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A COST-DRIVEN RESEARCH STRATEGY TOWARDS INDUSTRIALLY FEASIBLE HIGH-EFFICIENCY BACK-CONTACT BACK-JUNCTION SILICON SOLAR CELLS

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ABSTRACT: The development and improvement of silicon solar cells is often based on a top-down approach, achieving highest conversion efficiencies and then translating it to industrial equipment and fabrication routes. This work presents an alternative option to derive research and fabrication strategies focused on cost of ownership calculations. Given the necessary tools and insight into feasible production routes, this attempt can be very helpful and rewarding for (small) research facilities, existing solar cell fabrication plants or interested investors in the solar industry. A research strategy is exemplarily derived for the goal of industrially feasible back-contact back-junction solar cells, but many aspects can be generalized for different purposes. Several different fabrication routes are shown and compared to a PERC fabrication route. We find that a co-diffusion approach can offer significant cost reduction potential on cell level, from +21 $\%_{rel}$ down to -2$\%_{rel}$.
Keywords: Co-diffusion, Cost calculation, Interdigitated Back-Contact

1 INTRODUCTION

After a period of drought, the growth in photovoltaic industry has continued its formerly impressive run. With new capacities build up, more and more companies are also looking for novel and improved technology ("high-efficiency concepts"). One way to obtain highest efficiencies has been long known as the "interdigitated back-contact" (IBC) concept [1], where all electrodes are placed on the non-illuminated rear side, avoiding shading losses. However, proven industrial feasibility is pending.

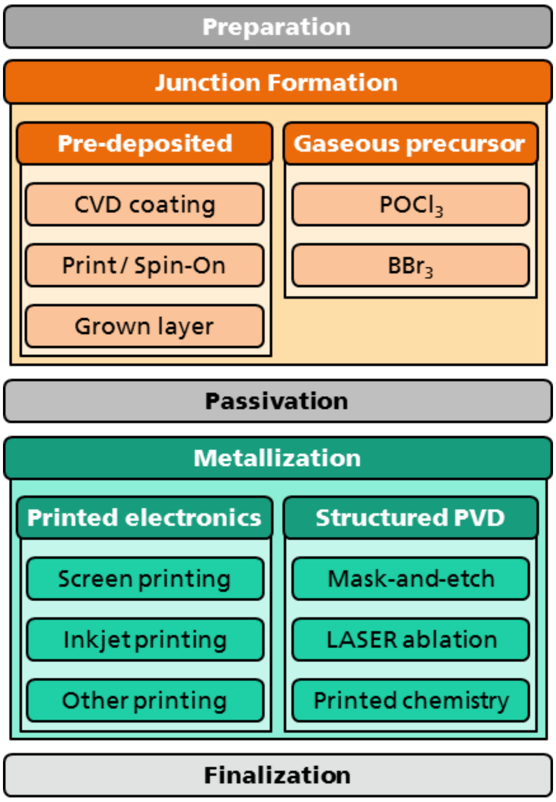

Figure 1: Simplified solar cell fabrication route focusing on different options for "Junction Formation" and "Metallization" (without claim for completeness). The presented studies focus on certain combinations of those, to build an IBC solar cell fabrication plant.

In earlier work by our institute, the performance of screen-printed boron-doping paste in the fabrication of high-efficiency IBC solar cells was investigated [2]. Back-contact back-junction silicon (BCBJ) solar cells with a mean efficiency of η = 20.9 % ± 0.3 % were fabricated and analyzed to reveal the possibilities and limitations of the chosen geometry and process details [3]. All cells were fabricated using the semi-industrial research facilities at Fraunhofer ISE PV-TEC [4], to allow an easy transfer of the evaluated process route into existing PV plants.

For a matured industry like photovoltaics, the cost-competitiveness of a fabrication sequence plays a major role. This work illustrates a method to quantitatively derive research and/or business strategies, focusing primarily on this aspect. Based on the results of these evaluations, cell experiments are currently running to demonstrate lean fabrication of high-efficiency IBC solar cells with minimal costs.

2 METHOD

In the following, an alternative research strategy is developed with a clear emphasis on cost of ownership calculations (COO). Remarkably, this attempt can be implemented with minimal resources, as long as a suited cost-calculation tool is available. Here, the bottom-up "SCost" tool [5] is utilized, designed after SEMI standards E35-0312 [6] and E10-0814E [7].

