Characterization of Multi-Hollow Cathode Discharge and Its Application of a(μc)-Si Deposition

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Abstract: High-density capacitively coupled plasma was produced with the effect of the multi-hollow cathode. In order to obtain the stable and uniform large area plasma, the various power supplies such as direct current (DC) power, and radio frequency (27.12 MHz) power were utilized to investigate the I-V characteristics, hollow cathode discharge effect, the spatial and temporal of electron temperature and electron density as well as the discharge uniformity. In the case of applications of this multi-hollow cathode discharge, the hybrid a(μc)-Si films were then deposited. The rate of as-deposited a(μc)-Si thin films, the deficit, the chemical and crystal structure varying with the discharge parameters, likely the ratio of Si source to diluted hydrogen gas, working pressure, the deposition temperature were also explored in this work.

Introduction

Thin film silicon, especially amorphous silicon (a-Si:H), as semiconductor channel layer for the solar cell is widely adopted in purpose of reducing cost and lightening the mass production. The a-Si:H cells, however, have unstable, degradation due to a Stabler–Wronski (SW)-like effect in the environment and the relative low efficiency. The alternative of poly-Si thin film, which demonstrates a high efficiency, is expensive cost [1- 4].

Recently, hydrogenated microcrystalline silicon (μc-Si:H) prepared from silane and hydrogen mixture using plasma enhanced chemical vapor deposition (PECVD) is an attractive trial in such as thin film solar cell application. The hydrogen dilution is considered to be a source of atomic hydrogen which affects the crystalline formation [5]. In future, using the hydrogenated μc-Si:H film these problems about the unstable operation property of a-Si:H and the high running cost of poly-Si shall be solved. The hybrid μc-Si solar cell because of its high efficiency and inexpensive might be essential selection for the solar calls.

The normal chemical vapor deposition provided a low growth rate of μc-Si film. With plasma enhanced CVD, on the other hand, the growth rate was significantly increased but not the quality. Although there have been many approaches for the high rate growth and high-quality μc-Si:H film fabrication [6–8], the quality of the films deposited at high rates is still left unsatisfied in terms of photovoltaic application. A high rate growth of the μc-Si:H is usually accompanied by a great number of dangling-bond defects in the resulting film, which act as recombination centers for photo-excited carriers, resulting in a deterioration in the device performance. In previous works [6, 9], the number of dangling-bond in μc-Si:H films prepared at high deposition rate has been reduced from the very high values obtained under conventional radio-frequency (RF) PECVD low pressure conditions to the lower values obtained by the use of VHF and high pressure conditions with optimization of SiH₄-depletion [10]. This is attributed to a reduction in Te of the plasma and the optimized SiH₄-depletion. The hollow cathode discharge (HC), especially the micro-hollow cathode discharge (MHC) therefore, can remarkably reduce the Te and improve the density of plasma due to the advantage of operation at high working pressure. With a cathode having specific surface structure, which enables the production of uniformly distributed and stable high density plasma spots near the cathode surface, aiming to introduce the radical separation effect into μc-Si:H deposition at high deposition rate [11].

In this paper, we employ MHC discharge to prepare hybrid μc-Si:H film with controllable
crystallization. The SiH$_2$Cl$_2$ instead of SiH$_4$ was used as precursor for the μc-Si:H film deposition. It obtains the crystallization of μc-Si:H films arrived at 70% in the optimal conditions of MHC plasma source.

**Experiments**

The MHC discharge adopted for μc-Si:H film-growth, more specifically, was a capacitively coupled RF-PECVD reactor with micro-hollow electrode constructed the discharge system. The numerous micro-hollows arranged on the cathode surface are also as the gas injection.

The typical deposition conditions include: plasma excitation frequency of 27.12 MHz, the flow rate of SiH$_2$Cl$_2$ was varied from 20 to 70 sccm, H$_2$ gas flow rate was 300 or 700 sccm. Initially, the substrate holder temperature was set at 200 °C. Corning glass was used as substrates. And the other controllable dispersion parameters were identified.

**Results and discussion**

**Fig.1** the characteristic of I-V in MHC Ar plasma. a-the gap is 7 mm, 20 Pa; b-the gap is 18 mm, 20 Pa

The characterization of I-V in MHC discharge was measured by and a digital oscilloscope (Tektronix DPO 4104). The current and voltage across the electrodes were measured by a wide band current probe (Tektronix 6021AC), a wide band voltage probe (Tektronix P6015A). The configuration of I-V in Fig.1 illustrates that the discharge in RF MHC is a typical hollow cathode discharge, especially in the case of short gap of 7 mm where the curve is similar to the configuration generated in direct current supply. While the gap between the RF electrode and the grounded one was larger, 18mm in here, the configuration of hollow cathode discharge is still visible, but the region of uniform glow discharge was narrow. It quickly transfers into arc discharge from the positive differential impedance.

