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Optical emission spectroscopy as a process control tool during plasma enhanced chemical vapor deposition of microcrystalline silicon thin films

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ABSTRACT

The decisive criterion associated with the species emission intensity ratio (Hα/SiH*) which characterizes the crystallinity of microcrystalline silicon (μc-Si) film was found to display an unstable behavior resulting from species concentration variation during μc-Si film growth with optical emission spectroscopy (OES) tool. In this study, a real-time process control system i.e. closed-loop system was developed. It aims to control the species intensity ratio with OES device in a very high frequency (VHF) plasma enhanced chemical vapor deposition reactor, via modulating the VHF power and silane dilution to improve μc-Si film growth for high efficiency a-Si/μc-Si tandem solar cell. The experiment results show that the closed-loop system stabilized the Hα/SiH* intensity ratio within a variation of 5% during the μc-Si film deposition process. Higher growth rate of μc-Si film with the same crystallinity was obtained in the closed loop system which consumed less power and SiH4 gas than in the open loop system, i.e. without process control.

1. Introduction

The significant advantages of using microcrystalline silicon (μc-Si) thin film material in micromorph, i.e. tandem thin film solar cell are available for developing high efficiency silicon thin film solar cell [1–4]. To absorb the infrared part of the solar spectrum efficiently, a μc-Si layer needs to be at least about 1–2 μm thick. Therefore, the production time is limited by the deposition rate of μc-Si thin film resulting in the bottleneck for developing high efficiency silicon thin film solar cell.

Researchers have studied in μc-Si thin film structure evolutions with the hydrogen dilution ratios [5] and Raman scattering in terms of different process parameter (e. g. the silane flow rate, the hydrogen flow rate, the total gas pressure, etc.) [6]. In recent years, the more investigations on the μc-silicon film's crystallinity and the deposition rate with optical emission spectroscopy (OES) has been researched for μc-Si thin film deposition [7–13]. Moreover, P. Torres et al. [14] have established the relationship between deposition rate and silicon film's crystallinity in open-loop system i.e. without real-time process control. It has also been demonstrated that the decisive criterion for silicon thin film growth is associated with the OES intensity ratio which characterizes the formation of an amorphous silicon (a-Si) or μc-Si thin film.

Although OES intensity ratio correlates to silicon film's crystallinity, Van den Donker et al. [15] found that the species SiH* and H_β emission intensity drift significantly with deposition time due to powder formation, transient SiH_4 depletion and plasma heating. That is, the reactive species concentration may not be constant throughout the deposition process. D. Ni et al. [16] demonstrated a method for real-time control of gas flow rate for thin film composition using OES in terms of robust operation. In this study, a real-time process control system i.e. closed-loop system was developed to stabilize the emission intensities of plasma species by modulating plasma power and SiH_4 gas flow rate during the whole process time for the improvement of microcrystalline silicon thin film deposition.

2. Experimental methods

A real-time process control system was developed in this study to monitor the species concentrations by deriving from their optical emissions in plasma deposition process. The system includes very high frequency (VHF) plasma enhanced chemical vapor deposition (PECVD), OES spectrometer and control unit. The schematic diagram of the experimental setup is shown in Fig. 1. The VHF PECVD equipment consists of a stainless process chamber and an aluminum load lock chamber. Hydrogen (H_2) and silane (SiH_4) entered the process chamber through a showerhead for μc-Si thin film deposition. A 40.68 MHz VHF power generator (AE, Cesar 4010) with a matching

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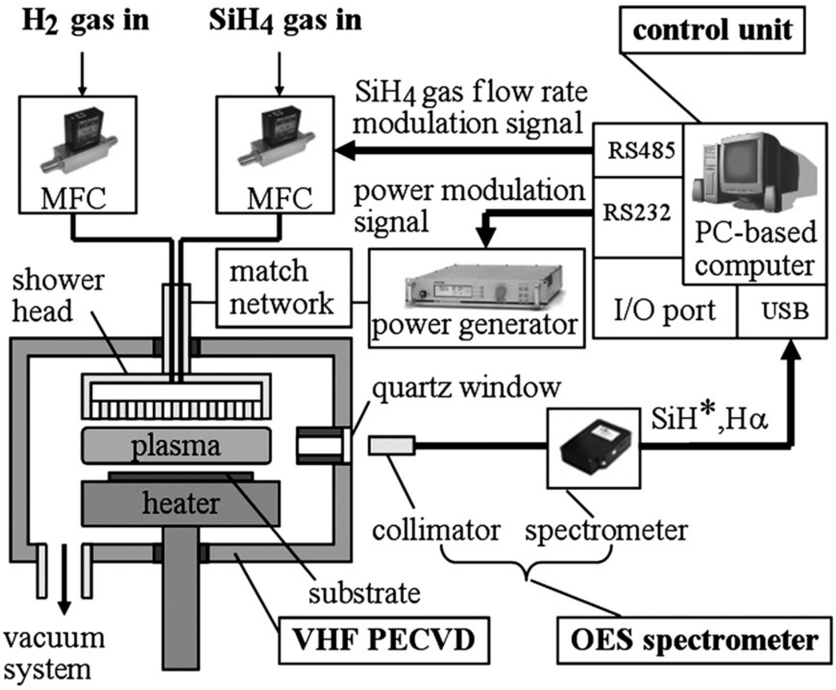

