Analysis of heating effect on the process of high deposition rate microcrystalline silicon*

Zhang Xiao-Dan(张晓丹)†, Zhang He(张 鹤), Wei Chang-Chun(魏长春), Sun Jian(孙 建), Hou Guo-Fu(侯国付), Xiong Shao-Zhen(熊绍珍), Geng Xin-Hua(耿新华), and Zhao Ying(赵 颖)

Institute of Photo-electronics Thin Film Devices and Technique of Nankai University, Key Laboratory of Photo-electronics Thin Film Devices and Technique of Tianjin, Key Laboratory of Photo-electronic Information Science and Technology (Nankai University), Ministry of Education, Tianjin 300071, *China*

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A possible heating effect on the process of high deposition rate microcrystalline silicon has been studied. It includes the discharge time-accumulating heating effect, discharge power, inter-electrode distance, and total gas flow rate induced heating effect. It is found that the heating effects mentioned above are in some ways quite similar to and in other ways very different from each other. However, all of them will directly or indirectly cause the increase of the substrate surface temperature during the process of depositing microcrystalline silicon thin films, which will affect the properties of the materials with increasing time. This phenomenon is very serious for the high deposition rate of microcrystalline silicon thin films because of the high input power and the relatively small inter-electrode distance needed. Through analysis of the heating effects occurring in the process of depositing microcrystalline silicon, it is proposed that the discharge power and the heating temperature should be as low as possible, and the total gas flow rate and the inter-electrode distance should be suitable so that device-grade high quality deposition rate microcrystalline silicon thin films can be fabricated.

Keywords: high pressure and high power, microcrystalline silicon, heating effect

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1. Introduction

In order to promote the industrialization of amorphous silicon/microcrystalline silicon (micromorph) tandem solar cells, microcrystalline silicon thin films with high growth rates have received much attention.[1−5]. In current practice, the high pressure and high power (hphP) combined with very high frequency (VHF) technique is considered the most effective method to realise the high deposition rate of microcrystalline silicon thin films.[6,7] However, to obtain device-grade quality high deposition rate microcrystalline silicon thin film, a relatively small inter-electrode distance is required for the hphP method because of the limitation of the discharge principle for the plasma enhanced chemical vapour deposition (PECVD) technique.[8]

The above mentioned conditions, high power, high pressure and small inter-electrode distance, will bring a new problem that the high powers coupled into the plasma start to substantially heat up the substrate. This problem was speculated on by Roschek *et al.*[9] Niikura *et al.* have reported that under certain high power conditions the substrate holder temperature could increase by more than 100 K during the film deposition.[10] Recently, van de Donker *et al.* also found that the performance of deposited solar cells decreased whenever the plasma induced heating caused a drift outside the ideal temperature window, of around 475 K ($\sim$ 200) °C.[11]

A suitable value for the substrate temperature, as one of the important deposition parameters for the deposition of microcrystalline silicon thin films, needs to be chosen. A relatively high substrate temperature will induce (220) preferential orientation and proper crystalline volume fraction (X_c), which are of benefit for the increase of the short circuit current density of solar cells.[12] However, a much higher substrate tem-

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†Corresponding author. E-mail: xdzhang@nankai.edu.cn

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perature will cause the incorporation of oxygen into the microcrystalline silicon thin films, which will significantly affect the long wavelength response of solar cells and thus result in the decrease of the short circuit current density. In the past, Nasuno *et al.*[13] proved that high conversion efficiency microcrystalline silicon solar cells could also be fabricated under a low substrate temperature (140 °C, even though a high oxygen content was found in the thin films. So, from the viewpoint of application, a relatively lower substrate temperature should be used for the deposition of microcrystalline silicon thin films. This is very important for p/i/n type micromorph tandem solar cells because the substrate temperature of the amorphous silicon top solar cells is usually not very high.

From the above mentioned, it can be concluded that the variation of substrate temperature during deposition will certainly lead to the variation of structural and electrical properties of microcrystalline silicon thin films. In order to control it more precisely and effectively, more detailed work is needed to know about the variation of substrate temperature during the deposition process.

