NOVEL LOW TEMPERATURE FRONT SIDE METALLISATION SCHEME USING SELECTIVE LASER ABLATION OF ANTI REFLECTION COATINGS AND ELECTROLESS NICKEL PLATING

A. Grohe, A. Knorz, M. Alemán, C. Harmel, S. W. Glunz, R. Preu, G. P. Willeke
Fraunhofer Institute for Solar Energy Systems (ISE), Heidenhofstrasse 2, D-79110 Freiburg, Germany

ABSTRACT: For the development of a new low temperature front side metallisation the selective opening of the front surface anti reflection coating is inevitable. Secondly the selective deposition of an electroplating seed layer is necessary. In this paper the approach of using a laser ablation process to selectively remove this layer is presented. The possibility to perform this step without inducing damage into the solar cell front surface is demonstrated by optical methods like scanning electron microscopy as well as lifetime measurements. Dark and light IV measurements on solar cells show the potential of the process when using photo lithographically defined titanium / palladium / silver front side metallisation by reaching an efficiency of 16.5% with a planar front surface. The possibility to circumvent this laboratory process by using electroless nickel plating is demonstrated as well.

Keywords: antireflection coating, laser processing, high-efficiency

1 INTRODUCTION AND MOTIVATION

Screen-printing of silver paste for the front side metallisation of crystalline silicon solar cells is still the most common process in industrial solar cell production. Although being a well-known process it contains some inherent drawbacks. Due to the poor aspect ratio and conductivity of the fingers as well as an increasing risk of finger disruptions when printing finer lines, the minimum achievable finger width and therefore the maximum short-circuit current j_{SC} is limited. Furthermore not only the design of the fingers but also the associated emitter profile limits the short-circuit current j_{SC} and open-circuit voltage V_{oc} and therefore the efficiency potential. Additionally, when it comes to the industrial production of passivated emitter and rear solar cells (PERC) the screen-printing process is detrimental for most rear side passivation layers due to its necessary high temperature contact formation step. Furthermore the mechanical impact leads to increasing wafer breakage as wafers will get thinner.

The solution to most of these problems lies in a process established in laboratories all over the world approximately 20 years ago. It consists of a photo-lithographically defined front side metallisation. Here several steps have to be conducted to complete the contact, including:

- full area covering of the front side with photo resist
- masking and exposure of this resist with UV light
- development of the exposed photo resist areas
- opening of altered photo resist areas defining the front metallisation fraction
- wet chemical etching of underlying anti-reflection coating
- full area evaporation of titanium, palladium and silver seed layer to establish good contact resistance
- lift-off of photo resist and residual metal
- thickening of seed layer by electroplating

However, for the implementation of this process sequence into industrial production the increased costs would overweight the efficiency gain by far. One solution to these problems, a laser ablation process for the selective opening of the dielectric antireflection coating, was presented earlier [1,2]. In this paper results of the current developments achieved in the application of the laser opening of anti reflection coatings are presented. The laser ablation process can be followed by a contact-less metallization method to form the complete front side contact. This metallisation itself is realized in two steps: first low resistivity contacts are established by electro less nickel plating, second these contacts are thickened by silver electroplating. The whole process is not only contact-free but also works without any adjustment, masking or sophisticated technologies like photolithography or evaporation. Additionally it shows the ability to produce fine lines with higher conductivity but without needing a high temperature contact firing step to form the contact. Electroless nickel plating was chosen due to its natural deposition selectivity at the silicon openings and the lower barrier height given by the nickel/silicon contact compared to silver/silicon interfaces [3]. Alternatively, metallisation techniques like ink-jet printing [4] could be used as well.

2 EQUIPMENT AND TEST STRUCTURES

2.1 Laser equipment

As already presented in [5] a laser used for the selective ablation of silicon nitride layers should feature a short wavelength and short pulse duration. Therefore the experiments were mainly performed on a frequency-tripled Nd:YVO_4 laser with a wavelength of 355 nm from Coherent. The laser head is mounted on an InnoLas laser system which guides the beam to the substrate via flying x-y-optics or alternatively a scanning head. This scanning head allows much faster beam velocities on the substrate surface and therefore a shorter process duration. Thus the use of long focal length focussing lenses at the scanning head expands the beam focus, which can be detrimental for a fine line ablation process.

