MICROMORPH CELLS GROWN AT HIGH RATE WITH IN-SITU INTERMEDIATE REFLECTOR IN INDUSTRIAL KAI PECVD REACTORS

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ABSTRACT

We report on results of tandem amorphous/microcrystalline (a-Si:H/µc-Si:H) silicon solar cells developed in commercial Oerlikon Solar KAI PECVD reactors, at an excitation frequency of 40.68 MHz. The cell structure consists of a stack of glass/front contact/pin a-Si:H/intermediate reflector/pin µc-Si:H/back contact. LPCVD (low-pressure chemical vapor deposition) ZnO (zinc oxide) is applied as front and back transparent conductive contacts. The silicon oxide based intermediate reflector (SOIR) is deposited in-situ.

Two regimes are studied here for µc-Si:H: (i) low silane concentration (SC) regime with SC < 10% and a growth rate of 0.40 nm/s and (ii) high silane concentration regime with SC ~ 30% and a lower total gas flux, where the growth rate could be raised up to 1 nm/s in a modified KAI-M reactor. In the low SC regime, our best micromorph tandem solar cells achieve initial efficiencies up to 10.9% for a cell size > 1cm^2 and in-situ SOIR. Under high SC conditions, the highest initial efficiency reached so far is 10.5%, again with in-situ SOIR. We demonstrate that high efficiency micromorph solar cells can hence be fabricated under conditions that are highly favorable to low-cost fabrication of tandem modules at an industrial level. Further investigations are now focused on the improvement of µc-Si:H material at 1 nm/s.

1 INTRODUCTION

In a recent study [1], we showed that microcrystalline silicon deposited under high silane concentration regime can be used for high efficiency micromorph tandem solar cells. In this regime, the silane concentration is increased up to 30% for a reduced total gas flow. The minimum necessary silane gas flow is calculated based on the desired deposition rate, under the assumption of maximum gas consumption within the plasma [2, 3]. There are three major advantages for high depletion deposition: (i) the feedstock gas consumption is reduced by a factor close to ten, (ii) the growth rate is increased up to 1-1.2 nm/s which leads to shorter fabrication times and finally (iii) a low RF power density (~0.2 W/ cm^2) can be used which implies a reduced substrate heating during deposition.

Here, we present the results obtained in this regime, as well as in the low silane concentration regime that leads to a higher efficiency but with a lower growth rate of µc-Si:H about 0.40 nm/s. The basic structure of a tandem micromorph consists of a stack of glass/front contact/pin a-Si:H/pin µc-Si:H/back contact. The thickness of the a-Si:H cell has to be kept as thin as possible to reduce the impact of the Staebler-Wronski effect [4]; its current thus generally limits the current of the whole tandem device. To overcome this issue, an intermediate reflector (IR) is introduced between the top and the bottom cells in order to increase the current of the first one. For a layer to act as intermediate reflector, its refractive index n must be lower than 3.8 at 600 nm (refractive index for silicon), to produce a refractive index step that leads to light reflection at the interface. The IR must be sufficiently conductive, but as transparent as possible to minimize the current losses due to absorption of light outside the active layers. Here we employ an IR that was developed in the KAI reactors, leading to a complete single-chamber process for the micromorph tandem.

2 EXPERIMENTAL

2.1 Sample

The single-junction µc-Si:H and tandem micromorph solar cells were deposited in pin configuration on AF-45 glass substrates covered with LPCVD (low-pressure chemical vapour deposition) ZnO (zinc oxide) as back and front contact [5]. A surface treatment, such as presented in [6] was applied to the front ZnO and a dielectric reflector is added to the back ZnO. The cells were deposited in Oerlikon KAI-S and KAI-M R&D deposition systems at an excitation frequency of 40.68 MHz. The solar cells are fully patterned with areas of 0.25 cm^2 or 1.2 cm^2.

