Towards industrial poly-silicon contacted solar cells with efficiencies above 26%

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Abstract - We present a detailed loss analysis of a 24.8% large-area n-type poly-silicon-contacted "TOPCon" cell manufactured in an industrial pilot-line. The results clearly show that the largest electrical losses arise from the boron-diffused front surface, while the key optical losses are due to parasitic absorption in the poly-silicon layer and reflection from the front fingers. Subsequent modifications to the cell process included thinner fingers and re-optimised boron diffusions on the front side, and thinner poly-silicon layers on the rear side. These changes led to increased device efficiencies of 25.4% and 25.7%. Further modelling indicates that efficiencies well above 26% are achievable with industrially-viable fabrication methods, especially if the front contacts can be made thinner and passivated with localised p+ poly-silicon, and if the bulk lifetime can be further improved.

Introduction

Doped poly-silicon passivating contacts have emerged as a key technology for the next generation of industrial crystalline silicon solar cells beyond the current industry-standard p-type PERC cells. Their outstanding surface passivation and low contact resistance have enabled very high efficiencies in the laboratory [1, 2], whilst their high compatibility with existing production technologies has led to many PV manufacturers trialling this technology in pilot lines, with several already moving to mass production. Jinko Solar, for example, have already installed 16GW of manufacturing capacity for poly-silicon contacted n-type cells, with a further 16GW planned [3].

To date, the industrialisation of poly-silicon contacts has been limited to the original "TOPCon" cell design – n-type cells with a full-area n+ doped poly-Si contact on the rear, and a boron-diffused p+ junction on the front. Large-area TOPCon cells fabricated in industrial settings have achieved multiple efficiency records over the past few years, including, for example, 24.8% in July 2020, 25.4% in October 2021 and 25.7% in April 2022 by Jinko Solar [4]. However, despite this rapid progress, identifying the best pathways to achieve above 26% in mass production with poly-silicon contacts remains an open challenge, and may require alternatives to the standard n-type TOPCon structure. Poly-silicon contacted cells also face stiff competition from silicon heterojunction technologies, which have similarly demonstrated their potential for very high efficiency in mass production.

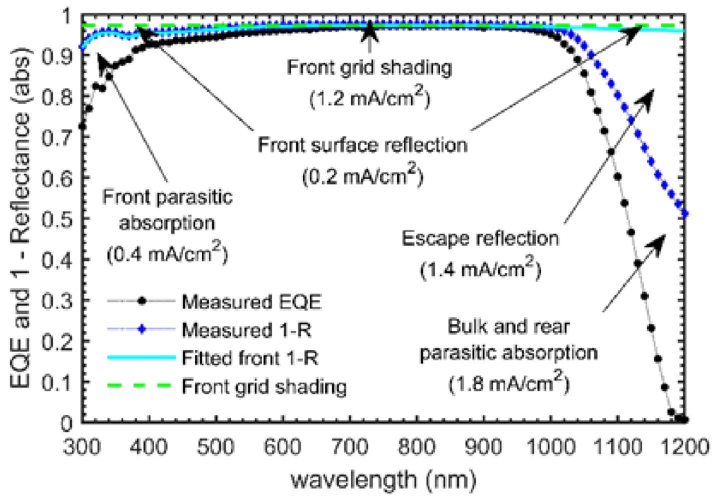

Figure 1: Optical loss analysis for the 24.8% TOPCon cell, expressed in terms of reductions in the short-circuit current density J_{SC} (mA/cm²).

In this work, we firstly present detailed power loss analyses of recent record cells produced at Jinko Solar, using 3-dimensional Quokka [5] simulations based on measured, industrially realistic input parameters. We briefly describe some of the process improvements that were implemented in order to reduce these losses and advance from 24.8% to 25.4% and then 25.7%. We then consider the improvements necessary to further increase beyond 26%, and show that efficiencies above 26.5% are in principle possible with industrial processing. Finally, we discuss the relative advantages and disadvantages of poly-silicon passivated cells in comparison to silicon heterojunction technology, with a focus on their feasibility for mass production at low cost.

Champion cell loss analysis

Figure 1 shows the origins of optical losses in the 24.8% champion cell [6], expressed in terms of reductions in the short-circuit current density J_{SC} (mA/cm^2). These optical losses were determined using measured EQE and reflectance data, coupled with optical modelling. They then allow us to estimate the electron-hole pair generation profile within the solar cell, which is used to determine the electrical (recombination and resistive) losses using 3-D Quokka 3 simulations, as shown in Figure 2 (top).

The primary optical losses in this device were found to be: parasitic absorption of infrared light at the rear poly-silicon contact and in the bulk; imperfect light-trapping of infrared light; and front grid shading. Front surface reflection and front parasitic absorption losses were relatively minor.

Figure 2 (top) shows the electrical losses arising from the various regions of the device. Note that the 'generated power' is the power due to electron-hole pair generation, determined after the optical losses are accounted for. The modelled efficiency (24.6%) is slightly lower than the measured efficiency for the champion cell (24.8%), due to the use of measured input parameters, rather than fitted parameters.

