Progress in low-cost n-type silicon solar cell technology

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***Abstract* — This article will review our recent progress in development of high-efficiency cells on n-type monocrystalline Si wafers. With boron-doped front emitter, phosphorous BSF, and screen-printed metallisation, at this moment such cells reach an efficiency of over 19%. We describe recent results of processing with reduced front contact area, and improved BSF and improved rear surface passivation, which are key parameters that limit the cell efficiency. The improved processing leads to an efficiency of 20%. The cell process has also been adopted for fabrication of metal-wrap-through back-contact cells. Without the improved contact recombination and BSF, an MWT cell efficiency of 19.7% is reached, 0.3% higher than the corresponding 'standard' (non-back-contact) cells.**

***Index Terms* — photovoltaic cells, silicon, n-type, bifacial.**

I. Introduction

Crystalline silicon solar cells based on n-type monocrystalline wafers offer considerable advantages for industrial production of high-efficiency photovoltaic modules [1]. Particular advantages are i) high minority carrier lifetime of n-type Si Cz wafers, not affected by light induced degradation and tolerant to many transition metal impurities, in contrast to p-type boron-doped Cz Si wafers; and ii) convenient use of a phosphorous-doped BSF and dielectric surface passivation, supporting high effective bulk diffusion length and high rear internal reflection. In addition, the phosphorous BSF allows open rear side metallisation by firing-through of a metallisation grid pattern, which results in bifacial cells that can be used for bifacial modules, and which allows the use of thin wafers.

In this article we will present recent results of process development for n-type bifacial cells, and back-contact cells based on essentially the same technology.

II. Cell Architecture and Cell Process

The basic cell architecture is given in Fig. 1. Information on the solar cell process has been given in [2]. The process was developed in ECN's pilot line. In June 2009, ECN, Amtech Systems, and Yingli Green Energy announced a three party research agreement, to further industrialize and develop the n-type open rear side cell. The project was dubbed "Panda". The best independently confirmed (ISE CalLab) efficiency from the Yingli pilot line is 19.5% (on 239 cm^2). After a production expansion announced in March 2010, and a second expansion announced in October 2010, Yingli Solar now has 600 MW of Panda production lines operational, with 19% stable average efficiency. The production cost is nearly the same as that of standard p-type monocrystalline Si cells.

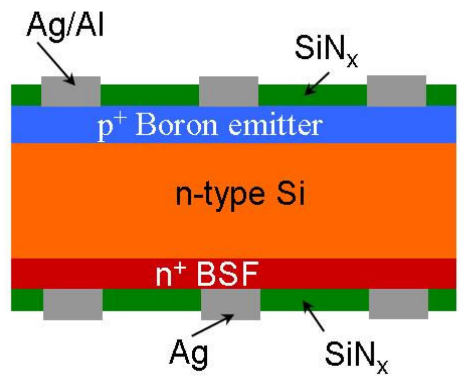

Fig. 1. Structure of the n-type cell.

II. Contact Recombination

To improve efficiency of the n-type cell, one of the possible approaches is to reduce contact recombination, on front and/or rear. Fig. 2 shows the effect of metal contacts on the Voc of the cell. The so-called 'implied Voc' is derived from light induced carrier density measurement, either on a cell half-fabricate without contacts, or on a cell with contacts [3]. The implied Voc corresponds well with the actual Voc if the sample is a completed cell. It can be seen that both front and rear contact grids result in a significant reduction of Voc.

From a variety of experiments of Voc as a function of metallisation coverage, we derived, for example, that the Jo of the front contacts is about 3000 fA/cm^2, and the impact of metal contact area on Voc is about 1.3-2.0 mV decrease per percent of increase of front metal contact area.

Table 1 shows the effect of a reduction of contact area by moving to fine-line stencil print (print results are shown in Fig. 3). The fine line print has the additional advantage of a gain of Isc. As a result, and despite a slight FF loss, the increase of cell efficiency is about 2% relative.

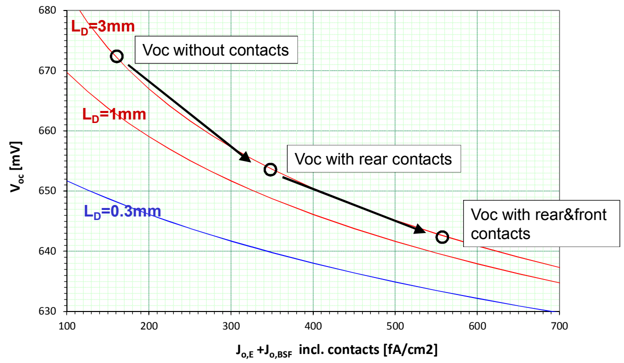

Fig. 2. Schematic of Voc and implied Voc changes due to contact recombination. The theoretical dependence of Voc on Jo and diffusion length L_D are also shown [4].

