Presented at the 35th PVSC, June 20-25, 2010, Honolulu, Hawaii

DECOUPLING CHARGE CARRIER COLLECTION AND METALLIZATION GEOMETRY OF BACK-CONTACTED BACK-JUNCTION SILICON SOLAR CELLS BY USING INSULATING THIN FILMS

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ABSTRACT

Back-contacted back-junction silicon solar cells with a large emitter coverage (point-like base contacts) and a small emitter coverage (point-like emitter and base contacts) have been fabricated and analyzed. These solar cells feature an insulating thin film on the rear side in order to decouple the charge carrier collection geometry and the geometry of the metallization. It has been found, that for the investigated solar cells an increased collection efficiency is observed due to a significant reduction of electrical shading losses. Thus, high short-circuit currents could be achieved for both solar cell structures. Different insulating thin films, such as ALD Al_2O_3 and PECVD SiO_x have been investigated. It has been found that ALD layers are already insulating for a thinner film thickness. By applying these insulating thin films to the investigated solar cell structures no significant shunts are introduced. For solar cells on 1 Ωcm *n*-type material and with a large emitter coverage an efficiency of 21.9% (V_{oc} = 673 mV, J_{sc} = 40.6 mA/cm^2, *FF* = 80.1%) could be obtained and for solar cells with a small emitter coverage an efficiency of 22.7% (V_{oc} = 706 mV, J_{sc} = 41.0 mA/cm^2, *FF* = 78.5%) has been achieved.

INTRODUCTION

In *n*-type back-contacted back-junction silicon solar cells, the boron-doped emitter and the phosphorus-doped back surface field diffusions and therefore the *p*-metal and the *n*-metal fingers are located on the rear side of the solar cell. Thus, optical shading losses can be avoided completely due to the absence of the front side metallization. This leads to a higher photo-generated current that can be collected by the emitter on the rear side of the solar cells. However, the presence of the non-collecting base-type diffusion on the rear side reduces the collecting emitter area. Therefore, the photo-generated charge carriers not only have to be transported vertically but also laterally to the collecting emitter on the rear side. In dependence of the geometry, this two-dimensional transport can lead to an inefficient collection for the minority charge carriers in the non-collecting area on the rear side. The reduced collection probability in this area is caused by an increased recombination and is known as electrical shading [1-3]. In order to minimize these electrical shading losses, an efficient collection of the minority charge carriers by the emitter on the rear side is required. This requirement is a strong driving force towards solar cells where the lateral distance for the transport of the minority charge carriers to the collecting emitter is reduced significantly. This can be achieved with a large emitter diffusion coverage with small point-like base contacts on the one hand [4-7] and a small emitter diffusion coverage with small point-like emitter and base contacts and reduced pitch distances on the other hand [8,9], see Fig. 1.

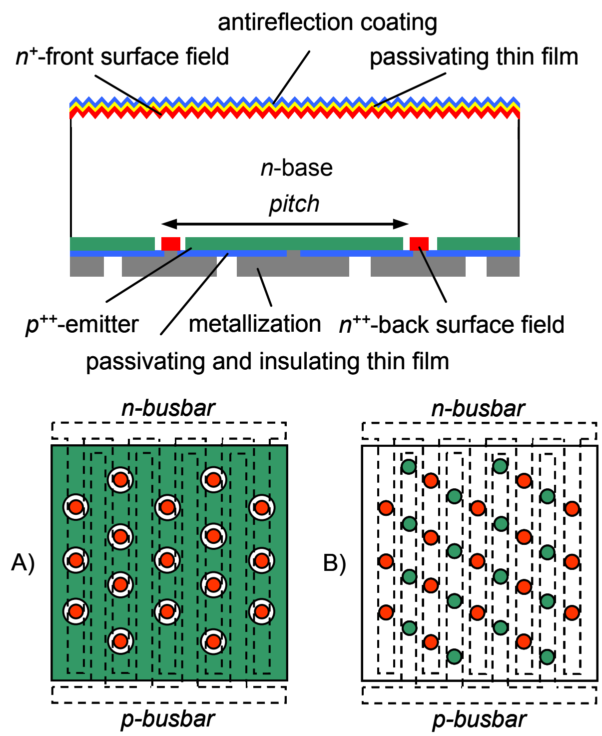

Figure 1: Schematic cross-section of the back-contacted back-junction silicon solar cell with a large emitter coverage featuring an insulating and passivating thin film (top) and schematic top view of the emitter and back surface field coverage on the rear side for a large emitter coverage A) (bottom, left) and a small emitter coverage B) (bottom, right). The interdigitated metallization and the busbars are also shown (dotted lines).

