The Q-Cells research line: a development tool for new silicon solar cell technologies

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ABSTRACT

This paper presents the Q-Cells research line (RL) as a core of the Reiner Lemoine Research Centre, including the technical set-up, the organization of the operation and current results of cell concepts processed in the RL on a regular basis. Trends of cell parameters for those processes are shown, and a focus is presented regarding the results of our high-efficiency cell concepts for multi- and monocyrstalline material processed in the RL with stabilized record efficiencies of 18.4% and 19.2%, respectively. In addition, we discuss the process flow and the results of a monitoring procedure that is used to check the rear-side passivation quality of the company's equipment. Results of our current passivation stack show a surface recombination velocity of below $S_{rear} < 10$cm/s, well suited to fabricating p-type Si solar cells with efficiencies above 20%.

Introduction

The production capacity of the photovoltaic industry has grown tremendously during the last few years with annual growth rates of around 30% [1]. New capacity can be built either from state-of-the-art technology or from new technologies with an increased ramp-up risk. A trade-off between speed and risk minimization is needed to keep pace with the tremendous developments encountered during the race for higher cell efficiencies, higher throughput, and lower costs per cell and per Wp respectively. The PV roadmap for c-Si gives an idea of the challenges to be expected in the years to come [2]. Thus, a tool is needed to close the gap between development at laboratory level for evolutionary and revolutionary new technologies and their fast implementation in the mass production environment.

Q-Cells has been producing solar cells for more then 10 years and has been ranked in the Top 10 Si solar cell producers for several years. Since 2010, the company has also been processing these solar cells into modules under its own brand name. These modules are consequently installed in solar systems, at utility scale as well as in rooftop installations of residential and commercial scale. Thus, Q-Cells is widening its scope from a cell producer to a provider of PV solutions. Much experience in mass production and automation, a high quality level during production and testing, as well as the availability of leading-edge technologies have been and will continue to be the basis for satisfying the demands of customers. In response to this, in 2007 Q-Cells built a research centre that was intended to fit current and future needs of Si solar cell development, characterization, module and cell reliability as well as equipment evaluation. The Reiner Lemoine Research Centre (RC) officially opened in summer 2008. It took about 12 months from the initial idea in summer 2006, to first equipment move-in onto the shop floor and a further six months to the start of processing in December 2007. The RL has been in regular operation since January 2008.

Conception of the Q-Cells research line

The RL is installed in an at-grade industrial building with a factory work floor of about 3000m^2 at the Q-Cells "Solar Valley" Campus in Bitterfeld-Wolfen, Germany as shown in Fig. 1.

The chemistry supply and disposal area is situated on one side of the building. Supply of H_2, N_2, SiH_4, O_2, KOH, DI-water, compressed air and cooling water, as well as the disposal of rinsing water and used chemicals, is connected to the Q-Cells bulk supply system. Supply and disposal of special chemicals is provided in Intermediate Bulk Containers (IBCs). A separated room for gases enables a centralized connection of special gases to the RL equipment. The piping to the point of use is fixed at the ceiling. This set-up enabled a fast and cost optimized building, installation and hook-up phase, and gives flexibility for future installations. This flexibility is vital to enable quick reaction to new machine trends. Fixed lanes for

