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RECENT DEVELOPMENTS ON LOW-COST INDUSTRIAL PROCESSING OF N-TYPE SILICON SOLAR CELLS

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ABSTRACT: We present the status of our process development of n-type silicon solar cells, and progress towards its industrial implementation. For cells with a so-called H-pattern front side metallization independently confirmed efficiencies for Cz wafers of 18.65% (239 cm^2) have been obtained, and since then, cells 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 bifacial cells with H-pattern metallization. Results are illustrated with data from Yingli PANDA pilot production.

1 INTRODUCTION

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 a little 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 the 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].

However, n-type cell processing has some challenges to overcome. Firstly, a high-quality and low-cost process for the formation of p-type emitters and n-type back-surface-field (BSF) needs to be developed. The passivation of these highly-doped p-type emitter regions cannot be easily accomplished by SiN$_x$, because of the positive fixed charges in these layers. These fixed charges will result in an inversion layer in the p-type emitter that will enhance the effective recombination. Thermal oxidation is an alternative passivation that works, but requires a long high-temperature process step. Another issue is developing a suitable metallization for the boron doped emitter. In this paper we will demonstrate that we have successfully overcome these challenges. Our latest results from 'lab to fab' on bifacial n-type cells with the single side junction at the front, and using an H-pattern metallization design will be presented.

2 EXPERIMENTS

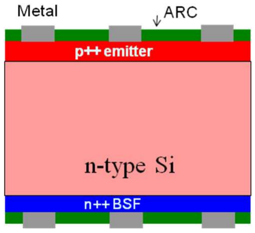

Figure 1: Structure of a bifacial n-type cell.

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 SiN$_x$ layer. The rear side metallization has an open structure. The open structure can be used for bi-facial modules and 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 metallization with a so-called H-pattern.

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 performed using equipment from Tempress. We are able to make boron emitters with a standard deviation in sheet resistivity of about 1.5 Ω/sq [13]. A mapping of the sheet resistance can be seen in Fig. 2. SiN$_x$ layers are deposited for anti-reflection and passivation purposes by plasma enhanced chemical vapor deposition (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 contacts.

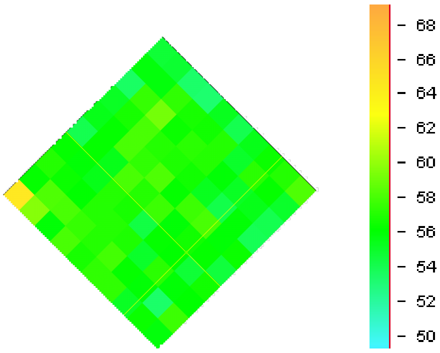

Figure 2: Sheet resistance mapping of a 60 Ω/sq boron emitter.

3 RESULTS AND DISCUSSION

3.1 Transfer to pilot line (H-pattern cells)

The process for cells with H-pattern metallization was first carried out in ECN's pilot line, and its potential for large scale manufacturing was demonstrated. Efficiencies over 18.5% were obtained using industrial viable processes [14]. 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 further develop the n-type cell with H-pattern metallization 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 made it possible to carry out 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 that the new factory would be able to produce cells with an average efficiency in excess of 18.5%. In July 2010 Yingli announced cells with an efficiency above 19% had been made 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. Another improvement carried out in the pilot line is the rear side passivation, which resulted in higher V_{OC} and J_{SC}. More details can be found in [15].

3.2 Results from pilot line

Table 1 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 [16]. 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 1: 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	19.3
237	637	38.0	79.5	19.2

*Independently confirmed by Fraunhofer ISE CalLab.

Also in the pilot line, larger series of cells were regularly processed to assess the stability of the efficiency in a normal production run. In Table 2 and Fig. 3, the results can be seen of such a test.

Table 2: 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	18.7

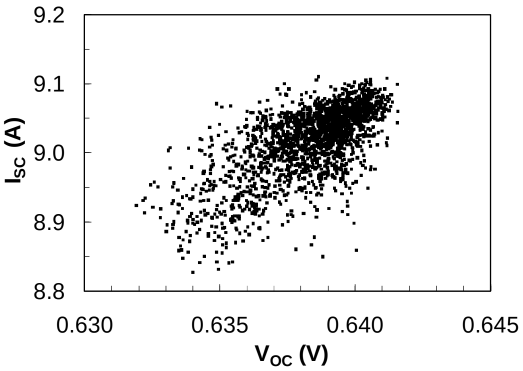

Figure 3: I-V results of a series of 2000 cells.

3.3 Discussion

The results of bifacial cells with H pattern metallization demonstrate that the process is industrially feasible. A process based on screen-printing was applied and resulted in efficiencies over 19% on large area (>200 cm^2) cells. As far as we know, these are the highest efficiencies using such a low-cost process technology. With novel processes it is expected that efficiencies above 20% are within reach.

These higher efficiencies have already been reported on small area cells and using laboratory processes. The best efficiency has been reached by Benick et al. [17]. A selective boron emitter, Al_2O_3 front surface passivation, thermal oxide passivation at the rear and evaporated contacts were applied, and they have reached 23.9% on 4 cm^2 cell area. Using a comparable process, but then with the so-called PassDop process (deposition of silicon carbide and laser doping) on the rear, an efficiency of 22.4% has been obtained on 4 cm^2 cell area by Suwito et al. [18].

On larger areas efficiencies over 18% have been reached by others as well. Richter et al. [19] reported 19.6% on 140 cm^2 cell area using jet-printing and plating for front side contact formation and Al evaporation for the rear contact. Mihailetchi et al. [20] has reached 18.6% on 241 cm^2 using a process based on screen-printing and comparable to the PANDA process. They also used Cz material. Veschetti et al [21] applied FZ material and BCl_3 tube diffusion for emitter formation. With a process based on screen-printing they have reached 18.4% on 125×125 mm^2 pseudo square cells.

4 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). However, they use 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. Nevertheless, we have developed an industrially feasible process based on low-cost technologies. For bifacial cells with an H-pattern metallization on front and rear 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 for bifacial cells with H pattern metallization 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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