manner shown in Fig. 8 (a). This leads to a higher solar cell cost. Moreover, the sensitive wavelength of the c-Si, especially its peak sensitivity, is on a longer wavelength than that of fluorescent light, as shown in Fig. 9.

On the other hand, the a-Si solar cell can generate high output voltage on one substrate by having a structure of the integrated type, as shown in Fig. 8 (b). This type has sensitivity characteristics almost similar to the spectrum distribution of fluorescent lights, as shown in Fig. 9, according to findings by the authors.

Table 3: Photovoltaic performance of various kinds of solar cells under illumination from fluorescent light

<table>
<thead>
<tr>
<th>No.</th>
<th>Voc (V)</th>
<th>Jsc (uA/cm²)</th>
<th>Pm (uW/cm²)</th>
<th>F.F.</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>a-Si</td>
<td>0.62</td>
<td>24</td>
<td>9.3</td>
</tr>
<tr>
<td>II</td>
<td>c-Si (designed for fluorescent lamps)</td>
<td>0.38</td>
<td>31</td>
<td>7.5</td>
</tr>
<tr>
<td>III</td>
<td>c-Si (regular)</td>
<td>0.27</td>
<td>16</td>
<td>2.2</td>
</tr>
<tr>
<td>IV</td>
<td>Ribbon c-Si</td>
<td>0.18</td>
<td>24</td>
<td>1.7</td>
</tr>
</tbody>
</table>

The photovoltaic performance of various kinds of solar cells under the illumination of fluorescent light are shown in Table 3. This table indicates that the a-Si solar cell exhibits excellent performance under fluorescent light. Therefore, the a-Si solar cell has great potential as a low-cost solar cell for consumer products.

4-2. a-Si solar cell module for consumer products

A number of different types of integrated a-Si solar cells has been developed use in pocket calculators, watches, clocks, and radios. Their modules are shown in Fig. 10. Since the a-Si solar cell is produced by a gas reaction, a-Si solar cell modules with various shapes can be produced as shown in this figure. The illuminated I-V characteristics of the module used for calculators (shown in Fig. 10, third from the left, top) are indicated in Fig. 11. A pocket calculator and watches powered by these integrated type a-Si solar cell modules are also shown in Fig. 12. As the world's first practical use of a-Si solar cells, a pocket calculator which was operated by the integrated a-Si solar cell module was marketed by SANYO in 1980.
5. APPLICATION OF THE a-Si SOLAR CELL AS AN ELECTRIC POWER SOURCE

The applications of a-Si solar cells as an electric power source are progressively increasing. The fact that (1) a-Si solar cells are formed by a gas reaction, and (2) there is no grain boundary, makes their use in large-area cell applications relatively simple.

The development of these large-area solar cells is progressing in research centers around the world in direct proportion to improvements in their conversion efficiency.21),22) This has also been accompanied by the trial production of solar panels utilizing these large-area solar cells.

A solar panel developed by the authors which consists of 20 integrated type solar cells, each measuring 10cm x 10cm, is shown in Fig.13. The size of this panel is 45cm x 60cm, and its conversion efficiency at the present time is approximately 3%. The conversion efficiency of such solar panels, however, is expected to increase as improvement is made in the conversion efficiency of the individual a-Si solar cells.

In order to identify the problems which exist in the development and practical application of a solar energy generating system comprised of a-Si solar cells, and to conduct a test of the lifetime of the a-Si solar cells, the authors constructed the model system shown in Fig.14. In this construction, 513 a-Si solar panels, each consisting of 20 a-Si
solar cells measuring $10\,\text{cm} \times 10\,\text{cm}$, are installed on the roof and surrounding eaves. This system is presently capable of generating 2 kW of energy.

6. THE FUTURE OUTLOOK FOR a-Si SOLAR CELLS

6-1. Cost

The a-Si solar cell is receiving considerable attention as a low-cost solar cell. Some of the reasons for this are as follows.

(1) The production process is a simple one, and automation is possible.

(2) Very little energy is required for production.

(3) The amount of materials necessary is small.

Based on the present SANYO production line, we calculated the cost of solar cell production by varying the production volume, using conversion efficiency as a parameter. The results of this calculation are shown in Fig.15. It can be seen from this figure that for the purpose of reducing the cost of a-Si solar cells, it is important to improve their efficiency, but a more effective means of cost reduction is to increase their production volume. For a production volume of $10^8$ W/year with a conversion efficiency of 8%, we estimate the cost to be about $0.25/W$. For a production volume of $10^9$ W/year with a conversion efficiency of 8%, however, we estimate the cost to be $0.15/W$.

6-2. Coming prospect

In 1975, Spear et al. announced that it is possible to control the electrical properties of a-Si. Within only five years the realization of a-Si solar cells, with the emphasis on consumer products, commenced. When compared to other similar examples of development, this progress has been lighting fast.

The present SANYO production line already possesses the capability of turning out a production volume of more than 30kW/year. Moreover, although the present emphasis is on pocket
calculators, the applications for these solar cells will continue to expand. In response to this, we expect the production volume to increase at a remarkably rapid pace.

We are now maintaining our basic production volume through present applications in consumer products, and continuing research on mass production methods and cost-reducing processes. At the same time, we are working toward improving the conversion efficiency of the a-Si solar cell. The conversion efficiency has now been improved to the level of 6 - 7% in small-area cells. This is a clear indication that the industrialization of a-Si solar cells for use as electric power sources is very near.

![Image of a-Si solar cell heat collector](image_url)

**Fig.16** a-Si solar cell heat collector in which a-Si solar cells are combined with a heat pipe collector.

In addition to this, Fig.16 shows the amorphous solar cell heat collector, developed by the authors, which utilizes a-Si film as an electric power source and also as a selective absorption film for the heat collector, resulting in a process which simultaneously produces electricity and heat. This process utilizes the a-Si film properties of (1) being transparent with regard to visible light, and (2) possessing a high degree of reflectance with regard to the infrared region, as shown in Fig.17. The upper figure shows the spectral distribution of AM-1 sunlight, and the radiated energy distribution from an object at 373°K. The lower figure shows the spectral distributions of the reflectance and emissivity of a-Si film. These measurements showed that this type of application would be one direction for the application of a-Si solar cells.

**Fig.17** Radiation and reflection spectra (1) Spectral distribution of AM-1 sunlight and the radiated energy distribution from an object at 373°K (2) reflectance and emissivity of a-Si film.

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