Development of laser-fired contacts for amorphous silicon layers obtained by Hot-Wire CVD

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Abstract

In this work we study aluminium laser-fired contacts for intrinsic amorphous silicon layers deposited by Hot-Wire CVD. This structure could be used as an alternative low temperature back contact for rear passivated heterojunction solar cells. An infrared Nd:YAG laser (1064 nm) has been used to locally fire the aluminium through the thin amorphous silicon layers. Under optimized laser firing parameters, very low specific contact resistances (ρ_c~10 mΩ·cm^2) have been obtained on 2.8 Ω·cm p-type c-Si wafers. This investigation focuses on maintaining the passivation quality of the interface without an excessive increase in the series resistance of the device.

Keywords

Hot-wire deposition, Laser firing, Heterostructure, Passivation

1. Introduction

The study of heterojunction silicon solar cells is an especially active research field since Sanyo reported outstanding conversion efficiencies over 20% with its so-called HIT (Heterojunction with Intrinsic Thin layer) solar cell structure [1]. Sanyo has definitely succeeded applying the HIT concept to bifacial solar cells fabricated on n-type crystalline silicon (c-Si) wafers, but very little is known about the fabrication process. The best doping type of the base is still controversial but most groups prefer working with p-type rather than n-type c-Si wafers. This choice allows the use of high quality n-doped amorphous silicon (a-Si:H) layers as heterojunction emitters. As it is well-known, p-doped a-Si:H layers are usually of poorer quality for any of the typical low temperature deposition techniques. Then, aluminium back-surface-field (Al-BSF) contacts are normally used for the rear side of p-type c-Si substrates. The high temperature step involved in the fabrication of the Al-BSF contact (700-800 ºC) is a severe drawback considering the present interest in either thinner or lower quality substrates [2]. In addition, the effective surface recombination velocity (S_{eff}) that can be achieved with Al-BSF contacts can not be reduced much below 10^3 cm/s [3].

On the other hand, excellent S_{eff} values below 100 cm/s have been reported for low temperature deposited dielectric films such as silicon nitride [4] or silicon carbide [5]. In particular, solar cells with intrinsic a-Si:H back surface passivation have reached efficiencies of 20.1% using the COSIMA structure (COntact formation to a-SI:H passivated wafers by Means of Annealing) [6]. In this case a fine shadow mask replaces the photolithographic step to evaporate aluminium stripe contacts separated 2 mm with fingers 100 μm wide. Such requirements could difficult a direct transference of this technology to mass production over large area wafers. By contrast, the recently developed laser fired contact (LFC) technology has a great potential for industrial applications [7]. The standard photolithographic process for contact hole formation followed by aluminium evaporation and sintering is replaced by a local laser-firing of the aluminium layer through the dielectric passivating layer. The laser technology is already present in the PV industry for several purposes (scribing, isolation, structuring) and conventional lasers can be adapted for a high throughput in-line production.

Over the last few years, our group has obtained good results in heterojunction solar cells fabricated using the Hot-Wire CVD technique [8]. In particular, 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. However, the actual V_{oc} is limited to lower values (630 mV) in the final devices due to the Al-BSF contact used at the rear side. In a recent work, the Al-BSF contact was replaced by low temperature deposited BSF contacts based on p-doped a-Si:H films with only partial success in complete devices [9]. Therefore, in this work we explore back surface passivation with intrinsic a-Si:H layers and the fabrication of laser fired aluminium contacts.

2. Experimental

The heteroestructures presented in this work were obtained on p-type (2.8 Ω·cm) CZ silicon wafers with (100) crystalline orientation and thickness of 350 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 a HWCVD set-up. The wire configuration consisted of two parallel tantalum wires 0.5 mm in diameter separated 3 cm, with the gas inlet centred 1 cm below the wires. The substrate was placed 4 cm above the plane of the wires. Additional details on the deposition system can be found elsewhere [10]. Table 1 summarizes the deposition conditions for both doping-type a-Si:H layers, the intrinsic layers used as a buffer in heterojunction emitters (I-buffer) and, finally, the intrinsic layers used for back surface passivation (I-back).

Type a-Si:H	T_s (ºC)	H_2 (sccm)	SiH_4 (sccm)	Doping (sccm)	Pressure (mbar)
I-buffer	100	-	2	-	3.5×10^{-3}
N	200	28	2	0.04	8×10^{-2}
P	100	4	2	0.04	2×10^{-2}
I-back	200	-	4	-	1×10^{-2}

Table 1: Deposition conditions to grow the silicon films used in this work. The wire temperature was 1600ºC for intrinsic and n-doped a-Si:H films, but 1750 ºC for p-doped films. The doping precursors were phosphine and diborane for n- and p-type films, respectively.

