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Deposition of microcrystalline intrinsic silicon by the Electrical Asymmetry Effect technique

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ABSTRACT

Depositing microcrystalline intrinsic silicon films is an important step for the production of thin silicon tandem junction solar cells. Due to the high cost of capital equipment, it is becoming increasingly important to improve the processing speed of thin silicon films for continued commercial viability. In this work, a combination of the excitation frequencies 13.56MHz + 27.12 MHz was used for thin silicon film deposition. According to the electrical asymmetry, the DC self bias on the RF electrode was varied by adjusting the phase between the two applied frequencies. A single junction microcrystalline cell with above 5.5% efficiency was deposited in a Gen5 PECVD process using the Electrical Asymmetry Effect (EAE). The deposition rate was higher than 0.8 nm/s. A similar increase of the deposition rate in a pure 13.56 MHz discharge led to a strong degradation of the μc-Si:H quality and the single junction cell performance fell to 4% efficiency. It was found that layers deposited using the EAE have a better uniformity compared to layers deposited in a pure 27.12 MHz discharge. In comparison to traditional RF-PECVD processes, electrically asymmetric discharges allow to achieve a regime of plasma conditions with low ion energies and high electron densities.

1. Introduction

The hydrogenated microcrystalline silicon (μc-Si:H) pin structure is an important part of a "micromorph" multi-junction (tandem) solar cell. It has a high stability and preferable band gap as a bottom component. The μc-Si:H solar cell part requires a thickness of about 1.5 μm and the deposition time of the intrinsic layer typically is about 30–60 min. Therefore a high deposition rate technique with high quality material is necessary.

There are several ways to get a high deposition rate of μc-Si:H without sacrificing of material properties. Best known are the deposition in the pressure regime > 5 mbar [1–4] and very high frequency (VHF) deposition techniques [5,6]. The promising results were mostly shown in laboratory scale reactors. The obstacles are: i) the narrower process window at the higher process pressures [7], ii) the higher non-homogeneity of the intrinsic layer thickness and the degree of crystallinity due to the standing wave effect for VHF excitation in large production reactors [8] and iii) the higher complexity of both VHF and higher pressure reactors compared to the conventional PECVD technique. Simpler and, therefore, more robust techniques to produce high quality μc-Si:H films on production size are required.

Ions gain kinetic energy when they are accelerated to the wall in the plasma sheath and only lose energy by neutral-ion collisions during this acceleration. The mean ion energy is reduced, if the ion mean free path becomes smaller than the plasma sheath thickness (by increasing pressure). Most likely that from a pressure of 6 Torr the majority of ions cannot gain an energy larger than the threshold energy for ion-bulk-atom displacement [9].

Therefore, higher pressure and VHF [10] methods provide low positive ion flux and energy due to the reduction of the electron temperature in the discharge, thus leading to a reduced ion bombardment.

Here, we focus on the deposition of single junction μc-Si:H cells by a Plasma Enhanced Chemical Vapor Deposition (PECVD) technique using the Electrical Asymmetry Effect (EAE) and the comparison of the results with conventional (13.56 MHz or 27.12 MHz) plasmas.

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2. EAE technique

In the previous investigations with a direct current bias voltage being applied on the substrate and the substrate holder, it was clearly pointed out that the application of a substrate biasing affects all the plasma properties and there is an influence on the deposited material's properties [11]. By applying a dc bias, the crystallinity of μc-Si:H is significantly changed [12] and the defect density is reduced [13]. Finally, an improvement of μc-Si cells within the high-rate regime has been achieved by using a DC bias voltage [14].

In this study, the electrical asymmetry of the discharge is controlled and a DC self bias voltage is generated via the EAE. Theoretical investigations [15] show that the EAE may allow controlling the ion bombardment during thin silicon film deposition in silane containing plasmas. Fig. 1 shows a diagram demonstrating the difference between a conventional RF and EAE reactors. In the electrically asymmetric case two discharge excitation frequencies are used (13.56 MHz and the even harmonic 27.12 MHz).

