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Black Silicon Laser-Doped Selective Emitter Solar Cell with 18.1% Efficiency

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Abstract

We report fabrication of nanostructured, laser-doped selective emitter (LDSE) silicon solar cells with power conversion efficiency of 18.1 % and a fill factor (FF) of 80.1 %. The nanostructured solar cells were realized through a single step, mask-less, scalable reactive ion etch (RIE) texturing of the surface. The selective emitter was formed by means of laser doping using a continuous wave (CW) laser and subsequent contact formation using light-induced plating of Ni and Cu. The combination of RIE-texturing and a LDSE cell design has to our knowledge not been demonstrated previously. The resulting efficiency indicates a promising potential, especially considering that the cell reported in this work is the first proof-of-concept and that the fabricated cell is not fully optimized in terms of plating, emitter sheet resistance and surface passivation. Due to the scalable nature and simplicity of RIE-texturing as well as the LDSE process, we consider this specific combination a promising candidate for a cost-efficient process for future Si solar cells.

Keywords: black silicon, reactive ion etching, laser doping, LDSE, plating

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1. Introduction

Nanoscale texturing of silicon (Si) surfaces has been shown [1, 2, 3, 4, 5, 6, 7] to reduce the total weighted average optical reflectance to well below 1 % over a broad range of wavelengths and incident angles. Compared to the typical front surface reflectance of ~ 2 and ~ 8 %, from conventionally textured mono- [8] and multi-crystalline [9] Si solar cells, respectively, nanoscale texturing such as described in [10, 11, 12] offers a potential of improved power conversion efficiency for Si solar cells due to reduced reflectance loss.

We use black silicon [13, 14, 11] nanostructuring to achieve low reflectance, which can be modelled in a mean-field approximation as a graded refractive index at the Si-air interface [15]. von Gastrow *et al.* [16] reported excellent passivation of black Si surfaces using atomic layer deposition (ALD) of Al_2O_3 . Repo *et al.* [17] achieved a power conversion efficiency of 18.7 % on 400 μm thick float-zone Si using cryogenic deep reactive ion etching (RIE) as texturing and plasma assisted atomic layer deposition (ALD) of Al_2O_3 for a passivated emitter rear locally diffused (PERL) cell and 22.1 % on an interdigitated back contact (IBC) cell with similar ALD-passivation [18]. Oh *et al.* [19] achieved a power conversion efficiency of 18.2 % on 300 μm thick float-zone Si by combining a metal-assisted wet etching black silicon process for texturing, tetramethylammonium hydroxide (TMAH) damage removal etch and thermal SiO_2 passivation. Yoo *et al.* [20] used industry grade Czochralski (Cz) Si and RIE texturing and achieved a power conversion efficiency of 16.7 %. Wang *et al.* [21] applied black Si by metal-assisted wet etching and ALD of Al_2O_3 on industry grade Cz Si and achieved 18.2 % efficiency.

The primary reason for the relatively low efficiencies reported for black Si solar cells so far is the significant emitter and surface recombination [19, 2] resulting from increased surface area, defects from the texturing process and increased emitter doping through the nanostructured surface yielding increased Auger recombination. These effects usually lead to reduced short-circuit current and open-circuit voltage. Thus, a selective emitter design could improve the effi-

ciency of black Si solar cells. In order to achieve a selective emitter without the use of multiple high-temperature process steps and photolithography, laser doping and subsequent self-aligned Ni/Cu-plating has been suggested by several groups [22, 23, 24]. The laser-doped selective emitter (LDSE) process offers
35 excellent sheet resistance control, self-alignment of front metal contacts to the local highly doped areas and a fast, low-temperature process scalable to industrial throughput. Hallam *et al.* achieved 19.3% efficiency for a LDSE solar cell on large-area Cz Si substrates using an industrial turnkey production line with the addition of laser-doping and plating [25]. The LDSE process has also been
40 successfully applied to bifacial silicon solar cells [26]. An important feature of the LDSE cell process is the replacement of screen-printed Ag front contacts with plated Ni/Cu-contacts. Due to the economic benefits of replacing Ag by Cu in the solar industry [27] and the extensive studies of Ni/Cu-plating applied for Si solar cells [28, 29, 30, 31] the self-aligned, high-performing Ni/Cu-plated
45 front contacts is an important and promising feature of LDSE solar cells.

