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High-Throughput Ion-Implantation for Low-Cost High-Efficiency Silicon Solar Cells

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Abstract

This paper presents the use of ion-implantation for high-volume manufacturing of silicon solar cells. Ion-implantation provides a unique opportunity to obtain grid-parity because it simplifies the fabrication of advanced cell structures. It is shown in production that a streamlined ion-implantation process with homogeneous phosphorus doped emitter can raise the efficiency of 239 cm^2 p-base Cz cells by 0.8 % absolute, from 18.3 % to 19.1 %, while reducing the process sequence by one step relative to traditional $POCl_3$ process. Average production cell efficiency is about 18.6 % with maximum exceeding 19 %. Several advanced cell structures were fabricated in R&D using ion-implantation and screen printed contacts. The advanced p-base structure with ion implanted selective emitter and local Al-BSF resulted in an efficiency of 19.6 %. In addition, three different n-base cell structures were fabricated using boron (B) and phosphorus (P) implantation followed by in-situ front and back passivation during the implant anneal: the n-base cell with B emitter, passivated P-BSF with local contact and full metal back gave 19.2 % efficiency, the implanted n-base bifacial cell was 19 % efficient, and the n-base back junction cell with B emitter in the rear and P front surface field resulted in 19 % efficiency.

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Keyword: Implantation; advanced cell structures; p- and n-base solar cell; back junction cell; bifacial cell; high efficiency

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1. Introduction

Crystalline silicon has been the workhorse of the PV industry since mid 1950's and is primarily responsible for the recent spectacular growth (> 40%/yr) and cost reductions in PV. In 2006, Si PV module prices were $4.0/W with installed system cost of $8.50/W and Levelised Cost of Electricity (LCOE) of ¢32/kWh for residential applications. Currently Si module prices are approaching ~$1.50/W for 15-16 % efficient Si modules, with installed system cost of ~$4.50/W and LCOE of ¢15/kWh for Phoenix, AZ type location [1]. However, installed system cost must decrease to ≤ $3/W with module efficiencies approaching 20 % to produce electricity at ¢10/kWh without government subsidies, which is often defined as grid parity in the US for residential applications. This will require innovation in manufacturable technologies that can enable higher cell efficiency at lower cost. High cell efficiency is important for grid parity because it lowers the cost associated with each link of the PV value chain (ingot, wafer, cell, module and balance of system (BOS).

Ion implantation provides a great opportunity to attain this goal because it simplifies the fabrication of high-efficiency advanced solar cells by reducing the complexity, number of processing steps and cost. Ion implantation is widely used in integrated circuit processing because of the high degree of dose uniformity, chemical purity of the beam (mass analysed) and controlled depth and profile. Ion implantation was used to produce mono-crystalline Si cells in early 1980's, but was restricted to small area laboratory cells and was subsequently abandoned because of the perception that it is too slow and expensive for solar cell manufacturing [2-4]. Recently, interest in ion implantation has been resurrected because of its potential to produce high-efficiency advanced cell structures with fewer processing steps [5, 6]. Ion implantation is enabling technology for low-cost high-efficiency Si cells because of the following reasons:

- Formation of very uniform single side junctions.
- Patterned implantation to form selective emitters and Interdigitated Back Contact (IBC) cells.
- Elimination of edge isolation.
- Elimination of dopant glass removal.
- In situ, high quality oxide passivation during implantation anneal at no additional cost.
- Flexibility in controlling profiles by varying energy, dose, and annealing recipes.
- Formation of boron (B) Back Surface Field (BSF) to replace traditional aluminium (Al) BSF to enable the use of thinner and less expensive wafers.
- Formation of B doped emitter and phosphorus (P) doped front or back surface fields to enable n-type front and back junction cells with no light induced degradation.

