FoilMet® - Connect: A new rear metallization upgrade for PERC and other cell concepts

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FoilMet® - *Connect:* a New Rear Metallization Upgrade for PERC and Other Cell Concepts

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Abstract. In this contribution the novel aluminum foil based rear metallization technology *FoilMet®* - *Connect* is introduced. With this technology, we combine the optical advantages of a foil metallized rear, known from *FoilMet®* - *Classic* and the high voltages of screen printed and furnace fired contacts usually applied in industrial PERC. The applied paste volume is reduced in the *FoilMet®* - *Connect* technology which we show to come with benefits in contacts formation during the firing process in a standard belt furnace. With this technology, we report an improvement in cell efficiency by $\Delta\eta = (0.25 \pm 0.15)\,\%_{abs}$ over a mono facial screen printed PERC. Therefore it is a high efficiency upgrade for most monofacial cell concepts based on screen printed metallization.

INTRODUCTION

First attempts to create a rear electrode using an aluminum foil at Fraunhofer ISE in 2005, simply applied a 15 µm thick aluminum foil from a discount store to a wafer and fired in a fast firing belt furnace. In the next developmental step, an adjusted laser fired contact (LFC) [1] process was introduced and successfully increased the adhesion between wafer and aluminum foil. Several single laser pulses locally melted the aluminum foil, penetrated the rear dielectric layer of the Passivated Emitter and Rear Cell (PERC) [2] and formed both an electrical and a mechanical contact between wafer and aluminum foil (Fig. 1 (a)). The contact therefore spanned an air gap a few micrometers wide, located between the rear of the passivation and the aluminum foil. This process features a huge cost saving potential [3], improved internal optical properties and a simplified cell production process [4]. In 2016 we calculated a cost reduction of nearly 50 % for the production of rear side passivation and metallization [5]. The *FoilMet®* - *Classic* cell concept was first introduced in 2007 [6] and a patent was granted in 2008 [7]. Since then *FoilMet®* - *Classic* has undergone further development [8, 9]. Particularly noteworthy is the development of a cost efficient solderable coating for the aluminum foil which is applied in an industrial high volume roll to roll process. The coating enables cell interconnection using conventional Infrared radiation (IR) soldering and module integration [10, 11].

Nano-second laser pulses are used to form the contacts of the *FoilMet®* - *Classic* cells. Defects in the silicon crystal, induced by the laser lead to lower voltages and a drop in cell efficiency. To achieve high voltages and cell efficiencies nevertheless, highly doped material with low bulk resistance and long pitch between the foil contacts were needed. The *FoilMet®* - *Connect* technology, introduced in this contribution, is meant to inherit the advantages of furnace fired screen printed (SP) contacts but retain the advantages of the *FoilMet®* - *Classic* technology at the same time.

Optical Advantages of a Foil Metallized Rear

One of the optical losses of a solar cell is the parasitic absorption of sunlight at its interfaces (Fig. 1 (a)). Since the focus here is on the rear of the *FoilMet®* solar cell, optical losses at the front are not addressed. The optical path length in silicon depends on the wavelength. When passing through the bulk, a large part of the visible light is converted. Light in the infra-red range, however, has a large optical path length and is therefore likely to pass the cell without being converted [12, 13]. A SiN_x layer is introduced at the interface for industrial SP solar cells to achieve higher

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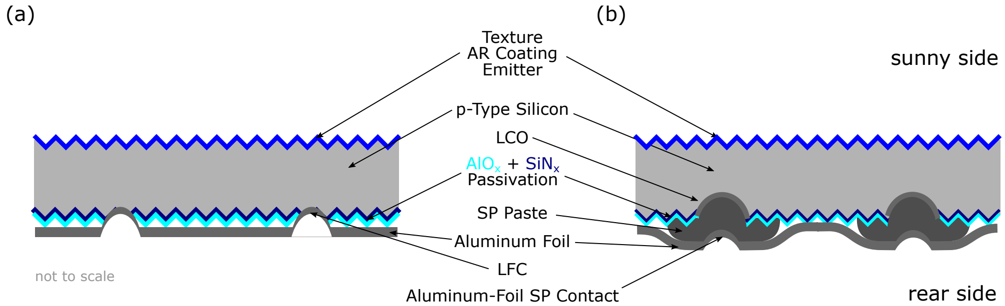

FIGURE 1. Comparison of the rear side technologies of (a) *FoilMet*® - *Classic* Cell and (b) *FoilMet*® - *Connect* Cell (side view). Optical loss mechanisms are sketched for the *FoilMet*® - *Classic* Classic approach.

voltages and improve internal reflection by guiding the light back and thus increase the probability of conversion. In contrast to an industrial SP PERC rear, where the SiN_x is located between silicon and SP aluminum, there is an air gap and a highly reflective aluminum foil behind the SiN_x layer of the *FoilMet*® solar cell.

