Pilot roll-to-roll PECVD system for fabrication of thin film Si solar cells

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Abstract

Our aim is the development of high-throughput production technology for high efficiency, amorphous and microcrystalline thin film silicon solar cells on flexible substrates. A roll-to-roll system, the FLEXICOAT300, is developed with three deposition chambers for the continuous deposition of, respectively, n-type Si, intrinsic Si and p-type Si. Novel RF and MW sources for plasma enhanced chemical vapour deposition (PECVD) are introduced in the roll-to-roll coater. The first trial depositions of a-Si solar cells show a promising efficiency of > 4 %.

Keywords: roll-to-roll, thin film Si, solar cells, flexible substrates

1. Introduction

Roll-to-roll processing has several advantages above batch processing, such as reduced handling costs, clean (closed) environment and the absence of pump-down cycles. Nowadays however, thin film solar cells are commonly produced in batch type systems and that is mainly because of unavailability of commercial roll-to-roll production equipment. The aim of ECN is the development of high-throughput production technology for high efficiency thin film silicon solar cells. For this purpose, ECN and Roth&Rau AG developed a roll-to-roll PECVD system, the FLEXICOAT300, with three deposition chambers for the continuous deposition of silicon n-i-p layers as applied in thin film Si solar cells. For both doped and intrinsic Si deposition processes, new types of plasma sources are designed.

In our concept for roll-to-roll production of thin film Si solar cells, steel foil is used as substrate of the solar cells. The stainless steel foil is coated with an insulating barrier layer, back-contact and -reflector, before the active Si layers are deposited in the FLEXICOAT300. On top of the Si layers, a transparent conductive oxide is sputtered. Finally, the layer stack is divided into cells by laser scribing. These cells are then monolithically interconnected by printed metallic lines and the total PV module is encapsulated. In principle, the same concept can be used for plastic substrates.

The research reported in this contribution focuses entirely on the roll-to-roll system for deposition of Si layers.

In this Contribution, we will present the FLEXICOAT300 and show the plasma characteristics of the RF and MW sources. Also, the progress of the deposition of individual Si layers and thin film Si solar cells is reported.

2. Experimental

2.1 FLEXICOAT300

The FLEXICOAT300 is a dedicated roll-to-roll coater for the continuous deposition of silicon on moving foil substrates. It contains five vacuum chambers: a pay-off chamber, three PECVD chambers, for n-type, intrinsic and p-type Si deposition respectively, and a take-up chamber. Fig. 1 shows a cross-section of the first half of the roll-to-roll coater. Foils of 300 mm width can be handled by the FLEXICOAT300. Both RF and MW sources are linear, and the entire system including plasma sources can be up-scaled to 1500 mm wide.

Plasma boxes shield the plasma and substrate, in order to reduce oxygen contamination of the deposited layers due to water desorption from the water-cooled walls. Gas locks are installed allowing to use different pressures in each of the deposition chambers and to prevent the contamination of the intrinsic chamber with dopant gases such as PH_3 and B_2H_6. All chambers are pumped with roots pumps allowing a base pressure in the range of 10^{-5} mbar.

Novel linear microwave (MW) and RF sources are implemented for intrinsic and doped layers, respectively. The intrinsic chamber is equipped with four linear microwave sources [1] with one MW antenna each and has an effective deposition area of 120×30 cm^2. The p-type and n-type chambers are equipped with linear RF sources [2]; each RF source consists of two electrodes. The effective deposition area in the p-type and n-type chambers is 20×30 cm^2.
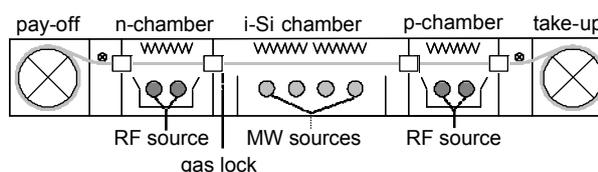

Fig. 1: Cross-section through the FLEXICOAT300 roll-to-roll coater.

2.2 MW source

The intrinsic layer is deposited with MW-PECVD as this combines high deposition rates homogeneously on large areas, with good layer quality [1,3]. The high deposition rates are needed for the deposition of the thick intrinsic Si layers, ~300 nm for a-Si and 1-2 μm for μc-Si. Fig. 2 shows the MW source. The MW antenna is placed inside a quartz tube to shield it from the plasma. So far, deposition rates up to 0.5 nm/s for device quality μc-Si layers have been achieved.
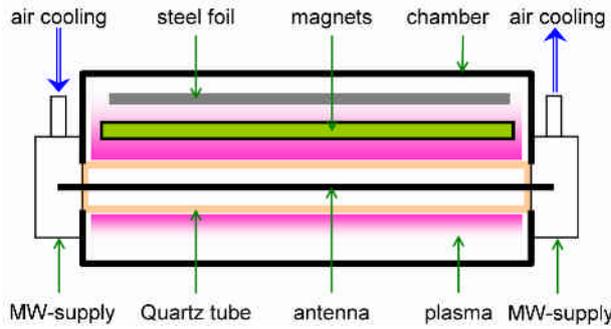
Fig. 2. Sketch of the MW source, looking along the rolling direction of the foil.

