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# Formation mechanism of incubation layers in the initial stage of microcrystalline silicon growth by PECVD*

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The incubation layers in microcrystalline silicon films ($\mu$c-Si:H) are studied in detail. The incubation layers in $\mu$c-Si:H films are investigated by bifacial Raman spectra, and the results indicate that either decreasing silane concentration (SC) or increasing plasma power can reduce the thickness of incubation layer. The analysis of the in-situ diagnosis by plasma optical emission spectrum (OES) shows that the emission intensities of the SiH*(412 nm) and $H_\alpha$ (656 nm) lines are time-dependent, thus SiH*/$H_\alpha$ ratio is of temporal evolution. The variation of SiH*/$H_\alpha$ ratio can indicate the variation in relative concentration of precursor and atomic hydrogen in the plasma. And the atomic hydrogen plays a crucial role in the formation of $\mu$c-Si:H; thus, with the plasma excited, the temporal-evolution SiH*/$H_\alpha$ ratio has a great influence on the formation of an incubation layer in the initial growth stage. The fact that decreasing the SC or increasing the plasma power can decrease the SiH*/$H_\alpha$ ratio is used to explain why the thickness of incubation layer can reduce with decreasing the SC or increasing the plasma power.

**Keywords:** microcrystalline silicon, incubation layer, bifacial Raman measurement, optical emission spectrum (OES)

**PACC:** 8630J，5270，7830

## 1. Introduction

Recently, hydrogenated microcrystalline silicon ($\mu$c-Si:H) thin films and solar cells have attracted more and more attention because of their potential for low-cost production.[1−10] Generally, the best conversion efficiency of $\mu$c-Si:H solar cell is achieved with an intrinsic layer deposited near the $\mu$c-Si:H/a-Si:H transition.[1−3] Such a $\mu$c-Si:H material is strongly dependent on the substrate and deposition condition, and its microstructure varies along the growth direction: an amorphous incubation layer regularly forms in the initial growth stage of layer, until fully microcrystalline growth sets in.[3−6] Besides the structural composition, other properties of the material such as electron transport, hydrogen content and defect density may be dependent on the thickness of incubation layer. Especially the presence of incubation layer at p/i interface of a p–i–n solar cell is believed to be harmful to the device performance.[4] For example, the carrier (electron) collection is disrupted and the transport property is even more complicated. Hence, how to reduce the thickness of incubation layer becomes a very important issue to improve the device performance. For this purpose, a seed-layer technique,[4−6] also called a two-step method,[7] is generally adopted, where an ultra-thin $\mu$c-Si:H seed layer grows on the substrate first at a very low silane concentration (SC), and then at a higher SC.

In this study, plasma-enhanced chemical vapour deposition (PECVD) is used for the preparation of high-quality $\mu$c-Si:H films and solar cells at a high

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pressure. The effect of deposition condition on the thickness of incubation layer is investigated by bifacial Raman measurement.[3] The OES measurement is carried out to study the physical mechanism of incubation layer. The incubation layer in single-junction $\mu$c-Si:H solar cell and the influence of the two-step method on incubation layer thickness are also studied.

## 2. Experimental details

The intrinsic silicon thin films were prepared in $SiH_4$ and $H_2$ mixture by radio-frequency plasma-enhanced chemical vapour deposition (RF-PECVD) at high pressures and high powers.[8] The background pressure of the deposition system was below $2.7 \times 10^{-4}$ Pa.

The $\mu$c-Si:H films and single-junction solar cells were deposited on 7059 glass and on $SnO_2$/ZnO coated glass, respectively. Raman scattering measurements were carried out with the excitation wavelength 632.8 nm of a He-Ne laser. Bifacial Raman measurement,[3] which combined the measurement from film-side with that from glass-side of the sample, was used to evaluate the last growth and the initial growth of the sample.