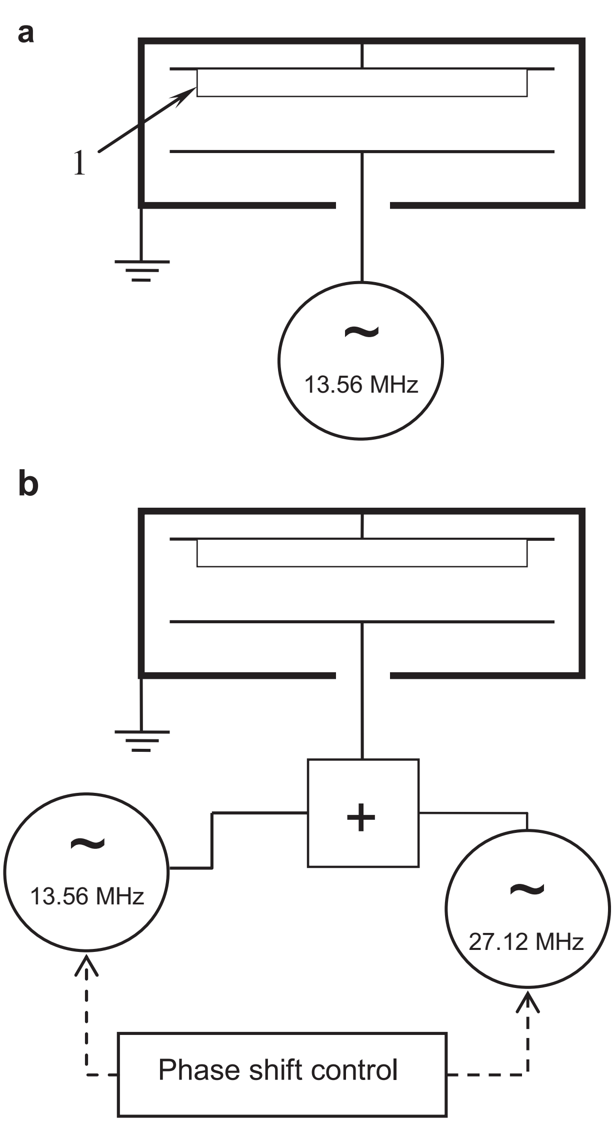

Fig. 1. Diagram of (a) A conventional RF (13.56 MHz) capacitively coupled reactor and (b) Reactor with plasma excitation by the EAE technique. 1 – is a substrate on the grounded electrode.

The group of Prof. Czarnetzki has demonstrated that the sheaths in front of the two electrodes will necessarily be asymmetric even in a geometrically symmetric discharge, if a temporally symmetric voltage waveform, that contains one even harmonic of the fundamental frequency, is applied to the discharge [16]. Fig. 2 shows the resulting sheath voltages as a function of time within one low frequency RF period. This is achievable with a dual-frequency discharge driven at a phase locked fundamental frequency and its second harmonic, e.g. 13.56 MHz and 27.12 MHz. It has been shown previously [15,16] that the EAE leads to the generation of a DC self bias voltage on the RF electrode as a function of the phase between the applied voltage harmonics in a geometrically symmetric reactor. The DC self bias depends almost linearly on the phase angle. Therefore, the EAE offers an opportunity for precise and convenient control of the ion energy bombarding the growing layer on the grounded electrode and the substrate by tuning the phase. The maximum ion energy can typically be changed by a factor of about three at both electrodes [16].

3. Experiment

The Phoebus system in Alzenau is a GEN5 (1100 × 1400 mm) pilot deposition line for thin film silicon tandem solar panels. Silicon hydrogenised microcrystalline layers are deposited by PECVD process in capacitatively coupled parallel plate reactors. Silane containing plasmas were excited by coupling in radio frequency power at 13.56 MHz, 27.12 MHz and by the EAE technique (see Fig. 1).

The RF-powered electrode system has a shower-head configuration, and is mounted with 1 cm electrode gap. The substrate was fixed on the aluminum holder-heater (grounded electrode). In this study, we generate a self bias voltage $V_{bias} = -45$ V to $+40$ V on the RF electrode and examine the effect of V_{bias} on both the μc-Si:H film deposition and the cell performance.

The process gas mixture was $SiH_4 + H_2$. The substrate temperature was 200 °C and the base pressure prior to deposition was always below 10^{-4} mbar. The intrinsic μc-Si:H layer has a thickness of 1.2–1.5 μm. The standard conditions were gas ratio $H_2/SiH_4 = 96$, pressure 11 mbar, and a plasma power density of 0.32 W/cm^2.

Phoebus is a multi-chamber deposition system connected through a tunnel chamber. Doped layers in this study were deposited in separate chambers without breaking the vacuum. The deposition reactors are conventional CCP-type RF-PECVD. For the deposition μc-Si:H layers the gas mixtures of SiH_4 and H_2 were

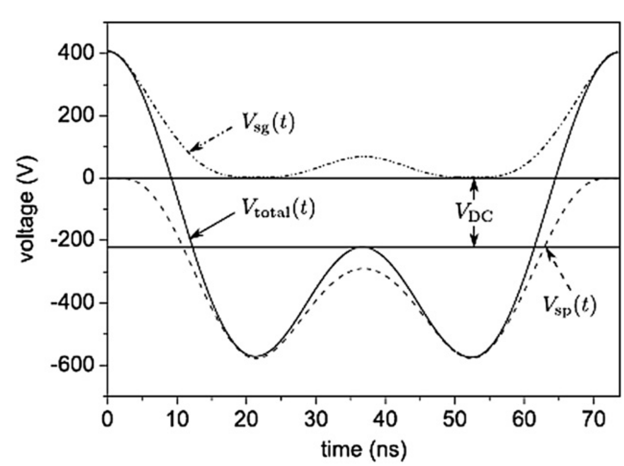

Fig. 2. The total voltage across the discharge, $V_{total(t)}$ in a capacitive Ar discharge resulting from a fluid model. The voltage across the grounded sheath is V_{sg} and the voltage across the powered sheath is V_{sp} [17].