Q.ANTUM – Q-CELLS NEXT GENERATION HIGH-POWER SILICON CELL & MODULE CONCEPT

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ABSTRACT: In this paper we report on our latest R&D cell and module results based on double-side contacted *p*-type Si solar cells characterised by a dielectric passivated rear surface and local point contacts – our so-called Q.ANTUM technology. In addition to our confirmed 19.5 % efficient world record multi-crystalline Si solar cell we present a new Q.ANTUM module with a world record energy conversion efficiency (ap) of 18.1 % based on 60 multi-crystalline cells. For *p*-type mono-crystalline Cz material we report on an independently confirmed cell efficiency of 20.2%. Furthermore, supported by R&D results Q-Cells decided to transfer the Q.ANTUM technology into pilot production in Thalheim, Germany. Finally, measurement results are reported demonstrating the maturity of our Q.ANTUM technology concerning reliability and secured energy yield.
Keywords: High-efficiency, Q.ANTUM, passivation, Q-Cells

1 INTRODUCTION

For a long period of time the design of commercially fabricated *p*-type Si solar cells hardly changed, whereas improvements of fabrication processes and production equipment contributed, and still contribute, to advanced cell performances. On the other hand, several high-efficiency cell structures are realized for mass production on *n*-type Si substrates as the back contacted cell by SunPower [1] and the HIT cell by Sanyo [2]. However, the *p*-type "Passivated Emitter and Rear Cell" PERC concept – which was one of the first high-efficiency cells realized in laboratories [3] and (with some additional high-efficiency features) still holds the world record with 25% efficiency on FZ Si [4] and 20.4 % on multi Si [5] – to our knowledge has not been realized in mass production so far. The cell design features a structure quite similar to the standard screen printed cell, with a *p*-type base and a full-area front side n^+-emitter. Thus this concept allows adapting most of its process steps from standard production lines. In contrast to the standard cell concept, the PERC structure implements a full area dielectric passivation layer on the rear with local openings to electrically contact the cell base with the rear metallisation.

Since the Q-Cells technological strategy is to follow the evolutionary cell and module development, our next step concerning the cell architecture is the replacement of the highly recombination active Al-BSF by a dielectric surface passivation layer while adapting most of the existing process technology. At the 1st Si PV conference in Freiburg this year we reported on R&D results of a high-efficiency *p*-type Si solar cell concept – our so-called Q.ANTUM technology. Median Q.ANTUM cell efficiencies on multi-crystalline (mc) Si batches of >18 % [6] and 19.5 % on mono-crystalline Si solar cells were reported [7]. Best achieved cell efficiencies on mc-Si were confirmed at 18.5 % resulting in a world record for a multi-crystalline module reaching 17.8 % (ap) efficiency [6]. Only two months later at the 2011 IEEE conference we reported on a multi-crystalline large area Si solar cell with an independently confirmed efficiency (total area) of 19.5 % [8]. Consequently, based on our Q.ANTUM technology Q-Cells holds the current world record on both multi-crystalline Si cells and modules [9].

In this paper we report on the latest results from R&D production of Q.ANTUM cells and modules in the Reiner-Lemoine Research Center. Using *p*-type multi-crystalline Si wafer material our R&D production lots reach median cell efficiencies of up to 18.8%. Based on these mc-Si cells we were able to break our own module world record by realizing an independently confirmed *new* world record module reaching an energy conversion efficiency (ap) of 18.1 %. For *p*-type mono-crystalline material we report on 20.0 % median efficiencies (19.6 % after light induced degradation) and an independently confirmed Q.ANTUM top cell efficiency of 20.2 %.

These results show and underline the maturity of the current stage of development of the Q.ANTUM technology in the R&D department at Q-Cells. We also report in this paper on the transfer of this technology from the Research Center into a pilot production line in Thalheim, Germany. Results of reliability tests and investigations that are needed to ensure consistently high and reliable energy yields for Q.ANTUM modules are shown.