2. Experimental details

All samples were prepared in the multi-chamber PECVD system with a powered electrode area of 225 cm^2. The grounded electrode is a substrate holder suitable for 100 cm^2 substrates. The details for the system setup can be found in Ref. [14]. An outer heating system was used in this equipment. The heating temperature in this system was controlled by a thermal couple using PID mode. The substrate temperature was calibrated using 'surface temperature indicating strips' made by TMC Company in UK.

All films were deposited on Eagle 2000 glass etched by 5% HF acid. The structural properties of the samples were characterised with Raman spectroscopy (LabRAM UV, equipped with 488 nm and 632.8 nm wavelength lasers). Excitation was carried out using 488 nm and 632.8 nm wavelength laser lights with a different expected probing depth. 488f and 632.8f denote the measurements from the film side and 488b and 632.8b from the glass side using 448 nm and 632.8 nm wavelength lasers, respectively.

3. Results and discussion

From Table 1, it can be seen that the higher heating temperature (T_h) and the high power density caused a more serious heating effect. The substrate surface temperature (T_s) of samples A and B, which were prepared at different discharge times (with some other conditions), increased by about 10 K when the discharging time increased from 5 to 35 minutes. By comparison, however, the substrate surface temperature difference of samples C and D deposited using a higher heating temperature reached about 35 K. So, the discharge time-accumulating heating effect was more serious under the higher heating temperature condition. In addition, samples E and F were prepared at a lower discharge power and higher heating temperature, their substrate surface temperature difference was limited to about 10 K. So it can be concluded that substrate surface temperature will increase during the deposition process on the one hand, and higher heating temperature and higher power density will cause a more serious heating effect on the other hand. The heating temperature applied for the microcrystalline silicon thin films with high deposition rate usually using high power and high pressure should be as low as possible in order to weaken the substrate surface temperature drift effect.

Table 1. Discharge time-accumulating and discharge power induced heating effect.

sample	T_h	time and condition	power density	T_s
sample A	215 °C	5 min mixing +5 min discharge	0.49 W/cm^2	185 °C
sample B	215 °C	5 min mixing +35 min discharge	0.49 W/cm^2	195 °C
sample C	245 °C	5 min mixing +5 min discharge	0.49 W/cm^2	210 °C
sample D	245 °C	5 min mixing +35 min discharge	0.49 W/cm^2	245 °C
sample E	245 °C	5 min mixing +5 min discharge	0.31 W/cm^2	200 °C
sample F	245 °C	5 min mixing +35 min discharge	0.31 W/cm^2	210 °C

These heating effects, at the same time, of course caused variation of the structural and electrical properties and the deposition rate during the discharge time. Figure 1 shows Raman results for samples A and B measured by 488 nm and 632.8 nm lasers from the film side and the glass side, respectively. Because different wavelength lasers detect different depths of thin films, these results actually indirectly reflect the structural change along the growth direction. Sample A showed almost the same shape curves for the different laser wavelengths which proved that sample A was typical amorphous silicon thin film. However, the structure of sample B gradually changed with its thickness which is evidence of the structure of the microcrystalline silicon thin film non-uniformity along the growth direction. Besides, its amorphous incubation layer was so thick to result in a sharp structure change, which is bad for the fabrication of high performance solar cells.[15] Here, it should also be noted that the crystalline content of sample B on the film surface side is higher, and this also could not exclude the effect of increased surface substrate temperature. As we know, a high surface temperature is able to increase the crystalline content of microcrystalline silicon thin films.[16] The relatively higher substrate temperature will give the thin film (220) preferential orientation and reasonable higher crystalline volume fraction (X_c), which is of benefit for the increase of the short circuit current density of solar cells.[17] However, a much higher heating temperature will weaken X_c. The results of sample D and sample B are shown in Fig. 2. Here it is proved that sample D ($X_c = 35\%$) prepared at higher substrate surface temperature compared with sample B ($X_c = 46\%$) indicates the relatively lower crystalline content, which means that it is disadvantageous for crystalline formation under a much higher substrate surface temperature.