The evident uniform discharge in HMC is shown in **Fig. 2** photos for (a) Ar and (b) H$_2$, respectively. As is demonstrated that plasma is rather uniform in the whole electrode, in particular, when the plasma was generated in H$_2$ gas environment. The dense electric field at the edge of hollows caused a high illumination in **Fig. 3(c)**, which is essential for the much more active radicals generated in HMC.

**Fig. 2** The photos of HMC in a-Ar and b-H$_2$

According to the measurement of the electron temperature Te and density Ne, it results that MHC can provide a high efficient dissociation rate of species than that in parallel panel electrodes. In **Fig. 3** one can see that the Ne arrived at 1.0 ×10$^{12}$ cm$^{-3}$ in H$_2$ plasma of MHC, over two orders of magnitude higher than that in the same structural capacitively coupled plasma, whereas the Te was remained almost identical. Te was reduced with working pressure after compared **Fig. 3(a)** with (b) based on Langmuir
probe measurement. As aforementioned, a low Te is benefit for the defects control in μc-Si:H films. It means that MHC shall be prior to using for hybrid μc-Si film deposition.

Fig. 3 Te and Ne in HMC H2 plasma dependent on the RF applied power. a-150 sccm; b-200 sccm

With regard to the deposition of μc-Si film films in MHC, the discharge parameters, such as the ratio of the gas flow rate, the RF power, temperature of the substrate holder, the working pressure, diluted Ar gas flowing rate, all influenced the film structure and morphology. However, the working pressure was emphasized in this work.

Fig. 4 shows that the film structure varied with the pressures. One can see that in FTIR spectra (Fig. 4(a)) SiH_n (n=1, 2) stretching mode at 630 and 2100 cm⁻¹ are visually observed. The two sharp FTIR peaks composed of 2080 and 2100 cm⁻¹ correspond to the surface SiH₂ bonds of a nanocrystallite grain boundary and bulk SiH₂ bonds, respectively. The peak intensities, corresponding to the residual hydrogen content in the film systematically increase with decreasing working pressure, a significant change of the SiH_n configuration is observed besides the peak intensity. The film crystallization is enhanced reversely with working pressure.

Raman spectroscopic was used to evaluate the crystallization of μc–Si:H. Fig. 4(b) compares the Raman spectra of the as-deposited μc–Si:H layers at different working pressures of 230, 600 and 800 Pa, respectively. Concerning the MHC μc–Si:H layers, sample c is a pure amorphous structure (peak at 480 cm⁻¹), whereas sample b is a heterogeneous structure composed of nanocrystalline material embedded in an amorphous matrix (peaks at 480 and 513 cm⁻¹). Raman spectrum of sample a exhibits a large peak at 520 cm⁻¹ compared to little one at 480 cm⁻¹ revealing a microcrystalline structure with small amorphous component as Fig. 4 (c) the Gaussian simulation. A crystallization of 71.4% can be achieved when the μc-Si film was deposited at gas ratio of SiH₂Cl₂/H₂=3/200sccm, 80W of RF power, 200–300°C of temperature, and the working pressure of 230 Pa.

The fast deposition of highly crystallized μc–Si:H:Cl film with lower defect density is expected because the efficient termination of dangling bond by efficient supply of SiHₓCly is accelerated with the abstraction of H and Cl as HCl at the depleted growing surface at the higher working pressure in MHC. A sufficient supply of deposition precursors such as SiH₃ at the growing surface under an appropriate ion bombardment is effective for the fast deposition of highly crystallized μc-Si films as well as for the
suppression of the amorphous incubation and transition interface layers at the initial growth stage.

Fig. 5 shows the AFM surface images of as-deposited μc-Si film at various applied powers. The root mean square (RMS) of roughness was measured in 80 W applied power in Fig. 5 (a) to be 1.33 nm. The RMS was 3.39 nm in Fig. 5 (b) when the sample was deposited in 200 W. There is clearly substantial roughening induced through the high applied power. According to the results of surface morphology measurement, it can assume that the films were grown in island model, and the size of the grains will be grown along with the increase of the input power.

Conclusions
In this paper a novel plasma source HMC for the stable and uniform large area plasma was reported. The characteristics of I-V in the radio frequency (27.12 MHz) power were typical hollow cathode discharge. With HMC plasma source a high crystallization of the hybrid a(μc)-Si films were deposited. A crystallization of 71.4% μc-Si can be achieved in optimal conditions. The crystallization of as-deposited a(μc)-Si thin films was seriously dependent on the working pressure.

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References