2 RESEARCH CENTER EXPERIMENTALS

In our Research Center we have been conducting R&D on high-efficiency Q.ANTUM cells for several months now. The weekly production cycle that amounts to 100 – 500 cells enabled the rapid and effective development of the cell and its fabrication processes as well as a fast build-up of expertise to interconnect and encapsulate this new cells into modules. This amount of cells provides statistically relevant information and thus enables revealing sensitive process parameters and optimal settings. We process our R&D runs using in-line and batch-process equipment with throughput capacities suitable for mass production. The tool interconnections are either fully-automated standard wafer carrier interfaces or manual loading/unloading interfaces. In order to display representative efficiency distributions under mass production conditions, and to study the influence of wafer quality on the high-efficiency performance of our cell concept, we use material from all areas of the corresponding bricks or ingots. Thus, defect-rich material from the bottom and top of the bricks is also included in the batches and therefore reflected in the median cell results.

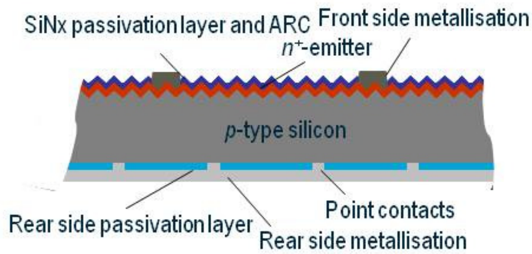

Figure 1: Schematic cross-section of the Q.ANTUM solar cell design with passivated rear (not to scale).

The fabrication process of the high-efficiency R&D Q.ANTUM cells is set up as follows. We texture 180 – 200 µm thick wafers using a standard isotropic inline-texturing process for mc-Si wafers and an alkaline batch-texture in the case of mono-crystalline material. We subsequently introduce a lowly-doped emitter by $POCl_3$ tube-diffusion. After wet-chemical edge isolation, we deposit the low-temperature dielectric surface passivation on front and rear. We use the laser-fired contact technology (LFC) [10] to realize the point contacts. Fig. 1 shows the cross-section of the Q.ANTUM cell concept.

3 RESEARCH CENTER RESULTS

3.1 R&D results of multi-crystalline Q.ANTUM cells

Our weekly R&D runs contain several mc-Si batches of 50–100 wafers. The results of the high-efficiency mc-Si batches processed during several weeks are shown in Figure 2. The box plots indicate the median values of the efficiency of the batches together with the minimum, maximum, and upper and lower quartiles (before light-induced degradation). The batches comprise Si material from various ingots and bricks based on different feedstock material. As mentioned above, they consist of wafer material, which represents the whole quality range of the corresponding silicon brick.

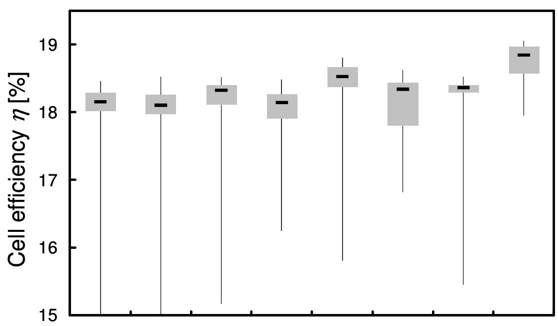

Figure 2: Boxplots of recent cell-efficiency results from our weekly R&D runs. Stable median cell efficiencies exceeding 18 % are achieved.

As shown in Figure 2 stable median cell efficiencies exceeding 18 % in R&D production are achieved. Median values of our champion mc-Si batch are measured to V_{oc} = 644 mV, J_{sc} = 37.7 mA/cm², FF = 77.4% resulting in a median efficiency of 18.8 %. These values are summarized in Table I.

3.2 R&D results of mono-crystalline Cz Q.ANTUM cells

Beside multi-crystalline Si we have also developed and optimized our Q.ANTUM concept on mono-crystalline boron doped Czochralski (Cz) Si material. However, the double-sided passivated cell design without a diffused high-low junction on the rear requires highly doped material [11] for two reasons: resistivity depending ohmic losses due to spreading resistance within the bulk [12] and the direct influence of the doping concentration on the dark saturation current and therefore the open-circuit voltage.

For multi-crystalline Si the reduced oxygen concentration within the material allows for processing highly doped Si and thus is well suited to the PERC cell design. However, the usage of boron (B) doped Cz grown mono-crystalline Si is challenging due to a potentially enhanced light-induced boron-oxygen (BO)-degradation [13]. As a consequence, using Boron as a dopant source for the base material of the high-efficiency PERC cell concept a low $[O_i]$-contamination within the Si material is essential [14,15].

