21% EFFICIENCY SILICON HETEROJUNCTION SOLAR CELLS PRODUCED WITH VERY HIGH FREQUENCY PECVD

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ABSTRACT

Silicon heterojunction solar cells have high open-circuit voltages thanks to excellent passivation of the wafer surfaces by thin intrinsic amorphous silicon (a-Si:H) layers deposited by plasma-enhanced chemical vapor deposition (PECVD). By using *in-situ* plasma diagnostics and *ex-situ* film characterization, we show that the best a-Si:H films for passivation are produced from deposition regimes close to the amorphous-to-crystalline transition. Based upon this finding, layers deposited in a large-area very high frequency (40.68 MHz) PECVD reactor were optimized for heterojunction solar cells. 4 cm^2 solar cells were produced with fully industry-compatible processes, yielding open-circuit voltages up to 725 mV and aperture area efficiencies up to 21%.

1. INTRODUCTION

Among high-efficiency devices, silicon heterojunction solar cells stand out for their high performance and potential for low production cost. Conversion efficiencies of 23% and open-circuit voltages up to 743 mV on thin wafers have been demonstrated [1]. Passivation of the crystalline silicon (c-Si) wafer surfaces is achieved with very thin intrinsic hydrogenated amorphous silicon (a-Si:H) layers, deposited by plasma-enhanced chemical vapor deposition (PECVD) or similar methods. The emitter and back surface field of the cell are formed with PECVD doped a-Si:H layers. The simple structure of these cells requires only low-temperature processes that are already used at the industrial scale.

To achieve high open-circuit voltage and therefore high efficiency, the passivation of the wafer surfaces by the thin intrinsic a-Si:H layers has to be as good as possible. An a-Si:H layer passivates a c-Si surface mainly by hydrogenation of the silicon dangling bonds, leading to a reduction of the interface defect density. It has been shown for thin film silicon solar cells that device-grade a-Si:H material is produced from deposition regimes close to the crystalline transition [2]. This can be achieved by using highly diluted or highly depleted silane (SiH_4) plasmas, for example. In this study, we show that the best a-Si:H film quality for c-Si passivation is also obtained close to this transition. When depositing on c-Si substrates, however, epitaxial growth has to be avoided because of its detrimental effect to passivation. Consequently, the amorphous-to-crystalline transition must be approached with caution when depositing on wafers.

2. EXPERIMENTS

Amorphous silicon layers were deposited in an automated large-area (electrode size 50 x 60 cm^2), narrow-gap (13 mm), parallel-plate PECVD reactor powered at very high frequency (VHF, 40.68 MHz). It is equipped with several *in-situ* plasma diagnostics, such as a plasma impedance probe, an optical emission spectrometer and an infrared laser-based spectrometer for silane density measurements [3]. Deposited layers were analyzed *ex-situ* with spectroscopic ellipsometry and by attenuated total reflectance Fourier transform infrared (ATR-FTIR) spectroscopy.

The structure of the 2 x 2 cm^2 heterojunction solar cells was as follows: Ag front grid / In_2O_3:Sn (ITO) 80 nm / p^+ a-Si:H 10 nm / *i* a-Si:H 5 nm / textured FZ *n* c-Si 230 μm / *i* a-Si:H 5 nm / n^+ a-Si:H 10 nm / ITO 200 nm / Ag back metallization. First, the *n*-type (100) FZ c-Si wafers were textured in KOH, wet-chemically cleaned, and dipped in HF just before PECVD. Intrinsic and doped a-Si:H layers were deposited using mixtures of SiH_4, H_2, PH_3 and $B(CH_3)_3$. Both ITO layers and the back metallization were deposited by DC magnetron sputtering. Finally, a front grid was screen-printed with a low temperature silver paste. All these fabrication steps are fully compatible for cell production at an industrial scale.

3. RESULTS AND DISCUSSION

3.1 Optimization of a-Si:H passivating layers

We have shown in a previous publication that a-Si:H layers used for c-Si wafer passivation can be efficiently tuned knowing the silane depletion fraction during

deposition [4]. Indeed, it appears that the depletion is a much more relevant parameter than other plasma properties. Good passivating layers were obtained from highly-depleted plasmas, i.e. close to the amorphous-to-crystalline transition. The depletion was measured *in-situ* during deposition with an infrared laser-based plasma diagnostic tool.