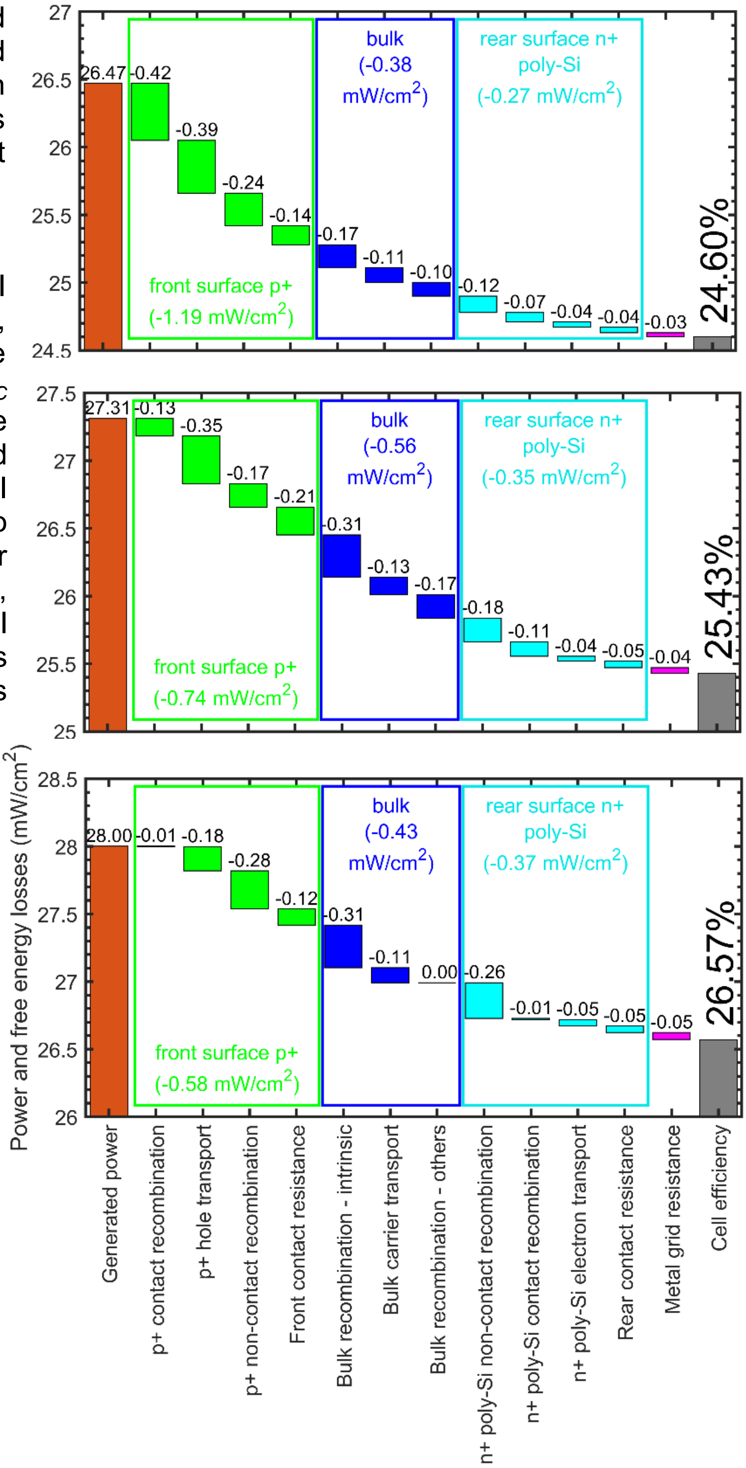

Figure 2: Electrical loss analysis, after accounting for optical losses, expressed in terms of power density loss (mW/cm²), for the 24.8% (modelled as 24.6%) champion cell (top), the 25.4% champion cell (middle), and the modelled 26.6% 'optimised' cell (bottom).

The three largest sources of electrical loss were all located at the front surface – recombination at the boron-diffused p+ contacts, resistive (transport) losses through the p+ region, and recombination at the non-contacted p+ regions. Intrinsic and extrinsic bulk recombination were less important. We found that recombination and resistive losses at the rear n+ poly-silicon contact were very small, and did not impact the device performance to a significant degree. This indicates that these poly-silicon contacts have the potential for even higher efficiencies, especially if the parasitic absorption within them can be reduced.

The results of this analysis guided several process changes at Jinko Solar. These included narrower fingers on the front side for reduced shading and recombination, narrower and heavier boron diffusions under the fingers, lighter boron diffusions between the fingers, and thinner poly-silicon layers at the rear for reduced parasitic absorption of infrared light. These improvements led to a 25.4% device, and more recently, with further reductions in the finger width, to a 25.7% cell. Figure 2 (middle) shows the estimated electrical losses for the 25.4% device. Clear improvements in the front side contact and non-contact recombination are evident. However, these improvements have made the device more sensitive to bulk and rear-side electrical losses.