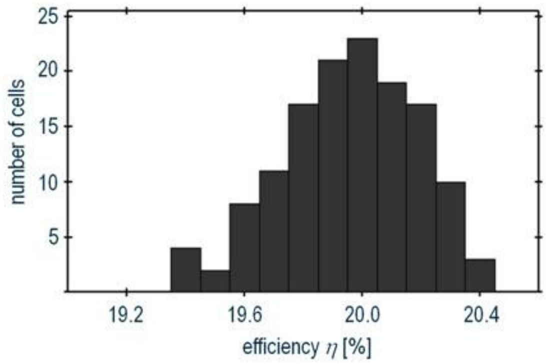

Figure 3: Histogram of a R&D run consisting of ~ 130 mono-crystalline Cz Si Q.ANTUM solar cells. We reach a median cell efficiency of 20 % with top efficiencies of up to 20.4 %.

Figure 3 shows the histogram of a R&D run consisting of ~ 130 mono-crystalline Si Q.ANTUM solar cells. The plotted efficiency is measured (inhouse measurement) after processing. Before light-induced degradation our mono batch achieves a median cell efficiency of 20.0%, corresponding to a median voltage of 646 mV, 38.9 mA/cm² short circuit current density and a fillfactor of 79.8 %. After light-induced degradation of the batch the voltages and currents of the cells slightly decrease and a stable median batch efficiency of 19.6% is achieved.

The performance of one of the best cells has been independently confirmed to a stabilized efficiency of 20.2 %. This measurement was taken after deactivating the light induced degradation due to boron-oxygen-complex formation as described in Ref. [16,17]. The *J*-*V*-curve of this cell as independently measured at the Fraunhofer ISE CalLab is shown in Figure 4. The PV parameters of the mono-crystalline batch and a single champion cell of our mono crystalline Q.ANTUM R&D runs are summarized in Table I.

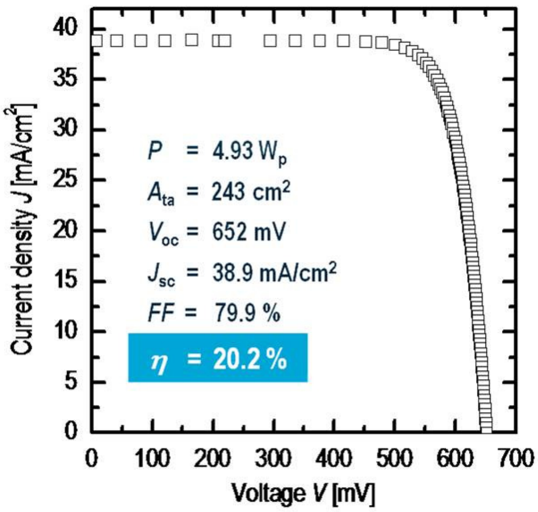

Figure 4: *J*-*V*-curve and parameters of our record *p*-type Cz large area Q.ANTUM cell. The data were independently confirmed by Fraunhofer ISE CalLab.

Table I: PV parameters of single Q.ANTUM cells and median values of batches of Q.ANTUM cells on different Si wafer material (total area 243 cm^2 measurement). Data marked by an asterisk were independently confirmed by Fraunhofer ISE CalLab.

	V_{oc} [mV]	J_{sc} [mA/cm^2]	*FF* [%]	η [%]
p-type Cz cell (*)	652	38.9	79.9	20.2
p-type Cz batch (median values) before degradation	646	38.9	79.8	20.0
p-type Cz batch (median values) after degradation	640	38.6	79.5	19.6
p-type multi batch (median values)	644	37.7	77.4	18.8

4 WORLD RECORD FOR MULTI-CRYSTALLINE Q.ANTUM R&D CELL AND MODULE

R&D cell lots produced on a weekly basis guarantee fast readouts of technological and conceptual variations and thus allow rapid development of the Q.ANTUM concept. The cells produced are also used to improve the performance of our module setup. Consequently we reported at the 1st Si PV conference 2011 in Freiburg on a new world record for a multi-crystalline module of 17,8 % [6]. Two months later at the 2011 IEEE conference we presented a multi-crystalline Si solar cell reaching a power output of more than 4.7 W and a world record efficiency of 19.5 % [8]. The efficiency of 19.5% has been independently confirmed and corresponds to a total area measurement (Figure 5 and Table II). Both the 19.5% efficient mc-Si solar cell as well as the 17.8% efficient mc-Si module are listed in the current "*Efficiency Tables*" of Green et al. [9].

