THIN FILM Poly-Si SOLAR CELL ON GLASS SUBSTRATE FABRICATED AT LOW TEMPERATURE

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ABSTRACT

The performances of thin film poly-Si solar cells with a thickness of less than 5 μm on a glass substrate have been investigated. The cell of glass / back reflector / *n-i-p* type Si / ITO is well characterized by the structure of naturally surface texture and enhanced absorption with a back reflector (STAR), where the active i-type poly-Si layer was fabricated by plasma chemical vapor deposition (CVD) at low temperature. The cell with a thickness of 2.0 μm demonstrated an intrinsic efficiency of 10.7% (aperture 10.1%), the open circuit voltage of 0.539 V and the short current density of 25.8 mA/cm^2 as independently confirmed by Japan Quality Assurance. The optical confinement effect explains the excellent spectral response at long wavelength for our cells through the PC1D analysis. The higher sensitivity at long-wavelength of our cell appeared in quantum efficiency curves is well correlated to the result of reflectance measurement. The efficiency of 9.3% cell with a thickness of 1.5 μm was proved to be entirely stable with respect to the light-soaking. Based on the result of various evaluation of diffusion length, it is postulated that the low temperature poly-Si prepared by plasma CVD gives a device quality of poly-Si film.

INTRODUCTION

The use of thin-film polycrystalline silicon (poly-Si) for solar cells is one of the most promising approaches to realize both high performance and low cost. Several thin film silicon growth techniques and theoretical calculations for solar cells have been reported [1-10]. To realize a cost-effective and high-performance of solar cell, we believe that following three issues are important. One is to develope the low temperature fabrication process, which enables the use of low cost substrate. Second is to develope the technology of large area production such as applied to the a-Si:H cells. Third is to develpo an optically enhanced structure to enable us to reduce film thickness. Taking into account these issues, we focus on the research for developing the thin film silicon with a thickness of less than 5 μm on glass substrate fabricated at low temperatures.

We have developed a novel cell structure and low temperature process for fabricating a thin-film poly-Si solar cell on glass substrates [1-4]. We have demonstrated the excellent short circuit current density of thin film poly-Si solar cell (2-4 μm thick) on glass substrate despite of the low temperature fabrication [1-4]. It is a key issue for thin film poly-Si solar cell design achieving a high efficiency to enhance optical absorption [10] since it enables the short circuit current density to be sufficiently high even in a few micron thick thin film poly-Si solar cell. We had a report on the clear demonstration of enhancement of optical absorption of a thin film poly-Si solar cell [11-16].

In this paper the recent results of optical and transport properties of thin film poly-Si solar cells below 5 μm are summarized.

EXPERIMENTAL

A summary of the cell fabrication process is as follows. After the formation of the back reflector on a glass substrate, *n*-type Si film was deposited on it by plasma CVD or an improved plasma CVD process [13]. Next, intrinsic(*i*) poly-Si film as an active layer was deposited on it by plasma CVD at a substrate temperature of less than 550°C. The junction was formed by the deposition of *p*-type Si films. ITO was deposited on the solar cell as a transparent electrode. A Ag grid electrode was formed on the top. All fabrication processes were carried out with a maximum process temperature of less than 550°C. It should be noted that the 'intrinsic (*I*-)' means that *i*-layer Si is fabricated by plasma CVD without any intentional doping. However, we believe that the *i*-layer has

Mat. Res. Soc. Symp. Proc. Vol. 507 © 1998 Materials Research Society

a slight n-type character since it is deposited on the n-type layer and the resulting impurity of i-poly-Si is thought to be oxygen [6]. Moreover the carrier concentration of i-layer would be in the range of $1x10^{15-16}/cm^3$ as discussed below. Further investigation is needed to determine the carrier concentration.

