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Performance improvement of amorphous silicon germanium single junction solar cell modules by low temperature annealing

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ABSTRACT

The performances of p–i–n amorphous silicon germanium (a-SiGe:H) solar cell modules were investigated post annealing at different temperatures. When the annealing temperature is 190 °C, the best performance of solar cell modules is obtained. The efficiency of solar cell modules is improved from 5.11% to 7.91%. The enhancement in quantum efficiency spectra at long wavelength post annealing may be attributable to there being significantly less absorption in intrinsic layer. The microstructural properties of the a-SiGe:H thin films are investigated post annealing at different temperatures. The results show that the low temperature annealing process leads to the improvement in the film microstructure.

1. Introduction

Hydrogenated amorphous silicon germanium (a-SiGe:H) thin film solar cell is a promising candidate for future photovoltaic power generation, because of their narrow band gap for use in tandem and triple junction solar cells. Alloying of a-SiGe:H with increasing germanium (Ge) content reduces the band gap and permits the optical band gap to be tuned and absorption coefficient to be increased at long wavelengths. However, the chemical inhomogeneity enhances the structural defects such as dangling bonds, vacancies and microvoids, which in turn degrade the optoelectronic properties of the material and influence the performance of solar cell [1,2]. In the latter half of the 1980s, more systematic programs were undertaken to develop and understand the properties of the a-SiGe alloys [3–5]. However, annealing reports in the a-SiGe alloys is much less. Xu et al. concluded that the hydrogen plasma annealing is, indeed, helpful for improving the quality of narrow bandgap a-SiGe:H alloys, mainly through control of bonded hydrogen configuration and content in the network [6]. Chen et al. found that thermal annealing of the cells at 150 °C in a vacuum eliminated the s-curve behavior observed by current density–voltage measurements. Annealing significantly alters crystallinity and conductivity of n-μc-Si:H layers [7]. J. David Cohen studied the annealing mechanisms of a-SiGe films with Ge fractions below 10 at.%. Comparing purely thermal annealing with light-induced annealing indicates that the relative anneal rate for the silicon and Ge defects is different [8]. J. David Cohen concluded that the annealing can reduce the defect densities [9].

The analysis results above do not mean that the annealing effects are entirely understood in a-SiGe:H. The paper reports the effect of post-deposition annealing on the performance of a-SiGe:H single junction solar cell modules and structural properties of a-SiGe:H films as a function of annealing temperature.

2. Experimental details

The solar cell modules were fabricated with the structure of glass/textured SnO_2:F/p–i–n a-SiGe:H/Al_2O_3-doped zinc oxide (AZO)/Al. The area of solar cell modules is 100 cm^2. The p-, i- and n-layer thicknesses are 20, 200 and 30 nm, respectively. The n layer is an amorphous silicon film. The p–i–n a-SiGe:H layers were fabricated in a capacitively coupled radio frequency plasma enhanced chemical vapor deposition system with a base vacuum of 10^{-5} Pa. The substrate temperature was fixed at 200 °C. The reactive gases for the deposition of the solar cells included silane (SiH_4), germane (GeH_4), hydrogen (H_2), diborane (B_2H_6) and phosphine (PH_3). The solar cell modules and films were subjected to different temperatures annealing under nitrogen (N_2) ambient for 40 min. Heating and cooling rates of 5 °C min^{-1} were chosen to minimize surface damage. The AZO films were deposited by intermediate frequency magnetron sputtering from a sintered ceramic Al_2O_3-doped ZnO (3 wt.%) in an argon atmosphere. Their square resistance was measured by four-point probe technique. The Al films were obtained by direct current (DC) magnetron sputtering from pure Al targets.

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Table 1
The performances of a-SiGe:H solar cell modules at different annealing temperatures, short-circuit currents (I_{sc}), open-circuit voltages (V_{oc}), fill factors (FF), efficiencies (η), series (R_s) and shunt resistances (R_{sh}).

Annealing temperature (°C)	η (%) (±0.15)	FF (±0.01)	V_{oc} (V) (±0.02)	I_{sc} (mA) (±0.38)	R_s (Ω) (±0.52)	R_{sh} (Ω) (±10.39)
0	5.11	0.41	5.60	222.38	18.09	131.94
150	6.91	0.51	5.92	228.75	5.08	198.41
190	7.91	0.58	5.92	230.50	5.15	207.95
210	7.86	0.57	6.00	229.75	4.14	209.64
230	7.69	0.55	6.08	230.00	4.32	220.50

The thicknesses of the thin films were determined by Bruker Dektak 150 Surface Profiler. The photocurrent versus voltage (I–V) characteristics of the fabricated solar cells were measured at 25 °C under 1-sun (AM1.5, 100 mW/cm^2) solar simulator radiation. The quantum efficiency (QE) measurements were performed in the wavelength range of 350–900 nm at zero bias voltage and without any bias light to evaluate the spectral response of the fabricated solar cells. The Fourier transform infrared spectroscopy (FTIR) absorption measurements were taken for samples on c-Si substrates by VARIAN Excalibur 3100 to obtain information on the H content and bondings. The Ge atom content was further determined by energy dispersive spectroscopy (EDS) measurement via EDAX TEAM-EDS integrated on the scanning electron microscope (ZEISS SIGMA). The atomic force microscope (AFM) (BRUKER) and scanning electron microscopy (SEM) (ZEISS SIGMA) were employed to characterize the surface morphology of the films.

