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Hydrogen passivation of multi-crystalline silicon solar cells*

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The effects of hydrogen passivation on multi-crystalline silicon (mc-Si) solar cells are reported in this paper. Hydrogen plasma was generated by means of ac glow discharge in a hydrogen atmosphere. Hydrogen passivation was carried out with three different groups of mc-Si solar cells after finishing contacts. The experimental results demonstrated that the photovoltaic performances of the solar cell samples have been improved after hydrogen plasma treatment, with a relative increase in conversion efficiency up to 10.6%. A calculation modelling has been performed to interpret the experimental results using the model for analysis of microelectronic and photonic structures developed at Pennsylvania State University.

Keywords: multi-crystalline silicon solar cells, plasma, hydrogen passivation
PACC: 8630J, 5275R, 6170W

1. Introduction

The multi-crystalline silicon (mc-Si) solar cells are considered to be one of the most promising solar cells, capable of achieving both high efficiency and stable performance with relatively low cost.[1,2] On the other hand, mc-Si contains many grain boundaries where exists a much higher density of defects, impurities and dangling bonds, so the efficiencies of the mc-Si solar cells are inferior to those of mono-crystalline ones. This is because the defects, impurities and dangling bonds in these regions act as trapping centres of the photo-generated carriers, playing killer-like actions for the lifetime of minority carriers. However, it is reported that the density of impurities and defects associated with grain boundaries could be partially moved out or passivated by gettering and hydrogen plasma treatment, significantly improving the performances of multi-crystalline solar cells.

Many methods of hydrogen passivation have been applied successfully,[3] including hydrogen ion implantations, hydrogen plasma treatment during plasma-enhanced chemical vapour deposition of silicon nitride[4] and microwave-induced remote hydrogen plasma process,[5] where the hydrogen plasma was generally created by RF or microwave power.

The motivation of this study is to develop a low-cost technology and a process for hydrogen treatment of mc-Si solar cells, which may be suitable for applications in industrial production.

For the interpretation of the experimental results, a numerical simulation is performed using a model for analysis of microelectronic and photonic structures (AMPS) developed at the Pennsylvania State University.

2. Experimental details

All the cells used in this work were manufactured using Bayer's p-type mc-Si wafers with a thickness of 300 μm, and a resistivity of about 1Ωcm. The grain size was in the range of 1–20 mm. After chemical, etching and cleaning, phosphorus diffusion was performed at 900 °C by using $POCl_3$. The antireflection coatings (ARCs) of TiO_2 were deposited by atmospheric pressure chemical vapour deposition (APCVD). Then metal contacts were screen-printed and sintered at 600 °C.

The hydrogen treatment experiments were per-

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formed using three different groups of solar cells. The first group was made without any SiO_2 or an ARC layers (Group I). The second group was prepared with SiO_2 passivation layer, but without ARC layer (Group II), and the third group was covered by SiO_2 and TiO_2 complex layers (Group III). The technological procedure is schematically shown in Fig.1.

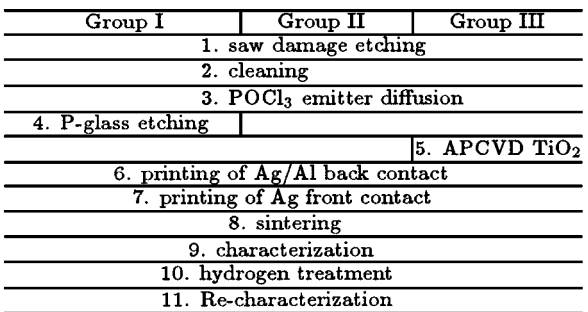


Fig.1. Procedure of the solar cell fabrication.

The hydrogen treatments were carried out using a simple system shown in Fig.2. The reaction chamber is a quartz tube with a diameter of 6cm.

Two tungsten-wire electrodes connected to an ac transformer were used for exciting the hydrogen plasma in the quartz tube, instead of using RF or microwave power. Solar cell samples were placed between the two electrodes. These samples were heated to 200–350 °C measured by a PtRh-Pt thermocouple in the quartz tube at a pressure of 26.6 Pa maintained by adjusting the flow of purified hydrogen while pumping. The temperature was kept stable during the discharge duration of 10–30 min. The samples were then cooled down to room temperature and removed from the tube. The illuminated I-V characteristics were measured under the illumination of AM1.5 and 100 mW cm^{-2} prior to and immediately after the hydrogen treatment for all samples.

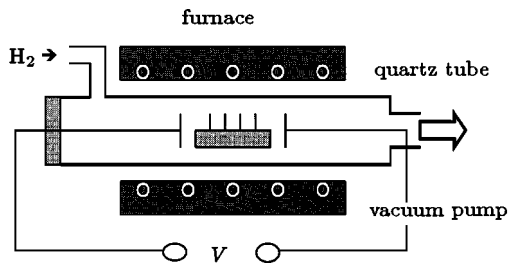


Fig.2. Experimental apparatus for hydrogen treatments.