Each MW source contains two linear arrays of magnets to improve the plasma confinement. Both layer quality and deposition rate are greatly affected by the arrangement of those magnets. Fig. 3 shows the ion current density, as measured with a multi-Langmuir probe, for two different magnet configurations. The ion current density is measured at the substrate level directly above the MW antenna. As can be seen in the figure, the second configuration has double the ion current density as the first configuration. This leads to a more than twofold increase in the deposition rate.
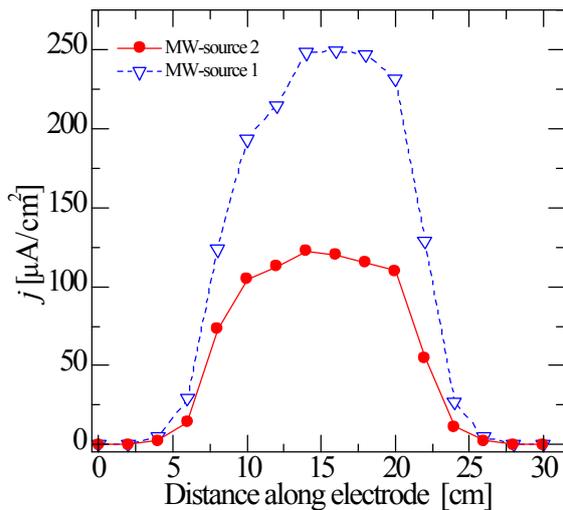

Fig. 3. Ion current density measured along the MW antenna at the substrate level. The sharp cut-offs at 5 and 25 cm are caused by the plasma box, which covers part of the substrate and therefore of the probe.

While the MW sources are excellent for deposition of intrinsic silicon, they are not suitable for doped layer deposition, since parasitic deposition of conductive layers on the quartz tube will decrease the microwave power that can be coupled into the plasma. For that reason, we had to resort to another plasma source for the growth of n-type Si and p-type Si.

2.2 Linear, symmetric RF source

The linear RF source has been developed by Roth&Rau AG and consists of two aluminium rods (with a diameter of about 30 mm) which are symmetrically connected to the

13.56 MHz RF generator (see Fig. 4), with a maximum power of 600 W [2]. The distance between the centre of the antennas and substrate is about 10 cm. This concept results in a significant voltage drop over the plasma sheath around the electrodes but only a small voltage drop over the plasma sheath around the substrate.

In contrast to conventional asymmetric RF sources, here the substrate does not form part of the RF network and therefore does not need to be grounded. The absence of the need for grounded substrates is a significant advantage in roll-to-roll processing. The pressure range in which this RF source can be operated is 0.01-1 mbar; if a magnetic field is applied the source can even be operated at pressures down to 0.001 mbar. For deposition of silicon layers we typically operate the source between 0.01 and 1 mbar and do not apply a magnetic field.
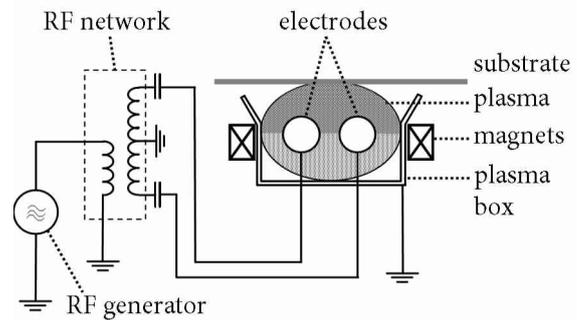

Fig. 4. Sketch of the linear RF source. The plasma is ignited between the two electrodes.

The RF source in the FLEXICOAT300 covers a width of 30 cm, but the source can simply be enlarged to widths of more than 1 m, provided that the power of the RF generator is also increased to more than 1.5 kW.

Uniformity over the width of the foil is required for roll-to-roll deposition of solar cells. The current density has been measured to analyse the uniformity of the plasma that is generated with the RF source. The current density is uniform along the length of the RF source within a few percent.