To demonstrate the optical advantage of foil metallization, wafers with rear side test structures were fabricated. On the rear of this wafers, aluminum paste was screen printed in form of small disks that form homogeneous patterns. The radius of the disks was altered and thus a variation of the degree of coverage of the aluminum paste from 0 % to 100 % was obtained. An aluminum foil attached onto the SP disks by means of laser completed the rear. Thus we have wafers which have partly a SP rear and partly a foil rear. A measurement of the internal reflection R of these wafer shows a decline with increasing degree of coverage of SP aluminum (Fig. 2 (a)) and presents the superior optical properties of the *FoilMet*® rear of nearly 20 $\%_{abs}$ at a wavelength of $\lambda = 1200\,\mathrm{nm}$.

Simulations show that an air gap larger than 100 nm strongly contributes to the reflection on cell level [14]. This was confirmed in an experiment [5] in which the reflection of cells with an air gap (air gap) and without air gap (no air gap) were compared for different SiN_x thicknesses (Fig. 2 (b)). In order to produce a foil-like backside without an air gap, a PVD aluminum layer was used. As previous, the internal reflection of the foil group (air gap) is higher in the long wavelengths regime. Furthermore, there is almost no change of the internal reflection depending on the SiN_x thickness in the foil group as predicted in the simulation and therefore the SiN_x layer thickness can be reduced.

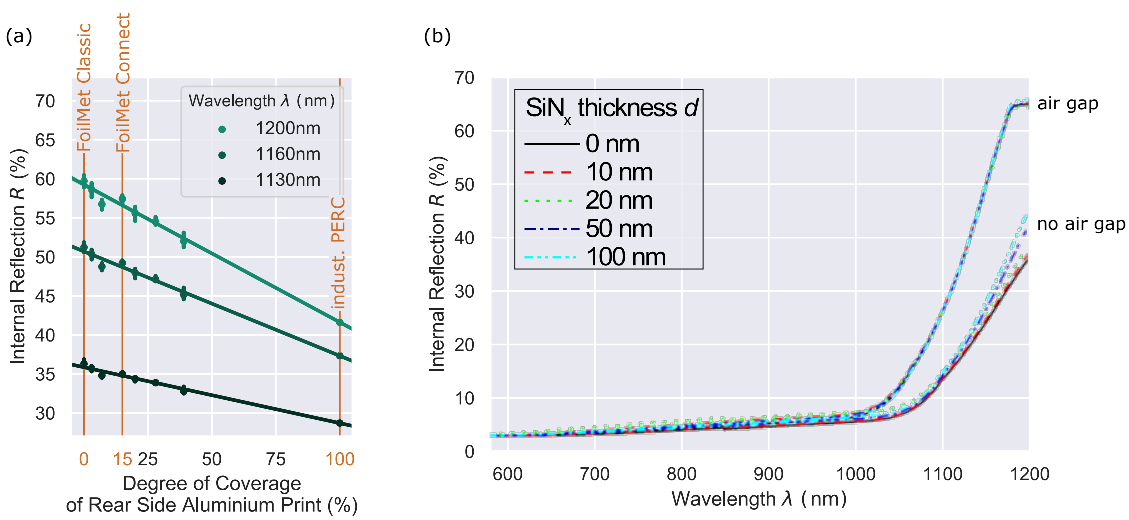

FIGURE 2. (a) One advantage of the aluminum foil is the improved rear reflection. The smaller the degree of coverage of SP aluminum on the rear underneath the aluminum foil the better the internal reflection. (b) Measurement of the internal reflection in the 600 nm to 1200 nm range, after foil attachment and laser-fired contacts, as function of SiN_x capping layer thickness. Data presented by Graf *et al.* [4]

RESULTS

Introducing *FoilMet®* - *Connect*

In recent years, PERC has established itself as industrial standard [15, 16], not least because of the enormous progress that has been made in contact quality by improving SP pastes and belt furnace firing processes. During the firing process at temperatures beyond 660 °C [17], aluminum dissolves silicon at the aluminum-silicon interface of the Laser Contact Openings (LCO) and a hollow filled with aluminum-silicon melt is formed. At the same time a diffusion of silicon into the aluminum melt of the paste occurs. During cool down, silicon recrystallizes at the solid silicon surface and forms a highly doped back surface field (BSF).

