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TANDEM TYPE SOLAR CELLS USING $a$-$Si:H$ AND $a$-$SiGe:H$ FILMS

G. Nakamura, K. Sato, H. Kondo, Y. Yukimoto and K. Shirahata

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Abstract - Tandem type solar cells with $a$-$Si:H$ and $a$-$SiGe:H$ and inverted p-i-n type solar cells of $a$-$Si:H$ are studied for increasing efficiency and improvement in photoconductivity of $a$-$SiGe:H$ is also studied.

Introduction - Conversion efficiency of $a$-$Si:H$ p-i-n solar cell is presently limited because minority carrier collection length is much shorter than the solar absorption length and because the spectral response is restricted to a very narrow region by the low optical gap in p-type region and high optical gap in i-type region.

Here, we study two types of cell structures to widen the spectral response region. The first is a tandem structure using $a$-$Si:H$ and $a$-$SiGe:H$ which has high collection efficiency in long wave region. The second is an inverted p-i-n structure using $a$-$Si:H$ which has high collection efficiency in short wave region.

In this paper, we study to improve photoconductivity of $a$-$SiGe:H$ for increasing efficiency of the tandem cells. Performance of both tandem cells and inverted p-i-n cells using various optical gap energies and with various film thickness are investigated for optimizing cell structure.

Experimental - Deposition of $a$-$SiGe:H$ films was carried out by a rf glow discharge decomposition of $SiH_4$ and $GeH_4$ mixture gas in a capacitive coupling equipment with parallel plate electrodes. Rf power ranging from 10W to 100W at 13.56MHz was fed to one electrode. Another electrode, on which substrates were placed, was grounded or connected to a DC power supply and which was heated during film deposition.

The reaction chamber was first evacuated to the pressure of 1x10^-6 Torr and then $SiH_4$ diluted with argon to 10% and $GeH_4$ diluted with hydrogen to 10% were introduced through each mass flow controller. The mixture ratio of $GeH_4$ to ($GeH_4 + SiH_4$) was controlled in the range from 0 to 1.

Dark and photoconductivity of $a$-$SiGe:H$ films were measured using gap type electrode with 7.5 cm in width and 6-10 μm in length. Transmission and reflection spectra of the films in visible region were measured for evaluating optical gap energy of the films.

Tandem type solar cells and inverted type solar cells were fabricated by the same manner as mentioned previously.

Current-voltage characteristics and collection efficiency of the solar cells were measured.

Improvement in photoconductivity of $a$-$SiGe:H$ - Fig.1 shows a relation between conductivity of $a$-$SiGe:H$ and glow discharge power with optical gap energy as a parameter. When the glow discharge power increased from 10W to 100W, photoconductivity ($\sigma_p$) increased by 2 orders of magnitude and dark conductivity ($\sigma_d$) increased by 3 orders of magnitude.

W. Paul reported that hydrogen attached preferentially to Si rather than to Ge and that defects connected to Ge degraded photo-electric...
properties of a-SiGe:H with high Ge content. G. Turban et al. reported that atomic hydrogen was believed to interfere with the growing film and might modify the film itself, especially for long residence time (low gas flow rate) and high concentration (high discharge power). They also reported that the ratio H/Si in a-Si:H increased when discharge power was increased. According to the authors, the experimental result, shown in Fig. 1, implies that the interference of atomic hydrogen with the growing a-SiGe:H causes to compensate the defects due to Ge.

Fig. 2 shows a relation between conductivity of a-SiGe:H and substrate temperature with glow discharge power and GeH₄ mol% as parameters. ϕₚh reached maximum at about 200°C–250°C and it decreased drastically above 300°C. These temperature are nearly equal to the temperature at which weak-bonded hydrogen in a-SiGe:H evolves.

Fig. 3 shows a relation between conductivity of a-SiGe:H and optical gap energy (E_gopt) of the films which are prepared following condition. Glow discharge power is ranging from 50W to 100W and substrate temperature is kept 200°C. For comparison, data obtained by Nakamura et al. are also presented in the figure. ϕₚh increased by 2 orders of magnitude when E_gopt decreased from 1.8eV to 1.35eV. On the other hand, ϕₚh showed almost constant value (10⁻⁴ – 10⁻⁵ (Ω·cm)⁻¹) and which was nearly equal to that of a-Si:H. Degradation in ϕₚh with the addition of Ge was eliminated by depositing at high discharge power (50W–100W) and low substrate temperature (200°C).

Fig. 4 shows a relation between the activation energy (E_a) of dark-conductivity and E_gopt. For comparison, data of a-SiGe:H, deposited at low discharge power (10W) and at high substrate temperature (300°C), are also presented in the figure (depicted "poor"). When E_gopt was the same, E_a obtained in this work was higher than that of "poor". This result implied that Fermi level shifted to the center of the mobility gap by depositing at high discharge power and at low substrate temperature.