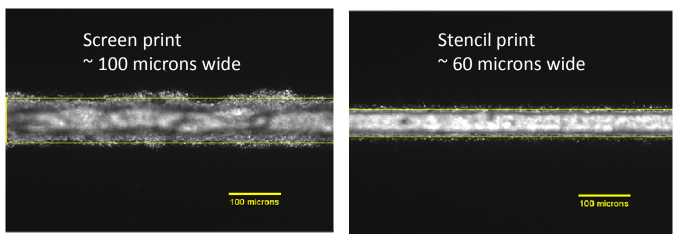

Fig. 3. Test of changing screen print by fine line stencil print.

TABLE I

EXPERIMENTALLY OBSERVED IMPROVEMENTS FROM SCREEN TO STENCIL PRINT

	Isc (%)	Voc (%)	FF (%)	η (%)
Test 1	+1.5	+0.6	-0.4	+1.9
Test 2	+2.6	+0.5	-0.9	+2.2
Test 3	+2.2	+0.4	-0.3	+2.3

III. REAR RECOMBINATION

The full area BSF results in a bifacial cell with good FF. However, negative consequences of the full area BSF are increased Auger recombination, surface recombination velocity, and free carrier absorption. Therefore we have developed and tested improved BSF to reduce these effects. Fig. 4 shows the effect of reduction of BSF dopant concentration on implied Voc. By increasing Rsheet of the BSF, there is a significant increase of implied Voc due to reduction of Auger recombination and reduction of surface recombination velcocity. Fig. 5 shows that also the free carrier absorption is reduced, as demonstrated by an increase of front escape reflectance [5].

The so-far best BSF results in a significant improvement of cell efficiency by about 0.4% absolute. Combining the fine line stencil print with the optimized BSF results in a cell efficiency of 20%, as shown in table II [5]. All cell results shown in this paper are based on in-house measurements with class AAA tester on an highly reflective and conductive chuck, against an externally calibrated reference cell.

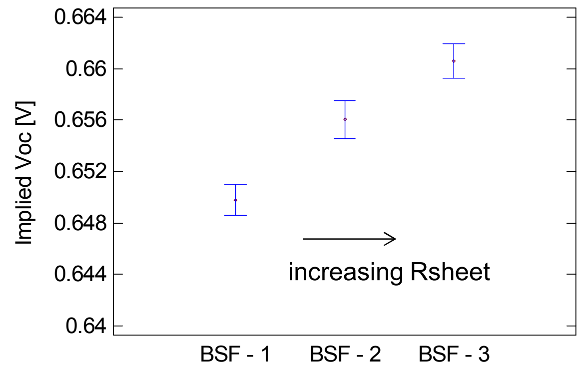

Fig. 4. Implied Voc of cell half-fabricates with 3 different BSF profiles with increasing Rsheet.

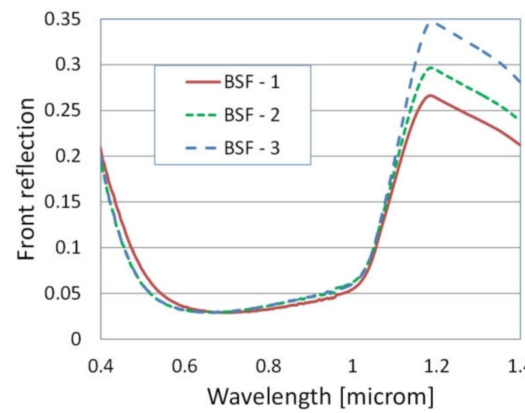

Fig. 5. Front reflection spectra of cells with 3 different BSF profiles with increasing Rsheet.

TABLE II

EXPERIMENTAL RESULTS OF THE COMBINATION OF IMPROVED BSF AND STENCIL PRINTED METALLIZATION

	Jsc (mA/cm²)	Voc (V)	FF	η (%)
Standard rear, avg	38.7	0.640	0.784	19.4
max	38.8	0.640	0.787	19.5
Improved rear, avg	39.2	0.648	0.780	19.8
max	39.3	0.649	0.783	20.0

IV. BACK CONTACT TECHNOLOGY

Metal-wrap-through (MWT) cell technology represents a comparatively small modification of mainstream Si PV process technology, but results in significant progress to high-efficiency rear-contact cell and module technology. The technology builds on standard 'H-pattern front contact' cell technology by adding a small number (10-30) of via-holes to wrap the front metallisation to the rear contacts for module interconnection. It increases the module efficiency by reduced shading loss (~2-3%), reduced series resistance (~3%), and reduced module inactive area. Fig. 6 shows a schematic layout of the MWT cell and module technology from ECN.

