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Development of Wider Bandgap n-type a-SiO_x:H for High Efficiency a-Si:H Single Junction and a-Si:H/a-$Si_{1-x}Ge_x$:H Tandem Solar Cells

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Abstract

In this study, n-type hydrogenated amorphous silicon oxide (a-SiO_x:H) has been developed and employed as a replacement of a-Si:H(n) in a-Si:H and a-Si:H/a-$Si_{1-x}Ge_x$:H thin-film solar cells. By incorporating oxygen in a-Si:H network, wider bandgap and lower absorption coefficient can be obtained. The effect of R_{CO2} on films properties and cell performance were investigated. As R_{CO2} increased from 0 to 0.17, the EQE response of a-Si:H single-junction cells has significant enhancement in the wavelength from 500 to 650 nm. As a result, the efficiency was improved from 7.0% to 7.8%. The enhancement was due to the less absorption loss in a-SiO_x:H(n) and the larger V_{OC} arising from larger bandgap. On the other hand, the efficiency of a-Si:H/a-$Si_{1-x}Ge_x$:H tandem solar cells achieve 9.2%, with increasing V_{OC} from 1.54 to 1.56 V.

1. Introduction

Hydrogenated silicon-based thin-film solar cells are one of the promising photovoltaic technologies because of its low material usage and large area deposition compared to crystalline silicon. Hydrogenated amorphous silicon (a-Si:H), which has a bandgap of 1.75 eV and a high absorption coefficient in visible region of the solar spectrum, has been widely studied and applied to solar cells. However, the conversion efficiency of a-Si:H single-junction thin-film solar cells are still relatively low owing to insufficient spectrum utilization. Therefore, by stacking two or more sub-cells with different bandgap absorbers, high efficiency silicon-based thin-film solar cells can be achieved. B. Yan et al. [1] has reported that the a-Si:H/a-$Si_{1-x}Ge_x$:H/nc-Si:H triple-junction cell with nc-SiO_x:H layer reached an efficiency of 16.3% by the better utilization of the solar spectrum.

To further improve the performance of photovoltaics, optical management is necessary. One of the techniques are the development of wide bandgap materials as the doped layer. By employing wide bandgap material as the doped layer in photovoltaics, the parasitic absorption can significantly be reduced. The n-type hydrogenated amorphous silicon oxide (a-SiO_x:H) is one of the promising materials due to its wider bandgap and lower refraction index than a-Si:H. The a-SiO_x:H(n) has been applied not only in silicon-based thin film solar cells, but also in heterojunction solar cells [2], which had shown significantly enhancement on cell performance. However, with the increasing bandgap of a-SiO_x:H(n), the electrical conductivity could deteriorated drastically [3]. In this study, we have developed a-SiO_x:H(n) to substitute a-Si:H(n) in both a-Si:H single-junction cells and a-Si:H/a-$Si_{1-x}Ge_x$:H tandem cells. The thin film characteristics and the corresponding cell performances are investigated and discussed.

2. Experiment details

The doped and absorber layers were deposited by a 27.12 MHz RF plasma enhanced chemical vapor deposition (PECVD) system with a transfer and a load-lock chamber. The a-SiO_x:H(n) thin film was deposited with a gas mixture of SiH_4, CO_2, H_2 and PH_3. Corning XG glass was used as a substrate to prepare the films for optical and electrical characterization. Single and tandem solar cells were prepared on textured SnO_2:F glass substrates in a superstrate configuration. The thickness of a-Si:H absorber in single-junction cell was kept at 300 nm. The thickness of a-Si:H and a-$Si_{1-x}Ge_x$:H absorbers in a-Si:H/a-$Si_{1-x}Ge_x$:H tandem cell was 120 and 250 nm, respectively. The substrate temperature was approximately 190 ºC.

The Tauc's bandgap of a-SiO_x:H(n) films were evaluated from the transmittance and the reflectance measured by a UV/VIS/IR spectrometer. The conductivity and the activation energy of the thin films were measured by a J-V measurement system with different substrate temperatures. External quantum efficiency (EQE) of cells was characterized under monochromatic light ranged from 300 to 800 nm. The conversion efficiency was obtained by a J-V measurement system with AM1.5G light source.

3. Results and Discussion

The film properties of a-SiO_x:H(n) on conductivity, bandgap (E_g) and activation energy (E_a) with different CO_2-to-SiH_4 ratio (R_{CO2}) are shown in Fig.1. As the R_{CO2} increased from 0 to 0.64, the E_g increased from 1.80 to 1.93 eV due to the higher bonding energy of Si-O bond than Si-H and Si-Si bonds. On the other hand, the conductivity decreased from 1.36×10^{-2} to 1.3×10^{-3} S/cm due to the degraded doping efficiency. This is likely due to the reduction of average coordination number with increasing oxygen content [4]. As the R_{CO2} increased from 0 to 0.17, the E_a slightly decreased from 0.24 to 0.22 eV which may be due to the doping effect of oxygen [5]. However, the conductivity did not obviously degrade which could be owing to the compensation of the degraded doping efficiency and the oxygen-doping effect.