To come closer to this transition without risking epitaxial growth, we tested additionally hydrogen (H_2) plasma treatments during a-Si:H growth. It is known that such treatments can lead to complete crystallization of a-Si:H, due to removal of strained bonds from the a-Si:H growth surface by H atoms [5]. Infrared spectroscopy of the treated and untreated a-Si:H layers shows significant differences in silicon-hydrogen bonding (fig. 1). The hydrogen content in the layer clearly increases when H_2 treatment is used. Lifetime measurements show that treated layers provide better c-Si passivation as-deposited, probably due to an improved hydrogenation of the interface. More details can be found in [6].

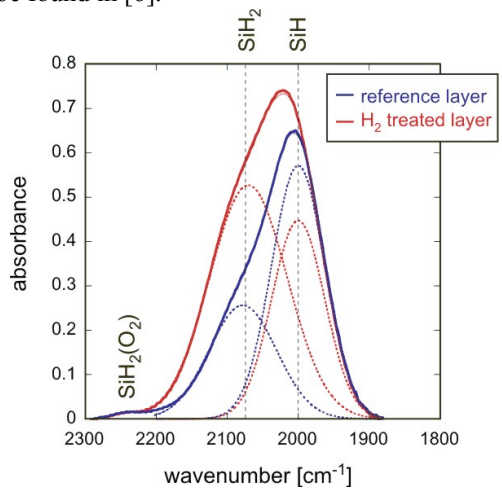

Fig. 1: Absorbance spectra of 15 nm thick H_2-treated and untreated a-Si:H layers deposited on (111) c-Si wafers measured by ATR-FTIR. Spectra were deconvoluted with two gaussians, centered at 2000 and 2080 cm^{-1} (monohydride and higher hydrides bonds respectively, stretching mode). Data taken from [6].

3.2 Application to silicon heterojunction solar cells

Based on these results, deposition conditions were optimized specifically to improve the passivation level. Carrier lifetimes up to 11.2 ms and 7.2 ms have been obtained on polished and textured wafers, respectively, with as-deposited a-Si:H layers as thin as 12 nm (lifetime values were measured at an excess carrier density of 10^{15} cm^{-3}). On solar cell precursors (textured wafers passivated with ~15 nm *in* and *ip* a-Si:H stacks), lifetimes up to 8.3 ms were measured as-deposited, giving a so-called implied open-circuit voltage of 734 mV. This demonstrates that layers deposited at relatively high deposition rates (> 0.6 nm/s) with VHF can provide excellent passivation. Heterojunction solar cells were completed with fully industry compatible processes, as described previously. The best 4 cm^2 solar cell shows an aperture area efficiency of 21% (fig. 2).

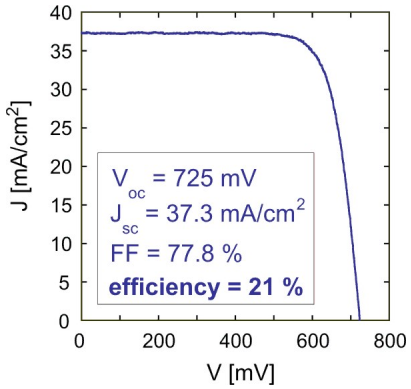

Fig. 2: IV curve of the best 2 x 2 cm^2 heterojunction solar cell.

4. CONCLUSIONS

The use of plasma diagnostics during PECVD and of film characterization tools after deposition are highly valuable for the optimization of devices. We have shown that good a-Si:H passivating layers are deposited from regimes close to the crystalline transition. This can be achieved by using highly-depleted silane plasmas and by applying additionally hydrogen plasma treatments. Produced in a large area industrial VHF PECVD reactor, medium-sized silicon heterojunction solar cells were optimized using this approach, yielding V_{oc}'s up to 725 mV and efficiencies up to 21%.

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