Since both *p*-metal and the *n*-metal fingers of these solar cells have to carry the same current, it is beneficial that the metal fingers have the same finger width. In this case, the *n*-metal finger for solar cells with a large emitter coverage is overlapping the emitter diffusion whereas the *p*-metal finger for solar cells with a small emitter coverage is overlapping the base-type diffusion. Therefore, spiking of the metal through a dielectric passivation layer on the rear side would introduce shunts. These shunts are leading to a reduced parallel resistance and would decrease the efficiency of these solar cells significantly. For this reason, the emitter and the back surface field diffusions generally have to be slightly larger than the *p*-metal and *n*-metal fingers [10]. Thus, the optimum geometry of the rear side diffusions is determined by the metal fingers so that there is always a trade-off between both of them.

In order to overcome these restrictions so that the charge carrier collection geometry and the metallization geometry can be decoupled, insulating thin films are required. The most challenging aspects of the investigated solar cell structures is the development of insulating thin films, which have excellent electrical insulation properties over a large area. This means that insulating thin films have to be without defects, such as pinholes, voids or cracks and have to prevent spiking of the metallization through the thin film. These defects will also increase the risk of shunting and reduce the parallel resistance of the solar cells significantly. Furthermore, the thin films should also insulate after the application of an annealing step at elevated temperatures. This annealing step is in most cases necessary to form the metal-semiconductor contact. For this reason different insulating thin films have been tested in preliminary experiments. Thin films such as ALD Al_2O_3 and PECVD SiO_x with different thicknesses have further been investigated in terms of their electrical, mechanical and structural properties [11]. Within the scope of the investigations, insulating thin films with a suitable insulation and which prevent the spiking of the metallization through the thin film have been analyzed and applied to the different solar cell structures. The impact of these insulating thin film for solar cells with a large and small emitter coverage on the short-circuit current, on the fill factor and on the open-circuit voltage are also shown.

INSULATING THIN FILMS

Experimental

The electrical properties of insulating thin films such as Al_2O_3 deposited by plasma assisted atomic layer deposition (ALD) and SiO_x grown by plasma enhanced chemical vapor deposition (PECVD) have been investigated by measuring the leakage current of these thin films with metal-insulator-semiconductor structures (MIS), see Fig. 2. The MIS structures were fabricated on *p*-type float-zone grown 250 µm thick 4 inch silicon wafers with a base resistivity of 0.5 Ωcm. The metalized areas consist of about 300 nm thick electron-beam evaporated aluminum. The measurement of the leakage current has been performed before and after a forming gas anneal (FGA) at a temperature of 350 °C, 400 °C and 450 °C for 15 min. It is essential that insulating thin films have excellent electrical insulation properties even for large areas. In order to get an idea of the dependence on the area, MIS structures with metal area contacts in the range of 0.2 cm^2 and 7.0 cm^2 have been used. For measuring the leakage current of the different insulating thin films, a voltage of 0.7 V has been applied. This voltage corresponds to an estimated open-circuit voltage that can be achieved with the investigated solar cell structures. Taking Schottky-like behavior of the metal-semiconductor contact at the front and at the rear of these MIS structures into account, the leakage current has been determined for a positive and a negative applied voltage.

