Investigation of Methods for Adhesion Characterization of Evaporated Aluminum Layers

Julia Kumm, Dirk Eberlein, Philip Hartmann, Winfried Wolke, Andreas Wolf, Ralf Preu

Fraunhofer Institute for Solar Energy Systems (ISE), Heidenhofstraße 2, 79110 Freiburg, Germany

***Abstract* — This paper analyzes methods for measuring the adhesion quality of aluminum (Al) rear metallization deposited by means of physical vapour deposition (PVD) on rear passivation layers of passivated emitter and rear silicon solar cells (PERC). Since the standard test procedures for adhesion testing of solar cells cannot be applied, a peel-test and a direct-pull method are introduced and used for measuring the adhesion of test samples; criteria for adhesion evaluation are developed and applied. The results of adhesion tests are compared and are in good general agreement. The applicability of the two methods is discussed and it is found that the peel-test shows more reliable results whereas the direct-pull method is easier in preparation. Moreover, the results of the test samples show sufficiently good adhesion quality for the PVD rear metallization of PERC solar cells.**

***Index Terms* — PVD, aluminum, Al-metallization, adhesion, photovoltaic cells, silicon.**

I. Introduction

PVD metallization is widely used for contacting PERC and many other solar cell concepts in research due to its high efficiency potential [1]. 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 PERC solar cells with PVD rear metallization a 2 µm thin Al layer is sufficient for a good lateral conductivity even for 156 mm wafers [2]. To enable industrial module integration of such PVD-PERC solar cells the development of an industrial feasible connecting technology is required. Different approaches for contacting the PVD metallization with the cell interconnectors have been reported [3]-[5]. For these interconnections the standard DIN EN 50461 defines a minimal adhesion of 1 N/mm in a 90°-peel-test for the joint. Obviously, for stable contacts of PVD-PERC solar cells an equally good adhesion of the evaporated Al on the passivation layer is required. However, little attention has so far been drawn to this aspect and the tape test recommended in DIN EN 50461 cannot guarantee sufficient adhesion as it only characterizes adhesion of 0.2-0.4 N/mm. To investigate the adhesion between PVD Al and passivation layers, in this work test samples representing PERC rear side structures [6] are processed under variation of commonly used passivation stacks and Al deposition parameters. Since it is not possible to perform the standardized peel-test on such samples, alternatives for an adhesion evaluation are required.

In this work we develop an alternative peel-test method with evaluation criteria suitable for investigating the adhesion between a PVD Al layer and an underlying passivation layer. Likewise, a direct-pull adhesion method is introduced and both methods are used for adhesion testing. The results of both methods are compared and applicability of the methods is discussed as well as the adhesion quality of the PVD Al on the test samples.

II. Experimental

We fabricate test samples as shown in Fig. 1.

