A NOVEL LINEAR RF SOURCE FOR PECVD OF THIN-FILM SILICON

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ABSTRACT: We present a new linear RF source for plasma enhanced CVD of amorphous and microcrystalline silicon. The source has been developed for application in continuous, roll-to-roll deposition of doped silicon layers, as part of a system in which the intrinsic silicon layers will be made by high-rate microwave PECVD. Plasma analysis, by Langmuir probing and by Retarding Field Analysis, shows that the plasma is homogeneous within ± 3% over the entire width of the source, and that the energies of ions arriving at the substrate are lower than 10 eV. The width of the deposition regime in this case is 30 cm, but the sources can be extended to achieve homogeneous deposition over widths of more than 1 m. The source is well suited for deposition of amorphous and microcrystalline silicon, and the transition from microcrystalline growth to amorphous growth occurs for SiH_4/H_2 flow ratios between 0.05 and 0.01.
Keywords: RF PECVD, a-Si:H, μc-Si:H, plasma, roll-to-roll

1 INTRODUCTION

The aim of ECN is the development of industrial scale fabrication technology for high efficiency solar cells based on amorphous (a-Si:H) and microcrystalline (μc-Si:H) silicon thin films on steel foil coated with an insulating layer. For this purpose we have developed a roll-to-roll PECVD system, the FLEXICOAT300 in collaboration with Roth&Rau [1].

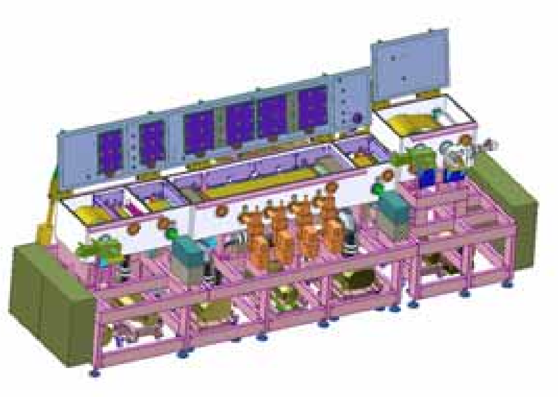

Figure 1: 3D drawing of the Flexicoat300

The FLEXICOAT300 has three deposition chambers and can handle webs with a width up to 30 cm. The intrinsic layer are deposited with microwave PECVD as this combines good quality with high deposition rates. However the linear microwave source employed by ECN is not suitable for deposition of doped layers. The quartz tube, shielding the antenna, will not transmit EM radiation when covered by a conducting doped silicon layer.

Radio frequency PECVD (RF-PECVD) is commonly used to deposit silicon layers for photovoltaic cells. In most industrial PECVD systems the plasma is generated in a capacitive mode. The grounded substrate then is typically part of the RF network and subject to bombardment by ions with energies in the range of 10-100 eV [2]. This bombardment with relatively high energy ions usually has a detrimental effect on the electronic quality of the silicon layers [3].

Here we present a novel linear RF source for PECVD, where the substrate is electrically disconnected from the RF network. As a result, the ion bombardment is very mild, with ion energies limited to values typically less than 10 eV. Another advantage of this novel RF source is the homogeneity of the plasma, allowing uniform deposition over large widths. In combination with a moving substrate large areas can be coated uniformly.

This work focuses on the plasma characteristics of the new RF source. Detailed results on intrinsic and doped silicon layer deposition with this source are presented in another paper at this conference.

2 EXPERIMENTAL SETUP

2.1 Description of the RF source

The RF source has been developed by the company Roth&Rau and consists of two aluminum rods (with a diameter of about 30 mm) which are symmetrically connected to the RF generator (13.56 MHz), with a maximum power of 600 W. The distance between center of the source 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.

The substrate does not form part of the RF network and therefore does not need to be grounded. 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.

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

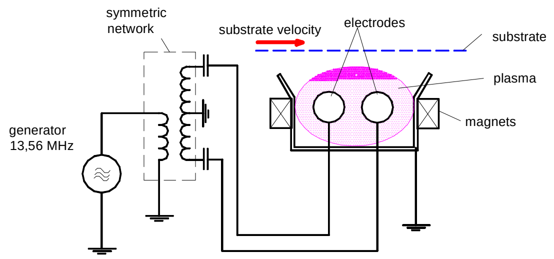

Figure 2: Linear RF plasma source for deposition of doped layers in the roll-to-roll system at ECN.