In partnership with Varian Semiconductor Equipment Associates (VSEA) Suniva Inc. and Georgia Institute of Technology have pioneered the use of ion implantation by demonstrating its potential through technology innovation and volume production of low-cost high efficiency cells. Varian Semiconductor has re-designed the implanters with higher beam currents and improved wafer handling which enable throughput of ~1000 156-mm wafers per hour. Furthermore, by relaxing some specification that are required by the semiconductor industry (e.g. spread of ion energy within the beam), the cost of the tool is now within an acceptable range. This paper shows the first successful implementation of ion implantation in achieving of 18.5-19 % efficient 239 cm^2 screen printed p-base Cz Si solar cells in volume production. The production cells use p-base Si with P implanted high sheet resistance homogeneous emitter. In addition, we have fabricated several 19-20 % efficient ion implanted advanced cell structures in R&D including a) p-base selective emitter cell with local Al-BSF, b) n-base front junction cell with B emitter, passivated P BSF with local contacts and full metal back, c) n-base implanted bifacial cell, and d) n-base back junction cell with implanted B emitter and P front surface field.

2. Volume production of ion-implanted 19% homogeneous emitter cells and its comparison with conventional $POCl_3$ diffused cells

Traditional n^+pp^+ solar cells in industry are fabricated with $POCl_3$ emitter diffusion, PECVD SiN_x AR coating, screen-printed and co-fired back silver, back Al, and front silver (Ag) contacts as illustrated in Fig. 1. These cells are fabricated on 156 mm Cz wafers (239 cm^2) with an efficiency of approximately 18.3 %. Nine process steps are required where each step is associated with the wafer travelling through a distinct and major piece of equipment.

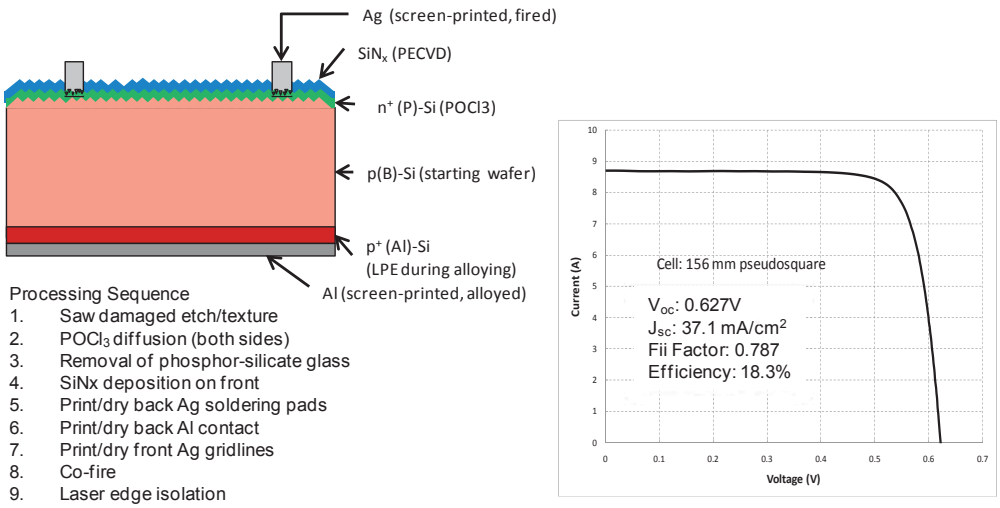

Fig. 1. Structure, performance and process sequence for $POCl_3$ diffused cell.