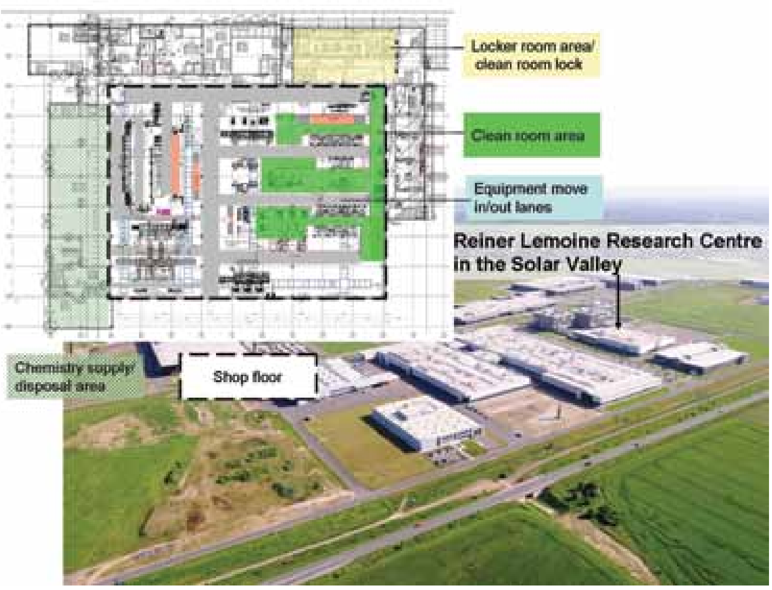

Figure 1. Layout of the Q-Cells RL with indicated main functional areas and view of the Q-Cells location in the Solar Valley area.

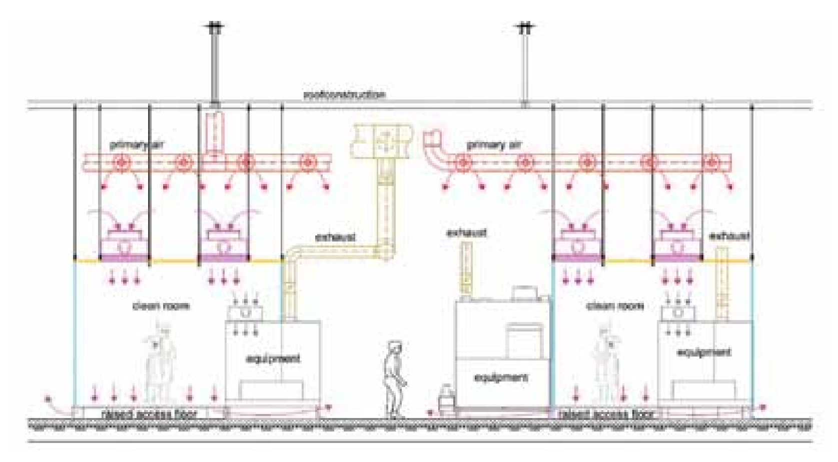

Figure 2. Schematic of the construction of the 'room-in-room' cleanroom concept applied in the Q-Cells research line [2].

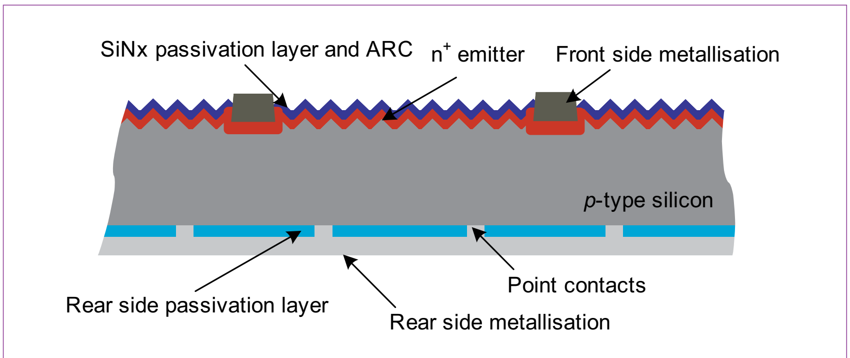

Figure 3. Schematic cross-section of the solar cell design with passivated front and rear (not to scale).

equipment move-in and move-out were defined to fulfil this requirement, as shown in Fig. 1. The RL can be used for the pre-production evaluation of new machine concepts and equipment types.

Throughput equipment was selected to enable experiments as well as production of standard multi- and monocrystalline Al-BSF-cells, back contact cell concepts as well as cell concepts with new front- and back-side passivation technologies [3–5]. A trade-off between processing small sized wafer batches and batches of up to several thousand wafers was realized by installing in-line and batch processing equipment having either automated standard wafer carrier interfaces to enable compatibility with the Q-Cells fab environment or manual loading/unloading interfaces. The equipment consists of more then 20 different production like proto-type machines, partially automated for wet chemical processing, diffusion, oxidation, and annealing, PECVD, PVD, laser processing, screen printing and patterning.