RESULTS AND DISCUSSION

The performance of poly-Si solar cell with STAR structure

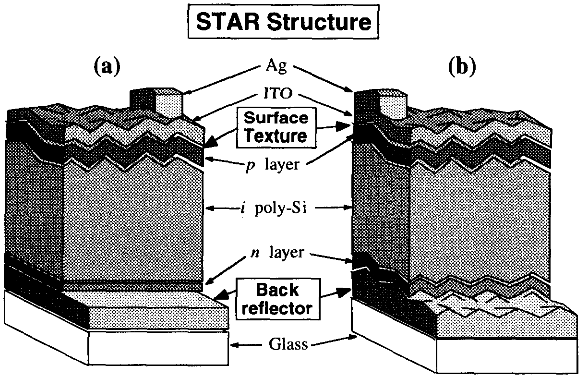


Fig. 1. Schematic view of our proposed thin film poly-Si solar cell with STAR (naturally Surface Texture and enhanced Absorption with back Reflector) structure. (a) first generation of poly-Si cell with flat back reflector, (b) second generation of poly-Si cell with rough back reflector for thinner cell

Figure 1(a) shows the schematic view of our first generation of thin film poly-Si cell with "STAR Structure", which means that the cell structure and properties are well characterized by naturally surface texture and enhanced absorption with a back reflector. One of the characteristics of this cell is its natural surface texture. An AFM image of the top surface of our poly-Si solar cell with STAR structure shows dendrite-like morphology with a surface roughness of the order of 0.12 μm for around 4 μm thick cell. Another characteristic of our thin film poly-Si is expressed by the columnar structure and strong (110) preferred orientation as determined by XRD measurement as shown in Fig. 2. The crystalline volume fraction was estimated by spectroscopic ellipsometry analysis on the basis of effective medium approximation model, which shows that more

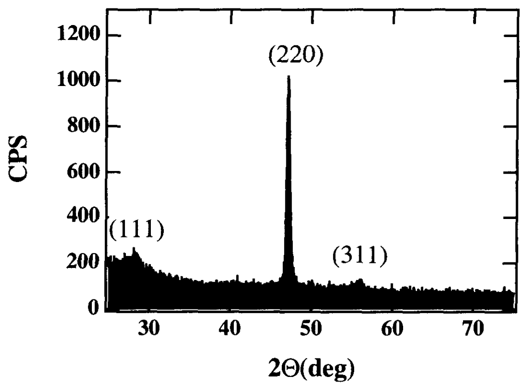


Fig. 2 XRD spectrum of low temperature poly-Si on glass substrate, Note that strong (110) preferred orientation

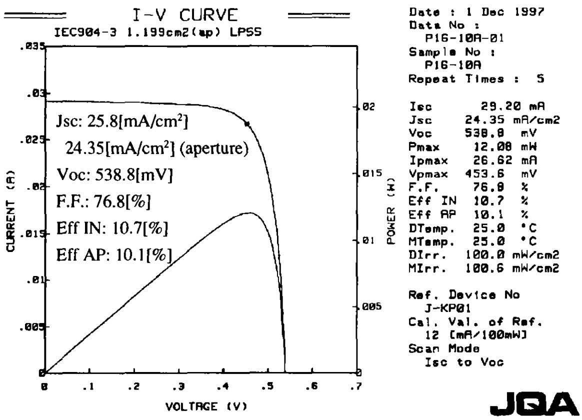


Fig.3 The performance of the 2.0 μm thick our poly-Si solar cell with STAR structure which was independently confirmed by Japan Quality Assurance (JQA). Eff IN and Eff AP represent the intrinsic and aperture efficiency of solar cell , respectively. The discrepancy between the intrinsic and aperture efficiency comes from the Ag grid electrode on the ITO.

than 90% are crystallized[14].

Figure1(b) shows the schematic view of our second generation of thin film poly-Si cell with "STAR Structure", where rough (textured) back reflector is used. This rough back reflector is useful for thinner cell. Since the feature size of natural surface texture strongly depends on the thickness of the cell, it is not good enough to give the good light trapping for thinner cell such as 1.5 μm. The detail will be cleared in the following discussion.

