Studies on the Outdoor Performance of Amorphous Silicon Solar Cells

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1. Introduction

The advantages of SCAF (series-connection through apertures formed on film) cells with plastic film substrate are as follows[1]:

(1) The output voltage can be adjusted based on the system requirements, and the wirings between the modules are simple due to the monolithic series-connected structure
(2) The cells can be applied on the slightly curved surface due to the flexible plastic film substrate
(3) Light weight cells can be realized due to the thin film structure

However, for practical uses, durability and the outdoor performance of the modules should be verified. Therefore, several accelerated tests were performed to evaluate the reliability of the modules. In addition, we are conducting the outdoor power generation tests to evaluate the effects of the azimuth and tilt angle, and material difference between crystalline silicon and amorphous silicon. The field tests verify the performance of the modules under the actual operating conditions on the roof. In this paper, we report the results of the outdoor field performance tests, which were conducted in the premises of Fuji Electric Corporate Research and Development Ltd.

2. Comparison of the Outdoor Performance of Several Solar Cell Modules

It is common practice to evaluate the performance of solar cells using a solar simulator and express the performance under standard conditions [i.e. irradiance: 1 kW/m^2, module temperature: 25°C and solar spectrum air mass (AM) 1.5]. However, it must be noted that it is seldom that the solar cells operate under the standard conditions during the field test. The performance of the solar cells varies depending on the operating environment. This is especially true for the amorphous silicon (a-Si) solar cells, as these cells exhibit a decrease of conversion efficiency at the initial irradiation and a recovery of the conversion efficiency by the thermal anneal. As a result, the amorphous solar cells exhibit different seasonal behavior from that of the crystal silicon (Si) solar modules. To maximize annual energy, it is common to install cells in the azimuth angle of 0° (toward the south) and position the tilt angle slightly lower than that of the latitude at the location of installation. But, due to limitations inherent at the installation location (e.g. the roof of a house), the actual installation conditions may differ from optimum conditions. We, therefore, installed several solar modules on the premises of Fuji Electric Corporate Research and Development Ltd. in Yokosuka City and measured the power generating status of these modules in order to evaluate the following aspects:

(1) Compare the amorphous solar cells to the crystal Si solar cells
(2) Compare the power generating performance of amorphous solar cells with different device structures
(3) Evaluate the effects of the module installation conditions (azimuth and tilt angle)

Below, we report the measuring system for the generated energy and the results of the tests to date.

2.1 Outline of the measuring system for the generated energy

Outline of the measuring system is summarized in Table 1 and some explanations are provided.

2.1.1 Type of modules and arrangement

Modules used for the tests consist of two types: the a-Si/a-Si module and the a-Si/a-SiGe module. Both types of modules are double-junction amorphous cells, which were developed by Fuji Electric. In addition, crystal Si solar cells and single-junction a-Si solar cells (a-Si single) were tested, in order to provide a comparison. The focus of the present experiment is the tandem (a-Si/a-SiGe) structure, which has a spectral response as shown on Fig.1. The rated power (nominal maximum output power) of several modules is summarized on Table 2. The listed values are the rated power of a-Si modules after stabilization.

To evaluate the power generating performance, each type of module was placed at the standard tilt angle of 6/10 (31°) and the performance was recorded. The effects of the installation conditions were evaluated using Ge tandem modules. The modules were installed on the roof of research facilities, and the arrangement was chosen to minimize unwanted shading from surrounding buildings and support structures.

2.1.2 Measuring system

In the regular solar power generating system, generated DC power is converted into AC power and the operating condition of the solar cells is controlled by the maximum power point tracking (maximum power: P_{max}). When the generated power of each module is measured, the power has to be consumed continuously by the load under the changing operating environment to keep the output power at P_{max}. In our tests, the generated power was consumed by the electronic load, while controlling the operating point by the P_{max} tracking circuit. The operating voltage and current were measured under these condition. Because the measured values are in DC, the generated power can be calculated by multiplying the voltage by the current. Generated power was measured at 10 second intervals and the mean power values over one minute were calculated and stored in the measuring computer. These data were automatically transferred to the database every day at 1:00 am. To date, there has been no deficit of measured data from this system.