Three main heterostructures have been considered in this work. First, the heterojunction emitter consisting in the stack of a thin (5 nm) intrinsic layer (I-buffer) followed by an n-doped layer 20 nm thick. Second, the low temperature deposited BSF contact was a p-doped layer of 50 nm deposited directly on the c-Si wafer. Last, back surface passivation with an intrinsic a-Si:H layer (I-back) of thickness 200 nm. The passivating properties of the different structures were measured by the contactless

Quasi-Steady-State Photoconductance (QSS-PC) measurement. In this technique, the effective lifetime τ_{eff} value is obtained as a function of the excess minority carrier density (Δn). In addition, the QSS-PC data implicitly contain information about the maximum open-circuit voltage that could be obtained from the solar cell precursor [11]. For instance, considering a solar cell fabricated on a p-type wafer with acceptor density N_A, the implicit-V_{oc} would be given by:

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

In order to fabricate laser fired contacts, an aluminium layer 2 μm thick was evaporated on the intrinsic a-Si:H passivating layer (I-back). The laser system is a Q-switched Nd:YAG laser (Starmark SMP 100 II Rophin Baasel) emitting at 1064 nm in TEM00. The power of the laser beam can be adjusted by varying the intensity of the continuous lamp that pumps the Nd:YAG crystal. The laser is operated in pulsed mode and we can also change the pulse repetition rate and the number of shots per spot. The laser beam is positioned by galvanometric mirrors and a focusing lens (focal length 254 mm) that allow to process samples up to 6 inches. In the electrical characterization of the point contacts we have considered that the total resistance (R_T) has two main contributions: the spreading resistance of the c-Si wafer (R_{SR}) and the resistance of the laser-fired contact (R_{LFC}) [12]:

$$R_T \approx R_{SR} + R_{LFC} \qquad R_{SR} = \frac{\rho}{\pi d} \arctan\left(\frac{4W}{d}\right) \;,\; R_{LFC} = \frac{\rho_C}{\pi \left(\frac{d}{2}\right)^2} \qquad (2)$$

where ρ is the resistivity and W the thickness of the wafer, while d is the diameter and ρ_c the specific contact resistance of the laser-fired contact. A ρ_c value in the range of 10 m$\Omega\cdot cm^2$ indicates a good quality laser-fired contact. Finally, in order to evaluate the passivation quality after the LFC process, we have chemically etched the aluminium layer to measure again the final τ_{eff} value.

3. Results & discussion

Figure 1 compares the QSS-PC data of the three different heteroestructures presented in this work. As it can be observed, the optimized n-type heterojunction emitter allowed an excellent τ_{eff} value of 750 μs at one-sun. Then, according to the QSS-PC measurement, the implicit-V_{oc} of this structure is over 690 mV. Although a strong effort has been done to optimize low temperature BSF contacts based on p-doped a-Si:H layers, to date the best τ_{eff} value was limited to 170 μs. Consequently, the optimized low temperature BSF contact would reduce the implicit-V_{oc} of the structure to 650 mV. Furthermore, we have experienced that carrier collection at the (p)a-Si:H BSF contact is not easy and “S-shaped” current-voltage characteristics could be observed in complete devices [9]. Rear surface passivation with an optimized intrinsic a-Si:H layer has reached a rather good τ_{eff} value of 400 μs with potential for a V_{oc} of 670 mV. As a comparison, a traditional Al-BSF contact would result in V_{oc} values typically limited to 630 mV (Table 2). These results indicate that rear passivation with an optimized intrinsic a-Si:H layer can indeed be a good choice if we succeed developing good quality laser-fired contacts.