2.2 Solar cell structure

For the experiments solar cells with the size of 20x20 mm² were used. They consist of a high efficiency solar cell structure on 4 inch large and 250 µm thick 1 Ω cm p-type float zone silicon.

The planar rear side is passivated by 105 nm thermally grown SiO_2 and covered by a 2 µm thick evaporated aluminum layer. The rear contacts are formed by the LFC (Laser-Fired Contact) technology [6].

The front side of those samples is either shiny etched or textured by random pyramids. The solar cell features a $POCl_3$ diffused emitter with a sheet resistance close to industrial standard for screen-printed solar cells with 50 Ω/sq. The anti-reflection coating consists of a silicon nitride layer deposited by PECVD or sputtering. The laser ablation is performed using different laser parameters. As the examinations focus on the influence of the laser ablation process on the underlying solar cell structures the metallisation process still features photo lithography. Therefore the front side is covered by photo resist after the laser ablation following the standard photo lithography scheme without the wet chemical opening of the front side anti reflection coating. This process can be used as a reference process to avoid alterations due to the process development of nickel plating.

As reference process to the laser ablation step as well as to evaluate the potential of the solar cell structure a complete high-efficiency process sequence is chosen. Here the openings of the anti-reflection coating are performed by a complete impact-free process, featuring photo-lithographic definition of the dielectric layer openings and wet chemistry instead of the laser ablation.

3 SILICON NITRIDE LASER ABLATION

3.1 Optical evaluation

As a first investigation light microscope and scanning electron microscope (SEM) pictures of laser ablated silicon nitride films on silicon surfaces were taken. By optically judging the appearance of the ablated regions, a first selection of appropriate process parameters can be done. An overview over some light microscopy and SEM pictures is shown in figure 1a to 1d.

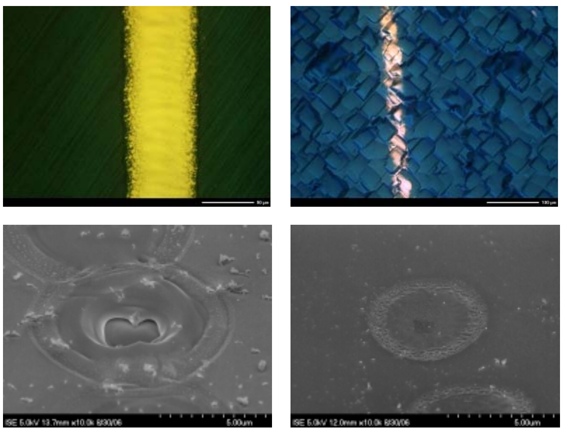

Figure 1a to d (top left to bottom right): 1a shows a silicon nitride layer structured by a laser with 532 nm wavelength and scanning head on a non-textured surface, 1b a silicon nitride layer removed a by 355 nm laser and fixed lense. The lower left 1c shows a severely damaged surface whereas in 1d no noticeable damage is visible.

The SEM pictures in figures 1c and 1d clearly indicate the difference between optimal and non optimal laser parameters, as the ablated region in figure 1c is severely damaged and molten areas can be seen. The light microscopy pictures in figure 1a and 1b already show the difficulties when changing the surface topology. Structured surfaces and especially steep edges of the structures are more difficult to selectively ablate than non-textured surfaces.

3.2 Lifetime measurements

To evaluate the laser-induced damage into the silicon wafer material, lifetime measurements were performed. Therefore 4 inch p-type float zone wafers with a thickness of 250 µm and shiny etched surfaces were coated with a 70 nm silicon nitride layer. On each wafer four areas (20 × 20 mm²) were defined by structuring the silicon nitride layer with decreasing line distance (see figure 2a). Then the silicon nitride layer was completely removed in a wet chemical process step. The wafers were cleaned and a new silicon nitride layer was deposited for microwave photo conductance decay measurements (MW-PCD). The inverse lifetime of the different areas can be plotted versus the covered area fraction. As reference, an untreated wafer was identically processed and measured. The resulting graphs after a final sintering step can be seen in figure 2b to 2d.

