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19% EFFICIENT N-TYPE SI SOLAR CELLS MADE IN PILOT PRODUCTION

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ABSTRACT: We present the status of our process development of n-base silicon solar cells, and progress towards its industrial implementation. Independently confirmed efficiencies for Cz of 18.65% (239 cm^2) have been obtained, and cells since then have already shown further improvement to more than 19%. To our knowledge these are the highest stable efficiencies obtained with industrial processing on 6 inch n-type wafers. We present an update of our process development, including efficiency improvements, transfer to 6 inch size, and key features of the current cells. Results are illustrated with data from Yingli PANDA pilot production.
Keywords: n-type, Silicon, High-Efficiency

1 THE CASE FOR N-TYPE SILICON CELLS

Currently, more than 80% of the solar cells produced worldwide are based on crystalline silicon [1]. The fraction of crystalline silicon cells made from p-type material is close to 95%, and only somewhat more than 5% is made from n-type material. Although the total amount of n-type crystalline silicon solar cells is limited, two important manufacturers, SunPower [2] and Sanyo [3], are using this material to produce high-efficiency solar cells. Both manufacturers apply advanced technologies and use high-quality monocrystalline base material. SunPower is manufacturing fully back-contacted cells (Interdigitated Back-Contact, IBC) and Sanyo is producing so-called HIT (Heterojunction with Intrinsic Thin-layer) cells. On these cell types efficiencies of 24% and 23%, respectively, have been reached. For the HIT cells both emitter and back-surface-field (BSF) are formed by the deposition of thin doped amorphous silicon layers.

The use of n-type material has several advantages over the use of p-type. Firstly, n-type material is less sensitive to many common metallic impurities, like Fe [4,5,6]. Because of this property, n-type material could have a higher tolerance for lower-quality feedstock [7,8]. Secondly, in n-type material boron-oxygen complexes are absent, and therefore it will not suffer from Light Induced Degradation (LID) [9,10,11]. Not specific for n-type, but in practice easier to realize on this material, compared to the traditional p-type cells with full Al back surface field, or PERC configuration cells with blanket metallization on the rear, is the possibility to create bi-facial cells and modules. Bi-facial cells have an advantage for annual energy yield. The gains in yield that can be obtained by using bi-facial modules vary depending on the reflectivity of the surroundings, but can be in the range of 5-20% according to Sánchez et al. in [12].

2 N-TYPE SILICON SOLAR CELLS CHALLENGES

There are numerous challenges that have to be dealt with when processing n-type material into solar cells. Firstly, a high-quality and low-cost process for the formation of p-type emitters and n-type BSF will have to be developed. The passivation of these highly-doped p-type emitter regions cannot be easily accomplished by SiNx, because of the positive fixed charges in these layers. These fixed charges will result in an inversion layer that will enhance the effective recombination. Thermal oxidation is an alternative passivation that works, but requires a long and high-temperature process step. Another issue is developing a suitable metallization for the boron doped emitter.

ECN has a long standing experience in developing processes for multi-crystalline silicon solar cells. In these developments the transfer towards industry is always born in mind. This has led to several successful industrial processes, such as acid texturing of multi-crystalline silicon, and industrial application of the PECVD silicon nitride. The aim for the n-type process was to develop a process that would be potentially suitable for large scale production. All issues with respect to n-type processing have been addressed in ECN's process development.

3 ECN'S N-TYPE CELL CONCEPT

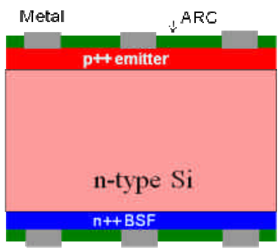

Figure 1: structure of the n-type cell

The structure of the fabricated n-type cells is illustrated in Figure 1. The rear side of the cells is passivated by a phosphorous back-surface field and a SiNx layer. The rear side metallization has an open structure. The open structure can be used for bi-facial modules, for more standard modules with an opaque rear side, the absorption of the cell can be enhanced by using highly reflective materials behind the cell. The front side of the cell has a boron emitter, and an antireflection coating of silicon nitride. The boron emitter is contacted with silver based metallisation.