Fig. 1. Schematic diagram of the experimental setup.

network is capacitively coupled to the showerhead to generate the plasma

The control unit consists of hardware of PC-Based computer and control program. The main function of PC-Based computer is to provide a platform to run the control program and I/O ports. The control unit acquires the species spectral intensity signals (e.g. Hα, SiH*) measured by OES spectrometer (Ocean, HR-4000) and sends the control signals to VHF power supply and mass flow controller to modulate the VHF power and SiH_4 flow rate, respectively. While the deposition process starts after the plasma ignition, the control unit stabilizes the species intensity of SiH* and Hα arriving at the desired values, respectively, via real time modulation of the process parameter (e.g. VHF power and SiH_4 gas flow rate). Fig. 2 shows the control diagram of the closed loop system. The step-control algorithm is of the following form:

$$U(t) = f_{SiH4}(t) = U(t) + M_{SiH4}(t) \tag{1}$$

$$V(t) = f_{power}(t) = V(t) + M_{power}(t) \tag{2}$$

$$\begin{aligned} M_{SiH4}(t) = {} & 0, -\varepsilon_{SiH*} < e_1(t) < \varepsilon_{SiH*} \\ & 1\,\text{sccm}, e_1 < -\varepsilon_{SiH*} \\ & -1\,\text{sccm}, e_1 > \varepsilon_{SiH*} \end{aligned} \tag{3}$$

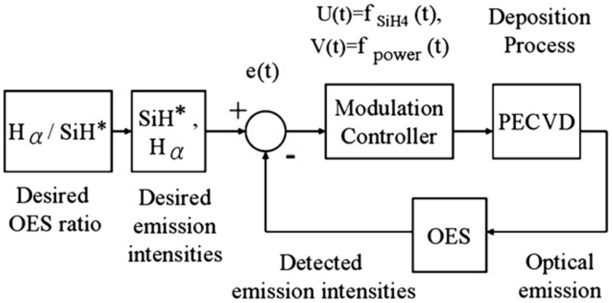

Fig. 2. A control diagram of the closed loop system.

$$\begin{aligned} M_{power}(t) = {} & 0, -\varepsilon_{H\alpha} < e_2(t) < \varepsilon_{H\alpha} \\ & 1\text{W}, e_2(t) < -\varepsilon_{H\alpha} \\ & -1\text{ W}, e_2(t) > \varepsilon_{H\alpha} \end{aligned} \tag{4}$$

where U is the controller output of SiH4 mass flow rate and V is the controller output of the VHF power, e(t) is the species intensity difference between desired value and the detected value by OES. The input of the modulation controller M(t) is defined as in Eqs. (3), (4) where ε is the tolerance of species intensity which is set at 2% of the desired species emission intensity.

The above algorithm is based on the experimental findings that the variation of power could modulate both the Hα and the SiH* intensities significantly. However only the SiH* intensity was significantly affected by the variation of SiH4 flowrate. The Hα intensity was nearly unchanged during the variation of SiH4 flowrate, primarily due to the high H2/SiH4 flow ratio in this study. Since it is very important in the

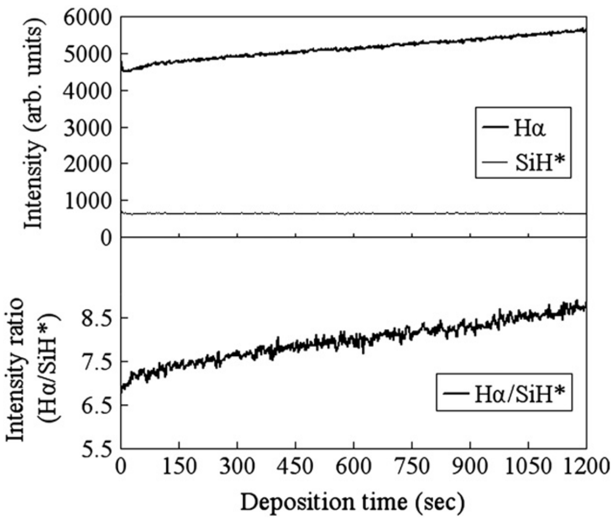

Fig. 3. The OES intensity variation during deposition of μc-Si thin film without control, i.e. open-loop system.