The advantages of the MWT technology are large: apart from the increase in cell and module efficiency, the module manufacturing can be done with higher yield, higher degree of automation and much smaller equipment footprint. Also, the MWT technology reduces stress from the interconnection process and thus allows thinner cells, offering additional cost reduction possibilities. Advances in mainstream H-pattern cell equipment and technology, such as selective emitter technology, can easily be incorporated in MWT.

ECN published preliminary results of combining metal-wrap-through with the n-type bifacial n-type cell process to result in n-type metal-wrap-through ("n-MWT") technology, in e.g. [6]. ECN, Yingli Green Energy, and Amtech Systems collaborate on further development and industrialisation of the n-MWT technology [7]

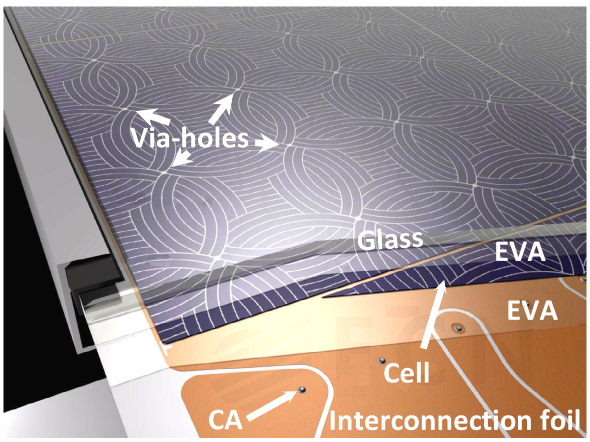

Fig. 6. Schematic 3D cross section of an MWT module manufactured using the ECN module interconnection technology.

The improvements of front metallisation and BSF, that were described above, have not yet been incorporated in the n-MWT technology. Best results without these improvements are given in Table III. The FF of the MWT cells is a matter of attention, and modeling shows that it can be improved considerably. The significant increase of Voc for n-MWT cells is due to the reduction of contact recombination, as described in section II. The efficiency gain of about 0.2-0.3% is in agreement with model calculations, and can be improved by further optimization (see also [7]).

An experimental 60-cell n-MWT module according to the technology described here, demonstrated a cell-to-module FF-loss of only 0.8% absolute, compared to 3% for a corresponding module of tabbed non-back-contact cells [8]. The power gain for the n-MWT module was 8 Wp compared to the tabbed non-back-contact module. This power gain can be increased by improving the reflectivity of the MWT interconnection foil. A first improvement of the foil reflectivitiy resulted already in approx. 1% improvement of cell-to-module Isc.

TABLE III
DIRECT EXPERIMENTAL COMPARISON OF N-TYPE BIFACIAL STANDARD (NON-BACK-CONTACT) AND MWT CELLS

	Jsc (mA/cm^2)	Voc (V)	FF	η (%)
"Standard" n-type, avg	38.4	0.638	0.791*	19.4
max	38.5	0.638	0.792*	19.5
n-type MWT, avg	39.5	0.644	0.771	19.6
max	39.6	0.644	0.772	19.7

* indicates FF is overestimated by approx. 0.2% abs due to shorting of the rear grid on the electrically conducting measurement chuck.

V. CONCLUSION

We have presented results of two improvements in key aspects that limit n-type Si bifacial cell efficiency: front contact recombination, and rear recombination and free carrier absorption related to the BSF. The improvements each resulted in a cell efficiency increase of about 0.4% absolute. As a result a best n-type Si cell efficiency of 20% was achieved.

We have also demonstrated an n-MWT cell process resulting in 0.2-0.3% absolute higher efficiency than the corresponding non-back-contact cell process (as yet still without the front metallisation and BSF improvements), and reached cell-to-module FF-loss of less than 1% absolute for a 60-cell n-MWT module.

We think the bifacial and MWT n-type Si cell processes strike a good balance between high efficiency and low-cost manufacturability, and have become (in the case of MWT: have the potential to become) a viable competitor within the range of technologies available and those being on the verge of entering the market. In addition, as we have shown by examples in this paper, there is clearly room for further development and improvement of the technology.

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