Back-Contacted Cells for Pilot Line Processing With >19% Efficiency

I.G. Romijn et al.
ECN Solar Energy

Introduction

The possibility of obtaining high efficiencies is a major strength of wafer silicon PV. Increasing solar cell efficiency will reduce the costs per watt and can be achieved with highly efficient back-contacted cells. We describe the development of a high-efficiency, back-junction, back-contacted cell, also known as an interdigitated back-contacted (IBC) cell that can be processed using low-cost, industrial methods. In Figure 1(a), we show a cross section of an n-type IBC cell. For comparison, a standard p-type cell is shown in Figure 1(b). The main structural differences are the location of the emitter and its contact, which is on the rear for the IBC cell instead of the front for the standard cell.

High efficiencies can be achieved on IBC cells, using n-type monocrystalline (Cz) material. This is because of the high quality of n-type Cz,[1,2] and because all current collecting contacts are located at the rear, eliminating all front shading losses (see Figure 1(a)).[3-5] However, most industrial crystalline silicon solar cells are based on the "standard" H-pattern concept with contacts on both sides and using p-type material (see Figure 1(b)),[6] because of the relatively low cost of processing and the material availability. Still, the highest efficiencies are reached in the industry by the companies SunPower and Sanyo, which are using n-type Cz material for their IBC or heterojunction solar cells, respectively, with efficiencies far above the 20 percent target.[3]

Since 2009, Siliken and ECN have been working in collaboration to develop a simplified process flow for IBC cells on n-type Cz monocrystalline silicon wafers to reduce the processing costs. In parallel, Siliken has been building a pilot production line to explore both mainstream and alternative cost-effective processing approaches that can be scaled to production while reaching stabilized efficiencies beyond 20 percent.[7] The challenge in this low-cost approach is that the IBC cell fabrication entails high-resolution patterning and alignment of regions for both n- and p-type diffusions and contacts, as well as excellent passivation for different doping types on the same surface.

In this work, we show that efficiencies of >19 percent can be achieved by fabricating IBC cells using currently well-established manufacturing process technologies alone, such as wet-chemical processing, tube furnace diffusions, plasma-enhanced chemical vapor deposition (PECVD) and screen printing for both metallization and diffusion patterning. The best cell results are presented and the primary loss factors analyzed using both characterization techniques and simulations. The results show that >21 percent efficiencies are possible if the fill factor (FF) is increased. A next step

