Industrial n-type solar cells with >20% cell efficiency

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To realize high efficiencies at low costs, ECN has developed the n-Pasha solar cell concept. The n-Pasha cell concept is a bifacial solar cell concept on n-Cz base material, with which average efficiencies of above 20% have been demonstrated. In this paper recent developments at ECN to improve the cost of ownership (lower Euro/Wp) of the n-Pasha cell concept are discussed. Two main drivers for the manufacturing costs of n-type solar cells are addressed: the n-type Cz silicon material and the silver consumption. We show that a large resistivity range between 2 and 8 Ωcm can be tolerated for high cell efficiency, and that the costs due to the silver metallization can be significantly reduced while increasing the solar cell efficiency. Combining the improved efficiency and cost reduction makes the n-Pasha cell concept a very cost effective solution to manufacture high efficient solar cells and modules.

Industrial n-type solar cells

The International Technology Roadmap for Photovoltaics [1] predicts n-type mono-crystalline material to reach ~30% of the mono-crystalline Si solar module market in 2015.

Compared to p-type material, n-type Cz material is known for its stable high lifetimes due to the absence of light induced degradation [2,3] and its higher tolerance for the most common metallic impurities like iron [4]. These higher lifetimes are subsequently reflected in higher efficiencies. And indeed, the highest efficiency crystalline Si modules currently on the market are based on the Sunpower® MaxeonTM technology [5] which uses n-type Cz material. Applying this technology Sunpower fabricates interdigitated back contact (IBC) solar cells with efficiencies of over 24% that enable module efficiencies above 20% [6]. Since the p-n junction is located at the rear of the cell, the IBC cell must be fabricated on Si wafers with a long minority carrier diffusion length in order for all the carriers to reach the emitter. Excellent front surface passivation is required as well. To enable these highest efficiencies, the production costs of these high efficiency cells are quite high due to the use of many complicated processing steps [7].

At ECN Solar, our aim is to develop high efficient, low-cost and robust solar cell and module concepts that can be easily adopted by industry. In 2010 we introduced our n-type Cz-silicon solar cell concept “n-Pasha” (Passivated all sides H-pattern) to the market together with the companies Tempress and Yingli [8]. In 2011, efficiencies of over 19% were reached with this cell concept, both at ECN and at Yingli. In 2012, the research and development on n-Pasha has continued, resulting in solar cell efficiencies of 20% at reduced costs per watt-peak [9]. In this paper we asses several aspects of the 20% n-Pasha cell concept which are important for the further industrialization. These are the stability of the 20% n-Pasha process over various large batches of n-Cz material and a wide range of base resistivity, and reduced costs for metallization.

The n-Pasha solar cell

To be able to reach high efficiencies, we use a bifacial cell design on 6 inch n-type Cz material. Figure 1 shows the basic configuration of our n-Pasha solar cell. The cell has an open rear side, making it suitable in principle for bifacial applications. When these cells are put into a bifacial module light can be collected from the front as well as from the rear adding to the efficiency gain. Both front- and rear side feature H-grid metallization patterns. Yingli's PANDA cells developed in collaboration with ECN and Tempress are based on this structure as well.

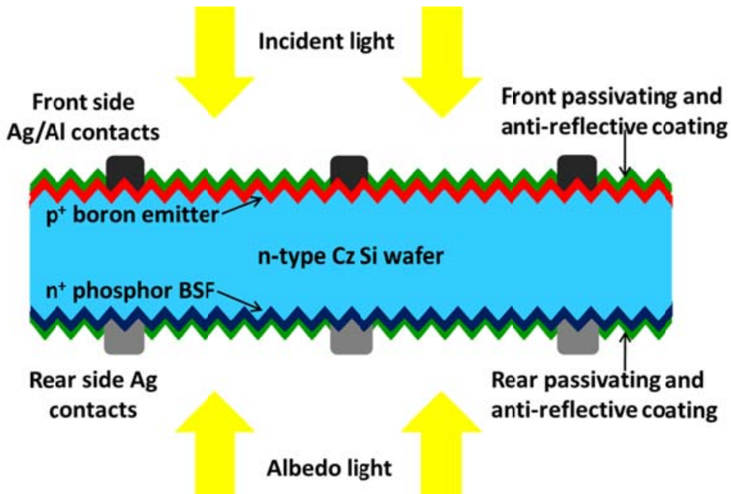

Figure 1. Cross section of the ECN n-pasha cell. Yingli's PANDA cells are based on this structure.

