High-precision alignment procedures for patterning processes in solar cell production

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Abstract
We present two approaches for high-accuracy aligning of patterning processes with each other when fabricating solar cells. We introduce the approaches on the example of two different patterning processes of which one is adjustable (laser process) and one is not adjustable (screen-printing process). The basic idea is to measure the coordinates of the applied structures of each involved patterning process at discrete grid points with respect to a reference coordinate system. We chose the grid points such that they completely define the final cell pattern. Then, we adjust the grid point coordinates of one of the patterning processes (the laser process) according to the pattern of the other process (the screen-printing process). The laser then performs the patterning by connecting the corrected grid points with each other in the desired direction. We perform the associated high-precision measurement of the patterns’ coordinates by using either a high-precision offline coordinate measuring machine or a high-resolution inline camera system with subsequent computer-based data processing. The latter inline method enables high throughput and is, in turn, of great interest for mass production of solar cells. In this paper, we demonstrate the alignment procedure approaches on “pPassDop” solar cells by adjusting a locally applied laser process to the directly following screen-printing step. This proof of principle includes both above-mentioned methods for coordinate determination in separate cell batches. Our innovative alignment procedures so far demonstrated the successful matching of 40-μm-wide screen-printed contact fingers to 70-μm-wide laser-processed lines over the entire area of 6-inch solar cells.

KEYWORDS
alignment, bifacial, coordinate correction, laser, patterning processes, PERC, PERL, pPassDop, screen printing, selective emitter, silicon solar cells

INTRODUCTION
Aligning two or more processes with each other is a task that is of relevance in the production of multiple solar cell designs. A prime example is the fabrication of p-type silicon bifacial passivated emitter and rear cells (biPERCs)1-3 with particularly narrow rear side aluminum contact fingers.4-7 Because of ever-smaller finger widths of the aluminum grid, the significance of an accurate alignment to the previously...
generated laser contact openings (LCOs) of the passivation layer becomes more and more relevant. Misalignment leads to low-quality contact formation with increased contact resistance and increased recombination activity in the areas with removed passivation layer and without metal coverage. The state-of-the-art alignment between laser processes and screen-printing processes is the approach in which fixed patterns for both processes are used with quite wide structure widths for one of the processes. The wide structures account for the accuracy of the laser tool as well as for the alignment tolerances of the screen-printing process. Thereby, either fiducial marks or wafer edges serve as reference coordinates.

Another example for which high-precision alignment is substantially important is the n-type silicon bifacial passivated emitter and rear locally diffused (bPERL) solar cell concept that is based on the "pPassDop" approach. Thereby, the pPassDop layer stack applied on the back consists of a thin silicon nitride (SiNx) layer capped by a boron-doped silicon nitride (SiNx:B) layer. The Al2O3/SiNx:B layer stack serves as both surface passivation and dopant source for laser doping to locally form highly p-doped back surface field (BSF) areas. For the silver-based screen-printing process that directly follows laser processing, accurate alignment of the contact grid with the laser-processed BSF pattern is crucial.

The laser process also forms a local BSF, if just a conventional, not boron-doped SiNx layer is applied on top of the Al2O3 layer (the Al2O3 layer is the only doping source). We recently demonstrated this for n-type silicon biPERL solar cells that are very similar to biPERCs. The two main differences for these biPERL solar cells are as follows: (a) the laser process that applies the LCO on the rear side needs to be adjusted to provide local doping and laser ablation, and (b) the grid is screen printed with silver-based metallization and not with aluminum-based one. Hence, this biPERL cell concept, which allows for significantly higher bifaciality in the range of about 90% because of much smaller rear-side finger widths, might be seen a natural evolution of the biPERC concept in the future. For further details on the two discussed biPERL cell concepts with either pPassDop layer stack or conventional Al2O3/SiNx layer stack, please refer to Lohmüller et al.

