CURRENT STATUS OF Q.CELLS´ HIGH-EFFICIENCY Q.ANTUM TECHNOLOGY WITH NEW WORLD RECORD MODULE RESULTS

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ABSTRACT: In this paper we report on our latest 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 record energy conversion efficiency (ap) of 18.5% based on 60 multi-crystalline cells. Using *p*-type mono-cast (mono-like-multi) material in combination with an alkaline textured surface median cell efficiencies of up to 19.7% are reported. With a independently confirmed record module output power of 283 W_p of a standard-sized 60-cell module we demonstrate the potential of this material in combination with our Q.ANTUM technology. Additionally to the R&D achievements we report on our progress in transferring the Q.ANTUM technology into mass production. Almost 1 Mio. Q.ANTUM cells were produced this year using high throughput equipment. Efficiencies of 17% beginning this year were increased to median efficiencies exceeding 18%. At the same time the yield could be increased to values comparable to the reference Al-BSF cell process. 60 cell modules were fabricated by conventional soldering interconnection technology receiving module power output exceeding 270 W. Intensive reliability tests were performed showing that Q.ANTUM modules pass all quality criteria necessary for IEC, “VDE-quality tested” and Q.Cells “Yield Security“ certificates. Low light behavior and outdoor system tests revealed a supreme energy yield of Q.ANTUM modules compared with Al-BSF technology.
Keywords: High-efficiency, passivation, Q.ANTUM

1 INTRODUCTION

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. This passivated rear cell concept on *p*-type Si calls for highly doped base material to reduce ohmic losses within the wafer due to lateral current transport and to minimize rear recombination losses by reducing the rear metallisation fraction. Multi-crystalline Si with an inherent low oxygen contamination within the material allows for processing highly doped Si and thus is well suited for the LFC/PERC cell design.

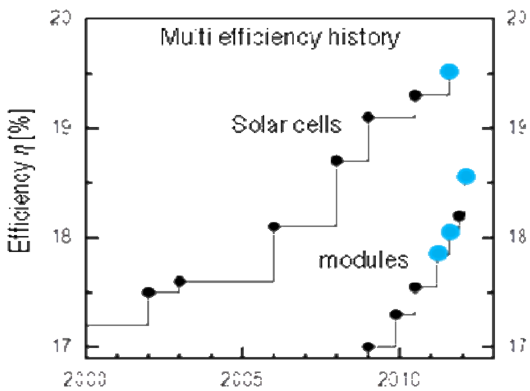

FIG. 1. Reported record solar cell and module efficiency history on multi-crystalline Si [2].

Figure 1 plots reported record cell (large-area sized) and module efficiencies from various groups during the last 10 years. On module level a remarkable average efficiency improvement of about 0.5%$_{abs}$ per year within the last three years could be demonstrated whereas for the large area multi solar cells the average improvement is about 0.2%$_{abs}$ within the last ten years. However, it is important to note that the improvements in terms of cell and module output power is even more pronounced than the efficiency improvement since cell and module areas were enlarged. For example, our current world record cell with a cell efficiency of 19.5% (blue symbol) reaches an output power of well above 4.7 W [1] compared to the record cell from 2002 with 2.5 W [2].

In this paper we present the latest results of Q.Cells´ Q.ANTUM technology. Using *p*-type multi-crystalline Si wafers (multi-cast crystallisation) we report on average cell efficiencies of up to 18.8% out of our R&D centre. Based on these mc-Si cells we are able to report on the third module world record (blue symbols in Fig. 1) by realizing an independently confirmed world record module reaching an energy conversion efficiency (aperture area 1.47 m^2) of 18.5%. Consequently, based on our Q.ANTUM technology Q.Cells holds the current world record on both multi-crystalline Si cells and modules.