n-Pasha cell processing. The main processing features of the n-Pasha cell are:

- Textured front side
- BBr_3 diffused emitter on the front
- Low doped $POCl_3$ BSF on the rear [9]
- SiN_x coating at both front and rear for (anti) reflective purpose
- Stenciled front side metal grid + screen print busbar [9]
- Screen print H-patterned metallization at the rear

Several publications in 2012 describe the steps that were taken to increase the efficiency of n-Pasha solar cells up to 20% [9,10]. By reducing metal coverage and improving the quality of the front side metallization, tuning the back surface field doping and improving the front and rear surface passivation, we have been able to obtain an average efficiency of 20%, with top efficiencies of 20.2% on high quality n-Cz material. The IV data for these n-Pasha cells are shown in table I.

TABLE I: Average and best cell IV characteristics for n-Pasha cells fabricated on high quality n-Cz material

	I_{sc} [A]	J_{sc} [mA/cm^2]	V_{oc} [V]	FF [%]	Eta [%]
Average	9.38	39.23	0.652	78.3	20.04
Best cell	9.40	39.33	0.653	78.8	20.23

Stability of the n-Pasha process.

To implement any solar cell concept into the industry, the processing needs to be stable within and between large batches of wafers, i.e both reproducibility and repeatability need to be demonstrated. Recently we have improved the front and rear side passivation of the n-Pasha cell, which has stabilized the n-Pasha processing such that the variation in V_{oc} and efficiency was drastically reduced. To assess the stability of the n-Pasha cell process, 2 large batches of wafers were processed at ECN. These batches consisted of material from two different industrial suppliers. The base resistivity ranged from 3 and 5.5 Ωcm, measured after a high temperature step to annihilate the thermal donors in the material. Material A had a lower material quality which was visible in a lower bulk lifetime and subsequently in lower efficiency results.

In table II the results for both batches of wafers are shown, including the standard deviation of the cell parameters. Especially for material B, high efficiencies were obtained. More importantly, for both materials the variation in cell parameters, especially the I_{sc} and V_{oc}, was very small. Average efficiencies of 19.5% (material A) and 19.7% (material B) were obtained, with top efficiencies of 19.8 and 19.9%. The variation is indicated by the standard deviation, and is only 0.13% for the efficiency for both materials.

TABLE II: Processing of large batches

	I_{sc} [A]	V_{oc} [V]	FF [%]	Eta [%]
Material A				
252 cells	9.25	0.649	77.4	19.5
Best cell	9.30	0.652	78.7	19.8
Std dev	0.02	0.002	0.03	0.13
Material B				
107 cells	9.25	0.650	78.0	19.7
Best cell	9.31	0.653	78.7	19.9
Std dev	0.02	0.002	0.04	0.13

The distribution of the efficiency of the two batches is also shown in Figure 2.

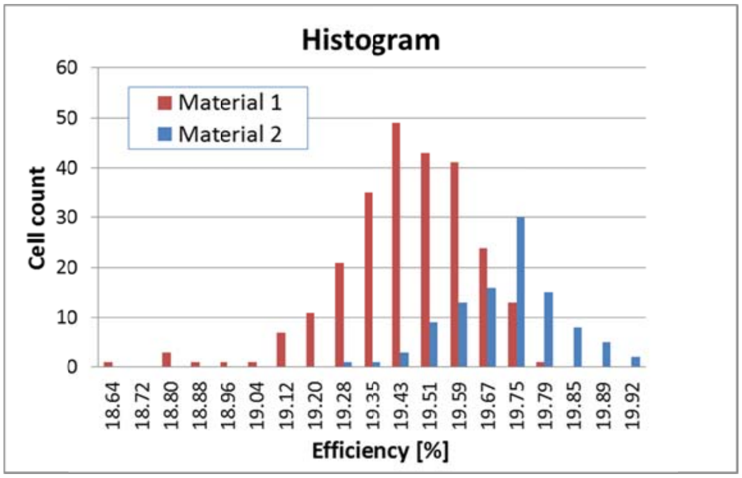

Figure 2: Efficiency distribution of >300 n-pasha cells fabricated on 2 different types of base n-Cz materials.

Efficiency dependence on base material.

One of the factors that makes some solar cell manufacturers reluctant to start n-type cell processing is the large range of resistivity in n-Cz ingots [11]. This is due to the high segregation coefficient of phosphorous in the Cz crystal growth process. Typical resistivity ranges for n-Cz material are from 0.5-2 Ωcm at the tail up to 8-10 or even 12 Ωcm at the seed of the ingot. The base resistivity variation is expected to influence the cell parameters: higher values for I_{sc} and lower FFs are expected for higher base resistivity [12].

