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# Progress in a-Si:H/c-Si heterojunction emitters obtained by Hot-Wire CVD at 200 °C

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**Abstract**

In this work, we investigate heterojunction emitters deposited by Hot-Wire CVD on *p*-type crystalline silicon. The emitter structure consists of an *n*-doped film (20 nm) combined with a thin intrinsic hydrogenated amorphous silicon buffer layer (5 nm). The microstructure of these films has been studied by spectroscopic ellipsometry in the UV–visible range. These measurements reveal that the microstructure of the *n*-doped film is strongly influenced by the amorphous silicon buffer. The Quasy-Steady-State Photoconductance (QSS-PC) technique allows us to estimate implicit open-circuit voltages near 700 mV for heterojunction emitters on *p*-type (0.8 Ω·cm) FZ silicon wafers. Finally, 1 $cm^2$ heterojunction solar cells with 15.4% conversion efficiencies (total area) have been fabricated on flat *p*-type (14 Ω·cm) CZ silicon wafers with aluminum back-surface-field contact.
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*Keywords:* Hot-wire deposition; Solar cell; Heterostructure

## 1. Introduction

Heterojunction solar cells with thin hydrogenated amorphous silicon (a-Si:H) films deposited at low temperature on crystalline silicon (c-Si) wafers have attracted the interest of the photovoltaic community due to their high-efficiency and cost-effective fabrication process. Sanyo Electric Co. has reported conversion efficiencies ($\eta$) over 19% for mass produced solar cells with the so-called Heterojunction with Intrinsic Thin-layer (HIT) structure [1]. In this device a very thin (5 nm) intrinsic a-Si:H buffer reduces interface recombination, which leads to impressing open-circuit voltages ($V_{oc}$) over 700 mV. Most groups, included Sanyo, use the Plasma-Enhanced CVD technique to grow the a-Si:H films [2–4].

Recently, the Hot-Wire CVD (HWCVD) technique has also demonstrated its potential to fabricate high-efficiency heterojunction silicon solar cells [5]. In the HWCVD technique, besides some technological advantages, the absence of ion bombardment reduces the damage to the c-Si surface. During the last years, our group has also obtained promising results in heterojunction solar cells by HWCVD [6,7]. In this work, we concentrate our effort in optimizing the heterojunction emitter on *p*-type c-Si. Besides, the importance of the thin intrinsic a-Si:H buffer and the influence of hydrogen pre-treatment are discussed in detail.

## 2. Experimental

In this study, the wire configuration has been modified with respect to our previous works to enlarge the homogeneous deposition area to 4 cm × 4 cm. Two parallel tantalum wires (∅ = 0.5 mm) separated 3 cm have been installed, with the gas inlet centered 1 cm below the wires. The substrate is placed 4 cm above the plane of the wires. The deposition conditions have been extensively investigated for this new configuration to obtain high-quality films. The optimized parameters are summarized in Table 1. The chemical procedure to clean the c-Si wafers before being introduced into the HWCVD chamber has been described elsewhere [7]. Here, we have considered three different structures as n-type heterojunction emitters. First, an *n*-doped layer 20 nm thick deposited directly onto the

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Table 1
Optimized deposition conditions for the thin silicon films used in the heterojunction emitters. The wire temperature is 1600 °C in all cases

| Type | $T_s$ (°C) | $H_2$ (sccm) | $SiH_4$ (sccm) | $PH_3$ (sccm) | $p$ (mbar) |
|---|---|---|---|---|---|
| Intrinsic | 100 | – | 2 | – | $3.5\times10^{-3}$ |
| $n$-doped | 200 | 28 | 2 | 0.04 | $8\times10^{-2}$ |

cleaned c-Si surface (sample A). Second, a stack consisting of a very thin a-Si:H buffer layer (5 nm) followed by a 20 nm thick $n$-doped layer (sample B). Finally, the same stack as in sample B but preceded by hydrogen pre-treatment during 1 min (sample C). In this case, the c-Si surface is exposed to 20 sccm of hydrogen dissociated by the wire at 1700 °C under a process pressure of $3\times10^{-2}$ mbar.

The microstructure of the films is estimated by fitting the pseudo-dielectric function ($\varepsilon=\varepsilon_1+i\varepsilon_2$) measured by spectroscopic ellipsometry (SE) using the Bruggeman model [8]. On the other hand, the recombination in the emitter was assessed by the contactless QSS-PC technique. In this technique, the minority carrier effective lifetime ($\tau_{eff}$) is measured as a function of an averaged excess minority carrier density ($\Delta n_{avg}$). High-quality $p$-type (0.8 Ω·cm) FZ silicon wafers have been used for these experiments to avoid the influence of bulk recombination in the QSS-PC data.