This work presents LDSE black Si solar cells fabricated on p-type Cz Si substrates textured by a single step, maskless RIE process. To our knowledge this combination has not been previously reported and the resulting cell is thus considered a first proof-of-concept. The emitter diffusion and surface passivation
50 were not fully optimized, since the main goal of this study was the combination of LDSE and RIE-texturing. The primary objective of this work is to investigate how laser doping and plating processes are affected by the RIE-textured surface and vice versa. It is not obvious how a differently textured surface affects e.g. electrical properties of the laser doped regions and subsequent plating.
55 The surface topology may alter the interaction between the laser beam and the material. Thus a different emitter profile may change the defect generation and risk of Schottky contact formation. Besides laser doping and plating, several process steps could be affected by changing from conventional to RIE-texturing: Emitter diffusion could change with effective surface area and deposition of anti-
60 reflective coating may not yield the expected layer thickness and uniformity due to the nanostructured front surface. Such effects could then further affect the

subsequent laser doping and plating processes. An example hereof is spurious plating on the surface in case of pinholes in the dielectric coating resulting from the different surface topology.

65 For these reasons there is a need for an investigation of such RIE-textured LDSE solar cells.

2. Approach

The maskless RIE process presented in this work is applied as the texturing step in the following solar cell fabrication process:

- 70 • Saw damage removal by etching in 30 % KOH at 75 °C for 2 minutes and subsequent cleaning in 20 % HCl at room temperature for 5 minutes and rinsing in deionized water.
- Texturing using maskless RIE at room temperature in a O₂ and SF₆ plasma with a gas flow ratio of O₂:SF₆ = 1:1, chamber pressure of 24
75 mTorr, 13.56 MHz radio-frequency platen power of 100 W using a SPTS RIE system.
- Emitter formation using a tube furnace from Tempres Systems with liquid POCl₃ as dopant source at a temperature of 840 °C and atmospheric pressure for 50 min in O₂ and N₂ ambient, followed by removal of phosphor-silicate glass (PSG) in 5 % hydrofluoric acid (HF).
80
- Plasma enhanced chemical vapour deposition (PECVD) of 75 nm hydrogenated amorphous silicon nitride (SiN_x:H) anti-reflective coating at 400 °C using a Roth & Rau MAiA tool.
- Screen-printing of Al rear contact with standard Al paste, which was fired
85 using a Sierra Therm infra-red fast-firing furnace, with a peak temperature set point of 835 °C and a belt speed of 4500 mm/min.

- Laser doping of the front surface using spin-on of 85 % phosphoric acid as doping source followed by laser doping using a continuous wave laser at a wavelength of 532 nm, 20 W laser power and 2-4 m/s laser scan speed.
- 90 • Light-induced plating of Ni acting as seed and barrier layer for the subsequent Cu plating
- Ni sintering using rapid thermal processing (RTP) in N₂ ambient at 350 °C for 2 minutes
- Light-induced plating of Cu onto the Ni seed layer
- 95 • Edge isolation by laser ablation using a 20 W Nd:YAG Lee laser tool.

The starting substrates were 25x25 mm² p-type, CZ mono-crystalline Si with a thickness of 200 μ m and a resistivity of 1-3 Ω cm.

Figure 1 shows a schematic cross-section of the fabricated solar cell.

100 3. Characterization

J-V curves and photovoltaic performance including short-circuit current density, J_{SC} , open-circuit voltage, V_{OC} , fill factor, FF, and power conversion efficiency were measured on complete cells under 1 sun illumination (1000 W/m², AM1.5G) using a ELH halogen light source, Advantest TR6143 DC Source Measurement Unit and Labview software for data collection. The illumination was
105 calibrated using the known short-circuit current of a reference mono-crystalline Si screen-printed solar cell.

A LEO 1550 Scanning Electron Microscope (SEM) was used to characterize the nanostructured surface topology.

110 Suns- V_{OC} [32, 33] measurements were performed using a Sinton WCT-120 Lifetime tester. The J_{SC} value from the IV-measurement was used.

Reflectance was measured using a Perkin Elmer integrating sphere and spectrometer. The absorptance was measured using a center mount sample holder

inside the integrating sphere.

115 External Quantum Efficiency (EQE) was measured without bias light using a
PV Measurement QE system and Internal Quantum Efficiency (IQE) was cal-
culated based on the EQE and reflectance measurements.