To check the dependency of our n-Pasha cell concept on base resistivity, we fabricated cells out of n-Cz material from different parts of one ingot. The base resistivity varied between 2.5 and 10 Ωcm. The results are shown in Figure 3 and 4.

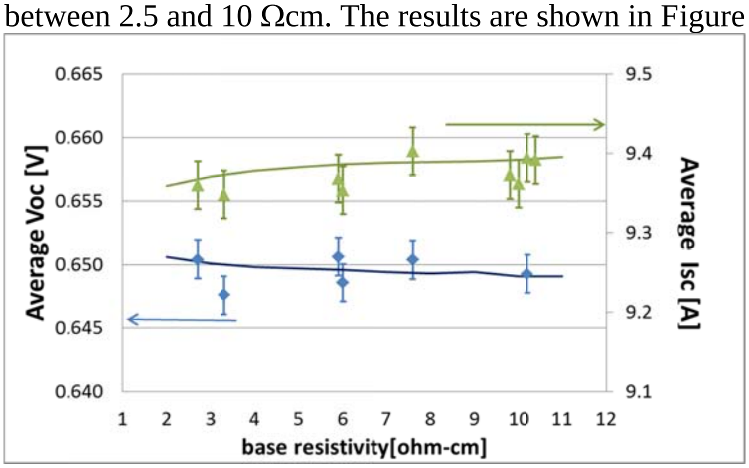

Figure 3: Average V_{oc} and I_{sc} as function of base doping of the n-Cz material. The error bars indicate the variation (max-min) within the IV results. The solid lines are PC1D fits using fixed values for all parameters except the base resistivity.

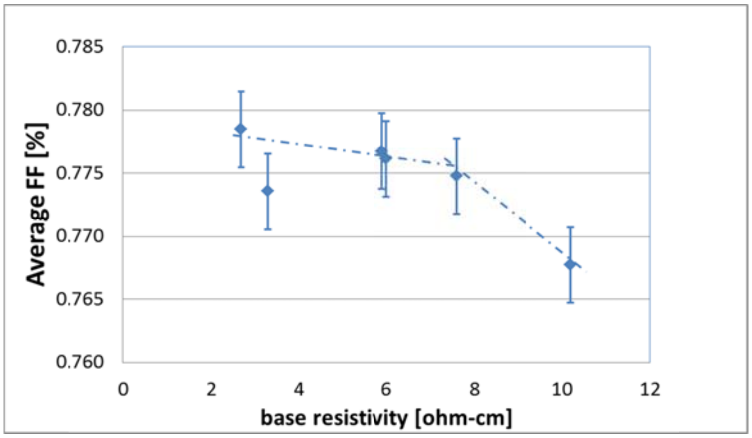

Figure 4: Average FF as function of the base resistivity of the n-Cz material.

As expected, the values for I_{sc} increase for higher base resistivity (and thus lower base doping) due to lower recombination losses. At the same time the values for V_{oc} decrease slightly for higher base resistivity. The values for V_{oc} and I_{sc} have been fitted using PC1D. The same high bulk lifetime has been assumed for all cases, while the base resistivity R_{base} has been changed from 2 to 10 Ωcm. All other parameters were kept the same. As can be seen in figure 3 V_{oc} and I_{sc} can be fitted quite well.

The FF decreases for higher base resistivity, see Figure 4. However, up to base resistivity of 8 Ωcm, the values remain high. The slight drop in FF up to 8 Ωcm is compensated by the increase in I_{sc}, which results in a stable and high average efficiency of 19.8% between 2 and 8 Ωcm. Only at the highest base resistivity used in this experiment (10 Ωcm), the FF drop is severe which limits the efficiency to around 19.6%. Modeling indicates that implementation of an improved rear metal grid design with more but smaller fingers will increase the fill factor and thus the efficiency for the whole base resistivity range of 2 to 10 Ωcm.

The results above show that using the n-Pasha cell concept high efficiencies can be obtained on n-Cz material with a large resistivity variation. This proves that the n-Pasha cell concept is an excellent route to high efficiency industrial solar cells from n-type base material.