All solar cell concepts discussed so far have in common that the screen-printing process immediately follows the laser processing, and, hence, the layout for the laser is adapted with respect to the actual screen-printing pattern. In addition to the already mentioned cell concepts, the alignment methods introduced in this paper can also be of great interest for other solar cell concepts. We discuss the applicability of the alignment procedures for both mass production and research and development (R&D) purposes. Examples for further cell concepts profiting from high-precision alignment are solar cells with selective emitters, either metallized by plated or screen-printed contacts.

As shown in our previous works in Lohmüller et al., the application of the alignment approaches allows for highly accurate alignment. On 6-inch p-type silicon biPERL solar cells, we aligned laser-doped BSF regions and screen-printed contact fingers with a total difference in width of only about 30 μm over the entire cell area (i.e., in Lohmüller et al., 40-μm-wide screen-printed contact fingers to 70-μm-wide laser-processed lines). This paper introduces the two alignment procedure approaches in detail and describes possibilities to determine the necessary pattern coordinates of interest. Further research on these alignment approaches with respect to occurring error sources and key aspects for achieving further improved alignment accuracy is currently underway and will be published elsewhere.

2 | ALIGNMENT PROCEDURE APPROACHES

We discuss the two approaches for the alignment procedure in the following sections for two patterning processes. However, the approaches might be also applicable, if additional adjustable processes are involved.

We first discuss the principle of the proposed approaches for a high-precision alignment between two patterning processes (referred to as "process 1" and "process 2") for R&D application. We choose the scenario such that process 1 (a laser process) should be adapted to process 2 (a screen-printing process). The applicability of the alignment approaches in mass production is then picked up in Section 2.4.

2.1 | Offset approach

This alignment approach is based on the use of reference samples as shown in Figure 1. Following an offset approach, the final cell pattern is applied on individual test wafers by both involved patterning processes. In addition to the pattern, the laser and screen-printing processes also apply fiducials that define the coordinate system regardless of the wafer edges, hereinafter referred to as the "fiducial coordinate system." In this work, we use two crosses as fiducial marks. They define the fiducial coordinate system as shown and described in Figure 1. The test wafers on which the pattern is applied should be chosen such that the structures are clearly recognizable in the respective characterization device that is used to measure their coordinates. In this work, the test wafers are taken from the cell wafers from chapter 4 after they have been passivated on both sides (i.e., before laser processing and screen printing).

In a next step, we analyze the pattern’s coordinates on the reference samples with respect to the fiducial coordinate system. The basic idea is to subdivide the pattern’s structures by means of discrete grid points as depicted in Figure 2. By measuring the grid point coordinates with respect to the fiducial coordinate system, we have the information, how accurate the patterning processes are in relation to their nominal position (i.e., to the position according to the designed layout), and how large the individual offset is at each grid point. Based on the discrepancy between nominal x-y-position and measured x-y-position at each grid point for the laser as well as the screen-printing process, corrected x-y-coordinates at the grid points can be calculated and used for the laser process, which is process 1 in the chosen...
scenario. When it then comes to solar cell processing, the screen-printing process (process 2) is aligned to the samples with respect to the fiducials, and, hence, the patterns should match.

Special care should also be taken when measuring the coordinates. Either the same machine is used for the reference samples from process 1 and process 2 to compensate possible systematic measurement errors or, when using two different systems, they should be properly calibrated to each other. In the best case, both systems are calibrated to metric units.

Figure 3 exemplifies the principle of the coordinate correction in the \( y \)-direction for a contact finger. The \( x \)-positions of busbar contacts or redundancy lines can be corrected in the same manner (not performed and discussed in this paper). Both patterning processes initially target to apply the pattern at the nominal grid point \( y \)-positions \( y_{i,j,\text{nom}} \) ( \( i \), grid point number; \( j \), finger number) marked by the black filled circles. As the basic accuracy of the process technologies is not perfect, the resulting \( y \)-positions for processes 1 and 2 may deviate from their nominal values. The \( y \)-offsets from the nominal \( y \)-positions are given by \( \Delta y_{1,i,j} \) for process 1 and \( \Delta y_{2,i,j} \) for process 2. Obviously, a global negative \( y \)-shift of process 2 does not lead to a proper alignment with process 1. Similarly, global rotation of the pattern applied by process 2 does not lead to proper alignment over the whole sample either. Hence, we propose to correct the pattern for the laser process with respect to the individually determined \( y \)-offsets at the grid points. In order to apply the screen-printed pattern in process 2 as accurate as possible on top of the laser-processed pattern, the corrected target \( y \)-coordinates for the laser-processed pattern calculate to