The 2.0 μm thick cell with this new "STAR Structure" demonstrated an intrinsic efficiency of 10.7% (aperture 10.1%), the open circuit voltage (Voc) of 0.539 V and the short current density (Jsc) of 25.8 mA/cm^2 as independently confirmed by Japan Quality Assurance, which is shown in Fig. 3. The prominently high Jsc was also obtained the same as previously reported for the 3.5 μm thick cell[11].

The light induced stability of 1.5 μm thick cell has been investigated under AM1.5, 100 mW/

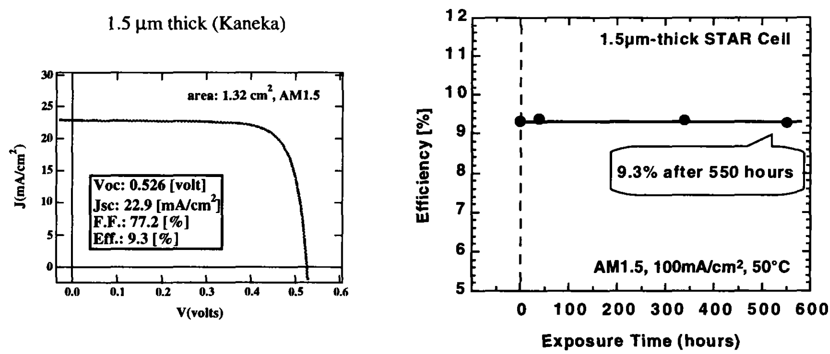


Fig.4 Initial efficiency and light-induced changes in eficiency for 1.5 μm thick poly-Si cell with STAR structure underAM1.5, 100 mA/cm^2, 50 °C and open-circuit conditions.

cm², 50 °C and open-circuit conditions, which is shown in Fig. 4 together with the initial cell efficiency. It was stable against the light-soaking similarly to the early work of microcrystalline by Meier et al[6,7].

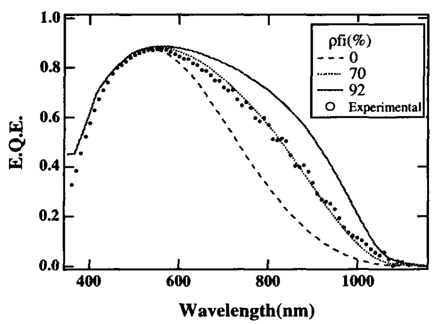
Both optical and transport properties of our cell are discussed as follows.

Light trapping of our STAR structure

First of all it is important to measure the optical constant such as absorption coefficient and refractive index for our low temperature poly-Si film. But the surface roughness coming from the naturally surface texture during the poly-Si growth by plasma CVD makes it difficult to determine the optical constant. Moreover the properties of low temperature poly-Si layer are non-isotropic (columnar growth) and the growth is strongly substrate-dependent. Recently A. Poruba et al[17]. reported that between 1.2 and 1.5 eV the optical absorption coefficient of microcrystalline and crystalline Si is nearly the same and that in the subgap region, defect-connected absorption is observed by CPM spectra. Although we do not know how close the absorption coefficient of our low temperature poly-Si film to their microcrystalline film, we would say that using the absorption coefficient of crystalline Si for our low-temperature poly-Si is well approximated to the first order.