Photoluminescence (PL) [34] was measured at open-circuit conditions using a
BTi luminescence imaging tool.

120 Cross-sectional Focused Ion Beam (FIB)/SEM images of the plated Ni/Cu front
contacts were taken using a Helios Nanolab 600 tool from FEI.

4. Results

Figure 2 shows a SEM image of the RIE-textured Si surface at 40° tilt before
any further processing. The nanostructures have a height of ~ 300 - 500 nm and
125 a distance between the structures of ~ 300 - 500 nm. The nanostructures are
conical-like hillocks randomly distributed across the entire solar cell surface.

Figure 3 shows the total light absorptance of the RIE-textured Si wafer before
any further processing as function of wavelength. The absorptance was mea-
sured using a centre-mount sample holder placed inside the integrating sphere.
130 The incident angle of the light source deviated 8° from normal incidence due to
the geometry of the measurement setup. The absorptance is $\sim 99\%$ in most of
the solar spectrum up to a wavelength of ~ 1000 nm, at which the light starts to
transmit through the $200\ \mu\text{m}$ thick Si wafer. The integrated average absorptance
is 99.2% in the wavelength range 300 - 900 nm and decreases to 91.7% from 900
135 to 1000 nm. The calculated absorptance of a $200\ \mu\text{m}$ Si wafer without any tex-
turing but with an assumed reflectance of 0% is plotted for comparison. Also,
the simulated absorptance of a $200\ \mu\text{m}$ Si wafer textured with upright random
pyramids with $75\ \text{nm}$ $\text{SiN}_x\text{:H}$ AR-coating is shown for comparison. It is seen
that RIE-texturing results in increased absorptance of wavelengths above 1000
140 nm compared to non-textured Si and similar absorptance of wavelengths above
 1000 nm compared to conventionally textured mono-crystalline Si solar cells.
This indicates some path-length enhancement of longer wavelengths within the

RIE-textured wafer. Based on the absorption coefficient of Si the path-length enhancement of RIE-textured Si is estimated to 20 times at a wavelength of 1100 nm.

The fabricated RIE-textured LDSE solar cells were characterized under 1 sun illumination (1000 W/m^2 , AM1.5G). Figure 4 shows the measured J-V curve of the best black Si LDSE cell at 1 sun. The short-circuit current density, J_{SC} , is 36.3 mA/cm^2 and open-circuit voltage, V_{OC} , is 624 mV. The power conversion efficiency is 18.1 % and the fill factor, FF, is 80.1 %. The pseudo light J-V curve and Suns- V_{OC} measurement seen in Figure 5 shows that the best black Si LDSE cell has a pseudo fill factor, pFF, of 82.3 % and a pseudo power conversion efficiency, pEff, of 18.7 % without the effect of series resistance. The high pFF indicates that shunting is low and the pseudo efficiency indicates that series resistance accounts for ~ 0.6 % point efficiency loss compared to the actual power conversion efficiency. The linearly increasing relationship between the illumination and V_{OC} seen in the bottom part of Figure 5 indicates that neither shunting nor Schottky contacts are significant for the best black Si LDSE cell. This is encouraging considering the effect texturing may have on laser doping and plating processes, which could lead to increased defect generation. This does not seem to be the case from the Suns- V_{OC} measurement. The increase in V_{OC} for intensities of 6-7 suns compared to the double diode model may be due to saturation of the surface recombination, which dominates the cell performance at 1 sun.

Table 1 shows measured J_{SC} , V_{OC} , power conversion efficiency and FF for three different RIE-textured LDSE solar cells processed at three different laser speeds. The results in Table 1 show that the three RIE-textured LDSE solar cells have efficiencies in the range 17.5-18.1 %. The differences are primarily due to differences in FF. The different fill factors may be explained by the different laser speeds according to the result in Figure 6, which shows Suns- V_{OC} at low injection for the three RIE-textured LDSE cells with different laser speeds. Figure 6 shows that a laser speed of 3 m/s leads to the highest open circuit voltage at low injection and an almost linear relationship between V_{OC} and illumination

intensity. The cell processed at a laser speed of 2 m/s has significantly lower
175 V_{OC} at low injection and a less linear relationship between V_{OC} and intensity.
This is also reflected in the lower pFF of this particular sample.

