

Silicon heterojunction solar cells: Influence of H₂-dilution on cell performance

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ABSTRACT

Surface passivation of hydrogenated amorphous silicon (a-Si:H) films is critically influenced by the hydrogen/silane ratio during PECVD deposition. Das et al. (2008) studied this effect with respect to the crystal orientation of c-Si wafer substrates. We revisit the effect of the hydrogen/silane ratio and observe modifications compared to their study: we obtain V_{OC} -values > 710 mV and find for textured and on (1 1 1)-oriented substrate surfaces that the effective carrier lifetime and V_{OC} -values of solar cells benefit from increasing the hydrogen/silane ratio. The implied open-circuit voltages from lifetime measurements on our samples agree well with the final solar cell open-circuit voltages. We achieve high surface passivation, resulting in $V_{OC} > 710$ mV and efficiencies up to 19.4% for 4 cm² solar cells.

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1. Introduction

Silicon heterojunction solar cells can provide high conversion efficiencies up to 23% and open-circuit voltages up to 743 mV [1] due to the excellent surface passivation of thin hydrogenated amorphous silicon (a-Si:H) films. The passivation quality of such a-Si:H films is critically influenced by the hydrogen/silane ratio during the PECVD deposition [2]. High hydrogen dilution promotes the formation of crystallites even on amorphous substrates such as glass. On c-Si wafers, high hydrogen/silane ratios can lead to (defected) epitaxial growth and thus low surface passivation quality [3]. Such adverse epitaxial growth also depends on the crystal orientation of c-Si wafer substrates [4,5]. We revisit the effect of the hydrogen/silane ratio with respect to the crystal orientation of c-Si wafer substrates. In our studies we choose plasma conditions that do not produce any Raman-detectable crystalline signal for 300 nm thick films on glass, even for very high hydrogen/silane ratios.

2. Experiments

For the a-Si:H depositions we use a CS 400P PECVD-cluster-system of von Ardenne. For the intrinsic and doped a-Si:H depositions we use a 13.65 MHz parallel plate PECVD reactor respectively with a diameter of 27 cm. The deposition parameters are given in Table 1. Plasma power, electrode distance and set temperature are

the result of optimization of the passivation properties of 10 nm thick intrinsic a-Si:H films on Si wafer substrates. The power density of 35 mW/cm² used in our study seems similar to the investigation of Das et al. with 30 W on their area of 30 × 35 cm² [5]. The specified temperature refers to the set-temperature within the bottom electrode of the deposition system. Our actual samples lie on an aluminum carrier situated on top of this bottom electrode. Thus the thermal contact between the 300 °C bottom electrode and our samples is weak. The actual sample temperature is therefore considerably lower than the set temperature and expected to lie in the range of 200–235 °C as commonly found in literature for well-passivating a-Si:H layers [6,7].

We fabricate solar cells on four different wafer surfaces; we use polished and damage etched 3 Ω cm n-type float zone (FZ) wafers with (1 0 0) crystal orientation, textured 3 Ω cm n-type FZ wafers where the (1 0 0) surface changes to pyramids with (1 1 1)-oriented facets and chemically polished 70 Ω cm n-type FZ wafers with (1 1 1) crystal orientation.

Prior to each (i)a-Si:H deposition the wafers were RCA-cleaned, followed by a 1% HF dip, subsequently rinsed in deionized (DI) water for 1 min and dried with dry nitrogen. We then deposit 5 nm (i)a-Si:H on each side of the wafers with the parameters given in Table 1. The silane concentration (SC) was varied from 4.2% to 33.3% and is given by $SC = [SiH_4] / ([SiH_4] + [H_2])$. Note that the similar experiment of Das et al. [5] employed higher concentration (10%) HF dips without subsequent rinsing in DI water.

The wafers were dipped in 1% HF for 1 min plus subsequent rinsing in DI water and drying in nitrogen prior to the following (n)a-Si:H and (p)a-Si:H depositions. After the a-Si:H depositions

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Table 1
Process parameters during a-Si:H depositions. Plasma power, electrode distance and set temperature are the result of optimization of the passivation properties of 10 nm thick intrinsic a-Si:H films on Si wafer substrates. The specified temperature is the set-temperature within the bottom electrode of our deposition system. The sample temperature is expected to be about 100 °C lower.

	Set-temperature [°C]	Deposition pressure [mbar]	Electrode distance [mm]	Power density [mW/cm ²]	SiH ₄ flow [sccm]	H ₂ flow [sccm]	PH ₃ flow [sccm]	B ₂ H ₆ flow [sccm]
(i)a-Si:H	300	0.85	50	35	5–40	105–80	–	–
(n)a-Si:H	300	0.85	50	35	20	88	12	–
(p)a-Si:H	220	0.85	50	35	20	84	–	16

