Presented at the 36th European PV Solar Energy Conference and Exhibition, 9-13 September 2019, Marseille, France

PLATED NI/CU/AG FOR TOPCON SOLAR CELL METALLIZATION

Benjamin Grübel[1], Gisela Cimiotti[1], Varun Arya[1], Tobias Fellmeth[1], Frank Feldmann[1], Bernd Steinhauser[1], Sven Kluska[1], Thomas Kluge[2], Dirk Landgraf[2], Markus Glatthaar[1]
[1] Fraunhofer Institute for Solar Energy Systems ISE
Heidenhofstr. 2, 79110 Freiburg, Germany
[2] Meyer Burger GmbH
An der Baumschule 6-8, 09337 Hohenstein-Ernstthal, Germany

ABSTRACT: Passivating Contacts is the next step in reducing recombination effects and improving c-Si solar cell efficiency. This work demonstrates the application of laser structuring and Ni/Cu/Ag electroplating as a new method to metallize solar cells with Tunnel Oxide Passivated Contact (TOPCon) [1] layers. Critical contact properties such as contact adhesion, contact resistance, contact recombination and optics of the metallization concept are characterized and evaluated for the application as bifacial metallization for TOPCon solar cells.
Front and rear side contact TOPCon solar cells with plated Ni/Cu/Ag metallization on the TOPCon layer showed the feasibility of the plating process allowing efficiencies up to 22.7 % with FF = 82.4 % and V_{oc} = 690 mV. The application in a full area rear side metallization design with planar TOPCon surface revealed limitations in contact adhesion (planar surface) and optics (J_{sc}, poor reflection of Ni). Both limitations can be prevailed by applying a bifacial contact design and implementing textured TOPCon surfaces. It could be demonstrated that the requirements on contact resistance and contact recombination for a locally plated metal contact on TOPCon can be fulfilled by laser structuring and plated Ni/Cu/Ag with average contact resistivity of $\rho_c = (0.2 \pm 0.1)$ mΩ·cm² and no noticeable iV_{oc}-loss after laser ablation.
Keywords: Plating, Passivated Contacts, Silicon Solar Cell, Metallization,

1. INTRODUCTION

Passivating metal contacts of TOPCon [1] solar cells are the next step in improving silicon solar cells. Recent publications showed record efficiencies of 26.1 % for a bifacial IBC solar cell [2] or 25.8 % for a front and rear contact solar cell [3] on 2 x 2 cm² solar cell size. Transferring the TOPCon technology to industrial scale requires alternative metallization than cleanroom deposition of PVD-Ag or TiPdAg. TOPCon solar cells with industrial screen-printing metal contacts on 15.6 x 15.6 cm² lead to η = 23.6 % [4].

Electroplating of a Ni/Cu/Ag-stack is an industrially feasible alternative to state-of-the-art screen printing for metallization of TOPCon solar cells. Besides the reduction of material costs by using Cu-plating instead of Ag pastes, finger widths down to 20 µm are allowed due to the laser structuring [5, 6]. Therefore, plating is a possible metallization technique to contact the rear side TOPCon layer. This implies considering several aspects such as contact adhesion, contact resistance ρ_c, contact recombination and optics (reflection of rear side metal). In this paper, we will show the feasibility of locally plated contacts on TOPCon layers taking into consideration the previous aspects.

2. EXPERIMENTAL

Metal contacts in c-Si solar cells have to fulfill certain requirements on contact adhesion, contact resistivity, contact recombination and optical behavior. Depending on the applied contact design (full area contact vs. local metal contact) these requirements can differ. Test samples with plated Ni/Cu/Ag contacts on (full area or local contact design) were fabricated to evaluate the contact properties of for these application cases.

2.1. Test sample design for contact characterization

The characterization of contact adhesion, contact resistance and contact recombination was performed with specific test samples.