\[
y_{1,i,j,\text{target}} = y_{i,j,\text{nom}} + \Delta y_{1,i,j,\text{corr}} = y_{i,j,\text{nom}} + (\Delta y_{2,i,j} - \Delta y_{1,i,j}) \tag{1}
\]

As the screen-printing pattern cannot be dynamically adjusted, the adjustment of the laser-processed pattern is the way to go for a highly accurate alignment for this exemplary process combination. Bringing the fiducials of both processes in accordance should lead to a match in the generated patterns. By applying an alignment procedure, the alignment accuracy is also independent of the individual basic accuracies of the two process technologies and of the wafer edges.

2.2 | Modular approach

Our modular approach allows determining the laser deformation and screen-printing deformation independently. The deformation of the laser field is described within a continuous function in the \( x \)- and \( y \)-direction. Therefore, the deformation of the laser field is determined by laser processing a symmetric grid structure as shown in Figure 4. The field distortion of the laser system is calculated as difference between the input parameters of the laser recipe and the measured grid positions. Since the sample can be rotated and translated within the measurement system, the measured coordinates are corrected with regard to these geometric transformations. The applied transformation minimizes the sum of squared distances between the coordinates of both patterns. Afterwards, continues functions are generated.
by fitting polynomials to the distortion field for the deformation in the x- and y-direction.

The deformation of the screen-printing process is calculated according to Section 2.1. The data are analyzed in the fiducial coordinate system. For every contact finger, the y-position of the printed contact finger is compared with the nominal position at discrete grid points.

For the calculation of corrected laser positions, both deformation patterns are taken into account. The corrected laser coordinates consider the y-offsets observed due to the screen-printing process and the laser distortion function.

2.3 | Coordinate determination of the pattern

As described in Sections 2.1 and 2.2, the key of the presented alignment approaches is the coordinate determination at discrete grid points of the applied patterns. The more grid points are taken into account, the more accurate the alignment can be realized.

We so far evaluated two different methods to determine the grid point coordinates. The first method uses a highly precise offline coordinate measuring machine for which the inaccuracy in the x- and y-direction is in the range of only a few microns. This system is based on an automatic microscope, which can take images of the structures and measures their real coordinates at predefined x-y-positions.

The second method is based on image recording with a high-resolution inline camera system and subsequent computer-based data processing. We use a line scan camera that is firmly attached in a measurement system. The resolution of each pixel corresponds to 20 μm × 20 μm. The samples pass below the camera either by means of a linear slide or by means of a conveyor belt. For the recorded images, we use sub-pixel fitting to determine the structures’ coordinates at the chosen grid points accurately by polynomial interpolation.

While the inline camera-based method is very interesting for all kinds of solar cell processing including mass production, the former offline method is a convenient approach for fabricating solar cells in R&D environments.

2.4 | Applicability in solar cell mass production

The proposed alignment approaches are of high interest for R&D purposes. Therefore, it is not of such importance how long the procedure takes or which equipment is used and which process is adapted. The alignment procedures can be applied to all cell concepts that have a requirement for high-precision alignment. This can be, eg, PERC solar
cells or other PERC derivatives for which a laser-doped selective emitter is meant to be electrically contacted by screen-printed and fired metal contacts.

