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Excellent thermal stability of remote plasma-enhanced chemical vapour deposited silicon nitride films for the rear of screen-printed bifacial silicon solar cells

B. Lenkeit*, S. Steckemetz, F. Artuso[1], R. Hezel

Institut für Solarenergieforschung Hameln/Emmerthal (ISFH), Am Ohrberg 1, 31860 Emmerthal, Germany

Abstract

In this work the thermal stability of the electronic surface passivation of *remote* plasma-enhanced chemical vapour deposited (RPECVD) silicon nitride (SiN) films is investigated with the aim to establish a cost-effective screen-printing and firing-through-the-SiN process for bifacial silicon (Si) solar cells. As a key result, RPECVD SiN films provide an excellently thermally stable surface passivation quality if they feature a refractive index in the range between 2.0 and 2.2. After a short anneal above 850°C the surface recombination velocity on 1.5 Ωcm p-type float-zone (FZ) Si remains at a very low level of about 20 cm/s. First bifacial silicon solar cells with screen-printed rear contacts on 1.5 Ωcm p-type FZ Si yield a very promising rear efficiency of 13.4%. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Surface passivation; Remote PECVD; Screen-printing; Bifacial solar cells

1. Introduction

The remote plasma-enhanced chemical vapour deposition (RPECVD) of amorphous hydrogenated silicon nitride (a-SiN_x : H, abbreviated as "SiN" throughout this work) films on p-type silicon (Si) results in greatly improved surface passivation properties compared to (i) the widely used low-frequency direct plasma-enhanced chemical vapour deposition technique and (ii) thermally grown SiO_2 [1,2]. At the

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* Corresponding author. Tel.: + 49-5151-999-304; fax: + 49-5151-999-400.

E-mail address: b.lenkeit@isfh.de (B. Lenkeit).

[1] Current address: Università di Roma "La Sapienza", Piazzale Aldo Moro, 5, 00125 Roma, Italy.

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same time SiN films serve as efficient antireflection coatings (ARC) [3] and efficient bulk passivation of multicrystalline Si due to the out-diffusion of hydrogen during a post-deposition anneal [4].

An excellent passivation of the rear surface is essential for a high rear efficiency of bifacial Si solar cells. Hence, RPECVD SiN films are optimally suited as highly efficient surface-passivating antireflection coatings for the partly metallised rear surface of low-resistivity p-type substrates. At ISFH, significant progress has recently been achieved in the area of bifacial Si solar cells as demonstrated by energy conversion efficiencies above 18% under front and rear illuminations [5]. These cells are characterised by a front and rear metal grid fabricated by means of vacuum evaporation through shadow masks, and the passivation of both surfaces by RPECVD SiN films. The aim of our investigation is to improve the cost effectiveness of these bifacial silicon solar cells by developing a low-cost screen-printing and firing-through-the-SiN process for the front and rear metallisations [6]. In this work we focus on the rear contact.

In the case of a firing-through-the-SiN process the SiN films have to withstand a firing step, which is typically in the range of 650–950°C, without degradation of the surface passivation quality. Since in the literature there are contradictory reports about the surface passivation stability of PECVD SiN films if a post-deposition thermal treatment is applied [7,8], we performed a comprehensive experimental study in order to determine the influence of several deposition parameters on the thermal stability of our RPECVD SiN films.

For optimisation of the bifacial Si solar cell fabrication process the experiments include (i) minority-carrier lifetime measurements on SiN/p-Si/SiN test structures as a function of the deposition parameters of the SiN films and the annealing conditions, (ii) contact and finger resistivity measurements of the screen-printed metal contacts as a function of the annealing conditions, and (iii) fabrication and characterisation of bifacial Si solar cells with screen-printed rear contacts.

2. Experimental

The SiN films are deposited in a commercial RPECVD reactor (Plasmalab 80, Oxford Plasma Technology). The process gases used are ammonia (NH_3) and silane (SiH_4). In this remote process only ammonia is excited outside the reactor by a 2.45 GHz microwave plasma source and mixed with silane within the deposition chamber. The SiH_4 flow rate is varied over a wide range resulting in different compositions of the SiN films indicated by refractive indices in the range of 1.9–2.5. Details on the deposition system and the deposition parameters have been reported elsewhere [9]. The thickness of the SiN films investigated in this study lies in the range of 60–80 nm. The refractive index and the thickness of the SiN films are measured with an ellipsometer (Plasmos GmbH) at the helium–neon laser wavelength of 632.8 nm.

