

Light Trapping for Thin-Film Silicon Solar Cells Fabricated on Insulator

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We have developed a new solar cell using thin-film silicon supported by a silicon substrate etched in a grid form. The light-trapping structures of this cell have been studied by considering rear surface light reflections, electrical power loss and mechanical strength. High rear reflectance can be obtained by employing a multi-layer rear electrode. The pattern of the rear substrate is designed to provide sufficient mechanical strength and to minimize the electrical power loss, taking account of the current flow path. A conversion efficiency of 14.2% for a practical size of $10 \times 10 \text{ cm}^2$ is obtained by applying these calculated parameters using a single-crystal silicon substrate.

KEYWORDS: thin-film silicon solar cell, light trapping, light reflection, silicon on insulator, zone melting recrystallization

1. Introduction

Many types of thin-film silicon solar cells have been developed over the last 15 years, because of their potential to lower cost and provide higher efficiency. Chu *et al.*¹⁾ fabricated thin-film silicon solar cells on a carbon substrate with 9.75% efficiency for a small size of 9 cm^2 . Kendall *et al.*²⁾ reported cells with 10.9% efficiency for a practical cell size of 100 cm^2 on a conductive ceramic substrate.

For the realization of high conversion efficiency, highly efficient optical confinement and high crystal quality of silicon films are essential for thin-film solar cells. However, since the rear surface of conventional structures is entirely covered with the substrate, highly reflective structures at the rear surface might not be easily formed. There was an attempt to form a textured structure on the surface of the supporting substrate to increase total reflection,³⁾ but the process to form this structure resulted in high cost, and the rough substrate surface was disadvantageous for active layer formation.

The cells recently developed in our laboratory⁴⁾ have overcome these problems. The crystallographic quality of the thin-film active layer supported by an insulator-coated substrate is improved by the zone melting recrystallization (ZMR) method. The contact of the rear electrode is obtained by partial substrate etching, and this opening of the substrate makes it possible to form a highly reflective structure. This cell fabrication method and the structure will be described in detail elsewhere.⁵⁾

On the other hand, many studies have been made on optical confinement of conventional photovoltaic devices,^{6,7)} assuming a flat-plate wafer whose entire rear surface can be designed for optical trapping; however, since the rear structure of our cell is composed of both openings and frames, it requires a new analysis technique to determine its light-trapping ability. This paper is concerned with the design of a new type of thin-film silicon solar cells considering not only light trapping but also mechanical strength and electrical power loss. Finally, the performance of the thin-film silicon solar cell will be described.

2. Results and Discussion

Figure 1 shows the structure of the thin-film solar cell. The thin-film silicon active layer is formed by ZMR and epitaxial growth on an insulator-coated $\sim 600\text{-}\mu\text{m}$ -thick heat-resistive substrate. In this study, single-crystal silicon is used as a substrate. In order to obtain the rear contact and light reflection, partial openings are fabricated on the rear surface by selective etching of the substrate. The cell size is $10 \times 10 \text{ cm}^2$. Rear surface texturing is not performed in this study. The main points of the light-trapping design for this cell structure are as follows.

- Light reflection at the rear opening.
- Light reflection at the rear frame.
- Mechanical strength in handling.
- Electrical power loss at the upper part of the frame.

In order to fully utilize the rear light reflection, a larger area of the opening is desired. However, a larger area leads to decrease in mechanical strength. Consequently, items a)–d) require comprehensive optimiza-