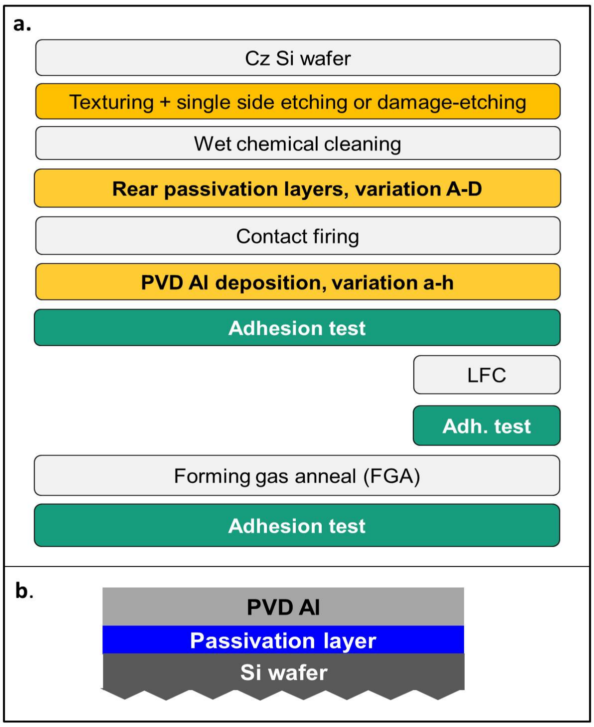


Fig. 1. a. Process flow of test sample fabrication. By varying substrate surface treatment, passivation layer and PVD process parameters, 18 different test structures are produced. Adhesion is tested before and after annealing, additionally some samples are locally contacted by means of the laser fired contact technology (LFC) [7]. This procedure leads to 42 different test structures. b. Cross-section of a test sample on which the adhesion between PVD Al and passivation layer is tested.

With this approach we receive 42 different sample types. Both adhesion methods, which are presented in the following, are performed using five samples of each.

The first method for adhesion testing is based on a 90° peel-test [8]. The challenge is to prepare the samples in such a way that one is able to grasp the PVD Al layer with a sufficiently large force to peel it off the wafer. This can be achieved by laminating the samples with ethylene vinyl acetate (EVA) as in the procedure described in Fig. 2.

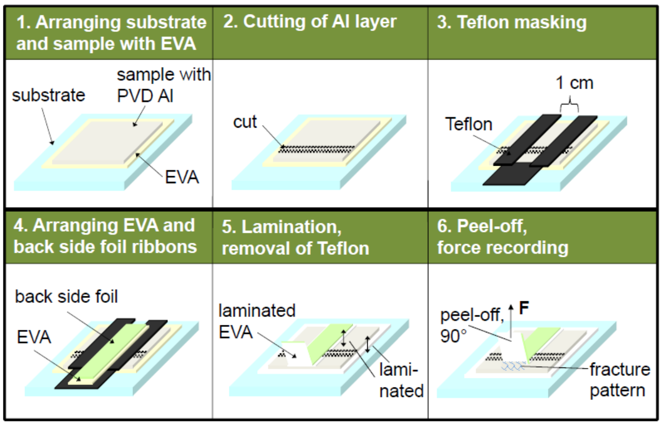


Fig. 2. Adhesion measurement with peel-test.

The sample is adhered to a stable substrate and a ribbon of back-side foil is fixed on the sample surface by EVA lamination. The contact width *W* between ribbon and sample can be defined by Teflon masking and is here chosen to be 1 cm. The sample needs to be cut perpendicular to the direction of the ribbon to enable peeling of the PVD Al layer. The ribbon is then peeled under an angle of 90°. The force that is needed for peeling is recorded and can be depicted in a force-time diagram.

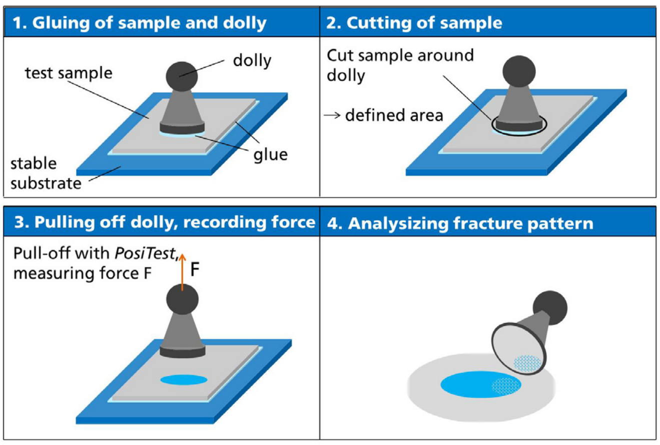


Fig. 3. Adhesion measurement with direct-pull method.

This can be assigned to the ribbon length and regarded as a force-distance diagram. Additionally, the fracture pattern is recorded with a camera.

The second method of adhesion testing is a direct pull [9] performed with the PosiTest AT-M by DeFelsko with the procedure shown in Fig. 3. The test samples are glued to a stable substrate, e.g. a metal plate and then a dolly, a metal stamp with a 20 mm diameter, is glued on the Al layer of the sample. The sample is then cut very closely around the dolly with a special cutting tool to receive a defined testing area. An increasing normal force is applied to the dolly until it is pulled off. The maximal force at pull-off and the fracture pattern are recorded.