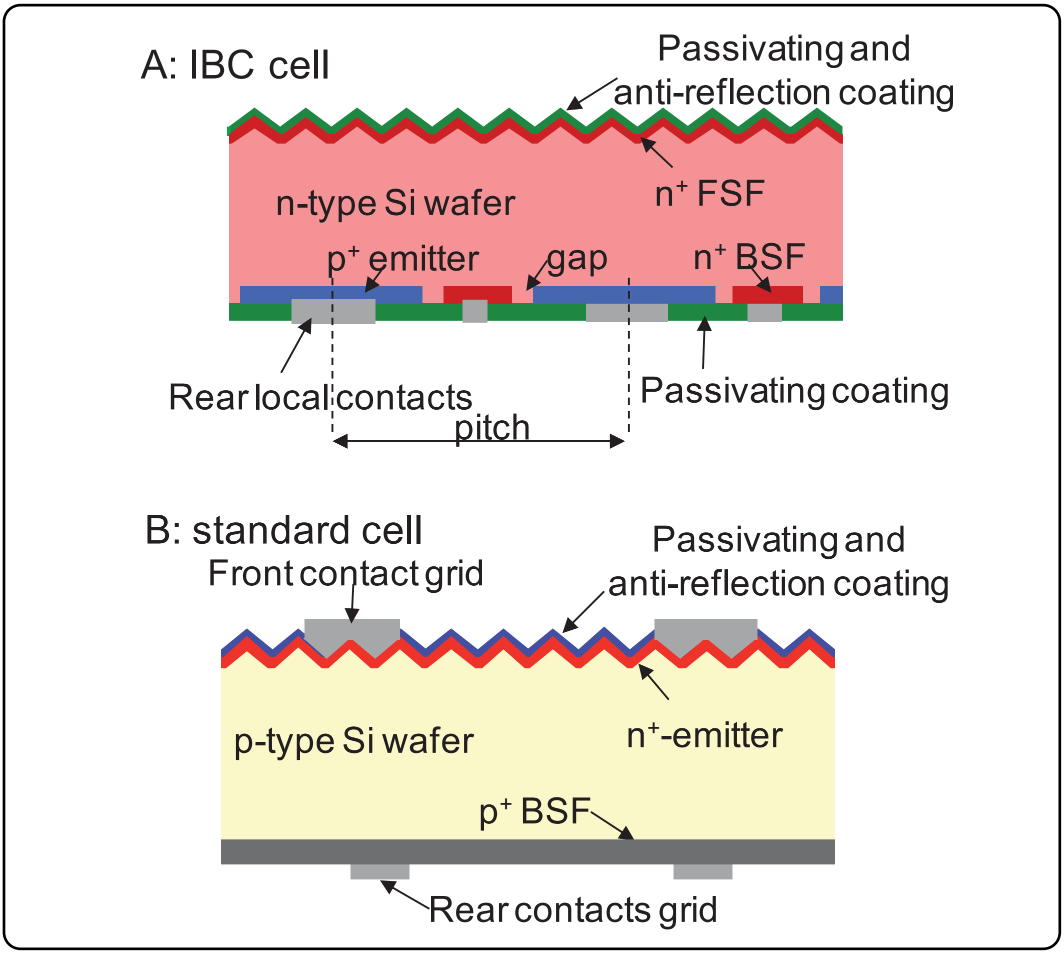


Figure 1 – (a): Schematic of an IBC cell, indicating the n^+-Front Surface Field (FSF), n^+-Back Surface Field (BSF), p^+ -emitter, contacts and passivating layers. The definition of pitch and gap are also included. All contacts are located at the rear. For comparison, a standard p-type cell is shown in Figure 1(b) with an n^+-emitter and contacts on the front and aluminum BSF and contacts on the rear.

would be to implement the new fabrication strategies and processing steps into the pilot production line to improve and optimize the cell concept further.

Solar Cell and Process Description

In Figure 2, a schematic 3D picture of the IBC device is shown, with the transport paths of the majority (electrons) and minority (holes) charge carriers. On the front side of IBC cells, the phosphorous-doped front surface field (FSF) not only serves to reduce recombination at the front surface, but also to improve the lateral transport of the majority carriers.[5] The latter is important when the contact pitch on the rear becomes large or when the resistivity of the material (Re,2,3) is high. On the rear of the IBC cell, the boron emitter and phosphorous BSF are separated by a non-doped gap. To reduce series resistance losses, the IBC cell design requires high patterning resolution to minimize lateral transport losses in the base. Furthermore, the device structure needs excellent surface passivation on both front and rear sides. Traditionally, high-quality silicon oxides have been used for this purpose, which benefit from a low-interface-state density. Finally, as the minority carriers need to travel to the emitter contacts on the rear of the cell via Rh,1,2, the cells are very sensitive to wafer quality.

In Figure 3, the process flow used to fabricate the IBC cells at ECN is shown. To