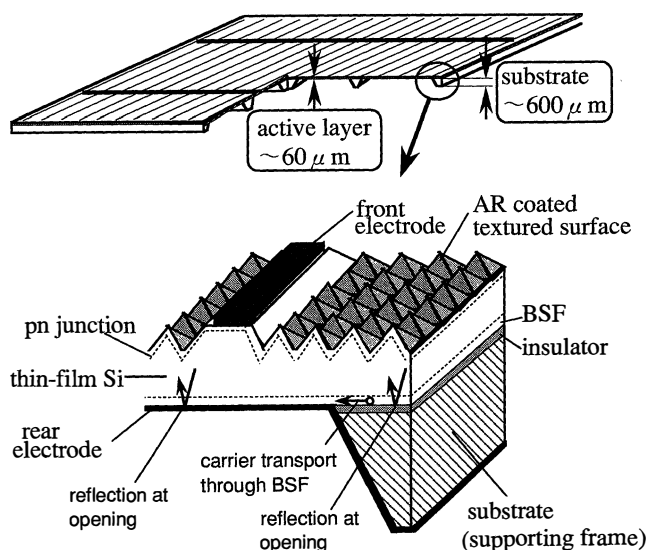


Fig. 1. Cell structure of thin-film silicon solar cell fabricated on insulator-coated substrate by zone melting recrystallization.

tion. From this point of view, each item above is discussed in the following sections.

2.1 Light reflection at rear opening

As shown in Fig. 1, this cell structure can be used to achieve high light reflectivity using rear surface treatments such as a textured structure or deposition of highly reflective metals. The requirements on the rear structure of the cell include high reflectivity as well as electrical conductivity. In order to realize reflectivity higher than that of conventional aluminum (Al) metal, we have adopted silver (Ag) metal and a transparent conductive indium tin oxide (ITO) film inserted between the thin Si film and Ag layer. This ITO film also plays the important role of an ohmic contact to the p^+ (BSF: back surface field) of the silicon film.

In Fig. 2, the results of the reflectance calculated at $\lambda=1000$ nm are shown, which includes the expected rear surface configuration for four different conditions. The matrix method^{8,9)} was used for the calculation, and calculated thickness of the ITO film was 900 Å. Comparing the result obtained using only Al film ($R=83.3\%$), the Ag film can increase the reflectance to $R=94.9\%$. Furthermore, insertion of the ITO film between Si and Ag makes it possible to obtain a sufficiently high reflectance of $R=98.5\%$. It is roughly estimated that the internal quantum efficiency, which is the light absorption, at $\lambda=1000$ nm is 0.319 ($R=0\%$), 0.525 ($R=94.9\%$) and 0.533 ($R=98.5\%$), and also that the enhancement of the short-circuit current density (J_{sc}) by the reflection of the rear electrode is 1.55 mA/cm² with Ag in comparison with the case of $R=0\%$, and is 1.6 mA/cm² with the ITO/Ag electrode. On the other hand, for low-cost fabrication (using the less-expensive Al electrode), insertion of the ITO film can improve the reflectance from $R=83.3\%$ to $R=95.2\%$. Since we have applied the ITO film, which has high electrical conductivity and high transparency as the inserted film, electrical and optical losses in the ITO layer are negligible.

2.2 Light reflection at rear frame

As shown in Fig. 1, incident light on the frame is partially reflected at the Si-insulator interface. Figure 3 shows the calculated reflectances ($\lambda=1000$ nm) at the Si-insulator interface for two types of conventional insulators (SiO_2 and Si_3N_4). Reflectances change periodically as functions of the film thicknesses. The maximum reflectance for the SiO_2 layer ($n=1.45$) is 51% and that

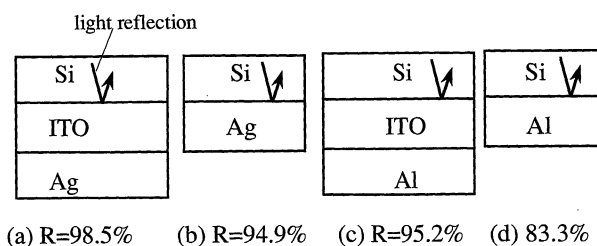


Fig. 2. Calculated reflectances for four different conditions of rear reflectors at opening.

