The a-Si:H/poly-Si Heterojunction Solar Cells

Sang-Su Kim, Do-Young Kim, Dong-Gun Lim, Junsin Yi, Jae-Choon Lee, and Koeng-Su Lim

Abstract

We present heterojunction solar cells with a structure of metal/a-Si:H (n-i-p)/poly-Si (n-p)/metal for the terrestrial applications. This cell consists of two component cells: a top n-i-p junction a-Si:H cell with wide-bandgap 1.8eV and a bottom n-p junction poly-Si cell with narrow-bandgap 1.1eV. The efficiency influencing factors of the solar cell were investigated in terms of simulation and experiment. Three main topics of the investigated study were the bottom cell with n-p junction poly-Si, the top a-Si:H cell with n-i-p junction, and the interface layer effects of heterojunction cell. The efficiency of bottom cell was improved with a pretreatment temperature of 900℃, surface polishing, emitter thickness of 0.43μm, top Yb metal, and grid finger shading of 7% coverage. The process optimized cell showed a conversion efficiency about 16%. Top cell was grown by using a photo-CVD system which gave an ion damage free and good p/i-a-Si:H layer interface. The heterojunction interface effect was examined with three different surface states; a chemical passivation, thermal oxide passivation, and Yb metal. The oxide passivated cell exhibited the higher photocurrent generation and better spectral response.

I. Introduction

The recent progress in a-Si:H/c-Si type of solar cells suggest a new class of low cost, high efficiency, and large area silicon based solar cells. In this paper, poly-Si substrate is selected to satisfy low production cost and large area requirements. Thin film amorphous silicon is adopted to increase the solar cell efficiency. Heterojunction cells formed by depositing a-Si:H on a c-Si substrate have been demonstrated recently to have efficiencies comparable to the world highest record. Historical survey in Table 1 shows a cell conversion efficiency of 21% using a-Si:H/c-Si cell structure 1-10]. The research work on heterojunction cells may provide a new way for the terrestrial applications because of its capability to reduce production costs with high efficiency on reasonably large area substrates. This paper studied the heterojunction solar cells stacked with two homojunction cells; top a-Si:H cell with n-i-p junction and bottom poly-Si cell with n-p junction.

Figure 1 shows the investigated structure of heterojunction solar cells. In this type of multi-junction cell, a-Si:H absorbs in the short wavelength domain and poly-Si converts photons in the longer wavelength region to photocurrent. The material and device investigations are composed of three main stream lines. The first study area was the bottom poly-Si cell examination, second the top a-Si:H cell, and third the interface layer examination of the heterojunction cell.

Table 1. The related research progresses.

Year	Historical Progresses
1983	Dr. Hamakawa's group in Japan developed a-Si:H (n-i-p-n)/poly-Si(p-type) cell with 12%.
1992	The conversion efficiency of 15.4% was shown by Dr. Hamakawa's group.
1993	Dr. Ciszek's Group at National Renewable Energy Laboratory achieved 8% efficiency on a-Si:H/poly-Si.
1994	Sanyo electric research center fabricated 21% cells with a-Si:H/c-Si.
1996	Dr. Topic's group at university of Ljubliana showed 16% a-Si:H/c-Si cell.

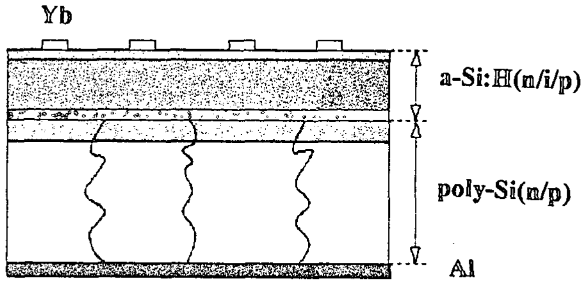

Fig. 1. The investigated structure of heterojunction solar cell.