The process is executed on industrial semi-square 6 inch n-type CZ wafers. The first step is texturing the wafers with random pyramids using alkaline etching. The diffusion is executed using equipment from Tempress. We are able to make boron emitters with a standard deviation in sheet resistivity of about 1.5 Ω/□ [13]. A sheet resistance scan can be seen in Figure 2

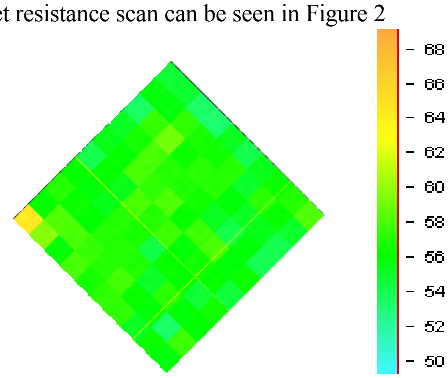

Figure 2: Sheet resistance mapping of a 60 Ω/□ boron emitter.

SiNx layers are deposited for ARC and passivation purposes by PECVD. Screen-printing is used to apply front and rear side metallization. We use a co-firing step to sinter the metallization pastes and form an electrical contact to the diffusion.

Solar cells made with this process have a combination of features, which makes them very attractive for industrial implementation.

- The cell is bi-facial. This feature can be exploited in bi-facial modules to generate additional power.
- There is a BSF. The BSF provides additional lateral conductivity at the rear side. This results in a good fill factor despite the open rear side metallization.
- There is no aluminum BSF, and hence no bending of the cells. The reduced mechanical stresses makes this technology suitable for thinner wafers.
- The n-type material has a high diffusion length which enhances the efficiency
- There is a good passivation of the front as well as rear surface.
- We use processing steps that can be executed on an industrial scale.
- The metallization process has several benefits
    - The metallization at front and rear side employs an open grid, hence we have a limited coverage and paste consumption.
    - The metallization can be applied with regular screen printing.
    - The metallization is compatible with current module manufacturing technology.

The process was first executed in ECN's pilot line, and its potential for large scale manufacturing was demonstrated.

4 TRANSFER TO INDUSTRY

In June 2009, Yingli Green Energy Holding Company Limited, ECN, and Amtech Systems, Inc., of which Tempress is a subsidiary, announced a three-party research collaboration agreement to develop the n-type cell further, in a project named PANDA. With the PANDA project Yingli strives to be at the forefront of the latest technological developments in the PV industry, and to play a crucial role in the introduction of the next generation of high efficiency solar cells. PANDA aims at significantly raising the efficiency of crystalline silicon solar cells and at commercializing the new technology quickly on Yingli's production lines. For Tempress the project allows to develop its diffusion technology and product port-folio for the PV industry. For ECN, the project allows accelerated development of the technology.

ECN drafted specifications and requirements for a pilot line. Based on these specifications Yingli realized a dedicated pilot line for execution of the PANDA project. Yingli was able to get the process running even before the first ECN personnel arrived on site.

Operating the pilot line served multiple purposes.

- Demonstrate the technology on pilot line scale.
- Assess whether the technology would be suitable for running on production scale.
- Gather information for drafting specs for production equipment.
- Identify remaining bottlenecks and solve those.
- Optimize the process in terms of processing time, number of steps, use of consumables.
- Produce cells for testing module assembly and module certification.
- Further development of the technology

An extensive test and development program was executed to tune and improve the process. The capacity of the pilot line and commitment of the team allowed to execute this program at a very rapid pace, leading to excellent results. Also the connections and weight of Yingli as major solar cell manufacturer helped to accelerate developments at equipment- and materials suppliers.

Excellent progress in the pilot operation led Yingli to announce a 300MW production of PANDA cells in March 2010. In June 2010, Yingli estimated to be able to produce in the new factory at an average efficiency in excess of 18.5%. In July 2010 Yingli announced having made cells with an efficiency above 19% in their pilot line, only 13 months after starting the project in June 2009.

There are several factors contributing to the steady increase in efficiency. The throughput of a dedicated pilot line allows the processing to be tuned and getting more stable. For example, the metallization has improved significantly, leading to good fill factors on 6 inch wafers, while maintaining or increasing the current. The impact of switching to a much improved metallization is shown in Table 1.

Table 1: I-V results improved metallization

V_{oc}	I_{sc}	FF	η (%)
-	+0.14A	+0.6%	+0.4%

The reason for the improvement is a narrower print (See Figure 3), reducing shading losses, while at the same time improving the conductivity of the metallization fingers.