We have developed a streamlined ion implantation process (known as ARTisun Select) for producing the cell structure shown in Fig. 2. Compared to the $POCl_3$ process, the novel ion implantation scheme reduces the number of process steps from nine to eight. A P implant step has been added to form a homogeneous emitter, but the phosphor-silicate glass removal step and the laser edge-isolation step have been eliminated. Both steps are considered "subtractive", referring to the removal of a material layer created earlier in the process (in this case, phosphor-silicate glass (PSG), and an n^+ layer that wraps from front to back of the wafer). Thus, once the saw damage is etched (an unavoidable subtractive step), all other processing steps are additive since the cell structure is built layer by layer. Note that the implant damage must be annealed (step 3), but since this is performed in an oxygen ambient, a passivating thermal oxide is obtained at no additional cost. Several thousand cells were fabricated in R&D and in pilot-scale runs prior to introducing this process into full production, with average efficiencies exceeding 18.6 %. The I-V curve of one of the 19.1 % cells produced is provided in Fig. 2. This cell was tested and validated by Fraunhofer Institute for Solar Energy Systems (ISE). The new process improved the cell efficiency by about ~0.8 % (absolute) relative to the $POCl_3$ cell in conjunction with one fewer processing step. This improvement in efficiency is attributed to several factors: a highly uniform emitter with elevated sheet resistance (> 65 Ω/□); the passivation of that emitter with thermal oxide; excellent screen printed contacts to the ion-implanted emitter; and the recovery of active cell area by eliminating the laser edge isolation trench. This required the engineering of an optimised combination of precise emitter doping profiles along with metal paste composition and firing to capture the benefits of a passivated

lightly doped emitter, while maintaining a high fill factor (0.798). Detailed cell analysis showed that oxide passivated ion implanted higher sheet resistance emitter had a superior short-wavelength response and a much lower front surface recombination velocity of 22000 cm/s as opposed to 65000 cm/s for the $POCl_3$ emitter. This resulted in 0.6 mA/cm^2 higher J_{sc}, 9 mV higher V_{oc}, and ~0.8 % higher absolute efficiency. The introduction of this novel low-cost, high-throughput manufacturing process is the first instance of ion implantation being used in volume production of high-efficiency solar cells.

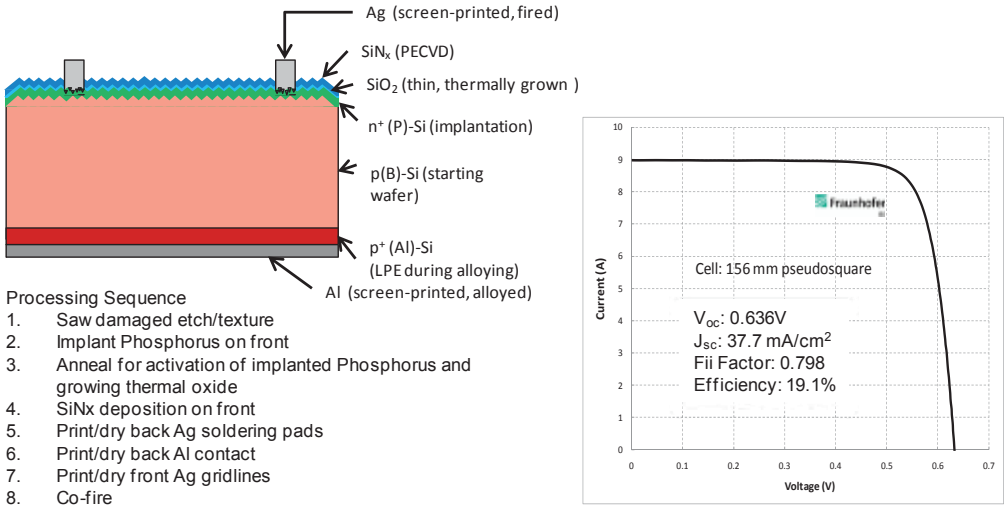

Fig. 2. Structure, performance and process sequence of ion-implanted cell with homogeneous emitter.

Suniva has the distinction of using the very first production tool called "Solion" built for mass production of ion-implanted solar cells and is currently producing ~25,000 cells/day with a target of 100,000 cells/day by the end of the year using 5 such tools. Figure 3 shows a histogram of 26,000 production cells with an average efficiency of 18.6 % and the maximum exceeding 19 %.