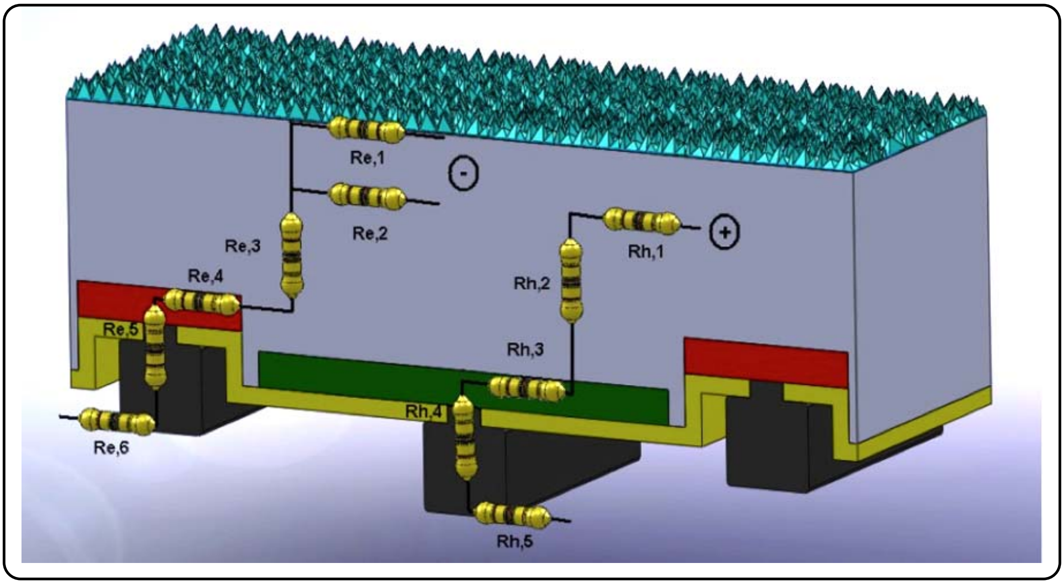


Figure 2 – Schematic 3D architecture of the device with a superimposed circuit model showing resistor corresponding to each contribution to the series resistance along the electron and hole paths. The created electrons will flow via the FSF (Re,1) and base (Re,2,3) toward the BSF (Re,4) and BSF contacts (Re,5,6), while the holes created will travel directly through the base (Rh,1,2) before they are collected at the emitter (Rh,3) by the emitter contacts (Rh4,5).[13]

enable an optimal light trapping, the front surface of the cells is textured (random pyramids), while the rear surface is polished. This is followed by the FSF diffusion, masking, diffusion and patterning of the emitter and BSF at the rear surface, passivation of both the front and back surfaces of the cell, and finally metallization with screen printing and firing. All patterning and metallization steps were executed using low-cost screen-printing methods. The contacts were formed during one firing step in an in-line belt furnace in which the metal contacts were etched through the passivating dielectric layers.

Solar Cell Process Optimization

Several optimization experiments were performed on the IBC structure, rear passivation and FSF formation. Experimental results show a decreasing FF for larger pitch due to increased series resistance. The pitch did not influence V_{OC} and J_{SC}, but higher J_{SC} values were found for larger emitter fractions and thus a larger current collecting area. The best cells were those with smallest pitch and largest emitter fraction, which is in line with simulations of IBC cells.[7] Several dielectric layers have been tested for their passivation on the rear surface of the IBC cells.[8] In this paper, IBC cells