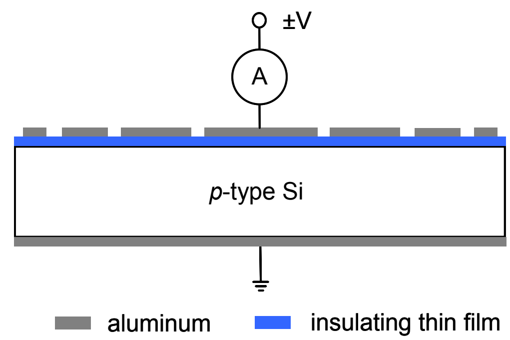

Figure 2: Schematic cross-section of the metal-insulator-semiconductor structure (MIS) with different metal areas to determine the leakage current of the insulating thin films. The metal layers consist of electron-beam evaporated aluminum.

Results

Based on calculations of the one-diode model with a variable shunt resistance, it has been found that a shunt resistance between 10^5 Ωcm^2 and 10^6 Ωcm^2 does not influence the fill factor *FF* significantly. To be on the safe side, a leakage current much lower than 1×10^{-6} A should therefore be determined for the investigated insulating thin films. The measured leakage currents of 50 nm and 200 nm thick ALD Al_2O_3 and of 300 nm and 1000 nm thick PECVD SiO_x insulating films directly after the deposition of the aluminum and after an additional FGA at 350 °C for 15 min are shown in Fig. 3. It can be clearly observed that before the additional temperature treatment the leakage current is very low for both the thicker and thinner insulating films and even for the larger metal areas. After the temperature treatment, the leakage current is increased dramatically for thinner ALD Al_2O_3 and PECVD SiO_x films and large metal areas. This can be attributed to the spiking of the metal through the thin films and defects such as pinholes in the thin films, which create a direct contact between the metal on top and the semiconductor underneath. Thicker insulating films also provide a suitable insulation even for annealing temperatures of 400 °C and 450 °C. Due to the difference between both deposition processes, ALD layers provide an excellent insulation even for thinner films. With the results of the electrical investigations of the thin films it is now possible to apply thin films with a suitable insulation to both solar cell structures.

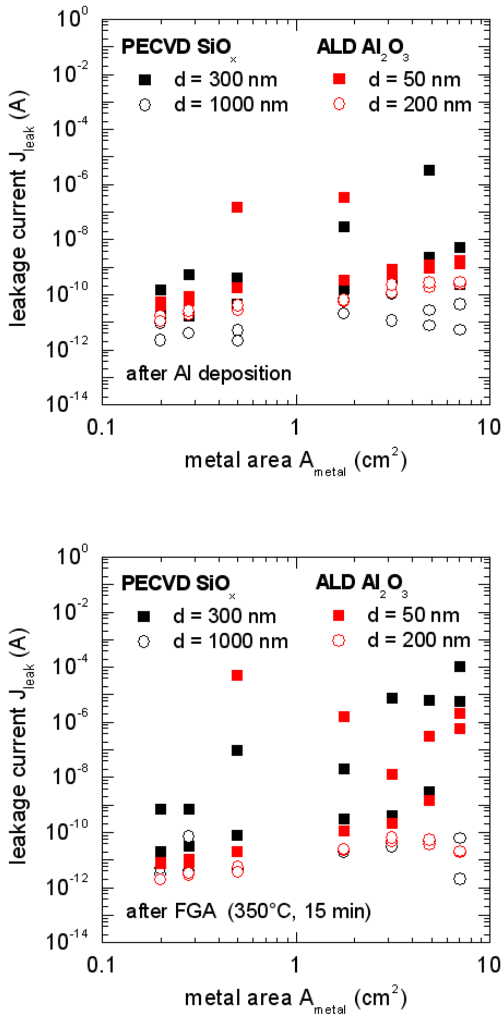

Figure 3: Leakage current vs. metal contact area of ALD Al_2O_3 and PECVD SiO_x insulating thin films with a thickness of 50 nm and 200 nm and 300 nm and 1000 nm, respectively. The leakage current has been measured directly after the aluminum deposition (top) and after a FGA at 350°C for 15 min (bottom).