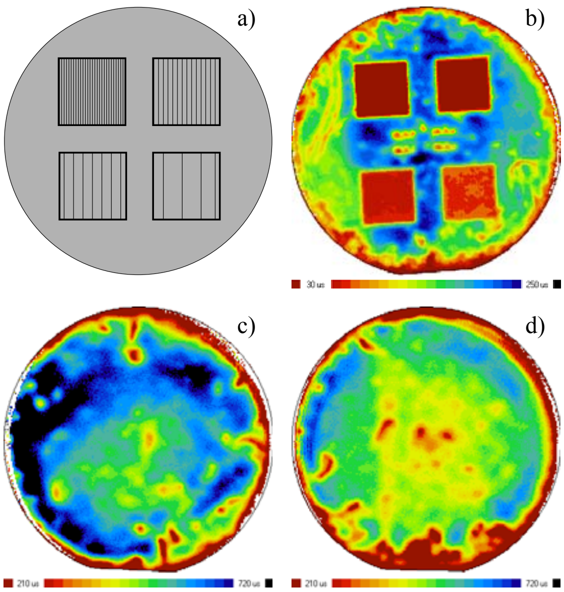

Figure 2a to 2d (top left to bottom right): Principle scheme of the laser structure for MW-PCD measurements (2a) and measurements of samples with laser ablated areas (2b and 2d) as well as a reference wafer (2d).

Figure 2b clearly shows the influence of a non optimal laser parameter on the lifetime in the silicon wafer. The dark red color indicate the low local lifetime. When choosing better laser parameters (figure 2d) no influence on the lifetime can be seen any more. The average lifetime of more than 400 µs indicates the absence of any laser damage, although the reference wafer even (figure 2c) reaches 537 µs average lifetime. Nevertheless, this difference might arise from process deviations and does not noticeably affect the solar cell performance due to the high average lifetime level.

3.3 SunsV_{OC} measurement on solar cells

The optimized laser ablation parameters were used to process solar cell test structures explained in chapter 2. The pseudo fill factors measured by SunsV_{OC} [7] on textured solar cells with a PECVD silicon nitride anti-reflection coating performed after the laser ablation and a subsequent sintering step are shown in figure 3. This sintering step is necessary to anneal the LFC and enhance the rear side passivation layer quality. The range of results of all photo lithographically defined references as well as the values of identical samples after the complete front side metallisation process are shown as well.

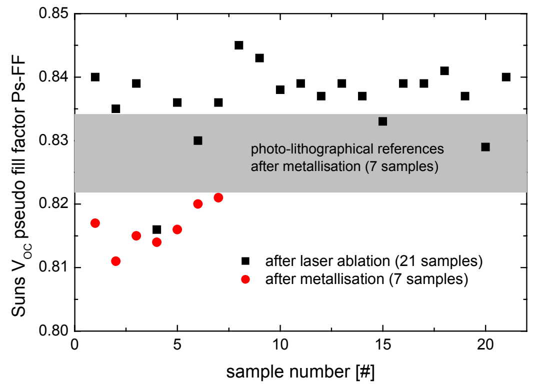

Figure 3: SunsV_{OC} measurement of laser ablated samples with PECVD silicon nitride anti reflection coating and textured front surface after laser ablation and after finished front side metallisation. The mean and standard deviation of all photo-lithographically defined references is indicated by the grey bar.

As the SunsV_{OC} method disregards all losses due to series resistance the results are not affected by factors like alignment problems. Therefore the values represent the maximum fill factor level achievable by the whole solar cell process. The very high pseudo fill factors of the laser-ablated samples directly after the measurement indicate the high quality of the laser ablation process. Additionally the good homogeneity and process stability is indicated by the high mean value of 83.7 % with a standard deviation of only 0.6 %. Nevertheless, after the metallisation process the pseudo fill factor drops slightly under the level of the reference samples, but still ranges well above 81 %.