2.2 Langmuir Probe Measurements

The principle of a single plasma probe measurement is shown in Figure 3. Our set-up consists of an array of 16 probes at a distance of 20 mm, located in the deposition chamber at the height of the substrate. IV curves of all probes are measured simultaneously by an electronic control unit. If a negative probe potential is applied (typically -25 V) the positive ion current density can be measured giving both information on the charge carrier density of the plasma and information on the ion bombardment by the plasma process on the substrate.

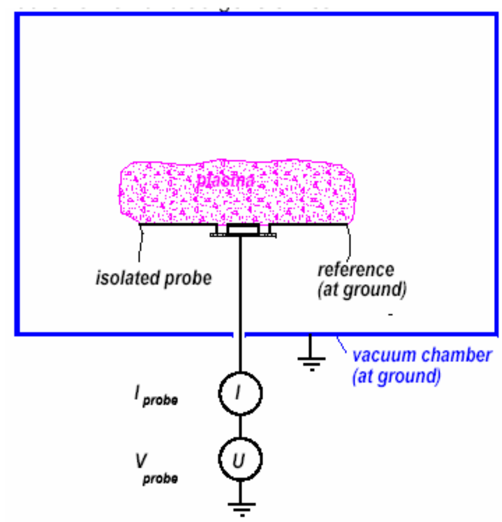

Figure 3: Principle of the Langmuir probe.

2.3 Retarding Field Analysis

A second important plasma feature determining the growth process of the silicon layers is the ion energy distribution of the ions impinging on the substrate. To measure the ion energy distribution we placed a single retarding field analyser (RFA) described in [4,5] at the height of the substrate at the centre of the linear plasma source. The principle of the energy analysis with the RFA is shown in Figure 4. A system of two grids (plasma grid and extraction grid) extracts particles from the plasma. The extraction grid can have a positive potential (measuring electron energy distribution) or a negative one (measuring ion energy distribution. The collector measures the particle current in dependence on the retarding voltage. In order to find the energy distribution of the extracted particles, one has to differentiate the curve with respect to the retarding voltage. Ion energies up to 200 eV can be measured by this method.

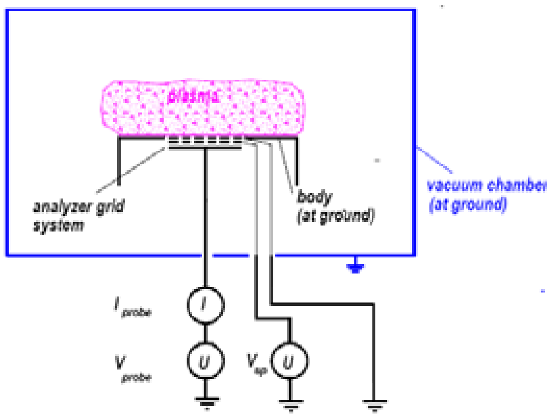

Figure 4: Principle of retarding field analyzer.

2.3 Optical Emission Spectroscopy

Optical emission spectroscopy (OES) in the wavelength range from 200 to 1000 nm has been performed during deposition and the characteristic lines of Hα, Hβ, Si* and SiH* in the plasma at respectively 656, 486, 288 and 412 nm, have been analysed. The OES data are sampled by a glass fibre through a small quartz window, at substrate level, i.e. about 10 cm above the central axis of the source.

2.4 Raman spectroscopy

Raman spectra have been measured on a Renishaw Raman spectrometer with a laser wavelength of 514 nm. The crystalline volume fraction X_c is calculated from the ratio of the amorphous and crystalline contributions according to

$$X_c = \frac{I_{520} + I_{505}}{I_{520} + I_{505} + I_{480}} \quad (1)$$

where I_n is the intensity of the peak at n cm^{-1}.

3 RESULTS

In order to prevent fouling of the probes by silicon deposition, we have performed the Langmuir probe measurements and RFA on pure H_2 plasma's only. The plasma densities over the width of the source, plotted in Figures 5 and 6 for two representative pressures, show an increase with increasing RF power. The steep drops in density, measured by the two outward probes, at 0 and 300 mm, are caused by the plasma box shielding. The uniformity of the plasma density in all cases is better than ± 3% over the width of the source, and is best for lower RF power levels.

Increasing the operating pressure leads to more compact plasmas between and around the aluminum rods, i.e. less extended plasma zones. As a result, the plasma density at the level of the substrate, as monitored by the probes, becomes smaller at higher pressures.