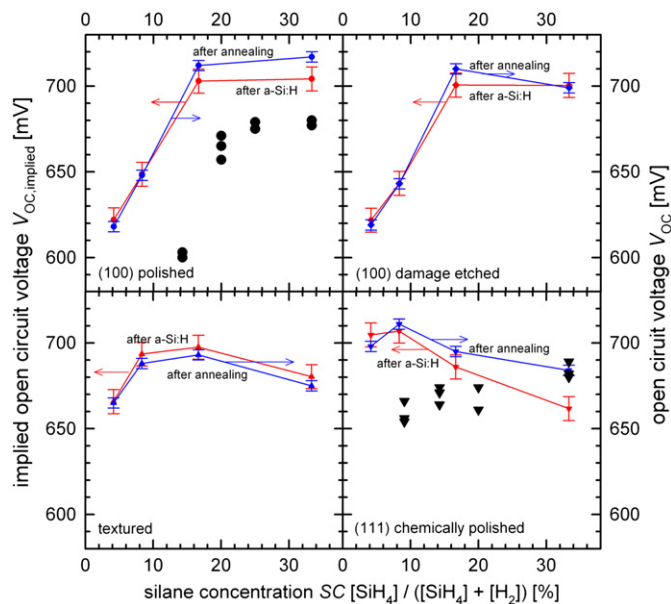


Fig. 1. The V_{OC} data for the four different surfaces of the samples are plotted as a function of the silane concentration. The $V_{OC,implied}$ data obtained from the lifetime measurements are shown as red symbols and the V_{OC} data from the J - V curves of our SHJ solar cells are shown as blue symbols. The red and blue lines are guides to the eye only. The black data points are V_{OC} data point reported by Das et al. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

we perform quasi steady state photoconductance decay (QSSPC) measurements and calculate implied open-circuit voltages ($V_{OC,implied}$) from the lifetime data [8]. ITO was sputtered onto both sides of the samples and the $V_{OC,implied}$ was measured again. After that we evaporated an aluminium grid on both sides and measured the J - V curves of the 4 cm² cells directly after evaporating the aluminium and after an annealing step for 5 min at 175 °C. J_{SC} was measured under illumination with a flash light while the J - V curves are measured under LED-array illumination ($\lambda=950$ nm) with an intensity that produces the same J_{SC} .

3. Results and discussion

The $V_{OC,implied}$ data obtained from the lifetime measurements and the V_{OC} data from the J - V curves of our SHJ solar cells are shown in Fig. 1. Fig. 1 plots the V_{OC} data for the four different surfaces of the samples as a function of the SC. We observe high $V_{OC,implied}$ values after the a-Si:H deposition for all types of sample surfaces (red symbols). However, we see different characteristic trends for the (1 0 0) and the (1 1 1) surfaces. For the samples with (1 0 0) surfaces (upper two graphs) we see a strong decrease of the V_{OC} for a SC < 16% whereas the cells with (1 1 1) surfaces

(lower two graphs) have still high V_{OC} for lower SC. We find a broad maximum of V_{OC} for the samples with (1 0 0) surfaces up to high SC whereas the samples with (1 1 1) surfaces have their V_{OC} maximum at a SC=8% for the chemically polished (1 1 1) surfaces. The textured samples reach their highest voltages at SC=16% and show a decrease of V_{OC} for higher SC. After ITO sputtering and Al-evaporation we anneal the solar cells for 5 min at 175 °C (blue data points in Fig. 1). We find that the V_{OC} -values reach again the level of the implied $V_{OC,implied}$ from the lifetime measurements prior to ITO sputtering.

Compared to the V_{OC} -values from Das et al. (black symbols) we achieve higher V_{OC} -values for (1 0 0)- and for (1 1 1)-oriented wafer substrates. We also observe a different trend of the V_{OC} -values for the (1 1 1) surfaces. While the V_{OC} -values from Das et al. decrease with higher hydrogen dilution we find an optimum of the V_{OC} -values at higher hydrogen dilution, i.e. SC=8%. This different behaviour may be associated with the different cleaning procedure and lower pressure in the experiment of Das et al.

We find - similarly to Das et al. - that for (1 0 0)-oriented Si wafer substrates very high hydrogen dilutions eventually lead to decreased surface passivation quality. Our reference Si-films on glass exhibit no Raman-detectable crystalline signal, but it is known that (1 0 0)-orientation facilitates silicon epitaxy [6,9]. Ross et al. [10] described how a crystalline substrate promotes the formation of crystalline growth in PECVD.

We therefore perform ellipsometry measurements using a Woollam M-2000 instrument. We investigated the polished (1 0 0) and (1 1 1) wafers after the (i)a-Si:H depositions with a silane concentration of 4.2% and 16%, respectively. The imaginary part of the pseudodielectric function $\langle \epsilon_1 \rangle + i \langle \epsilon_2 \rangle$ is shown in Fig. 2. The (1 0 0) sample with the film deposited with a low silane concentration (SC=4.2%) clearly shows a crystalline signature. This is a distinct difference to the film deposited with a high silane concentration (SC=16%) on the (1 0 0) substrate, and also different to both types of film depositions (i.e., SC=16% and SC=4.2%) on the (1 1 1) wafers. Thus, measured effective carrier lifetime data correlates well with the structural properties of the deposited films. We therefore attribute the decay of passivation quality of (1 0 0)-oriented wafers with increasing hydrogen dilution to the formation of defected epitaxial growth [6].

In our experiment we observe that the absolute V_{OC} values for the textured surfaces are lower than for the planar surfaces. It is well known that the surface passivation quality depends on the thickness of the (i)a-Si:H layer. In particular, it has been shown by Olibet [11] that textured surfaces lead to a reduced layer thickness by a factor of 1.7 in comparison to planar surfaces due to the enlarged surface area.

In order to test the influence of the local layer thickness on the surface passivation of our textured samples, we perform the following experiment: We choose the deposition regime with 16% SC of Fig. 1 and prepare a-Si passivation and solar cells on planar and textured wafers with two different (i)a-Si:H layer deposition durations. Fig. 3 shows V_{OC} data of textured and planar wafers coated in the same deposition process, that leads to 5 nm thick (i)a-Si:H layers on planar surfaces. Also shown in Fig. 3 are

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