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Low temperature back-surface-field contacts deposited by hot-wire CVD for heterojunction solar cells

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Abstract

The growing interest in using thinner wafers (<200 µm) requires the development of low temperature passivation strategies for the back contact of heterojunction solar cells. In this work, we investigate low temperature deposited back contacts based on boron-doped amorphous silicon films obtained by Hot-Wire CVD. The influence of the deposition parameters and the use of an intrinsic buffer layer have been considered. The microstructure of the deposited thin films has been comprehensively studied by Spectroscopic Ellipsometry in the UV–visible range. The effective recombination velocity at the back surface has been measured by the Quasi-Steady-State Photoconductance technique. Complete double-side heterojunction solar cells (1 cm^2) have been fabricated and characterized by External Quantum Efficiency and current–voltage measurements. Total-area conversion efficiencies up to 14.5% were achieved in a fully low temperature process (<200 °C).

Keywords: Hot-wire deposition; Solar cell; Heterostructure; Passivation; Ellipsometry

1. Introduction

The investigation of heterojunction silicon solar cells has gained much interest since Sanyo reported outstanding conversion efficiencies over 20% with its so-called HIT (Heterojunction with Intrinsic Thin layer) solar cell structure [1]. Although Sanyo uses the HIT structure on both sides of n-type c-Si substrates, most groups limit their investigation to the heterojunction emitter on p-type wafers [2,3] due to the difficulty in obtaining good quality boron-doped a-Si:H films by the usual deposition techniques. In the case of p-type c-Si substrates, an aluminum back-surface-field (Al-BSF) is usually used as a back contact to focus on understanding and optimizing the heterojunction emitter. The standard industrial process to form the Al-BSF involves the alloying of an aluminum screen-printing paste (~20 µm) at relatively high temperatures (700–800 °C). The effective surface recombination velocity (S_{eff}) obtained with optimized Al-BSF contacts can not be reduced much below 10^3 cm/s [4]. Wafer warping during the cooling process is a severe drawback of Al-BSF contacts, especially taking into account present efforts to fabricate solar cells with wafers thinner than 200 µm [5]. Alternatively, excellent surface passivation can be achieved with low temperature deposited dielectric films such as silicon nitride [6] or silicon carbide [7]. This approach is superior to the Al-BSF contact due to its much lower surface recombination velocity (S_{eff}<100 cm/s), but requires a point contact patterning of the backside as proposed with the PERC (Passivated Emitter and Rear Cell) concept [8]. Point contact formation based on photolithography is unlikely to succeed in industrial production, but the recently developed laser fired contact (LFC) technology has great potential for future applications [9]. However, the laser set-up and the beam positioning system introduce a relatively complex additional process. That being said, low-temperature deposited BSF contacts based on heavily boron-doped thin silicon films have been much less studied, though their implementation in solar cells could be straightforward [10].

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The main reason is the already mentioned lower electronic quality of deposited (p)a-Si:H films.

Although most groups, including Sanyo, use the Plasma-Enhanced Chemical Vapour Deposition (PECVD) to grow the a-Si:H films, the Hot-Wire CVD (HWCVD) technique has also recently demonstrated the potential to fabricate state-of-the-art heterojunction silicon solar cells [2]. In the HWCVD technique, besides some technological advantages, the absence of ion bombardment reduces the damage to the c-Si surface. Over the last few years, our group has also obtained good results in heterojunction solar cells by HWCVD and a conversion efficiency of 15.4% was recently reported [11]. In particular, the optimized heterojunction emitters with structure (n)a-Si:H/(i)a-Si:H/(p) c-Si showed implicit V_{oc} values close to 690 mV measured by the Quasi-Steady-State Photoconductance (QSS-PC) technique. The actual V_{oc}, however is limited to lower values (630 mV) in the final devices due to the Al-BSF contact used at the rear side. Thus, we explore the reduction of back surface recombination by means of low temperature deposited BSF contacts based on boron-doped a-Si:H films with and without intrinsic buffer layer. This work includes the micro-structural characterization of these samples by Spectroscopic Ellipsometry (SE) in the visible-UV range. Additionally, the QSS-PC technique was used to measure the S_{eff} values that can be obtained with these low temperature deposited back contacts. Finally, complete double-side heterojunction solar cells were fabricated on p-type c-Si substrates.

