Effect of hydrogen dilution on intrinsic a-Si:H layer between emitter and Si wafer in silicon heterojunction solar cell

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Received 12 April 2007; received in revised form 27 August 2007; accepted 8 September 2007
Available online 5 November 2007

Abstract

In silicon heterojunction solar cells, a thin intrinsic amorphous-silicon (a-Si:H) buffer layer between a doped emitter and a c-Si wafer is essential to minimize carrier recombination. This study examines the effect of H\textsubscript{2} dilution on the properties of the intrinsic a-Si:H layers deposited on Si wafers by plasma-enhanced chemical vapor deposition. A H\textsubscript{2}/SiH\textsubscript{4} ratio of 2~4 led to improvements in the quality of intrinsic a-Si:H films and in the performance of passivation compared to a-Si:H film without H\textsubscript{2} dilution. A high H\textsubscript{2}-dilution ratio, however, degraded the passivation of the a-Si:H film. The Si heterojunction solar cells with an optimal intrinsic a-Si:H layer showed an efficiency of 12.3%.

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Keywords: Silicon solar cell; Heterojunction; Passivation; Hydrogen dilution

1. Introduction

The a-Si:H/c-Si heterojunction solar cells are promising because they are based on Si wafer-based technology. Also, a low-temperature (<300 °C) process affords the possibility of additional cost savings through the use of thinner and lower grade Si wafers by avoiding the degradation caused by high temperatures and wafer bowing due to the aluminum back-surface field process. In heterojunction solar cells, control of the interface between different materials becomes an important factor for high performance. In particular, the suppression of carrier recombination at the p/n interface is crucial. To reduce interface recombination, the use of a thin intrinsic a-Si:H buffer between the p-type emitter and the n-type wafer was proposed, and a considerable suppression of surface recombination was reported [1]. Other groups [2,3] have also shown that the insertion of intrinsic layer increased the efficiency of solar cells. This intrinsic layer should be amorphous to ensure high performance [4,5] because partially epitaxial Si layers have more defects than amorphous films [4]. The deposition at low substrate temperature (∼100 °C) could achieve high open-circuit voltage ($V_{OC}$), while high deposition temperature degraded solar cell properties, which was believed to be related with partial epitaxial growth [5].

In a-Si:H deposition, H\textsubscript{2} dilution is generally adopted because it can lower electron temperature in the plasma [6] and suppress the formation of reactive (poly) silane radicals [7]. H\textsubscript{2}-diluted a-Si:H film also showed less photo-induced degradation [6,8]. However, in the case of the intrinsic a-Si:H buffer layer for Si-based heterojunction solar cells, there have been no reports which clearly show the effect of H\textsubscript{2} dilution.

In this report, the effect of H\textsubscript{2} dilution on the growth of an intrinsic a-Si:H layer was investigated. H\textsubscript{2} dilution was found to improve the quality of a-Si:H films and the Si...
wafer passivation. The performance of solar cells also improved by using an optimized intrinsic a-Si:H buffer layer.

2. Experimental details

Single-side polished (100) p-type, float-zone (FZ) Si wafers were used for the study on the effect of H2 dilution. The Si wafers were 675 μm thick and had a resistivity of 11Ωcm. Prior to deposition of a-Si:H layers, the Si wafers were cleaned by ultrasonic rinsing in acetone–methanol–deionized water. Native oxide was removed by a 30 s dip in 1% hydrofluoric acid. The intrinsic a-Si:H layer was deposited with plasma-enhanced chemical vapor deposition (PECVD) at a fixed SiH4 partial pressure of 50 mTorr. Doped (n, p-type) a-Si:H films were also deposited with PECVD. Table 1 describes the deposition conditions of a-Si:H films for wafer passivation and solar cell fabrication.

3. Results and discussion

3.1. The effect of H2 dilution

Fig. 1(a) shows the effective lifetime as a function of the H2/SiH4-dilution ratio of R and film thickness of the intrinsic a-Si:H layer deposited on both sides of a wafer. The intrinsic a-Si:H layers were prepared at a substrate temperature of 100 °C at which the highest lifetime values were observed (unpublished). The τeff of the samples shown in Fig. 1(a) were determined at 1 sun illumination. As shown in Fig. 1(a), the τeff is strongly dependent on the H2 dilution ratio and film thickness of intrinsic a-Si:H layers. While the samples with an intrinsic a-Si:H layer, prepared without H2 dilution, showed τeff which was almost the same as that of an n-type a-Si:H/p c-Si/n-type a-Si:H sample without an intrinsic a-Si:H layer (diamond mark in Fig. 1(a)), the samples with H2 dilutions during the deposition of the intrinsic layer greatly enhanced the τeff. The τeff of the sample, which contained 10-nm-thick intrinsic a-Si:H films with H2 dilution of 2–4, is longer than 3 ms. This corresponded to a recombination velocity parameter Sτeff of 10 cm/s. However, further increase of the H2 dilution (R = 6) decreased the lifetime values, which implied the deteriorated passivation of the intrinsic a-Si:H layer. It was reported that both high substrate temperature [4,5] and high H2 dilution [10,11] can lead to epitaxial growth on Si wafers, and partial epitaxial growth can result in poor passivation performance [4,5]. Observed degradation in measured lifetime in the case of R = 6 may be related with poor partial epitaxial growth on Si wafers. Fig. 1(a) also shows that the lifetime decreases with increasing film thickness. The observed effect of film thickness on τeff is believed to be due to the reduced electric field in a thicker intrinsic a-Si:H film.