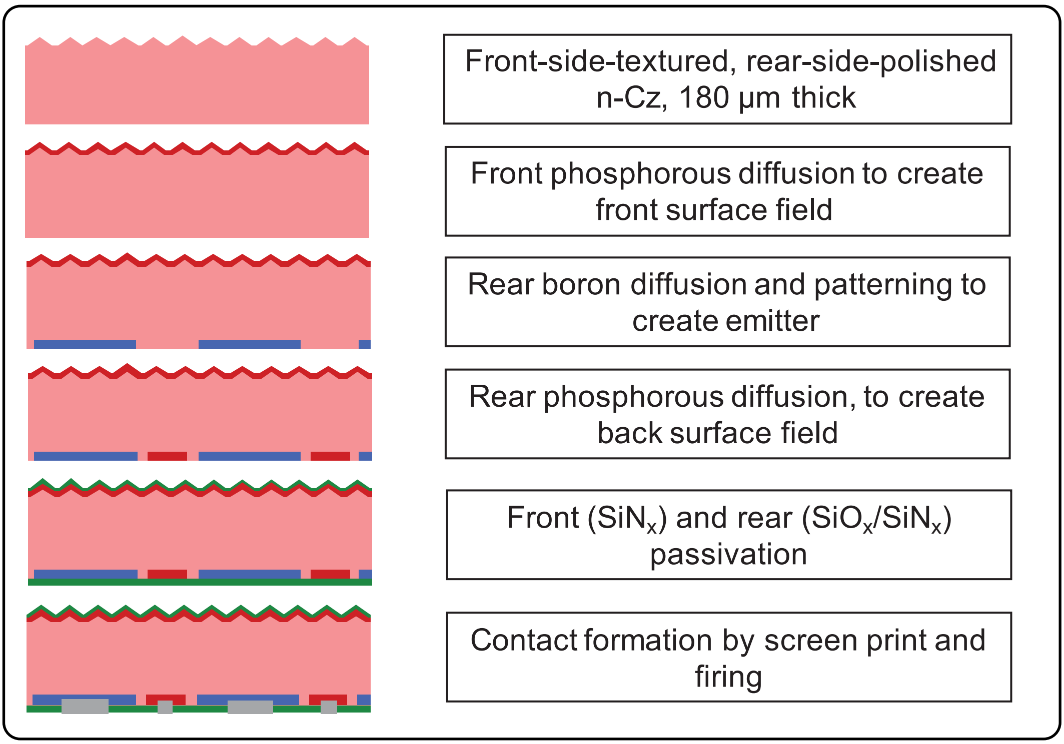


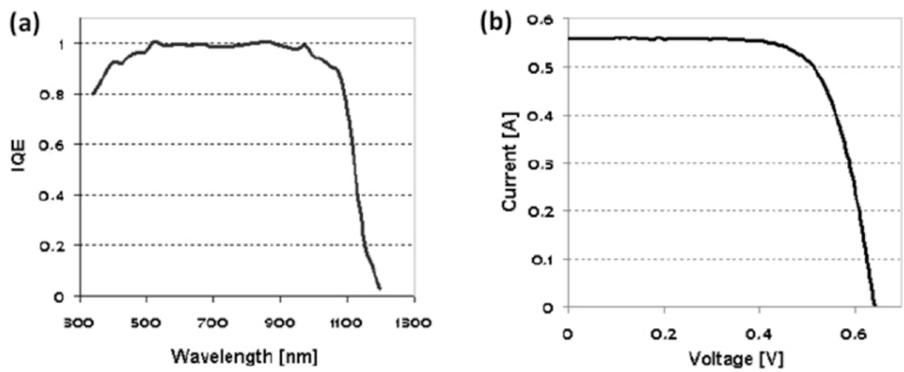
Figure 3 – Process flow used for fabricating >19 percent interdigitated back-contact solar cells at ECN.

using SiO_2+SiNx:H[9] for the rear-surface passivation will be presented. A good FSF has to combine a low phosphorous surface doping to reduce the front-surface recombination, with a deeper diffused area to assist carrier conduction and reduce the electron series resistance Re,1.[10] Several tests were performed to optimize the phosphorous profile. Very low emitter recombination currents (J_{0e} = 20 - 44 fA/cm^3) were achieved for an FSF with phosphorous surface doping below $1*10^{19}$ cm^3.

Best Cell Results

The overall experimental results show that several factors play an important role in obtaining high efficiency including high emitter fraction, small pitch and high material quality. Figure 4 shows both (a) internal quantum efficiency (IQE); and (b) IV data, as well as a summary of measured parameters corresponding to a best cell of 19.1 percent efficiency. For this cell, the emitter fraction was 80 percent, the pitch was 2 mm and a SiO_2+SiNx:H stack was used to passivate the emitter, base and BSF on the rear side.

The IQE results are very good; reaching unity in a broad wavelength range, with characteristic drops in the blue response mainly due to absorption of light in the SiN_x layer, and in the red close to the band gap limit. High current collection is shown by a J_{SC} value as high as 41.6 mA/cm^2. Spectral mismatch measurements later confirmed a mismatch correction of only 0.3 percent, verifying a J_{SC} of 41.5 mA/cm^2. The values for V_{OC} are lower than expected from the simula-



Pitch [mm]	Area (cm^2)	Isc (A)	Jsc (mA/cm^2)	Voc (V)	Jsc * Voc (mA* V/cm^2)	FF	Eta (%)
2	13.2	0.551	41.6	0.641	26.7	0.715	19.1

Figure 4 – (a) IQE; (b) IV and Table of Measured Parameters Corresponding to the Best IBC Cell Fabricated

tions; the value of 641 mV may be limited due to recombination losses at the contacts, or non-optimal passivation. Alternative advanced passivation schemes for both the contact area and for the emitter-BSF-gap structure may further improve the V_{OC}.

The FF for the IBC cells were quite low; all remained below 72 percent. Flash measurements under open-circuit conditions showed pseudo fill factors (PFF) of above 81 percent. This indicates the primary losses in FF are not caused by shunting of the cells.