Nano-second laser pulses are used to form the contacts of the *FoilMet®* - *Classic* cells, thus the contact formation takes place in a fraction of the time of a furnace firing process and there is no time for the aluminum-silicon dynamics to heal the defects induced by the LFC process to the silicon crystal.

The *FoilMet®* - *Connect* technology is meant to inherit the advantages of furnace fired SP contacts but retain the advantages of the *FoilMet®* - *Classic* technology at the same time. Similar to the *FoilMet®* - *Classic* cell, there is an aluminum foil on the rear of the *FoilMet®* - *Connect* cell. Underneath, however, there is a layer with SP discs, to which the aluminum foil is welded by means of a laser and thus a mechanical and electrical contact is established (Fig. 1 (b)). As with conventional LCO, these SP discs form a high quality and well shielded contact with the silicon during the furnace firing process. Additionally, *FoilMet®* - *Connect* comes with cost benefits in manufacturing: i) the elimination of the silver pads due to the application of a solderable aluminum foil, ii) the reduction of the SP aluminum quantity that also comes with advantages for the firing process in terms of waste management and furthermore, iii) the disk pattern can be printed with a stencil instead of a screen and iv) the reduction of the SiN_x for rear passivation. Therefore, in actual cost calculation *FoilMet®* - *Connect* and PERC breaks even in terms of manufacturing costs per cell, regardless of the additional laser process step.

Contact Formation During Furnace Firing Process

From industrial screen printed PERC cells it was observed that the contact is not always completely filled but a void has formed instead [18, 19, 20]. A common practice to reduce the formation of voids is to previously intermix silicon into the paste [18] but this lowers the conductivity. Another approach is to reduce the volume of the paste body [21], which is easily accessible via the disc size of the *FoilMet®* - *Connect* rear.

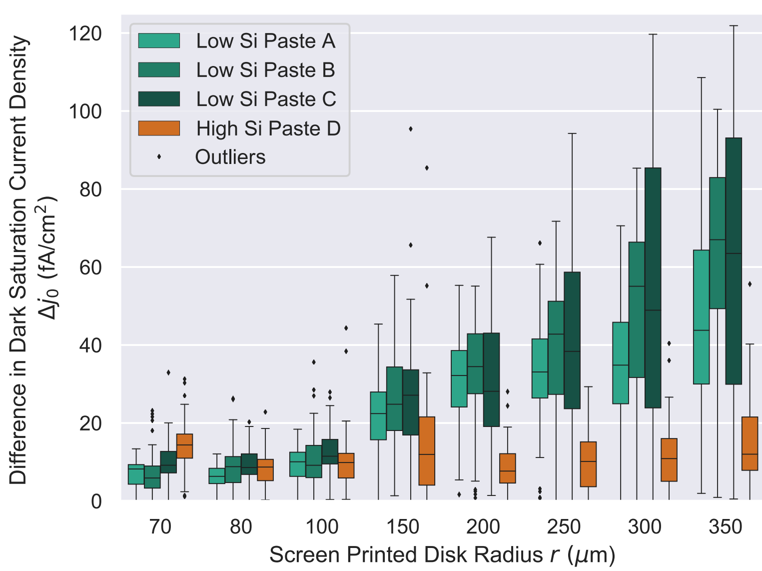

FIGURE 3. Δj_0 is plotted against the disc radius for three pastes with low silicon (Si) content (green) and one with high Si Content (orange). Δj_0 decreases with the disc size. Presented as Tukey Boxplot with whiskers with an 1.5 interquartile range fence [22].