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Ⅱ. Experimental

After PC-1D device simulation, we took an experimental procedure in the order of a surface etching, $POCl_3$ doping, poly-Si solar cell, surface passivation, emitter layer modulation, a-Si:H film growth, and heterojunction cell characterization. Figure 2 shows the investigated experimental procedures. The cell area of $4cm^2$ was selected in PC-1D simulation with 3% grid shading area. Investigated substrate thickness was varied from $50\mu m$ to $600\mu m$. Intrinsic defect incorporation in poly-Si substrate changed from $10^{10}cm^{-3}$ to $10^{16}cm^{-3}$. Back ground doping concentrations $10^{13}cm^{-3}$ to $10^{19}cm^{-3}$ with resistivity variation of 500Ω-cm to 0.01Ω-cm were investigated. The influence of bulk carrier lifetime studied from 10^{-8}sec. to 10^{-4}sec. Front phosphorous doping controls the surface recombination velocity and junction depth. Front doping examined from $10^{16}cm^{-3}$ to $10^{19}cm^{-3}$ and surface recombination velocity 10^2 to 10^8cm/s. A-Si:H cell takes a cell structure of n-i-p junction due to low carrier mobility. Some parameters used in the simulation are energy bandgap of 1.8eV, electron mobilities $0.1\sim1cm^2/V.s$, hole mobilities $0.01\sim0.1cm^2/V.s$, area $4cm^2$, carrier lifetime 10^{-8}sec, front surface recombination velocity 10^4cm/s, and back surface recombination velocity 10^7cm/s.

Experimental investigations were started with poly-Si substrates wafer size of 10cm×10cm, thickness $350\mu m$, resistivity $1\sim5\Omega$-cm, and minority carrier lifetime $5\mu s$. A grain size of poly-Si substrate was ranged from 5mm to 50mm giving an average size of 16.9mm. The pretreatment of poly-Si was done in N_2 or N_2+H_2 gas flowing at the rate of 2.5 *liter*/min., by temperature variation of 600, 700, 800, 900, 1000℃, and with time ranged from 30min. to 320min. Schottky diodes were fabricated to characterize the optical and electrical properties before and after the pretreatment. The low barrier metals of Cr, Yb, and Al were evaporated for Schottky contact. After a chemical etching of poly-Si in KOH or KOH+IPA+DI water, we used phosphorous doping for a junction formation. Resistivity was measured by four point probe system of Signatone S-30. The junction depth about $0.5\mu m$ and surface sheet resistivity of $23\sim27\Omega/\square$ were achieved by $POCl_3$ diffusion. A diamond saw cutter (Buehler ISO-9001) was employed to isolate n-p junction poly-Si cell.

A glass substrate with ITO coating was used for the study of top a-Si:H cell. Table 2 shows the growth conditions of photo-CVD system for the top a-Si:H cell. A metal Yb evaporation gave an ohmic contact to n-type a-Si:H. For the solar cell characterizations, an incident light beam was irradiated to ITO side. The diode characteristics and light I-V were investigated for an electrical study. Spectral response was examined using a Jobin Yvon XC-150 monochromator MAP23 scanning controller, and Keithley 617. A standard cell released from NASA Lewis Research Center was used in spectral response calculation. Transmittance (T) of the a-Si:H film was measured by using an HP 8153A lightwave multimeter.

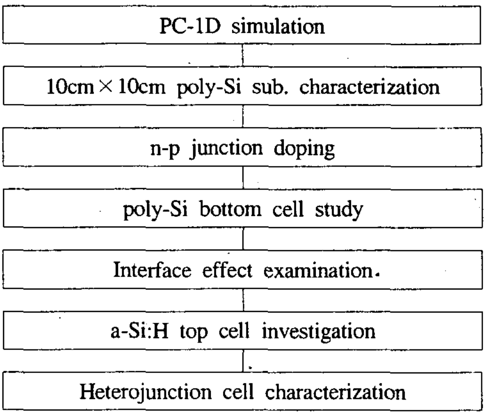

Fig. 2. Experimental procedures used in the research work.

Table 2. The growth conditions of photo-CVD system for the top a-Si:H cell.