2 RESULTS R&D CENTRE

2.1 Alkaline textured of mono-cast Si

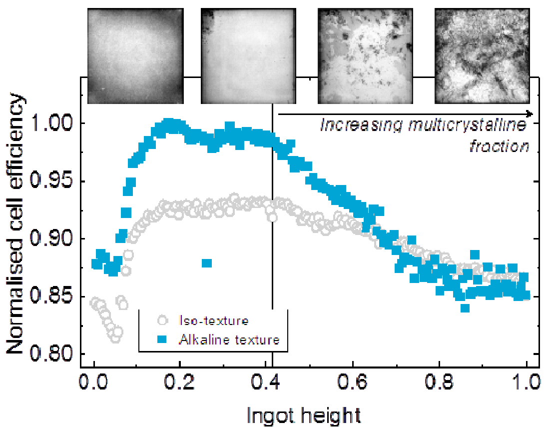

Fig. 2: Normalized efficiencies of multi-cast and mono-cast cells with either isotropic or alkaline textured front side.

On standard Al-BSF solar cells the impact of the front side texturing process on the solar cell efficiency is demonstrated using mono-cast Si substrates. With an increasing ingot height the fraction of poly-Si increases as indicated by the photoluminescence mappings of passivated wafers. Figure 2 shows the impact of the texturing - either alkaline or isotropic - processes on the cell efficiency versus the ingot height. Data are normalized to the maximum cell efficiency achieved by an alkaline textured mono-cast solar cell. The effect of iso- and alkaline texture on the solar cell efficiency is demonstrated on neighbouring wafers of a particular mono-cast brick which is 100% monocrystalline from the bottom to approximately 40% of the ingot height. In this case, the efficiency gain using alkaline texture can be up to 7.5% relative. From 40% to the ingot top, the multi-crystalline fraction increases. The higher the multi-crystalline fraction, the lower is the advantage of alkaline texture. It vanishes if more than 50% of the wafer area is multi-crystalline.

2.2 Q.ANTUM cell design

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 multi-cast Si wafers and an alkaline batch-texture in the case of mono-cast 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. The front metallization is realized by fine-line printing in combination with a plating processing step. We use the laser-fired contact technology (LFC) [3] to realize the point metal contacts on the rear. A more detailed description can be found in Ref. [4].

2.3 R&D Q.ANTUM solar cell results

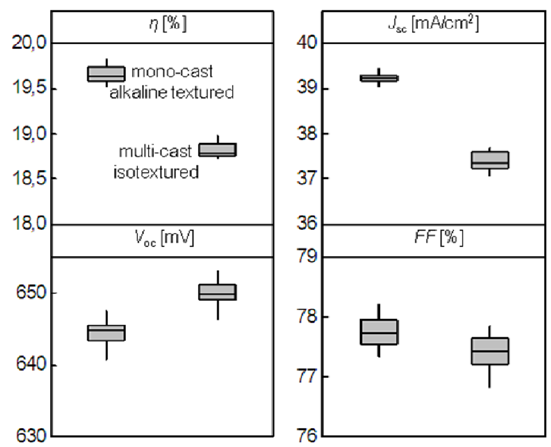

FIG. 3. *I-V* characteristics of Q.ANTUM solar cells used for our new world record modules. The multi-cast cells feature an isotextured surface whereas the mono-cast cells are alkaline textured.

Figure 3 displays the *I-V* parameter of the Q.ANTUM solar cells used for the module fabrication, thus each boxplot comprises 60 cells. The cells based on mono-cast Si feature an alkaline textured front side whereas the multi-cast cells are isotextured. For the mono-cast cells we used Si substrates from the lower ingot region where the mono fraction is above 90% of the total area (between 0.2 – 0.4 of the ingot height, see Figure 2).

Our mono-cast cells reach an average efficiency of 19.7% and 18.8% for the multi-cast cells. It can be observed that the higher cell efficiency of the mono-cast cells mainly arises from an increased J_{sc} of about 2 mA/cm^2 as a result of improved light absorption. An average open circuit voltage of 650 mV could be reached with the multi-crystalline cells. We find a slightly decreased open-circuit voltage V_{oc} of about 645 mV for the mono-cast cells. The difference of 5 mV can be explained by the surface enlargement due to the both side alkaline textured surface thus increasing the overall surface recombination on both front and rear.

The results on mono-cast Si are similar to the previously reported results on Cz-Si [5].

2.4 New module records based on Q.ANTUM technology

TABLE I. Photovoltaic parameters our R&D 60-cell Q.ANTUM champion modules. The module based on multi-cast wafers is optimized for max. efficiency (aperture area) whereas the mono-cast module architecture is optimized for max. output power. Data are independently calibrated at Fraunhofer ISE CalLab.