The strategy is developed in three steps: First, a previously published (research focused) fabrication route is translated into SCost, with the setup of a COO calculation for each process step and relating process equipment. Second, different alternative interlinked process routes are build, altering a small number of process steps each, with different equipment. Third, these alternatives are implemented as well and a COO calculation for each process route is carried out. The generated data is then analyzed in a generalized framework, as described below, for a simplified but still insightful discussion about the suggested alternatives.

2.1 Generalized Framework

It has earlier been described how the competitiveness of different cell concepts can be compared along the PV

value chain by their COO normalized to their output power ("Cost-per-Wattpeak") [5]. As process routes can vary significantly, a simplified scheme for the depiction of the fabrication routes is chosen, consisting of five generic steps:
"Preparation" such as cleaning and surface texturing, "Junction Formation" with different dopant sources and high-temperature steps, "Passivation" of wafer surfaces, "Metallization" of *p*- and *n*-type dopings and "Finalization" of the production cycle such as I-V or other quality tests. This scheme and a number of different options for "Junction Formation" and "Metallization" (without claim for completeness) are shown in Fig. 1.

For a given fabrication route, industrial tools are chosen within SCost for COO calculations. The function of these tools is accredited to one of the five generalized steps and their cost contribution is summed up, for comparison. For all routes a most likely fabrication scheme has been assumed.

2.2 Mathematical Description

The cost of ownership is calculated as a sum of all utilized tools and fabrication steps, including factors like yield loss and capacity utilization within SCost [8]. The cost for any given fabrication route *i* is then

$$C_\mathrm{i} = \sum\nolimits_\mathrm{j} c_\mathrm{j},$$
$$i \in \{\mathrm{PERC},\ \mathrm{IBC}_1,\ \mathrm{IBC}_2, \dots\},$$
$$j \in [1, \dots, n_\mathrm{i}]\ ,$$

with different numbers of process steps n_i.

Each fabrication route implies a different mean output power under standard test conditions of the finished devices $P_\mathrm{i}^\mathrm{out}$. We calculate a value based cost of ownership, given as the ratio of C_i and $P_\mathrm{i}^\mathrm{out}$, which is often referred to as "Cost-per-Wattpeak"

$$\xi_i = C_i / P_i^\mathrm{out},$$
$$[\xi_i] = 1\ \text{€ct}/W_p.$$

To derive a cost-driven research strategy, we need to be able to compare two different fabrication routes. Here, we take ξ_i as the sole figure of merit for different routes and translate the order to rate the routes:

$$\xi_i < \xi_j \Rightarrow\ i \prec j,$$
$$i, j \in \{\mathrm{PERC}, \mathrm{IBC}_1, \mathrm{IBC}_2, \dots\}.$$

In reality, this certainly does not hold true for all business decisions. For example, both values should not be to close, and/or the relation should hold true for some time. Also, if, for example, an existing plant has to be transitioned to achieve an alternate route, the difference needs to include a significant margin, covering additional costs like necessary trainings, downtime during migration etc., not included in this COO calculation. With uncertainties in the scalability between routes, high variance in the production outcomes or other factors that cannot directly be accounted for in this quantity, the derivation of true relation between process routes becomes even more involved.

Neglecting these limitations in the following, we shape a first order statement, to separate the two a priori unknown quantities C_i and $P_\mathrm{i}^\mathrm{out}$ ($\equiv P_\mathrm{i}$ in the following). Assuming parity between two different routes we have

$$\xi_i = \xi_j \Leftrightarrow \frac{C_i}{P_i} = \frac{C_j}{P_j} \Leftrightarrow \frac{C_i}{C_j} = \frac{P_i}{P_j}$$

Under standard test conditions, one derives P_i from the input Power P_0, with the photon conversion efficiency η according to

$$P_i = \eta \cdot P_0,$$

allowing for the identity

$$\frac{C_i}{C_j} = \frac{P_i}{P_j} = \frac{\eta_i \cdot P_0}{\eta_j \cdot P_0} = \frac{\eta_i}{\eta_j}.$$

For comparison, the costs for different routes C_i are normalized to an industrial *p*-type LCO PERC process sequence [9] C_PERC in the following. This also eliminates some potential systematic errors in the calculations.