Layer / Conditions	p-type	intrinsic	n-type
Sub. Temp.[℃]	250	250	250
Hg Temp.[℃]	20	30	20
Pressure [Torr]	0.4	0.2	0.7
Flow rate [SCCM]	SiH_4 : 3.0 B_2H_6 : 0.4 H_2 : 60.0	SiH_4 : 12.0	SiH_4 : 10.0 PH_3 : 1.2 H_2 : 99.0
Thickness [Å]	150	7000	250

Ⅲ. Result and Discussions

1. PC-1D Simulations

As poly-Si thickness was decreased, we observed increased open circuit voltage (V_{oc}) and reduced short circuit current (I_{sc}). For the poly-Si solar cells, the optimum thickness figured out to be about $100\mu m$ from the simulations. We investigated doping density of the front, bulk, and back side. PC-1D simulation results suggest that the best working substrate resistivity is 0.1Ω-cm for the heterojunction cell applications. The I_{sc} and V_{oc} exhibited the highest value at a proper doping density and the values decreased for the higher or lower doping densities. Since the front doping density greatly influences many parameters such as contact resistance (R_c), series resistance (r_s), and surface recombination, care must be taken to select a proper value. As doping density is reduced, a junction depth and V_{oc} were reduced as shown in Fig. 3. The front doping density of $10^{18}cm^{-3}$ exhibited the highest efficiency. As the surface recombination velocity varies from 10^2cm/s to 10^8cm/s, the cell efficiency changed from 17% to 14%. Back side doping densities ranged from $10^{16}cm^{-3}$ to $10^{20}cm^{-3}$ showed a little effect on the I_{sc} and V_{oc}. A metal aluminum may be good enough to form a back

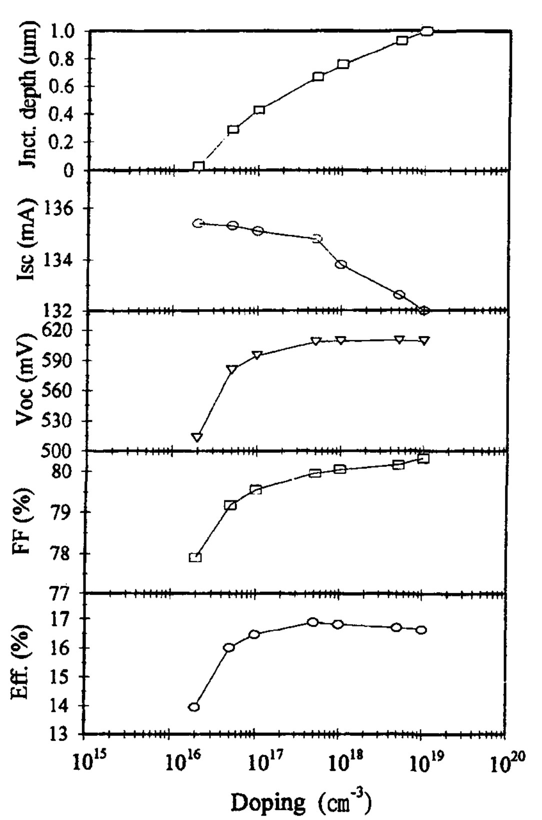

Fig. 3. The variation of cell characteristics as a function of doping density for poly-Si cell.

side electrode, gettering, and p^+ majority carrier barrier formation.

The minority carrier lifetime and diffusion length are the very important cell parameters. Defects and potential barriers at the grain boundaries of poly-Si limited the conversion efficiency of solar cells. High quality poly-Si can be achieved by the combinations of pretreatment, gettering, and passivation[11-14].

As minority carrier lifetime increase, the carrier diffusion length and cell efficiency are increased until the diffusion length reaches the cell thickness. Figure 4 indicates that if minority carrier lifetime is 10^{-5}sec, we can achieve higher than 19% efficiency using a poly-Si alone. The prior mentioned poly-Si pretreatment, grain boundary passivation, and gettering processes can contribute to increase the minority carrier lifetime. Under the light illumination conditions, the front surface recombination velocity greatly influences the cell efficiencies so that a surface treatment is critical. A surface potential due to the surface charge was investigated from 0.001eV to 0.5eV. The surface potential above 0.01eV started to degrade I_{sc} and V_{oc}. The surface charge must be kept below 10^{11}cm^{-3} to maintain a less surface potential effect.