Table 1 Outline of the measuring system for the generated energy

Item	Description
Location of the measurement	Yokosuka City North latitude 35°13′ East longitude 139°37′
Measured items	Irradiation, generated power and energy, ambient temperature, module temperature, wind velocity
Measured modules	Four types (2 modules for each type) a-Si/a-Si, a-Si/a-SiGe, crystal Si, a-Si single
Azimuth angle	East, west, south and north
Tilt angle	Standard tilt angle : 6/10 (31°) and vertical (partly)
Measurement of the generated energy	Operating point was controlled by P_{max} control circuit. Operating voltage and current were measured while the generated energy was being consumed by the electronic load.
Measuring interval	Measuring interval : 10 seconds, mean values were calculated at 1 minute interval.
Data processing	Data was transferred daily from the measuring computer to the Oracle data base automatically. Integrated and mean values were calculated at minimum 10 minutes interval.

Fig.1 Structure of the tandem film-substrate solar cell and spectral response

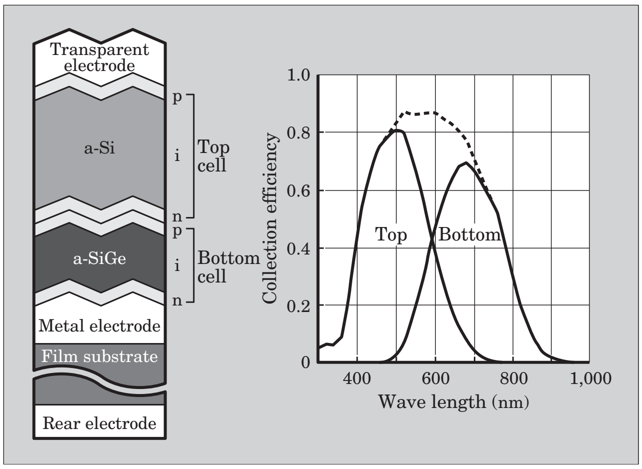


Table 2 Rated power of several modules (at the standard test conditions)

Type (abbreviation)	Device	Rated power (W)
Ge tandem	a-Si/a-SiGe	23
Si tandem	a-Si/a-Si	20
Crystal Si	Crystal Si	52
a-Si single	a-Si	28 (value on the nameplate)

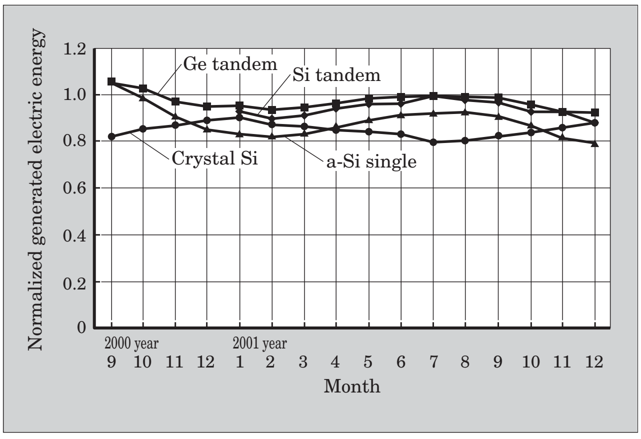
2.2 Comparison of the generated energy of several solar modules

On September 14, 2000, we started the measuring three solar module types: the Ge tandem, the crystal Si, and the a-Si single. Later in the study (December, 2000), the Si tandem was added.