Contact adhesion

The contact adhesion of full area plated Ni/Cu contacts on n-type TOPCon was investigated on standard n-type FZ-Si with a base resistivity of 1 Ω·cm. Half of the samples featured a random pyramid texture while the rest had a planar surface. The silicon wafer was covered on both sides with a thin oxide layer followed by the deposition of highly doped poly-Si layer. The poly-Si is passivated with a 70 nm SiN_x layer as displayed in Figure 1. All the samples were fully laser ablated on both sides by a pulsed UV-ps laser to reproduce the actual laser process sequence for real solar cells. Subsequently the samples were fully area plated according to the process sequence displayed in Figure 5. Half of the samples featured an annealing after Ni plating aiming Nickel silicidation (Si_xNi_y) for improved contact resistance and contact adhesion [5]. Unreacted Ni is removed with 65% nitric acid (HNO_3) [7] followed by a second Ni deposition and finished with Cu/Ag plating.

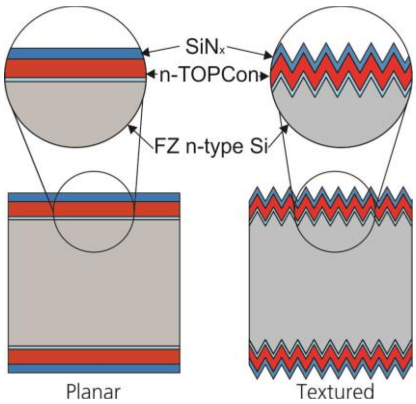

Figure 1: Schematic cross section of samples with FZ n-type Si bulk, a stack of thin oxide layer (SiO_x) and n-type

poly-Si on both sides passivated with an ARC layer (SiN_x) on planar and on random pyramid texture.

Contact resistance

In order to determine the contact resistance of plated Ni/Cu contacts on laser structured n-type TOPCon surfaces, similar samples as for the contact adhesion were used as displayed in Figure 1. Only difference is that only samples with a random pyramid texture were taken. Further the poly-Si layer thickness on the front side was 150 nm and 50 nm on the rear side. The front side is defined as the side where the characterization contact resistance is performed. Contact resistance structures consisting of 100 fingers with a length of 10 mm and a pitch of 1.3 mm were applied by similar laser process. These structures were then metallized as described in section 2.3

Contact recombination

The characterization of the recombination of the laser contact openings (LCO) was performed on industrial TOPCon samples provided by Meyer & Burger, Hohenstein-Ernstthal before laser processing and metallization. These consist of an n-type bulk with a bulk resistivity of 1-1.5 Ω·cm. The front side features a boron emitter on a random pyramid surface texture and passivated with a SiN_x/AlO_x stack. The rear side is covered by a 100-150 nm TOPCon layer. In order to characterize the impact of the laser and plating finger structures were used. These structures were laser ablated on the TOPCon within 24 fields as displayed in Figure 2. The remaining fields were used as reference fields without laser and plating impact. The laser ablated finger structures consist of 20 fingers with a length of 20 mm and an average width of 13 µm as shown in Figure 3. The characterization was performed by photoluminescence imaging (PL) at 1 sun which was calibrated with a QSSPC lifetime measurement [8, 9].

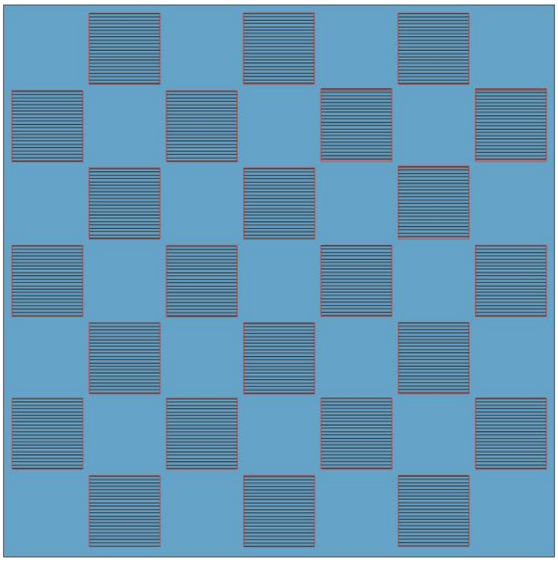

Figure 2: Schematic drawing of laser ablated structures on TOPCon side of the samples. The remaining blue fields act as reference fields without laser treatment.