SOLAR CELLS

Experimental

The investigated back-contacted back-junction silicon solar cells with an insulating thin film were fabricated on *n*-type float-zone grown 200 µm thick silicon wafers with a base resistivity of 1 Ωcm using photolithography. The front side has been textured with inverted pyramids and passivated by a shallow 150 Ω/□ n^+-type front surface field (FSF) diffusion. A thin thermally grown silicon dioxide SiO_2 and an antireflection coating of PECVD SiN_x have been applied to reduce the front side recombination and improve the optical properties of the solar cell. On the rear side, a deep boron-doped p^{++}-type emitter and a deep phosphorus-doped n^{++}-type back surface field (BSF) diffusion have been applied with sheet resistances of about 10 Ω/□ and 70 Ω/□, respectively. It is worth mentioning that the diffusion profiles have so far not been optimized. For the passivation of the boron-doped emitter a passivating thin film of 20 nm thick ALD Al_2O_3 is applied [12]. An ALD Al_2O_3 as well as a PECVD SiO_x insulating thin film has been applied on the rear side of the solar cells. The passivating and insulating thin films have been opened locally in order to contact the diffused regions with the *p*- and *n*-metal fingers. The interdigitated metallization grid consists of about 2.5 µm electron-beam evaporated aluminum and has been accomplished by lift-off technique. Additionally, a low-temperature annealing in room atmosphere for 15 min with a maximum temperature of 450°C has been performed. The pitch distances for the solar cells have been varied between 50 µm and 800 µm. The BSF diffusions are created as point-like diffusions in a hexagonal design for both solar cell structures and cover about 4% of the rear side. For the solar cell structure with a large emitter coverage, the undiffused gap between the BSF diffusions and the emitter diffusion is kept constant for all pitch distances and is about 6 µm wide. Thus, the emitter fraction on the rear side depends on the pitch distance and is between 87% and 91%. That means for a larger pitch distance the number of BSF diffusions is decreased. For the solar cell structure with a small emitter coverage, the emitter is realized as point-like diffusions as well and the emitter area on rear side is also about 4%. Both solar cells structures feature a metal-semiconductor contact area on the rear side, which is only about 1% of the total area for the p^{++}-type and the n^{++}-type diffusion

Results

The best results for the investigated solar cell structures that feature an insulating thin film are presented in Table 1. In addition to efficiencies of 22.7% reported by King *et al.* [13] and the exceptionally high efficiency of more than 23.0% that will be announced by Cousins *et al.* [14] at this conference, this is one of the highest reported efficiencies at one sun for back-contacted back-junction silicon solar cells.

structure	V_{oc} (mV)	J_{sc} (mA/cm^2)	*FF* (%)	η (%)
A)	large emitter coverage			
	673	40.6	80.1	21.9
B)	small emitter coverage			
	706	41.0	78.5	22.7

Table 1. Results of silicon solar cells with insulating thin films determined on a designated area of 3.97 cm^2 (calibrated measurements at Fraunhofer ISE CalLab).

The *FF* for both solar cell structures indicates that no significant shunts are introduced to the solar cells due to defects in the thin film and due to spiking of the metallization through the thin film. By minimizing electrical shading losses in the non-collecting base-type area on the rear side, high short-circuit currents J_{sc} for both solar cell structures could be realized. For the solar cell with a large emitter coverage, the open-circuit voltage V_{oc} is limited to about 670 mV mainly by Auger recombination in the highly-doped emitter. Simulations show, that with an optimized boron-doped emitter diffusion profile, a V_{oc} up to 700 mV should be possible. Besides improving the V_{oc}, an optimized boron-doped emitter diffusion profile will also increase the short-circuit current and reduce free carrier absorption losses (FCA) in the emitter [15]. For the solar cell structure with a small emitter coverage, a high V_{oc} of more than 700 mV has been obtained due to the reduction of the highly-doped diffusion areas on the rear side and the excellent surface passivation of the *n*-type base with an ALD Al_2O_3 passivating thin film [16].