An FT-IR measurement (Fig. 1(b)) shows that the transmittance of the H2 diluted sample (R = 4) was larger than that of the undiluted sample (R = 0) near the wavelength of 2100 cm−1. It is well known that a peak at 2000 cm−1 originates from a-Si:H stretching mode in compact material, and the observed peak at 2100 cm−1 equation [9]:

\[ S_{\text{eff}} \leq \frac{W}{2\tau_{\text{eff}}} \]

Here, W is the wafer thickness and τeff is the measured carrier lifetime.
implies that a-Si:H stretching mode comes from the internal surface of voids in a-Si:H film [12]. This suggests that the samples with a H2-undiluted intrinsic layer may have porous structures with many Si dangling bonds inside the a-Si:H film, resulting in low transmittance at 2100 cm\(^{-1}\). Poor film quality of H2-undiluted intrinsic a-Si:H layer means that the intrinsic layer has high defect density, and this could lead to a low lifetime of the Si wafer which were passivated by the undiluted (R = 0) a-Si:H film.

To study the effect of H2 dilution on film quality and interface of intrinsic a-Si:H/c-Si, HR-TEM analysis was performed for samples with and without H2 dilution. TEM images shown in Fig. 2 demonstrate that there is no severe partial epitaxial growth in the film regardless of H2 dilution. However, lattice images are observed above the Si wafers and the thickness of the lattice images are 0.6 and 1.3 nm for the H2-undiluted sample (Fig. 2(a)) and H2-diluted sample (Fig. 2(b)), respectively. These lattice images imply that slight partial-epitaxial growth occurred in both samples, but the hydrogen dilution increased the thickness of the epitaxial layer. However, H2 dilution of R = 4 led to much better passivation of the Si wafer, as shown in Fig. 1(a). This can be attributed to the improved property of an intrinsic layer grown with H2 dilution as evidenced by the FT-IR result (Fig. 1(b)).

### 3.2. Fabrication of solar cells

Solar cells both without and with an intrinsic a-Si:H layer (R = 0, 4) were fabricated on p-type FZ Si wafers. In Fig. 3(a), the generation–recombination current before threshold voltage in the case of the sample with H2-undiluted intrinsic a-Si:H layer (R = 0) was higher than that of the sample without an intrinsic a-Si:H layer. The solar cell with a H2-diluted intrinsic a-Si:H layer (R = 4) shows a lower generation–recombination current compared to the sample without an intrinsic a-Si:H layer. This result agrees well with the effective lifetime data (Fig. 1(a)), which implies that the n-type a-Si:H/undiluted intrinsic...
a-Si:H (R = 0)/p c-Si junction has more defects and the n-type a-Si:H/H\(_2\) diluted intrinsic a-Si:H (R = 4)/p c-Si junction has less defects than simple n-type a-Si:H/p c-Si junction. The photo \(I-V\) curve under AM 1.5 condition (Fig. 3(b), Table 2) shows that the fill factor increases from 63.7% to 65.7% for samples with a H\(_2\)-diluted intrinsic a-Si:H buffer, but decreases to 58.3% for samples with a H\(_2\)-undiluted intrinsic a-Si:H layer. Solar cell efficiency was measured to be 10.3% and 12.3% for samples with a H\(_2\)-undiluted a-Si:H layer and a H\(_2\)-diluted (R = 4) a-Si:H layer, respectively. A decrease in the efficiency from 11.9% to 10.3% was also observed by introducing a H\(_2\)-undiluted intrinsic a-Si:H layer in the solar cell. This is mostly attributed to the increased carrier recombination, which is illustrated by the \(V_{oc}\) drop of 24 mV, as shown in Fig. 3(b).

### 4. Conclusion

The H\(_2\)-dilution effect on the intrinsic a-Si:H layer and the Si heterojunction solar cell was investigated. A low H\(_2\) dilution (R = 2, 4) during the deposition of the intrinsic a-Si:H layer improved the passivation performance, resulting in a longer effective lifetime of the Si wafer. FT-IR results demonstrated that improved quality of the a-Si:H layer contributed to the longer effective lifetime of samples with H\(_2\)-diluted intrinsic a-Si:H layer. Dark \(I-V\) curves and solar cell performance showed that a low H\(_2\)-dilution for the intrinsic a-Si:H layer could increase solar cell efficiency from 10.3% to 12.3% by reducing defects in the intrinsic a-Si:H layer.

### Acknowledgements

This work was supported by the Center for Distributed Sensor Network at GIST.

### References