III. Results And Discussion

Interpretation of the peel-test results is straightforward if the test can be considered as a classic peel-test as referred to in standard DIN EN 50461. In the ideal case the Al layer is peeled off the passivation under the peel angle α on the complete peel area and - as the Al layer is cut perpendicularly to the peel direction - the energy introduced by the peel force can exclusively be attributed to breaking up the adhesive bonds between Al and passivation layer (in distinction to the cohesive bonds within the evaporated Al layer). Then (and if plastic deformation can be neglected) the peel-force F per contact width W can be interpreted as area-normalized binding energy γ between the layers [8]

$$\gamma = F/W \cdot (1-\cos\alpha) \xrightarrow{\alpha=90^\circ} F/W \qquad (1)$$

and a comparison with the standard enables easy evaluation of the results. In fact, different fracture patterns which often prohibit this interpretation are observed and the deduction of a binding energy from the measured force is only possible in some cases. Therefore, we suggest that, additionally to the measured force, the fracture pattern should always be taken into account for the evaluation of the adhesion quality from a peel-test as depicted in the following examples.

As an example Fig. 4 shows a sample with very low adhesion between evaporated Al and passivation as well as its ribbon after peeling and the corresponding force-time diagram.

The fracture pattern and the force-time diagram show multiple sections. Section A shows higher forces which result from the start of peeling. Section B can be used best for evaluating the adhesion quality between PVD Al and passivation layer. Here the Al is practically completely peeled off the passivation layer which corresponds to a classical peel-test and can therefore be interpreted as such. The peel-forces of about 3 N can be used to estimate an area-normalized binding energy γ after (1) to

$$\gamma \approx \frac{3N}{1cm} = 0{,}3\frac{N}{mm} = 300\frac{N}{m} = 300\frac{J}{m^2} \qquad (2)$$

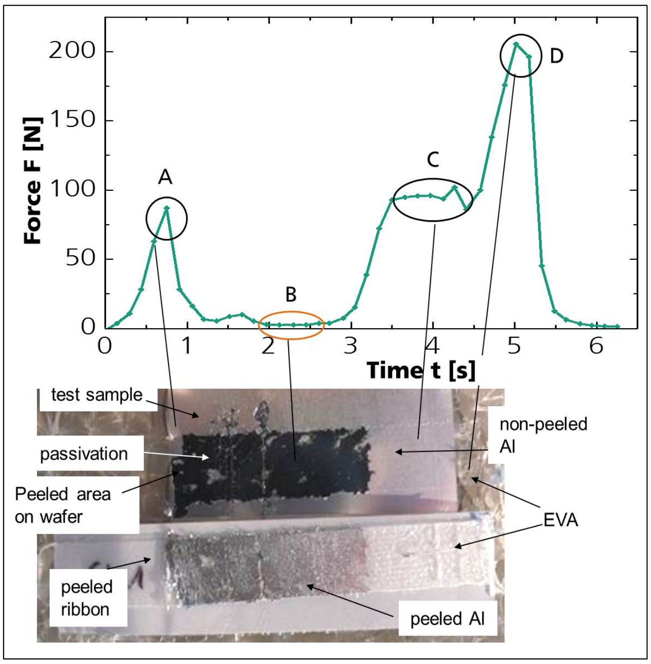


Fig. 4. Example of force-time diagram and fracture pattern of a peel tested sample with very low adhesion between PVD Al and passivation layer.