The quantum efficiency spectra of both 4.7 μm and 1.9 μm thick solar cell with STAR structure were investigated, and are shown in Fig. 5 (a) and (b). Experimental results are plotted as the open circles in this figure. A relatively high quantum efficiency at long wavelength was observed for both 4.7 μm and 1.9 μm thick silicon solar cell. Note that the Jsc for AM 1.5 obtained by the integration of the quantum efficiency curve of each cell is over 27 mA / cm² for 4.7 μm and 25 mA

a) Cell thickness: 1.9 μm



b) Cell thickness: 4.7 μm

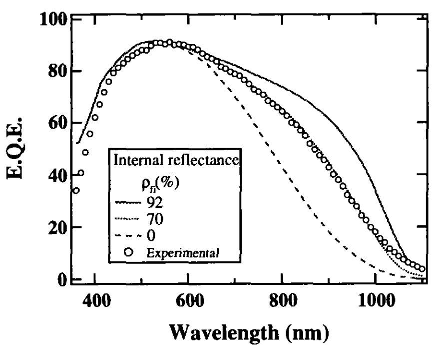


Fig. 5 The external quantum efficiency (E.Q.E.) spectra of; (a) 4.7 μm and (b) 1.9 μm thick solar cell with STAR structure, respectively. Experimental results are plotted as the open circles. The three curves (broken line, dotted line, solid line) are the calculated curves for ρ_{fi}= 0, 70, and 92% based on PC1D under the conditions listed in Table I, respectively. ρ_{fi} is defined as the internal global reflectance at the front surface in PC1D.

Table I Conditions for the PC1D calculation of the curves shown in Fig. 5 (a) and (b).

p-layer thickness:	30 nm
i layer thickness:	1.9µm,4.7µm
diffusion length:	7 µm
p & n layer doping density:	10 cm
i layer doping density	10 cm
surface recombination velocity: Sr	10 cm/s
back surface recombination velocity: Sb	10 cm/s
front internal reflectance: ρ_{fi}	0, 70, 92%

/ cm^2 for 1.9 µm thick cell, respectively. Experimental results of each cell are modeled from PC1D[18,19] by assuming the light trapping parameter (ρ_{fi}), which is defined as the internal global reflectance at the front surface in PC1D. The three curves shown in Fig. 5 (a) are the calculated curves for ρ_{fi}= 0, 70, and 92 % with an assumption of constant back reflectance (95 %) for each case, respectively. Other conditions for the calculation are listed in Table I. The shape of the experimental curve was well modeled from PC1D by assumption for ρ_{fi} =70% and an appropriate diffusion length L_{dif} = 7 µm for each case. It should be mentioned that the surface feature of the back reflector is different from each other. As mentioned below we used the more rough back reflector for the cell with 1.9 µm thick cell. The coincidence of calculated values for both ρ_{fi} and diffusion length of each cell happened to be seen. It is not clear whether it is meaningful or not. Here we would like to point out that our proposed STAR structure enables the few micron thick cell to obtain sufficient photon absorption by facilitating light trapping.

We have investigated the much thinner cell of 1.5 µm, which will help to overcome the low deposition rate of poly-Si prepared at low temperature. It is important to reduce the film thickness with maintaining the cell efficiency. Since as already mentioned our proposed feature size of naturally surface texture depends on the thickness of the cell, it is not good enough to give the high Jsc in 1.5 µm thick cell. It is necessary to apply the another method for giving the textured feature such

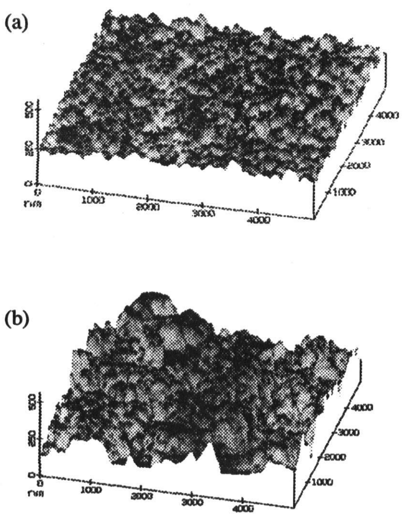


Fig. 6 The surface morphology of two kind ((a) cell on flat back reflector, (b) cell on rough back reflector) of 1.5 µm thick cells with ITO (80nm) at the top of it as seen by AFM.