A cleanroom area of 600m^2 (see Fig. 1) was integrated into the shop floor using a 'room-in-room' concept. Fig. 2 shows a schematic cross-section of the cleanroom. It is designed to maintain class M6 down to M3.5 at 0.5µm according to the process requirements. Using this concept, the whole shop floor can be held at a cleanroom level of M6.5 without the need for additional filter equipment.

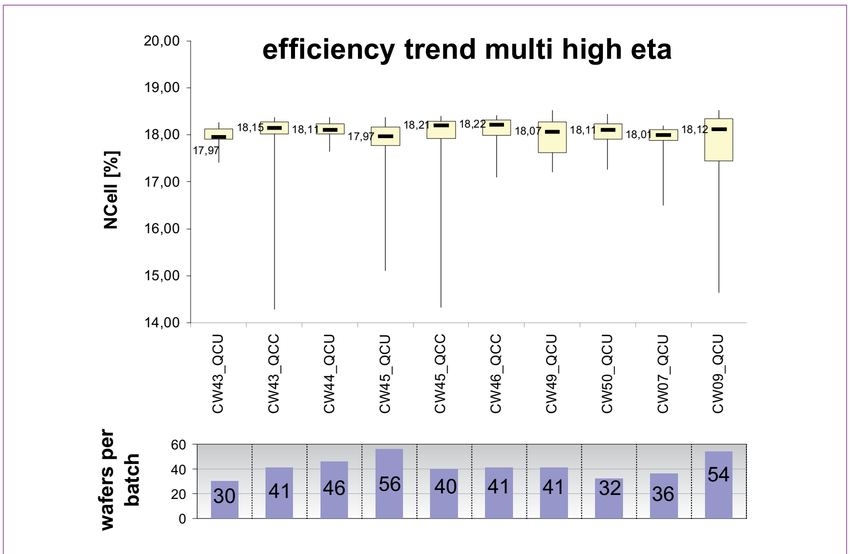

Figure 4. Trend of the high efficiency multi batches processed in the RL during week 43 in 2010 and week 9 in 2011. Each batch contains between 30 and 60 wafers.

Organizational set up within Q-Cells

Organizing a strong operation RL was a key success factor. The strong mass production manufacturing competence of Q-Cells was capitalized using synergies and by gaining experienced production line staff to join the RL organization. These employees and a core team of engineers and technicians have been the backbone of the RL organization together with newly hired skilled workers. The responsibilities in processing and engineering respectively are shared between the front end of line (FEOL – processing until ARC) and back end of line (BEOL – metallization process + test). Experiments, base line monitoring processes, pre-production, and production orders have been processed since spring 2008 on a regular two-shift work base from Monday to Friday. Round-the-clock shift work was tested during a six month period and can be introduced on demand after clearance with the local Q-Cells workers council. This enables high flexibility during the introduction of new products with reduced impact on the standard production lines.

Maintenance and facility management support as well as IT and logistics services are delivered from the Q-Cells production organization and were not built up within the organization of the RL. Besides the cost savings, the experience and know-how, equipment, service contracts, cleaning services and other synergies can be implemented as a 24/7 support, ensuring a lean RL organization that is focused on research and development activities.

Results

Processing different pilot and monitoring processes as well as experiments in parallel, standard procedure in semiconductor manufacturing is a new way of working in the PV industry. A tight planning procedure, clearly documented recipes, well-defined supply notes for the process of record and standard operating procedures enable this high flexibility, which is carried out by RL's operational team.

A pilot series fabrication of high-efficiency *p*-type Si solar cells on a regular basis both on 156 × 156mm² sized mono- and multicrystalline Si wafers is one of the processes maintained in the RL. The pilot series is based on technological features like low-temperature surface passivation on both sides with local contacts on the rear and fine line-printed grid metallization in combination with plating at the front (see in Fig. 3).