Top cell optimization was also carried out by the similar approach as in the bottom cell case. The a-Si:H layer thickness, doping density, carrier lifetime, and recombination velocity were varied to find an optimized cell efficiency[15]. Thin film a-Si:H layer thickness about 0.3μm exhibited the maximum efficiency.

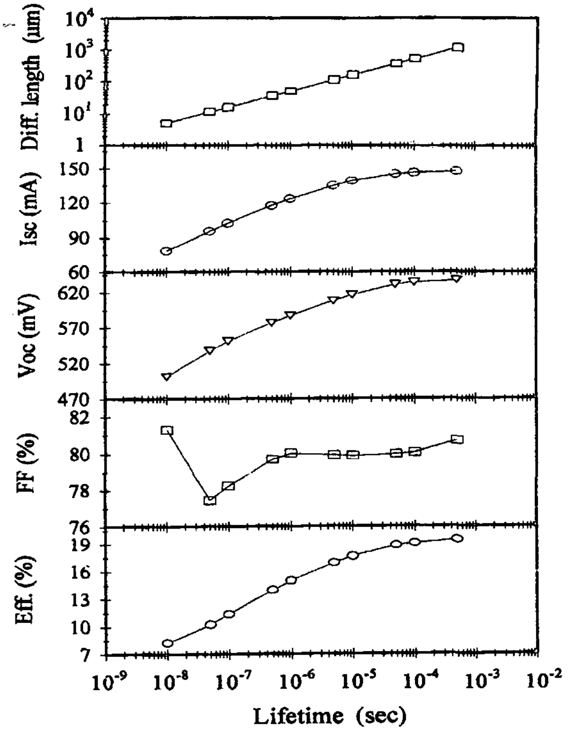

Fig. 4. The effect of minority carrier lifetime on poly-Si cell.

In the heterojunction cell, if the intrinsic a-Si:H layer is too thick, then most of the incident lights will be absorbed in the amorphous layer, and bottom poly-Si contributions will be reduced. An intrinsic a-Si:H layer thickness of 0.4μm is recommended to increase the conversion efficiency of heterojunction cell[16]. As the n-type doping density was increased, the I_{sc} was decreased due to the increasement of recombination probability. The lower doping density just enough to create internal built-in electric field and low contact resistance can be in the order of 10^{18}cm^{-3}. P- and n-layer thickness from 5nm to 30nm were investigated. As thickness was reduced, the cell efficiency and I_{sc} were increased with the reduced recombination process. We recommend 10 nm doped layer thickness for the actual uniform a-Si:H film growth. If, however, the a-Si:H layer thickness of 10nm or less can be grown in a homogeneously, then the thinner film is preferred. Having put an emphasis on the carrier lifetime for the bottom poly-Si cell, we also examined the same parameter for the top cell. The examination result on the carrier lifetime changed from 10^{-9}sec. to 10^{-6}sec. indicates the strong sensitivity to the cell efficiency. If we improve minority carrier lifetime from 1×10^{-8}sec. to 5×10^{-8}sec, the cell efficiency increased from 10.4% to 12.1%.

2. *Poly-Si Bottom Cells*

The pretreatment of poly-Si reduces dislocation site. Phosphorous treatments at a temperature between 800~900℃ getter impurities such as Ni, Fe, and Cu. These experimental efforts

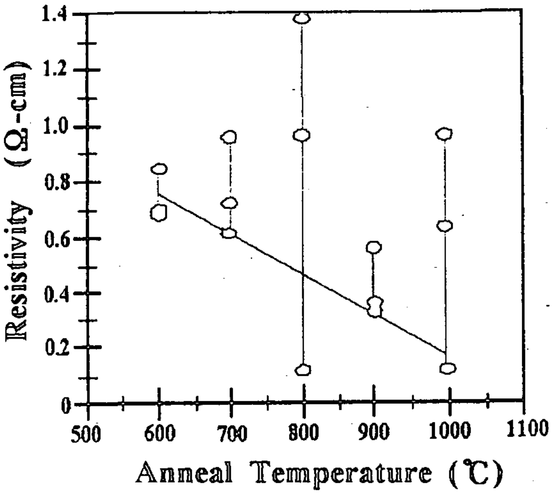

Fig. 5. Resistivity changes as a function of pretreatment temperature.