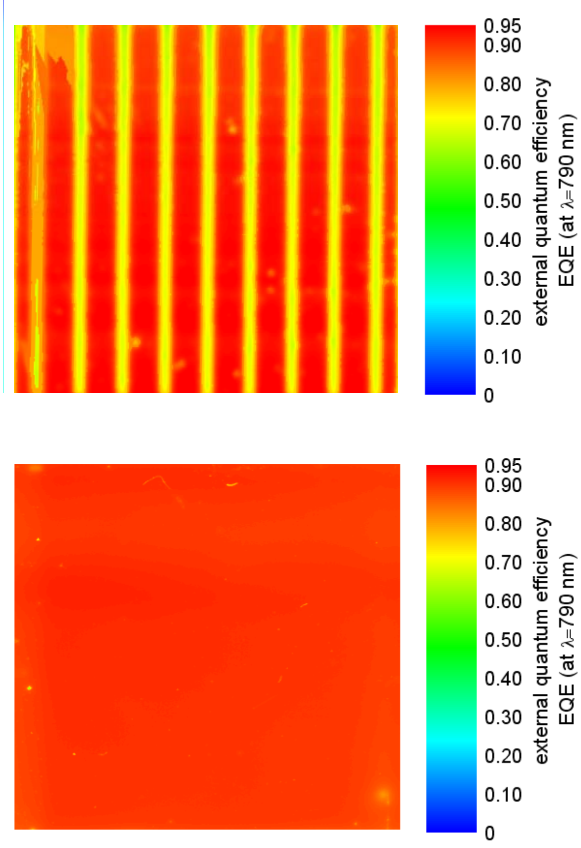

Figure 4: Local external quantum efficiency *EQE* measured with the spectrally resolved laser beam induced current method (SR-LBIC) for a wavelength of 790 nm. For the 2x2 cm² solar cell structure with a large non-collecting base-type area (top) electrical shading losses are clearly visible, whereas for a 2x2 cm² solar cell with a large emitter coverage (bottom) electrical shading losses are minimized.

In Fig. 4, the local external quantum efficiency *EQE* are compared qualitatively for a solar cell structure with a large non-collecting base-type area and a solar cell structure with a large emitter coverage. For the solar cell structure with a large non-collecting area the emitter diffusion is about 1600 µm wide and the non-collecting base-type diffusion has a width of 600 µm. It can be clearly identified that in the non-collecting base-type area, the local *EQE* is strongly reduced to about 0.65 and 0.7 due to electrical shading. For this reason, the J_{sc} of this solar cell is limited to 39 mA/cm². In contrast, the homogeneous local *EQE* of about 0.95 of the solar cell structure with a large emitter coverage which features an insulating thin film on the rear side shows that electrical shading losses in the base-type diffusion area can be avoided. This leads to an increased J_{sc} of about 41 mA/cm² for this solar cell structure.

CONCLUSIONS

Back-contacted back-junction silicon solar cell structures with a large emitter coverage (point-like base contacts) and a small emitter coverage (point-like emitter and base contacts) have been fabricated and analyzed. These solar cells feature an insulating thin film in order to decouple the charge carrier collection and the metallization geometry. It has been found that 200 nm thick ALD Al_2O_3 and 1000 nm thick PECVD SiO_x insulating films are suitable for both solar cell structures and that ALD layers are already insulating for a thinner film thickness. These insulating thin films have been applied to back-contacted back-junction silicon solar cells. In this way, the collection efficiency has been increased and thus electrical shading losses have been reduced significantly. For solar cells with a large emitter coverage, an efficiency of 21.9% (V_{oc} = 673 mV, J_{sc} = 40.6 mA/cm², *FF* = 80.1%) could be obtained. Solar cells with a small emitter coverage have achieved an efficiency of 22.7% (V_{oc} = 706 mV, J_{sc} = 41.0 mA/cm², *FF* = 78.5%). The *FF* of these solar cell structures indicate that no significant shunts are introduced to the solar cells due to defects in the thin film and due to spiking of the metallization through the thin film.

ACKNOWLEDGEMENTS

The authors would like to thank A. Leimenstoll, F. Schätzle, S. Seitz, N. König and E. Schäffer for process technology and measurements. Fruitful and valuable discussions with Martin Bivour and Jan Benick are gratefully acknowledged. Wesley Dopkins is recognized for thoroughly proofreading the manuscript. This work was supported by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety under contract number 0329849A (Th-ETA).

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