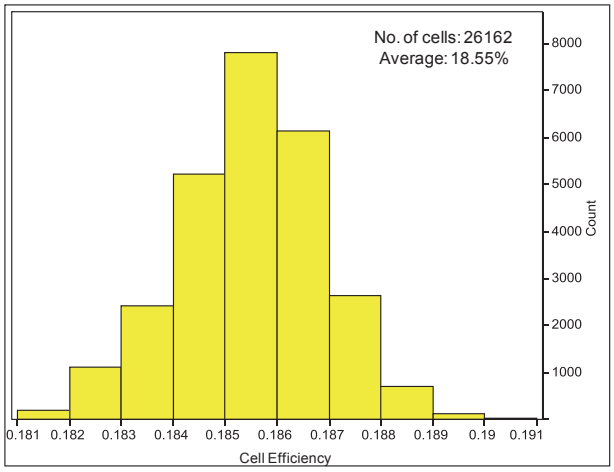

Fig. 3. Efficiency histogram of 26,000 ion-implanted production cells.

3. Ion-implanted p-base selective emitter cell with local Al-BSF

Figure 4 shows the structure of this advanced solar cell with selective emitter on the front and dielectric passivated local Al-BSF on the back. Our model calculations show that this structure can achieve ≥ 20 % efficient screen printed solar cell on commercial grade silicon. Ion implantation provides a unique opportunity to simplify the fabrication of this advanced structure because it allows the formation of single side selective emitter as well as high quality front and back passivation in a single high temperature step. Since there is no cross diffusion and glass formation, it eliminates the need for masking the diffusion or removal of diffusion glass by wet chemistry. It is important to recognise that this structure requires high quality front and back surface passivation to attain its potential. Ion implantation anneal accomplishes this at no additional cost or processing step.

In this study selective emitter was formed successfully by two in-situ implants. First, the entire wafer is implanted with a lower dose to create the high sheet resistance field region. A proximity mask is then inserted between the wafer and the ion beam without removing the wafer, and a second implant follows. Openings in the mask define a grid-pattern of heavily doped regions to which the front screen printed contacts are aligned. As in the case of the homogeneous emitter, the implant damage is annealed in a tube furnace similar to those used for $POCl_3$ diffusion. The process sequence is essentially the same as that for the homogeneous emitter. In-situ oxidation also helps in contact alignment if this alignment is carried out by pattern recognition. Because the oxide grows much faster on the heavily-doped n-type regions, the grid pattern is easily visible after oxidation. Following the implant anneal, the wafers are sent through a standard PECVD SiN_x deposition step. Since the passivating oxide under the SiN_x contributes to the AR effect, a thinner SiN_x layer is needed which enhances the throughput of the PECVD machine. While most selective-emitter strategies being attempted or used in production require one to four additional steps [7-10], the same structure is achieved with one less process step using our masked ion implantation approach. Implantation energy, dose and anneal conditions were selected to achieve 100 Ω/□ sheet resistance in the field and ~50 Ω/□ under the grid area of the selective emitter. In-situ thin oxides were grown on the front and rear surfaces during the implant anneal and capped with appropriate SiN_x coating prior to forming the screen printed contacts. A laser was used to open vias through the rear dielectric stack followed by screen printing of Ag grid on the front and a fritless Al on the rear. Finally both the contacts were co-fired in a conventional belt furnace to form the grid contact on the front and a local Al-BSF in the rear. The light I-V curve in Fig. 4 shows that this process sequence and structure produced 19.6 % efficient cells, which represent the highest efficiency fully screen printed 239 cm^2 cells on commercial grade Cz silicon.