were aimed at the improvements of poly-Si bulk defect states, minority carrier lifetime, mobility, and diffusion length. To reduce the grain boundary effect, this paper employed pretreatment, $POCl_3$ gettering, and surface passivation. The minority carrier lifetime of a commercially available poly-Si wafer is in the range of 5μs. A measured resistivity varied depending on how many grains were included inside the four point probes. The resistivity increased as the number of grain boundaries increased. Because of the grain boundary effect, the measured resistivity exhibited large deviations. Several spots were measured and averaged the values. Fig. 5 shows the measured resistivity as a function of pretreatment temperature. The observed trend shows a small reduction of resistivity with the increase of pretreatment temperature. This can be explained by the reduced defect density as the pretreatment temperature increased. We recommend a pretreatment temperature above 900℃, 30min. The pretreatment time showed almost no difference for the time duration above 30min. Photocurrent characteristic study before and after pretreatment showed about the same result because the as-cut poly-Si had a high surface recombination centers. A surface polishing in HNO_3:HF with 6:1 volume ratio gave an improved light I-V characteristic as the pretreatment temperature increased.

The resistivity of n-type emitter layer showed a variation of 0.02~0.09Ω-cm. A calculated doping density for the measured resistivity ranged from $5.1\times10^{16}cm^{-3}$ to $2.3\times10^{17}cm^{-3}$. To increase open circuit voltage and to reduce series resistance, we need to increase doping density to $1\times10^{18}cm^{-3}$ for a future work. Various grid patterns were investigated with a cell area of 0.11~1.5cm^2 and grid shading area of 2~7%. As grid finger spacing and a finger width were reduced, we observed an improved conversion efficiency. The improvements were mainly come from the increased I_{sc} while V_{oc} remained almost constant value. As grid spacing was reduced, the improved I_{sc} was observed because the less grain boundaries were included for the photogenerated current collection. This result suggests the grain boundaries are still need to be passivated for the higher conversion efficiency.

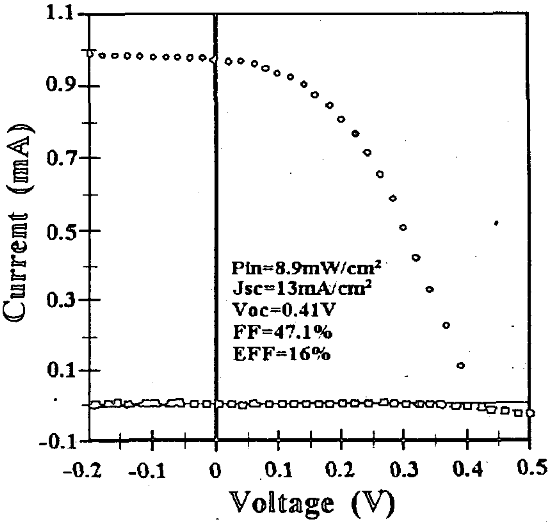

Fig. 6. Light and dark I-V characteristics curve with an incident light intensity of 8.9mW/cm^2.