After Ni/Cu-plating it was clear that significant spurious plating had occurred
and that the surface had local scratches and pinholes through the dielectric, in
which Ni and Cu has plated unintentionally. The top part of Figure 7 shows
180 photographs of the finished cells where the plating defects are visible. The bot-
tom part of Figure 7 shows a SEM-image of the RIE-textured surface of the
final cells, where an example of the spuriously plated Ni/Cu is also visible. In
order to investigate the lines defined by the laser, optical microscope images
were taken. The top image in Figure 8 shows an optical microscope image of
185 laser-doped lines on the RIE-textured Si surface. The image was taken at the
point where a metal finger intersects the busbar. The laser-scribed lines are
approximately 20 μm wide with $\sim 5 \mu\text{m}$ laser damage on each side of the lines.
Note that each busbar consists of 10 separate lines about 20 μm wide, spaced
 $\sim 80 \mu\text{m}$ apart and metallized in the same light-induced plating process as the
190 fingers. The middle image of Figure 8 shows an optical microscope image of
the Ni/Cu-plated metal lines in this case from the busbar lines. It is seen that
the plated contacts are between 18 and 28 μm wide. The total contact fraction
is $\sim 2.5 \%$ of the total cell area assuming 23 μm wide fingers. The bottom
image in Figure 8 shows a top-view SEM-image of a Ni/Cu-plated line. In the
195 SEM-image an example of spurious metal plating is also seen.

Figure 9 shows a SEM-image of the cross-section of a laser-doped line plated
with Ni/Cu. The cross-section was defined by a Focused Ion Beam (FIB). The
plated metal line is $\sim 30 \mu\text{m}$ wide and $\sim 10 \mu\text{m}$ in height. The layer on top of
the Ni/Cu-line is Pt used solely for sample protection during FIB cutting. Note
200 that the black silicon nanostructures can be seen on the sides of the laser-doped
line. The nanostructures are not seen in the laser-doped region in the center of
the plated Si region, since the Si in this region has been melted and re-solidified
during the laser doping process.

Figure 10 shows EQE and IQE of the complete 18.1% cell and total reflectance

205 of the RIE-textured Si with ~ 75 nm $\text{SiN}_x\text{:H}$ anti-reflective (AR) coating, before any further processing. The IQE is calculated from the measured EQE and reflectance. The IQE plotted in Figure 10 might be underestimated, since the reflectance was measured on textured Si with AR-coating but without any metal, while the EQE was measured on the complete cell. The beam spot of the
210 light source of the EQE-measurement was placed between two metal fingers, but any metal present within the beam spot of the EQE-measurement will increase reflectance and thus decrease EQE and thereby the calculated IQE, since the reflectance on Figure 10 is measured without any metal on the surface. The low IQE for short wavelengths may be due to a too highly doped emitter resulting
215 in increased Auger recombination and may also be due to increased surface recombination at the nanostructured Si surface.

The measured short-circuit current density can be compared to the expected value calculated from the EQE and the solar spectrum to verify consistency in the measurements. Let $E_\lambda(\lambda)$ be the solar spectral irradiance as a function
220 of wavelength λ according to AM1.5G and $Q_{\text{ext}}(\lambda)$ the measured EQE. Then the spectral current density is $J_\lambda(\lambda) = e\lambda E_\lambda(\lambda)Q_{\text{ext}}(\lambda)/(hc)$ since hc/λ is the photon energy and e the unit charge, while h is Planck's constant and c the vacuum speed of light. It follows that the expected short-circuit current density is

$$J_{\text{SC}} = \int_{\lambda_{\text{min}}}^{\lambda_{\text{max}}} \frac{e\lambda}{hc} E_\lambda(\lambda) Q_{\text{ext}}(\lambda) d\lambda. \quad (1)$$

225 A numerical integration using $\lambda_{\text{min}} = 300$ nm and $\lambda_{\text{max}} = 1200$ nm results in the expected short-circuit current density 36.5 mA/cm² which is in almost perfect agreement with the 36.3 mA/cm² that was measured.

Figure 11 shows the total reflectance of the RIE-textured surface with AR-coating before and after Ni/Cu-plating, respectively, as function of wavelength.
230 It is clear that after metal plating the reflectance of the complete cell increases significantly. However, the increase is presumably partly due to the spurious plating seen in Figure 7. The beam spot size of the light source was ~ 2 cm in diameter and covered the majority of the cell area including the busbar and

metal fingers.