Figure 2 shows the monthly change of the normalized generated energy of several solar modules. The normalized generated energy is the total generated energy divided by the product of rated power × irradiation period converted into 1 kW/m^2. This represents the ratio of total generated energy at the actual outdoor environment to the calculated energy, assuming that the energy conversion efficiency is operating under the standard conditions. Figure 2 shows that the monthly normalized generated energy of crystal Si modules is high in winter and low in summer. On the contrary, the monthly normalized generated energy of amorphous modules is low in winter and high in summer. This result is due to the following two reasons:

(1) Generally, semiconductor type solar cells have

Fig.2 Monthly normalized generated energy



negative output temperature characteristics. Amorphous solar cells show the same characteristics when the temperature rapidly changes but irradiation conditions remain constant. But, photo-induced defects are annealed and the conversion efficiency is improved during the summer in amorphous silicon cells. The output deviation of crystal Si, having a negative dependence on temperature, is roughly twice that of the amorphous type and these temperature coefficients range from －0.004 to －0.005, and －0.002 to －0.0025 for the crystal Si and the amorphous type, respectively.

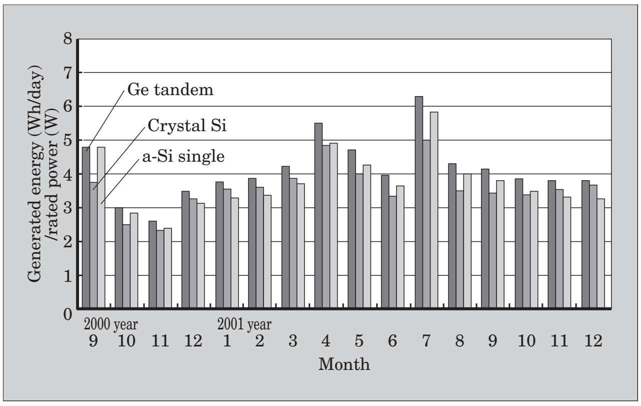
(2) Relatively, summer irradiation has higher energy in short wave length region and winter irradiation has higher energy in long wave length region. The amorphous type, which has a larger optical gap and higher short wave length sensitivity compared with those of crystal type, has an advantage in summer and disadvantage in winter.

Figure 3 shows the monthly change of the generated energy (Wh) per rated output (W) for Ge tandem, crystal Si and a-Si single solar cells. The solar power generating system user will usually select the solar modules based on the rated (nominal) power, which is the performance at standard conditions (i.e. irradiation: 1 kW/m^2, module temperature: 25°C, air mass 1.5). Despite the fact that different cell types may have similar power ratings, it is important to note that the actual generating energy varies depending on the type of solar cells. Table 3 shows the actual annual energy generated (from January, 2001 to December, 2001) from the three type solar cells under investigation. The following sections will serve to further elucidate these measured data.

2.2.1 Comparison of crystal Si and amorphous type (Ge tandem)

Generated energy on 2001 per rated power of 1 W was 1,540 Wh and 1,350 Wh for the Ge tandem and crystal Si, respectively. Generated energy of Ge tandem is about 14 % higher than that of crystal Si. Values are the measured energy on the DC side.

Fig.3 Monthly change of generated energy (Wh) per rated power of 1 W



Available energy on AC side can be obtained by multiplying by the inverter efficiency (0.9).

This result suggests that the user can gain more energy by applying the Ge tandem. Considerable differences during summer can be observed from Fig. 3. According to Fig. 2, the normalized generated energy of both types is almost identical in winter, but the difference in summer is as much as 20 %. The measured module temperature in summer was about 60°C, which is much higher than the standard module temperature of 25°C. The reason for such a discrepancy in power generated during summer is due to the large negative temperature coefficient of crystal Si.

2.2.2 Difference of the normalized generated energy by the device structure among amorphous types

As can be seen from the monthly change of the generated energy on Fig. 2, the declination of the performance of Ge tandem due to the initial irradiation is smaller than that of a-Si single. In addition, the fluctuation of the power generating performance by season is also small. Annual generated energy per rated power 1 W was 1,540 Wh and 1,384 Wh for the Ge tandem and the a-Si single, respectively (Table 3). Ge tandem has 11 % higher performance. The purpose of adopting the tandem structure, as shown on Fig. 1, was to realize a thinner electrical conversion layer than that of single junction structure, to increase the electrical field, and to increase the absorbed energy while suppressing the initial deterioration due to irradiation. From the test results of the generated energy, we were able to verify that the tandem structure is effective.

