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Towards >25% Efficiency of Passivating-Contact Solar Cells in Mass Production

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Abstract. We report efficiencies of >24% being consistently achieved in mass-production of passivating-contact solar cells. Furthermore, the certified efficiency of cells from our pilot line has reached 25.3% with 730 mV open-circuit voltage. An analysis of the cell performance, including simulations, shows that the cells' rear-side is nearly ideal, while there remains potential for further optimization of the front emitter and passivation.

Keywords: Silicon Solar Cells, Passivating Contacts, Mass Production

1. Introduction

The higher efficiencies possible with passivating-contact cell concepts such as tunnel-oxide passivated contact (TOPCon) [1] and heterojunction (HJT) are a major reason for the shift towards these technologies as PERC nears the ends of its efficiency roadmap. Importantly, cells employing passivating contacts are also well-positioned for a future including tandem-on-silicon cell concepts, e.g. with perovskite top cell [2], or also interdigitated back contact (IBC) cells.

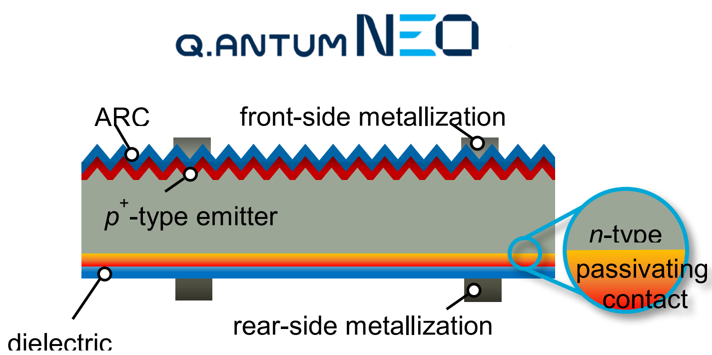

Figure 1. Cross-section diagram representing the Q.antum Neo n-type solar cell with passivating contact.

At Qcells, we have developed the Q.antum Neo technology, which is a n-type cell with passivating-contact technology (Fig. 1). The cell has a p+, boron-doped emitter on the front side, and has the n-type passivating contact on the rear. Qcells' passivating-contact technology benefits from sharing a number of process similarities to PERC, including wet chemistry and diffusion processes, dielectric passivation, and screen-print metallization with high temperature firing. As most steps in our passivating-contact cell process flow have some analogy in PERC, except for a n-polysilicon layer on the rear, this speeds up the learning for commercial mass production. Here, we report on our successes with developing and ramping passivating-contact cell technology in mass production.

2. Development of Passivating Contacts for Mass Production

Figure 2. Simplified process flow of Q.antum Neo solar cell.

The process flow that we have developed for passivating-contact cells is quite lean and cost-effective. The overall process flow from the raw wafer to finished cell is outlined in Fig. 2. The main steps include: wafer texturing, boron emitter diffusion, edge isolation, deposition of the passivating contact, cleaning, dielectrics deposition, and metallization. Notably, there are only 2 additional key steps, compared to PERC: the passivating contact and cleaning. Thus, it can be a simple and low-cost cell technology that is competitive to PERC, particularly when considering the significantly higher cell efficiencies.

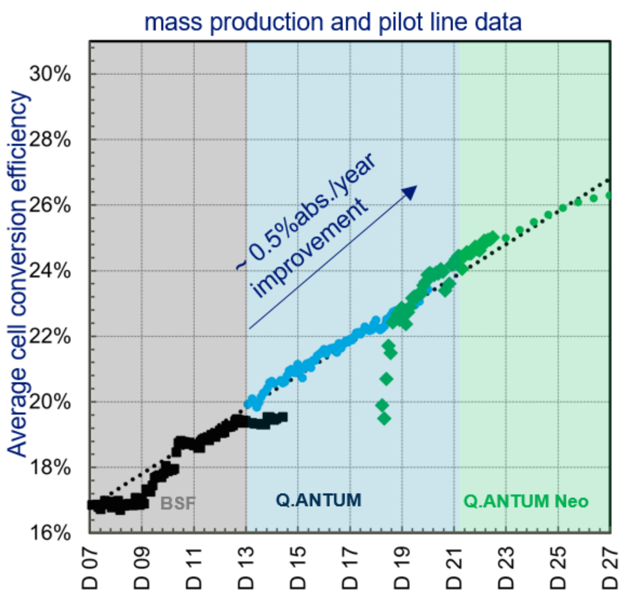

Figure 3. Learning curve of cell efficiency over time at Qcells, showing approx. 0.5%abs yearly improvement.

