Metal pinning through rear passivation layers: characterization and effects on solar cells

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Abstract

We investigate local defects in rear passivation layers, in which the metal is forming a contact to silicon pinning through an insulating layer. At first, we studied these contacts by measuring the layer resistivity of different dielectrics sandwiched between Al and Si. Our study includes the influence of parameters like the surface roughness, the metallization techniques and the post-metallization annealing. In addition, we propose a characterization of these contacts on solar cell level, using photoluminescence-imaging performed before the finalization of the rear contacts. A good correlation between the contacts and the dark saturation current density suggests that these contacts can harm the rear surface passivation quality.

1. Introduction

Until recently most of the rear passivated solar cells were produced on small surface, and many of them were featuring evaporated metal contacts [1]. Technological improvements in rear-surface passivation techniques and contact-formation techniques allow the production of large-area rear passivated solar cells using mass-production equipment. The use of large-area wafers, the need of driving the process cost down, and the used firing steps increase the probability of defects formation in the passivation layer. Through some of these defects in the passivation layers, metal would penetrate forming a weak contact with silicon. In this paper we will call them “metal pinning through dielectric” (MPTD).

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As the MPTD are most of the time unwanted, their electrical activity is not controlled and they represent a potential danger for the passivation quality.

2. Formation of defects in the passivation layers

In order to characterize and quantify the defects through the passivation layer we perform measurements of the layer resistivity under conditions close to the one at the rear of a solar cell. On the front side of the wafer the dielectric under investigation has been deposited and covered by aluminum dots (the Al thickness is higher than 0.5 µm), while the rear side of the sample was entirely covered by aluminum, forming a planar contact on the rear. We used p-type wafers with a resistivity of 1 Ω cm. Two types of samples have been prepared with evaporated aluminum and screen-printed aluminum. Then the resistance is measured via contacting front and rear of the sample (see figure 1). From the measured resistance $R_s$ and the area of the dot size the area normalized resistance is calculated.

![Diagram](https://via.placeholder.com/150)

Fig. 1: Setup used for the measurement of the dielectric layer or dielectric layer resistivity.

2.1. MPTD of evaporated aluminum

Three different round-shaped dot sizes have been prepared for these samples (diameter of 1 mm, 3 mm and 6 mm), for each parameter variation we measured an equal amount of dots of each size. For the resistance measurement we used a picoamperemeter applying successively 1 V and -1 V. This technique is further described by Reichel et al. [2]. Despite the high accuracy of this measurement technique in the high resistance range, it is limited in current, giving a minimum for each dot size (see figure 2a). Therefore the values obtained in this study can only be interpreted as an indicator of the resistance given by the dielectrics.

![Graph](https://via.placeholder.com/150)

Fig. 2: (a) Resistance for different types of surface preparation leading to different surface topography. The aluminum is evaporated, the dielectric layers are PECVD SiN, and SiO, with thicknesses ranging 100 – 200 nm., The samples have been annealed during 25 min at a temperature between 300°C and 450°C. Between 270–400 dots were measured per variation. (b) Explanation of the box diagram.
In many solar cell process flows, no firing would be performed after the deposition of aluminum, eventually an annealing (with temperature ranging 300°C - 450°C) could occur at the end of the solar cell process. The dielectrics used for this study are SiO$_x$ and SiN$_x$ by plasma-enhanced chemical vapor deposition (PECVD) with a thickness between 100 nm and 200 nm. Fig. 2 shows the measured resistivities based on samples with three different surface topographies, including all layer types, layer thicknesses, and annealing temperature variations. We obtain a very large range of values for the resistivity spreading over 11 orders of magnitude. This indicates that at the microscopic scale the contacts that are formed have probably very different sizes, densities and/or contact resistances. We can observe two main groups of resistance: the first in the range of $10^9 \ \Omega \ \text{cm}$ corresponding to uncontacted dots, the second in the range of $10^2 \ \Omega \ \text{cm}$ corresponding to dots having a good contact. We notice that for the textured samples almost all the measured values are situated in the low resistivity region, while for the smooth surface roughness, the values are scattered broadly with emphasis to higher resistance. We conclude that surface preparation and the resulting topography is a dominant factor (within the described study) for the formation of MPTD.