Finally, one can relate the differences in costs and efficiency by rearranging

$$\Delta C = C_i - C_j \ \Leftrightarrow C_i = C_j + \Delta C,$$

which leads to

$$\frac{C_i}{C_j} = \frac{C_j + \Delta C}{C_j} = 1 + \frac{\Delta C}{C_j}$$

and analogously for η. Plugging these into the former relation equals

$$\frac{C_i}{C_j} = \frac{\eta_i}{\eta_j} \Leftrightarrow 1 + \frac{\Delta C}{C_j} = \ 1 + \frac{\Delta \eta}{\eta_j} \Leftrightarrow \frac{\Delta C}{C_j} = \frac{\Delta \eta}{\eta_j}.$$

This means, a cost difference normalized to the reference route cost has to equal the efficiency difference normalized to the reference efficiency (including sign) for both routes assumed to be equal. All these relations are of course only valid for one chosen reference point at a time. One might as well do the same with an inequality between two routes (e.g. for an improvement), carefully checking for signs of quantities.

The relation between costs and efficiency can also be graphically displayed by "cost-efficiency indifference curves" as shown in [10]. In this work, we avoid the assumption of absolute efficiencies (*cf*. Section 4).

If one finds a relative cost difference between two routes $\Delta C / C_\mathrm{Ref}$ one can then rearrange the last equation to get a first order estimate for a suitable efficiency difference $\Delta\eta$ between these two routes

$$\Delta \eta = \eta_\mathrm{Ref} \cdot \frac{\Delta C}{C_\mathrm{Ref}},$$

with the same limitations for validity as mentioned during this section.

3 COST OF OWNERSHIP CALCULATION

In the following, first the COO calculations of different routes are discussed. As mentioned above, we utilize SCost as the tool of choice. It has been developed and updated at Fraunhofer ISE since the first predecessors from as early as 1998 [11], to represent an accurate and up-to-date database. This was only possible due to helpful insight from projects with our partners and various sources from within the industry.

For comparability, all of the following calculations are based on a European PV plant placed on a green field, scaled to an output of 12,000 cells/hour[1], which amounts to about 500 MW depending on the actual cell efficiency.

The COO can be calculated for all stages up to system cost and even LCOE within SCost. For simplicity, the following arguments are only based on cell level production costs (€/Cell), neglecting overhead costs like Selling, General and Administrative Expenses (SG&A), Research and Development Expenses (R&D), capital cost, and wafer costs. This of course further restricts the applicability of the results, but avoids inclusion of uncertain or varying aspects like module integration or system installation costs. Nold *et al.* [5] have shown that at all stages of the PV value chain, area proportional costs are related to the cell output power, favoring high efficiency concepts even more the further downstream the PV value chain the economic assessment is executed. These positive attributes are also neglected in the following.

With the neglection of wafer cost, also the difference between *p*-type doped substrates and *n*-type doped substrates is excluded here. As IBC solar cells are usually fabricated on the latter, more expensive, wafers, this can lead to diametral cost effects avoided at this point.

3.1 Costs for Proof-of-Principle IBC Route

As a starting point, the proof-of-principle investigations regarding screen-printed boron-paste are chosen, as described in earlier work [2]. The fabrication of high-efficiency IBC cells was demonstrated on large-size wafers with active cell areas of 4 cm² (designated area, shaded busbars) and 243 cm² [3]. More details on properties of screen-printed boron-paste or process details can be found in the given references.

For “Junction Formation” and “Metallization”, full area deposition technologies (PECVD, PVD) have been used in combination with wet-chemical based mask-and-etch processes. These involve multiple steps, a number of tools and therefore result in a high process complexity. When translated into a virtual solar cell plant via SCost calculations, this also shows high fabrication costs.

To set the goals for further research, different options are possible. One could increase the mean efficiency of finished devices, such that they compensate the additional costs, for example with variations of the employed geometries. We will show, why this is not always an option, when considering a viable reference technology. Another way is to alternate the fabrication sequence such that efficiencies are increased or at least stable, while fabrication costs are reduced.