The EQE and the absorptance of a-Si:H single-junction solar cells with various R_{CO2} of a-SiO_x:H(n) are demonstrated in Fig. 2. As the R_{CO2} was 0.17, the EQE response

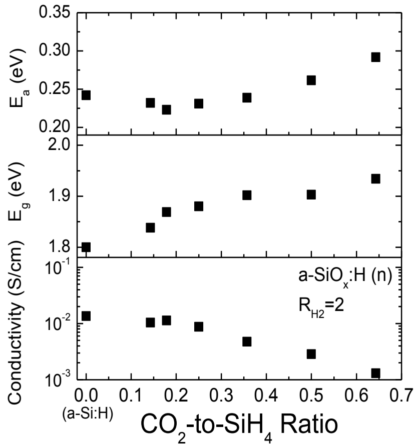

Fig. 1 Effect of R_{CO2} on conductivity, E_g and E_a of a-SiO$_x$:H(n) films.

had significant enhancement compared to a-Si:H(n) in the wavelength from 500 to 650 nm, due to the reflection of long-wavelength light back to absorber by a-SiO$_x$:H(n). This resulted in the increased of J_{SC} from 10.9 to 11.7 mA/cm^2, which was a relative increment of 7.3%. Further increased R_{CO2} to 0.25 degraded the EQE response, which could be due to the decrease of conductivity and the increase of E_a. The cell performance of a-Si:H single-junction solar cells with different R_{CO2} was summarized in Table I. Compared to the cell with a-Si:H(n), the cell with a-SiO$_x$:H(n) prepared with R_{CO2} of 0.25 had better cell performance. As the R_{CO2} increased to 0.17, the V_{OC} increased from 0.927 to 0.934 V due to the widening in the bandgap and the decreasing in E_a. As a result, the cell efficiency increased from 7.0% to 7.8%, which was a relative increase of 11.4%.

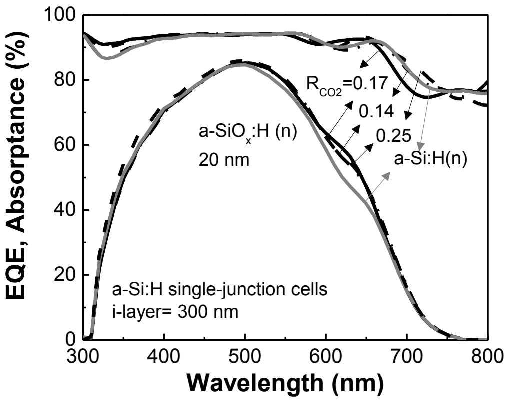

Fig. 2 EQE and absorptance of a-Si:H single-junction solar cells with different R_{CO2} of a-SiO$_x$:H(n)

Table I Cell performance of a-Si:H single-junction solar cells with different R_{CO2}

R_{CO2}	V_{OC} (V)	J_{SC} (mA/cm^2)	FF (%)	η (%)
a-Si:H(n)	0.927	10.9	70.0	7.0
0.14	0.929	11.4	70.3	7.5
0.17	0.934	11.7	71.5	7.8
0.25	0.930	11.3	71.2	7.5
0.35	0.916	11.2	68.9	7.1

We have also employed the a-SiO$_x$:H(n) in the top-cell of a-Si:H/a-Si$_{1-x}$Ge$_x$:H tandem cells. The EQE response and the cell performance of a-Si:H/a-Si$_{1-x}$Ge$_x$:H tandem cells was shown in Fig. 3 and Table II. It can be seen that the V_{OC} increased from 1.54 to 1.56 V, and the efficiency increased from 7.9% to 9.2% as the a-Si:H(n) was replaced by 10nm a-SiO$_x$:H(n). This enhancement was due to the wider bandgap of a-SiO$_x$:H(n) and the higher FF of the top cell. The EQE response of a-SiO$_x$:H(n) with thickness of 10 nm had low J_{SC} from the top-cell because a-SiO$_x$:H(n) may be too thin to provide sufficient electrical field. After optimizing the thickness to 15nm, the cell attain to current matching which had a highest J_{SC} of 8.4 mA/cm^2 from the top cell. Furthermore, the V_{OC} increased from 1.56 to 1.59 V which may be due to the providing sufficient electrical field in top cell..

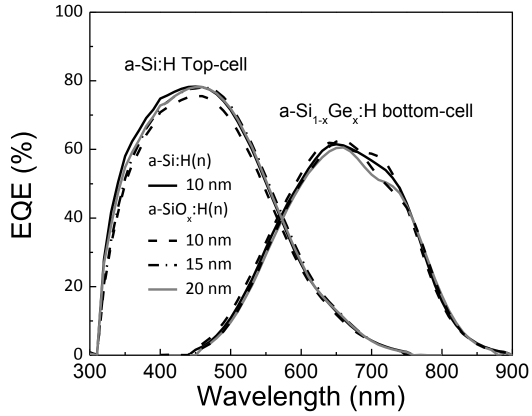

Fig. 3 EQE of a-Si:H/a-Si$_{1-x}$Ge$_x$:H tandem cells with a-Si:H(n) and a-SiO$_x$:H(n).

Table II Cell performance of a-Si:H/a-Si$_{1-x}$Ge$_x$:H tandem cell with replacement of a-Si:H(n) by a-SiO$_x$:H(n)

Top-cell n-layer	Thickness (nm)	V_{OC} (V)	J_{SC} (mA/cm^2)	FF (%)	η (%)
a-Si:H	**10**	1.54	8.1	63.5	7.9
a-SiO$_x$:H	**10**	1.56	7.9	74.8	9.2
	15	1.59	8.4	64.5	8.6
	20	1.58	8.2	64.7	8.4

4. Conclusions

In this study, wider bandgap a-SiO$_x$:H(n) was employed in a-Si:H single-junction and a-Si:H/a-Si$_{1-x}$Ge$_x$:H tandem cells for improving the optical properties as well as the cell performance. The efficiency of a-Si:H cells with the replacement of a-Si:H(n) by a-SiO$_x$:H(n) prepared at R_{CO2} of 0.17 increased from 7.0% to 7.8%. In a-Si:H/a-Si$_{1-x}$Ge$_x$:H tandem cell, the high efficiency of 9.2% was achieved with a-SiO$_x$:H(n) of 10 nm in the top cell.

Acknowledgements

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