The OES measurement was performed through a quartz window to diagnose the plasma characteristic during the deposition. The interesting lines are $H_\alpha$ (656 nm) and SiH* (412 nm), which has been reported to be a good measure of atomic hydrogen and precursors $SiH_x$ ($x = 1 - 3$), respectively.[9−10]

## 3. Results

### 3.1. Influences of SC and plasma power on incubation layer

Figure 1(a) shows bifacial Raman spectra measured on a $\mu$c-Si:H intrinsic layer deposited at SC = 1.5%. The layer in the beginning growth stage is fully amorphous (as seen in the glass-side spectrum), while the top layer of the sample is partly crystalline (as seen in the film-side spectrum). This well indicates the presence of incubation layer during the initial deposition of this sample.

When the SC decreases to 1.2%, there appear obvious c-Si peaks in the bifacial Raman spectra as shown in Fig.1(b), and the crystallinity measured from the film-side spectrum is higher than that from the glass-side spectrum. This demonstrates that the incubation layer still exists during the initial deposition at SC = 1.2%. However, the crystallinity of sample deposited at SC = 1.2%, obtained from either the film-side spectrum or the glass-side spectrum, is higher than that at SC = 1.5%. Therefore, these above-mentioned results demonstrate that decreasing the SC is an effective way to reduce the thickness of the incubation layer.

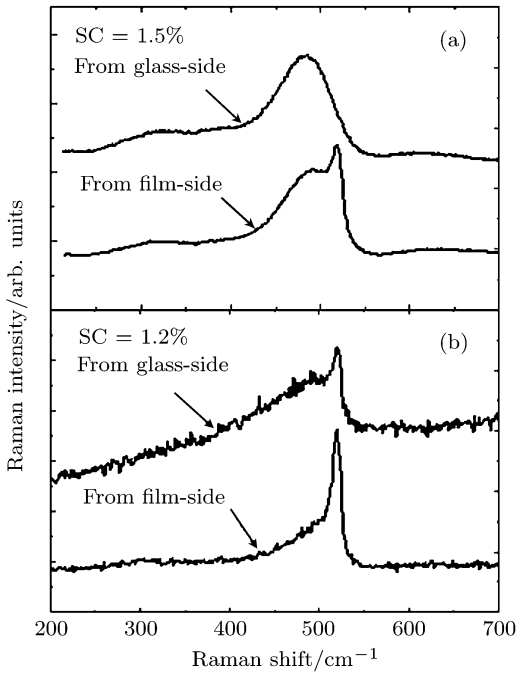



**Fig.1.** Bifacial Raman spectra of samples deposited at (a) SC = 1.5% and (b) SC = 1.2%.

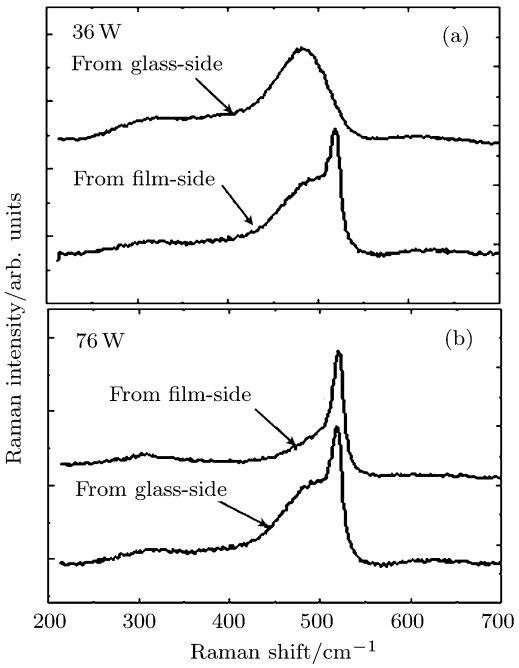



**Fig.2.** Bifacial Raman spectra of samples deposited at (a) 36 W and (b) 76 W.

Bifacial Raman spectra of samples deposited at plasma powers of 36 W and 76 W are shown in Fig.2. The spectra show that there exist also incubation layers in these films. As shown in this figure, the crystallinity of sample deposited at 76 W, obtained from either the film-side spectrum or the glass-side spectrum, is higher than that at 36 W, which indicates that increasing the plasma power is another effective way to reduce the thickness of incubation layer.