An experiment in which the radius of the SP discs on top of the LCO has been varied for three pastes with a low (Low Si Paste) and one paste with high silicon (High Si Paste) proportion illustrates the advantage of small paste volumes. For this purpose, a special screen was produced that contains test fields with different disk radii and associated blank reference fields. For each sample, the dark saturation current density j_0 was measured. If the test fields are compared with their reference fields, the difference in dark saturation current density Δj_0 can be calculated and used as a measure of damage to the rear. Decreasing the diameter of the disc leads to a reduction of Δj_0 down to radius of 70 µm for low Si paste A, B and C (Fig. 3). However, high Si paste D shows small Δj_0 values unaffected by the variation of the disc diameter. Since SP pastes with low and high silicon proportion show the same Δj_0 values for small disk sizes there is no need to intermingle silicon into the aluminum paste.

Solar Cell Efficiencies with *FoilMet®* - *Connect* and screen printed PERC

As a proof of concept, mono facial solar cells with 156.75 mm edge length are produced from two wafer types to benchmark the *FoilMet®* - *Connect* cell to our best known PERC standard. The first wafer type was manufactured by Solar World Innovations and is characterized by a SiO_xN_y rear surface passivation [23]. The second wafer type, however, comes with a standard $AlO_x - SiN_x$ stack at the rear.

The experiment was performed in two groups, having identical front-side metallization and the same LCO parameters and layout.

One group, however, was completed with the *FoilMet®* - *Connect* rear with a disk radius of 100 µm and a degree of coverage of 15 % (Fig. 2 (a)) and low Si paste A, while the other represents our best known standard PERC process with high Si paste D and without soldering-pads.

The foil metallized group surpasses its SP competitor for both wafer types in terms of conversion efficiency by an average of $\Delta\eta = (0.25 \pm 0.15)\,\%_{abs}$ (Fig. 4 (a)). The remarkable gain in J_{SC} of $(0.27 \pm 0.13)\,\mathrm{mA\,cm^{-2}}$ was obtained due to the well known superior optical attributes of the foil covered rear side (Fig. 4 (b)). Due to the excellent conductivity fo the Al foil compared to SP aluminum, the series resistances is reduced by $\Delta R_S = (0.05 \pm 0.02)\,\Omega\,\mathrm{cm}^2$ whereas the *FF* is unaffected (Fig. 4 (c)). In contrast to the *FoilMet®* - *Classic* technology, the contacts of our presented technology benefit from the SP and firing process - even with low silicon content paste - and achieve the same V_{OC} level as the LCO competitor with high silicon content paste (Fig. 4 (d)).

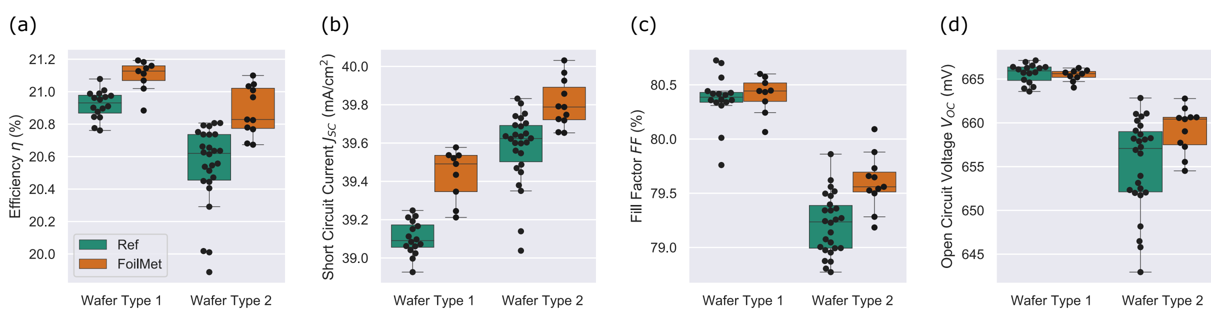

FIGURE 4. I-V-measurement results of $156.75 \times 156.75\ \mathrm{mm}^2$ sized Cz PERC cells with identically processed front side featuring *FoilMet®* - *Connect* rear side metallization and a LCO reference. Presented as Tukey Boxplot with whiskers with an 1.5 interquartile range fence [22].

CONCLUSION

With this contribution we introduce the novel *FoilMet®* - *Connect* technology. In *FoilMet®* - *Connect* we preserved the optical advantages of a foil metallized rear from *FoilMet®* - *Classic* and could transfer the high contact quality from cells with a screen printed and furnace fired rear.

By manufacturing solar cells with improved efficiency we could prove that the *FoilMet®* - *Connect* approach is a high efficiency capable upgrade specifically for PERC and potentially for all high efficiency monofacial concepts based on screen printed metallization.

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