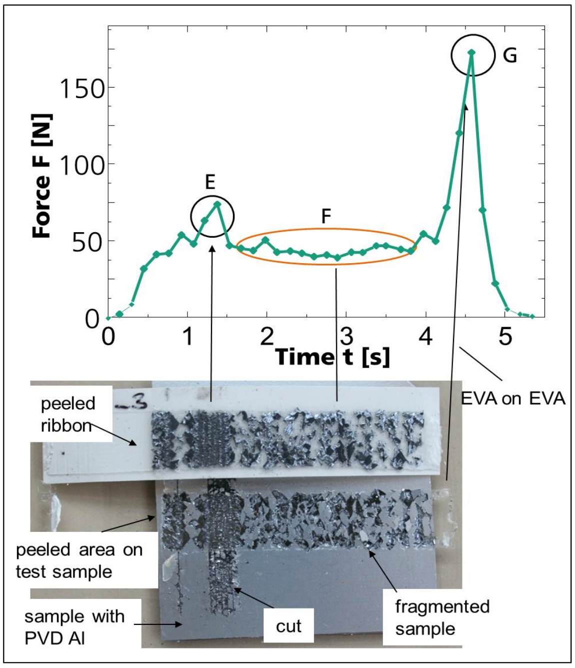


Fig. 5. Example of force-time diagram and fracture pattern of a peel tested sample with very high adhesion between PVD Al and passivation layer.

A comparison of this value to the minimal adhesion of 1 N/mm as defined in standard DIN EN 50461 shows that the adhesion of this sample is not sufficient. Between section B and C the ribbon loses contact to the PVD Al layer which results in much higher forces in section C. Although the adhesion energy between PVD Al and passivation is much lower than the energy of almost 10 N/mm introduced by the peel-force, the layers are not separated. The Al layer stays intact as the introduced energy cannot just go into breaking the adhesive forces, but additionally has to exceed the cohesive forces within the PVD Al layer, so that the part that would be peeled could be separated from the remaining part. To do so, even higher energies would be needed. Instead, in this case, the EVA is separated from the PVD Al and the recorded forces in section C gives no information about the adhesion between PVD Al and passivation layer. This demonstrates the importance of the cut during sample preparation. The very high forces in section D correspond to the very tight binding between two laminated EVA layers.

In case of a stronger adhesion between PVD Al and passivation layer the sample tends to fragment under the peeled ribbon as can be seen in Fig. 5.

Section E and section G should not be taken into account for adhesion evaluation as section E shows higher forces around the cut and section G shows very high forces where two EVA layers are laminated together.Section F can be used best for adhesion evaluation but as the wafer fragments under the high forces during peel-off an interpretation corresponding to a classic peel-test is not valid and a numerical value for the binding energy cannot be deduced. However, the recorded forces are much higher than the requested 10 N/cm and no separation of PVD Al and passivation layer on the splinters can be observed. Therefore, it is concluded that the layers possess a very high adhesion.

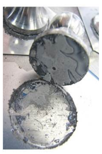
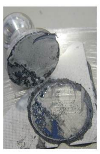
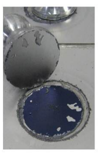
Hence, for adhesion characterization with the presented peel-test we propose a combined evaluation of fracture pattern and force-time diagram for categories on an ordinal scale as depicted in Table 1. The lowest two categories, and as already depicted especially the lowest one, describe a situation that can be interpreted as a classic peel-test, so that they can be linked to the standard DIN EN 50461: If the forces remain below 10 N/cm as it is the case in the category “very low”, the standard is failed. If the forces exceed 10 N/cm as in the category “low” – and in all higher categories - the standard is fulfilled.

TABLE 1:
EVALUATION CRITERIA FOR PEEL-TEST

Adhesion category	Symb.	Description of force and fracture pattern
very high	++	Under high forces (≥35 N) the sample fragments into little pieces in the peel-off area, no separation between Al and passivation layer.
high	+	Fragmentation of the sample under high forces (≥35 N), few small fragments show separation of Al from passivation layer.
moderate	O	Fragmentation of the sample under high forces (≥30 N), many patches of Al separate from passivation layer.
low	-	Under moderate forces (10-30 N) the sample structure is left intact apart from the detachment of few splinters, big patches of Al separate from the passivation layer.
very low	--	Under small forces (≤10 N) the Al layer is separated from the passivation layer, the sample is left practically intact.