In the initial phase of developing passivating-contact technology for large-volume production, we achieved a rapid learning rate, with >1% efficiency increase per year during 2019 and 2020 in our pilot line (Fig. 3). Approximately 0.5% per year efficiency gain is more typical for cell technologies reaching maturity, as observed previously for Al-BSF and PERC [3]. As PERC is already approaching its maximum efficiency potential, it is difficult there to maintain a 0.5% annual learning rate, but by switching to passivating-contact cells we expect that such efficiency increases can continue for several additional years.

Since the beginning of 2022, the cell efficiency is consistently >24%. The distribution of cell efficiencies is non-normal with a tail towards lower efficiencies (Fig. 4), as is typical in production. Nonetheless, the distribution is fairly narrow, around +/- 0.2%abs. This leads to a good yield, so that there is only a negligible fraction of cells with low efficiency.

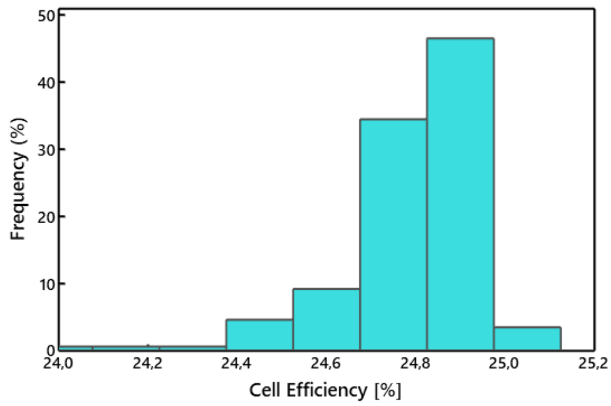

Figure 4. Histogram of cell efficiency data from April 2023, showing high cell efficiencies and narrow distribution.

Cells in our pilot line have now demonstrated up to 25.3% efficiency, with open-circuit voltage (Voc) up to 730 mV. The certified measurement was done by ISFH and the I-V data plotted in Fig. 5. The Voc is even slightly higher than the 724 mV measured for the record 25.8% TOPCon lab cell from Fraunhofer ISE [1]. Note that ISE's cell was measured with a designated illumination area, whereas our result includes the full area of the cell.

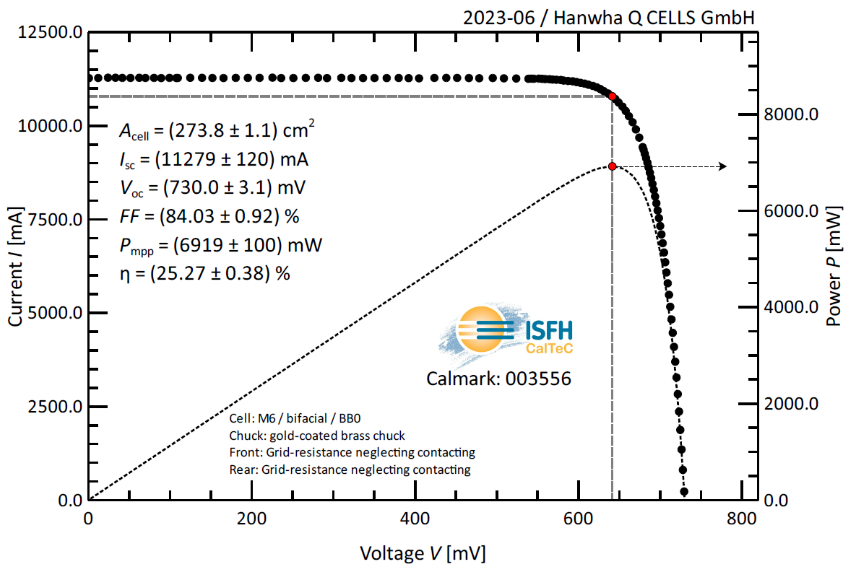

Figure 5. Certified I-V measurement of Q.antum NEO cell from pilot line with 25.3% efficiency.