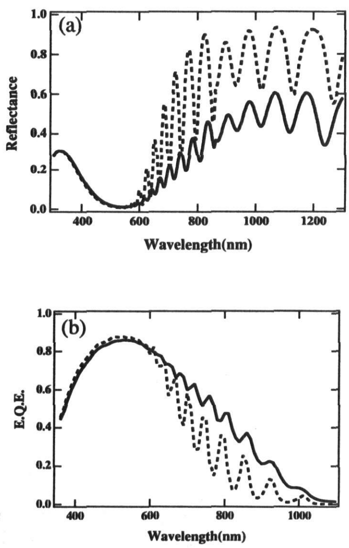


Fig. 7 The reflectance (a) and the quantum efficiency curves (b) of two kind of 1.5 µm thick solar cells with ITO (80nm), respectively. The solid line and dotted line show the reflectance of the cell with surface morphology of Fig. 6(b) and (a), respectively.

as by controlling the surface feature of back reflector. We have investigated the enhanced optical absorption of 1.5 μm thick cell for the several surface feature prepared by changing the feature structure of back reflector.

Figure 6 show the surface morphology and the reflectance of two kind of 1.5 μm thick solar cells with ITO (80 nm) at the top of it as seen by AFM measurement. The surface texture is changed by that of back reflector, while the rest of conditions are fixed. The AFM picture shows that both of the surface is rough. When carefully looking at these pictures, one is fairly smooth with a surface roughness less than 0.02 μm (flat) and the other has a surface roughness of the order of 0.21 μm (rough). The former and the latter one will be named by flat and rough, respectively.

Figure7(a) and (b) show the reflectance and the quantum efficiency curves of the 1.5 μm thick cells with above two kind of surface. In Fig. 7(a) the minimum reflectance at wavelength of 550 nm is appeared at both samples, which is attributed to the effect of 80 nm thick ITO. The excellent reduction of reflectance near long wavelength region was observed for the cell with rough surface. The effect of surface structure depends on the size of texture relative to the wavelength of incident light. For texture size from 0.1 μm to a few microns, there can be strong interaction between light and features. Although the feature size of rough one is about 0.21 μm, the reduction of reflectance at wavelength more than 600 nm is clearly observed in Fig. 7(a). It is concluded that both reflected and refracted light can be strongly scattered and that small texture works as a optical trapping of thin film Si solar cell.

The quantum efficiency curves of the 1.5 μm thick cells with above surface texture have been investigated and are shown in Figure 7(a) and (b). Note that the Jsc of the cell with flat and rough surface calculated from these curves are 18.5 and 22.1 mA/cm^2, respectively. These curves coincide with each other for the wavelength shorter than 600 nm and are separated for lomger wavelength regime. The difference of the sensitivity for long wave-length region is well correlated with that of reflectance in Fig. 7(a) From the relationship between the reflectance and quantum efficiency, rough back reflector works as a optical trapping of thin film cell. The details of interference amplitude together with the simulation results observed in Fig. 7 will be discussed elsewhere.

By the introduction to the rough back reflector together with optimizing the deposition conditions, we have prepared the 10.7% efficiency cell with a thickness of 2.0 μm, which is already shown in Fig. 3.

Transport properties of low temperature poly-Si

For understanding of our low-temperature poly-Si cell, it is important to know the minority carrier life time (diffusion length) and carrier concentration of the i-layer. These values estimated from both the simulation and various experiments for 3.5 μm thick cell are summarized in Table II. The carrier concentration determined indirectly by the numerical analysis of quantum efficiency curves and thickness dependence on Jsc is of the order of $10^{15\text{-}16}$/cm^3. While direct measurement such as C-V method is now carrying out[3]. The diffusion length is evaluated from three methods. One is from the numerical analysis of quantum efficiency curves in the same way as that in Fig. 5, leading to the diffusion length of 7 μm. Second one is derived on the basis of the effective diffusion length estimated from the evaluation of the inverse quantum efficiency[18] near the wavelength of 700-800 nm, which is shown in Fig. 8. The calculated effective diffusion length of 36 μm gives the diffusion length of 12 μm, based on the assumption of effective surface recombination velocity of 100 cm/sec and diffusion constant of 20 cm^2/sec. Thirdly we have tried the SPV method for the direct measurement of diffusion length. The SPV measurement was performed in the p-i-n structure. The diffusion length was determined by the intercept from the linear extrapolation of inverse surface photovoltage vs light