It is reported that a disadvantage of the tandem structure is spectrum fluctuation from solar irradiation. Because the irradiation must be absorbed equally among all cells (top cell and bottom cell), spectrum fluctuation destroys the balance of irradiation among cells. However, when considering the power generation results of the present study, this effect is negligible.

The measuring period for Si tandem was relatively short. The initial deterioration stage was included in the test period for annual generated power. As a result, it is not easy the compare the performance quantitatively. However, when considering only the monthly normalized generated energy (Fig. 2), it can be

Table 3 Generated energy on January to December, 2001

Type (abbreviation)	Total generated energy (Wh)	Generated energy (Wh) per rated power of 1W (Wh/W)	Generated AC energy (Wh) per rated power of 1W (Wh/W)*
Ge tandem	35,582	1,540	1,386
Si tandem	30,281	1,495	1,346
Crystal Si	70,523	1,350	1,215
a-Si single	38,739	1,384	1,246

* : AC energy is the measured generated energy of the solar cells multiplied by 0.9 (inverter efficiency)

seen that the behavior of Si tandem is similar to that of Ge tandem.

2.3 Effect of the installation conditions

2.3.1 Dependence of the generated power on azimuth angle

On Ge tandem modules, generated energy at several azimuth angles was measured at the fixed tilt angle of 6/10 (31°). As shown on Fig. 4, monthly change of the relative generated energy (assuming 1 for south) at each azimuth angle reached a minimum in December and a maximum in June. This result was expected due to the reported solar elevation. In December, the relative generated power ranged from 0.54 to 0.58 for east and west, and 0.14 to 0.19 for north. In July, the difference of the generated energy by the azimuth angle was small. Total generated energy in 2001 was 0.79 for east, 0.81 for west and 0.59 for north, assuming 1 for south (Table 4). The measured generated energy corresponds to the measured value of the pyranometer, which was placed on each azimuth angle with the same tilt angle as the solar modules.

2.3.2 Generated energy of the vertically arranged modules

Assuming the modules are installed on walls, the generated energy at the vertical surface was measured and compared to that of the standard tilt angle (31°). Azimuth angle was south. As expected from the solar elevation, the relative generated energy at the vertical wall (1 at south) was maximum (0.96 to 0.99) in December and minimum (0.29) in July, as shown on Fig. 5. The average value in 2001 was 0.60 as shown on Table 5.

2.4 Summary

We were able to verify that the Ge tandem structure solar cells with plastics film substrate, which are currently being aggressively developed by Fuji Electric, generate 10 % higher annual energy (Wh) than crystal Si solar cells. This is important for the photovoltaic power generation system users, and will allow users to save money spent on electrical energy. The main factor causing the difference in the amount of energy produced is that the actual outdoor operating temperature is much higher than the standard temperature (25°C), which is used as the basis of the rated power. This is due to the fact that the conversion efficiency will be improved in summer, as opposed to crystal Si, which has a higher negative temperature coefficient and is negatively affected by conversion efficiency in the summer. In summer, the generated energy of amorphous Ge tandem solar cells per rated 1 W of power is 20 % higher than that of crystal Si. This means that Ge tandem solar cells are suitable for peak-cut during the greatest power demanding period.

Among the various structures of the devices, we verified that the annual performance of the Ge tandem is higher than that of a-Si single.