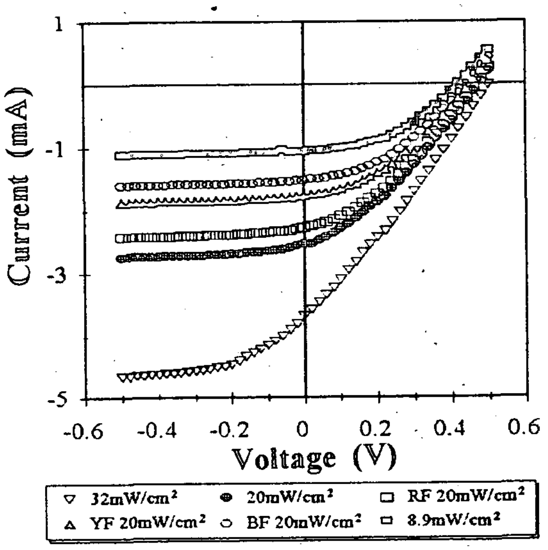

Fig. 7. Changes in I_{sc} and V_{oc} at the various light intensities.

Fig. 6 shows I-V characteristics with voltage variation of -0.2V~0.5V and I_{sc} of 13mA/cm^2. Considering the input power density, we regard the I_{sc} relatively high. However, V_{oc} exhibited rather low value as 0.41V because of the low doping density of emitter layer. The investigated metals were Cr, Yb, and Al. The metal Yb exhibited the better I-V characteristics and easy evaporation. Contact heat treatment in N_2 atmosphere was investigated to improve the top ohmic property at the temperature of 300, 400, 500, 600℃ for 15min. The conversion efficiency about 2% increased as the top contact heating varied from 300℃ to 500℃. However, temperature above 600℃ caused a drastic decrease of efficiency because Yb diffused through the entire emitter layer. Figure 7 shows the variations in I_{sc} and V_{oc} at the various light intensities. As the light intensity was increased from 8.9mW/cm^2 to 100mW/ cm^2, the cell efficiency was reduced from 16% to 12%. The efficiency reductions can be explained by the high series resistance. The calculated series resistance showed over 10Ω-cm from the divided differentials of photocurrent and voltage. To reduce the series resistance of the poly-Si cells, we need to increase the n-type doping density.

3. Heterojunction Solar Cells

Top cell was examined after the a-Si:H film growth on glass substrate. ITO coated glass showed about 85% optical transmittance for wavelength less than 700nm and transmittance approached to 100% for the higher wavelength. After a-Si:H film growth on ITO, we observed that the short wavelength photons were absorbed by the a-Si:H layer. An optical transmittance peaks appeared at the wavelength of 660nm and 760nm. From the peak maxima spacing the thickness of a-Si:H film calculated as 660nm using a refractive index of a-Si:H as 3.8. The open circuit voltage of a-Si:H top cell exhibited 0.8V as shown in Fig. 8. The conversion efficiency of a-Si:H top cell showed about 5%. Most of the photocurrent was contributed from the wavelengths between 450nm and 650nm. Heterojunction cells were investigated with three different types depending on the interface states. Firstly, the entire poly-Si surface was chemically passivated. Secondly, passivating poly-Si substrate with thermal oxide, we removed grid finger area to make a contact with a-Si:H. Lastly, heterojunction solar cell with a Yb metal deposited at the interface of a-Si:H and poly-Si. The heterojunction cells exhibited photocurrent domination either by top a-Si:H cell or bottom poly-Si cell.

Figure 9 shows the photocurrent versus the incident wavelength. Heterojunction cell passivated by chemical shows most of the photocurrent is generated over the low wavelengths. This result suggests top a-Si:H layer dominated total photocurrent generation. Considering PC-1D simulation and experimental results, we infer that a-Si:H thickness is rather thick for this type of heterojunction cell. Further investigation will be directed to achieve reduced a-Si:H thickness around 300~400nm. However, the cell passivated by the thermal oxide shows the higher photocurrent generations in the longer wavelengths indicating that the major current contributions are coming from the bottom poly-Si cell. Thermal oxide may have impeded photo-generated carrier movement from a-Si:H top cell to the bottom poly-Si cell. Fabrication processes such as PR removal after oxide window opening and organic cleaning steps may have given an interface layer on the heterojunction. This thin interface layer acted as a blocking layer for current flow and cured the interface states by post annealing at 300℃. Figure 10 shows the spectral response of oxide passivated cell. As anneal temperature reached 300℃, photocurrent contributions were observed over the wide rage of wavelength indicating that photocurrent generations came from both of the top and bottom cells.