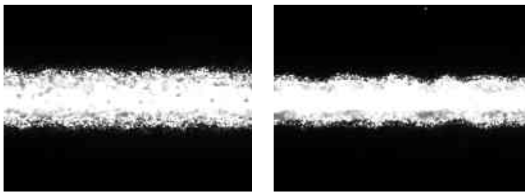

Figure 3: Narrower fingers with improved metallization

The rear surface passivation has improved as well, resulting in increased current and voltage of the cells. Table 2 shows the impact of the improved rear passivation on the I-V characteristics of the cell. Because the cell is bi-facial, the spectral response can be measured on both front and rear side, and hence the IQE for front and rear side is available. Figure 4 shows the changes in front- and rear side IQE between the groups. Clearly visible is the increase in the blue response of the rear side IQE, indicating improved rear surface passivation.

Table 2: I-V results for improved rear passivation

V_{oc}	I_{sc}	FF	η
+3mV	+0.4A	-	+0.2%

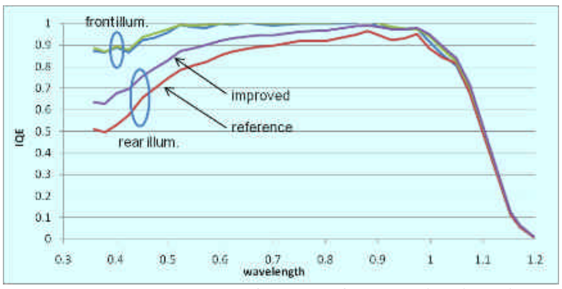

Figure 4: Improvement of rear surface passivation shown in an IQE plot.

5 RESULTS FROM PILOT OPERATION

Table 3 show efficiency measurements obtained in the pilot line. For this cell technology there are two issues that make calibrated measurements difficult, related to the presence of an open rear side. The cell is partially transparent. The reflectance of a measurement chuck (and in general the presence or absence of a measurement chuck) can therefore influence the current. A conductive chuck can also short circuit the rear metallization, influencing the fill factor. For the calibrated cells therefore, a thin full metallization was evaporated on top of the rear side, to allow an unequivocal measurement. The effect of this added rear side blanket metallization on in-house measured I-V parameters was actually minimal, in all parameters < 0.2%. For the in house measurements, the cells were measured as-is on a brass chuck, and because of the uncertainties this causes we can only report with confidence > 19.0%.

Table 3: ECN and PANDA project results

area (cm^2)	V_{OC} (mV)	J_{SC} (mA/cm^2)	FF (%)	η (%)
240	638	36.7	79.5	18.58*
240	635	37.5	78.2	18.65*
237	638	37.8	77.0	18.59*
237	637	38.0	79.6	19.33
237	637	38.0	79.5	19.24

* confirmed by ISE CalLab.

Also in the pilot line, larger series of cells were processed to assess the potential for running stable in fabrication at a sufficient efficiency. In Table 4 and Figure 5, the results can be seen of such a test.

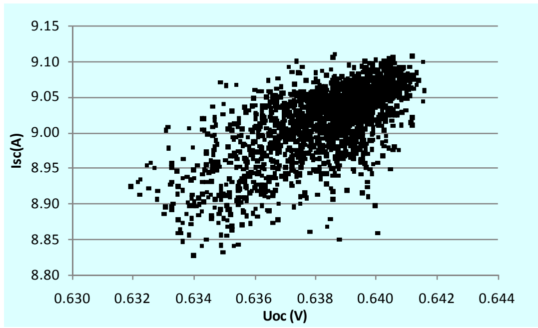

Figure 5: results on a series of 2000 cells.

Table 4: average I-V results for a large series of cells.

I_{sc} A	V_{oc} mV	FF %	Area cm^2	J_{sc} mA/cm^2	η (%)
9.0	639	78.1	239	37.5	18.71

6 CONCLUSIONS

Using n-type base material can lead to higher efficiencies thanks to its lower sensitivity to most common metallic impurities and the absence of boron-oxygen complexes, and advantages of the bi-facial cell structure. Up to now only SunPower and Sanyo are able to manufacture cells with efficiencies above 20% on industrial scale (using n-type material). They use, however, advanced processing.

When processing n-type solar cells, there are non-standard processing methods to be used, in particular in the areas of diffusion and emitter passivation. We have developed an industrially feasible process based on low-cost technologies, with which we are able to make 18.65% (independently confirmed) efficient cells on 6 inch wafers. In house measurements more recently already demonstrated higher efficiencies.

The PANDA processing strikes a good balance between efficiency and manufacturability, and is a viable competitor within the range of technologies already available and those being on the verge of entering the market. One demonstration of the good manufacturability is the rapid progress from lab to pilot to factory (all in about 1 year).There is certainly much opportunity for further development of the technology.

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