Potential for >26% efficiency

Considering options for further improvements in device performance, we have also modelled an 'optimised' device, with ambitious but realistic values for recombination, resistance and metallisation parameters/geometries. Key changes include: reduced recombination currents under the front fingers through application of localised p+ poly-silicon contacts; removing bulk impurities and defects so that the bulk lifetime is determined by intrinsic recombination only; applying even narrower fingers on the front side for reduced shading and recombination; recombination currents at the metal contacts on the front and rear poly-silicon layers reduced to the same values as non-contacted regions; and optimisation of the wafer resistivity leading to the use of more lightly-doped wafers. These assumptions result in an efficiency of 26.6%, with the breakdown of electrical losses shown in Figure 2 (bottom). Note that the p+ contact recombination losses have been almost eliminated due to the application of p+ poly-silicon under the front fingers. The device parameters for this optimised cell are shown in Table 1 below, together with the measured parameters for the 24.8% champion cell for comparison.

Table 1: Device parameters for the 24.8% champion cell and the modelled 26.6% cell

Cell	V_{OC} (mV)	J_{SC} (mA/cm^2)	FF (%)
24.8% champion cell	715	41.6	83.4
26.6% modelled 'optimised' cell	738	42.4	85.0

Taken one at a time, the efficiency increments arising from each of these key changes are shown in Table 2 below, with the 25.4% device taken as the reference case. We note that the magnitude of these increments depends strongly on the order in which they are implemented, and we do not suggest that this is necessarily the order in which they would be implemented in practice. Nevertheless, even if only some of these goals can be achieved, or partially achieved, we believe that efficiencies well above 26% in production are feasible.

Table 2: Modelled efficiency increments with device improvements

Reference case	Poly-silicon under front fingers	Intrinsic bulk lifetime	Narrower front fingers	Reduced recombination at metal contacts	Wafer resistivity optimisation
25.4%	25.8%	26.0%	26.1%	26.3%	26.6%

We note that achieving narrower fingers on the front surface is an important feature in these devices. This not only reduces metal shading, but significantly reduces recombination losses for cases without p+ poly-silicon contacts under the front fingers. Achieving sufficiently narrow lines (down to 20 microns) with screen-printed contacts is challenging, but not impossible. Alternatively, electro-plated fingers based on seed layers could be a viable alternative method, as has been demonstrated recently on large-area poly-silicon contacted cells [7].

Discussion

It seems likely that the successor to the conventional PERC cell will be based on either doped poly-silicon contacts or amorphous silicon heterojunctions. Both have the potential to achieve above 26% efficiency with industry-compatible fabrication methods. However, there are some distinct differences between these two technologies. Firstly, heterojunctions have generally provided better surface passivation, leading to higher cell voltages. However, this advantage is likely to be reduced as poly-silicon contacts improve, and especially if they can be applied to both polarity contacts, which is currently not the case in industrial TOPCon cells. This is reflected in the modelled V_{OC} of close to 740mV for the optimised cell presented above.

On the other hand, the much greater transparency of the boron-doped front surface, compared to the amorphous silicon/TCO stack in a heterojunction cell, is a distinct advantage for poly-silicon devices, leading to significantly higher cell currents. However, this gain is partly offset by parasitic absorption in the poly-silicon layer on the rear side, and is further reduced after encapsulation. We also note that alternative TCO's with greater transparency are under very active development [ref].

The higher processing temperatures in the poly-silicon route also create some advantages. They enable extremely effective impurity gettering by both n+ and p+ poly-silicon films [8], which helps to reduce the impact of impurities on the bulk lifetime, increasing the fraction of an ingot that is suitable for high efficiency cells. Whilst this is helpful for n-type wafers, it is even more important for p-type wafers, and may enable alternatives to the standard n-type TOPCon architecture to be considered. The firing of screen-printed contacts also enables hydrogenation of bulk defects, such as oxygen-related defects. Finally, poly-silicon contacts require similar fabrication tools as the current PERC lines, whereas heterojunction technology requires mostly new infrastructure, with higher capital costs – although these could fall significantly if produced at very large scale.

Conclusions

Detailed loss analysis of a champion 24.8% large-area n-type TOPCon solar cell revealed significant electrical losses due to recombination and resistance at the front surface, and optical losses due to parasitic absorption in the rear poly-silicon contact and front grid shading. Several process improvements were implemented as a result, including narrower fingers on the front side, heavier and narrower boron diffusions under the fingers, and thinner poly-silicon layers at the rear for reduced parasitic absorption. These improvements led to a significant increase in performance, firstly to 25.4% and then 25.7%. Considering options for further improvements, including p+ poly-silicon under the front fingers, reduced bulk recombination, and even narrower fingers, we show that it should be possible to achieve efficiencies as high as 26.6% with the TOPCon architecture using industrially-compatible techniques.

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