Further Improvements on the IBC Cells

As shown in Figure 2, series resistance is present in many forms within the cell, including the emitter and BSF contact resistance; the emitter and BSF internal resistance; the base resistance perpendicular and parallel to the plane; as well as the series resistance through the FSF. From simulations as well as experiments, the pitch is found to be one of the major factors influencing the series resistance, and thus the FF as well as efficiency. Both will increase for smaller pitches. Besides this, other factors such as cell and contact (busbar) design may influence the FF. This will be further tested in new experiments.

Figure 5 presents the light-beam-induced current (LBIC) maps of one of the IBC cells. The LBIC is done at a wavelength of 976 nm, thus giving a measure of the IQE response of the rear of the cell. The highest IQE is seen in the region of the emitter (blue), the lowest in the BSF (orange/red), with intermediate values in the gap (green). This indicates that the passivation of the BSF and probably also below the BSF contact lines still needs to be improved, which will enable higher values for J_{SC} and V_{OC}.[11]

Furthermore, both the experimental and simulation results indicate that reducing the size of the BSF and gap, and the size of the contact area, will help to increase the efficiency of the cell.

Obtaining a higher FF – close to 80 percent – while maintaining the same values for J_{SC} and V_{OC}, should give efficiencies of over 21 percent. This could be achieved by decreasing the pitch and improving the contact design. Improvement of the BSF area passivation will enable higher values for V_{OC}, and efficiencies close to 22 percent should be within reach.

Industrialization of the IBC Cell

Currently, the process described is being transferred to Siliken's high-efficiency pilot production line. The facility consists of an ISO-7 clean room and custom-designed batch tools with minimum throughputs exceeding 200 wafers/hour. The facility is designed to evaluate cost-effective production routes for >20 percent efficiency IBC cells, as well as other high- efficiency concepts such as laser-doped selective emitter (LDSE), passivated emitter rear contact (PERC) and hetero-junction intrinsic-layer (HIT) concepts. In addition to the process technologies used for the fabrication of the IBC cells described in this article, the pilot line features alternative thin film deposition and patterning approaches, such as sputter deposition (PVD) and reactive-gas etching (dry-etching).

Sputtering technology is a well-proven deposition technology in PV manufacturing and has been demonstrated for both passivation and even high-throughput metallization.[12] The custom PVD tool allows for multiple-material stacks based on both metals and oxides, as well as advanced *in situ* thermal processing. This tool will be used to explore both advanced passivation and metallization schemes for IBC solar cells. Dry etching also has a history in PV manufacturing, particularly for batch edge-isolation. The custom-designed tool at the line uses inductively coupled plasma technology for enhanced etch rates and homogeneity, and it will be used for both advanced texturing and pattern transfer applied to IBC cell processing.

Conclusions

The results show that 19.1 percent efficiency IBC cells have been successfully fabricated using low-cost fabrication techniques such as screen printing for patterning to create the p-n fingers and metalization. In general, the results show higher efficiencies for larger emitter fraction and smaller pitch, with best results in this study obtained for a large emitter fraction of 80 percent and a small pitch of 2 mm. The cell was passivated with SiO_2+SiNx:H for the emitter, BSF and gap, and excellent J_{SC} values of 41.6 mA/cm^2 have been achieved. The IQE values are close to unity in a broad wavelength range. The high PFF indicate that the cells are not shunted, and if the fill factor can be increased to 80 percent, efficiencies of >21 percent can be achieved.

References

1 L.J. Geerligs et al. "Progression of n-type base crystalline silicon solar cells," Photovoltaics International, 12th ed., pp. 96-102, 2011.