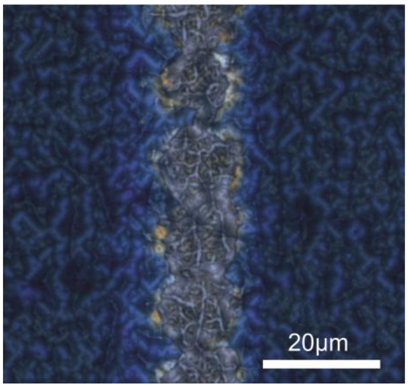

Figure 3: Laser ablated finger structure on the rear side TOPCon layer with an average opening width of 13 µm

2.2. Solar cells

In this work solar cells with an area of 2x2 cm² were fabricated on a shiny etched n-type 4” FZ wafer with a base resistivity of 1 Ω·cm. The front side features random pyramids formed by alkaline texturing and a 130 Ω/sq boron emitter. The emitter was passivated by a stack of AlO_x and SiN_x. The local front side contacts were made by thermal evaporation of Ti/Pd/Ag. The rear side TOPCon layer was deposited as described in Ref. [10] with a thickness of the poly-Si of 90 nm passivated with SiN_x. The front and rear side passivation were activated by an atomic hydrogen treatment (RPHP) [11] at 425°C. The rear was initially metallized with PVD-Ag. After standard IV-characterization the PVD-Ag was wet chemically removed and Ni/Cu was plated on the rear side including an annealing step (350°C, 60 s). The sample was then again IV-characterized.

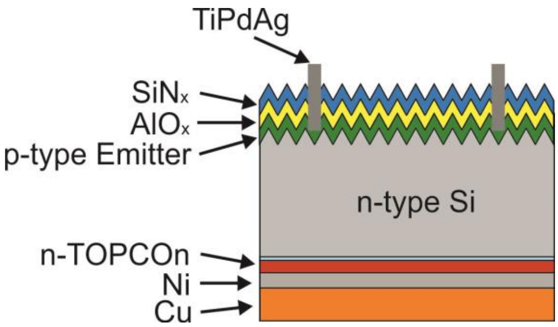

Figure 4: Schematic cross section of the layout of the front and rear contact 4” sample with TiPdAg on the front side and full area plated Ni/Cu on the rear side

2.3. Plating process

The applied process sequence at Fraunhofer ISE for plating on TOPCon is displayed in Figure 5. In the case that the TOPCon layer is coated with an ARC layer, this has to be removed depending on the desired pattern. In this work a pulsed UV-ps laser is used to pattern the ARC layer resulting in a cross section as displayed in the Figure 5 on top.

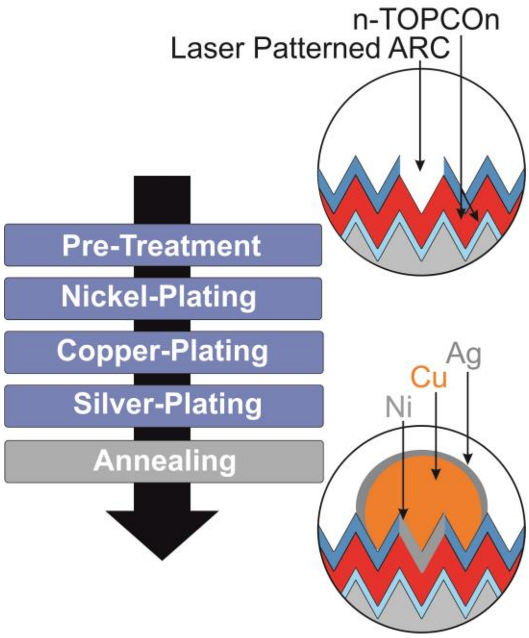

Figure 5: Plating process sequence used in this work with cross section of surface of TOPCon solar cell precursor with patterned ARC and after Ni/CU/Ag deposition

In order to remove any kind of interface oxides at the TOPCon-Metal interface [12, 13] a wet-chemical pre-treatment consisting of low concentrated HF solution is performed. Subsequently, the metal stack of Ni, Cu and Ag is deposited by plating resulting in structures as displayed in Figure 6 with a width of 20 µm and height of 8 µm.