In addition, we found that the annual generated energy of the north-facing modules, is about 60 % of that of south-facing modules. Moreover, we found that

Fig.4 Dependence of the generated energy on azimuth angle (January to December, 2001)

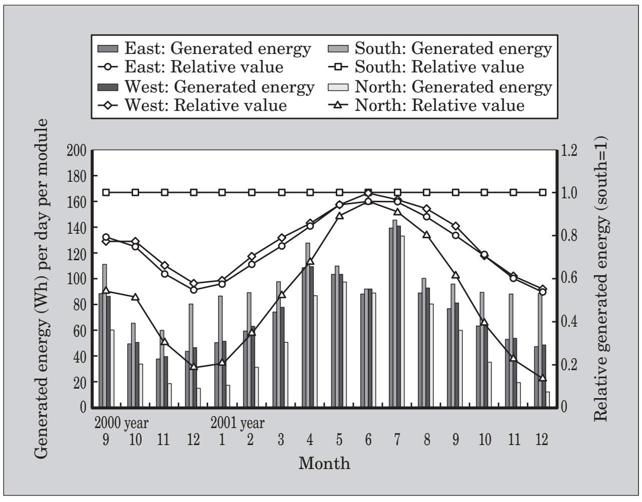


Table 4 Dependence of the annual generated energy on azimuth angle

Azimuth angle	Annual generated energy (Wh)	Relative values (south=1)
East	27,922	0.79
South	35,582	1
West	28,634	0.81
North	20,830	0.59

Fig.5 Dependence of the generated power on tilt angle

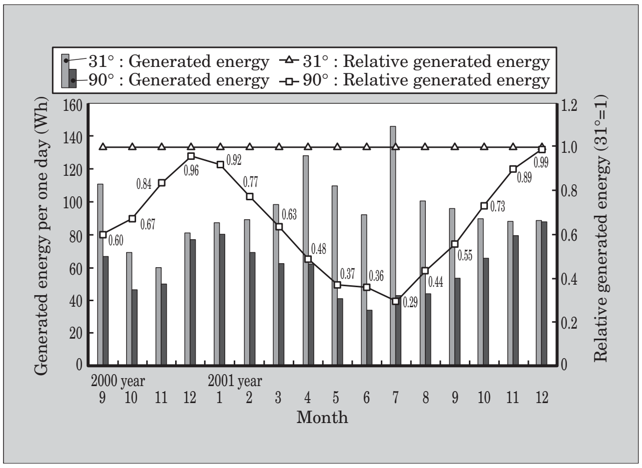


Table 5 Dependence of the generated power on the tilt angle (January to December, 2001)

Tilt angle	Annual generated energy (Wh)	Relative values (31°=1)
31° (normal)	35,582	1
Vertical	21,254	0.60

the annual generated energy of modules, which are installed vertically and face south, is about 60 % that of the tilted modules (31°).

In the near future, we would like to further analyze the effects of temperature and irradiation spectrum and continue the investigation on the large scale solar power system installed at Fuji Electric Human Resources Development Center Co. Ltd. As generated energy may be affected dramatically by environmental variables, a new standardized method, one which simulates actual operating environmental conditions, should be established for the verification of the performance of solar modules.

3. PV System for the Health Promotion Center

The solar modules composed of SCAF cells are being developed by Fuji Electric. In order to evaluate the performance of new modules in the outdoor environment, we installed two different type modules on the roof of the Health Promotion Center of Fuji Electric Corporate Research and Development Ltd. The continuous power generation tests were began in January, 1999. Below, we report the power generation test results.

3.1 Power generating system

Table 6 depicts an outline of the photovoltaic power generation system (PV system), which was installed at the Health Promotion Center. In the actual operating condition tests, we tested two different modules with a-Si tandem cells (a-Si/a-Si). Output from each module was converted into AC by an inverter. This output was then supplied to the load, and was used to power measuring and control equipment.

3.2 Specifications of the modules

In the actual operating condition tests, two distinct modules were used: Type A and Type B.

Type A : The surface is covered by a glass plate and the circumference is framed with aluminum.

Type B : The surface is covered by fluoric film, and integrated with roof tile.

The construction of type A is fundamentally the same as that of the conventional crystal Si solar module but instead of using crystal Si cells this type uses SCAF cells. In the SCAF cells, a flexible plastic film substrate is used. On SCAF cells, connections between the unit cells can be done automatically without the need for any production line wiring work. As a consequence, the wiring work is dramatically simplified and the cost for mass production may be reduced.