One of the arguments in favour of a symmetric linear RF source is the supposedly low energy ion bombardment. Typically, the ion energy distribution of commonly applied asymmetric RF sources shows a narrow maximum at 7-10 eV, but a long tail is observed, extending to 60-100 eV [2]. The ion energy distribution of the novel symmetric RF source, installed in the FLEXICOAT300, is plotted in Fig. 5.
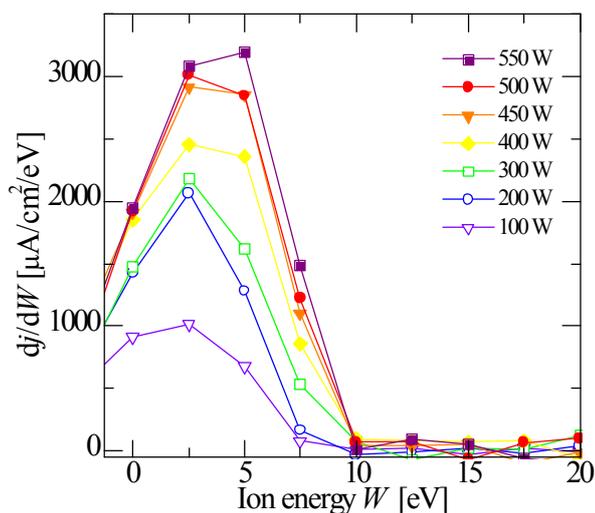
Fig. 5. Plasma characteristics at the sample surface of a H_2 plasma at 0.1 mbar for several RF powers. The graph shows the ion energy distribution as determined by retarding field analysis at the centre of the electrode on substrate level.

The ion energy distribution of the symmetric RF source shows a narrow maximum at 3-7 eV too, but there is a clear cut off: from 10 eV onwards no significant signal in the ion distribution is observed. Therefore, the novel RF source leads to a very mild ion bombardment on the surface of the substrate.

This leads to "soft" deposition conditions for doped Si and SiC layers. The low ion bombardment energy makes this source also very attractive, for instance, for crystalline silicon surface treatments like passivation by thin SiNx or a-Si layers. With this RF source, device quality n-type a-Si:P and μc-Si:P have been deposited at economically feasible deposition rates, 0.2-0.4 Å/s [4].

3. Results & Discussion

3.1 Doped layers

The heart of thin film Si solar cells consists of three Si layers. In the centre, the thick absorber layer is made of high-quality defect-poor intrinsic Si. Here, the charge carriers, holes and electrons, are created by absorption of photons. A donor-doped layer (n-type) and a acceptor-doped layer (p-type), on opposite sides of the intrinsic Si, create an electric field across the absorber layer, thereby separating the holes and electrons and creating the photocurrent. The resulting stack is indicated as p-i-n or n-i-p solar cells.

The donor-doped layer is made by doping the Si layer with P or As. In the PECVD process this can be done by adding PH_3 to the process chamber as reported elsewhere [4].

Acceptor-doped layers are made with PECVD by substituting B or Al. In our system we use B_2H_6. However, the optical band gap of the resulting p-type a-Si layer is too low, leading to too much absorption in this layer. To improve the optical quality of the p-type layer, CH_4 is added to the process chamber, resulting in the deposition

of silicon carbide layers. As shown in Fig. 6, the addition of methane increases E_g, although σ_d decreases. Increasing the B_2H_6 flow reverses this process. Although the optical band gap is increased, the drawback is that the electronic properties decrease and an optimum trade-off between the two properties has to be found.
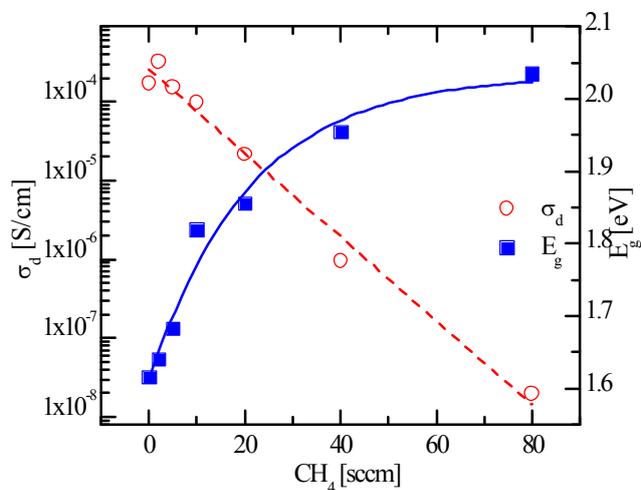

Fig. 6. σ_d (left axis, open circles) and E_g (right axis, solid squares) as a function of CH_4 flow. The lines are guides to the eye.

3.2 Intrinsic layers

The quality of intrinsic layers is mainly determined by the electronic properties and the defects in the layer. Typically, the photo-to-dark ratio of the conductivity and the activation energy of the dark conductivity are taken as yardstick for the electronic properties. Table 1 shows these parameters for intrinsic a-Si deposited with the novel linear MW source. Clearly, the layers, deposited with MW-PECVD, are of device quality.