2.2 Characterization techniques

Electrical characteristics of the cells are obtained from current-voltage measurements measured under a WACOM solar simulator in standard test conditions (25 °C, AM1.5g spectrum, and 1000 W/m^2) as well as external quantum efficiency measurements (EQE). The short-circuit current density is calculated from the measurement of the external quantum efficiency (EQE) curve, by integrating, over the wavelength range from 350 to 1000nm, the product of EQE times the incoming spectral density of photon flux of the solar spectrum.

The solar cells are light-soaked under open-circuit conditions at a temperature of 50°C, under an AM 1.5-like spectrum (1000 W/m^2).

To assess the material's quality of the µc-Si:H i-layer incorporated in the single-junction devices, Fourier transform photocurrent spectroscopy (FTPS) was employed. This technique allows the acquisition of the absorption spectrum over several orders of magnitude; the setup consists of a FTIR spectrometer from which the output beam is focused on the solar cell. Further details can be found in [7].

The FTPS spectra were calibrated at 1.35 eV, by setting the absorption coefficient of the µc-Si:H cell to the known value of crystalline silicon, i.e. $\alpha_{c\text{-}Si}$ (1.35 eV) ~ 240 cm^{-1} The defect-related absorption, which is defined as the absorption coefficient value at 0.8 eV, is directly related to defect density and, hence, to the i-layer material's quality, see e.g. [7-8].

3 RESULTS

As previously mentioned, the thickness of the top a-Si:H is kept as thin a possible by implementing an intermediate reflector between the top and the bottom cells of the micromorph tandem. Hence, for progress towards industrialization, effort was concentrated towards the development of an in-situ intermediate reflector in the KAI reactors, see [1] as well. As starting point, an ex-situ silicon oxide-based intermediate reflector (SOIR) was originally used in our tandems; it was deposited by very-high frequency PECVD at 110 MHz, and 200 °C in a small area reactor. Further details for this SOIR were given in [9].

The effect of the introduction of this particular SOIR on the external quantum efficiency (EQE) curves of the top and bottom cells of a micromorph tandem solar cell is shown in Fig. 1. We observe that the quantum efficiency of the top cell is enhanced for wavelengths between ~ 550 and 800 nm; this increase in EQE leads in that case to an absolute gain in short-circuit current density of 1.03 mA/cm^2, whereas the short-circuit density of the bottom cell is reduced by 1.64 ma/cm^2. This loss can easily be compensated by an increase of the μc-Si:H i-layer thickness without (strongly) affecting the light-induced degradation.

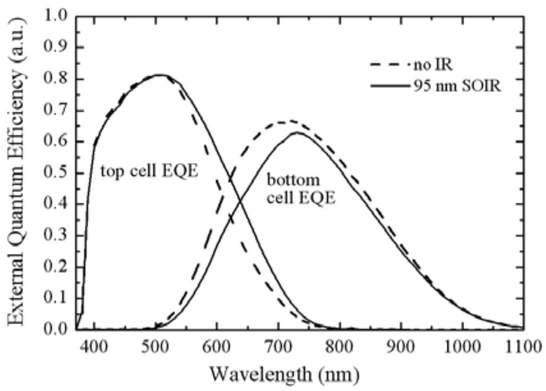

Figure 1: External Quantum Efficiency measurement of micromorph tandem solar cell (area 0.25 cm^2), deposited under low depletion conditions with and without 95 nm thick PECVD silicon oxide based intermediate reflector (ex-situ). The thicknesses of the layers are 250 nm for the top cell and 1.6 μm for the bottom cell.

Next, in order to get a complete process in the KAI reactors for the micromorph tandems, an in-situ SOIR was developed. Its reflectance and transmittance values, as measured by a Perkin-Elmer spectrometer type lambda 900, are presented in Fig. 2 for a spectral range from 320 to 2000 nm. The refractive index n was estimated by fitting the transmittance and reflectance spectra [10]: n ~ 2 at 600 nm.

