Thin Solid Films 532 (2013) 56–59

Contents lists available at SciVerse ScienceDirect

Thin Solid Films

journal homepage: www.elsevier.com/locate/tsf

The influence of the electrical asymmetry effect on deposition uniformity of thin silicon film

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ARTICLE INFO

Available online 6 January 2013

Keywords:
Thin films
PECVD
Solar cells

ABSTRACT

The deposition of amorphous and microcrystalline silicon is an important step in the production of thin silicon film solar panels. Deposition rate, layer uniformity and material quality are key attributes for achieving high efficiency in such panels. Due to the multilayer structure of tandem solar cells (more than 6 thin silicon layers), it is becoming increasingly important to improve the uniformity of deposition without sacrificing deposition rate and material quality. This paper reports the results of an investigation into the influence of the electrical asymmetry effect (EAE) on the uniformity of deposited layers. 13.56 MHz + 27.12 MHz excitation frequencies were used for thin silicon film deposition in a Gen5 reactor (1100 × 1400 mm). To change the plasma properties, the DC self bias voltage on the RF electrode was varied by adjustment of the phase angle between the two frequencies applied. It was found that the layers deposited by EAE method have better uniformity than layers deposited in single frequency 27.12 MHz discharge. The EAE provides additional opportunities for improvement of uniformity, deposition rate and material quality.

1. Introduction

The best silicon thin film tandem cell and modules currently demonstrate a conversion efficiency of more than 12% [1], but production costs are still rather high.

Plasma enhanced chemical vapor deposition (PECVD) of intrinsic and doped layers of silicon is an important part in the production of thin silicon solar modules. Lower process costs and a higher efficiency product can be achieved by increasing the deposition rate and improving uniformity of the deposited layers. It is well known that very high frequency (VHF) discharge allows a significant increase in deposition rate [2,3] without any deterioration in film quality. Additionally, the reduction of the ion bombardment energy of the film surface reduces the internal stress and improves material quality [4].

About four years ago Leybold Optics GmbH introduced a system for industrial manufacturing of the silicon based layer system of the silicon thin film tandem cell [5].

This paper presents the results of a study into the dependence of the uniformity of amorphous silicon film on the technological parameters of the electrical asymmetry effect (EAE) process: the power ratio of the frequencies and the bias voltage on electrode.

1.1. The electrical asymmetry effect

Theoretical investigation [6] shows that EAE may allow control of plasma properties (for example the ion bombardment) during thin silicon film deposition in plasma containing silane. Fig. 1 shows a scheme demonstrating the difference between a conventional RF and EAE reactors. In the EAE case the two discharge excitation frequencies are used (here: 13.56 MHz and its even harmonic 27.12 MHz).

It has been shown previously [7] that if the excitation waveform contains one even harmonic of the fundamental frequency, the sheaths in front of the two electrodes could be asymmetric even in a geometrically symmetric discharge (Fig. 2). This can be achieved with a dual-frequency discharge driven at a phase locked fundamental frequency and its second harmonic, here, for example: 13.56 MHz and 27.12 MHz. It has also been shown previously [6,7] 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 harmonics applied in a geometrically symmetric reactor. The DC self bias has an almost linear dependence on the phase shift angle. This provides an opportunity for precise and convenient control of the ion energy reaching the growing layer on the ground electrode and substrate by tuning the phase [7].

1.2. The problem of uniform layer deposition

As we mentioned before, VHF PECVD allows high deposition rates. Compared to conventional RF, the VHF plasma has the advantage of higher electron density and lower plasma potential, resulting in higher deposition rates and higher film quality [8]. However, when the VHF wavelengths approach the dimensions of the electrode, the voltage distribution of the standing wave takes on a complex two-dimensional pattern, making it difficult to achieve homogenous deposition over large areas [9]. The increase in the excitation frequency is limited due

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http://dx.doi.org/10.1016/j.tsf.2012.12.105

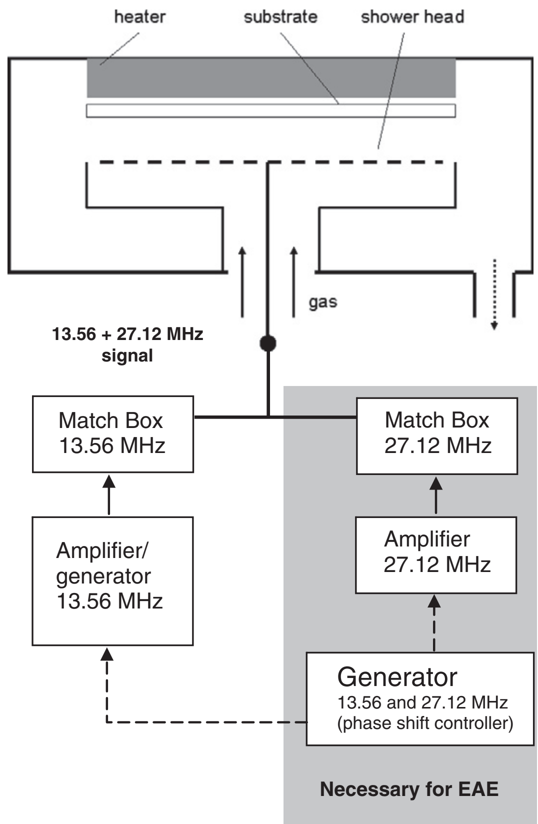

Fig. 1. Diagram of a conventional RF (13.56 MHz) capacitive coupled reactor refitted (gray zone) in a reactor with plasma excitation using the EAE technique.

to the standing wave non-uniformities observed in large area reactors [10]. It is also important to consider that one reason why "thin film solar cells have not achieved the growth of crystalline PV is the lack of large area equipment" [11]. Therefore, a solution is required which allows to increase deposition rates without reducing film quality and the uniformity of film thickness across the substrate.