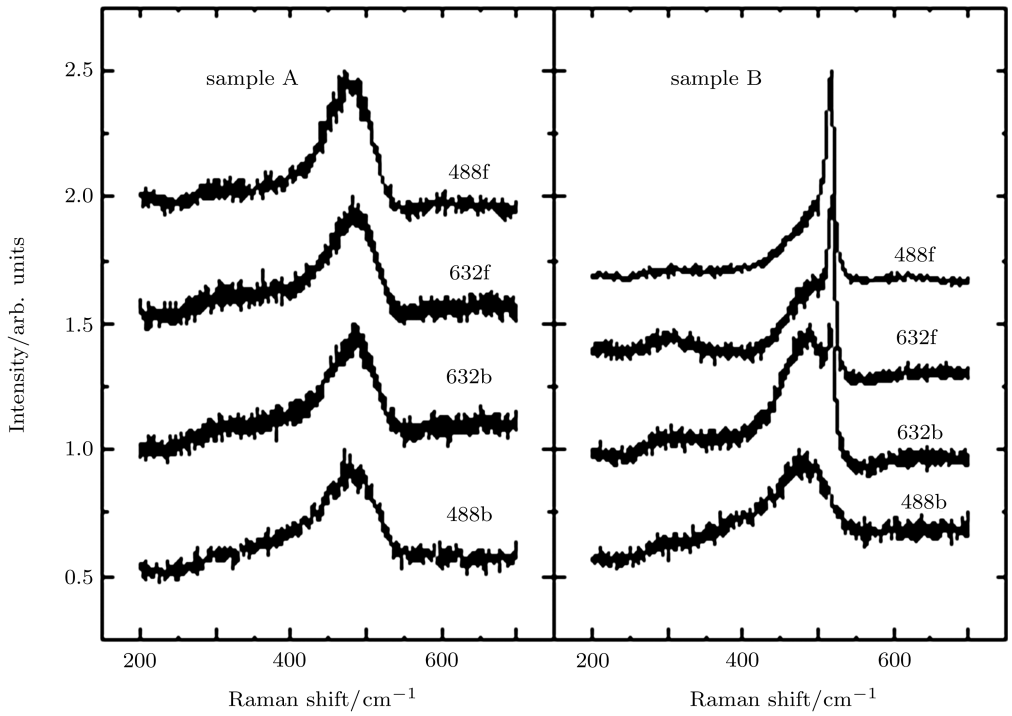


Fig. 1. Raman spectra of samples A and B measured by 488 nm and 632.8 nm lasers from the film side and the glass side, respectively.

The discharge power as one of the deposition parameters is also very important for the modification of crystalline content and deposition rate. Figure 3 shows Raman results of samples F and D prepared at different input powers. Even though the structure of the thin film sharply changed from amorphous to relatively high crystalline volume fraction (X_c), it is evident that the variation trend of sample D was very different from sample F. The X_c on the surface film side of sample F measured from the film side with the 488 nm laser was very high which means that the surface substrate temperature of the thin film at the end

of the deposition process around 200 °C is suitable for obtaining the relatively higher crystalline content. However, the X_c of sample D was lower than sample F because the high input power caused the surface substrate temperature to increase to 245 °C during the 30 min discharge deposition process. A high surface temperature combined with high power results in low X_c. In addition, the results of samples F and D measured by the 632 nm laser from the film side show the relatively higher X_c of sample D than sample F, which proves that relatively high input power will increase the X_c of thin film under a suitable surface substrate temperature.