The silicon samples used in this study are monocrystalline, shiny-etched, (100)-oriented p-type float-zone (FZ) Si wafers with a resistivity of 1.5 Ω cm and a thickness of 200–300 μm. All Si wafers received a standard RCA clean before film deposition.

The surface passivation quality of the symmetrical SiN/p-Si/SiN structures is measured by the contactless light-biased microwave-detected photoconductance decay (MW-PCD) technique. All measurements of the effective minority-carrier lifetime τ_{eff} are performed under low-injection conditions at room temperature with a modified Phoenicon MRM system. Technical details of the measurement system are described in Ref. [10]. From the measured τ_{eff} we determine the differential effective SRV [11]. The calculation of the SRV from the measured effective lifetimes requires the knowledge of the bulk lifetime of the p-type Si base material. For the determination of the bulk carrier lifetime we use the accurate method described in Ref. [10]. Prior to the MW-PCD measurement all lifetime samples are illuminated for 12 h with "white" light from a halogen lamp, since some annealed SiN films show a degradation already under 'white' light illumination. It is important to note that in contrast to some PECVD SiN films prepared by direct plasma techniques [12] these RPECVD SiN films do not need a forming gas anneal at 500°C for an improvement of the surface passivation quality.

The firing treatments are carried out in an infrared (IR) three-zone beltline furnace (RTC LA-310). Several commercially available pure Al pastes as well as Ag pastes that contain a small fraction of Al are used to ensure a low contact resistance on p-type silicon. To allow simultaneous measurement of the contact resistance, finger resistivity and average surface recombination velocity (SRV) on a single sample, the pastes are printed as a finger grid (finger width $\sim 100\,\mu\mathrm{m}$, finger distance $\sim 2\,\mathrm{mm}$) onto both surfaces of symmetrical SiN/p-Si/SiN structures. For contact resistance measurements a simplified transfer length method (TLM) [13] on a specially designed test pattern is used. The finger resistivity is evaluated from the same test pattern. Special attention is paid to find the optimum firing temperature profile, yielding the minimum contact resistance. For every investigated firing temperature (varied from 750 to 920°C) the beltspeed is varied in the range of 8–40 in/min, resulting in firing times between 10 and 60 s in the high-temperature zone.

3. Results

3.1. Thermal stability of RPECVD SiN films

The requirements for surface passivating SiN films are a low SRV after the contact firing cycle and an optimal refractive index of 1.9 and 2.1 for single- and double-layer AR coatings in air, respectively, and of 2.2 for an AR-coated solar cell encapsulated in a photovoltaic module with a 2 mm B270 glass cover and a 1-mm thick EVA layer [4]. For optimisation of the rear surface passivation of screen-printed bifacial Si solar cells we performed a comprehensive experimental study in order to determine the influence of several deposition parameters (pressure, plasma power, gas mixture and gas flow) on the thermal stability of the electronic surface passivation of the RPECVD SiN films.

In general, the SRV of the SiN films degrade with increasing firing time and temperature. From all investigated SiN deposition parameters the resulting refractive

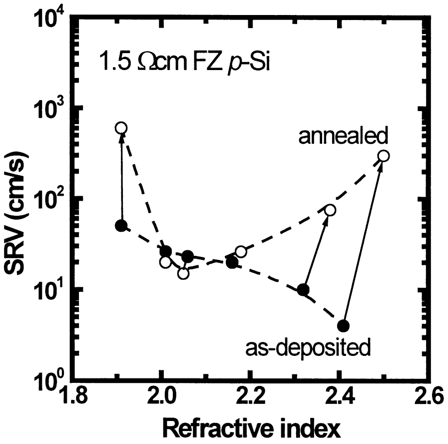

Fig. 1. Measured surface recombination velocity (SRV) of RPECVD SiN films (i) as-deposited (solid circles) and (ii) after annealing (open circles) as a function of the refractive index. All SiN films were deposited at 400°C, the annealing treatments were carried out in a three-zone beltline furnace with an annealing temperature above 850°C at the optimised firing cycle. The SiN films were illuminated for 12 h with "white" light from a halogen lamp prior to the MW-PCD measurement. The arrows indicate the change in refractive index during annealing, the dashed lines are guides to the eyes.

index has the dominant effect on the thermal stability. As a representative example, Fig. 1 shows the measured SRV of RPECVD SiN films deposited at 400°C before and after annealing above 850°C for 20 s as a function of the refractive index. The refractive index is varied by changing the SiH_4 gas flow while all other deposition parameters are kept constant in this experiment. The annealing is performed with the same temperature firing cycle that is optimised to receive a low contact resistance of Ag/Al and pure Al rear side pastes on p-type Si.