Figure 5 shows a comparison of the internal quantum efficiency (IQE) and reflectance data of a traditional $POCl_3$ diffused cell and two selective emitter cells with full and local Al-BSF. It is clear that selective emitter cell with full Al BSF has a superior short wavelength response compared to the ~60 Ω/□ $POCl_3$ diffused emitter cell. In addition, passivated local Al BSF cell has much better long wavelength response and rear surface reflectance. Detailed measurements and analysis in Fig. 6 show that implementation of passivated selective emitter lowered the FSRV from 65000 to 15000 cm/s and incorporation of local Al BSF reduced the BSRV from 400 to 130 cm/s and improved the back surface reflectance from 65 to 95 %. As a result, this ion-implanted advanced cell structure gave 29 mV higher V_{oc}, 1.4 mA/cm^2 higher J_{sc} and 1.3 % higher efficiency compared to the traditional $POCl_3$ diffused cell. Further process optimisation is expected to increase the efficiency to 20 % .

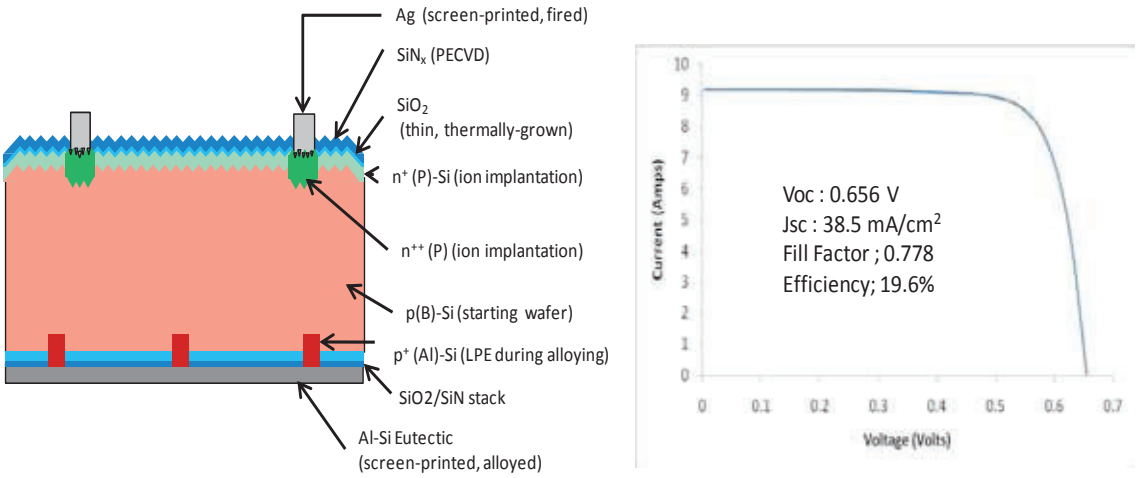

Fig. 4. Structure and performance of ion-implanted p-base selective emitter cell with local Al-BSF.

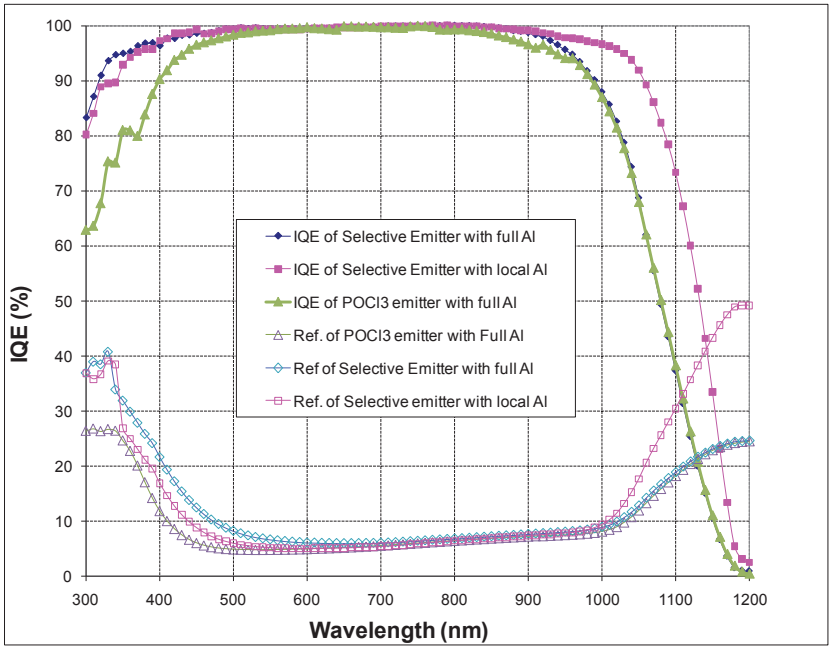

Fig. 5. IQE and reflectance of $POCl_3$ emitter cell and two selective emitter cells with full Al BSF and local Al BSF.