The cell's short-circuit current density (Jsc) is not that high, mainly as the antireflection coating (ARC) was optimized for light incident through module glass (as is typical in production) rather than from air. The cell is made with M6-size n-Cz wafers (area = 274.2 cm²), with wafer resistivity in the range 0.3-2.1 Ohm-cm, and post-processing thickness of approx. 150 µm. The pilot-line cells, including the certified record cell, all have industrial screen-print metallization and firing.

A key advance in achieving the high cell voltage was reducing the recombination from the cells' front side. This was accomplished by: firstly, engineering the front metal contact to decrease its recombination and improve its contact to silicon; secondly and in concert, the optimization of the emitter, including its dopant profile and surface passivation.

Modules developed using Q.antum Neo passivating-contact cells also exhibit excellent efficiencies. For example, a module with 132 half-cells (M6 wafer) was built, and achieved 22.6% efficiency, based on its total front area. The normalized I-V curve of this module is shown in Fig. 6. Even higher performance is expected in the near future. With foreseeable improvements at the cell- and module-level, we expect to soon have module efficiencies over 23%.

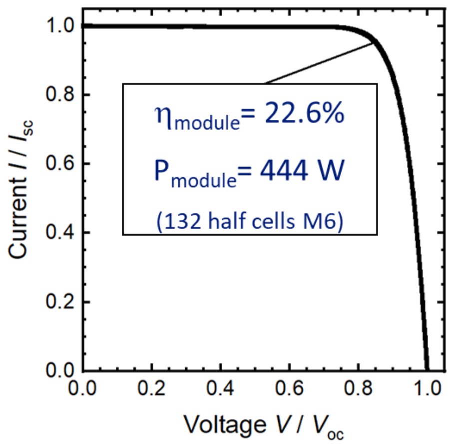

Figure 6. Performance of Q.Tron module with 132 M6-size half-cells, using Q.antum Neo technology.

3. Loss Analysis and Further Efficiency Potential

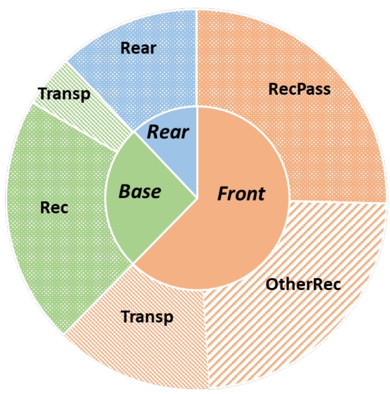

Figure 7. Energy loss analysis of 25.3% TOPCon cell.

An analysis of the energy loss channels for the cells was done, aided by Quokka2 (Fig. 3). It shows that the cells' rear-side is nearly perfect; this is not surprising considering that the n-polysilicon passivation stack achieves $J_{0,pass}$ ~ 2 fA/cm², calculated from QSSPC measurements on test wafers.

Interestingly, recombination from the bulk (Rec,base) constitutes the second largest individual contribution to energy loss. This despite assuming a nearly perfect wafer for the simulation. Which highlights how much the other loss terms have been suppressed, so that the intrinsic recombination from the bulk (due to Auger) takes a significant role.

As the front side contributes the largest share of energy loss, improvements here will be crucial to further raising the cell efficiency. In particular, looking at recombination from the emitter and its surface passivation (RecPass,front), including the Auger term from doping.

We calculate that further optimization of the emitter could decrease $J_{0,e}$ up to 5 fA/cm², but obviously this must be done without negative impacts on $J_{0,met}$ (front metal recombination) or transport/resistance. Via improvements to the emitter and also cell optics, an efficiency exceeding 26% should be reachable. Thus, we are optimistic about the future cell efficiencies that can be obtained with our passivating-contact technology.

Data availability statement

Requests for supporting data can be made to the authors. Due to legal and confidentiality constraints, not all data may be made available by Qcells.

Author contributions

All authors contributed as a team to the results in this publication. B.G. Lee, F. Stenzel and J. Müller outlined the paper and put together the figures. B.G. Lee wrote the manuscript.

Competing interests

The authors declare no competing interests.

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