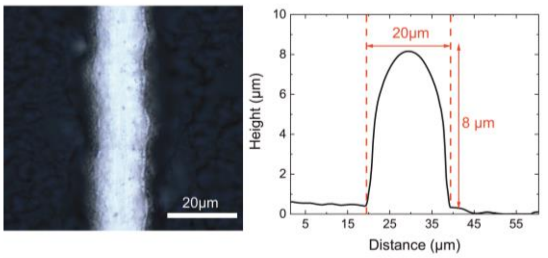

Figure 6: Plated finger according to the process sequence displayed in Figure 5 with measured profile by laser microscopy

3. RESULTS AND ANALYSIS

3.1. Adhesion

Reliable contact adhesion is besides contact recombination and contact resistance an essential requirement for a solar cell metal contact. Apart from the optical evaluation of the adhesion, tape tests of plated contacts allow a qualitative characterization of the contact adhesion [14].

The contact adhesion evaluation in this work is performed on sample designs which allow contact adhesion measurements as well as on samples for contact resistance measurements. The first step of sample preparation involves dicing (chip dicing saw) the solar cell in stripes with a width of 1cm. This step allows characterization of contact adhesion of the full area metallized samples as well as of the samples for contact resistance measurement by transfer length method (TLM) [15]. As second step the tape test is performed on the remaining samples which feature sufficient adhesion after the dicing process.

On the planar surface the plated metal stack showed no sufficient adhesion to withstand the tape test. Only few planar samples that were annealed showed sufficient adhesion. In contrast to these results, the textured samples and the ones that were annealed particularly reveal to have a better adhesion.

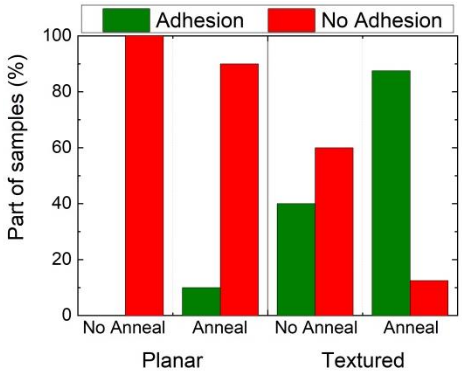

Figure 7: Qualitative evaluation of contact adhesion by tape test measurements of planar and textured samples depending on the surface topography and annealing step

3.2. Contact resistance

The contact resistance of locally plated contacts was determined by transfer length method (TLM) [15]. The results of the measurements are presented in Figure 8 in reference to the HF pre-treatment time. The contact resistance tends to a minimum for HF pre-treatment of 60 s with a smaller distribution with $\rho_c = (0.2 \pm 0.1)$ mΩ·cm². The mean contact resistance for all pre-treatment duration groups is below 1 mΩ·cm².

It has to be noted that the TLM analysis did not take into account any current pathways outside of the poly-Si layer, since bulk material and poly-Si feature the same polarity. That might results in an overestimation of ρ_c [16].

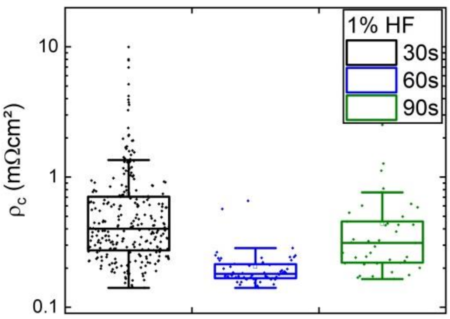

Figure 8: Contact resistance ρ_c of plated Ni/Cu on n-type TOPCon layers depending on HF pre-treatment before plating

3.3. Contact recombination

The evaluation of the contact recombination of laser contact opening is displayed in Figure 9. The PL image was taken after the laser ablation and Ni plating on the TOPCon side. In order to quantify the information of the PL image at 1 sun, an additional QSSPC measurement was made resulting in a mean iV_{oc} value in the center of the sample. Applying this to the whole sample according to [9], a mean iV_{oc} value for the laser ablated (red fields & black values) and non-laser ablated (white values) could be determined. It can be seen that nearly all laser and reference fields feature $iV_{oc} > 680$ mV. Further, no clear difference between adjacent laser and reference field can be observed. In Table II the mean values of all reference and laser ablated fields revealing the absence of any loss due to the laser ablation and Ni plating process.

Figure 9: PL image after laser ablation on n-type TOPCon measured from the non-laser ablated side. The iV_{oc} values are determined by QSSPC measurement. The red fields with black values reveal the position of the laser ablated structures on the other side, while the white values are reference fields.