2. Experimental

All the heterostructures presented in this work were obtained on p-type (0.95 Ω·cm) FZ silicon wafers with (100) crystalline orientation and thickness of 300 μm. 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 the ultra-high vacuum deposition system. All the thin silicon films were grown by HWCVD under the deposition conditions summarized in Table 1. Separate chambers were used to grow the doped and intrinsic thin silicon films to avoid cross-contamination. The wire configuration of both chambers consisted of two parallel tantalum wires 0.5 mm in diameter separated 3 cm, with the gas inlet centered 1 cm below the wires. The substrate was placed 4 cm above the plane of the wires. The deposition conditions for the boron-doped layers have been extensively investigated for this configuration, as it was previously done for the phosphorous-doped ones [11].

Table 1
Deposition conditions used to grow the silicon films of the bifacial heterojunction solar cells

Film	T_s (°C)	H_2 (sccm)	SiH_4 (sccm)	Doping (sccm)	Pressure (mbar)
i	100	–	2	–	3.5×10^{-3}
n	200	28	2	0.04	8×10^{-2}
p	100	2	1.5	0.02	1×10^{-2}
p^+	100	4	2	0.04	2×10^{-2}

The wire temperature was 1600 °C for intrinsic a-Si:H and n-doped films, but 1750 °C for p-doped films. The doping precursors were phosphine and diborane for n- and p-type films, respectively.

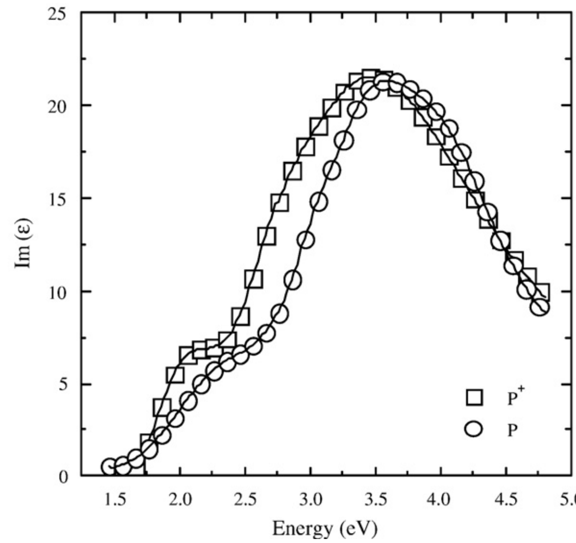

Fig. 1. Imaginary part of the pseudo-dielectric function measured by SE for the two samples without intrinsic buffer layer (symbols). The lines are the result of the fit with the optical model given in Table 2.

In this work, four different low temperature deposited BSF contacts were considered. These structures incorporate p-type a-Si:H layers of two different doping levels (Table 1) deposited either with a 5 nm intrinsic buffer layer or directly on the c-Si surface. In order to easily identify these samples, they have been labelled P, IP, P^+ and IP^+. The microstructure of these films was deduced from the fit to the pseudodielectric function ($\varepsilon=\varepsilon_1+i\varepsilon_2$) measured by SE according to the Bruggeman model [12]. The passivating properties of the different low temperature deposited BSF contacts were assessed by the contactless QSS-PC measurement. In this technique, the S_{eff} value is obtained as a function of an average excess minority carrier density (Δn) [13]. Finally, complete double-side heterojunction solar cells were fabricated with the different low temperature BSF contacts under study. In all cases, the heterojunction emitter was the stack of a thin intrinsic buffer layer (5 nm) followed by a 20 nm thick (*n*)a-Si:H film (Table 1). The front contact consisted in an indium-tin-oxide (ITO) anti-reflecting coating (80 nm) deposited by RF magnetron sputtering, followed by an evaporated silver grid (2 μm) with 8% shadowing. The active area of the solar cell is 1 cm^2. The rear contact is finished with an stack of ITO (80 nm) and silver (1 μm) deposited on the (p)a-Si:H film.

3. Results and discussion

We measured the imaginary part (ε_2) of the pseudo-dielectric function by SE for all the samples under study. The experimental curves have been fitted according to the Bruggeman model. As an example, in Fig. 1 we show the experimental (symbols) and calculated (lines) data for the two samples without buffer layer (P, P^+).

From the raw data, amorphous structures were expected as no crystalline features are visible. The high values of ε_2 indicate