Finally, flat $p$-type (14 Ω·cm) CZ silicon wafers with aluminum back-surface-field (Al-BSF) contact have been used to fabricate complete heterojunction solar cells. The front contact consisted of an indium-tin-oxide (ITO) anti-reflecting coating (80 nm) deposited by RF magnetron sputtering, followed by an evaporated silver grid with 8% shadowing. The active area of the solar cells is 1 $cm^2$.

## 3. Results and discussion

In Fig. 1 the imaginary part of the pseudo-dielectric function ($\varepsilon_2$) measured by SE is compared for the three samples previously described (symbols). Amorphous and crystalline silicon reference materials used in the Bruggemann model to fit the experimental data are also shown in the same plot (lines). The two-peak characteristic observed for sample A, resembling the c-Si model, is typical of epitaxial growth [9]. Actually, the fit with the Bruggemann model leads to a high crystalline fraction (Fc) of 90% for this sample. By contrast, the broad bands observed in sample B indicate an essentially amorphous growth, even though the deposition conditions of the $n$-doped layer are the same. The lower $\varepsilon_2$ values measured in sample B compared to A indicate a higher porosity, with a void fraction (Fv) close to 40%. A similar Fv value can be estimated for sample C. However, in this case the fit indicates a crystalline growth with Fc about 30% in the whole structure. This change indicates a strong influence of the hydrogen pre-treatment on the emitter microstructure, though no significant difference in the surface roughness was observed.

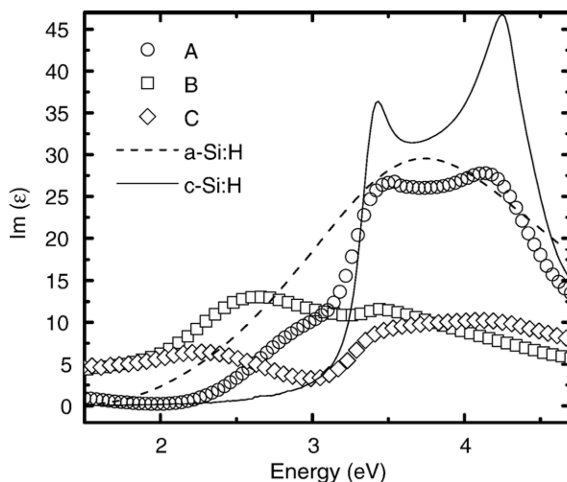


Fig. 1. Imaginary part of the pseudo-dielectric function ($\varepsilon_2$) measured by SE for the samples under study. The spectra of amorphous and crystalline silicon materials used as a reference in the Bruggemann model are also shown.

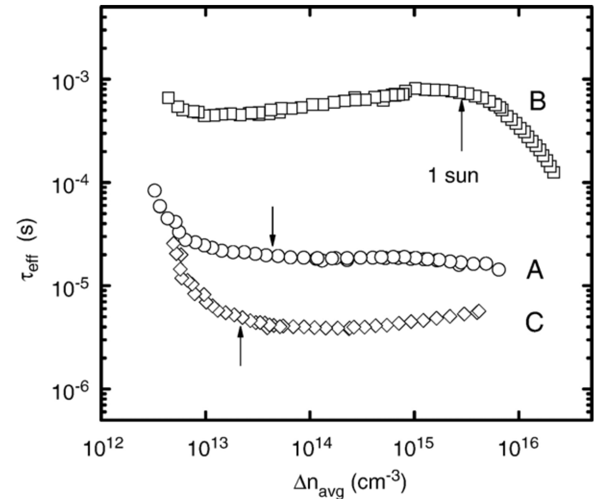


Fig. 2. Effective lifetime ($\tau_{eff}$) as a function of the excess minority carrier density for the samples under study. Arrows point the values at one-sun irradiance.

Fig. 2 shows the QSS-PC data for the same set of samples. As it can be observed, the intrinsic a-Si:H buffer layer improves the effective lifetime at one-sun irradiance ($\tau_{eff}$) from 17 µs in sample A to 750 µs in B. The hydrogen pre-treatment used in sample C results in a drastically reduced $\tau_{eff}$ value of 4 µs, even with the presence of the intrinsic layer. In addition, the QSS-PC data implicitly contain information about the maximum $V_{oc}$ value that could be expected from the heterojunction emitter [10]. As it is shown in Fig. 3, the longer $\tau_{eff}$ value measured in B leads to an excellent implicit-$V_{oc}$ of 695 mV at one-sun irradiance, whereas it is limited to 590 mV in sample A. A lower value of 570 mV is obtained in sample C, in agreement with the shorter $\tau_{eff}$ value.

The group at NREL has clearly demonstrated the importance of an abrupt heterojunction to reduce interface recombination [11]. In this sense, high-quality a-Si:H films are far more effective passivating layers than mixed-phase or highly defective epitaxial ones. Then, the highest performance of sample B agrees with its negligible crystalline fraction. However, the absence of an a-Si:H buffer (sample A) results in a defective low-temperature epitaxy with moderate passivating properties. Finally, the hydrogen pre-

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