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Controlling the c-Si/a-Si:H interface in silicon heterojunction solar cells fabricated by HWCVD

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ABSTRACT

This paper deals with the engineering of the hetero-interface between intrinsic amorphous silicon (i-a-Si:H) layer and the n-type crystalline silicon (c-Si) wafer during the fabrication of the Silicon Heterojunction (SHJ) solar cell by the Hot Wire Chemical Vapor Deposition technique. It is known that this interface and the associated surface passivation of the c-Si is key to obtaining high efficiency heterojunction solar cells. The monitoring of this interface was carried out using high-resolution transmission electron microscopy (HRTEM). The HRTEM data of the c-Si/a-Si:H interface reveals a drastic dependence on the filament temperature (T_f) used during the deposition of the i-a-Si:H layer. Detailed analysis of the solar cell characteristics indicates that the cells where one has an abrupt crystalline/amorphous interface shows higher conversion efficiency compared to those where we have a rough and a defective interface or where there are indications of local epitaxy in the a-Si:H layer. The second parameter which was engineered is the bulk defect density of the intrinsic a-Si:H layer. Though the thickness of i-a-Si:H layer in case of SHJ solar cells is only around 5 nm and serves the purpose of passivating the dangling bonds on the c-Si wafer, the bulk defect density of this layer cannot be ignored. We have achieved a-Si:H films with acceptable bulk defect density without dilution of the silane gas with hydrogen. The bulk defect density of the i-a-Si:H layer has been determined by the constant photocurrent method (CPM) and is correlated to the performance of SHJ solar cells. A direct consequence of these control parameters was observed in the improvement of the external quantum efficiency near 600 nm wavelength region.

1. Introduction

A major component of photovoltaic energy today is still captured by conventional c-Si p-n junction solar cells, however, there is a significant amount of research going on driven by the idea of replacing them (Shi et al., 2014; Chen et al., 2014; Beiley et al., 2013; Mali et al., 2013; Di et al., 2013; Agarwal and Dusane, 2015). The requirement of high processing temperature and thick Si wafers in the case of the c-Si p-n junction solar cell technology result into a costly product and hence a large energy payback time (Darling and You, 2013; De Wild-Scholten, 2013). This is a major impediment in extending the application sectors for such solar cell technology which is still industry centric (Peng et al., 2013). Silicon heterojunction (SHJ) solar cells have gained much attention in recent years because of its low processing temperature (~200 °C) and high efficiency compared to conventional p-n junction silicon solar cells (Masuko et al., 2014; Taguchi et al., 2014; Hernández-Como et al., 2011). SHJ are considered to be the third generation because of its low cost while maintaining the high efficiency. SHJ solar cells are a combination of both the bulk c-Si and thin film solar cell technology, taking advantage of both (Masuko et al., 2014). The a-Si:H/c-Si heterojunction in SHJ solar cell is formed by depositing the emitter layer (doped a-Si:H) over the surface of the c-Si substrate which makes the latter to be the part of the junction. The passivation of dangling bonds which are present on the c-Si surface is an important step prior to emitter layer deposition in this structure (Wang et al., 2005). To achieve this, various passivation techniques have been implemented such as atomic hydrogen treatment, wet chemical route, and buffer layer depositions (Lee et al., 2011; Huang et al., 2011; Deligiannis et al., 2014; Angermann et al., 2009; Jeong et al., 2008). In 1992, first time Sanyo introduced the i-a-Si:H layer in between the c-Si and doped emitter layer (Tanaka et al., 1992). The insertion of i-a-Si:H layer greatly reduces the saturation current density (J_o) and hence increases the open circuit voltage (V_{oc}) of the final device

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(Tanaka et al., 1992). The high potential of this solar cell fabricated using plasma enhanced chemical vapor deposition (PECVD) technique is recently demonstrated by Panasonic in their commercially available HIT solar cells which are double-sided heterojunction structures with the textured silicon surface (Masuko et al., 2014). However, it is still a challenge to obtain such high performance as seen from the reports of other groups working in this area (Wu et al., 2009; Page et al., 2011; Descoeudres et al., 2015). This is because of limited information in the literature regarding the process parameters which yield the desired c-Si/a-Si:H interface and the electronic quality of the a-Si:H layer required to achieve high conversion efficiencies.

There have been different views regarding the nature of the c-Si/a-Si:H interface in terms of its microstructure observed through TEM studies. Centurioni et al. claim that complete epitaxial intrinsic silicon layer is beneficial for the good performance of SHJ solar cells (Centurioni et al., 2004). This study thus suggested that having any kind of buffer layer such as i-a-Si:H layer may not be an essential requirement. However, these conclusions do not match with those who show that if an abrupt c-Si/a-Si:H interface is achieved then it leads to very good performance of the SHJ solar cells (Fujiwara and Kondo, 2007; Wang et al., 2006). Thus a detail optimization effort involving a systematic variation of the process conditions leading to a control over the c-Si/a-Si:H interface is warranted.

In this study, the a-Si:H/c-Si interface has been studied in detail using HRTEM, since it is one of the finest techniques to study structural aspects with its high-resolution images. i-a-Si:H layer has been deposited on n-c-Si by HWCVD technique under different deposition condition. It is well accepted, that the filament temperature (T_f) in the case of HWCVD has a strong influence on the growth kinetics and properties of i-a-Si:H layer (Pant et al., 2001; Soni and Dusane, 2011). Therefore i-a-Si:H layer has been deposited on c-Si wafer at various T_f values to modify the interface as well as the quality of i-a-Si:H layer.