Annealing of SiN films featuring a refractive index below 2.0 and above 2.2 results in a deterioration of the surface passivation quality. In contrast, SiN films featuring a refractive index of 2.0–2.2 show a significant improvement of the SRV down to a value of 4 cm/s after firing. However, after an additional "white" light illumination from a halogen lamp for 12 h the SRV increases again to the initial value of about 20 cm/s. Nevertheless, this result indicates a remarkably high thermal stability of the optimised RPECVD SiN films. The application of a screen-printed finger grid on these SiN-passivated samples increases the SRV up to 250–350 cm/s. Simulations reveal that these values still allow rear efficiencies of about 16–17%.

3.2. Bifacial Si solar cells with screen-printed rear contacts

In order to demonstrate the impact of the previously optimised contact firing cycle on the final cell performance, simplified bifacial solar cells are produced with a screen-printed rear contact grid. Fig. 2 shows a schematic cross-sectional view of the

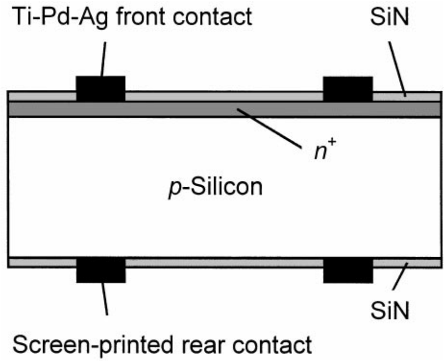

Fig. 2. Schematic cross-sectional view of the investigated bifacial n^+p-Si solar cell.

Table 1

Measured front- and rear-illuminated 1-sun performance parameters of the best bifacial n^+p-Si solar cell with a screen-printed rear contact grid (4 cm^2, 200 μm thick, 1.5 Ω cm p-type FZ Si wafers, textured surfaces, RPECVD SiN SLARC)

Illuminated surface	J_{sc} (mA/cm^2)	V_{oc} (mV)	FF (%)	η (%)
Front	36.8	612	77.3	17.4
Rear	28.4	606	77.7	13.4

prepared bifacial n^+p-Si solar cell. The processing sequence is already described in Ref. [6]. The emphasis was mainly put on the optimisation of the rear surface with a screen-printed contact grid. Therefore, high-quality starting material (p-type FZ Si wafers with a resistivity of 1.5 Ω cm) and a high-quality front surface is used. In this case, all differences in cell performance can clearly be related to process variations of the rear surface. The front surface is characterised by a single-diffusion emitter ($POCl_3$ source, sheet resistance 100 Ω/sq), a Ti/Pd/Ag front metal grid fabricated by means of vacuum evaporation through a shadow mask and a single-layer AR coating (RPECVD SiN with a thickness of 72 nm and a refractive index of about 2.1).

Table 1 shows the measured front and rear illuminated 1-sun parameters of our best bifacial Si solar cell with a screen-printed rear contact grid according to the above-mentioned optimised firing cycle. The achieved rear efficiency of 13.4% on 1.5 Ω cm p-type FZ Si is comparable to a rear surface with a vacuum-evaporated contact grid featuring the same metallisation fraction. The internal quantum efficiency (IQE) of bifacial Si solar cells with screen-printed rear contact grid is measured and compared with a simultaneously processed reference solar cell featuring a vacuum-evaporated rear contact. The analysis of the infrared wavelength range from 800 to 950 nm as described in Ref. [14] reveals that for an optimised processing sequence neither the bulk lifetime nor the rear surface passivation is reduced due to the contact firing cycle with an annealing temperature exceeding 850°C.

4. Summary

RPECVD SiN films with an excellent thermal stability of the electronic surface passivation are presented. From all the investigated SiN deposition parameters the resulting refractive index has the dominant effect on the surface passivation quality of annealed SiN films. After a short anneal above 850°C the surface recombination velocity (SRV) on 1.5 Ω cm p-type FZ Si remains at a very low level of 20 cm/s. First results for a bifacial solar cell featuring screen-printed rear contacts on 1.5 Ω cm p-type FZ Si yield a very promising rear efficiency of 13.4%. This value is comparable with bifacial solar cells featuring a vacuum-evaporated contact grid without a local back surface field but with the same metallisation fraction [5]. This strikingly demonstrates the high potential of the RPECVD SiN films as rear surface passivation for Si solar cells with a screen-printed rear contact grid and firing-through-the-SiN process.

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