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Short communication

High deposition rate processes for the fabrication of microcrystalline silicon thin films

S. Michard, M. Meier*, B. Grootoonk, O. Astakhov, A. Gordijn, F. Finger

Institute of Energy and Climate Research 5 - Photovoltaik, Forschungszentrum Jülich, 52425 Jülich, Germany

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ABSTRACT

The increase of deposition rate of microcrystalline silicon absorber layers is an essential point for cost reduction in the mass production of thin-film silicon solar cells. In this work we explored a broad range of plasma enhanced chemical vapor deposition (PECVD) parameters in order to increase the deposition rate of intrinsic microcrystalline silicon layers keeping the industrial relevant material quality standards. We combined plasma excitation frequencies in the VHF band with the high pressure high power depletion regime using new deposition facilities and achieved deposition rates as high as 2.8 nm/s. The material quality evaluated from photosensitivity and electron spin resonance measurements is similar to standard microcrystalline silicon deposited at low growth rates. The influence of the deposition power and the deposition pressure on the electrical and structural film properties was investigated.

1. Introduction

Hydrogenated microcrystalline silicon (μc-Si:H) deposited by plasma enhanced chemical vapor deposition (PECVD) is a widely used material for absorber layers in thin-film silicon solar cells [1,2]. Microcrystalline silicon is a mixed phase material consisting of nano-crystals, grain boundaries, amorphous tissue, and voids. The crystalline volume fraction depends on the preparation conditions and is critical for the function of μc-Si:H as absorber layer in a solar cell. In particular intrinsic μc-Si:H is applied as an absorber layer in the bottom cell in amorphous/microcrystalline tandem solar cells [1,2]. To provide appropriate light absorption (especially in the long wavelength range) and to obtain current matching between the top and bottom components of the tandem cell a μc-Si:H absorber layer with a thickness of >1 μm is required. Under usual deposition rates of about 0.5 nm/s the deposition of a 1 μm thick absorber layer takes 33 min. To reduce manufacturing costs this process time has to be reduced by means of increased deposition rate of μc-Si:H.

The density of RF power is the key deposition parameter to control the growth rate. With a newly installed deposition system we are able to apply a power density up to 5 W/cm^2. By increasing the deposition power the dissociation of the involved process gases is enhanced which facilitates the faster film growth. At the same time the energy of ions in the plasma is increased which leads to heavier ion bombardment of the surface of the growing film. This heavier bombardment is believed to be a main cause for the film quality deterioration in terms of defect density at high deposition rates [3]. Two approaches are effective to preserve high material quality at elevated growth rates. First, the use of high pressure deposition regimes (HPD) [4,5] and, second, the application of high excitation frequencies in the VHF ($\nu_{ex} > 30$ MHz) range [6–8]. In the HPD regime the energy of the bombarding ions is reduced by the application of deposition pressures of typically 1–10 hPa (1 hPa = 100 Pa = 1 mbar). The increase of the deposition pressure causes a reduction of the mean free path which suppresses acceleration of the species involved in the glow discharge [4]. The application of high excitation frequencies leads to a reduction of the plasma potential and therefore to thinner plasma sheaths. The ions entering the sheath are accelerated by a weaker electric field over a shorter distance compared to the application of low excitation frequencies [9].

In this work we explore, based on the results of previous studies [10,11], the high deposition rate regimes (HPD + VHF) in order to improve the deposition rate of the device quality μc-Si:H. Newly installed deposition equipment allowed for the variation of the deposition power P and the deposition pressure p over an extended range with respect to the previous studies [10,11].

The aim is to increase the deposition rate of μc-Si:H with a phase mixture known to be best for device performance (crystalline volume fraction between 40% and 60%). During the further description this material will be referred to as optimal phase mixture material (OPM) [1,10,12].

* Corresponding author. Tel.: +49 2461 611552.
E-mail address: ma.meier@fz-juelich.de (M. Meier).

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Table 1
Summary of investigated deposition parameters.

Name	Hydrogen flow Q (sccm)	Deposition power P (W)	Electrode distance d_e (mm)	Deposition pressure p (hPa)
Series A	200	50; 100; 200; 400; 600	10	5
Series B	200	100	10	3; 5; 8

Samples deposited at 400 W of series A were investigated by electron spin resonance measurements.

2. Experimental details

Microcrystalline silicon layers were prepared in a recently installed multi chamber deposition system with parallel plate PECVD reactors. The new deposition system was designed and constructed through a close collaboration between our institute and our industrial partners (Von Ardenne Anlagentechnik GmbH and Forschungs- und Applikationslabor Plasmatechnik GmbH Dresden). The deposition system enables the processing of p-type, n-type and intrinsic layers which are necessary for solar cell devices. To avoid cross contamination of the growing film each material type is fabricated in a different, but similarly designed, chamber. The plasma excitation frequency used in the present study is 81.36 MHz. The 10 cm × 10 cm squared substrate is placed on the grounded and heated electrode above the powered electrode. The distance d_e between substrate and electrode can be varied in situ between 5 mm and 25 mm. A showerhead gas supply through the powered electrode is used for homogeneous layer processing. Multi stage pumping systems provide high purity deposition processes. This new deposition system was optimized for silicon layer depositions at very narrow electrode gaps, high working pressures and high deposition powers (up to 1000 W) in order to expand the deposition regimes toward high density plasma and explore challenging high deposition rate processes which go still beyond the promising results presented earlier [10] and which are relevant for successful industrial production of thin film silicon photovoltaic modules.

