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Ultra-high quality surface passivation of crystalline silicon wafers in large area parallel plate reactor at 40 MHz

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ABSTRACT

We use a new in-house, large area and automated deposition system: the usable deposition area is 410×520 mm with RF-frequency of 40 MHz. We deposit intrinsic a-Si:H layer on flat p-type or n-type c-Si wafers after performing an HF dip. The overall recombination of these double-side passivated c-Si wafers is measured with an effective lifetime measurement set-up. We pay particular attention to the uniformity of the passivation obtained on the whole deposition area.

We point out a major role of hydrogen dilution on quality of c-Si passivation. Excellent uniformity is obtained on the whole area with implied open-circuit voltages (V_{oc}) in a ±1.5% range. We achieve excellent passivation with overall lifetimes approaching 7 ms (at $\Delta n \approx 4.5 \cdot 10^{14}$ cm^{-3}) resulting in implied V_{oc} of 708 mV on p-type c-Si; and lifetimes superior to 4.7 ms resulting in implied V_{oc} of 726 mV on n-type c-Si (S_{eff} less than 2 cm/s for both). These results open the way to very high efficiency heterojunction solar cell fabrication in large area reactors.

1. Introduction

Based on constant innovation, crystalline silicon (c-Si) solar cells are still dominating the photovoltaic market. One of these innovations consists in combining the c-Si technology with the amorphous silicon (a-Si:H) one. Fuhs et al. have first used heterojunctions of a-Si:H and c-Si as devices [1]. Then, Sanyo has industrially developed this concept for solar cells [2]. Advantages of heterojunction (HJ) solar cells are plentiful: outstanding surface passivation, low temperature process, high conversion efficiency and the ability to process very thin wafers (<150 μm). Moreover, HJ solar cells exhibit better temperature characteristics than conventional c-Si ones which means that more power is generated in outdoor conditions for the same *nominal* conversion efficiency.

In order to industrialize this technology in Europe, one has to first demonstrate excellent passivation on large areas. In this paper, we report first results of passivation obtained with a new large area parallel plate reactor in the Institute of Microtechnology of Neuchâtel. This VHF-PECVD system is compatible with industrial requirements: load-lock (reproducibility, throughput), etching plasma for reactor cleaning (reproducibility), multi-chamber (avoiding cross-contamination), and a fully-automated and large area (more than 0.21 m^2). A particular attention has been paid to the uniformity of deposition.

2. Experiments

We use a new in-house-built, large area deposition system whose deposition area is 420 mm×510 mm and the electrode dimensions are 510 mm×600 mm. It is a VHF-PECVD set-up with a 40 MHz frequency. SF_6 plasma is available to etch walls. The load-lock allows high throughput and the plasma box of type KAI-M (from Unaxis) enables to associate isothermal heating in the reactor with differential pumping, which greatly reduces process contamination. To increase reproducibility, we always start deposition on samples after SF_6 etching and identical coatings of the walls. Some depositions have been duplicated to evaluate the reproducibility. We deposit a-Si:H layers on glass (Schott AF 45, 0.5 mm) and/or FZ c-Si wafers (n-type and p-type). We systematically deposit 45 nm of intrinsic a-Si:H (i a-Si:H) on both sides of c-Si wafers. We only use one chamber of the system since we deposit i a-Si:H. We perform an HF dip to strip off the native oxide (45″, 4% diluted in DI water) on c-Si samples and immediately load them afterwards into the VHF-PECVD reactor which is always pumped down to a pressure below 10^{-6} mbar before deposition. Amorphous layers are all deposited at 200 °C.

To investigate the a-Si:H properties and the deposition rate, spectroscopic ellipsometry (SE) measurements were carried out with a phase-modulated spectroscopic ellipsometer (UVISEL 2 Horiba Jobin Yvon). The overall recombination of c-Si samples is measured with an effective lifetime measurement (τ_{eff}) set-up (Sinton WCT-100). This measurement consists in illuminating samples with a flash lamp generating therefore excess carriers in the c-Si bulk ($\Delta n = \Delta p$). The τ_{eff} of these photogenerated carriers is then measured via the change of the wafer conductivity and an implied V_{oc} at 1 sun can be deduced

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(which has been proven to be very similar to the *real* V_{oc} of a solar cell with the same structure) [3,4]. We also use infrared camera lifetime mapping (ILM) measurements to quantify the uniformity of passivation on the same c-Si wafer. This technique is based on the infrared emission of photogenerated free carriers [5]. Results of τ_{eff} will be shown after thermal annealing that was performed at 180 °C during 90 min in a programmable process furnace (ATV-PEO 603) with a controlled nitrogen atmosphere.