Moreover, the alignment procedures can be of great interest to cell manufacturers for mass production. When producing alignment-critical solar cell devices, the alignment procedure in conjunction with the camera-based inline approach is an option to decrease the used structure sizes significantly. Table 1 shows some examples of potential solar cell concepts that might profit from improved alignment accuracy in mass production. In case a screen-printing process is process 2 (as has been discussed above), the preceding laser process is required to ensure the coordinate correction. This applies to, e.g., biPERC and biPERL devices. Further examples are PERC devices that are based on the “nPassDop” approach, in which a phosphorus-doped SiNx layer is applied on the front side that provides phosphorus for laser doping a selective emitter. In general, in case process 2 is not flexibly adjustable with respect to its applied pattern, the preceding flexible process 1 is adapted.

For the case of an integrated production line where process 1 and process 2 follow each other more or less directly, the patterns are in each case directly recorded and evaluated so that the coordinates' correction for process 1 can take place instantaneously. Then, there would be no need for special reference wafers as each wafer would get a corrected pattern that is based on the offsets determined on the previous wafers. The result could be a nearly ideal alignment, where only random process fluctuations would occur.

On the other hand, if process 2 is flexibly adjustable, this process can be adapted to the pattern applied by process 1. This applies to selective emitter PERC solar cells in conjunction with plated metallization. In this case, process 1 applies the selective emitter to the front side of the samples. This can be a laser process or mask-and-etch approaches that are based on screen printing, ink-jetting, or others. The cells then undergo several intermediate fabrication steps until they finally receive their LCO treatment for opening the front passivation layer and the plated contacts. Based on the examined patterns of both processes, the pattern for the LCO process is adapted accordingly.

3 | REFERENCE SAMPLES AND LAYOUT CORRECTION

In Section 4, we will present results for 6-inch p-type Czochralski-grown silicon (Cz-Si) biPERL solar cells. For the fabrication of these cells, we use the above-discussed alignment procedures for correcting the laser pattern on the rear side. In this section, we explain in detail and step by step how the coordinate correction is performed using the offset approach. The repeatability of the process technologies is also not perfect. Therefore, it makes sense to create and to evaluate multiple reference wafers and then to conduct the corrections on the basis of statistics.

We fabricate and examine the reference samples comprising the final cell pattern (see Figure 1) in the R&D environment of the PV-TEC laboratory at Fraunhofer ISE. We use an offline high-precision coordinate measurement machine to acquire the pattern's coordinates at the chosen grid points as shown in Figure 2.

For both rear-side patterning processes that follow each other directly (process 1, laser doping of the rear BSF, and process 2, silver-based screen printing of the rear grid), the final cell layout is applied on three reference wafers each. Figure 5A,B shows the structure sizes applied by the laser process and the screen-printing process, respectively.

We apply the offset approach according to Equation (1) only for the y-positions of the fingers; see also Figure 3. We do not correct the x-positions of busbars and redundancy lines. We choose seven grid points per finger for reconstructing the rear side grid and for adjusting the laser-doping process; see Figure 2. The grid points are defined as the intersections between the fingers and the busbars as well as between the fingers and the redundancy lines on the left and right sides of the wafers. A layout of five busbar

| Solar Cell Concept | Process 1 | Process 2 | Coordinate Correction Performed in |
|--------------------|-----------|-----------|------------------------------------|
| biPERC             | LCO       | Screen printing | Process 1                         |
| biPERL (“pPassDop”)| Laser doping BSF | Screen printing | Process 1                         |
| biPERL (Al2O3/SiNₓ)| Laser doping BSF | Screen printing | Process 1                         |
| PERC (“nPassDop”)  | Laser doping selective emitter | Screen printing | Process 1                         |
| PERC (plated metallization) | Selective emitter | LCO | Process 2                         |

Abbreviations: biPERC, bifacial passivated emitter and rear cell; biPERL, bifacial passivated emitter and rear locally diffused; BSF, back surface field; LCO, laser contact opening.
and 120 finger grid is chosen. However, the busbars are neither lasered nor screen printed; they just define the breakdown positions for the grid points. Hence, in total, 836 positions per reference sample (the finger at the top and at the bottom has no redundancy line) are characterized and used for the alignment procedure.