In figure 3 the resistivity is plotted for damage-etched and shiny-etched samples, coated with PECVD SiN$_x$ and SiO$_x$, with different annealing temperatures applied. As it is expected, thick dielectrics have the tendency to be more resistive than thinner dielectrics of the same composition. SiN$_x$ shows a higher resistivity than SiO$_x$, especially for annealing temperatures above 400°C, while for the samples coated with SiO$_x$, a strong decrease in the resistivity can be observed in this range of temperature. This phenomenon is generally explained by a reduction of the SiO$_2$ by the Al, which can than penetrate the dielectric layer, and form a contact [3].

![Fig. 3: Resistivity of PECVD SiN$_x$ and PECVD SiO$_x$ layers for evaporated Al dots as a function of the layer thickness and the annealing temperature. The samples are all shiny etched or damage etched, showing no major difference between these two surfaces roughnesses. Between 16-40 dots measured per variations.](image)

2.2. MPTD of screen-printed aluminum

We also studied the formation of MPTD with screen-printed aluminium and firing, as this type of metallization is often used in the fabrication of PERC solar cells. Six different dot sizes have been prepared (with a diameter of 1 mm, 2.5 mm, 5 mm, 10 mm, 15 mm and 25 mm). The passivation layer used for this study is a 20 nm thick layer of PECVD Al$_2$O$_3$, covered by 80 nm of PECVD SiN$_x$ or PECVD SiO$_x$. All the samples have been fired at a set peak temperature of 870°C for 2 - 3 s. For the resistance evaluation, we measure the intensity voltage (IV) curve between -5 V and 5 V. The resistance
was then fitted on the linear part of the IV curve. This technique offers a higher accuracy in the low resistance range compared to the one described in section 2.1.

The resistance is plotted in figure 4. We notice that using screen-printing, a higher ratio of samples is contacted compared to the Al-deposition using evaporation. The as-cut samples present a very low resistance due to their rough surface. The samples coated with SiOₓ present resistances which are orders of magnitude lower than for the evaporated Al even on shiny-etched surfaces. The last could be explained by the fact that the critical temperature for PECVD SiOₓ (~400°C), observed in fig. 3, is much lower than the temperature used for the firing (870°C). At high temperatures, aluminium can reduce SiO₂, in this case it seems that the aluminium was also pinning through the Al₂O₃ deposited by PECVD[3]. After firing the SiOₓ layer might be consumed completely.

Defects in the passivation layer have been observed using scanning electron microscopy (SEM). In an example (figure 5) a contact can be observed between silicon and metal, as well as a cavity in the screen-printed metal.

![Figure 4](image.png)

**Fig. 4:** Resistance measured for PECVD Al₂O₃ - SiNₓ and Al₂O₃ - SiOₓ layer stacks, for screen printed Al dots fired at 870°C, as a function of the wafer surface roughness. Between 20-40 dots measured per variations.

![Figure 5](image.png)

**Fig. 5:** SEM picture of the cross section of a sample coated with screen-printed aluminum after firing. We observe a local opening of the passivation layer with metal penetrating in the silicon. A cavity is also observed in the aluminum due to local melting of the eutectic. In fact the melting temperature of the Si-Al eutectic is lower than the one of pure aluminum.

To conclude this section, we measured the resistivity of dielectric layers in different conditions close to their application in solar cells (see figure 1). The annealed samples with evaporated aluminum generally
have a higher resistivity than the fired screen-printed samples. The surface preparation is also a very important parameter [5]: The rougher the wafer, the lower the resistivity, with very low resistivities for textured and as-cut samples. Samples deposited with PECVD SiNₓ show a higher resistivity compared to samples coated with PECVD SiOₓ especially after a temperature step over 400°C. This is probably due to the reduction of SiOₓ by aluminum at high temperatures. Finally, the combination of resistance measurement with a quantitative pinhole investigation [4] could help to further understand the cause of the formation of MPTD.