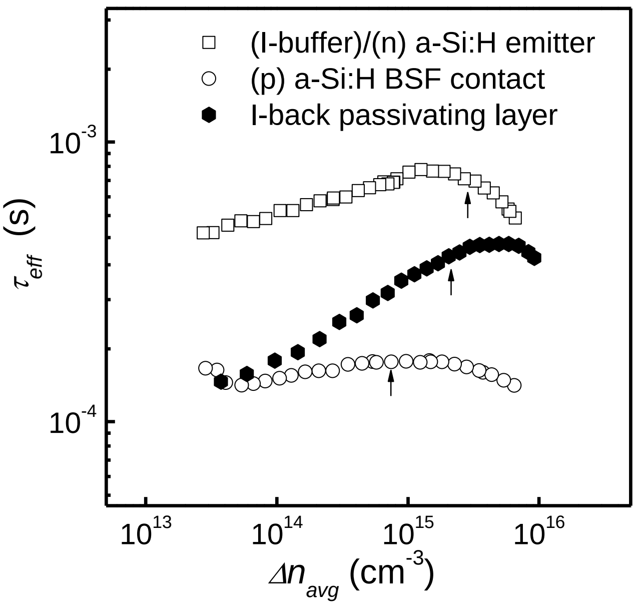

Figure 1: Effective lifetime (τ_{eff}) as a function of the excess minority carrier density (Δn) for the three studied structures: n-type heterojunction emitter with intrinsic buffer layer, low temperature BSF contact based on p-doped a-Si:H layer, and intrinsic a-Si:H back passivating layer. The arrows point the τ_{eff} values at one-sun irradiance.

type	S_{eff} ($cm \cdot s^{-1}$)	limited V_{oc} (mV)
Intrinsic a-Si:H	44	670
(p)a-Si:H BSF	10^2	650
Al-BSF	10^3	630

Table 2: Effective surface recombination velocity ($S_{eff}=W/2\tau_{eff}$) and implicit-Voc values of the different rear side structures for heterojunction solar cells.

In a first step, we started the optimization of the laser-firing process in order to obtain a very low contact resistance. Since very slight differences were observed with the repetition rate frequency (not shown), we finally fixed this parameter to 4 kHz in all the experiments. By contrast, clear differences were observed with the intensity of the lamp pumping the Nd:YAG crystal (figure 2). Actually, the lamp intensity is the main factor determining the power of the laser beam. The point contact diameters measured in the optical microscope images were used to calculate the specific contact resistance of the laser-fired contacts (figure 3). For lamp intensities higher than 20 A satisfactory ρ_c values (~10 $m\Omega \cdot cm^2$) can be obtained with 500 shots/spot. A higher number of shots did not lead to a significant reduction in the contact resistance (not shown).

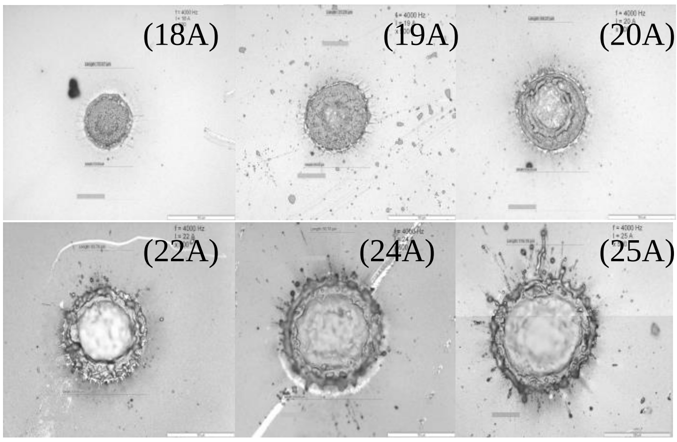

Figure 2: Top optical microscope (x50) images of laser-fired contacts formed at different lamp intensities with a repetition rate of 4 kHz and 500 shots/spot.

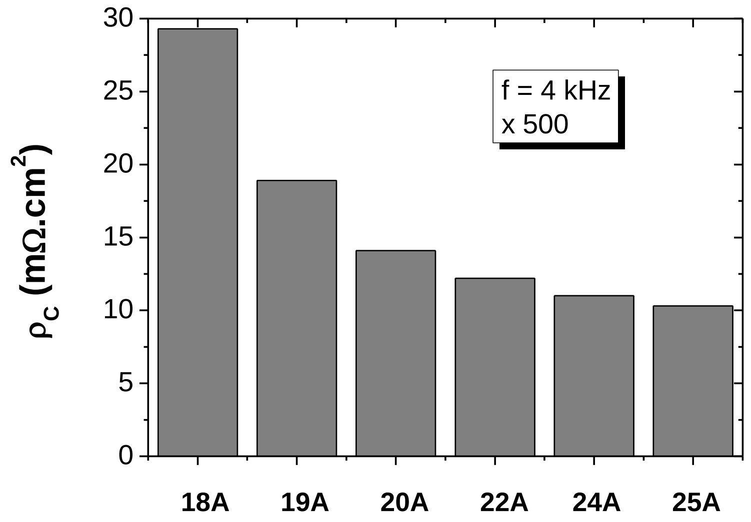

Figure 3: Specific contact resistance ρ_c of the laser-fired contacts as a function of the lamp intensity. The repetition rate was 4 kHz and we used 500 shots/spot.