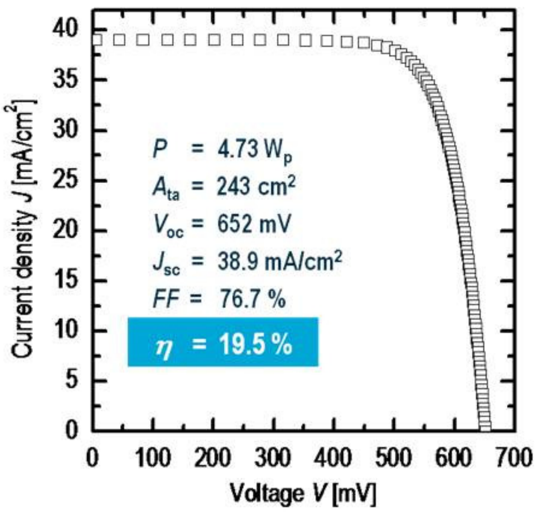

Figure 5: *J*-*V*-curve and parameters of our World Record multi-crystalline large area Q.ANTUM cell. The data were independently confirmed by Fraunhofer ISE CalLab.

In this work, we present a new Q.ANTUM based world record mc-Si solar module with an independently confirmed conversion efficiency of 18.1%. The module contains 60 Q.ANTUM cells. Our new module outperforms our own record module and, to our knowledge, has the highest energy conversion efficiency of a multi-crystalline Si solar module achieved so far.

Table II: PV parameters of our large-area mc solar cell and mc module world records. All data have been independently confirmed by Fraunhofer ISE CalLab.

	V_{oc} [V]	I_{sc} [A]	*FF* [%]	η [%]
mc-Si Cell	0.652	9.46	76.7	19.5
mc-Si Module	38.74	9.14	75.3	18.1

Figure 6: Picture of our independently confirmed World Record multi-crystalline R&D Q.ANTUM module.

Table II displays the PV parameters confirmed at the Fraunhofer ISE CalLab and Figure 6 shows a picture of the Q.ANTUM module. With the parameters given, our 60-cell Q.UANTUM module has - to our knowledge - the highest energy-conversion efficiency achieved for a mc-Si solar module so far. Thus, we beat all records including our own by at least 0,3 % abs.

5 TRANSFER OF Q.ANTUM TECHNOLOGY INTO PILOT LINE PRODUCTION

As a consequence of high performance and stability of our R&D Q.ANTUM results Q-Cells is now transferring this technology into a pilot production line in Thalheim, Germany. As a first step we are focusing on the fabrication of multi-crystalline Si wafers. This involves working on throughput ramping in order to increase the amount of Q.ANTUM modules produced. The development of monitoring methods for the newly implemented process steps as well as the training of operators and the investigation of single process stabilities under high and continuous throughput need attention.

After processing the Q.ANTUM cells in the pilot line, they are converted into high-efficiency solar modules in our own module line.

5.1 Q.ANTUM with superior low light performance

Particularly for solar cells with dielectric passivation layers on the non-diffused rear base surface the avoidance of an injection dependency of the base surface recombination velocity is a very important task [18]. Aberle *et al.* found the non-ideal diode behaviour of high-efficiency PERL cells due to injection dependency of the rear surface passivation to be a main limiting factor of such cells [18]. Highly injection dependent recombination velocities cause reduced fillfactors, and even more importantly cause weak low light performances of these solar cells. Consequently, a non-ideal rear surface passivation causes a reduced energy yield under outdoor illumination conditions compared to the standard cell technology with an injection independent BSF (back surface field) layer on the rear.