Both ways can be pursued with a wealth of options. We show in the following, how a cost-driven research strategy can help to identify those who can compete on a level of industrial feasibility.

3.2 PERC Reference Process

We implement a PERC fabrication sequence simplified in the same fashion for SCost as above, based on published work from our institute [9] for accessibility. We chose this cell type as a reference technology,

1 As mentioned before, this way the results are not directly transferable to (highly specific) transition processes for existing plants, but are more general.

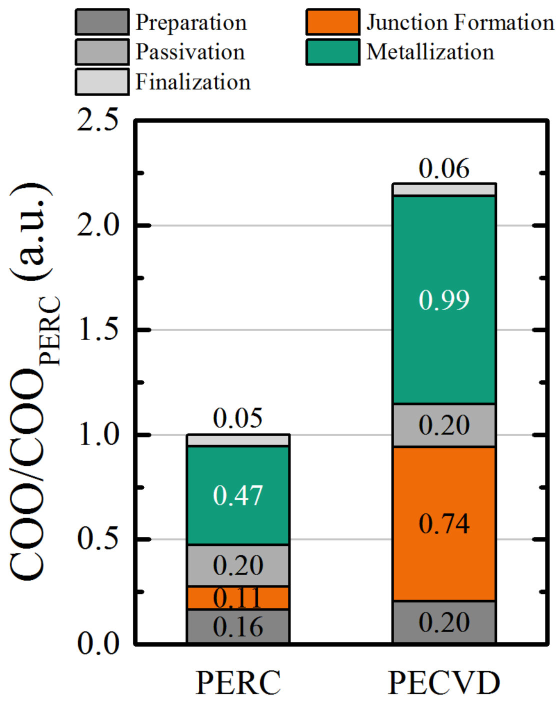

Figure 2: A normalized cost distribution is given for a *p*-type Cz PERC LCO reference process and the research oriented approach, as presented in last year’s paper [2], translated into an industrial fabrication plant. Major increases are found for “Junction Formation” and “Metallization” due to the high number of mask-and-etch steps. Different strategies to reduce these contributions are given in the text.

although the dominant fabrication route is still the Al-BSF solar cell. Nevertheless, more and more manufacturers are changing to or installing new capacity for PERC. The comparison between PERC and IBC routes might therefore be more relevant, but as mentioned above arbitrarily limits the applicability of the results.

When comparing both fabrication routes, we group fabrication steps into the generalized framework. We normalize the costs per piece to the PERC sequence, as explained above. Again, this does not include wafer costs or a scaling to the output power of the device. The result is shown in Fig. 2.

We develop six different IBC routes as shown in Fig. 3, with a focus on different process steps for “Junction Formation” and “Metallization”. The details are given in the following section.

3.3 Alternative Process Steps for IBC Fabrication Routes

Other research groups have shown IBC process sequences based on sequential diffusion, where areas are also modified with mask-and-etch processes between several high-temperature steps [12]. As full process sequences are rarely disclosed, we compare the publications of different groups and make some educated guesses to derive a fabrication sequence for implementation in SCost. Such routes have shown very high conversion efficiencies of up to 24.4 % for a silicon homojunction [13, 14] and are therefore highly justified especially in a research context. Considering a cost calculation with current prices however, an industrial