## 3.2. Temporal evolution OES and incubation layer

Why does the incubation layer exist during the initial deposition of $\mu$c-Si:H? What is the intrinsic reason that decreasing the SC and increasing the plasma power can reduce the thickness of incubation layer? Additionally, since increasing the plasma power and decreasing the SC can have a similar influence on the incubation layer, these two methods must have some common characteristic. Therefore, we carry out OES measurement to explore the common characteristic in the process of either increasing the plasma power or decreasing the SC, which is probably related to the physical mechanism responsible for the variation in thickness of incubation layer in the process.

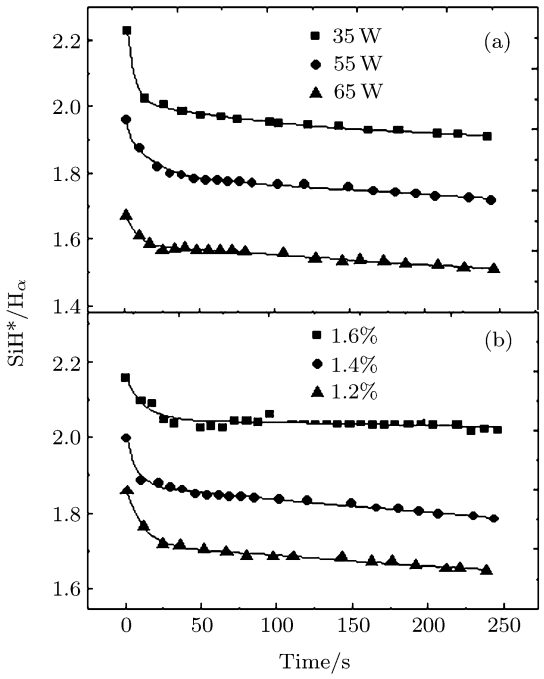



**Fig.3.** Temporal evolutions of SiH*/$H_\alpha$ ratio for (a) power series and (b) SC series.

The temporal evolutions of SiH/$H_\alpha$* ratio for power series and SC series are respectively shown in Fig.3, in which the solid symbols are for experimental data and the lines are for fitting curves by using a double-exponential function. From Fig.3 it can be seen that OES intensity is time-dependent. As soon as the plasma appears, a relatively high SiH*/$H_\alpha$ ratio can be observed. And then this ratio drops off quickly in the first 50 s, which implies that the relative content of atomic hydrogen in the plasma becomes higher. Subsequently the SiH*/$H_\alpha$ ratio drops off slowly and tends to be saturated. Additionally, either increasing the plasma power or decreasing the SC can cause the curves to shift towards lower values.

In practice, the temporal evolution of SiH/$H_\alpha$* ratio can be used to explain the presence of incubation layer. The influence of increasing plasma power or decreasing SC on the incubation layer also can be illustrated by OES results. Detailed discussion will be carried out in the next section.

## 3.3. Effect of two-step method on incubation layer

In solar cells the carriers are transported along the growth direction, so the presence of incubation layer will disrupt the carrier collection. In order to reduce the thickness of the incubation layer and eliminate its effect on cell performance, a novel two-step growth method for i-layer has been proposed, where an ultrathin $\mu$c-Si:H layer initially growing at a low SC can serve as a seed layer to facilitate an epitaxial-like growth of high-crystallinity $\mu$c-Si:H under the condition of higher values of SC.

In this study sample 1 was deposited at a constant SC = 2%, while sample 2 grew by using the two-step method for i-layer, or rather, sample 2 was deposited at SC = 1% for ten minutes, and then at SC=2% for fifty minutes (see Table 1).

**Table 1.** Deposition conditions of i-layers of solar cells prepared by using the two-step method.

| Sample No | Intrinsic-layer | |
|---|---|---|
| | Silane concentration | Time/min |
| 1 | 2% | 60 |
| 2 | 1% | 10 |
| | 2% | 50 |

Bifacial Raman measurements of the above samples, which were carried out from p-layer side and n-layer side respectively, are shown in Fig.4. It can be seen that the crystallinity of the sample deposited at

a constant SC is much less than that deposited by using the two-step method. This demonstrates that the two-step method could effectively reduce the incubation layer at the p/i interface.