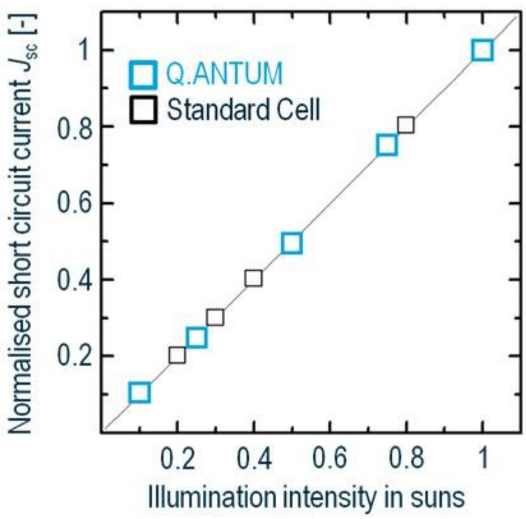

Figure 7: Low illumination performance of our Q.ANTUM cell and a “standard” BSF cell. The measured J_{sc} values of both cell types show a perfect linear behaviour (straight line).

Figure 7 shows measured short circuit current densities of Q.ANTUM cells and standard BSF cells normalised to 1 sun versus the illumination intensity. The current collection probability in a front junction cell is a function of the recombination velocity of the rear surface S_{rear}. A linear correlation between normalized current density and the illumination intensity thus indicates a stable rear passivation also under low injection conditions. Figure 7 illustrates that this aim has been well achieved by our Q.ANTUM solar cell.

To demonstrate the importance of this criterion Figure 8 shows the measured and normalized conversion efficiencies of our Q.ANTUM cell compared to the standard BSF cell and a PERC cell with a non-ideal injection dependent rear surface passivation quality. The data display mean values of 4 cells each normalized to 1 sun illumination. The PERC cell with the non-optimised rear side passivation decreases in efficiency with decreasing illumination more pronouncedly than the BSF reference and the Q.ANTUM cell. The PERC cell in Figure 8 may perform well under 1 sun conditions but looses up to 8 % in efficiency relative to the BSF cell under low illumination intensities e.g. 0.1 suns. However, the Q.ANTUM cell even benefits at low illumination intensities, compared to the BSF cell. This can be explained by two effects: our optimised rear passivation is stable under different conditions *and* for another effect – a more pronounced series resistance of the Q.ANTUM cell compared to the BSF cell. The point contact formation of the Q.ANTUM cell inherently leads to higher internal series resistances due to the spreading resistance contribution [11]. Solar cells with higher series resistances profit from low light conditions as the power loss due to the series resistance is a quadratic function of the current density. As a result of the injection independent S_{rear} *and* the series resistance impact the Q.ANTUM cell even shows an improved energy yield at low light conditions compared to the standard BSF as displayed in Figure 8. Measurements of Q.ANTUM and BSF cell show a 0.5% relative increased energy yield at an illumination of 400W/m², and more than 1.5% relative gain at 100W/m² for our Q.ANTUM technology.

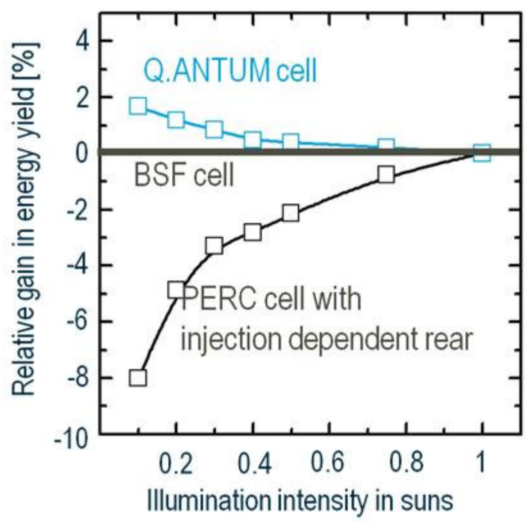

Figure 8: Measured and normalized (to 1 sun) energy conversion efficiencies displayed as a relative gain compared to the BSF cell. Our Q.ANTUM technology shows an improved performance at low light intensities.

5.2 Q.ANTUM assures Q-Cells quality standards

Various investigations and stress tests are done on cell as well as on module level in order to ensure a reliable and high energy yield for the final modules. Among others the modules undergo the well known standard IEC 61215 test series including temperature cycle-, damp-heat-, humidity-freeze, UV- and mechanical load tests. The aim of this test is to display the stress the modules face during outdoor operation. The Q.ANTUM modules passed all IEC 61215 related tests with significantly less degradation than the allowed 5 %.