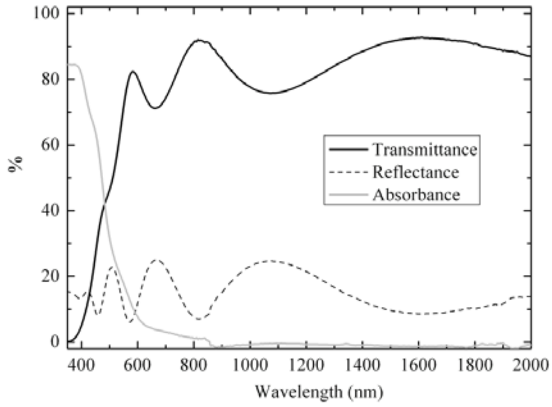

Figure 2: Transmittance, reflectance and absorbance as a function of wavelength for the in-situ SiO based intermediate reflector developed in the KAI deposition system.

Fig. 3 shows the initial IV characteristics of the best micromorph tandem cell obtained under low SC conditions with in-situ SOIR (cell area: 1.2 cm^2). The initial efficacy is equal to 10.9% for a μc-Si:H growth rate of 0.40 nm/s; a relative degradation of about 10 to 12% is expected.

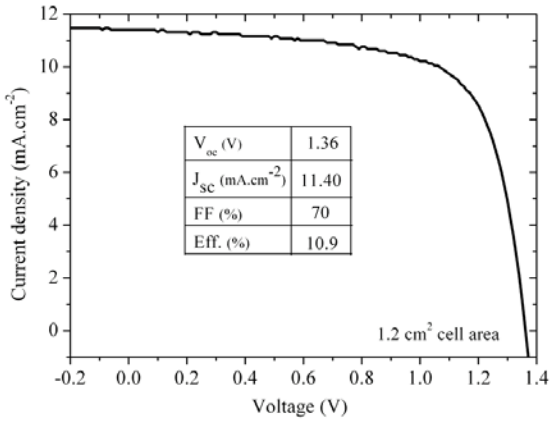

Figure 3: Initial I-V characteristics of a-SiH/μc-Si:H tandem solar cell deposited under low SC conditions with in-situ SiO-based intermediate reflector (SOIR). The cell thicknesses are ~ 300 nm for the top a-Si:H cell, ~ 2 μm for the bottom μc-Si:H cell. The short-circuit current density of the tandem is limited by the bottom cell.

In order to further reduce deposition costs, the effort was then focused on decreasing the deposition time of μc-Si:H. In order to raise the growth rate without powder formation issues, the KAI-M reactor was slightly modified. Single-junction solar cells were first deposited: an initial efficiency of 7.0% is obtained versus 8.2% under low silane concentration conditions. The electrical performances of the single-junction μc-Si:H solar cell at 1 nm/s is presented in Fig. 4.

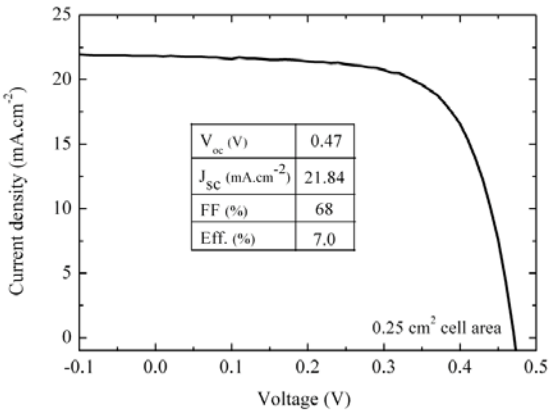

Figure 4: Initial I-V characteristics of μc-Si:H single-junction solar cell deposited under high silane concentration regime at 1 nm/s. The cell thickness is 1.2 μm

Further optimization is under way to increase the efficiency; however, in order to better understand the reduction in efficiency observed at 1 nm/s, the quality of the μc-Si:H material in the single-junction cells was checked with Fourier Transform Photocurrent Spectroscopy (FTPS). Absorption spectra are presented in Fig. 5 for both high and low silane concentrations.