Performances of tandem type solar cells and inverted p-i-n type solar cells—Three kinds of tandem type solar cells were fabricated. Cross section of tandem type solar cell is shown in Fig. 5. Three materials were applied to i layer in the bottom cell. The first was a-Si:H with E_gopt of 1.95eV. The second was a-Si:H with E_gopt of 1.75eV. The third was a-SiGe:H with E_gopt of 1.55eV. I layer in top cell was a-Si:H with E_gopt of 1.95eV. P and n layers were doped a-Si:H. Thickness of ITO was 850A, thickness of i layer in top cell was ranging from 350A to 1050A, thickness of i layer in bottom cell was 4000A. Thickness of front n layer was 70A, thickness of p layer in tunnel junction are 50A and thickness of p layer on stainless steel was 300A. Fig. 6 shows dependence of J_SC and V_OC as a function of E_gopt in bottom cell. J_SC increased as E_gopt was decreased because bottom cell was able to absorb photons in long wavelength region, while V_OC decreased as E_gopt was decreased because V_OC of the bottom cell was restricted by E_gopt. Fig. 7 shows relations between J_SC and thickness of i layer in top cell. For comparison, data of the inverting p-i-n type solar cell are also presented in the figure. In the case of inverted p-i-n type solar cell, J_SC increased monotonously as thickness of i layer increased because absorbed photon increased. While, in the case of tandem type solar cell, J_SC reached maximum value at some value of thickness. Then, photocurrent in top cell was equal to that in bottom cell. Further
increase of i layer in top cell caused to decrease $J_{SC}$ because 
photocurrent in bottom cell was decreased. 

According to the experimental results shown in Fig.6 and Fig.7, we 
optimized $E$opt in bottom cell and thickness of i layer in top cell and 
we fabricated p-i-n tandem type solar cell with i layer in top cell of 
700Å and with $E$opt in bottom cell of 1.55eV-1.6eV. This tandem type 
solar cell showed maximum efficiency of 5.9%, $V_{OC}$ of 1.64V, $J_{SC}$ of 
5.8 mA/cm² and fill factor of 0.62. Efficiency of this tandem type solar cell 
was higher than that of previous work because quality of a-SiGe:H was 
improved. 

Fig.8 shows collection efficiency vs. wavelength characteristics of 
the tandem type solar cell comparing with that of the inverted p-i-n 
type solar cell having efficiency of 6.04%. In long wave length region 
, collection efficiency of the tandem type solar cell was clearly 
improved.

For obtaining some information about quality of a-Si:H which composed 
the top cell, we investigated performances of a-Si:H inverted p-i-n type 
solar cells. 

For determining optimum thickness of i 
layer, we evaluated performances of inverted p-i-n type solar cells with 
various thickness of i layer. Maximum efficiency was obtained around 
thickness of 4000Å. 

Inverted p-i-n type solar cells with i layer of 4000Å, n layer of 
120Å, p layer of 180Å and ITO of 800Å showed maximum efficiency of 
6.62%, $V_{OC}$ of 0.86V, $J_{SC}$ of 13.2mA/cm² and fill factor of 0.58. 

Table I shows performances of amorphous solar cells developed in our 
laboratory. The inverted p-i-n type solar cell shows efficiency of 3.1% 
with area of 100cm². This implies that quality of a-Si:H is 
sufficiently high and that improvement of a-SiGe:H is necessary for 
increasing efficiency of tandem type solar cell.

Conclusion- (1) Degradation in photoconductivity of a-SiGe:H was 
eliminated because of depositing at high discharge power (50W-100W) and 
at low substrate temperature (200°C). (2) Tandem type solar cells with 
efficiency of 5.9% was fabricated because of applying improved a-SiGe:H 
and optimizing cell structure. (3) Inverted p-i-n type solar cells with 
efficiency of 6.62% were fabricated because of adjusting thickness of 
i layer. 

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-1,p.291. 2)W.Paul:"Fundamental Physics of Amorphous Semiconductor"( 

Table I Performances of amorphous solar cells

<table>
<thead>
<tr>
<th>Cell type</th>
<th>$\eta$ (%)</th>
<th>$V_{OC}$ (V)</th>
<th>$J_{SC}$ (mA/cm²)</th>
<th>F.F.</th>
<th>$A_{tot}$ (cm²)</th>
<th>$P_{tot}$ (mW/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tandem</td>
<td>5.9</td>
<td>1.84</td>
<td>5.8</td>
<td>0.82</td>
<td>85x10⁻²</td>
<td>100</td>
</tr>
<tr>
<td>nip</td>
<td>6.62</td>
<td>0.85</td>
<td>13.2</td>
<td>0.58</td>
<td>85x10⁻²</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>4.33</td>
<td>0.85</td>
<td>8.2</td>
<td>0.58</td>
<td>4.9</td>
<td>90.8</td>
</tr>
<tr>
<td></td>
<td>3.11</td>
<td>0.78</td>
<td>7.58</td>
<td>0.48</td>
<td>100</td>
<td>91.9</td>
</tr>
</tbody>
</table>
Fig. 1 Conductivity vs. RF power
Fig. 2 Conductivity vs. Substrate temperature
Fig. 3 Conductivity vs. \( E_{\text{opt}} \)
Fig. 4 Activation energy vs. \( E_{\text{opt}} \)
Fig. 5 Cross section of tandem cell
Fig. 6 \( V_{\text{OC}} \) and \( J_{\text{SC}} \) vs. \( E_{\text{opt}} \) in bottom cell
Fig. 7 \( J_{\text{SC}} \) vs. Thickness of i layer in top cell
Fig. 8 Collection efficiency vs. wavelength