Figure 9: Q-Cells Yield Security for more reliability. Q.ANTUM includes all of our quality standards.

Moreover, Q-Cells solar cells and modules stand out by our newly developed seal of quality, "Q-Cells YIELD SECURITY", which combines three features: Our crystalline Si solar cells and modules include our developed anti PID (potential induced degradation) technology (APT) [19], they are protected against hot spots (HSP) and can be traced across the entire value chain due to their individual coding (TRA.Q) [20].

Each of our new Q.ANTUM cells and modules feature these quality aspects; they are laser marked for single wafer identification and are protected against Hot-Spots due to our testing procedure which identifies and removes each affected solar cell directly after processing. The prevention of PID for our Q.ANTUM modules is described in detail in the following chapter.

5.3 Q.ANTUM is not susceptible to PID

The standard system architecture of PV installations exposes solar modules to bias voltages of several hundred volts. Recently, it became apparent that high bias voltages can have negative effects on the long term performance of standard screen-printed crystalline Si solar cells. – the so called potential induced degradation (PID) [19,21]. A high potential difference between the grounded module frame and the active cells in modules was found to be potentially hazardous to the parallel resistance of the cells and thus to the yield of the solar system. At the 2011 IEEE conference in Seattle Q-Cells reported on results proving that PID on our products is effectively prevented by an adapted cell process established at Q-Cells [19]. Thus, we also applied this technology for our Q.ANTUM cells and consequently tested modules with respect to their PID sensitivity. Figure 10 shows the data of Q.ANTUM modules compared to a module which is PID sensitive according to testing conditions published in Ref. [19]. We have found a perfect stability of our Q.ANTUM modules showing no degradation due to PID effects.

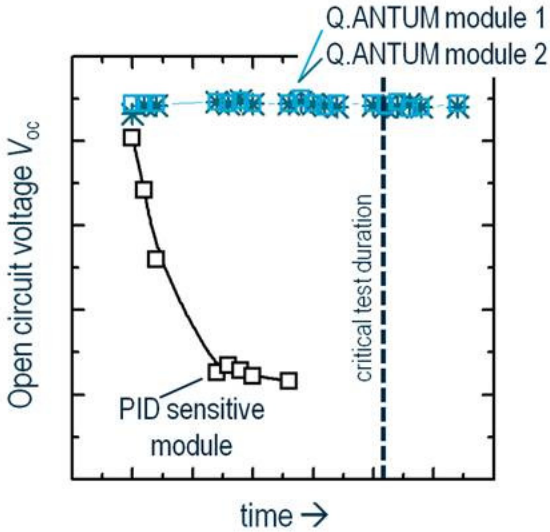

Figure 10: Results of a PID test (-600V, wet surface, 25 °C) of two Q.ANTUM modules and one module susceptible to PID. Q.ANTUM includes the Q-Cells anti PID technology and thus shows no degradation effect.

6 SUMMARY

We have reported on our latest R&D cell and module results based on double-side contacted *p*-type Si solar cells featuring a dielectric passivated rear – the Q.ANTUM concept. Besides the already confirmed world record 19.5 % efficient multi-crystalline solar cell we realized a new multi-crystalline world record module reaching an energy conversion efficiency (ap) of 18.1 %. Furthermore, Q.ANTUM mono-crystalline Cz lots reached median cell efficiencies of up to 20.0 % after processing and an independently confirmed top cell efficiency of 20.2 %. Q-Cells decided to transfer the Q.ANTUM technology on multi-crystalline Si into a pilot production line in Thalheim, Germany. Among other tests Q.ANTUM modules successfully passed the IEC 61215 test. Further measurement results on the low-light behaviour and PID susceptibility as well as the included features like hot-spot protection and TRA.Q demonstrate the maturity of our new Q.ANTUM technology concerning reliability and secured energy yield.

7 ACKNOWLEDGEMENT

This work has been supported in frame of the Adaptum project(0904/00109) by EFRE, Sachsen Anhalt, the Alba II project (0329988C) by BMU, and of the HiFy project (1004/00062) by EFRE, Sachsen Anhalt.

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