3. Results and discussion

The photovoltaic parameters of the open-circuit voltage V_{oc}, the short-circuit current density J_{sc}, the fill factor FF, and the conversion efficiency η of the solar cell samples used in this study are listed in Table 1; they were duplicated from the illuminated I-V measurement prior to and immediately after the hydrogen treatment.

Table 1. Characteristics of cells before and after hydrogen plasma treatment.

Cells	H pass.	V_{oc}/mV	J_{sc}/mA cm^{-2}	FF/%	η/%
Group I	before	555	27.9	66.7	10.3
	after	560	28.6	67.5	10.8
	before	516	27.4	63.2	8.9
	after	532	27.8	64.2	9.5
Group II	before	543	27.6	66.2	9.9
	after	550	28.8	68.8	10.7
	before	530	27.2	68.5	9.9
	after	558	29.2	69.0	11.2
Group III	before	550	29.8	65.5	10.7
	after	556	29.4	67.2	11.0
	before	533	28.8	64.3	9.9
	after	538	28.4	65.3	10.0

The experimental results show that the improvements in the performance of the solar cells are significant after the hydrogen treatment. For Groups I and II, all the photovoltaic parameters, J_{sc}, V_{oc} and FF, increase after hydrogen passivation, and the average efficiencies of the solar cell samples in the two groups increase by about 5.7% and 10.6%, respectively. For Group III, a little decrease in the short-circuit current

density J_{sc} is observed. Yet a little increase in V_{oc} and FF, even in conversion efficiency (η), is observed also. According to the following formulae of V_{oc} and FF[6]

$$V_{oc} = \frac{kT}{q}[\ln(J_{sc}/J_0) + 1], \tag{1}$$

$$FF \cong \left\{1 - \frac{1}{\ln(J_{sc}/J_0)}\right\}\left\{1 - \frac{\ln[\ln(J_{sc}/J_0)]}{\ln(J_{sc}/J_0)}\right\}, \tag{2}$$

we can easily conclude that the reverse saturation current density J_0 of the solar cells decreases. The decrease in J_0 suggests an improvement in the quality of material properties and p-n junction after hydrogen atomic passivation of dangling bonds in the grain boundaries and interfaces.

In order to reach an insightful understanding of the passivation mechanism, we have employed the AMPS[7,8] in lifetime mode, a first principles computer program developed at Pennsylvania State University, to simulate devices used in this study. AMPS uses finite differences and the Newton–Raphson technique to solve a complete set of nonlinear coupled equations, involving Poisson's equation and two continuity equations. Details of this model have been explained and utilized elsewhere.[9]

By appropriate choice of material and device structural parameters, 0.4 μm-thick n-layer with N_D $=10^{19}$cm^{-3}, 300 μm-thick p-base with $N_A = 10^{17}$cm^{-3} and minority carrier lifetime τ_e=10^{-6} s, n/metal contact barrier-height ϕ_{cn}=0.5 eV (for electrons) and p/metal contact barrier-height ϕ_{cp}=0.5 eV (for holes) and front surface reflectivity of R_F=8% (for incident light with wavelength range from 0.4 to 1.1 μm), a baseline model (supposed to represent samples before the hydrogen treatment) was constructed, which performs extremely close to our experimental cells.

Figure 3 shows the calculated illuminated J-V characteristics of this modelled baseline cell. From the point of view of the cells, only three possible effects would be induced by hydrogen treatment at 200–350 °C for tens of minutes. (1) Lengthening of the minority carrier's lifetime, resulting in an overall enhancement of solar cell performances, especially the short-circuit current density J_{sc}. (2) Perfection of contact, leading to a reduction of the n/metal and p/metal barrier-heights. (3) Deterioration of ARC: TiO_2, causing a rise of the front surface reflectivity (only valid for Group III).

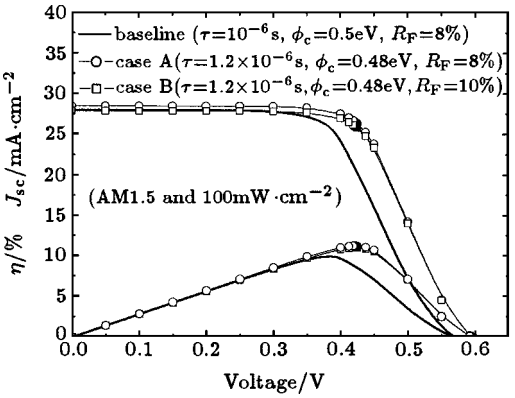


Fig.3. Characteristics of modelled solar cells.