3.1 | Laser process

For laser processing, we use a pulsed infrared diode-pumped solid-state disk laser with a wavelength of 1030 nm. The system is equipped with a galvanometer scanner system. Prior to processing, we perform a correction of the laser scan field to calibrate the laser system. In order to put each of the three reference samples at the same position within the laser scan field, the wafers are aligned on the system’s chuck with help of three metal pins. The laser-doping process yields BSF stripe widths \( w_{BSF} \approx 70 \, \mu m \); see Figure 5A. For each reference sample, the measured \( \Delta y_{1,i,j} \) of the 836 grid points with respect to their nominal \( y \)-positions are depicted in Figure 6 (displayed as color code). The \( y \)-offsets change from positive values at the samples’ tops to negative values at the samples’ bottoms. Thereby, the \( y \)-offset range is at \(-19 \, \mu m < \Delta y_{1,i,j} < 14 \, \mu m \). No significant difference in the signature of the \( y \)-offset graphs is evident between the three reference samples in Figure 6A-C. The fact that the three reference wafers show similar offsets is also seen in the histograms depicted in Figure 7. This result indicates a high reproducibility of the laser system, whereas its absolute accuracy is not important. Furthermore, the mean \( y \)-offset is \( \Delta y_{1,i,j} \), considering all three laser-processed reference wafers are only \( \Delta y_{1,i,j} = (-2.6 \pm 15.6) \, \mu m \). The error is given as three times the standard deviation \( \sigma \) throughout this paper. Hence here, \( 3\sigma = 15.6 \, \mu m \). This \( y \)-offset and the fluctuation range are quite small, indicating a quite proper overall calibration of the laser system.

3.2 | Screen-printing process

The screen-printing process with silver-aluminum paste yields finger widths \( w_f \approx 40 \, \mu m \) after contact firing; see Figure 5B. Figure 8 illustrates the measured \( y \)-offsets \( \Delta y_{2,i,j} \) of the 836 grid points for the three reference samples. Obviously, the \( y \)-offset signature is different to that of the laser-processed reference samples in Figure 6. However, the general trend is the same: at the samples’ tops, the values are positive, while they are rather negative at the sample’s bottoms. The absolute offset range is at \(-11 \, \mu m < \Delta y_{2,i,j} < 15 \, \mu m \) for the screen-printed samples and is thus comparable with that of the laser-processed ones. As before, also for the screen-printed reference samples, no significant difference in the signature of the \( y \)-offset is observed, neither in Figure 8A-C nor within the \( y \)-offset histograms.
shown in Figure 9. Again, also the screen-printing process yields a quite high reproducibility. The mean $\Delta y$-offset $\Delta y_{2ij}$ considering all three screen-printed reference wafers is only $\Delta y_{2ij} = (0.4 \pm 15.6) \mu m$. This average $\Delta y$-offset with its error of $3\sigma = 15.6 \mu m$ is again quite low, indicating a high-quality true-to-scale pattern transfer by the used screen mesh.

As we want to apply the results of the alignment procedure on real solar cells with a batch size of about 200 wafers, it is of interest how the screen-printed pattern changes over several printing steps. Hence, we also examine the time evolution of the screen distortion by measuring the third, 50th, and 200th printed wafer in the solar cell batch. The applied screen has been used for printing several wafers before the experiment to exclude the effect of initial deformation. As before, the measured $\Delta y$-offsets are plotted as color plots and histograms in Figures 10 and 11, respectively. The overall $\Delta y$-offset signature does not change significantly (see Figure 10), while the $\Delta y$-offset range slightly increases with the number of prints (see Figure 11). From an $\Delta y$-offset range of initially $-10 \mu m < \Delta y_{2ij} < 13 \mu m$ for the third print, the range increases to $-10 \mu m < \Delta y_{2ij} < 15 \mu m$ for the 50th print and to $-20 \mu m < \Delta y_{2ij} < 17 \mu m$ for the 200th print. However, this change is quite small, and, hence, the alignment approach using reference samples is applicable for a solar batch of several hundreds of solar cells.

