

Development of Nearly Crystallized P-type Hydrogenated Amorphous Silicon Oxide as Window Layer in a-Si:H Single-junction and a-Si:H/a-Si_{1-x}Ge_x:H Tandem Solar cells

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Abstract

The p-type hydrogenated amorphous silicon oxide (a-SiO_x:H(p)) thin films prepared with high hydrogen-dilution were developed and employed in a-Si:H single-junction solar cells and a-Si:H/a-Si_{1-x}Ge_x:H tandem solar cells. The a-SiO_x:H(p) with H₂-to-SiH₄ flow ratio (R_{H2}) of 150 could achieve an optical bandgap of 2.28 eV and a conductivity of 1.15×10⁻⁵ S/cm. The a-Si:H single-junction cell utilizing the nearly crystallized a-SiO_x:H(p) as window layer significantly enhanced spectral response of short-wavelength range compared to p-type hydrogenated silicon carbide (a-SiC_x:H(p)). The a-SiO_x:H(p) window layer has also been applied in a-Si:H/a-Si_{1-x}Ge_x:H tandem solar cell. An efficiency of 8.6% with V_{OC}=1.55 V, J_{SC}=8.2 mA/cm², and FF=67.5% was achieved.

1. Introduction

In thin-film silicon-based solar cells, an ideal window layer needs to be transparent and conductive to minimize parasitic optical and electrical losses in solar cells. Compared to a-SiC_x:H(p) which has been widely used in a-Si:H cells, the a-SiO_x:H(p) possesses a lower absorption coefficient and a higher bandgap due to the incorporation of oxygen[1]. To make the defective oxide materials applicable, an appropriate hydrogen dilution need to be conducted during the deposition [2]. The hydrogen radicals can passivate the dangling bonds on the growing surface and promote the relaxation of the species on the bonding site [3]. However, over a threshold value of hydrogen dilution, the hydrogen radicals will lead to the phase transition from amorphous to microcrystalline, which could decrease the bandgap thus increased the band offset at p/i interface. Hence, the better film quality and higher conductivity of a-SiO_x:H(p) by increasing the hydrogen dilution without entering the regime of microcrystalline is challenging for the development. In this work, the effect of H₂-to-SiH₄ flow ratio on optical, electrical, and structural properties of a-SiO_x:H(p) films were studied. Furthermore, the effect of a-SiO_x:H(p) employed in a-Si:H cells and a-Si:H/a-Si_{1-x}Ge_x:H tandem cells as window layer were also investigated.

2. Experimental Details

Silicon-based thin films were prepared with a single chamber process by a 27.12 MHz plasma-enhanced vapor deposition (PECVD) system equipped with in-situ NF₃ plasma cleaning. The a-SiO_x:H(p) films were deposited by introducing B₂H₆ and CO₂ with highly H₂-diluted SiH₄. The

crystalline volume fraction of films was examined by a Raman spectrometer (λ=488 nm). The conductivity was measured with Ag electrodes in a coplanar configuration. The optical bandgap (E₀₄, the photon energy at which the absorption coefficient is 1.0E+04 cm⁻¹) was obtained by a UV/VIS spectrophotometer measurement. The cell structure was glass/TCO/a-SiO_x:H(p)/a-Si:H(i)/μc-SiO_x:H(n)/Ag. The solar cells with a patterned area of 0.25cm² were characterized by an AM1.5G illuminated J-V measurement system and a quantum efficiency instrument.

3. Results and Discussion

Figure 1(a) shows the Raman spectrum of SiO_x:H(p) deposited at different R_{H2}. The spectrum can be deconvoluted to four peaks located at 430, 480, 510 and 520 cm⁻¹ each represent. We have found that as R_{H2} increased from 2.7 to 150, the Raman spectrum showed only a-Si:H phase. As R_{H2} over 150, the peaks for intermediate fraction and transverse mode of c-Si were observed, which was due to the formation of crystalline phase in the film. Fig 1(b) shows the dependence of R_{H2} on the crystalline volume fraction (X_C), activation energy (E_a) and conductivity (σ) of SiO_x:H(p). With increasing R_{H2} from 2.7 to 150, the E_a decreased from 0.65 to 0.41 eV and the σ increased from 1.04×10⁻⁷ to 1.15×10⁻⁵ S/cm. The more hydrogen radicals could remove the disorder configurations and improve the film quality. Thus, the doping efficiency may be enhanced, resulting in the increased σ. As R_{H2} was over 150, the amorphous phase started to transform to microcrystalline. The σ increased from 1.15×10⁻⁵ to 2.01×10⁻¹ S/cm and the E_a decreased from 0.41 to 0.07 eV, which might be thanks to more efficient doping in crystalline phase [4].