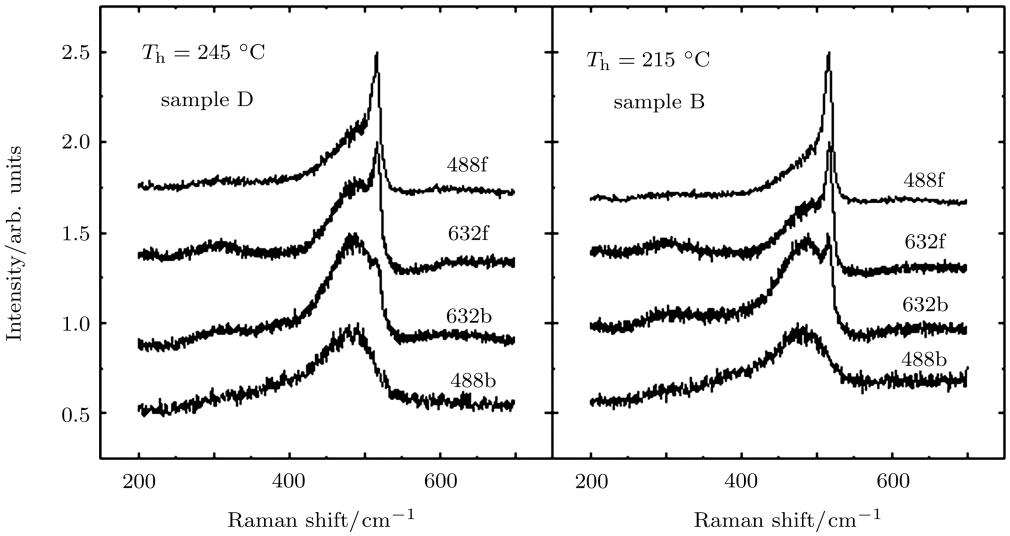


Fig. 2. Raman spectra of samples D and B measured by 488 nm and 632.8 nm lasers from the film side and the glass side, respectively.

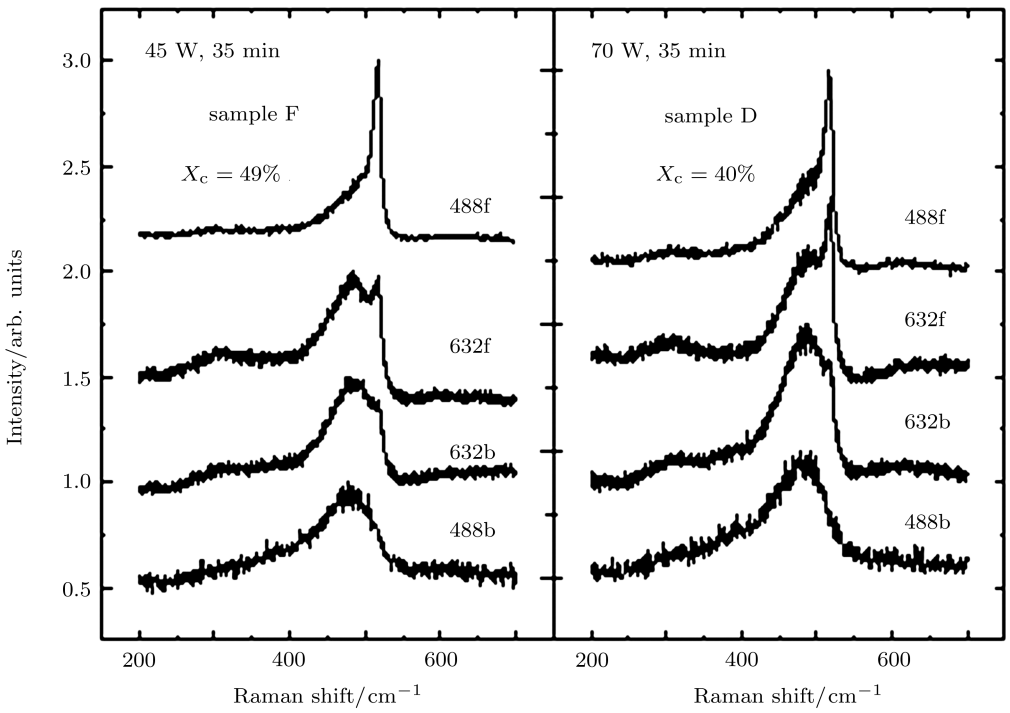


Fig. 3. Raman spectra of samples F and D measured by 488 nm and 632.8 nm lasers from the film side and the glass side, respectively.

The inter-electrode distance is also very important for the fabrication of high deposition rate microcrystalline silicon films. There is a possible heating effect because a temperature change induced by varying only the inter-electrode distance was also observed. As shown in Table 2, a quite serious heating effect can also be caused by a small inter-electrode distance, which means the amount of the resource gas which takes part in these complex reactions in plasma is small, and then the particles (e.g. radicals and ions etc.) produced by electron–molecule collisions take a shorter time to reach the substrate surface than a large inter-electrode distance and they are expected to experience fewer collisions which may reduce their energy. At the same time, a certain input power will offer a larger electric field, and give particles with more energy obtained in the plasma between a smaller inter-electrode distance. In this way, the particles arriving at the substrate growth surface actually possess more energy, which may heat up the substrate by their collisions with the substrate surface. Figure 4 indicates Raman results of samples G and H using 448 nm and 632.8 nm wavelength lasers measured from the film side and the glass side, respectively. It is evident that a relatively small inter-electrode distance is of great benefit for the fabrication of uniform films along the growth direction if other deposition parameters are kept unchanged.