Note that for an inline camera-based alignment approach, the actual screen-printed pattern can be determined consistently, and the laser pattern can thus be adjusted in real time for each wafer individually.

### 3.3 Coordinate correction

The $y$-coordinates of the grid points for the laser process are corrected according to Equation (1) as described in Section 2.1. For correction, we use the respective average values per grid point from the three reference samples for the lasered pattern (Figure 12A) and the screen-printed pattern (Figure 12B). The resulting correction matrix for the laser process is shown in Figure 12C. A positive value means that the target laser coordinate is shifted upwards and vice versa. From Figure 12C, it is also clear that a precise alignment throughout the whole wafer cannot be achieved by simply shifting or rotating the screen-printed pattern with respect to the laser-processed pattern.

### 4 APPLICATION ON $p$-TYPE Cz-Si biperl solar cells

As mentioned in Section 3, we apply the alignment procedure approaches on two solar cell batches to fabricate 6-in. $p$-type Cz-Si biperl devices. In Section 4.1, we first discuss the implementation of the offset approach using a high-precision offline coordinate
measuring machine. Then, in Section 4.2, we examine the modular approach by using a high-resolution inline camera system and demonstrate a proof of principle for the introduced alignment approach in mass production.

### 4.1 Alignment with the offset approach using a high-precision offline coordinate measuring machine

We fabricate 6-inch p-type Cz-Si biPERL solar cells and aim to ensure the accurate alignment between the laser-doped BSF and the screen-printed silver-aluminum contact fingers on the rear side by correction of the laser pattern according to Section 3. Figure 12C shows the applied coordinate correction at the grid points for the laser pattern in the y-direction. We apply five busbars on the cells’ rear sides with a nonfiring through silver paste, as the area below the busbars is not laser processed and thus does not feature a BSF. More details on the fabrication of these cells and their current-voltage data are found in Lohmüller et al.\textsuperscript{13}
In order to check the alignment on the finished solar cells, we randomly select five finished solar cells and take automatic light-microscope images on each cell at the 836 grid points used for the laser’s coordinate correction (images not shown). We examine the images in terms of whether the screen-printed fingers are fully applied within the laser-processed BSF areas or not. In the more than 4000 taken images, we always find that the contact fingers are fully located within the laser-processed BSF stripe, mostly in the center or near the center. For three cells, we also take 20 manual light-microscope images each; see Figure 13. These images are recorded at representative measuring points between the busbar contacts. As is seen, the screen-printing process applies the contact fingers more or less in the middle of the lasered BSF stripes. At some positions, the fingers are not centered, but they are always completely within the lasered area. A quantitative analysis of the centerline $y$-offset $\Delta y_{\text{center}}$ between the screen-printed fingers and the laser-processed BSF areas from the images in Figure 13 is shown in Figure 14. The alignment accuracy for all three examined solar cells lies at $-7 \mu m \leq \Delta y_{\text{center}} \leq 9 \mu m$.

These results demonstrate the successful application of the proposed alignment procedure. Therewith, we succeeded in aligning 40-μm-wide screen-printed contact fingers reliably over the entire area of 6-in. biPERL solar cells to the 70-μm-wide laser-processed BSF stripes.

### 4.2 Alignment with the modular approach using a high-resolution inline camera system

For the biPERL solar cell batch in which we apply the alignment approach on the basis of the high-resolution inline camera system to extract the grid point coordinates, two different types of reference samples are used. For the laser-processed samples, we use the kind of pattern sketched in Figure 4. The lines in the $x$- and $y$-direction have a distance of 5.08 mm and form a symmetric pattern with $31 \times 31$ intersections. These intersections are evaluated on the taken images, which yields knowledge of the field distortion of the laser system at each $(x, y)$-coordinate throughout the pattern’s dimension. For screen printing, reference samples with the final cell layout (Figure 1) as discussed in Sections 3 and 4.1 are used.