A typical trend of high-efficiency multi batches processed during a period of several weeks is shown in Fig. 4. The box plot indicates the median values of the efficiencies of the batches together with minimum, maximum, upper and lower quartiles. It is important to note that the processed wafers in each batch represent the distribution of whole Si bricks. Thus, the spread also includes the defect rich material from the bottom and top of the brick. The batch sizes vary between 30 and 60 wafers as indicated beneath the diagram. The different batches comprise Si wafers based on different feedstocks (without additional light-induced degradation).

Figs. 5 and 6 show the *I-V* characteristic (total area measurement) of high-efficiency mono- and multicrystalline Si solar cells processed in our RL. The data of the mono and multi cells are independently confirmed by Fraunhofer ISE CalLab. The cell area of the monocrystalline cell is 239.0cm² and the multi cell 243.4cm², respectively.

High current densities of 38.4mA/cm² (mono) and 36.8mA/cm² (multi) are reached due to the optimized front side metallization, improved infra-red light trapping and efficient current collection due to the passivating dielectric layer on the rear side and the lowly-doped emitter as shown in Fig. 3. The combination of the emitter and the passivated rear side enables open circuit voltages of 644mV on monocrystalline Si (after light-induced degradation). The corresponding efficiency reaches 19.5% before and 19.2% after degradation respectively as indicated in Fig. 5 [6].

Similar combinations of emitter and passivation stack features result in open circuit voltages of 647mV on multicrystalline poly-Si wafers as shown in Fig. 6. A more detailed analysis of these results compared to a standard BSF cell design can be found in [7].

We link the cell development in our RL close to our module technology by finishing the processed cells into large area modules. This enables an efficient technological development for maximum output power at module level. With an independently confirmed module efficiency of 17.84% on an aperture area of 1.5m², we reported on a new multicrystalline module world record [8]. We realized a 60-cell module with a power output of 268Wp at STC using multicrystalline cells with rear-side passivation.

Monitoring processes are necessary in a research line environment to ensure a high level of quality and to guarantee a fast failure analysis in case of deviations. Such monitoring runs in parallel to the cell production in the RL to check the performance of single processing steps or sequences. In particular, for the cell design described in Fig. 3, we monitor the rear-side passivation scheme by lifetime samples and the surface passivation quality during the processing sequence of the solar cell. Fig. 7 describes the process flow of this lifetime monitoring using Boron-doped (resistivity ~ 10Ωcm) monocrystalline Cz Si wafers. We measure the lifetime by QSSPC method to detect the lifetime at different injection levels and by photoluminescence to evaluate the homogeneity of the passivation quality as shown in Fig. 8. We detect handling issues on the passivation quality especially after firing, such as tweezers or scratches; however, our optimized passivation stacks results in a surface recombination velocity of below S_{rear} < 10cm/s, which is well suited to fabricate *p*-type Si solar cells with efficiencies above 20%.

The discussed pilot process for multi material demonstrates typical average efficiencies about $1\%_{abs}$ above our standard

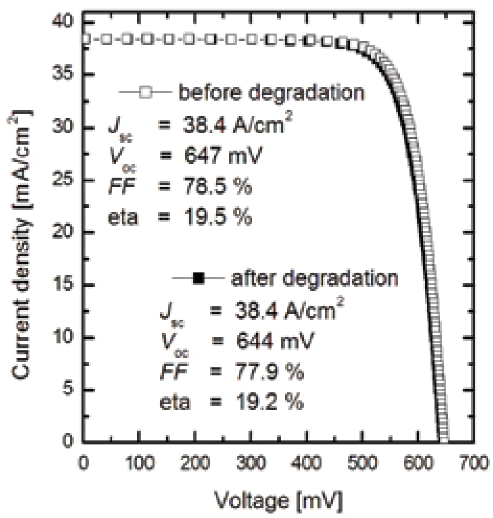

Figure 5. ***I-V*** **characteristic (total area measurement) of a 6" monocrystalline Si solar cell before and after light-induced degradation. The data are independently confirmed by Fraunhofer ISE CalLab.**