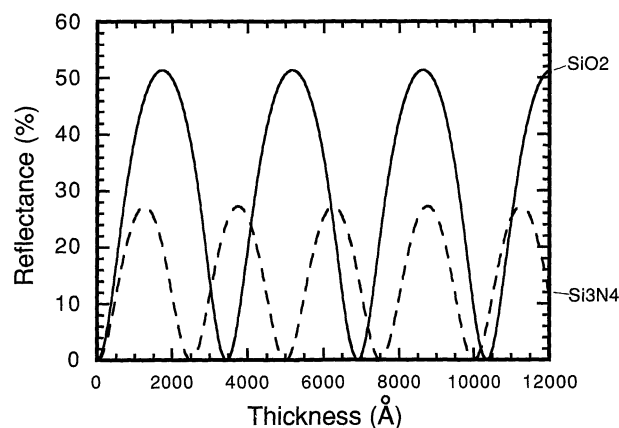


Fig. 3. Calculated reflectances at the upper part of the frame. Solid and dashed lines show reflectances of SiO_2 and Si_3N_4 , respectively.

for Si_3N_4 ($n=2.0$) is 28%. This is because the reflectance tends to be higher for a larger difference of refractive indices between the silicon and insulator than for a lower one. Therefore, SiO_2 is a better material for use as the insulator of the thin-film cell. If the material of the insulator can withstand the high-temperature ZMR process, air or highly reflective metals are more suitable than insulators to obtain higher reflection, because such materials have large refractive index differences with silicon. The calculated result shows the maximum reflectance of 51% for SiO_2 at thicknesses of about 1700 Å, 5200 Å, 8600 Å, and 12000 Å. In the case of thin films (less than 2000 Å), high-quality silicon film is difficult to obtain due to its tendency to aggregate or form holes in the insulator. On the other hand, thick films (more than 10000 Å) lead to more cracks or surface roughening, aside from their higher costs. Therefore, 5200 Å or 8600 Å is a suitable thickness for the insulator of this cell.

2.3 Mechanical strength

In industry, conventional solar cells use about 200- μm -thick silicon wafers with the size of 10 cm square because of the ease of wafer handling without wafer fracture. In this regard, we have evaluated the strength of thin-film solar cells using a three-point bending rupture test analysis.

The fracture limit (P_c) of a plate is expressed as

$$P_c = \frac{2W\zeta t^2}{3L}, \quad (1)$$

where W is the cell width, L is the cell length, ζ is the stress limit of silicon, and t is the substrate thickness. Although the fracture limit of the supporting frame shown in Fig. 1 has a complicated form, the strength of the plate must be proportional to the area of the frame as a first approximation. Moreover, in the case of a synthesized structure (a thin film is mounted on a thick substrate), if the film is sufficiently thin compared to the substrate, the stress caused by the thin film is negligible in this calculation. Considering these assumptions, Fig. 4 shows the results of the allowable area of the opening for handling during fabrication as a function of

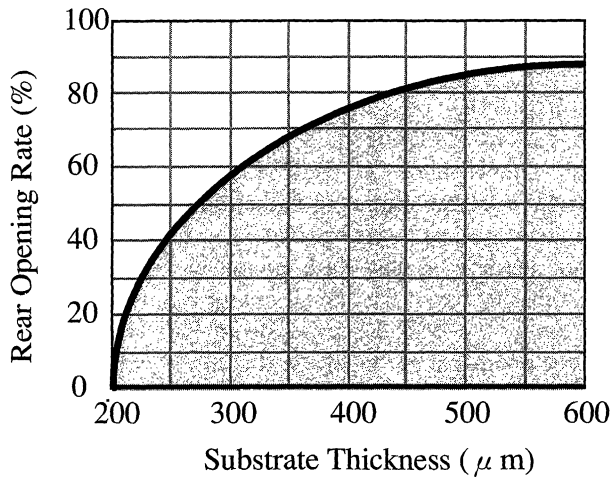


Fig. 4. Calculated possible rear opening area as a function of substrate thickness. Shaded part indicates possible range for handling.

the substrate thickness. The curve indicates that the strength of the cell is equal to that of the 200- μm -thick wafer. For example, the result shows that 84% of the area can be opened for a 600- μm -thick substrate. The shaded part shows the possible range for handling. Equation (1) suggests that the strength of the cell is proportional to the square of the substrate thickness; thus it is advantageous to employ a thicker substrate.