	V_{oc} (V)	I_{sc} (A)	*FF* (%)	η_{ap} (%)	*P* (*W*)
Multi-cast	39.0	9.15	76.2	18.5	
Mono-cast	38.8	9.74	75.1		283

Table 1 showed the *IV*-parameters of the new 60 cell Q.ANTUM world record poly-Si solar module with an efficiency of 18.5% measured on an aperture area of 1.47 m². The improvement compared to the previously reported record module mainly originates from a fill-factor improvement from 75.3% to now 76.2% which can be explained by an enhanced conductivity of the front side fingers. The open-circuit voltage Voc = 39.0 V of the 60-cell module reflects very well the average Voc of the single cells of 650 mV as shown in Fig.3.

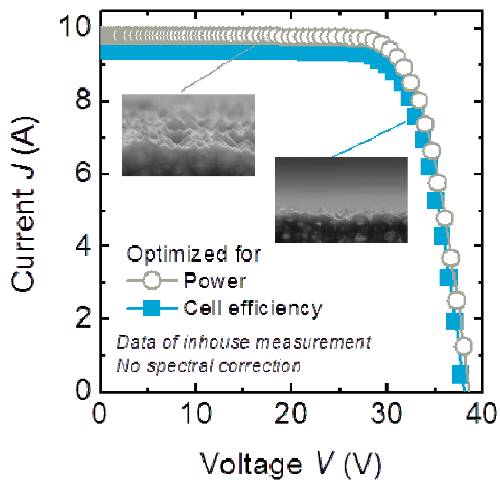

FIG. 4. *I-V* characteristics of our new world record efficiency (multi) and power (mono-cast) module.

In addition Table 1 shows the *IV*-parameter of a standard sized module (1.67x0.99 m²) with record output power of 283 W based on the alkaline textured mono-cast cells from Fig. 3. Comparing the multi-cast and the mono-cast module an increase in the short-current from 9.15 A to 9.74 A can be observed mainly resulting from the different front side texturing process. The in-house measured *IV*-curves of the modules together with SEM images of the front side textured cells are shown in Fig.4.

3 RESULTS OF TRANSFERING Q.ANTUM TO MASS PRODUCTION

3.1 Cell efficiency and yield

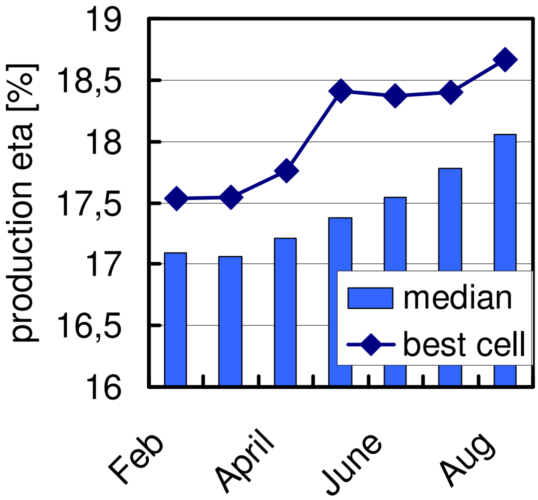

FIG. 5. Q.ANTUM efficiency development in production line over last months. Shown are median and best values.

Beginning of 2012 Q.Cells started to run continues Q.ANTUM cell fabrication on our pilot production line. A simplified process sequence compared to the R&D line is used. An existing Al-BSF solar cell production line was retrofitted by adding two additional tools: one for the deposition of the dielectric and one laser machine for the LCF. We do not use any plating steps in the Q.ANTUM production. Until August almost one million cells were produced. Fig. 5 shows the development of both the best Q.antum cell per month and best median batch efficiencies. Due to a thorough optimisation of the complete process sequence with focus on the dielectric deposition process as well as the laser process the median efficiency could be increased from around 17% to values exceeding 18%. Best median efficiencies using mc-Si wafers reaches 18.1%. Peak cell efficiency was 18.7% in August.