The above three effects can be simulated by varying minority carrier's lifetime (τ_e for p-type mc-Si wafer), contacting barrier-heights ϕ_{cn} and ϕ_{cp}, and front surface reflectivity R_F of the baseline model, separately. As can be expected, the reduction in τ or R_F would lead to an ascent in J_{sc}, and a reduction in ϕ_{cn} (ϕ_{cp}) would reduce the series resistance, therefore enhancing V_{oc} and FF. However, any single change of τ_e, ϕ_{cn} (ϕ_{cp}) or R_F could give rise to reasonable fittings to experimental results listed in Table 1. This apparently verifies the complexity of impacts upon mc-Si solar cell performances induced by hydrogen treatment.

Changing τ from 10^{-6} to 1.2×10^{-6} s and ϕ_{cn} (ϕ_{cp}) from 0.5 to 0.48 eV (the latter is denoted here as case A, representing samples of Groups I and II after hydrogen treatment), the calculated J_{sc} from 28.0 to 28.3 mA cm^{-2}, V_{oc} from 571 to 596 mV, FF from 0.622 to 0.659 and η from 9.93% to 11.11% were obtained, showing an excellent comparability with realistic outputs of Group I and Group II.

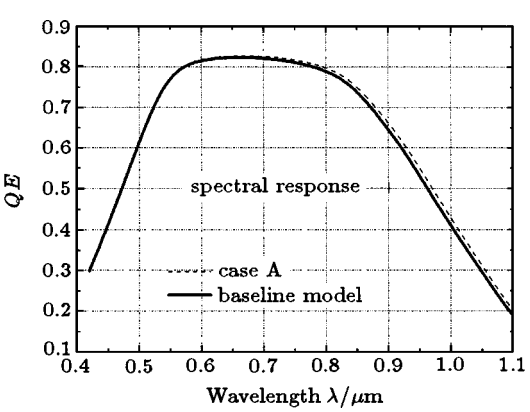


Fig.4. The calculated spectral response of case A and baseline model.

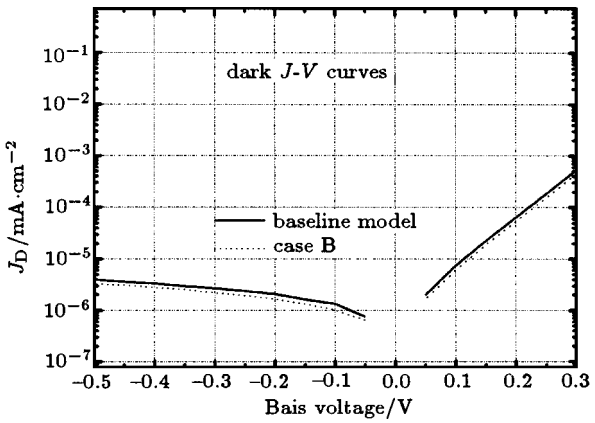


Fig.5. The calculated dark J-V curves of case B and baseline model.

To interpret the experimental results for Group III, incorporation of an increased reflectivity (implying deterioration in ARC) is needed. Again, changing τ from 10^{-6} to 1.2×10^{-6} s, ϕ_c from 0.5 to 0.48 eV and R_F from 8% to 10% (denoted here as case B, representing samples of Group III after hydrogen treatment), simulation also provides good fitting to Group III. Figure 4 is an illustration of the calculated spectral response of case A and that of the baseline model. It indicates that the spectral response is improved after the hydrogen treatment for Group I and Group II, leading to an increase in J_{sc}. Figure 5 demonstrates the dark J-V curves of case B and the baseline model, which confirms the deduction that the hydrogen treatment could decrease the reverse leakage current J_0 according to Eqs.(1) and (2).

4. Conclusion

A simple process has been implemented for hydrogen passivation of mc-Si solar cells. The experimental results indicate that the performances of mc-Si solar cells are improved significantly by means of hydrogen plasma treatment. Some of the samples gain a relative increase in conversion efficiency up to 10.6%. The increase in J_{sc} suggests an improvement in material properties, especially the minority carrier lifetime. The enhancement in V_{oc} and FF can be attributed to the reduction of contact barrier height. The light descent in J_{sc} for the third group samples with TiO_2 covering is the compromise between the improvement in the material property and the deterioration of ARC. AMPS simulation supports the explanation.

References

[1] Zhao J *et al* 1998 *Appl. Phys. Lett.* **73** 1991
[2] Wang Y Q *et al* 2002 *Chin. Phys.* **11** 492
[3] Zhang S B *et al* 2002 *Acta Phys. Sin.* **51** 111 (in Chinese)
[4] Elgamel H E *et al* 1995 *J. Appl. Phys.* **78** 3457
[5] Sopori B L, Deng X and Benner J P 1994 *First WCPEC, IEEE* (Hawaii) p 1615
[6] Fahrenbruch A L and Bube R H 1983 *Fundamental of Solar Cells* (New York: Academic)
[7] Fonash S J *et al* 1991 *J. Appl. Phys.* **69** 7059
[8] McElheny P J *et al* 1988 *J. Appl. Phys.* **64** 1254
[9] Hu Z H *et al* 2003 *Acta Phys. Sin.* **52** 224 (in Chinese)