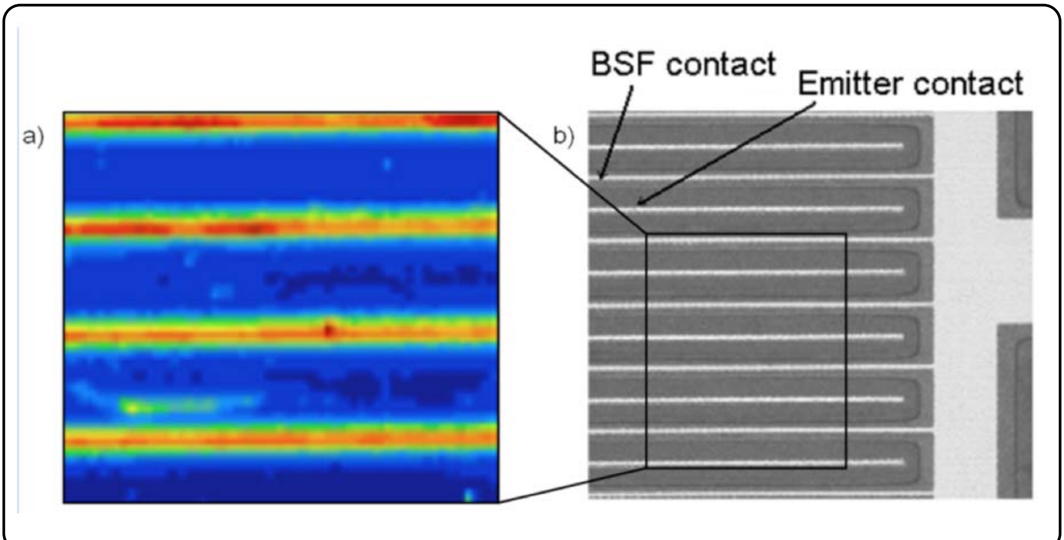


Figure 5 – (a) LBIC measurement showing the local IQE of the cell; (b) Optical image showing BSF and emitter contacts. Highest IQE is shown in blue, lowest in red.

2. D. Macdonald and L.J. Geerligs, "Recombination activity of interstitial iron and other transition metal point defects in p- and n-type crystalline silicon," App. Phys. Lett., vol. 85, 2004, pp. 4061-4063.
3. P.J. Cousins et al. "Gen III: Improved Performance at Lower Cost," 35th IEEE PVSC, 2010, pp. 275-277.
4. P. Engelhart et al. "Laser structuring for back junction silicon solar cells," Prog. Photovolt: Res. Appl. vol. 15, 2007, pp. 237-243.
5. F. Granek et al. "Enhanced Lateral Current Transport Via the Front N+ Diffused Layer of N-Type High-Efficiency Back-Junction Back-Contact Silicon Solar Cells," Progress in Photovoltaics, 17, 2009, pp. 47-56.
6. J. Bultman et al. "Inline processing of crystalline silicon solar cells: the holy grail for large-scale manufacturing?", Photovoltaics International 5th ed. pp. 77-83, 2009.
7. F.J. Castano et al. "Industrially feasible >19% efficiency IBC cells for pilot line processing," Proc. 36th IEEE PVSEC, Seattle, 2011.
8. M.W.P.E Lamers et al. "Towards 21% efficient n-CZ IBC based on screen printing" in 26th EU-PVSEC. 2011, Hamburg, Germany; submitted.
9. V.D. Mihailetchi, et al. "Nitric acid pre-treatment for the passivation of boron emitters for n-type base silicon solar cells," Appl. Phys. Lett., 92, 2008, p. 063510.
10. F. Granek et al. "Front surface passivation of n-type high efficiency back-junction silicon solar cells using front surface field," Proc. 22nd EPVSEC, 2007, Milan.
11. C. Reichel et al. "Investigation of electrical shading effects in back-contacted back-junction silicon solar cells using the two-dimensional charge collection probability and the reciprocity theorem," J. Appl. Phys. 109, 2011, p. 024507.
12. D. Reinwand et al. "Industrial sputtering metallization technology for crystalline silicon solar cells," 24th EU-PVSEC, 2009, Hamburg, Germany, pp. 1479-1482.
13. F. Granek, Ph.D. thesis, p. 108, Fraunhofer ISE, 2009. ■

About the Authors

I.G. Romijn,[1] A.A. Mewe,[1] I. Cesar,[1] M.W.P.E. Lamers,[1] Y. Komatsu,[1] E. Bende,[1] A.W. Weeber,[1] D. Morecroft,[2] M. Cascant,[2] H. Yuste[2] F.J. Castano[2]

[1]ECN Solar Energy; the Netherlands

[2]Siliken, High-efficiency solar cell pilot line, R&D department, Ciudad Politécnica de la Innovación – UPV; Valencia, Spain