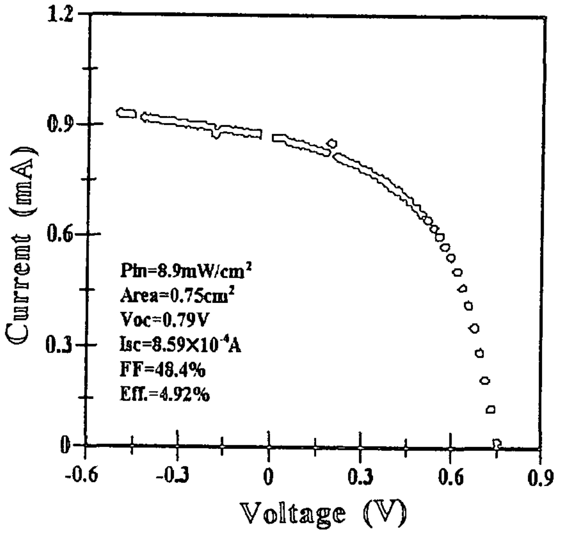

Fig. 8. The light I-V characteristic of top n-i-p junction a-Si:H cell.

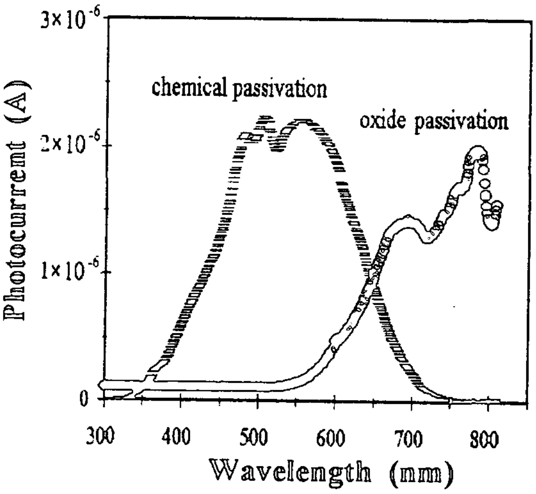

Fig. 9. Photocurrent characteristics of the heterojunction solar cells.

The last type of heterojunction cell used Yb metal as an interconnecting layer for a-Si:H top cell and poly-Si bottom cell. Photocurrent and spectral response showed the worst properties among the investigated types. A low barrier metal Yb makes an ohmic contact to n-type poly-Si but forms a rectifying contact to p-type a-Si:H. An improved heterojunction cell may be achieved, if we adopt a metal that can give an Ohmic contact to top cell as well as bottom cell. Figure 11 shows light I-V characteristics for the chemically passivated heterojunction cell. Open circuit voltage shows two time higher than that of poly-Si homojunction

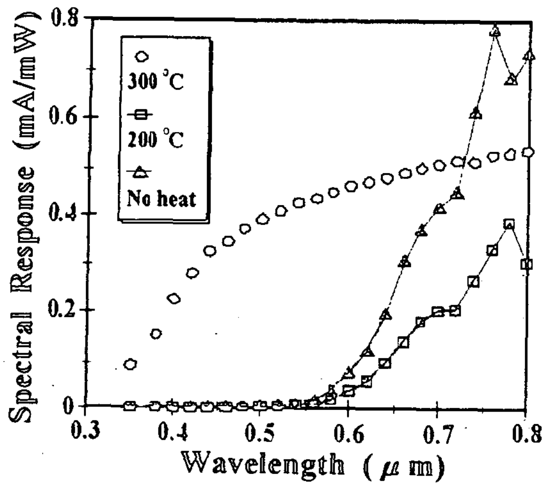

Fig. 10. Spectral response on the SiO_2 surface polished sample.