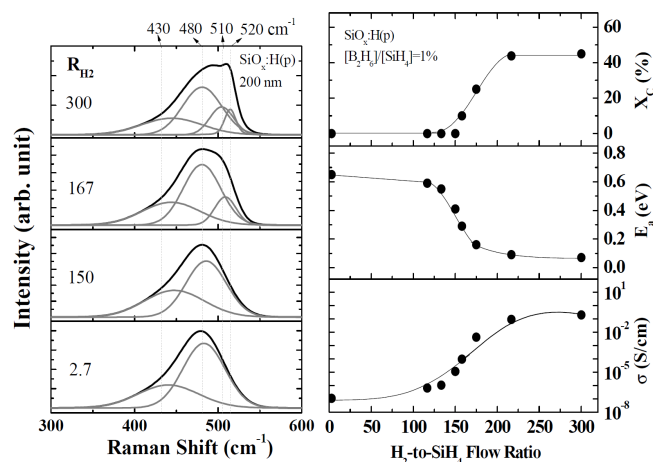


Fig1. (a) The Raman spectrum of p-type SiO_x:H deposited at difference R_{H2} and (b) the dependence of R_{H2} on X_C, E_a and σ of SiO_x:H(p)

The EQE and cell performance of $\text{SiO}_x\text{:H(p)}$ with different R_{H_2} as window layer employed in a-Si:H single-junction solar cells was shown in Fig. 2. As can be seen, when R_{H_2} increased from 2.7 to 300, EQE was significantly enhanced in the short-wavelength region, which may be due to the reduced absorption loss in the p-layer. The J_{SC} increased from 13.2 to 13.6 mA/cm^2 with increasing R_{H_2} . However, the EQE of long-wavelength range slightly decreased as R_{H_2} over 2.7. With R_{H_2} increased from 2.7 to 150, the FF increased from 42.3% to 60.1%, which should be due to the increase in conductivity of p-layer. However, as R_{H_2} further increased to 300, the FF gradually decreased to 57.9%, which may arise from the crystalline phase in the p-layer that led to the poor p/i interface. Moreover, we have found that the V_{OC} decreased from 0.89 to 0.82 V with increasing R_{H_2} , which may owing to the increased band offset at the p/i interface.

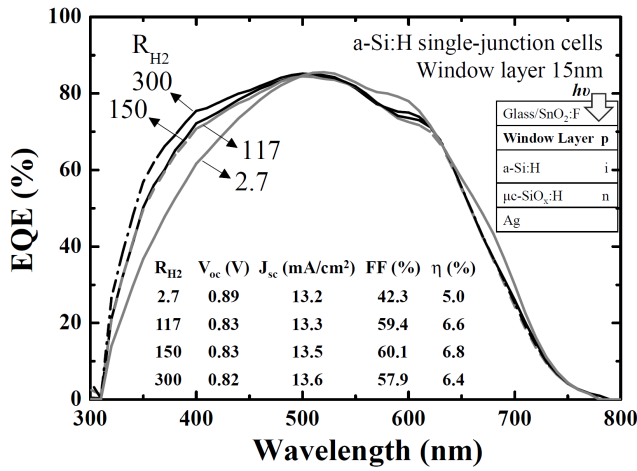


Fig2. The effect of H_2 -to- SiH_4 flow ratio in $\text{SiO}_x\text{:H(p)}$ on EQE and the performance of a-Si:H cells

The p/i interface has been proposed to dominate the V_{OC} because of its larger V_b (built-in voltage) and the injection of the limiting carrier (holes) [5]. This indicates that V_{OC} is sensitive to the deposition condition, impurity and band potential at p/i interface [6]. In order to reduce the band offset between a- $\text{SiO}_x\text{:H(p)}$ ($E_0=2.28\text{eV}$) and a-Si:H(i) ($E_g=1.75\text{ eV}$), a thin a- $\text{SiC}_x\text{:H(p)}$ ($E_0=2.15\text{eV}$) layer was inserted between the p/i interface. The EQE and cell performance of a-Si:H cells with a- $\text{SiO}_x\text{:H(p)}$ ($R_{\text{H}_2}=150$) compared to a- $\text{SiC}_x\text{:H(p)}$ were shown in Fig.3. As can be seen, the employment of a- $\text{SiO}_x\text{:H(p)}$ enhanced the J_{SC} in the short-wavelength region, which was due to higher E_0 of a- $\text{SiO}_x\text{:H(p)}$ than that of a- $\text{SiC}_x\text{:H(p)}$. The J_{SC} increased from 13.4 to 13.7 mA/cm^2 and the cell efficiency increased from 7.0% to 7.4%.