Now we consider the pattern of the frame. Possible basic patterns are honeycomb, circle and grid. In the case of a honeycomb pattern, it is flexible in the transverse direction, resulting in higher stress on the thin film. A circular pattern cannot achieve high packing density, resulting in a small area of the opening. Therefore we concluded that the simple grid pattern is suitable for thin-film solar cells.

2.4 Electrical power losses

As shown in Fig. 5, carriers generated at the upper part of the frame travel laterally to the rear electrode at the opening through a BSF layer, causing electric power loss. We calculate this power loss approximately using

$$P_{\text{loss}} = 8 \left(\frac{W}{L_f} \right)^2 \int_0^{W/2} \left(J_{\text{ph}} \cdot x \cdot \frac{L_f}{2} \right) \cdot \frac{\rho_{\text{BSF}}}{d_{\text{BSF}} \cdot \frac{L_f}{2}} dx$$

$$= \frac{J_{\text{ph}}^2 \cdot W^2 \cdot W_f^3 \cdot \rho_{\text{BSF}}}{6 \cdot L_f \cdot d_{\text{BSF}}} \quad (2)$$

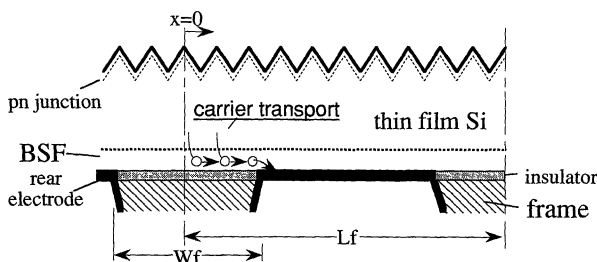


Fig. 5. Schematic of the generated carrier transport through the BSF layer on the upper part of the frame.

where W_f is the width of the frame, L_f is the center-to-center spacing of frames, W is the cell size, ρ_{BSF} is the resistivity of BSF, d_{BSF} is thickness of BSF and J_{ph} is short-circuit electric current density.

Figure 6 shows calculated results of electrical power loss as a function of the rate of the opening area for two

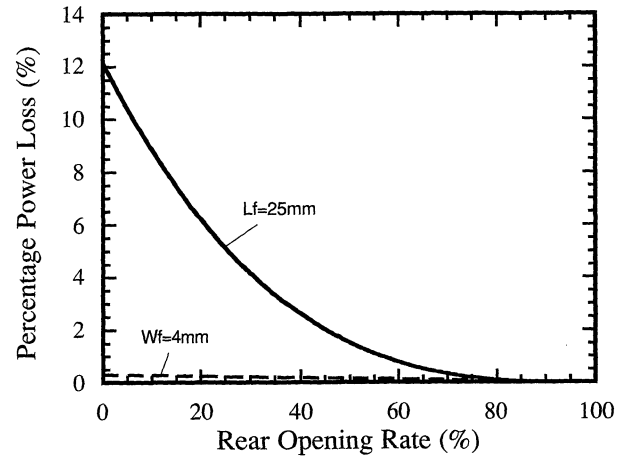


Fig. 6. Calculated power loss as a function of the rate of the rear opening area.