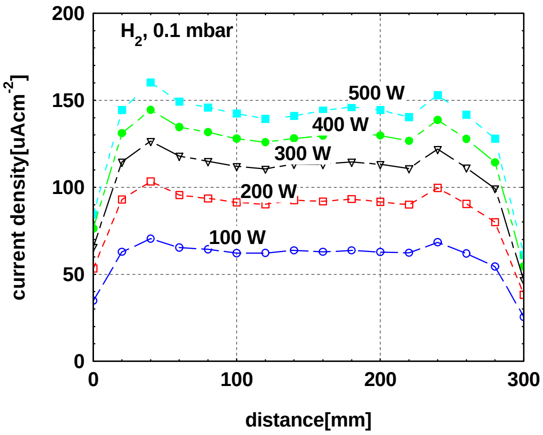

Figure 5: Ion density profile of hydrogen plasma generated by the linear RF source at 0.1 mbar as a function of RF power.

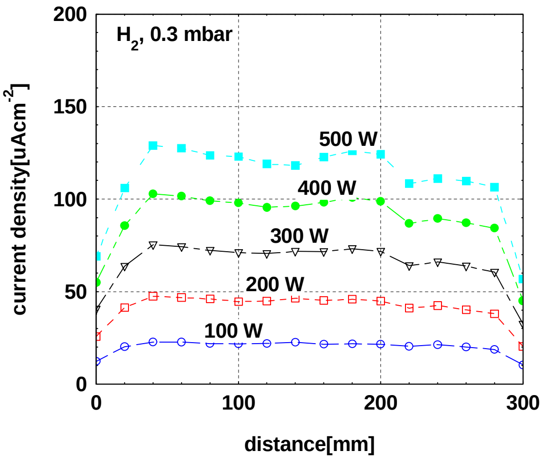

Figure 6: Ion density profile of a hydrogen plasma generated by the linear RF source at 0.3 mbar.

Ion energies at the level of the substrate, measured with RFA and plotted in Figure 7, are characterized by a narrow peak at about 3 eV. Even for the highest RF powers that can be applied, the maximum ion energies remain below 10 eV. This is well below the displacement threshold for Si atoms in the Si lattice (12-14 eV), indicating that the plasma will not cause lattice damage to the Si film during deposition.

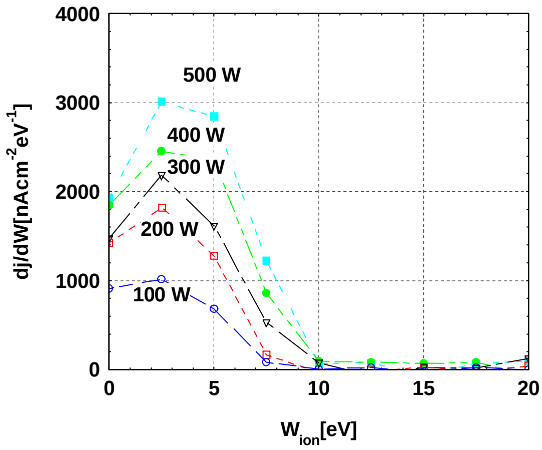

Figure 7: Ion energy distribution of the linear radio frequency plasma source versus applied RF-power at 0.1 mbar hydrogen.

Optical emission spectroscopy results for a series in which we varied the operating pressure are shown in Figure 8. The RF power in this series was 450 W. The ratios of Hβ/Hα and Si*/SiH*, indicators of the mean electron temperature, show a decreasing tendency with increasing operating pressure. So, we conclude that an increase of the pressure leads to both a decrease of electron density and electron temperature at the substrate.

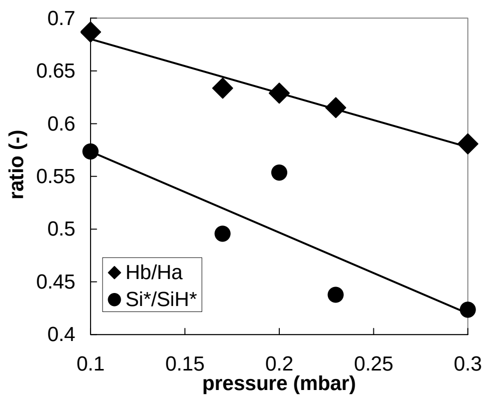

Figure 8: Ratio of Hβ/Hα and Si*/SiH* emission intensities versus operating pressure for H_2/SiH_4 plasma with a flow ratio of 99. The lines are linear fits to the data.