235 Figure 12 shows an open-circuit photoluminescence (PL) image of the 18.1 %
cell after Ni plating and sintering. The PL-image shows increased recombination
at the laser-doped, Ni-plated busbar and fingers, which is expected for Si-metal
interfaces. Furthermore, circular points or agglomerations of lower PL-signal
intensity can be seen all over the surface. This indicates that the firing temper-
240 ature used after rear Al screen-printing was slightly too high for the particular
samples, leading to a non-uniform back-surface field.

5. Discussion

The power conversion efficiency of 18.1 % of the black Si LDSE cell fabricated
245 in this work is comparable to the best efficiencies reported for front-contacted
black Si solar cells [17, 19, 21]. Table 2 shows selected cell results reported for
black Si solar cells [11]. From Table 2 it appears that the cell in this work has
superior fill factor compared to existing black silicon cells, while J_{SC} and V_{OC}
are on par or slightly reduced compared to [17]. The lack of improvement to J_{SC}
250 and V_{OC} may be explained by the unintentionally too heavily doped emitter, in-
adequate surface passivation and the unintentional spurious plating; optimized
processing is thus expected to improve both key parameters significantly. The
very high fill factor on the other hand is due to a near optimum laser power
and scan speed used during laser doping of the best device, resulting in very
255 low contact resistance. We note that the optimum laser doping conditions are
different from those on planar silicon probably due to stronger coupling of the
laser power into the structure.

In general, this result is encouraging considering that industrial grade Cz Si
wafers were used and that the complete cells in this work were not fully opti-
260 mized:

First of all the cells had significant spurious plating as shown in Figure 7. This
induces a direct loss of current, since the reflectance of the complete cells is

significantly higher than a similar cell without spurious plating. The reflectance difference is shown in Figure 11 and the additional integrated average reflectance
265 in the range 300-1000 nm attributed only to spurious plating can be estimated by the following considerations: The integrated average reflectance in the range 300-1000 nm is 1.20 % before plating and 6.38 % after plating. The front contact grid only covers ~ 2.5 % of the cell area assuming 23 μm wide fingers. Based on the metal grid coverage the grid itself only accounts for additional reflectance of
270 ~ 1.23 % assuming 50 % reflectance of Cu in the wavelength range 300-1000 nm. The spurious plating must account for the difference between the additional reflectance after plating and reflectance from the grid. Thus the spurious plating accounts for ~ 3.95 %. This is a direct reflection loss, which can be at least partly avoided by minimizing spurious plating. Furthermore, spurious plating
275 in scratches such as seen in Figure 7 is likely to cause increased surface recombination, since the plated metal contacts directly to a lightly doped emitter, which shields minority carriers less than a heavily doped emitter, thus causing enhanced recombination at the metal-Si interface. It is however encouraging that the Suns- V_{OC} measurement in Figure 5 does not indicate any increased
280 defect generation or Schottky contact formation.

The Suns- V_{OC} result in Figure 6 indicates the relationship between laser speed and pseudo FF. From the result in Figure 6 it seems that 3 m/s leads to the most ideal performance, ultimately leading to a higher FF and power conversion efficiency than the cells processed at 2 and 4 m/s, respectively. The lower
285 V_{OC} at low injection for the cell processed at 2 m/s may be due to increased laser damage at the slower scan speed leading to increased Shockley-Read-Hall recombination in the laser doped regions. The pseudo FF of the cell processed at 4 m/s is almost as high as for 3 m/s. However, the FF is still significantly lower, which indicates that the problem for this cell is rather series resistance.
290 This may be due to a lighter doping caused by the faster scan speed. Thus, it seems that a laser speed of 3 m/s is close to the optimal compromise between minimized laser damage and minimized series resistance for RIE-textured laser-doped solar cells.