In contrast to the biPERL pPassDop solar cells from Section 4.1, where the laser-processed BSF width is larger than the contact finger width, for these cells, it is the other way round. The BSF width is $w_{\text{BSF}} \approx 37 \mu m$, and the contact finger width is $w_{l} \approx 65 \mu m$; see Figure 15. Additionally, the BSF is also formed below the busbar contacts. Instead of 120 fingers as used in Section 4.1, we here use 150 fingers and five busbars. The grid is applied using a (pure) silver paste this time. More details on the fabrication of these cells are found in Lohmüller et al.\textsuperscript{12}
To check the alignment on the finished solar cells, we select two cells out of the batch and take manual light-microscope images. Figure 16 shows a selection of these images at six representative measuring points close to the upper and lower cell edges. This time, also a group of cells is fabricated for which the laser pattern has not been corrected; see Figure 16A. Clearly visible are the brightly appearing areas, in which the contact fingers do not completely cover the BSF. A simple shift or rotation of the screen-printing pattern with respect to the laser-doped BSF would not lead to a more precise alignment. In contrast, for the cell in Figure 16B with corrected laser coordinates, no bright areas are visible over the entire cell area as the contact fingers are properly aligned to the BSF areas covering them completely. Thus, the alignment procedure that is based on taking images with a high-resolution inline camera system is successfully demonstrated.

The peak energy conversion efficiencies for the biPERL pPassDop solar cell with corrected laser coordinates are $\eta_{\text{front}} = 19.8\%$ and $\eta_{\text{rear}} = 17.6\%$ for the front and rear sides, respectively. The resulting bifacility is $\beta = \eta_{\text{rear}}/\eta_{\text{front}} = 89\%$. For the biPERL pPassDop cell without corrected laser coordinates, the measured peak efficiencies are $\eta_{\text{front}} = 19.7\%$ and $\eta_{\text{rear}} = 17.2\%$, yielding a bifacility $\beta = 87\%$. As both groups have been screen-printed mixed together, the only difference between both groups are the used laser coordinates. Hence, the application of the alignment procedure enables to increase both the front and rear side efficiencies by 0.1%$_{\text{abs}}$ and 0.4%$_{\text{abs}}$, respectively.

5 | SUMMARY AND CONCLUSION

High-precision alignment of patterning processes with each other in solar cell production becomes more and more relevant as advanced cell concepts with local structures enter mass production. We introduce a procedure to ensure a highly accurate alignment between these patterning processes and exemplify its applicability on the basis of $p$-type Cz-Si biPERL pPassDop solar cells. The basic idea of the approach is to subdivide the cell's pattern in discrete grid points, to extract the grid point coordinates by means of recorded images with respect to a reference fiducial coordinate system, and to adapt the laser process to the actual screen-printing pattern. We demonstrate two approaches for image recording and coordinate extraction at the grid points, namely, the usage of (a) an offset approach using a high-precision offline coordinate measuring machine and (b) a modular approach using a high-resolution inline camera system with subsequent computer-based data processing. For both methods, we show accurate alignment of the screen-printed contact fingers to the laser-processed BSF areas over the whole 6-in. biPERL solar cells. Thereby, the total structure widths of the BSF and the metal fingers differ not more than 30 $\mu$m from each other, which is a challenging task. It is worth mentioning that this approach also makes it possible to see how stable the individual patterning processes are. Besides the biPERL solar cells, other cell concepts such as conventional bifacial PERC solar cells or PERCs with selective emitter and galvanic metallization can profit from improved alignment accuracy by an alignment procedure that is compatible with mass production. Such a procedure needs to be inline compatible, and thus, the examined camera-based inline image recording method is the option of choice. Therewith, it is conceivable to instantaneously correct the pattern applied by a laser process to the pattern of a more or less directly following screen-printing process or to the pattern formed by preceding other patterning processes.
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