With the direct-pull method - in the ideal case - the stress which is needed to break up the adhesive forces between the two materials can be determined. If, by pulling up the dolly, the Al layer is completely separated from the passivation layer, the maximal force before adhesion failure gives direct information about the area-normalized binding forces. Obviously, a direct comparison to the ideal peel-test - from which an area-normalized energy is deduced – is not valid. Furthermore, this interpretation of the direct-pull method does not apply if the adhesion of the glue is inferior to that of the other layers, as it is the case for most of our samples. It can be observed that the measured maximal force does hardly correlate with adhesion quality, therefore we suggest the evaluation criteria depicted in Fig. 6, which base on fracture pattern analysis.

TABLE 2:
EVALUATION CRITERIA FOR DIRECT-PULL METHOD

Adhesion	very high	high	moderate	low	very low
Symbol	++	+	o	-	--
Description of fracture pattern	No separation between Al and passivation layer	Separation of Al from passivation layer in the form of few very small flakes.	Separation of Al from passivation layer in some small areas.	Separation of Al from passivation in form of bigger patches, that can take up to 50% of total area.	Separation of Al from passivation layer on more than 50% of the area.
Example					

Direct linking of these direct-pull criteria to the peel-test criteria or the standard is not possible as the methods base on different physical properties. Therefore, we focus on practical comparability of both methods. All 42 sample types are measured with both methods, evaluated according to the introduced criteria and the adhesion results of both methods are compared in the following. As can be seen in Fig. 6 for 31 of 42 sample types an agreement between both methods is observed.

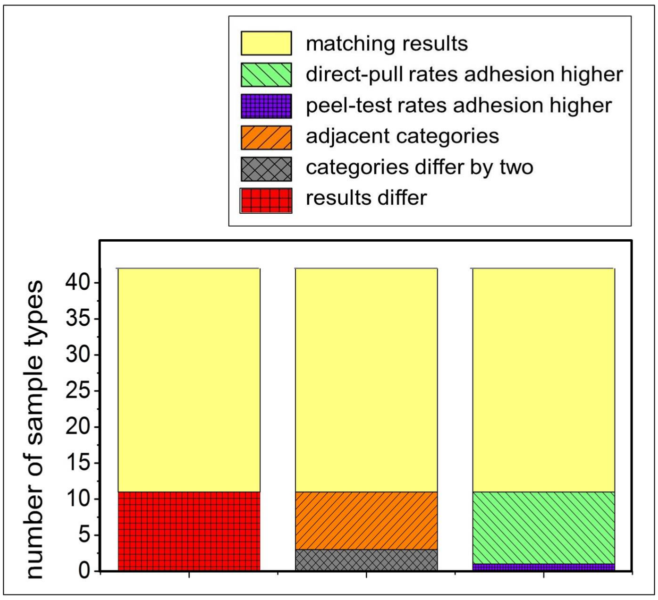


Fig. 6. Comparison of adhesion results. Number of sample types with matching and differing adhesion results when measured with both adhesion testing methods.

Of the 11 types with differing results, 8 results are in adjacent categories and 3 differ by two categories. With just one exception, in case of disagreeing results the direct-pull method rates the adhesion better than the peel-off test.

Since thereof most results (8 of 10 samples) differ between “moderate”, “high” and “very high” adhesion, it is concluded that the direct-pull method shows a lower sensitivity to small adherence defects.

Despite some differences between the adhesion results measured with both methods and the introduced criteria are in good agreement. We therefore conclude that both methods might be applied for adhesion testing. Since the direct-pull method tends to rate adhesion better than the peel-test, its results should be interpreted more carefully, but as it is quicker and easier in preparation it can be very useful for a first assessment.

For ten test structures which seem most realistic for industrial application of evaporated Al layers the results of adhesion measurements after FGA are shown in Fig. 7.