Not only efficiency could be increased by over 1% absolute over the last six months, but also the quality yield improved significantly. The quality yield includes all optical and electrical criteria and was normalised to the Al-BSF reference process. In Fig. 6 the normalized quality yield of the Q.ANTUM production is shown since February. Starting 15% below the yield of the Al-BSF production, we reached in July and August values similar or even slightly better than the Al-BSF reference due to a thorough optimisation and stabilisation of the process sequence. High efficiency and high yields are mandatory to run a cost effective production. Using 60 Q.ANTUM cells and conventional solder interconnection technology glass-foil modules were produced in our module production line in Thalheim. Peak power output exceeding 270 W were reached for Q.ANTUM modules. This excellent results show the successful transfer of the Q.ANTUM technology from the R&D lab into production environment.

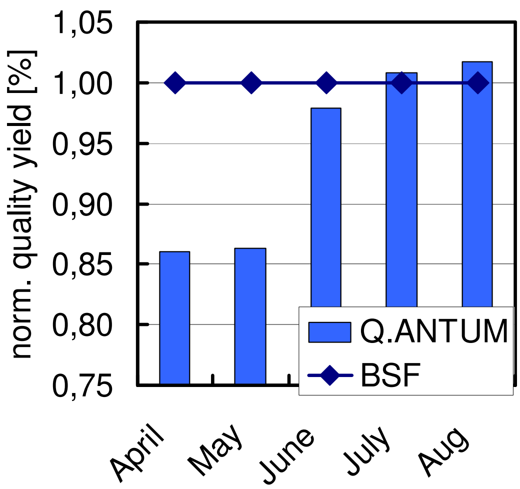

FIG. 6. Evolution of the quality yield of the Q.ANTUM production normalized to the BSF reference process. Starting around 15% below the BSF reference, now similar values are reached.

3.2 Energy yield of Q.ANTUM modules

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 [6]. 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 [6]. Highly injection dependent recombination velocities cause reduced fill factors 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.

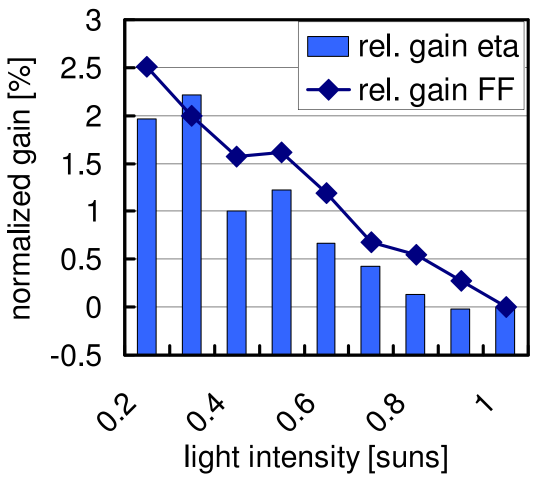

FIG. 7. Weak light behaviour of Q.ANTUM modules, shown is the normalized relative gain compared to Al-BSF Modules of the fill factor and the efficiency as a function of the illumination intensity.

In pervious publications the Q.ANTUM passivation layer was investigated [7]. The excellent and injection independent passivation quality was shown. Moreover the efficiency behaviour of cells was investigated under different illumination intensities. Due to the injection independency the weak light behaviour of the Q.ANTUM technology is superior that the Al-BSF reference cells.

Fig. 7 shows the normalized (to 1 sun) efficiency and fill factor of a Q.ANTUM module as a function of the illumination intensity. Displayed are relative gains compared to the Al-BSF reference module for different illumination intensities. Q.ANTUM modules show 1% relative gain compared to the Al-BSF reference at 0.4 suns and 2% relative gain at 0.1 suns. The better weak light behaviour can be explained by two effects: the injection independency of Q.ANTUM passivation (similar as the Al-BSF reference), and a more pronounced series resistance of the Q.ANTUM cell compared to the Al-BSF reference. The point contact formation of the Q.ANTUM cell inherently leads to higher internal series resistances due to the spreading resistance contribution [8]. 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. In Fig. 7 we can see that the relative gain in efficiency is caused by the relative gain in fill factor due to the additional series resistance in case of the Q.ANTUM technology. There is no difference in the weak light behaviour of Jsc and Voc comparing Q.ANTUM and AL-BSF modules.

An extremely good low light behaviour of 99.5% @ 200 W/m² was measured compared to 97.5% in case of the Al-BSF.