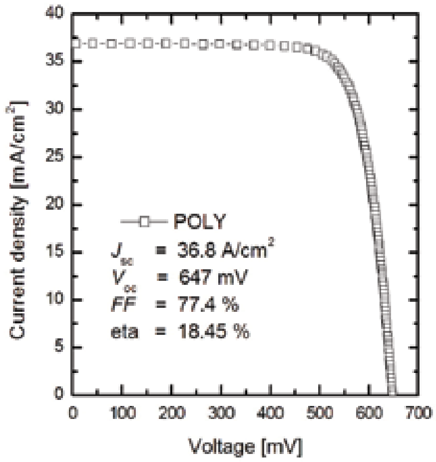

Figure 6. ***I-V*** **characteristic (total area measurement) of 6" multicrystalline Si solar cells using poly Si feed stock material (after light-induced degradation). The data are independently confirmed by Fraunhofer ISE CalLab.**

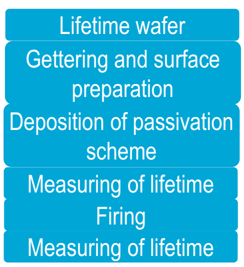

Figure 7. Process sequence to monitor the passivation quality of Q-Cells' rear side passivation scheme before and after a firing step.

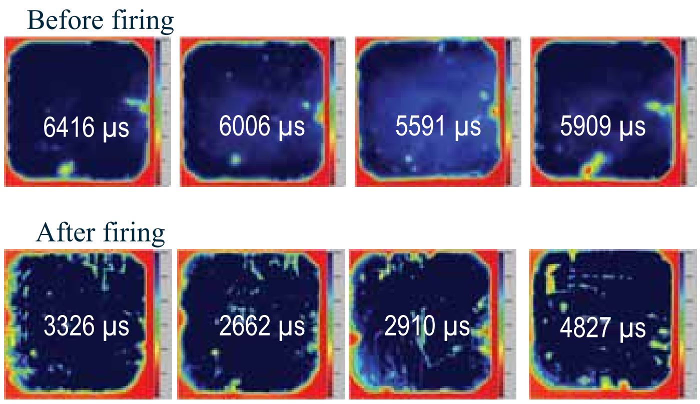

Figure 8. Photoluminescence images of lifetime monitoring wafers having our rear side passivation scheme on both wafer sides before and after a firing step. The effective lifetime is additionally quantified by QSSPC measurement at an injection level of $\Delta n = 5\times10^{14}cm^{-3}$.

BSF multi cell product. Some process features are therefore transferred into the production using this knowledge. The resulting mass production of ready cell concepts will ensure future technology leadership.

Summary

In this paper we presented the RL of the Q-Cells Reiner Lemoine Research centre as a development tool for Si-based high-efficiency solar cell concepts. The flexible design is well suited for current and future development requirements in order to satisfy the needs for fast transfer of new concepts into high volume production. High flexibility of the RL ensures fast reactions to current and future technology trends. Results of our high-efficiency cell concepts for multi and for mono material with record efficiencies of 18.4% and 19.2% respectively, as well as process flows and results of a monitoring procedure were discussed. Results of our current passivation stack show a surface recombination velocity of below $S_{rear} < 10cm/s$, which is well suited to fabricate p-type Si solar cells with efficiencies above 20%. Following our strategy to optimize our technology for maximum module output we reported on a new world record of multicrystalline large area module efficiency. The RL establishes itself as a powerful tool for fast process transfers into production and ensures in this way the sustainability of Q-Cells as a leading supplier of c-Si solar cells, PV modules and PV solutions.

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About the Authors

Markus Fischer received his Ph.D. in electrical engineering in 1997 from the University of Stuttgart. After working in the semiconductor industry for Siemens, Philips and NXP in different engineering and management functions he joined Q-Cells SE in 2007. The Q-Cells research line is part of his responsibility as director of R&D Processes.

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