Table I: Mean values of reference and laser ablated and Ni plated fields

Field	*iVoc*
Reference	688 ± 4 mV
Laser ablated	689 ± 3 mV

3.4. Small area plated TOPCon

The solar cell results for the 2x2 cm² samples are presented in Table I. As described in the experimental section the TOPCon layer of the same solar cell was first metallized with PVD-Ag and afterwards chemically etched and re-plated with Ni/Cu. The results show a high solar cell efficiency level for both metallization types with 22.7 % for Ni/Cu plating and 23.1 % for PVD-Ag. The plated solar cell is mainly limited by a reduced J_{sc} of about 1 mA/cm² due to less ideal reflectance of nickel compared to silver. Further, the adhesion of Ni on a planar rear side is not satisfactory. However, a *FF* of 82.4 % for the best solar cell suggests an excellent contact resistance. Further a reduction of V_{oc} (~5 mV) occurs for the plated cells, though the V_{oc} level of 690 mV proving the intact passivation of the TOPCon contact.

Table II: Light IV results of front and rear contact 2x2cm² n-type solar cell with TOPCon metallized by PVD-Ag and subsequently etched and re-plated by Ni/Cu.

Rear side metallization	V_{oc} [mV]	J_{sc} [mA/cm²]	*FF* [%]	*pFF* [%]	η [%]
PVD-Ag	694	41.0	81.0	83.0	23.1
Plating	690	39.9	82.4	83.5	22.7

4. DISCUSSION

In order to produce a TOPCon solar cell with the benefits of bifacially plated contacts several aspects such as contact adhesion, contact resistance ρ_c, contact recombination and optics need to be considered.

The solar cell results of the 2x2 cm² featuring a full area rear side plating contact show the principal feasibility of this contact system allowing high efficiencies up to 22.7 % with high V_{oc} (690 mV) and *FF* (82.4 %). The limiting factor compared to a PVD-Ag metallization is J_{sc} that is reduced around 1 mA/cm² due to worse reflection of Ni compared to Ag. Further, the contact adhesion on planar surfaces is not sufficient. In order to overcome the J_{sc} -loss the full area contact can be changed to a local contact leading to a bifacial solar cell design with a non-planar rear side and passivated topography. The required laser structuring of the ARC on textured surface leads to the formation of laser induced periodic structures (LIPPS) enforcing mechanical adhesion solving that aspect as well [17]. The usage of a laser ablation process for local contact systems induces a reconsideration of the aspects of contact recombination and contact resistance. From the results displayed in Figure 8 it can be deduced that the contact resistance of plated contacts on laser opened TOPCon layer is below 1 mΩ·cm². In addition, the results of Figure 9 and Table I show that no iV_{oc}-loss of plated contacts on laser openings on TOPCon layer in the range of 100-150 nm is visible. Merging all the findings leads to the conclusion that bifacial Ni/Cu plating fulfills all requirements to be applicable as metallization for TOPCon solar cells with bifacially plated contacts.

5. CONCLUSION

In this work we investigated the critical aspects contact adhesion, contact resistance ρ_c, contact recombination and optics for the solar cell were investigated. The results from each aspect suggest the feasibility of contacting such a bifacial solar cell concept with Ni/Cu plating.

6. ACKNOWLEDGMENTS

The authors would like to thank their colleagues at the Fraunhofer institute for solar energy systems (ISE) for their help with the experiments and solar cell characterization. This work was funded by the German Federal Ministry for Environment, Nature Conservation and Nuclear Safety within the research project "PVBAT 400" (FKZ: 0324145) and "NEXTSTEP" (FKZ: 0324171)

7. REFERENCES

[1] F. Feldmann, M. Bivour, C. Reichel, H. Steinkemper, M. Hermle, and S. W. Glunz, "Tunnel oxide passivated contacts as an alternative to partial rear contacts," *Solar Energy Materials and Solar Cells*, vol. 131, pp. 46–50, 2014.

[2] F. Haase, C. Hollemann, S. Schäfer, A. Merkle, M. Rienäcker, J. Krügener, R. Brendel, and R. Peibst, "Laser contact openings for local poly-Si-metal contacts enabling 26.1%-efficient POLO-IBC solar cells," *Solar Energy Materials and Solar Cells*, vol. 186, pp. 184–193, 2018.