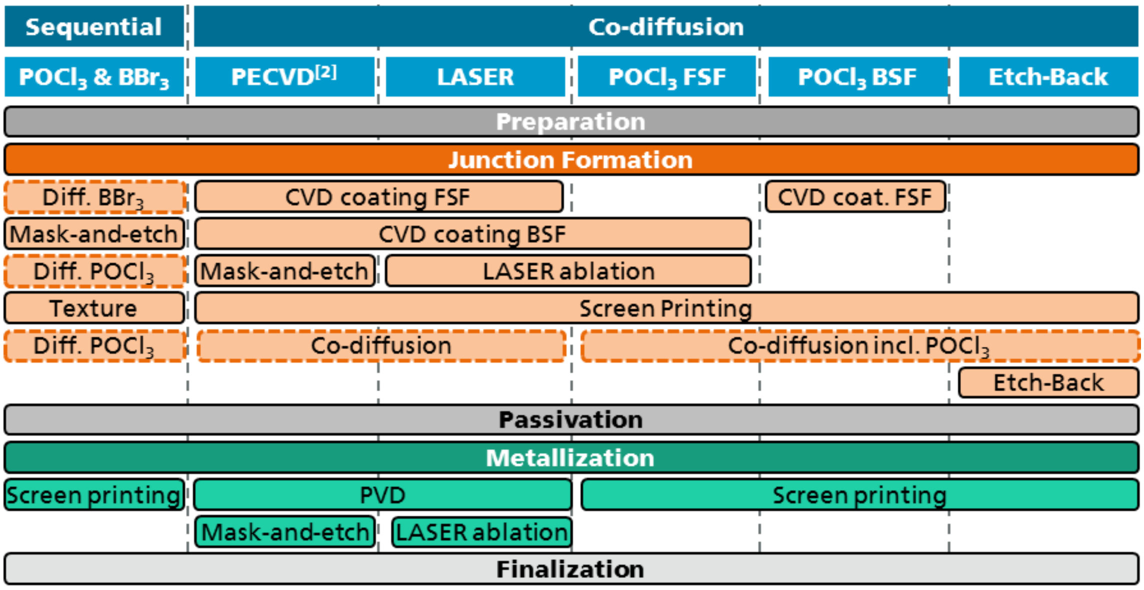

Figure 3: Different combinations of process options for IBC cell fabrication are shown. Orange (dashed) boxes indicate high-temperature steps. Details for processes are given in the text, as well as the calculated COO.

implementation is questionable, as shown below. This of course changes, if new tools or materials are introduced and scaled for mass market fabrication, which cannot be accounted for in this paper.

The sequential diffusion might offer some benefits, like improved gettering of defects, but requires multiple high-temperature steps, which are cost-intensive and therefore increase the "Junction Formation" costs. To effectively avoid multiple high-temperature processes, simultaneous "co-diffusion" of several dopants has been introduced in other work. This is enabled with a combination of different doping sources, *e.g.* solid CVD coatings (structured or full-area), gaseous precursors ($POCl_3$) or printed sol-gels. All the other process sequences incorporate such a diffusion approach, to reduce the increased "Junction Formation" cost in relation to the PERC process.

A way to avoid mask-and-etch steps, the other factor severely increasing the cost in the proof-of-principle process sequence, is direct structuring, *e.g.* with LASER ablation or printed chemistry [15]. The combination with co-diffusion drastically reduces the fabrication costs and is shown below to be the key advantage over sequential diffusion. To reduce the costs of "Metallization", structured screen printing of metal pastes is a suitable choice. For "Junction Formation", the formerly established screen-printable boron-doping paste offers the unique possibility of structured application and minimal process steps in combination with gaseous precursors.

3.4 Alternative IBC Routes

In the following, we describe the six IBC routes addressed in this work and their process details. The results of the SCost implementation can be found in Fig. 4, sorted by their (normalized) COO. They will be discussed in this order in the following. In contrast to Fig. 2, where CVD coatings were applied via PECVD, we additionally show a similar process there, which only substitutes PECVD for APCVD. While APCVD is a cheaper process than PECVD, this does only lead to a minor cost reduction for the "Junction Formation" as its effect is diminished due to the many other involved steps at this point. The following variations are nevertheless based upon APCVD, if coatings are implemented.

The implementation of a sequential diffusion shows a significant cost contribution of "Junction Formation" due to several high-temperature steps. As texturing of the front side is done later, within the process sequence (see Fig. 3), a part of the cost is shifted from "Preparation" to "Junction Formation" in our description.

The "LASER" termed variation demonstrates alternative structuring of CVD and PVD layers with LASER ablation. Given that cell performance is not constrained, this displays an effective way to reduce the costs down to a mere 20 % premium compared to the PERC process. The effect is larger in the "Metallization" costs, as less steps are involved overall (*cf.* PECVD vs APCVD above). If metallization is realized by one screen printing step instead (not shown), some additional costs can be saved (~15 % premium), while also reducing the number of process steps. For this, we assume a single Ag metallization paste for both polarities. All other process routes have been calculated with screen-printed metallization (see Fig. 3).