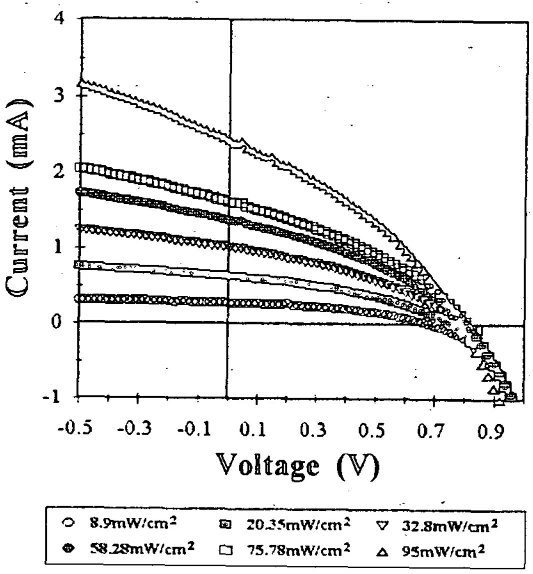

Fig. 11. Light I-V properties on the chemically passivated cell.

cell. Because chemically passivated cell shows most of the photocurrent generation by the top a-Si:H, the achieved current density was lower than that of the oxide passivated cells. The I_{sc} for the various light intensities is given in Fig. 12. Due to rather high series resistance of bottom cell, the I_{sc} of the heterojunction cell started to saturated for the light intensity above 45 mW/cm^2. For the investigated heterojunction cells, we recommend an anneal treatment for the oxide passivated cells and thinner a-Si:H layer for the chemically passivated cells.

Ⅳ. Conclusions

Three major investigations were extended from the simulation to the experiment with poly-Si, a-Si:H, and heterojunction cells. The pretreatment above 900℃, $POCl_3$ doping and gettering, surface polishing, and Al back side mentalization were contributed to improve the light I-V characteristics of poly-Si solar cells. With the recommended conditions, we were able to achieve 16% conversion efficiency. Further studies will be directed to reduce the thickness of poly-Si substrate and to increase the doping concentration for the higher V_{oc} and lower r_s. Taking all the theoretical and experimental results into considerations, we recommend heterojunction cell with the following conditions. Top a-Si:H doped layer thickness of 10nm, intrinsic layer thickness 400nm, oxide passivated interface, and top Yb contact metal. Bottom poly-Si wafer thickness of 100μm, resistivity 0.1Ω-cm, minority carrier lifetime 5μs, front n-type doping density 10^{18}cm^{-3}, pretreatment above 900℃, emitter thickness of 0.43μm.

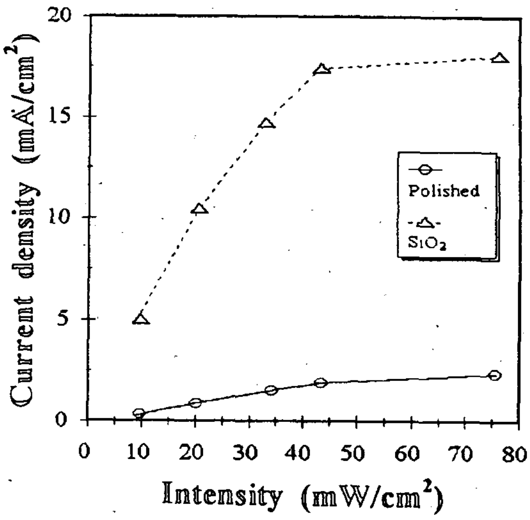

Fig. 12. Changes in I_{sc} for the various light intensities.

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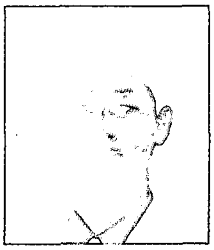

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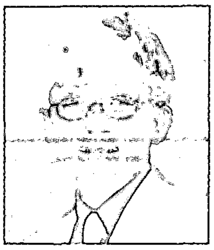

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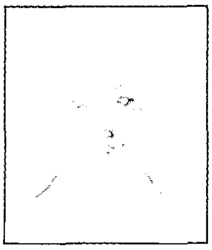

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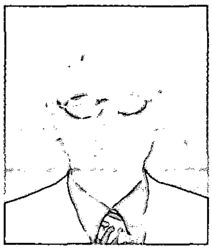

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