Effects of filter gap of cluster-eliminating filter on cluster eliminating efficiency

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Abstract We have developed a cluster-eliminating filter which reduces amount of amorphous silicon nanoparticles (clusters) incorporated into a-Si:H films. We have measured film thickness dependence of a ratio of a hydrogen content associated with Si-H$_2$ bonds ($C_{SiH2}$) to that with Si-H bonds ($C_{SiH}$) as a parameter of the filter gap ($d_{gap}$). The cluster removal efficiency increases with decreasing $d_{gap}$. $C_{SiH2}$ and the ratio of $C_{SiH2}$ to $C_{SiH}$ decrease with increasing the film thickness, suggesting the amount of incorporated clusters is high near the interface between the film and the substrate.

1. Introduction
Hydrogenated amorphous silicon (a-Si:H) is most widely employed as a top cell material of thin film Si tandem solar cells [1-9]. The light-induced degradation of a-Si:H limits the efficiency of the tandem solar cells, because light exposure initially reduces the efficiency owing to the degradation [10-20]. For a-Si:H film deposition, SiH$_3$, high order silane (HOS) radicals in a size range below 0.5 nm, and amorphous silicon nanoparticles (clusters) in a size range between 0.5 nm and 10 nm are generated in silane discharge plasmas and they form films [21, 22]. SiH$_3$ radicals are the main deposition precursor for high quality films. HOS related radicals and clusters are minor deposition precursors and are incorporated into films during the deposition and may degrade film qualities. The degradation tends to be slightly reduced using H$_2$ dilution and VHF discharge frequency [23-25]. Although the mechanism of the degradation is still unclear, large polymerized molecules in plasmas are an important factor of the degradation [26-28]. In our recent studies, a-Si:H films with a less volume fraction of clusters in the films have been found to show less light induced degradation. We have succeeded in depositing highly stable a-Si:H films using a multi-hollow discharge plasma chemical vapor deposition (CVD) method by which the volume fraction of clusters in films deposited in the upstream region is significantly reduced by driving clusters towards the downstream region [27-38]. Using this method, we have successfully deposited cluster-free a-Si:H films with a stabilized defect density of $4.7 \times 10^{15}$ cm$^{-3}$ at a rate of 3.0 nm/s [30]. The films show high stability against light exposure.

In this paper, the cluster-eliminating filter was installed in the upstream region of multi-hollow discharge plasma CVD reactor. This cluster-eliminating filter is developed to reduce a volume fraction ($V_f$) of amorphous silicon nanoparticles above approximately 1 nm in size incorporated into a-Si:H films. By employing the filter together with the multi-hollow discharge plasma CVD reactor, the $V_f$ value is reduced below 1/180 compared to that for the conventional device quality films [39].

Here, we report effects of the filter gap on the cluster eliminating efficiency.
2. Experiment
The cluster-eliminating filter reduces the contribution of the clusters to deposition of films using the difference between the sticking probability of the clusters and the surface reaction probability of the SiH$_3$ radicals [39]. Cluster removal in the filter takes place by collision and attachment to the surface of the filter plates, since the sticking probability of clusters above 2 nm in size to the surface is nearly 100%, whereas the surface reaction probability of SiH$_3$ is 30%. The filter was composed of two stainless-steel plates of 0.1 mm in thickness with 8 or 9 slits of 1 mm in width. The slits of one plate were covered by the other plate as shown in figure 1 (top view) and figure 2 (side view) and these plates were placed at a distance of below 0.5 mm, being shorter than the mean free path of SiH$_3$ and that of clusters.

These plates were placed at a filter gap distance ($d_{\text{gap}}$) of 0.2-0.5 mm. The distance from cluster-eliminating filter to one of the grounded electrode was 8 mm. The distance from substrate to cluster-eliminating filter was 2 mm. We applied this cluster-eliminating filter to deposition a-Si:H films.

For deposition experiments, a-Si:H films were deposited by a multi-hollow discharge plasma CVD method as shown in Figure 3. For the method, clusters, which were generated in the discharge region, were driven toward the downstream region by gas flow, because the gas flow velocity in the discharge region was much faster than the diffusion velocity of clusters. Therefore, cluster-free a-Si:H films were deposited on a n-type c-Si substrate of 20x20 mm$^2$ in the upstream region. Gas of SiH$_4$ was supplied at a flow rate of 5 sccm. The total pressure was 0.1 Torr. Discharge frequency and power were 60 MHz and 40 W. Under these condition, a-Si:H films with 100-500nm thickness were deposited at $T_s$= 180°C. The hydrogen content in films was determined by Fourier-transform infrared spectroscopy (FT-IR; JASCO FT-IR6200).
3. Results and discussion

The gap between two plates (d_{gap}) is an important parameter of the filter. d_{gap} relates to the transmittance of clusters. First, we studied dependence of deposition rate on d_{gap} as shown in Figure 4. The deposition rate decreases with decreasing d_{gap}. The decrease of the deposition rate indicates that the filter transmittance of SiH\textsubscript{3} decreases. To optimize the filter structure, we have measured film thickness dependence of a hydrogen content associated with Si-H\textsubscript{2} bonds (C_{SiH2}) and a ratio of C_{SiH2} to that with Si-H bonds (C_{SiH}) as a parameter of d_{gap} as shown in figures 5 and 6, respectively. For d_{gap}= 0.5 and 0.3 mm, the ratio considerably decreases with increasing the film thickness, whereas the ratio gradually decrease with increasing the thickness for d_{gap}= 0.2 mm. The decrease of the ratio indicates that large amount of Si-H\textsubscript{2} bonds exists on the surface of the films and/or Si-H\textsubscript{2} bonds generates during the initial deposition phase. Previously, we have found that incorporation of clusters in the initial deposition phase is much higher than that in the steady state [40]. C_{SiH2} in clusters is much higher than that in bulk a-Si:H films. These results indicate that the cluster removal efficiency increases with decreasing d_{gap}.
4. Conclusions
We have applied the cluster-eliminating filter to deposit a-Si:H films. The cluster removal efficiency increases with decreasing d_gap. The incorporation of clusters in the initial deposition phase is much higher than that in the steady state.

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