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# Bifacial heterojunction silicon solar cells by hot-wire CVD with open-circuit voltages exceeding 600 mV

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## Abstract

Double-sided (bifacial) heterojunction silicon solar cells have been fabricated by Hot-Wire CVD on both p- and n-type crystalline silicon substrates. In these devices, doped microcrystalline silicon layers are combined with thin intrinsic amorphous silicon buffers. Such heterojunction with intrinsic thin layer concept is applied to obtain both the low temperature deposited emitter and back surface field contact. Especially remarkable is the performance of the solar cell fabricated on p-type c-Si. This device yields a total area (1.4 $cm^2$) conversion efficiency of 13.3%, with an open-circuit voltage of 619 mV, short-circuit current density of 29.0 mA $cm^{-2}$ and fill factor of 74.1%. The substrate temperature is kept below 200 °C during the whole fabrication process.

*Keywords:* Silicon; Heterojunction; Solar cell; Hot-Wire CVD

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## 1. Introduction

The cost of high efficiency crystalline silicon (c-Si) modules is hindering the progress of the PV industry as a viable alternative for clean energy production. Therefore, cell manufacturers are searching different approaches that could allow the desired cost reduction. For instance, considering that c-Si wafers represent about 30–50% of the module price, the final cost would be significantly reduced by increasing the number of wafers processed from a given ingot. Nowadays, very thin c-Si wafers (<200 μm) can be produced with moderate kerf losses. However, in c-Si cells with minority carrier diffusion lengths similar to the wafer thickness, rear surface recombination becomes important [1]. Although thermal oxidation very effectively passivates the c-Si surface [2], thin wafers tend to warp at the high temperatures (~1000 °C) involved in the process. On the other hand, low cost multicrystalline silicon wafers are not compatible either with high temperature steps due to strong lifetime degradation [3]. Therefore, low temperature surface passivation schemes using thin films of hydrogenated amorphous silicon (a-Si:H) [4,5], silicon carbide (a-$SiC_x$:H) [6] or silicon nitride (a-$SiN_x$:H) [7,8] have gained special interest due to their compatibility with both thin and low quality c-Si substrates.

The heterostructure formed between a-Si:H and c-Si is particularly interesting, since intrinsic films can be used for passivation and doped ones to form either the emitter junction or the back surface field (BSF) contact. Certainly, the most successful result is the Heterojunction with Intrinsic Thin-layer (HIT) cell developed by Sanyo Electric Co. with record 19.5% conversion efficiency in mass-produced modules [9]. Sanyo uses Plasma-Enhanced Chemical Vapour Deposition (PECVD) to grow the a-Si:H thin films, but very little is known about the specific technological process. The HIT concept is used on both sides of n-type Czochralski (CZ) wafers, i.e., p-doped/intrinsic and n-doped/intrinsic a-Si:H stacks are used to form the emitter and BSF contact, respectively. These double-sided structures have been called bifacial HIT cells in the literature [10]. Such excellent results by Sanyo moved many groups worldwide to investigate heterojunction silicon solar cells. Most groups use p-type c-Si wafers, though the best doping type of the base is still subject of discussion [11]. Several groups have already reported encouraging results with a-Si:H emitters deposited by PECVD. For instance, Tucci and de Cesare have reported a conversion efficiency ($\eta$) of 17% (total

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area) for a heterojunction solar cell fabricated on a textured p-type CZ silicon wafer (350 μm) with aluminium BSF [12]. Sherff et al. have also obtained a remarkable $\eta = 15.9\%$ (total area) for a solar cell on a textured p-type CZ silicon wafer (200 μm) with boron-diffused BSF [13]. The group at Utrecht University has reported $\eta = 14.8\%$ (active area) on a p-type float zone (FZ) silicon wafer (375 μm). Unlike other heterojunction solar cells, this last device includes a low-temperature deposited BSF consisting of a highly p-doped hydrogenated microcrystalline silicon layer (μc-Si:H) [14].

The Hot-Wire Chemical Vapour Deposition (HWCVD) technique has attracted much less attention to fabricate heterojunction silicon solar cells. However, some technological advantages could be argued in terms of deposition rate, gas decomposition and scalability. Besides, the reduced ion bombardment could result beneficial for the interface between amorphous and crystalline silicon, whereas higher densities of atomic hydrogen may passivate the c-Si surface. To our knowledge, the best heterojunction solar cell by HWCVD has been fabricated by the group at NREL, a 1 $\text{cm}^2$ device of $\eta = 16.9\%$ (total area) on a flat p-type FZ silicon wafer with aluminium BSF contact [15]. This solar cell yielded an open-circuit voltage ($V_{oc}$) of 645 mV, short-circuit current density ($J_{sc}$) of 33.1 mA $\text{cm}^{-2}$ and fill factor (FF) of 79.2%. Concerning our group, we started the research on heterojunction silicon solar cells by HWCVD a few years ago. In a previous work, we reported very low effective surface recombination velocities ($S_{eff} < 100$ cm $\text{s}^{-1}$) with intrinsic a-Si:H passivating layers on c-Si wafers [5]. During the last years, we have also presented studies on both emitters and BSF contacts deposited by HWCVD on c-Si [16]. Now, in this work, we finally present our first double-sided (bifacial) heterojunction silicon solar cells fully processed at low temperature (200 °C).