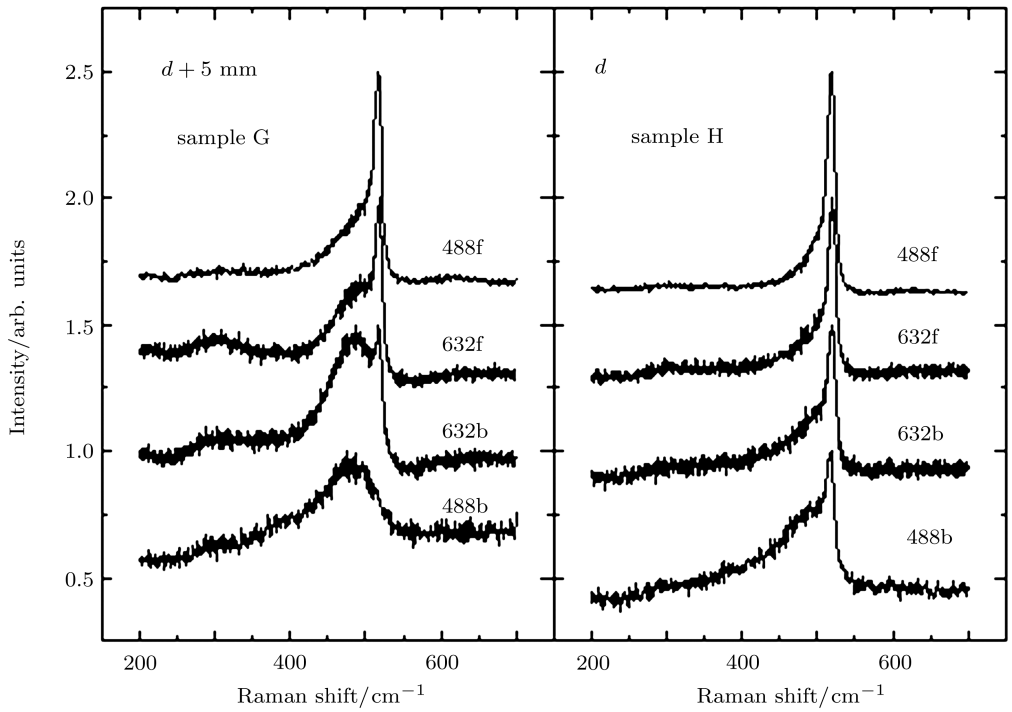


Fig. 4. Raman spectra of samples G and H measured by 488 nm and 632.8 nm lasers from the film side and the glass side, respectively.

Table 2. Inter-electrode distance induced heating effect.

sample	T_h	time and condition	inter-electrode distance	T_s
sample G	215 °C	5 min mixing +35 min discharge	d+5 mm	195 °C
sample H	215 °C	5 min mixing +35 min discharge	d	207 °C

Table 3 demonstrates that the total gas flow rate also has a big effect on the heating substrate holder. Furthermore, a low total flow rate will cause the enhancement of the substrate surface temperature, and this may also be one reason why high deposition rate microcrystalline silicon thin films based on the hphP technique usually need a relatively high total gas flow rate.

Table 3. Total flow rate induced heating effect.

sample	T_h	time and condition	total gas flow rate	T_s
sample M	230 °C	5 min mixing +15 min discharge	high total flow rate	180 °C
sample N	230 °C	5 min mixing +15 min discharge	low total flow rate	210 °C

4. Conclusions

Possible heating effects on the deposition process of high rate microcrystalline silicon have been studied. They include discharge time-accumulating, discharge power, inter-electrode distance, and total gas flow rate-induced heating effects. It is found that all of them directly or indirectly caused an increase of substrate surface temperature during the deposition process of microcrystalline silicon thin film, and affected the properties of materials with increasing time. This phenomenon is serious for the high rate deposition of microcrystalline silicon thin films because a relatively high power and small inter-electrode distance are usually needed. Through analysis of the heating effect above occurring in the deposition process for microcrystalline silicon, it is proposed that discharge power and heating temperature should be as low as possible to fabricate high deposition rate microcrystalline silicon thin film.

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