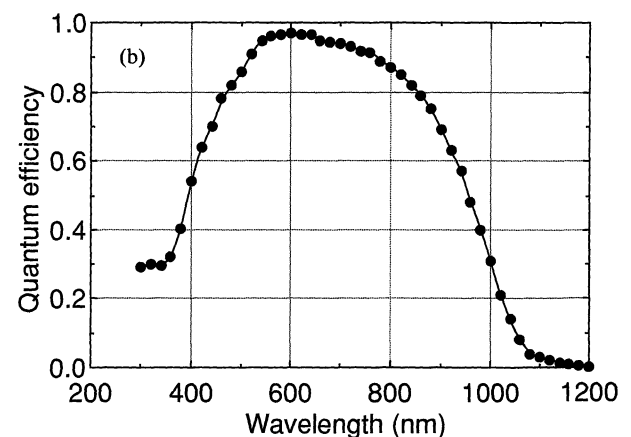
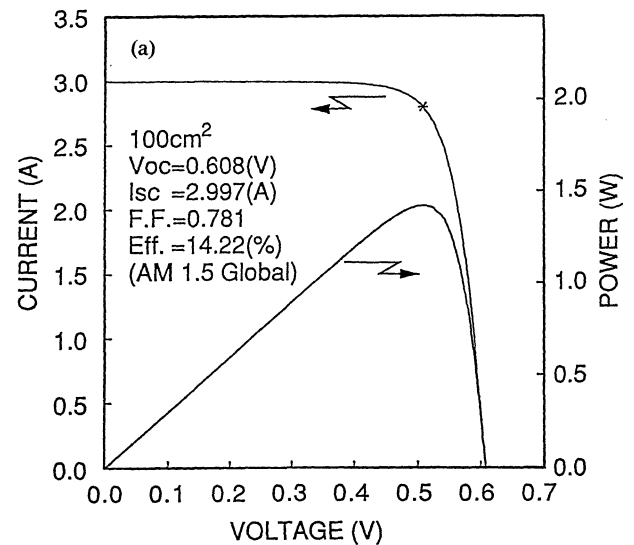


Fig. 7. I - V characteristics (a) and spectral response (b) of a thin-film silicon solar cell with a cell size of $10 \times 10 \text{ cm}^2$ under simulated AM1.5, 100 mW/cm^2 .

cases: one with the width of the frame (W_f) fixed at 4 mm and the other with the center-to-center spacing (L_f) fixed at 25 mm. In this calculation, $\rho_{BSF}=10^{-3} \Omega \cdot \text{cm}$, $d_{BSF}=3 \mu\text{m}$, $W=10 \text{ cm}$ and $J_{ph}=35 \text{ mA/cm}^2$ are assumed. The decrease of the opening area leads to the increase of power loss. The large power loss at the region of the small opening area for $L_f=25 \text{ mm}$ indicates that a wide W_f of more than 4 mm generates large power loss. Equation (2) indicates that the power loss is proportional to the third power of W_f . Then, the power loss increases drastically with wider W_f , which is equal to longer carrier transport distance. Therefore, in order to decrease the power loss, a slender frame with many lines is advantageous over a wide frame with few lines for the same area of the opening.

2.5 Fabrication of solar cells

Applying the results from the above sections, we have fabricated a thin-film silicon solar cell. Since it was the first fabrication of this type of cell, not all parameters could not be optimized in this study. Fabricated cell parameters were as follows: 600- μm -thick silicon substrate, ITO (900 Å)/Ag rear electrode at the openings, SiO_2 layer as an insulator (1 μm thick), $W_f=4 \text{ mm}$, $L_f=25 \text{ mm}$, and rate of the opening area was 60%. As shown in Fig. 7(a), a high efficiency of 14.2% can be obtained with the new thin-film solar cell having an area of $10 \times 10 \text{ cm}^2$ and high quantum efficiency at a longer wavelength of the 60 μm thin-film silicon solar cell (Fig. 7(b)).

3. Conclusions

The light-trapping structure of the thin-film silicon solar cell has been studied by considering the mechanical strength, the electrical power loss and the rear surface light reflections at both the opening and the frame. At the rear opening, very high reflectance (98.5%) can be obtained by inserting a transparent conductive ITO film between the Si and rear Ag metal without an increase of electrical power loss. At the upper part of the

supporting frame, a high reflectance (51%) can be obtained using a SiO_2 layer with low refractive index as an insulator by optimizing its thickness. The limit of the area of the rear opening is determined by the limit of the mechanical strength. A thicker substrate leads to fewer occurrences of cell fracture, because cell strength is proportional to the square of the substrate thickness. A simple grid pattern is suitable for the rear frame, leading to low damage of the thin film and a wide opening area. Electrical power loss due to current flow through a BSF layer can be suppressed by using a slender frame rather than a wide one, because the power loss is proportional to the third power of the carrier transport distance. A high efficiency of 14.2% for a practical size of $10 \times 10 \text{ cm}^2$ is obtained in a cell fabrication applying these calculated parameters.

Acknowledgement

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