3.3 Dark IV measurements

After finishing the complete solar cell process a dark IV measurement was performed. The resulting graphs can be seen in figure 4 with the resulting fit parameters shown in table 1. Due to a hump in I_{02} the dark IV curve of the textured sample with laser ablation could not be fitted properly setting the second diode ideality factor n_2 on the value of 2. All measurements exhibit a excellent dark IV curve. The fit parameters range in a region enabling very high light IV values. The visible difference in the lower left area of the graphs originates from a difference in parallel resistance R_P. Nevertheless values of more than 10 kΩ cm² do not affect the solar cell performance any more.

Table 1: Values of the fit on the dark IV curve in figure 4 for three different solar cells named with **L**aser **A**blation on **P**lanar or **T**extured front side as well as a **P**hoto **L**ithographically defined **T**extured one.

	I_{01}	n_1	I_{02}	n_2	R_S	R_P
	[A/cm²]		[A/cm²]		[Ωcm²]	[kΩcm²]
LA P	3.0×10^{-13}	1	8.7×10^{-9}	2	0.68	55.1
PL T	4.5×10^{-13}	1	1.7×10^{-9}	2	0.82	11.8

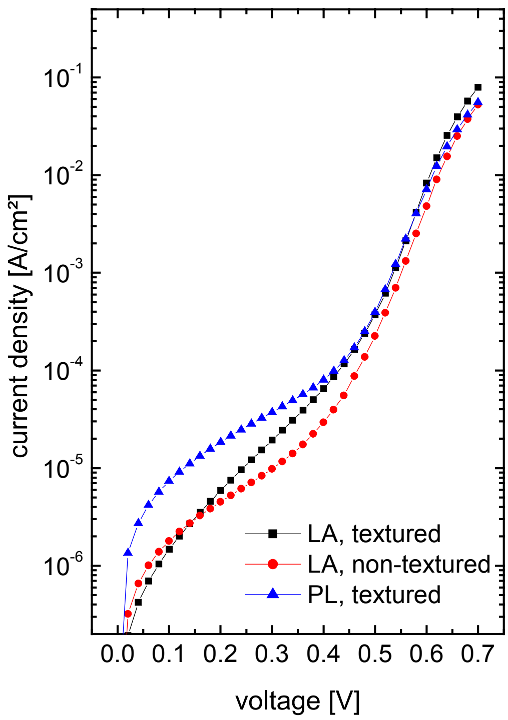

Figure 4: Dark IV measurement of laser ablated samples. The dots represent the sample with a non-textured surface and laser ablated silicon nitride, whereas the squares and triangles represent the textured laser ablated samples as well as the references.

3.2 Light IV measurements

The values of the light IV measurement performed on the samples from figure 4 and table 1 are shown in table 2 and 3.

Table 2: Comparison of non-textured samples (**L**aser **A**blation on **P**lanar front side as well as a **P**hoto **L**ithographically defined one).

Sample	V_{OC}	Pseudo FF
	[mV]	[%]
LA P	644.3	84.4
PL P	645.0	82.8

The alignment of the structured photo resist acting as evaporation mask for the front side metallisation with the underlying laser ablated openings of the anti reflection coating evoked some technical problems in the solar cell process. Therefore only values for V_{OC} from the light IV measurement as well as the pseudo fill factor from the Suns VOC measurement are compared in table 2. Furthermore, stains on the silicon nitride anti reflection coating lead to a significant loss in short circuit current density. Thus only the best samples of the processed solar cells are presented. Table 3 shows a comparison of the light IV measurements for the laser ablated samples with non-textured and textured surface.

Table 2: Light IV measurements of the laser ablated samples (**P**lanar or **T**extured front side).

Sample	V_{OC}	J_{SC}	FF	η
	[mV]	[mA/cm²]	[%]	[%]
LA P	644.3	32.80	0.780	16.5
LA T	626.2	35.23	0.746	16.5

Nevertheless the laser ablated sample confirm the expectations from the $SunsV_{OC}$ and dark IV measurements. The high solar cell parameters achieved with the non-textured surface are comparable to the reference and therefore indicate the successful realization of the laser ablation process. Even the transition to textured surfaces shows promising results. Here V_{OC} is limited due to the silicon nitride stains and the fill factor due to the misalignment, so by avoiding these problems better values should be reachable easily.