[3] A. Richter, J. Benick, F. Feldmann, A. Fell, M. Hermle, and S. W. Glunz, "n-Type Si solar cells with passivating electron contact: Identifying sources for efficiency limitations by wafer thickness and resistivity variation," *Solar Energy Materials and Solar Cells*, vol. 173, pp. 96–105, 2017.

[4] Y. Chen, D. Chen, C. Liu, Z. Wang, Y. Zou, Y. He, Y. Wang, L. Yuan, J. Gong, W. Lin, X. Zhang, Y. Yang, H. Shen, Z. Feng, P. P. Altermatt, and P. J. Verlinden, "Mass production of industrial tunnel oxide passivated contacts (i-TOPCon) silicon solar cells with average efficiency over 23% and modules over 345 W," *Prog Photovolt Res Appl*, vol. 41, p. 46, 2019.

[5] S. Kluska, J. Bartsch, A. Büchler, G. Cimiotti, A. A. Brand, S. Hopman, and M. Glatthaar, "Electrical and Mechanical Properties of Plated Ni/Cu Contacts for Si Solar Cells," *Energy Procedia*, vol. 77, pp. 733–743, 2015.

[6] S. Kluska, A. Lorenz, B. Grübel, A. Büchler, J. Bartsch, G. Cimiotti, F. Clement, V. Arya, A. A. Brand, J. Nekarda, S. Nold, M. Glatthaar, S. Hörnlein, and A. Mette, "Plated Fine Line Metallization For PERC Solar Cells," *35th European Photovoltaic Solar Energy Conference*, 2018.

[7] S. Franssila, *Introduction to microfabrication,* 2nd ed. Chichester, West Sussex, England, Hoboken, NJ: John Wiley & Sons, 2010.

[8] D. Macdonald, J. Tan, and and T. Trupke, "Imaging interstitial iron concentrations in boron-doped crystalline silicon using photoluminescence,"

[9] M. Glatthaar, D. Kray, N. Bay, J. Burschik, G. Cimiotti, N. Fritz, S. Kleinschmidt, H. Kuhnlein, A. Losel, O. Luhn, H. Nussbaumer, A. Rodofili, R. Sastrawan, M. Sieber, J. Schramm-Moura, and A. Trager, "Application of SunsPL for fast laser chemical process development," in *2011 37th IEEE Photovoltaic Specialists Conference*, Seattle, WA, USA, Jun. 2011 - Jun. 2011, pp. 2866–2869.

[10] F. Feldmann, M. Bivour, C. Reichel, M. Hermle, and S. W. Glunz, "Passivated rear contacts for high-efficiency n-type Si solar cells providing high interface passivation quality and excellent transport characteristics," *Solar Energy Materials and Solar Cells*, vol. 120, pp. 270–274, 2014.

[11] S. Lindekugel, H. Lautenschlager, T. Ruof, and S. Reber, "Plasma Hydrogen Passivation for Crystalline Silicon Thin-Films," (eng), 2008.

[12] M. Morita, T. Ohmi, E. Hasegawa, M. Kawakami, and M. Ohwada, "Growth of native oxide on a silicon surface," *Journal of Applied Physics*, vol. 68, no. 3, pp. 1272–1281, 1990.

[13] T.-a. Miura, M. Niwano, D. Shoji, and N. Miyamoto, "Kinetics of oxidation on hydrogen-terminated Si(100) and (111) surfaces stored in air," *Appl. Phys. Lett.*, vol. 79, no. 8, p. 4373, 1996.

[14] G. V. Calder, F. C. Hansen, and A. Parra, "Quantifying the Tape Adhesion Test," in *Adhesion Aspects of Polymeric Coatings*, K. L. Mittal, Ed., Boston, MA: Springer US, 1983, pp. 569–582.

[15] D. K. Schroder, *Semiconductor material and device characterization*. Hoboken, New Jersey, Piscataway, New Jersey: IEEE Press Wiley-Interscience; IEEE Xplore, 2006.

[16] Stefan Eidelloth and Rolf Brendel, "Analytical Theory for Extracting Specific Contact Resistances of Thick Samples From the Transmission Line Method,"

[17] J. Bonse, S. V. Kirner, S. Höhm, N. Epperlein, D. Spaltmann, A. Rosenfeld, and J. Krüger, "Applications of laser-induced periodic surface structures (LIPSS)," in San Francisco, California, United States, 2017, 100920N.