2. Experimental details

The Phoebus system in Alzenau is a Gen5 (1100×1400 mm) pilot deposition line for thin film silicon tandem solar panels (Fig. 3). Silicon layers were deposited by a PECVD capacitive coupled parallel plate reactor. Plasmas containing silane were excited by coupling in radio frequency power at 13.56 MHz, 27.12 MHz and by the EAE technique (see Fig. 1).

The process chamber contained a parallel plate reactor comprising a live electrode connected to two matchboxes (13.56 MHz and 27.12 MHz) and counter-electrode at close-to-ground potential, both about 1.6 m×1.3 m in size. A process gas manifold was an integral part of the live electrode. The plasma gap determined by distance of the glass surface to the surface of the live electrode was set to 10 mm. The co-planarity of the electrodes was better than ±0.3 mm across their entire area. The temperatures of both electrodes were individually controlled, independent of the power dissipated by the plasma. During conditioning of the process chamber, the electrode temperature was set to 200 °C. Before carrying out experiments, the process chamber was preconditioned by coating the process area with a primer layer.

We simultaneously applied the different power levels of 13.56 MHz and 27.12 MHz to generate different levels of positive and negative self bias voltage on the RF electrode. The effect of V_{bias} on thin silicon film deposition uniformity over the substrate was then analyzed.

The process gas mixture was SiH_4+H_2. The base pressure prior to deposition was always below 10^{-2} Pa. The standard conditions for deposition were a pressure of 400 Pa and a plasma power density of <0.05 W/cm^2. The film thicknesses were measured by an Alpha-Step IQ® surface profiler. The uniformity of the layers across the substrate was calculated by:

$$U\% = 100\% \times (\text{Max}-\text{Min})/2 \text{ averaged}.$$

3. Results and discussion

At an excitation frequency of 13.56 MHz the deposited layer uniformity was better than 17%. The typical deposition rate for device quality

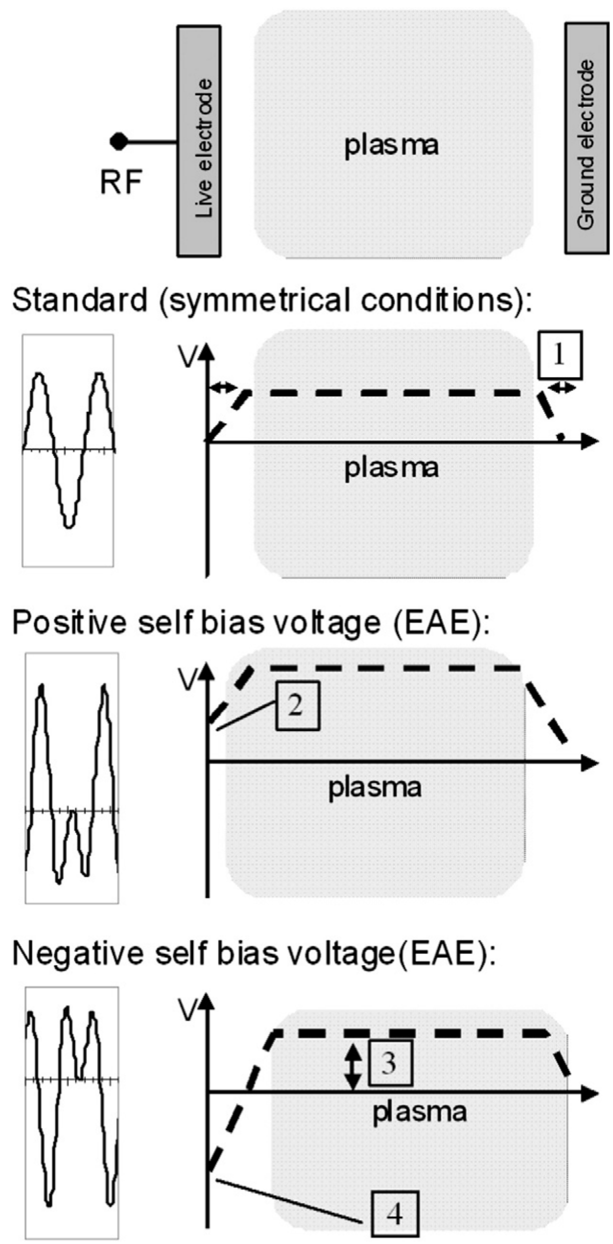

Fig. 2. RF signal on the live electrode (left) and time averaged electrical potential between electrodes (right). From top: scheme of discharge between electrodes; symmetrical conditions, no DC self bias on live electrode, sheath thicknesses are equal; non-symmetrical conditions: positive DC self bias voltage on live electrode, at live electrode the sheath is thinner; negative DC self bias on live electrode, sheath at ground electrode is thinner. On figure: 1 — sheath thicknesses; 2 — positive self bias voltage; 3 — plasma potential; 4 — negative self bias voltage.