3. Characterization of metal pinning through the rear dielectric layer in solar cells

3.1. Experimental

Industrial-type rear passivated solar cells were produced in order to study the influence of MPTD. The rear surface is passivated using a stack of thin thermal oxide and a PECVD layer stack. The solar cells present screen-printed contacts on the front and on the rear. In order to contact the screen-printed aluminium and the silicon through the passivation stack, laser-fired contacts (LFC) [6] are formed on the rear. However, in our case the solar cells were mainly characterized before the LFC process, meaning that the aluminium was already lying on the passivation layer with no contact to the silicon.

3.2. Characterization by photoluminescence-imaging

The solar cells were measured by means of photoluminescence (PL) imaging before the formation of the base contacts. The images were performed under open-circuit (OC) and short-circuit (SC) conditions. Under OC conditions, the PL image should be homogenously bright, while reduced intensities indicate material- or process-induced defects. In case of finished contacts, the PL image under SC conditions should look homogeneously dark, because all the charge carriers are drained out of the cell without being able to recombine radiatively. If no contacts were formed, the PL signal is expected to be the same for OC and SC conditions and deviations can be attributed to MPTD. The solar cell characteristics before LFC were mainly limited by a very high series resistance because the contacts have not been formed yet. Although no current is expected to flow under SC conditions, we can observe that a low amount of current was collected through local contacts formed at MPTD. The PL image under SC conditions (figure 6b) presents dark spots and large dark areas compared to the OC PL image (figure 6a). Under SC conditions the local junction potential is dropping in the regions that are contacted by MPTD, inducing a low PL-intensity.
Fig. 6: Photoluminescence correlation between contact and recombination area, (a) PL image in OC condition before LFC, (b) PL image in SC condition before LFC, (c) ratio of $j_{\text{col}} / j_{\text{lum}}$ under SC condition before LFC, (d) dark saturation current density of the finished cell.

We use a simple model in order to extract the local ratio of current that can be collected in SC ($j_{\text{col}}$) over the light-generated current ($j_{\text{lum}}$). The PL signal is proportional to the recombination current. The current generated in the solar cell has only the option to recombine or to be collected at the contact. Under OC condition it is obvious that all the generated current recombines, so we can therefore scale the recombination current using the OC PL image. Under SC conditions, the current that does not recombine is collected. Therefore the ratio of collected current over the generated current can be written as

$$j_{\text{col}} / j_{\text{lum}} = 1 - \frac{PL_{\text{sc}}}{PL_{\text{oc}}},$$

(1)

where $PL_{\text{oc}}$ and $PL_{\text{sc}}$ are the PL signals under OC and SC conditions, respectively. Figure 6c is an image of the ratio of $j_{\text{col}}$ over $j_{\text{lum}}$ which is independent from the local lifetime. One should note that due to a small amount of reflected light which cannot be filtered, this method does not provide accurate values for ratios exceeding 90%. In figure 6d we plot the dark saturation current of the finished solar cell (after LFC); this image has been calculated from voltage calibrated PL measurements using the method presented in ref. [7].

By comparing the image of the collected current ratio before LFC and the dark saturation current on the final cell, we can observe a good correlation. An increased dark saturation current indicates in this
case a stronger recombination due to a poor quality of passivation stack and aluminum layer caused by MPTD spots. The increased recombination can be explained by the fact that the surface recombination velocity (SRV) of a silicon surface in direct contact with metal is typically higher than the SRV of an area passivated by a dielectric. The formation of this contact is therefore harmful for the local passivation quality.

4. Conclusion

In this paper we investigated the uncontrolled formation of contacts through the passivation, by metal pinning through the passivation layer.

In the first part of the paper, we studied the formation of these contacts based on the measurement of the dielectric layer resistivity. This includes the influence of parameters like surface roughness, metallization technique and post-metallization annealing for different dielectrics.

In the second part of the paper, we propose a characterization of these contacts on solar cells. The characterization based on photoluminescence imaging is performed before the finalization of the rear contacts. A good spatial correlation between the contacts and dark saturation current density suggests that these contacts can harm the rear surface passivation quality.

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References