Vailable online at www.sciencedirect.com

SciVerse ScienceDirect

Energy Procedia 27 (2012) 325 – 329

Energy Procedia

SiliconPV: April 03-05, 2012, Leuven, Belgium

Integration of Al_2O_3 as front and rear surface passivation for large-area screen-printed p-type Si PERC

B. Vermang[a,b], P. Choulat[a], H. Goverde[a], J. Horzel[a], J. John[a], R. Mertens[a,b], and J. Poortmans[a,b]

[a]*Imec, Kapeldreef 75, 3001 Heverlee, Belgium*
[b]*University of Leuven (ESAT), Kasteelpark Arenberg 10, 3001 Heverlee, Belgium*

Abstract

Atomic layer deposition (ALD) of thin Al_2O_3 ($\leqslant$ 10 nm) films is used to improve both front and rear surface passivation of large-area screen-printed p-type CZ Si passivated emitter and rear cells (PERC). As emitter passivation, the SiN_x anti reflection coating (ARC) is capped with Al_2O_3, giving improved hydrogenation during co-firing and a front recombination current ($J_{0,front}$) of 128 ± 5 fA/cm^2. As rear surface passivation, a blister-free stack of $Al_2O_3/SiO_x/SiN_x$ is employed, leading to optimal back reflection and a rear recombination current ($J_{0,rear}$) of 92 ± 6 fA/cm^2. Internal quantum efficiency (IQE) measurements clearly confirm the improved passivation properties of both Al_2O_3-based stacks, even compared to passivation stacks based on thermally grown SiO_2.

© 2012 Published by Elsevier Ltd. Selection and peer-review under responsibility of the scientific committee of the SiliconPV 2012 conference. Open access under CC BY-NC-ND license.

Keywords : Photovoltaics, Si ; PERC ; surface passivation ; Al_2O_3, ALD

1. Introduction

As published in the International Technology Roadmap for Photovoltaics (ITRPV), the specific costs per Watt peak of PV modules are expected to decrease by 8 to 12 % per year. According to the Crystalline Silicon PV Technology and Manufacturing (CTM) Group this implies that recombination losses at front and rear side of the crystalline Si solar cells must be reduced as indicated in Fig. 1 [1].

Research on aluminum oxide (Al_2O_3) as surface passivation for p-type Si already started long time ago [2,3]. In the meanwhile, its underlying passivation mechanism is understood quite well as a combination of chemical passivation of interface defects and field-effect passivation caused by a high density of fixed negative charges [4,5,6]. More recent research has also shown its potential as capping layer of positively charged dielectrics to passivate n-type Si surfaces [7].

1876-6102 © 2012 Published by Elsevier Ltd. Selection and peer-review under responsibility of the scientific committee of the SiliconPV 2012 conference. Open access under CC BY-NC-ND license.
doi:10.1016/j.egypro.2012.07.071

This work develops and integrates an approach using thermal ALD of Al_2O_3 to improve as well front and rear surface passivation of large-area screen-printed p-type Si PERC.

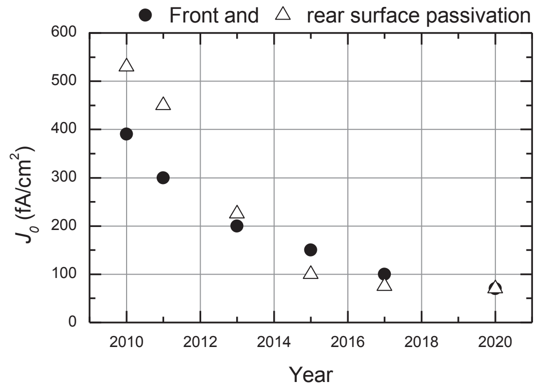

Fig. 1. Expected trends for recombination losses $J_{0,front}$ and $J_{0,rear}$ as reported by the CTM Group [1]

2. Results and discussion

2.1. Rear surface passivation

As p-type Si surface passivation, a stack of $Al_2O_3/SiO_x/SiN_x$ is used. The Al_2O_3 film ($\leqslant$ 10 nm) has been capped with SiO_x/SiN_x to optimize the back reflection at long wavelength. Also, the Al_2O_3 film has been out-gassed prior to SiO_x/SiN_x deposition to prevent blistering of the full stack after co-firing. More details can be found in [8], where a $J_{0,rear}$ of 92 ± 6 fA/cm^2 is approximated for the $Al_2O_3/SiO_x/SiN_x$ rear surface passivation, well in line with the ITRPV roadmap beyond 2015 [1]. In the meanwhile, by optimizing the Ag screen printing paste and grid, average and maximum efficiencies of large-area screen-printed $Al_2O_3/SiO_x/SiN_x$ rear surface passivated p-type Si PERC have been increased. An average and maximum cell efficiency of respectively 19.4 and 19.5 % has been obtained, as shown in Table 1.