Table 1.
Material parameters for intrinsic a-Si and criteria for device quality material [5].

	a-Si	Device quality
E_{act}	0.884	0.85
σ_d	2.8×10^{-11}	$< 1 \times 10^{-10}$
σ_{ph}/σ_d	1.5×10^6	$> 1 \times 10^5$

Fig. 7 shows the absorption curve for a typical intrinsic a-Si layer, as measured by FTPS [6]. Note that the absorption values cover over 7 orders of magnitude. The defects in the intrinsic a-Si are in the band tail states and the mid-gap states. These are quantified by the Urbach tail energy E_{urb} and the α at 0.8 eV, respectively. E_{urb} can be found by determining the steep decline below the band gap at ~1.80 eV.
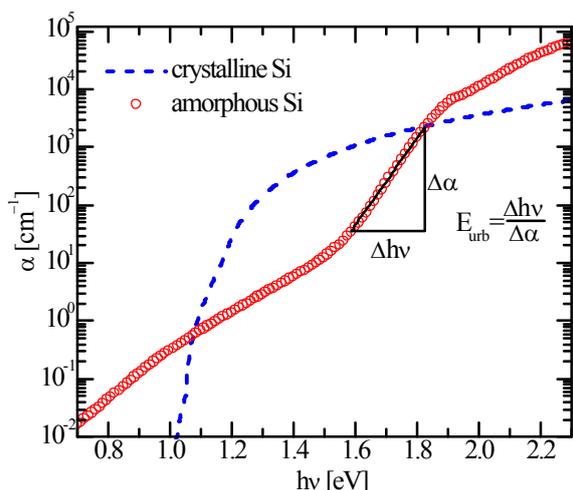
Fig. 7. Absorption α as a function of the energy $h\nu$ for device quality thin film a-Si sample. For reference, the absorption coefficient for single crystalline Si with $E_g = 1.12$ eV is shown (dashed line).

3.3 Solar cells

Using the above presented layers, we fabricated a-Si solar cells on small pieces Asahi-U superstrates, which we attached to the metal foil in the Flexicoat300. The reason for using this glass superstrate was to have a well defined top TCO. The solar cells either incorporated a-Si or a-SiC as window layers, i.e. the layers that face the sun. Fig. 8 shows I-V curves for a-Si solar cells, one with p-type a-Si and the other with p-type SiC.
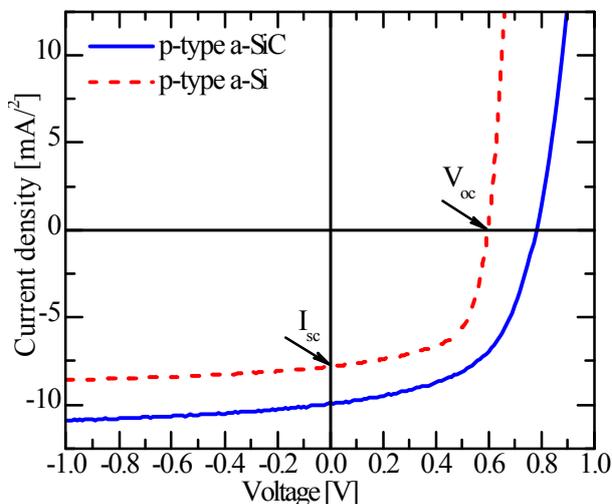

Fig. 8. I-V curves for solar cells with an a-Si window layer (dashed) and an a-SiC window layer (solid).

SiC window layers have two advantages over p-type Si layers, mainly because the band gap of SiC is higher than for carbonless p-type Si, see Fig. 6. This results in a higher cell voltage, V_{oc} since the built-in potential V_{bi} is increased. Secondly, the higher band gap is accompanied by a lower absorption. This means that more light passes through the p-layer and can be absorbed, i.e. create charge carriers, in the intrinsic layer. Consequently, the generated

current, Isc, is higher. Both effects can be observed in the I-V curves in Fig. 8.

4. Conclusion

To conclude: we developed, in collaboration with Roth&Rau AG, a roll-to-roll PECVD system, the FLEXICOAT300, with three deposition chambers for the continuous deposition of silicon n-i-p layers. The RF-sources apply a low energy ion bombardment to the substrate. Intrinsic layers with sufficient quality for solar cells can be grown with the MW sources. The deposition rate is strongly influenced by the magnet configuration around the MW-antenna. First trial depositions of a-Si solar cells on Asahi TCO glass, fabricated using the novel RF and MW sources in the FLEXICOAT300, show an efficiency of > 4%.

Acknowledgements

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