Assuming that the spurious plating is due to pinholes and other non-uniformities
 295 in the dielectric AR-coating, the problem could be minimized by increasing the
 thickness of the $\text{SiN}_x\text{:H}$ layer. The layer may be even thinner than expected,
 because the deposition rate in the PECVD process may not be the same for
 RIE-textured Si compared to conventionally textured Si. Even a non-uniform
 layer would not induce spurious plating as long as the dielectric layer is com-
 300 pletely covering the Si surface with sufficient thickness to completely isolate the
 surface from the plating electrolyte. It is assumed that the pretreatment using
 hydrofluoric acid (HF) immediately prior to Ni plating further increases the
 risk of pinholes, since the $\text{SiN}_x\text{:H}$ coating is etched by HF to some degree. A
 negative effect of increasing the $\text{SiN}_x\text{:H}$ thickness could be increased reflectance
 305 and absorption in the AR-coating. However, the AR-properties of the $\text{SiN}_x\text{:H}$
 coating are less critical on RIE-textured Si, due to the very low reflectance from
 the black Si surface itself. The increased absorption in the AR-coating could
 be minimized by adjusting the layer thickness and the HF process in order to
 minimize pinholes, while maintaining an acceptably low absorption in the AR-
 310 coating.

The phosphorus emitter was too heavily doped resulting in a sheet resistance of
 40 Ω measured with a 4-point probe after phosphorus diffusion. This was un-
 intentional, since the full area sheet resistance of such selective emitter should
 ideally be on the order of 100 Ω , which was also measured on planar Si reference
 315 wafers from the same diffusion process. This suggests that the decreased sheet
 resistance is due to faster diffusion of dopant atoms through the nanostructured
 Si surface. By decreasing time and temperature of the diffusion process, we ex-
 pect to improve the emitter in future studies. From the QE measurement seen
 in Figure 10 a significant decrease in EQE and IQE is seen for wavelengths below
 320 600 nm. This indicates significant emitter and surface recombination, which is
 expected from black Si, if the surface is not well passivated. Since a standard
 $\text{SiN}_x\text{:H}$ AR-coating was used as the only passivation layer on these cells, it is
 expected that the short wavelength response can be significantly improved in
 future studies by optimizing the $\text{SiN}_x\text{:H}$ coating or by applying different dielec-

325 tric coatings.

From the PL-image in Figure 12 small circular structures with slightly lower PL-signal can be seen. We suggest that this is due to a too high firing temperature used for rear Al screen-printing on these particular samples. We expect this to be improved in future studies.

330 By combining the potential improvements mentioned above significantly higher power conversion efficiency of this new kind of cell structure is expected. This will be investigated in future studies.

6. Conclusion

Ni/Cu-plated black Si LDSE solar cells have been fabricated on industrial
335 grade Cz Si substrates textured in a single step, maskless RIE-process. The best cell has a power conversion efficiency of 18.1 % with a fill factor of 80.1 %. Since the cell was not optimized in terms of spurious plating, emitter sheet resistance and surface passivation, it is expected that the efficiency of black Si LDSE cells will be significantly higher in the near future. To our knowledge this
340 is the first RIE-textured LDSE cell reported and we therefore consider this a proof-of-concept.

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Figure 1: Sketch of the black Si LDSE solar cell structure. The cells are textured in a single-step, maskless RIE process. The highly doped regions of the selective emitter is formed by means of local laser doping using phosphoric acid dopant and a continuous wave laser. The rear contact is screen-printed and fired Al and the front contacts are plated Ni/Cu. The dimensions of the different layers are not to scale.

Figure 2: SEM-image at 40° tilt of the RIE-textured Si surface before any further processing. The nanostructures have a height of ~ 300 - 500 nm and a distance between the structures of ~ 300 - 500 nm. The nanostructures are conical-like hillocks randomly distributed across the entire solar cell surface.

Laser Speed	Efficiency [%]	J_{SC} [mA/cm ²]	V_{OC} [V]	FF [%]	pFF [%]
2m/s	17.5	36.0	0.624	77.9	81.0
3m/s	18.1	36.3	0.624	80.1	82.3
4m/s	17.5	35.8	0.624	78.4	82.0

Table 1: Power conversion efficiency, short-circuit current density, open-circuit voltage and fill factor at 1 sun illumination (1000 W/m^2 , AM1.5G) of conventionally and RIE-textured LDSE Si cells with laser speeds of 2, 3 and 4 m/s, respectively. Furthermore, the pseudo fill factor, pFF, determined by Suns- V_{OC} measurements is given.

Figure 3: Light absorbance of the black Si surface before cell processing as function of the wavelength. The absorbance was measured with a center-mount inside an integrating sphere. The incident angle of the light source deviated 8° from normal incidence due to the geometry of the measurement setup.