Table 1. Overview of the cell characterization results (AM1.5 G) for 149 cm^2 $Al_2O_3/SiO_x/SiN_x$ rear passivated p-type CZ Si PERC. The cells are 150 µm thick, have a base resistivity of 1.5 Ω.cm and an emitter resistance of 60 Ω/sq. A more detailed processing sequence is given in [8]

	J_{SC} (mA/cm^2)	V_{OC} (mV)	FF (%)	η (%)
Avg. (4 cells)	38.1 ± 0.1	645 ± 1	78.9 ± 0.1	19.4 ± 0.0
Best cell	38.2	646	78.9	19.5

2.2. Front surface passivation

In high injection regimes, where $\Delta n >> N_{dop}$, the recombination in the emitter region can be distinguished from the bulk recombination due to the injection level dependence of the minority carrier lifetime in the emitter region and of the bulk. By plotting the inverse effective minority carrier lifetime reduced by the inverse Auger carrier lifetime versus the excess carrier density, it is possible to extract the emitter saturation current density $J_{0,front}$, which is directly proportional to the slope of the resulting curve; see the equation shown in Fig. 2.

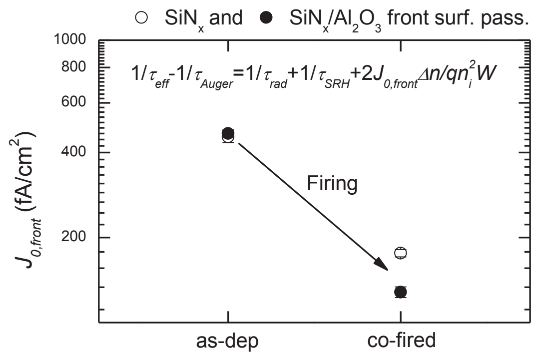

Fig. 2. Emitter saturation current density for symmetrically $POCl_3$ diffused (60 Ω/sq) textured p-type CZ Si, which are passivated by SiN_x or SiN_x/Al_2O_3 and co-fired at 865 °C peak firing temperature

This emitter saturation current density is measured by quasi-steady-state photo-conductance (QSSPC) for symmetrically $POCl_3$ diffused (60 Ω/sq) textured p-type CZ Si wafers passivated by SiN_x or SiN_x/Al_2O_3, as-deposited and after a co-firing at 865 °C peak firing temperature, see Fig. 2. In this Figure, as-deposited the $J_{0,front}$ is equivalent for SiN_x and SiN_x/Al_2O_3 emitter passivation. However, by capping the SiN_x anti reflection coating (ARC) by Al_2O_3, the $J_{0,front}$ is decreased from 176 ± 5 to 128 ± 5 fA/cm^2 after co-firing. Hence, a fired stack of SiN_x/Al_2O_3 clearly leads to improved emitter passivation, which is caused by enhanced hydrogenation of the Si/SiN_x interface: the Al_2O_3 film has a high H content and is known to be a good diffusion barrier [9]. The same effect has been reported for SiO_2/Al_2O_3 stacks [7]. Note that in the calculation of $J_{0,front}$ the front metallization has not been included.

Unfortunately, obtaining a good fill factor (*FF*) on large-area screen-printed SiN_x/Al_2O_3 front surface passivated p-type Si PERC has not been evident. Therefore, best solar cell efficiencies are not yet reported in this paper.

2.3. IQE analysis

Fig. 3(a) gives a comparison of IQE at low wavelength for SiN_x, SiO_2/SiN_x and SiN_x/Al_2O_3 passivated 60 Ω/sq emitters, and at long wavelength for SiO_x/SiN_x, $SiO_2/SiO_x/SiN_x$ and $Al_2O_3/SiO_x/SiN_x$ rear surface passivation stacks (SiO_2 and SiO_x denote thermally grown oxide and lower quality oxide deposited at much lower temperature, respectively). The IQE graphs at lower wavelength clearly show the improved emitter passivation by using a SiN_x/Al_2O_3 stack; it passivates the front surface even better compared to a thermal oxidation. Also at long wavelength, the chart confirms the improved rear surface passivation by using the $Al_2O_3/SiO_x/SiN_x$ stack; also here the Si surface passivation is better using Al_2O_3 compared to a thermal oxidation.

An additional advantage is shown in Fig. 3(b), where the IQE is depicted at long wavelength with and without 1 sun of illumination for SiO_x/SiN_x, $SiO_2/SiO_x/SiN_x$ and $Al_2O_3/SiO_x/SiN_x$ rear surface passivation stacks. This figure clearly shows that SiO_x/SiN_x or $SiO_2/SiO_x/SiN_x$ rear passivated cells have a reduced response at low illumination levels or are bias light dependant, while the $Al_2O_3/SiO_x/SiN_x$ passivated cells are not. See [10] for a detailed discussion on bias light dependency of positively and negatively charged passivation layers of p-type Si solar cells.