The J-V characteristics of a-Si:H/a- $\text{Si}_{1-x}\text{Ge}_x\text{:H}$ tandem cell with a- $\text{SiO}_x\text{:H(p)}$ and a- $\text{SiC}_x\text{:H(p)}$ window layer were shown in Fig.4. With the employment of a- $\text{SiO}_x\text{:H(p)}$ in the top cell, the cell efficiency was improved from 8.19% to 8.60%, as compared to a- $\text{SiC}_x\text{:H(p)}$. The enhancement was ascribed to the increased FF from 64.3% to 67.5%, which was due to the decreased series resistance resulting from the higher conductivity of a- $\text{SiO}_x\text{:H(p)}$ ($1.15\times 10^{-5}\text{ S/cm}$) compared to a- $\text{SiC}_x\text{:H(p)}$ ($6.20\times 10^{-6}\text{ S/cm}$).

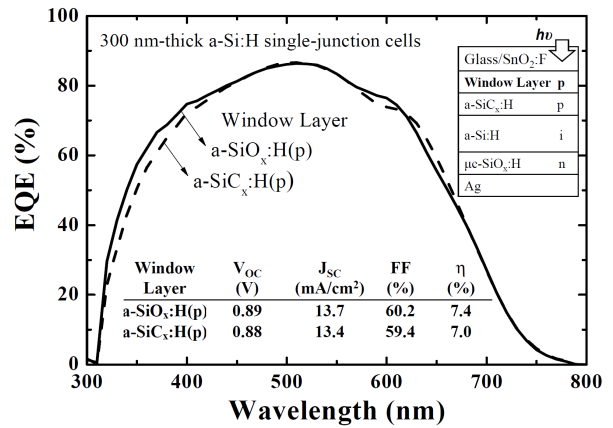


Fig3. EQE and cell performance of a-Si:H cells with a- $\text{SiO}_x\text{:H(p)}$ and a- $\text{SiC}_x\text{:H(p)}$ as the window layer

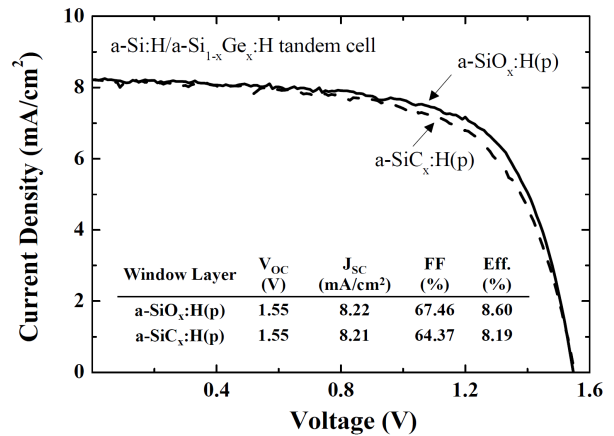


Fig4. The cell performance of a-Si:H/a- $\text{Si}_{1-x}\text{Ge}_x\text{:H}$ tandem cells with a- $\text{SiO}_x\text{:H(p)}$ and a- $\text{SiC}_x\text{:H(p)}$ as window layer

4. Conclusions

The high hydrogen-dilution a- $\text{SiO}_x\text{:H(p)}$ films with high conductivity of $1.15\times 10^{-5}\text{ S/cm}$ and low absorption coefficient was developed and employed as window layer in a-Si:H and a-Si:H/a- $\text{Si}_{1-x}\text{Ge}_x\text{:H}$ solar cells. The cell efficiency of a-Si:H cell with a- $\text{SiO}_x\text{:H(p)}$ as window layer increased from 7.0% to 7.4% compared to a- $\text{SiC}_x\text{:H(p)}$. The employment of a- $\text{SiO}_x\text{:H(p)}$ in a-Si:H/a- $\text{Si}_{1-x}\text{Ge}_x\text{:H}$ tandem cells improved the efficiency from 8.19% to 8.60%. Consequently, the high hydrogen-dilution a- $\text{SiO}_x\text{:H(p)}$ is a suitable material to be a window layer in amorphous silicon-based thin-film solar cells.

Acknowledgements

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References

- [1] K. Yoon et al., *Journal of Non-Crystalline Solids*, **357** (2001) p. 2826
- [2] S. Guha et al., *Journal of Applied Physics*, **52** (1981) p. 859
- [3] S. Vepřek et al., *Philosophical Magazine B*, **45** (1982) p. 137
- [4] K. Prasad et al., *MRS Proceedings*, **219** (1991) p. 469
- [5] S. S. Hegedus et al., *Journal of applied physics*, **63** (1988) p. 5126
- [6] F. Jeffrey et al., *Applied physics letters*, **48** (1986) p. 1538