Among various deposition parameters we focus on the variation of the deposition power P, the deposition pressure p and the silane concentration (SC) as summarized in the Table 1. The SC is calculated according to equation 1

$$SC = \frac{Q[SiH_4]}{Q[SiH_4] + Q[H_2]} \quad (1)$$

where $Q[SiH_4]$ is the silane mass flow and $Q[H_2]$ the hydrogen mass flow into the deposition chamber. The hydrogen flow was kept constant at 200 sccm. For each investigated parameter set a variation of SC was carried out to cover the whole material range from microcrystalline (μc-Si:H) to amorphous (a-Si:H) silicon growth. Depending on the SC the deposition time was adjusted to obtain silicon layers with a thickness of ~300 nm.

10 cm × 10 cm glasses (Corning Eagle 2000) were used as substrates for electrical and Raman measurements. Continuous wave X-band (9.3 GHz) electron spin resonance (ESR) measurements were carried out for certain material compositions using a commercial Bruker ELEXSYS E500 spectrometer. In this case Al-foil served as a temporary substrate for further ESR powder preparations as described in reference [13]. A calibrated sputtered silicon sample with 2×10^{15} spins was used as a secondary standard for spin density and g-value evaluation [14].

Conductivity measurements were performed at 300 K under vacuum with coplanar silver contacts after annealing the samples for 30 min at 440 K in vacuum. The photoconductivity σ_{ph} was measured under halogen lamp illumination calibrated with a photodiode against AM1.5 standard illumination. The photosensitivity as a measure of material quality was calculated as a ratio of photoconductivity σ_{ph} to dark conductivity σ_d.

The deposition rate R_D has been calculated from the film thickness and the deposition time (accuracy: ±1 s). The film thickness was measured ex situ after the deposition of the film by a surface profilometer Veeco Dektak 6M (accuracy: ±20 nm).

Raman spectra were measured using a commercial Raman Renishaw inVia microscope with an argon laser excitation with a wavelength of 532 nm. The Raman intensity ratio I_C^{RS} as a semi-quantitative measure for the crystalline volume fraction of the investigated film was calculated according to reference [15].

3. Results

Fig. 1a shows the deposition rate for layers prepared at different deposition powers as a function of silane concentration. The material was prepared at deposition powers between 50 W and 600 W at a deposition pressure of 5 hPa and an electrode distance of 10 mm (series A in Table 1). Within considerable scatter we observe an increase of the deposition rate with an increase of SC in the range of 0.5–11.5%. There is no trend for an increase of the deposition rate with increasing deposition power at a given value of SC. This is an indication for silane depletion already at a deposition power of 50 W. In other words nearly every silane molecule in the glow

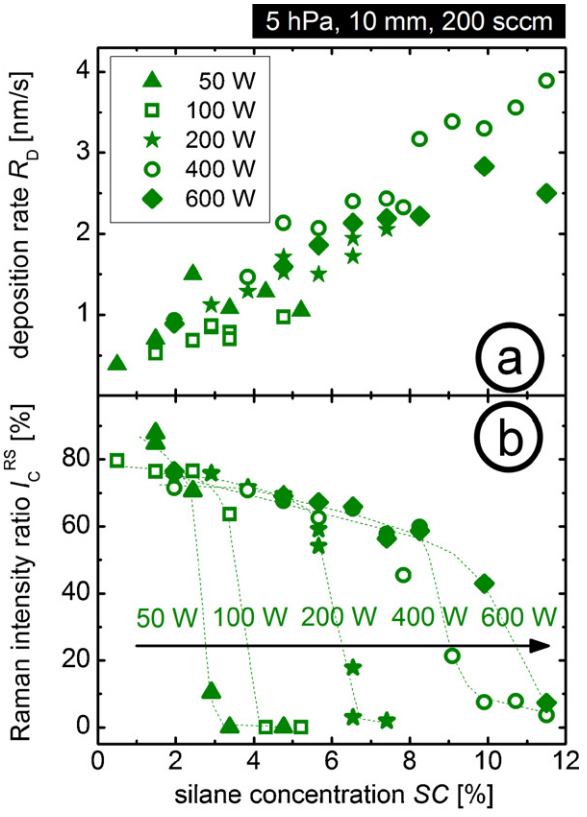

Fig. 1. Deposition rate R_D (a) and Raman intensity ratio I_C^{RS} (b) as a function of the silane concentration, SC calculated using Eq. (1), for the series with varied deposition power (series A).