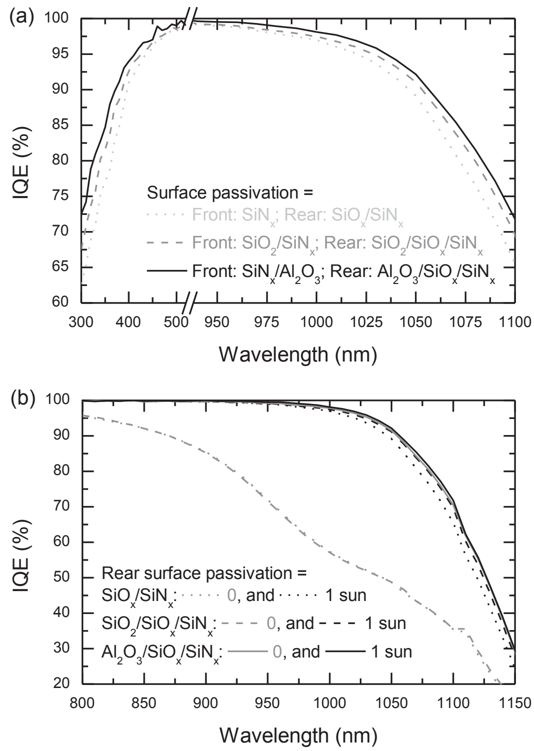

Fig. 3. (a) Comparison of IQE (1 sun bias illumation) at low and high wavelength for the specified front and rear surface passivation stacks. (b) IQE values recorded at 0 or 1 sun bias illumination at high wavelength for the specified rear surface passivation stacks

3. Conclusions

This work has developed and integrated an approach using ALD of Al_2O_3 to improve as well front and rear surface passivation of large-area screen-printed p-type Si PERC: (a) As emitter passivation, the SiN_x ARC is capped with an ultrathin Al_2O_3 layer ($\leq$ 10 nm), and after co-firing the emitter passivation is improved significantly. (b) As p-type Si surface passivation, a stack of $Al_2O_3/SiO_x/SiN_x$ is used. The Al_2O_3 film ($\leq$ 10 nm) has been capped with SiO_x/SiN_x to optimize the rear internal reflection at long wavelength. Also, the Al_2O_3 was out-gassed prior to SiO_x/SiN_x deposition to prevent blistering of the full stack during co-firing.

Realistic estimations for the recombination currents $J_{0,front}$ and $J_{0,rear}$ of the proposed passivation stacks are respectively 128 ± 5 and 92 ± 6 fA/cm^2, well in line with the ITRPV roadmap after 2015 [1].

Acknowledgements

The authors greatly acknowledge the support of the IMEC Industrial Affiliated Partner (IIAP-PV) program and the imec PV support team.

References

[1] International Technology Roadmap for Photovoltaics, Results 2011. Retrieved March 28, 2012, from http://www.itrpv.net

[2] Hezel R, and Jaeger K. Low-temperature surface passivation of silicon for solar cells. *J. Electrochem. Soc.* 1989;**136**:518-523.

[3] Agostinelli G, Delabie A, Vitanov P, Alexieva Z, Dekkers HFW, De Wolf S, and Beaucarne G. Very low surface recombination velocities on p-type silicon wafers passivated with a dielectric with fixed negative charge. *Sol. Energy Mater. Sol. Cells* 2006;**90**:3438-3443.

[4] Simoen E, Rothschild A, Vermang B, Poortmans J, and Mertens R. Impact of forming gas annealing and firing on the Al_2O_3/p-Si interface state spectrum. *Electrochem. Solid-State Lett.* 2011;**14**:H362-H364.

[5] Schmidt J, Merkle A, Bock R, Altermatt PP, Cuevas A, Harder NP, Hoex B, van de Sanden MCM, Kessels WMM, and Brendel R. Progress in the surface passivation of silicon solar cells. *Proceeding 23rd European Photovoltaic Solar Energy Conference* 2008;Valencia,Spain:974-981.

[6] Gielis JJH, Hoex B, van de Sanden MCM, and Kessels WMM. Negative charge and charging dynamics in Al_2O_3 films on Si characterized by second-harmonic generation. *J. Appl. Phys.* 2008;**104**:073701.

[7] Dingemans G, van de Sanden MCM, and Kessels WMM. Excellent Si surface passivation by low temperature SiO_2 using an ultrathin Al_2O_3 capping film. *Phys. Status Solidi RRL* 2011;**5**:22-24.

[8] Vermang B, Goverde H, Tous L, Lorenz A, Choulat P, Horzel J, John J, Poortmans J, and Mertens R. Approach for Al_2O_3 rear surface passivation of industrial p-type Si PERC above 19%. *Prog. Photovolt: Res. Appl.* 2012;**in press**:doi:10.1002/pip.2196.

[9] Dameron AA, Davidson SD, Burton BB, Carcia PF, McLean RS, and George SM. Gas diffusion barriers on polymers using multilayers fabricated by Al_2O_3 and rapid SiO_2 atomic layer deposition. *Journal of Physical Chemistry C* 2008;**112**:4573-4580.

[10] Prajapati V, Cornagliotti E, Lorenz A, Vermang B, John J, Poortmans J, and Mertens R. Illumination level independence in relation to emitter profiles on industrial high efficiency local Al-BSF cells. *Proceedings 26th European Photovoltaic Solar Energy Conference* 2011;Hamburg,Germany:1052-1057.