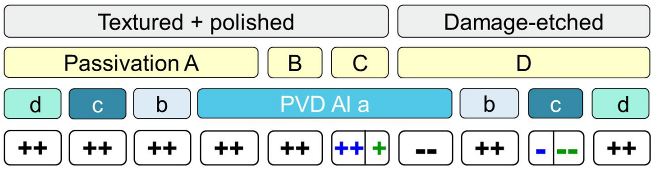


Fig. 7. Results of peel-test and direct-pull adhesion analysis for two surface morphologies, four passivation layers (A-D) and four parameter sets during Al deposition (a-d). If the results of both methods coincide, just one symbol is displayed. If the results differ, the measured adhesion of the direct pull test is shown on the left and that of the peel-test on the right side.

The adhesion quality clearly depends on the passivation layer as well as on the PVD process parameters. As the results show great differences in adhesion quality between the sample types, attention should be drawn to this aspect when designing a PERC rear structure with PVD Al rear metallization to avoid adhesion failure on cell interconnecting. The results show that a far better than sufficient adhesion can be achieved for all investigated passivation layers if the appropriate PVD process parameters are chosen.

IV. Summary And Outlook

In this paper, the adhesion between evaporated Al and passivation layers on the rear side of PERC solar cells is investigated. Two methods, a peel-test and a direct-pull method, are introduced and compared. Due to a lack of applicable adhesion measurement standards for characterizing adhesion on these sample structures, novel evaluation criteria are defined. The criteria only partly rely on the measured force, and in addition, take into account a fracture pattern analysis. The methods are in good agreement, but further development of adhesion measurement guidelines for this application is recommended. On PERC-like test samples the adhesion of PVD Al metallization on several passivation layers is tested. Although the results show big differences in adhesion quality, an adaption of the process parameters during Al deposition allows for a more than sufficient adhesion for all passivation layers.

Acknowledgement

The authors acknowledge the support of all co-workers at Fraunhofer ISE and the partial funding of this work by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) under contract number 0325241 (GRIPS).

References

[1] A. Blakers, A. Wang, and A. Milne, "22.8% efficient silicon solar cell," *Applied Physics Letters*, vol. 55, pp. 1363–1365, 1989

[2] J. Nekarda, D. Reinwand, A. Grohe, P. Hartmann, R. Preu, R. Trassl, and S. Wieder, "Industrial PVD metallization for high efficiency crystalline silicon solar cells," *34th IEEE Photovoltaic Specialists Conference,* 2009

[3] V. Jung and M. Köntges, "Al/Ni:V/Ag metal stacks as rear-side metallization for crystalline silicon solar cells," *Progress in Photovoltaics: Research and Applications*, 2012

[4] H. Schulte-Huxel, R. Bock, S. Blankemeyer, A. Merkle, and R. Brendel, "Aluminum-based mechanical and electrical laser interconnection process for module integration of silicon solar cells," *IEEE Journal of Photovoltaics*, vol. 2, No. 1, pp. 16-21, 2012

[5] M. Heimann, P. Klaerner, C. Luechinger, A. Mette, J. W. Mueller, M. Traeger, T. Barthel, O. Valentin, and P. Wawer, "Ultrasonic bonding of aluminum ribbons to interconnect high-efficiency crystalline-silicon solar cells," in *2nd International Conference on Crystalline Silicon Photovoltaics*, 2011

[6] C. Schwab, A. Wolf, M. Graf, N. Wöhrle, S. Kühnhold, J. Greulich, G. Kästner, D. Biro, and R. Preu, "Recombination and optical properties of wet chemically polished thermal oxide passivated Si surfaces," *IEEE Journal of Photovoltaics*, 2012

[7] E. Schneiderlöchner, R. Preu, R. Lüdemann, and S. W. Glunz, "Laser-fired rear contacts for crystalline silicon solar cells," *Prog. Photovolt: Res. Appl.*, vol. 10, pp. 29-34, 2002

[8] N. Aravas, K.-S. Kim and M. J. Loukis, "On the mechanics of adhesion testing of flexible films," *Materials Science and Engineering*, A107, 1989

[9] R. Jacobsson and B. Kruse, "Measurement of adhesion of thin evaporated films on glass substrates by means of the direct pull method," *Thin Solid Films*, vol. 15, pp. 71-77, 1973