With the introduction of a gaseous precursor ($POCl_3$) as dopant source for front side doping instead of a CVD source ("$POCl_3$ FSF"), additional costs can be saved without increasing complexity and reasonably expecting better passivation properties, as shown in earlier work [16]. This change is in principle, decoupled from other process parameters, which has also been shown. It is therefore a very suitable and promising approach for cost-effective IBC fabrication and one of the objectives for the derived research strategy.

If the gaseous precursor is instead used for the back surface field doping ("$POCl_3$ BSF") the process is cheaper, as a screen-printed boron-paste can be additively applied on a substrate as a pattern, saving one additional step compared to the "$POCl_3$ FSF" approach. From a technological point of view, the process route becomes more complex, as some interdependencies between the rear side dopings exist in such a setup. This is not covered in the COO calculations, but has to be kept in

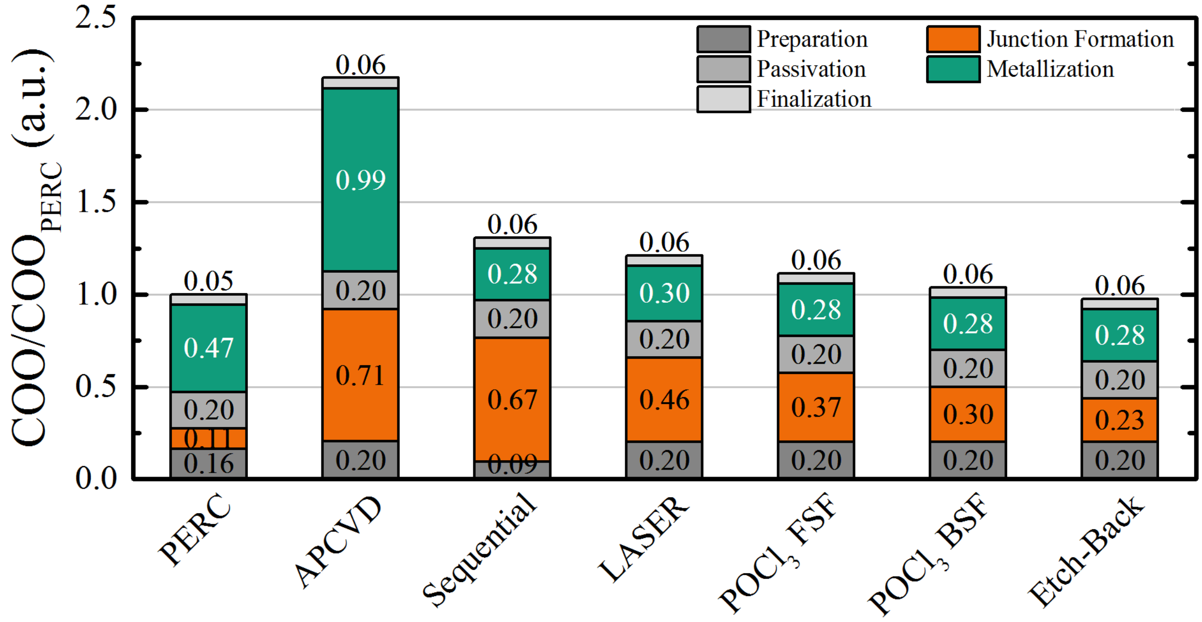

Figure 4: A number of different variations in the process chain are shown with the resulting costs per piece (no wafer costs, no scaling to output power) normalized to the PERC reference route. The main differences are realized in "Junction Formation" and "Metallization". while the other contributions remain similar for all routes.

mind for further decisions.

If no CVD dopant source is used at all, the front and rear side are similarly doped by a gaseous precursor. In such a case, a front side etch-back should be introduced to satisfy the different demands for front- and rear side Phosphorus dopings ("Etch-Back"). This does not change the total number of process steps, but shifts the cost contribution to a wet-chemical process instead, which may be even cheaper with a suitable setup according to our calculations.

As can be seen from Fig. 4, the costs for the last three fabrication routes are close to unity, when normalized to the PERC reference process. We will discuss the conclusions and the thereof derived research strategy in the next section.