3. Results and discussion

3.1. Hydrogen dilution of intrinsic a-Si:H

We explore a wide process window with silane plasma spreading a three-fold range in pressure from 0.3 mbar to 0.9 mbar. We change power density and hydrogen dilution ratio ("H_2 ratio" = $[H_2]/[SiH_4]$). For this set, we use lightly-doped p-type (130 Ω·cm) FZ c-Si wafers with a (100) orientation and a thickness of 525 µm. By means of SE measurements, we check that the material deposited is amorphous and not microcrystalline. Fig. 1 shows passivation results after annealing of different 45 nm thick i a-Si:H layers deposited on this p-type c-Si. One can clearly distinguish two groups of samples whatever pressure: one with hydrogen dilution ratio above 2 and one with low hydrogen dilution ratio. The first group presents low τ_{eff} and even more peculiarly an important negative slope in the τ_{eff} curves for Δn above $3\cdot10^{14}$ cm^{-3}. SE measurements enable to confirm that no epitaxial growth occurs in this higher range of hydrogen dilution. The second group of p-type c-Si samples exhibits very high τ_{eff} and thus implied high V_{oc} whatever the pressure (parameters in caption of Fig. 1). The best τ_{eff} is 6.8 ms at $\Delta n = 3.5\cdot10^{14}$ cm^{-3} and an implied V_{oc} of 708 mV for sample number 5 (no hydrogen dilution). In this well-passivated set, the deposition rate is diverse ranging from 3 Å/s to 12 Å/s. We want to highlight that we reach outstanding passivation without paying a particular attention to HF cleanliness. Contrary to many teams [6,7], we have not noticed, until now, a specific sensitivity of the c-Si surface passivation to HF dip (neither the agedness of the solution nor the resistivity of the used DI water).

3.2. Homogeneity

To an industrial purpose, we extensively study spatial uniformity of this new deposition set-up. In order to examine the homogeneity of a-Si:H properties, we place six glass samples over the whole deposition area. Spectroscopic ellipsometry is used to rapidly characterize a-Si:H properties and thicknesses. One can see, on Fig. 2, the ellipsometric spectra of i a-Si:H deposited on these six glass samples. Spectra are very similar with only slight differences in the near infrared–visible region, linked to thickness variation. The UV region of spectra which is related to the material properties is exactly the same. We apply the Tauc–Lorentz dispersion law to fit our experimental data which enables excellent fits (χ^2 always inferior to 0.25). A roughness layer consisting of 50% of a-Si:H and 50% of void is systematically added to the model. The empirical Tauc–Lorentz expression for the imaginary part of the dielectric function is [8]:

$$\varepsilon_{im}(E) = \frac{A\cdot E_0\cdot C\cdot\left(E-E_g\right)^2}{E\cdot\left[\left(E^2-E_0^2\right)^2+C^2\cdot E^2\right]} \text{ if } E>E_g;\varepsilon_{im}(E)=0 \text{ if } E\le E_g$$

where A is a prefactor, E_0 is the peak transition energy, E_g is the gap energy and C is a broadening parameter. As one can notice, A is proportional to the height of ε_{im} and is related to the material density; C is correlated to the degree of disorder in the material (the higher C, the