The ratios of Hα/SiH and Hα/Si* are generally considered as indicators for the deposition regime: ratios much larger than 1 indicate a microcrystalline growth regime whereas ratio's smaller than 1 point to a growth regime of amorphous silicon. The exact ratio at which transition from microcrystalline silicon growth to amorphous silicon growth will be observed depends of course not only on details of the plasma source (frequency, ion energies), and substrate conditions (temperature) but also on details of the OES measurements itself (like the spectral transmission of window and fibre and the spectral sensitivity of the detector. Nonetheless we can observe a steep decrease of the ratio's Hα/SiH and Hα/Si* at SiH_4/H_2 gas flow ratio's between 0.01 and 0.1 (see Figure 9), and that is where we expect the transition from microcrystalline silicon growth to amorphous silicon growth to take place.

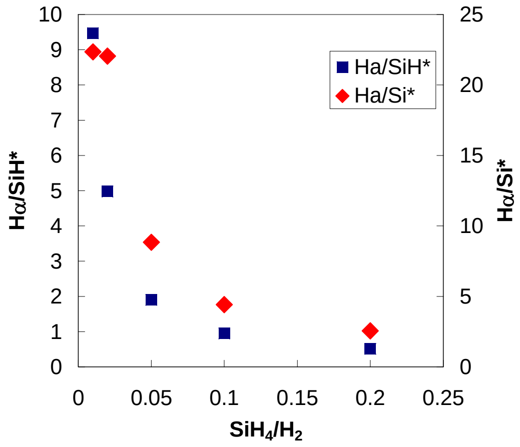

Figure 9: Ratios of Hα/SiH and Hα/Si* emission intensities as a function of SiH_4/H_2 gas flow ratio.

Raman measurements, see Figure 10, confirm these OES observations. It can be observed that for SiH_4/H_2 flow ratios below 0.05, the deposited layers have a high crystalline fraction X_c, of more than 50 %, and that the crystalline fraction drops to negligible values at flow ratios of 0.10 and higher.

The deposition rate seems to correlate linearly with the SiH_4/H_2 ratio. The growth rate of microcrystalline silicon is in the range of 0.01 nm/s, and for amorphous silicon values of 0.05 nm/s and higher are obtained. These rather low deposition rates are well suited for fabrication of thin doped layers, but make this RF source less suitable for the fabrication of the intrinsic absorber layer in thin film silicon solar cells.

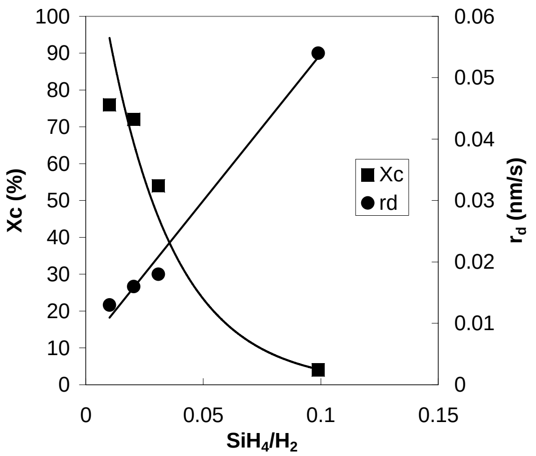

Figure 10: Crystal fractions (X_c) and deposition rates (r_d) for intrinsic layers grown at various SiH_4/H_2 ratio's. The trend lines serve as a guide to the eye.

4 CONCLUSIONS

The new linear RF source generates uniform plasmas with density variations at the level of the substrate less than ± 3% over the entire width of the source. The source can be operated at power levels between 100 and 550 W.

We have observed that the plasma density and the mean electron temperature decrease with increasing pressure, indicating that highest deposition rates can be obtained at lower pressures. For microcrystalline silicon, growth rates in the range of 0.01 nm/s are obtained whereas the growth rate for amorphous silicon is 0.05 nm/s and higher. These deposition rates are appropriate for deposition of thin doped layers.

The transition from microcrystalline to amorphous silicon growth takes place in the SiH_4/H_2 flow ratio regime between 0.05 and 0.1. This transition is accompanied by a rapid decrease of optical emission ratios of Hα/SiH and Hα/Si*.

The concept of the novel RF source leads to low energies of ions arriving at the substrate during deposition (< 10 eV). This makes that the RF source is very well suited for deposition of layers which have to maintain or improve the surface defect density of the substrate.

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