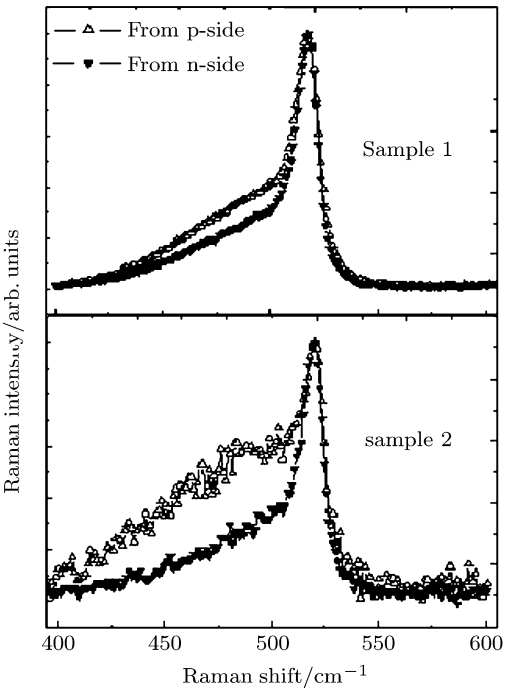



**Fig.4.** Bifacial Raman spectra of samples.

## 4. Discussion

Generally, the SiH*/$H_\alpha$ ratio can be used to indicate the relative contents of precursors and atomic hydrogen in the plasma, or rather, a high SiH*/$H_\alpha$ ratio implies a low hydrogen content, and a low SiH*/$H_\alpha$ means a high hydrogen content. For the deposition of $\mu$c-Si:H films by using PECVD, sufficient atomic hydrogen density per monolayer is crucial to the nucleation and crystallinity. In the initial stage after the plasma appears, a high SiH*/$H_\alpha$ ratio causes the initial layer to tend towards amorphization. Although the SiH*/$H_\alpha$ ratio drops off quickly and the thickness deposited during this period is very thin, it still does harm to nucleation and crystallinity of a successive film since the former deposited layer simultaneously serves as a substrate for a successively deposited film. Consequently, the incubation layer grows gradually until a fully crystallized film is achieved.

Either decreasing the SC or increasing the plasma power can cause the SiH*/$H_\alpha$ ratio to decrease, which implies an increase in atomic hydrogen density in the plasma. The SiH*/$H_\alpha$ ratio is still time-dependent during deposition at a lower SC or higher plasma power, but this ratio greatly decreases and it is even less than the saturated value obtained at a higher SC or lower plasma power. Thus, when deposition is carried out at a lower SC or higher plasma power, the amorphized tendency of the initially deposited thin layer, which is formed during the short period of the initial stage where the SiH*/$H_\alpha$ ratio drops off quickly, is inhibited. And even a microcrystalline thin layer, which serves as the nuclei for a successively deposited layer, is formed directly on the glass substrate because of high density of atomic hydrogen in the plasma. As a result, the thickness of incubation layer is much reduced.

Although the nucleation and crystallinity are not only related to phase reaction but also influenced by surface reaction on the growth surface and properties of substrate, the above OES results at least can be used to partly explore the mechanism for the formation of incubation layer from an angle of plasma phase reaction, and also give the reason why decreasing SC or increasing plasma power can reduce the thickness of incubation layer.

When the two-step method is used to deposit intrinsic layer in p–i–n solar cells, the SC is very low for the first layer, which results in lower SiH*/$H_\alpha$ in the plasma and the quick nucleation. The highly crystallined first-layer can act as a seed layer for the successive layer. Thereby the thickness of incubation layer is reduced, and the crystallinity is improved.

## 5. Conclusions

We have investigated the influence of deposition condition of i-layer on the incubation layer in detail. Temporal evolution of OES is also used to study the physical mechanism of incubation layer. The following conclusions can be drawn from our experimental results.

(1) Either decreasing silane concentration (SC) or increasing plasma power can reduce the thickness of incubation layer.

(2) Temporal evolution of OES shows that a high SiH*/$H_\alpha$ ratio makes a great contribution to the formation of an incubation layer in the initial growth stage. Either decreasing SC or increasing plasma power can reduce the SiH*/$H_\alpha$ ratio, thus the thickness of incubation layer decreases.

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