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Full Length Article

Adhesion quality of evaporated aluminum layers on passivation layers for rear metallization of silicon solar cells

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A B S T R A C T

This paper characterizes the adhesion quality of evaporated aluminum rear metallization on rear passivation layers of silicon solar cells. A peel-test is introduced for adhesion rating and the adhesion quality between various Al and passivation layers on test structures is compared and discussed. The results show that the adhesion strongly varies with passivation type and evaporation parameters. Strong adherence is attributed to the formation of a strongly bonded, extended interphase layer. We derive factors that influence adhesion quality on our sample structures and find that an intimate contact between the layers and elevated temperatures are very important parameters. Additionally, a sufficiently high adhesion quality for an evaporated rear metallization of passivated emitter and rear cells (PERC) is achieved for all investigated passivation layers.

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1. Introduction

For a large number of silicon solar cell concepts in research metallization by means of physical vapor deposition (PVD) represents a well-suited contacting method with a very high efficiency potential [1,2]. Due to being a contactless technology it is well suited for thin wafers; metallization by PVD also highly reduces contact material consumption compared to industrially dominating screen-printed rear contacts, thus offering a cost saving potential for industrial application. For passivated emitter and rear cells (PERC) with PVD rear metallization a 2 μm thin Al layer is sufficient for a good lateral conductivity even for 156 mm sized wafers with 2 or 3 busbars [3] but incompatible with a conventional solder process for cell interconnection. To enable industrial module integration of such solar cells the development of an industrially feasible connecting technology is required. Different approaches for contacting the PVD metallization with the cell interconnectors have been reported [4–12]. For these interconnections the standard DIN EN 50461 defines a minimal adhesion of 1 N/mm in a 90°-peel-test for the joint and therefore for the PVD Al layer on the passivation layer. Adhesion failure between evaporated Al and SiN_x passivation layers has been observed already by Heinemeyer et al. [13] but to our knowledge, the reasons have not been systematically investigated, yet. Since a sufficient adhesion of the metallization is vital for stable cell interconnection this issue is addressed in this work.

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Measurable, macroscopic adhesion bases on microscopic properties of the layers and the underlying substrate: the type of interface, the character of chemical and mechanical bonding as well as internal and thermal stresses [14–16]. These microscopic properties, as well as the macroscopic adhesion, depend on the involved materials, the surface morphology and are moreover strongly influenced by the used process parameters. In general, the correspondence between microscopic properties and macroscopic adhesion is complex and not fully understood or predictable [17].

Al and other metal layers deposited by PVD on thermally grown SiO_2 were investigated previously [18–29] under various aspects; the topic of adhesion was touched by a few. Strong adhesion was achieved between Al and thermally grown SiO_2 when Al and Si are strongly bonded via oxygen atoms (Al-O-Si). Due to a high heat of Al_2O_3 formation, reaction

$$3\,SiO_2 + 4\,Al \rightarrow 2\,Al_2O_3 + 3\,Si \tag{1}$$

was found to take place for Al on SiO_2 if in intimate contact, resulting in an Al-Al_2O_3-Si-SiO_2 interface. The Al_2O_3 was found to be non-continuous and porous, therefore more Al diffuses to the SiO_2 layer to continue the reaction and free Si diffuses into the Al layer and forms precipitates, if sufficient activation energy is provided [18]. If due to this intermixing the interfacial [29] materials extend over several nm, as described in Ref. [26], we here refer to this as a continuous 'interphase' layer - in contrast to an abrupt interface, compare [15]. The extent of the chemisorption effect by reaction (1) was investigated in several publications [18–22] and for the activation energy values

between 1.35 and 2.54 eV were reported. The plurality of results and an apparent dependence on the specific conditions make reliable predictions on similar applications difficult.

Investigations of Al layers and Si_3N_4 layers [30,31] showed that reaction

$$Si_3N_4 + 4\,Al \rightarrow 4\,AlN + 3\,Si \quad (2)$$

proceeds at the interface. To a small extent this reaction was found to proceed also at room temperature, forming mainly amorphous AlN which then separates Al and Si. At elevated temperatures the AlN barrier is overcome by Al and Si, the reaction continues and the interphase AlN layer keeps growing. To our knowledge, adhesion properties have not been characterized for this material combination.

In this work, we investigate the adhesion quality specifically for PVD Al layers on common silicon solar cell passivation layers, mainly comprising SiO_x and SiN_x films.

To get hold of the most relevant factors for adhesion quality in this application and to practically obtain a sufficient adhesion, in this work we process test samples under variation of commonly used passivation stacks and variation of Al deposition parameters. Focus of the investigation is laid on evaporated Al layers as the deposition of a 2 μm thick Al layer can be realized with industrial throughput much more economically by evaporation than by sputtering. Then we experimentally characterize the adhesion between PVD Al layer and passivation layers by using our peel-test method described in Ref. [32].

We compare the measured adhesion qualities and propose some explanations on microscopic scale.