<u>Silver reduction</u>

Reducing the Ag consumption has been a driving force to improve the cost effectiveness of the n-Pasha solar cells. In Figure 5, the silver consumption on the front and rear side of n-Pasha cells, relative to that of 2011, is shown. Average consumption for a standard p-type solar cell is also shown. For the front side of n-Pasha, the silver consumption has been reduced in 2012 by almost 40% relative by 1): adopting stencil print [9,10] which enables thinner fingers without loss in fill factor, and by 2): replacing the standard busbar paste by an improved busbar paste [13]. Both changes also contributed to an efficiency gain of around 0.5% absolute. For the rear side, the silver reduction that was realized in 2012 is even more drastic. Thinner fingers and again an improved silver paste [14] enabled a silver reduction of 70% without any efficiency loss. Our goal for 2013 is to decrease the Ag consumption even further to only 50% of the original consumption on the front, and to only 25% on the rear by further paste and pattern optimization.

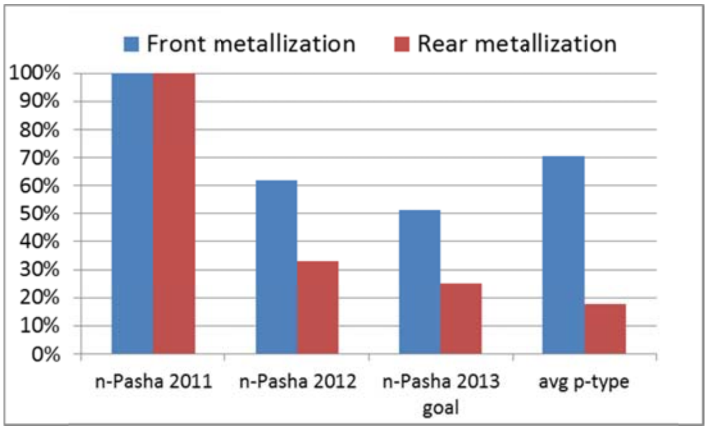

Figure 5: Relative silver reduction for front and rear metallization for n-Pasha, and comparison to average usage of silver on p-type cells

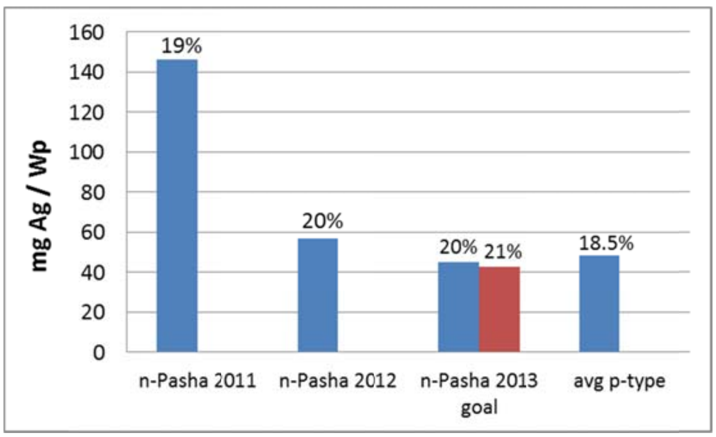

Figure 6: Silver consumption per cell per output power (watt-peak) for n-Pasha cells in 2011 (19% efficiency), n-Pasha cells in 2012 (20% efficiency) and n-Pasha cells with target Ag reduction for 2013 (shown for both 20% and 21% efficiency). All are compared to p-type cells with average 18.5% efficiency.

For solar cell manufactures, the total silver consumption per output power (watt-peak) is very important for their cost of ownership calculations. This parameter can be seen in Figure 6. The first two columns show the silver consumption of n-Pasha cells made in 2011 with 19% average efficiency and of n-Pasha cells made in 2012 with 20% average efficiency. In 2013, the silver consumption will be reduced further as is shown in Figure 5, and of course we also aim to improve the efficiency up to values of 21%. Therefore the silver consumption target in 2013 is calculated for both 20% and 21% efficiency. In the last column, values for a typical p-type Cz solar cell with average efficiency of 18.5% are shown. The figures show that the silver consumption per watt-peak of n-Pasha cells is comparable to p-type cells in 2012, and will be lower in 2013.

Summary

In 2012 we have been able to reduce the silver consumption of n-Pasha cells drastically by 40% on the front and 70% on the rear. Furthermore we have shown that a wide resistivity range (2-8 Ωcm) does not limit the cell efficiency for n-Pasha solar cells, and that large batches of cells can be processed with only a small variation in IV results. In combination with the increased cell efficiency of 20% makes this the n-Pasha cell concept a very cost effective solution to manufacture high efficient solar cells and modules.

Acknowledgments

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