2. Experimental

We have used 500 μm thick phosphorus doped mono-crystalline (100) Czochralski (CZ) grown silicon wafers having the resistivity of 1–2 Ohm-cm for fabricating the SHJ solar cells. The silicon wafers were dipped in 2% HF for 1 min prior to the i-a-Si:H layer deposition. The Si substrates were loaded into the HWCVD preparation chamber dedicated for deposition of intrinsic layers through the load lock chamber immediately after HF etching. The base pressure in all the chambers of the cluster tool is maintained at 10^{-7} mbar prior to the deposition of the intrinsic and doped silicon layers. Different dedicated chambers were used to deposit intrinsic and doped Si layers to avoid any cross contamination as shown in Fig. 1.

The layers were deposited by hot wire chemical vapor process using a tantalum filament. The projected surface area of the filament was approximately equal to 5 cm^2. The substrate is placed 7 cm above from the filament plane. The substrate was heated to 180 °C during the i-a-Si:H and doped a-Si:H layer deposition. All the parameters except T_f were kept constant during the deposition of intrinsic and doped layers for SHJ solar cells fabrication are listed in Table 1. The intrinsic layer is deposited at different T_f values ranging from 1550 to 1850 °C with a step size of 100 °C. Intrinsic a-Si:H layers of thickness around 500 nm were also deposited on the glass substrate to measure the bulk defect density in the film. The constant photocurrent method (CPM) (Sciencetech, Canada) was used to measure the deep defect density in the a-Si:H films (Vaněček et al., 1983). The coplanar electrode geometry was used for CPM measurements. For the coplanar configuration, Al was evaporated to form the metal contacts with a gap of 0.5 mm between the two contacts. The bias voltage was kept constant at 100 V. The number of photons was adjusted to keep the photocurrent constant when the photon energy was varied. The description of experimental set up is given elsewhere (Wadibhasme and Dusane, 2013). The value of alpha measured at 1.3 eV is considered to be defect related absorption in the bandgap of a-Si:H material. Finally, The density of defect states (N_D) in a-Si:H layer can be calculated from the following relation (Wyrsch et al., 1991).

$$N_D = 2 \times 10^{16}(\mathrm{cm}^{-2}) \times \alpha(\mathrm{cm}^{-1})(at 1.3 eV) \quad (1)$$

The SHJ solar cells were fabricated where the a-Si:H layer of 5 nm followed by a p-type a-Si:H layer of 10 nm was deposited by the HWCVD in different deposition chambers to avoid cross contamination. At the front side of the SHJ solar cell, the transparent electrode Al doped Zinc Oxide were deposited using RF magnetron sputtering method. The top Aluminium finger pattern was deposited through a mask to complete a cell over an area of 4 cm^2. The back metallization was of Aluminium deposited by resistive evaporation but was not sintered. The dark and light I-V characteristics of the solar cell were measured using the Keithley 2400 source measurement unit (SMU) under AM1.5 intensity from a standard solar simulator. The i-a-Si:H/c-Si interface is studied using HRTEM [JEOL JEM-2100F].

The External Quantum Efficiency (EQE) measurements were performed using the standard EQE system, provided by Sciencetech, Canada. The tungsten halogen lamp is used for the monochromatic light source, while Xenon lamp is employed as a white bias light during the measurements. The EQE of the SHJ cells was measured over the spectral range of 400–1200 nm. Initially, the monochromatic light over the given spectral range was calibrated using a reference pyroelectric detector. The spot size of the light used for calibration is kept consistent for further EQE measurements of the cells, so that any ambiguity in the results could be avoided.

3. Results and discussion

To study the a-Si:H/c-Si interface, i-a-Si:H layers with 40–50 nm thickness are deposited on the c-Si substrate at various T_f. The other process parameters of i-a-Si:H layer were kept constant as mentioned in Table 1. The thickness of the i-a-Si:H film is measured using Dektek Profilometer as well as from the cross-sectional HRTEM images. The T_f is an important process parameter in HWCVD which plays a significant role in the a-Si:H film quality as well as the deposition rate. Fig. 2 shows the variation of deposition rate (r_d) as a function of T_f. It is clear that as the T_f increases from 1550 to 1750 °C the r_d increases from 3 to 8 Å/sec and then becomes almost constant at 1850 °C. The increasing dissociation rate of Silane as a function of T_f up to 1750 °C may be the reason of increased in r_d. However, a further increase in T_f results in high atomic hydrogen density in the gas phase which etches the weak Si-Si bonds and hence limits the r_d. This behaviour of r_d as a function of T_f is also reported elsewhere (Tsuji et al., 1996; Heintze et al., 1996).

The cross-sectional HRTEM images of the i-a-Si:H/c-Si interface at different T_f are shown in Fig. 3. The i-a-Si:H layer when deposited at different T_f exhibits distinctly different i-a-Si:H/c-Si interface. When the i-a-Si:H layer is deposited at T_f = 1550 °C we see a local epitaxy and crystalline growth up to 5 nm near the c-Si surface as can be seen in Fig. 3a. This is essentially due to the very low deposition rate of a-Si:H film at this T_f. The low deposition rate favors the crystalline phase in the initial growth of a-Si:H layer on the c-Si wafer (Seitz et al., 2001). The dissociated gas species have sufficient time to migrate over the c-Si surface to find the lower energy state to enable the epitaxial growth. However, as