In conclusion, a good compromise between low structural damage and good electrical contact could be obtained with a repetition rate of 4 kHz, a lamp intensity of 22 A and 500 shots/spot. In order to study the influence of the laser-fired contacts in the passivation quality, two different point patterns (pitch distances of 0.7 mm and 1 mm) were fired on wafers passivated with intrinsic a-Si:H layers (I-back). The relative variation due to the LFC process measured by QSS-PC after the chemical etch of the aluminium layer is shown in figure 4. The τ_{eff} value is reduced to 50% with the 0.7 mm pitch, but it remains over the 80% for 1 mm. In terms of open-circuit voltage, this means a reduction of only a few percent that is less than 20 mV for a typical V_{oc} around 650 mV.

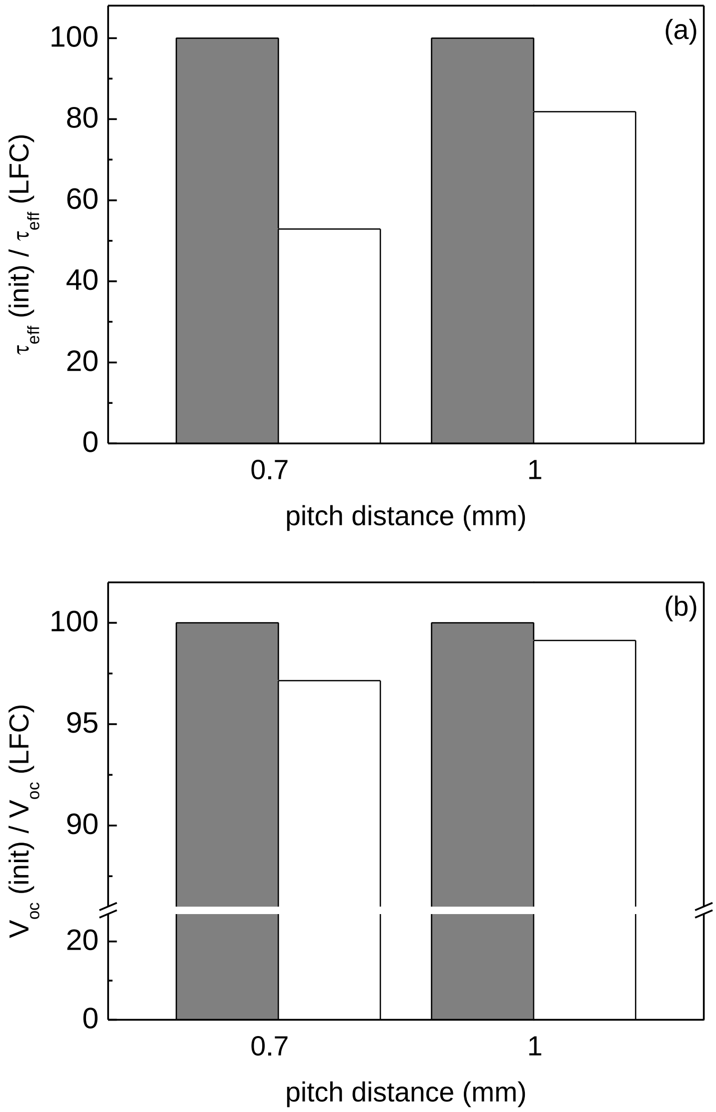

Figure 4: Comparison between the passivation quality (τ_{eff}, implicit-V_{oc}) for two laser-fired contact patternings of different pitch. As expected, the passivation quality is more affected by the denser pattern.

4. Conclusions

In this work, we have shown that intrinsic a-Si:H layers deposited by HWCVD allow a good passivation quality on (2.8 Ω·cm) p-type c-Si wafers. Implicit-V_{oc} values up to 670 mV overcome the typical values that can be achieved with traditional high temperature Al-BSF contacts. We have also succeeded in obtaining very low specific contact resistances (~10 $m\Omega \cdot cm^2$) with aluminium laser-fired contacts. In addition, the partial degradation in the passivation quality has little effect in the expected V_{oc} of the device (<20 mV). In future works, we expect to fabricate complete heterojunction solar cells by HWCVD incorporating laser-fired contacts at the rear side.

Acknowledgments

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