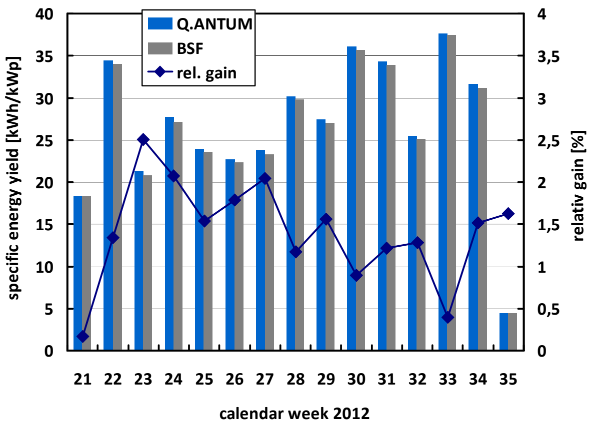

FIG. 8. Specific weekly energy yield of Q.ANTUM and Al-BSF PV system installed near Thalheim for the last half year.

In order to investigate the effect of superior weak light behaviour on the energy yield ground mounted PV systems with around 2.5 kWp were installed near Thalheim. 2 Q.ANTUM systems and two Al-BSF systems were installed. In Fig. 8 the weekly specific energy yield of both technologies and the relative gain of the Q.ANTUM technology are displayed from May to August 2012. The Q.ANTUM systems exhibit a slightly better (~1.5%) energy yield compared to the Al-BSF reference. We expect an increased difference during the next half year due to the higher fraction of low illumination intensities.

3.3 Reliability

Intensive reliability investigations and stress tests are done on cell as on module level in order to ensure a high module quality and to guarantee a lifetime exceeding 25 years. Fig. 9 gives an overview on the main tests performed so far. Certification according to the well known IEC 61730-1 (ed. 2), IEC 61730-2 and IEC 61215 were successfully passed with significantly less degradation than the allowed 5%. Additional tests necessary for VDE Quality-Tested certification according to VDE-QT-PV001:2012/01 were successfully passed as well.

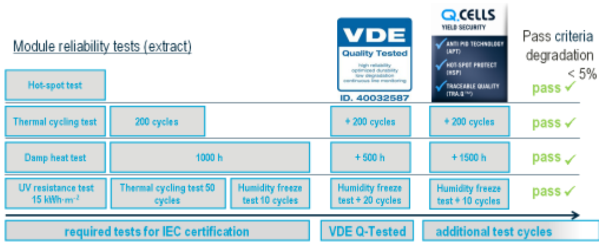

FIG. 9. Performed module reliability test (extract) with Q.ANTUM modules.

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 solar cells and modules include our anti PID (potential induced degradation) technology (ATP) [9], they are protected against hot spots (HSP) and they can be traced across the entire value chain due to their individual coding (TRA.Q) [10]. Every Q.ANTUM cell and module features these quality aspects.

Right now the climate chamber tests are still ongoing till the modules finally will reach their end of life. So far Q.ANTUM modules passed more than 600 thermal cycling tests, more than 3000 h damp heat tests and more than 40 humidity freeze tests with degradation less than 5%.

4 CLUSIONS

We presented the latest results of Q.Cells’ high-efficiency solar cell and module concept Q.ANTUM. Our optimized rear passivation concept in combination with fine-line printing resulted in record module efficiencies of 18.5% based on isotropic textured multi-crystalline Si substrates. In addition we adapted our Q.ANTUM process on mono-cast (mono-like-multi) Si wafer. An average cell efficiency of 19.7% of our top cells and a record module output power of 283 W could be achieved. A simplified process sequence of Q.ANTUM was successfully transferred in a pilot production line. More than 1 Mio. cells were produced so far with maximum median efficiencies of 18.1% and peak efficiencies of 18.7% with the same quality yield as for the Al-BSF reference process. Peak module power output exceeds 270 W.

Q.ANTUM modules exhibit extremely good weak light behaviour of 99.5% at 200 W/m² illumination intensity and shown an superior energy yield compared to Al-BSF.

Q.ANTUM modules successfully passed all reliability tests required for IEC and VDE Q-tested certificates. Moreover Q.ANTUM assures all features included in Q.Cells Yield security.

These results demonstrate the maturity and readiness for mass production roll-out of the Q.ANTUM technology.

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