Table II List of transport properties estimated from both the simulation and various experiments for 3.5 μm thick cell.

carrier concentration:	10^{15}-10^{16} cm^{-3}
front internal reflactance:	70%
effective recombination velocity:	10^2-10^3 cm^{-3}
surface recombination velocity(SPV):	50 cm/s (p-i)
diffusion length(PC1D):	7 μm
diffusion length(IQE):	12 μm (L_{eff} 35μm)
diffusion length(SPV):	18 μm (670nm - 980nm)

penetration depths for 670 nm and 980 nm at constant photon flux of 10^{15}/cm^{2}sec as shown in the inset of Fig. 8. The resulting diffusion length is 17 μm for 3.5 μm thick cell which is beyond the SPV detection limit (measured diffusion length is longer than that of thickness). It would be at least said that the diffusion length is longer than that of thickness, and further investigation is needed. Based on the result of various evaluation of diffusion length and carrier concentrations, it is postulated that the low temperature poly-Si prepared by plasma gives a device quality of poly-Si film, which is thought to be performed by both the hydrogen passivation during the deposition and inactivation of impurity of low temperature process.

The SPV method was applied for investigating the uniformity of our cell. We have prepared a thin film Si solar cell with the size of 5 inches by 5 inches. Figure 9 shows the contour-map of diffusion length determined by SPV method. The uniformity of diffusion length is quite excellent over 5 inches substrate.

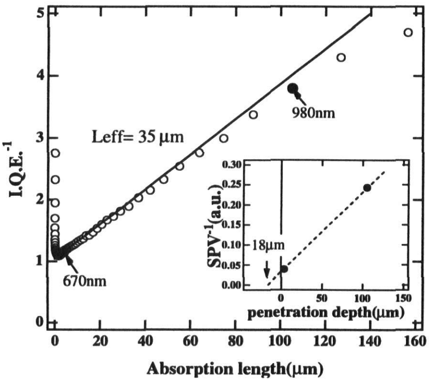


Fig. 8 The effective diffusion length of the cell estimated from the evaluation of the inverse quantum efficiency vs absorption length[18, 19].The relationship between inverse surface photovoltage and light penetration depths for 670nm and 980nm at constant photon flux of 10^{15}/cm^{2}sec as also shown in the inset of this figure. Note that the used wavelenth of SPV values marked in this figure at closed circles locate within the linear extrapolation reagion.

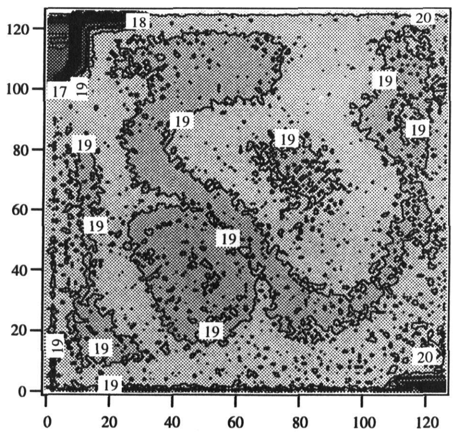


Fig. 9 The contour-map of difusion length for 5 x 5 inches substrate determined by SPV method. The unit of the values indicated this map is μm.

CONCLUSION

We have demonstrated the highest intrinsic efficiencies of 10.7% (aperture 10.1%) of ploy-Si solar cell with STAR structure, which was stable with respect to light-soaking.

ACKNOWLEDGMENT

This work was supported by the NEDO as a part of the New Sunshine Program under MITI.

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