2. Experimental

2.1. Sample preparation

We fabricate test samples which represent solar cell rear side structures [33], see Fig. 1b), with the process flow shown in Fig. 1a).

Czochralski (Cz) grown p-type Si wafers with a thickness of 200 μm are textured with random pyramids in alkaline solution and rear-side wet chemical polished, or instead just saw damage-etched (SDE).

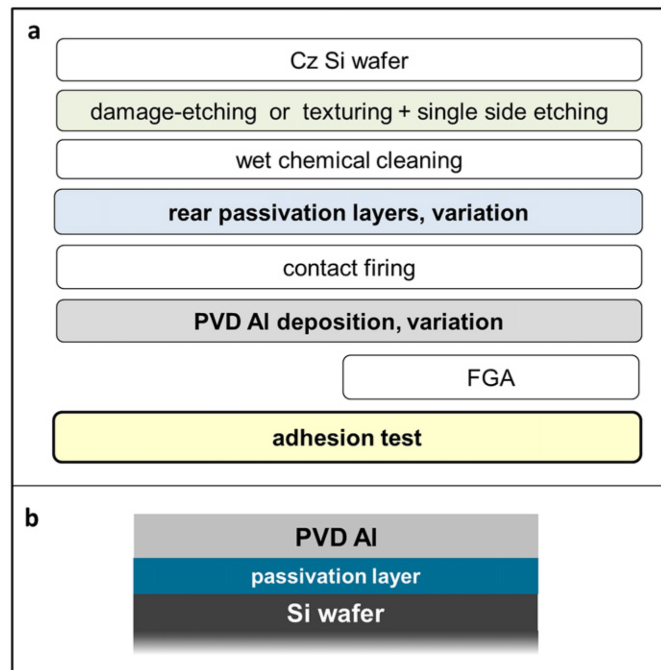

Fig. 1. a) Process flow of test sample fabrication. b) Schematic cross-section of a test sample (not to scale) to characterize the adhesion between PVD Al and passivation layer.

After a cleaning step, we process one of four commonly used passivation layers, listed in Table 1, on the rear side of each wafer. After a firing step to reproduce a cell process with screen-printed front contacts, the samples are stored in ambient several days until we metallize the samples and no special cleaning or surface treatment is performed before deposition. They receive a 2 μm thick Al layer via sputtering or thermal evaporation on an inline pilot system Aton 500 by Applied Materials with a throughput of 540 wafers per hour. Four different deposition processes are applied as listed in Table 2.

By varying substrate surface treatment, passivation layer and PVD process parameters, we fabricate a variety of different test structures and the adhesion of all these sample structures is then characterized on 2–6 samples. Samples of all types are forming-gas annealed (FGA) for 3 min and 40 s at 350 °C, again followed by adhesion testing to investigate the influence of an FGA on layer adhesion. Some samples are additionally analyzed by SEM images. We will present and discuss the most interesting adhesion results of all these tested sample structures below.

2.2. Deposition temperature

To consider a dependency of adhesion quality on deposition temperature, the substrate temperatures during the evaporation process is measured on the different samples. Even when on all samples the Al layer is deposited with the same reference evaporation process, we are aware that the deposition temperature may vary for the different sample types, mainly due to thickness variations and differences in emissivity.

- Thickness variation: We find the SDE wafers to be about 20 μm thicker than the textured and single side polished samples since the etching processes for texturing and polishing remove more wafer material. As thicker wafers possess a larger volume and therefore a higher thermal capacity, they do not heat up as much during the evaporation process [34]. In contrast, the different surface morphologies alone do not influence the deposition temperature very strongly [34].
- Emissivity variation: During the deposition process the passivated side of the wafer is soon covered with a growing Al layer, possessing a very low emissivity of $\varepsilon < 0.1$. Therefore the thermal radiation and thus the sample temperature during deposition are mainly determined by the emissivity of the Al free side, which is covered with a thermal oxide in the case of the thermally oxidized samples as illustrated in Fig. 2. As the emissivity is different for Si ($\varepsilon \approx 0.66$) and SiO_2 ($\varepsilon \approx 0.77$) this results in a lower deposition temperature for the thermally oxidized samples [34,35].

Therefore we measure the substrate temperature on our adhesion samples during the reference evaporation process for all the different passivation layers with thermocouples. The measured peak temperatures are depicted in Table 3.

Although the absolute temperatures and temperature differences should be regarded with care due to measurement error and deposition inhomogeneities, we trust the general tendency which confirms that the samples with passivation layers that are processed by PECVD on one side only ('AlO_x/SiO_x' and 'AlO_x/SiN_x') experience substrate

Table 1
Investigated passivation layers.

Passivation type	Passivation process
Th. SiO_2/SiO_x	10 nm thermally grown SiO_2 + 90 nm PECVD SiO_x
AlO_x/SiO_x	10 nm PECVD Al_2O_3 + 90 nm PECVD SiO_x
AlO_x/SiN_x	10 nm PECVD Al_2O_3 + 80 nm PECVD SiN_x
Th. SiO_2	100 nm thermally grown SiO_2

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