Figure 4: Current density-voltage characteristic of the best black Si LDSE solar cell under 1 sun illumination (1000 W/m^2 , AM1.5G). The short-circuit current density, J_{SC} , is 36.3 mA/cm^2 and open-circuit voltage, V_{OC} , is 624 mV . The power conversion efficiency is 18.1% and the fill factor, FF, is 80.1%

23
 Figure 5: Result of the Pseudo Light J-V (top) and (middle) Suns- V_{OC} measurement of the best black Si LDSE cell processed at a laser speed of 3 m/s. The measurement shows a pseudo fill factor, pFF, of 82.3 % and a pseudo efficiency, pEff, of 18.7 % without the effect of series resistance.

Figure 6: Suns- V_{OC} measurement at low injection of three black Si LDSE cells processed at laser speeds of 2, 3 and 4 m/s, respectively.

Figure 7: (Top) Photographs of 2 of the final²⁵ black Si LDSE solar cells. The images show significant spurious plating of Ni/Cu and scratches in the front surface. (Bottom) SEM-image at 52° tilt of the RIE-textured surface of the final black Si LDSE solar cell surface. The SEM-image also shows examples of spuriously plated Ni/Cu.

Figure 8: (Top) Optical microscope image of the laser-doped lines on the black Si front surface before Ni/Cu-plating. (Middle) Optical microscope image showing the width of the Ni/Cu-plated metal lines in this case from the busbar. (Bottom) Top-view SEM-image of a Ni/Cu-plated metal line.

Figure 9: SEM-image at 52° tilt showing the cross-section of a Ni/Cu-plated metal line. The cross-section was defined by a Focused Ion Beam (FIB). The plated metal line is $\sim 30\ \mu\text{m}$ wide and $\sim 10\ \mu\text{m}$ in height. The layer seen on top of the Ni/Cu-line is Pt used solely for sample protection during FIB cutting. Note that the black silicon nanostructures are visible at the edges of the plated Ni/Cu line.

Figure 10: External and Internal Quantum Efficiency and total reflectance as function of wavelength of the 18.1% black Si LDSE solar cell. The reflectance data are for RIE-textured Si with AR-coating before any further processing. The IQE is calculated based on the measured EQE and reflectance of the surface measured before laser and plating processes. EQE was measured without any bias light.

Figure 11: Total reflectance of the RIE-textured Si surface with AR-coating before and after laser doping and Ni/Cu-plating, respectively, as function of wavelength. The beam spot size of the light source was ~ 2 cm in diameter and covered the majority of the cell area including the busbar and metal fingers.

Figure 12: Open-circuit Photoluminescence (PL) image of the cell after Ni plating and sintering, but before Cu plating and edge isolation. The feature in the bottom left corner of the image is due to the shape of the screen-printed Al on the rear.

Author	Texturing	Eff.	J_{SC}	V_{OC}	FF	Cell Type
		[%]	[mA/cm ²]	[V]	[%]	Passivation, Cell Area
This work	RIE	18.1	36.3	0.624	80.1	CZ LDSE SiN _x , 6.25 cm ²
Repo <i>et al.</i> [17]	RIE	18.7	39.2	0.632	75.8	FZ PERL ALD Al ₂ O ₃ , 4 cm ²
Yoo <i>et al.</i> [20]	RIE	16.7	36.8	0.617	76.0	CZ Screen-printed SiN _x , 156.25 cm ²
Oh <i>et al.</i> [19]	MACE*	18.2	36.5	0.628	79.6	FZ, evaporated contacts Thermal SiO ₂ , 0.8081 cm ²
Wang <i>et al.</i> [21]	MACE*	18.2	41.3	0.598	75.1	CZ, evaporated contacts ALD Al ₂ O ₃ , 0.92 cm ²
Savin <i>et al.</i> [18]	RIE	22.1	42.2	0.665	78.7	FZ, IBC ALD Al ₂ O ₃ , 78.5 cm ² (4")

Table 2: Selected black silicon solar cell results reported in literature. The table shows power conversion efficiency, J_{SC} , V_{OC} , fill factor and type of solar cell and Si substrate. For further details about the cell type we refer to the references. *Metal-Assisted Chemical Etching (MACE).