Type B is being developed in conjunction with building construction material manufacturers for the purpose of easy installation. Fuji Electric will manufacture the SCAF cells and encapsulate them with resin and protective film. The construction material manufacturers provided roof tiles and installed the solar cell modules. Glass covers and frames, which were used for the conventional modules, were eliminated in our developing modules and this significantly lightened the weight of the solar modules.

The type B model is relatively easy to wire and can be applied in a flexible manner. Because glass plates and frames are not required, direct material costs can be reduced and light weight construction can be realized. Due to these advantages, it is anticipated that there will be a large market for these models in the future.

Table 6 Outline of PV system for the Health Promotion Center

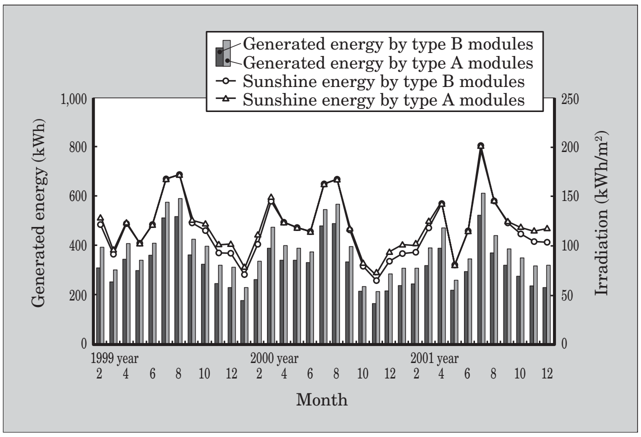
Item	Type A	Type B
Device structure	Si tandem	Si tandem
Installation area (aperture)	48.0 m^2	44.1 m^2
Installation tilt angle	19.3°	12.6°
Number of modules	80 modules	294 modules
Rated output of the installation	3.2 kW	3.0 kW

3.3 Power generating performance

Figure 6 shows the appearance of the Health Promotion Center. Type A is installed on the left side and type B is installed on the right side. We began testing in the middle of January 1999, approximately three years ago. Figure 7 shows the monthly generated energy for the three year study period. The difference of the generated energy between the modules is mainly due to the difference of the power generating surface area and the tilt angle of the installation. Both modules generated energy proportional to the irradiation and operated stably. Average annual generated energy per rated kW during the three year study period was approximately 1,360 kWh in DC (AC output was 1,209 kWh). This generated energy could reach a value of 1,495 kWh, which corresponds with the results at the test site detailed in Chapter 2. Generated

Fig.6 Appearance of the Health Promotion Center

Fig.7 Monthly change of the generated energy



energy was 10 % higher than that of the crystal type solar cells.

Based on the three years of power generation test results, sufficient data has accumulated in order to show that both A type and B type modules are suitable for practical uses.

We will continue these tests under actual operating conditions. These data will be collected and analyzed.

4. Conclusion

We introduced the outdoor performance of amorphous solar cell modules with a plastic film substrate. We were able to verify that the Si/Ge tandem structure amorphous solar cell, currently being developed by Fuji Electric, provides 10 % higher annual generated power than that of crystal Si solar cells. This is due to the excellent power generating characteristics of amorphous solar cells at high temperatures. This quality will be regarded as advantageous and desirable to users.

In addition, the reliability of the flexible modules (the models without glass cover on the module surface) is being refined. At present, the flexible modules have almost the same reliability as that of the conventional modules (the models with glass cover). In the near future, the flexible modules will be widely used in marketplace due to their flexibility and light weight design.

An increase in the a-Si film deposition rate and a reduction in the amount of man-hours necessary to produce a module are being realized. Fuji Electric will continue to make an effort to enhance all aspects of the business of solar cells and continue to research and develop cells, which possess remarkable features.

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Reference

(1) Yoshida, T. et al. A New Structure A-Si Solar Cell with Plastic Film Substrate. 1st World Conference on Photovoltaic Energy Conversion. USA. 1994, p.441-444.