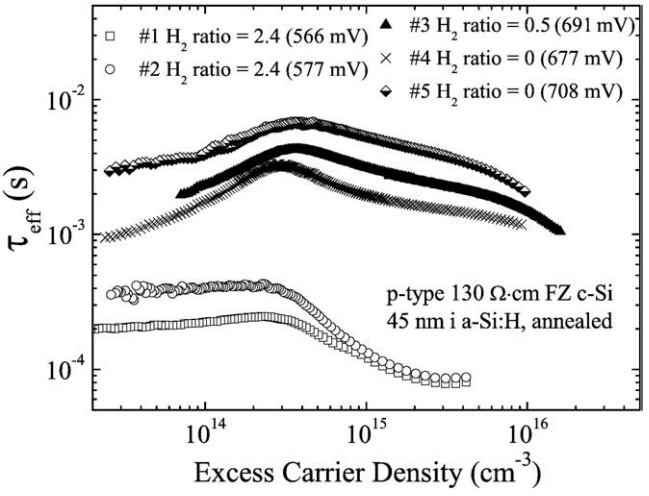

Fig. 1. Effective lifetime as a function of excess carrier density of double-side passivated p-type 130 Ω·cm FZ c-Si samples (results *after* annealing). Implied V_{oc} of each sample is in brackets. "H_2 ratio" = [H2]/[SiH4]. Pressure of plasma deposition varies as follows: #1 p = 0.6 mbar (H_2 ratio = 2.4); #2 p = 0.9 mbar (H_2 ratio = 2.4); #3 p = 0.6 mbar (H_2 ratio = 0.5); #4 p = 0.3 mbar (H_2 ratio = 0); #5 p = 0.9 mbar (H_2 ratio = 0).

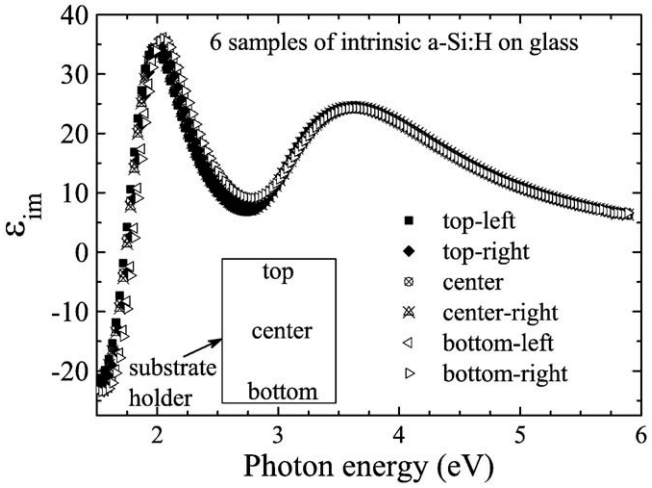

Fig. 2. Ellipsometric measurements. Imaginary part of pseudo-dielectric function of i a-Si:H films deposited on six glass substrates placed dispersed on the deposition area. Deposition conditions are as follows: p = 0.6 mbar and H_2 ratio = 0.5 (#3 of Fig. 1).

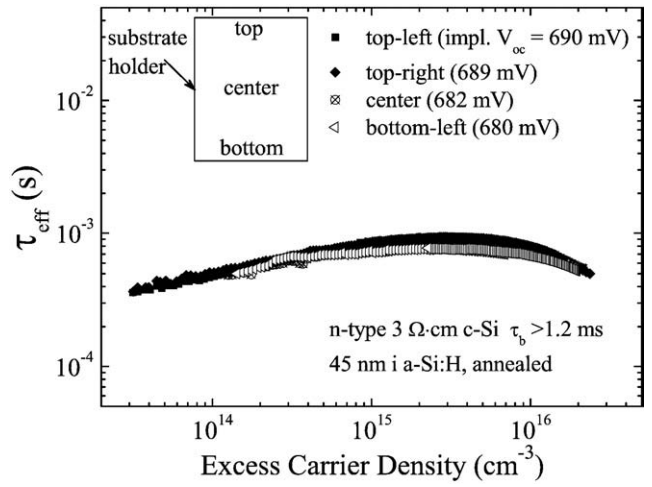

Fig. 3. Effective lifetime as a function of excess carrier density for n-type c-Si quarter-wafers (FZ, 3 Ω·cm, τ_b > 1.2 ms) passivated by 45 nm of i a-Si:H. The implied V_{oc} of each sample is given in brackets. One can note the excellent uniformity.