## 2. Experimental

All the heterostructures presented in this work were obtained on FZ silicon wafers with (100) crystalline orientation and thickness around 400 μm. The resistivities of p-and n-type c-Si wafers were around 1 and 5 Ω cm, respectively. Before deposition, silicon wafers were cleaned in a $H_2SO_4:H_2O_2$ (2 : 1) solution. Then, dipped in 5% HF until they become hydrophobic and immediately introduced into the load lock chamber of an ultra-high vacuum deposition system. All the thin silicon films were grown by HWCVD under the deposition conditions summarised in Table 1. The doping precursors were $B_2H_6$ and $PH_3$ added in a few percent of standard cubic centimetre (sccm) to the gas mixture. Separate chambers were used to grow the doped and intrinsic thin silicon films to avoid cross-contamination. Tantalum wires 0.5 mm in diameter were installed in both chambers. The growth rate was around 10 nm $\text{min}^{-1}$ for doped μc-Si:H films and 12 nm $\text{min}^{-1}$ for intrinsic a-Si:H ones. A hydrogen treatment of the c-Si surface was done before depositing the films. It consisted of exposing the c-Si surface to 20 sccm of hydrogen dissociated by the wire heated at 1700 °C. Thereby, the c-Si surface is hydrogenated for a few minutes at a process pressure of 3.0 Pa. Several works account for the beneficial effect of such hydrogen treatments [17,18].

Table 1
Deposition conditions used in this work to obtain the HWCVD thin silicon films of the double-sided heterojunction solar cells

| Type | $T_s$ (°C) | $H_2$ (sccm) | $SiH_4$ (sccm) | Doping (sccm) | Pressure (Pa) |
|---|---|---|---|---|---|
| (i) a-Si:H | 200 | – | 4 | – | 1 |
| (n) μc-Si:H | 200 | 76 | 4 | 0.08 | 3 |
| (p) μc-Si:H | 125 | 100 | 4 | 0.2 | 3 |

The wire temperature was 1600 °C for intrinsic a-Si:H and n-doped μc-Si:H films, but 1750 °C for p-doped μc-Si:H films.

The heterojunction silicon solar cells were fabricated following the double-sided structure $(n^+)$μc-Si:H/(i)a-Si:H/(p)c-Si/(i)a-Si:H/$(p^+)$μc-Si:H, and symmetrically for n-type c-Si. The thickness of both doped μc-Si:H layers was 50 nm, whereas thin intrinsic a-Si:H layers were about 5 nm thick. Before finishing the device, the effective lifetime ($\tau_{eff}$) as a function of the average excess minority carrier density ($\Delta n_{avg}$) was measured by the contactless Quasi-Steady-State Photoconductance (QSS-PC) technique [19]. The QSS-PC data implicitly contain information about the open-circuit voltage expected from the solar cell precursor. For instance, considering a solar cell fabricated on a p-type wafer with acceptor density $N_A$, the expected $V_{oc}$ value would be given by:

$$V_{oc} = \frac{kT}{q} \ln\left[\frac{\Delta n(N_A + \Delta p)}{n_i^2} + 1\right] \qquad (1)$$

where $k$ is the Boltzmann's constant, $T$ the temperature in Kelvin, $q$ the elementary charge and $n_i$ the intrinsic carrier concentration in crystalline silicon. Under high irradiance, both excess carrier densities in Eq. (1) can be equalled to the $\Delta n_{avg}$ determined by QSS-PC.

In order to finish our heterojunction solar cells, an indium-tin-oxide (ITO) layer 90 nm thick was deposited by RF magnetron sputtering on the emitter. A shadow mask is used to define a device area of 1.4 $\text{cm}^2$. The ITO layer has a sheet resistance around 50 Ω and serves to collect the current and also as antireflection coating. Then, a grid of silver with 8% shadowing was thermally evaporated (500 nm) through a shadow mask on top of the front ITO layer. Finally, we deposited a back reflector on the back side consisting in a double layer of sputtered ITO (90 nm) and evaporated silver (500 nm).

## 3. Results and discussion

In this work, we have focused on doped μc-Si:H films instead of a-Si:H ones due to their much better electrical properties. The use of n-doped a-Si:H films has also allowed significant results in a previous work [20]. However, heterojunctions with p-doped a-Si:H layers become more complex due to the rather low conductivity of these films by HWCVD. This problem seems to be related to the intrinsically high concentration of atomic hydrogen in HWCVD processes,