5 NICKEL PLATING

As a next step some laser ablated samples were plated in a nickel solution. The benefit of this approach is the deposition of a nickel seed layer only on bare silicon when choosing optimal parameters. Therefore an additional masking step to protect the front side from unwanted metallisation is unnecessary.

First experimental results of nickel plated openings conducted by laser ablation are shown in figures 5a to 5d.

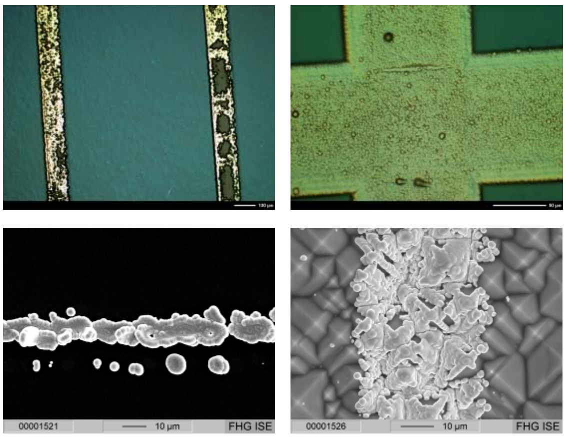

Figure 5a to 5d (top left to bottom right): Nickel deposition on laser ablated openings.

By choosing the right set of process parameters the nickel deposition can be optimized drastically. As the first lines were only incompletely covered by nickel (figure 2a) the contact area was completely metallized using optimal nickel deposition parameters (figure 2b). Figure 2c and 2d show that even fine lines and textured surfaces can be covered by a nickel seed layer.

The results of the finished cells will be reported elsewhere.

6 SUMMARY AND CONCLUSION

In this paper an approach to circumvent the limitations of conventional screen-printed solar cell front side metallisation is presented. As necessary steps towards the realization of a low temperature process capable of achieving high quality contacts the selective opening of the solar cells front side anti reflection coating as well as the deposition of a metal seed layer were identified. For the opening of the contact areas, laser ablation of the silicon nitride layer was performed. By characterizing the laser-ablated areas by light microscopy and SEM as well as MW-PCD it can be shown that the silicon nitride layer can be removed without damaging the underlying silicon surface. The solar cells processed by using laser ablation showed promising light and dark IV curves, high pseudo fill factors and lead to a maximum efficiency of 16.5 % on planar surfaces with a 50 Ω / sq. emitter and PECVD silicon nitride anti-reflection coating. The successful deposition of a nickel seed layer on the laser ablated openings is presented as well.

Next steps will include further optimization of the silicon nitride opening process by using adapted laser equipment as well as the production of solar cells using the nickel deposition with subsequent silver plating for the front side metallisation.

ACKNOWLEDGEMENTS

The authors would like to thank all colleagues at Fraunhofer ISE, especially A. Leimenstoll, S. Seitz, P. Richter, A. Pohl, F. Granek, A. Herbolzheimer, K. Krüger and E. Schäffer for the production and characterization of the high efficiency solar cell test structures.

REFERENCES

[1] C.E. Dubé and R.C. Gonsiorawski, Proceedings of the 21st IEEE PV Specialists Conference, 1990, pp. 624-628

[2] R. Preu, S. W. Glunz, S. Schäfer, R. Lüdemann, W. Wettling et al., Proceedings of the 16th EUPVSEC, 2000, Glasgow, UK, pp. 1181-1184

[3] D. K. Schroder and D. L. Meier, IEEE Trans. Electron Devices ED-31, 1984, pp. 637-647

[4] K. F. Teng and R. W. Vest, IEEE Electron. Dev. Lett. 9, 1988, pp. 591-593

[5] A. Grohe, C. Harmel, A. Knorz, S.W. Glunz, R. Preu, G.P. Willeke, Proceedings of the WCPEC 4, 2006

[6] R. Preu, E. Schneiderlöchner, A. Grohe, S. W. Glunz, G. Willeke, Proceedings of the 29th IEEE Photovoltaics Specialists Conference, 2002, pp. 130-133

[7] R. A. Sinton and A. Cuevas, Proc. of the 16th EUPVSEC. 2000. Glasgow, UK