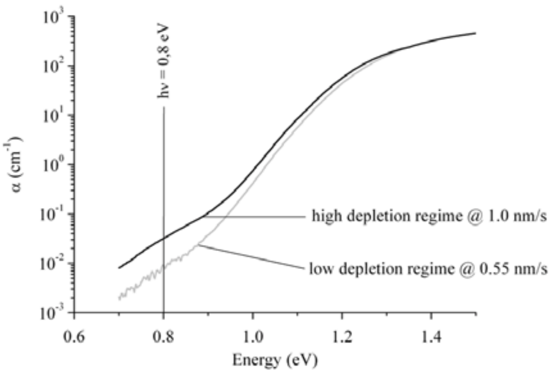

Figure 5: Absorption spectra as a function of energy for single-junction μc-Si:H solar cells deposited under 2 regimes: (i) high silane concentration (SC ~ 30%) at 1 nm/s, (ii) low silane conditions (SC < 10%) at 0.40 nm/s

The highest material's quality (i.e. the lowest α(0.8 eV) value) is obtained under low SC conditions; the defect-related absorption is increased by a factor ~ 3.5 when high SC regime is used. The larger defect density measured is thus probably responsible for the discrepancy observed in the electrical performances (V_{oc}, FF) between single-junction cells deposited in both regimes. Nevertheless, we cannot exclude some issues of crystallinity or defects at the doped/i-layer interfaces (these defects are not detected by FTPS) as well. Furthermore, the i-layer crystallinity, that may be slightly different in both regimes, can also influence the defect-related absorption value (we observe typically a minimum of α(0.8 eV) for Raman crystallinites of the order of 50%, see e.g. [9]).

Still, very promising results of micromorph tandem have been obtained under high SC conditions with in-situ SOIR, as shown in Fig. 6 with an initial efficiency of 10.5% for an a-Si:H top cell ~ 220 nm thick and a μc-Si:H bottom cell thickness of 1.8 μm. The short-circuit densities are perfectly matched with 11.4 mA/cm^2 in the top cell and 11.3 mA/cm^2 in the bottom cell.

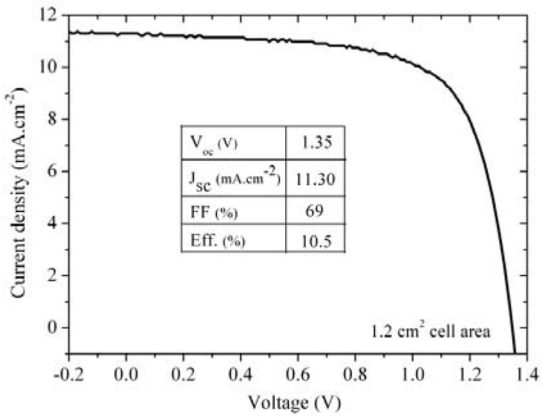

Figure 6: Initial I-V characteristics of a-SiH/μc-Si:H tandem solar cell deposited under high SC and low total gas flow conditions with in-situ SiO-based intermediate reflector (SOIR). The cell thicknesses are ~ 220 nm for the top a-Si:H cell, 1.8 μm for the bottom (limiting) μc-Si:H cell, deposited at 1 nm/s

4 CONCLUSIONS

As commonly stated, the major goal for thin-film photovoltaics is to further lower the price per watt peak for modules. Such a goal will be achieved by simultaneously increasing the devices efficiency as well as reducing the fabrication costs. We have presented here the latest results of development towards industrialization in industrial KAI reactors and demonstrated the feasibilty of using:

- high depletion conditions for μc-Si:H material deposition at growth rates up to 1 nm/s leading to high efficiency tandem micromorph solar cells with an initial efficiency up to 10.5% (10.9% under low SC conditions);

- an efficient in-situ SOIR in the KAI reactors.

Additional investigations are now focused on device optimization in the various plasma regimes, also including SOIR layers. In particular, the material's quality of μc-Si:H at 1 nm/s should be further improved.

5 ACKNOWLEDGMENTS

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