3. Results and discussion

Table 1 shows the performance of a-SiGe:H solar cell modules at different annealing temperatures, short-circuit currents (I_{sc}), open-circuit voltages (V_{oc}), fill factors (FF), efficiencies (η), series (R_s) and shunt resistances (R_{sh}). The performances were improved post annealing to a great extent. We observed that I_{sc} and FF first increased and then decreased with increasing of annealing temperature, whereas V_{oc} showed slight change. When the annealing temperature was 190 °C, I_{sc} and FF increased to the maximum values. The best performance of solar cell modules was obtained. The efficiency of solar cell modules was improved by almost 40% in comparison to non-annealing. Up to 280 °C, the solar cell module had almost no efficiency.

The R_{sh} and R_s of a solar cell are important parameters that affect its performance [10,11]. Low R_{sh} and high R_s all cause power losses. Their main impact is to reduce the fill factor, although excessively high R_s and low R_{sh} values may also reduce the short-circuit current. Fig. 1 shows the R_{sh} and R_s of eight different performance a-SiGe:H solar cell modules before and post 190 °C annealing. The improvement of I_{sc} and FF is consistent with the increasing and decreasing of R_{sh} and R_s post annealing, respectively. In addition, Table 1 also shows an increase and decrease in R_{sh} and R_s post annealing at different temperatures.

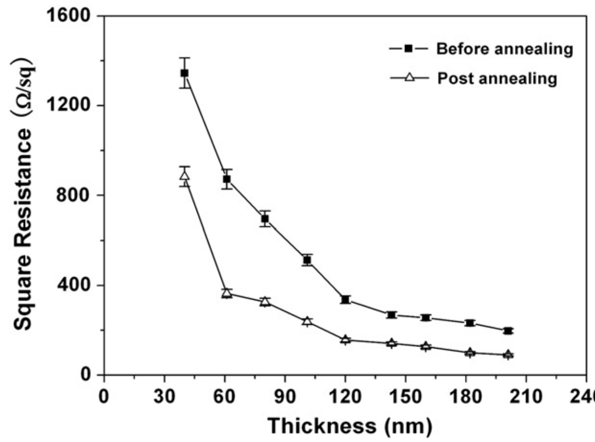

Fig. 2. The square resistance of AZO films of different thicknesses before and post 190 °C annealing.

One of the contribution to R_s is the resistance of AZO films in a solar cell. The effect of AZO film thickness on the cell performance has been described elsewhere [12]. The AZO films were deposited on glass substrates by sputtering. The AZO films were subjected to 190 °C annealing in N_2 ambient for 40 min. Fig. 2 shows square resistance of AZO films of different thicknesses before and post annealing. It can be seen that square resistance all decreased post annealing, which decreased the R_s of a solar cell, then improved performances of solar cell modules.

QE curves of the a-SiGe:H solar cell modules with 90 nm-thickness AZO film before and post annealing were shown in Fig. 3. Clearly, the annealing increased the quantum efficiency greatly, especially in the long wavelength. It means that increased QE might result from an improved material quality in the whole intrinsic layer.

To analyze the causes of annealing further, a-SiGe:H thin films with 640 nm thickness were deposited on quartz and silicon substrates. The Ge atom content measured by EDS is 33.67%. The optical gap defined via the Tauc plot is 1.51 eV [13]. Their microstructural properties were investigated post annealing at different temperatures. Fig. 4 shows FTIR absorption spectra for a-SiGe:H films. The Si – H bond configuration dominates and controls the total amount of hydrogen in the a-SiGe:H

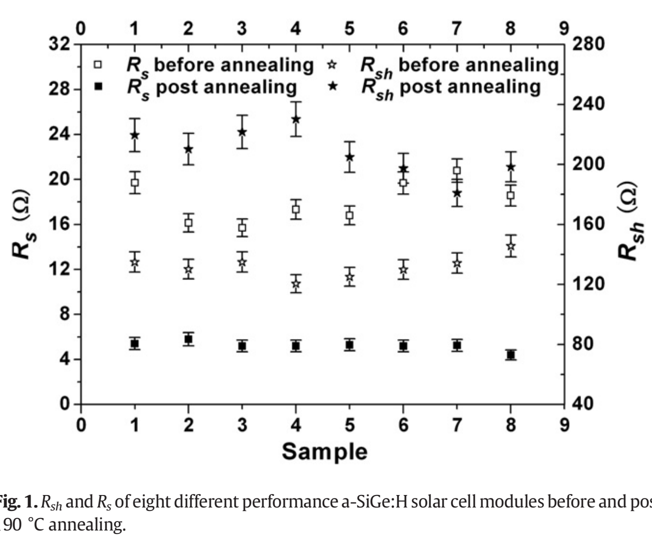

Fig. 1. R_{sh} and R_s of eight different performance a-SiGe:H solar cell modules before and post 190 °C annealing.

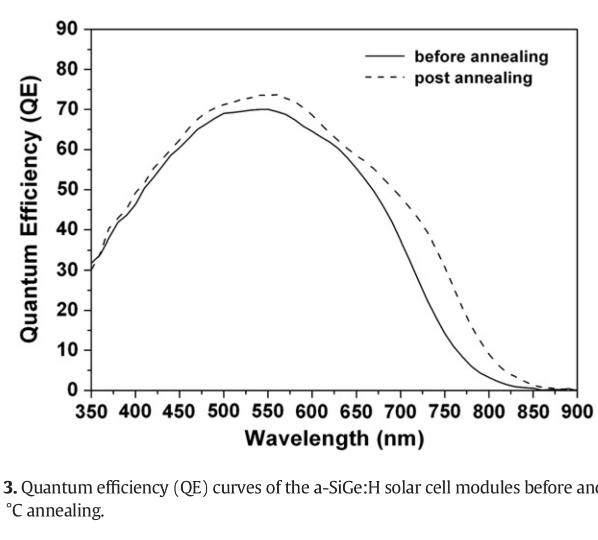

Fig. 3. Quantum efficiency (QE) curves of the a-SiGe:H solar cell modules before and post 190 °C annealing.