4 RESULTS AND DISCUSSIONS

With the normalized COO values, one can now estimate, simulate or test the cell efficiencies of the displayed fabrication routes for a complete comparison. Experimental results of large sample sizes offer the most reliable reasoning for practical business decisions. The use of simulations is highly dependent on the quality, reliability and applicability of input parameters. Where possible this should be done with supporting experiments as closely to the final solar cells as possible. A pure estimation of achievable efficiency should only be used for a first impression and inherently offers large uncertainties, rendering quantitative comparisons impossible.

Lacking experimental results, we choose a different way for the interpretation of the obtained figures. As derived earlier, we relate the change in normalized COO to the solar cell efficiency to estimate a suitable efficiency difference. This number is then used to deduce a decision, which fabrication routes should be taken into consideration for a cost-driven research strategy. The results are shown in Fig. 5. As the efficiency for the reference technology has a quite significant impact, we show three different assumptions from 21 % to 22 %.

Unsurprisingly, the "APCVD" route has to be considered not-feasible for industrial fabrication as it has been derived from a proof-of-principle investigation.

We find that a sequential diffusion needs to surpass a PERC efficiency by more than 6 $\%_{abs}$, based on our calculations and current market prices. Such an advantage has so far never been shown. As mentioned earlier, these calculations do not include wafer prices or scaling of area proportional costs in later fabrication stages. Current *n*-type Cz wafer prices exceed the *p*-type Cz wafer price remarkably and we do not expect the scaling reductions to cover those. Summarizing all these

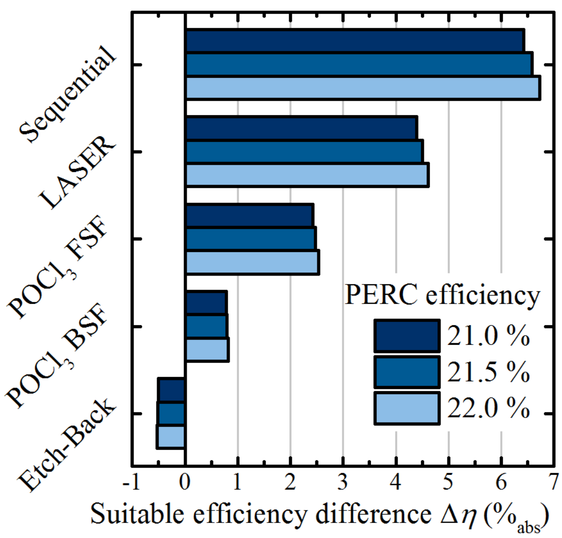

Figure 5: Suitable efficiency difference with respect to different PERC efficiencies based on COO calculation.

aspects makes the sequential diffusion very unlikely for industrially feasible fabrication.

The "LASER" process route, based on thermal co-diffusion, but laser structuring of full area APCVD and PVD depositions, is significantly cheaper than the sequential diffusion, but still requires a huge efficiency increase for parity with a PERC fabrication route. Although one could argue about scaling effects and other benefits, we discard this approach for now, given the high uncertainties and the significant amount of needed improvement. We instead address the co-diffusion setups, with a gaseous dopant source.

The most expensive process flow here ("$POCl_3$ FSF") needs an efficiency improvement of some percent relative to the PERC solar cells, to allow industrially feasible fabrication. This is done via co-diffusion from three different dopant sources, simultaneously driven into the wafer. These decoupled sources make for a high tunability of the fabrication process and should therefore be addressed in future research.

The two more sophisticated process routes of this kind are even closer in their costs to the PERC reference process. It should hence be aimed at trying to solve the inherent challenges of these routes, to maximize the gap between these routes and the PERC process in the value based cost of ownership, to cover for the (volatile, but momentarily) increased wafer price. Any additional efficiency gain is still desirable for additional area-related scaling cost effects.

5 CONCLUSIONS AND OUTLOOK

The herein derived calculations imply that in the near term, only the introduction of co-diffusion offers substantial cost reduction potential towards industrially feasible routes for IBC cell fabrication. Additionally, the use of screen-printed boron-doping paste is shown to close the gap towards the reference technology, due to its unique properties, when used as a simultaneous dopant source and barrier in a co-diffusion setup.

Consequently, we focus our ongoing research on the establishment of lean co-diffusion processes utilizing screen-printed boron-doping paste and the involved challenges of gaseous and solid dopant sources. Based on the experimental results, the derived research strategy aims at the most promising fabrication route for industrially feasible solar cell production.

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