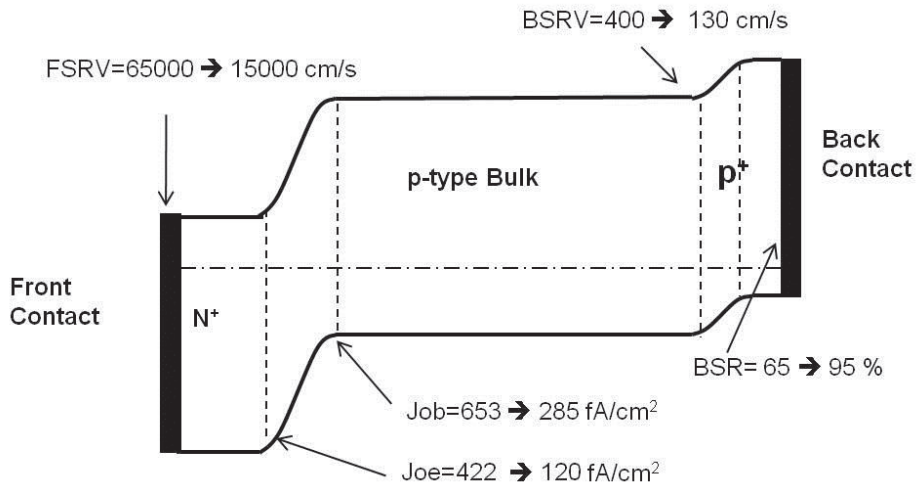

Fig. 6. Quantitative improvement in FSRV, BSRV, J_{oe}, J_{ob} and BSR in a selective emitter with LBSF cell compared to the conventional $POCl_3$ diffused cell.

4. N-base front junction p^+nn^+ cells with full metal back and bifacial structures

N-type cells have become an active area of investigation because of the significant light-induced degradation in high-efficiency p-type devices. In this paper, we investigated the use of B implantation to form the p^+ emitter. Compared to P implantation , B implantation is a lot more challenging because of B cluster formation, incomplete amorphisation and activation, formation of B rich layer, difficulty in passivating textured B surfaces, and maintaining high lifetimes (> 1 ms) during annealing.

In this section we report on two front junction n-type cells which were fabricated by implanting B on the front and P on the back. Separate B and P anneals as well as co-anneals were investigated. So far separate anneals have produced better results for these two structures. Energy, dose and anneal conditions were tailored to obtain sheet resistances in the range of 60 to 90 Ω/□. Both junctions were capped with in-situ thermal oxide and SiN_x stack. Two separate back metallisation schemes were adopted. In one case we fired local Ag contacts through the dielectric to contact the n^+ region and then connected them with fritless screen printed metal. In the second case we made bifacial cells with co-fired grid lines on front and back. These two structures are shown in Fig. 7. We were able to achieve 19.2 % efficiency on full metal back cell and 19.0 % on bifacial device. The bifacial device had slightly lower J_{sc} (37.6 mA/cm^2) compared to the full metal device (38.4 mA/cm^2) partly because of the difference in back surface reflectance. Detailed cell analysis in Fig. 8 shows that the full back metal device had an emitter saturation current density (J_{oe}) of 122 fA/cm^2 and a base saturation current density (J_{ob}) of 365 fA/cm^2, resulting in a V_{oc} or 645 mV. Implantation profiles, bulk lifetime and surface passivation are being optimised to achieve 20 % efficiency for these structures.

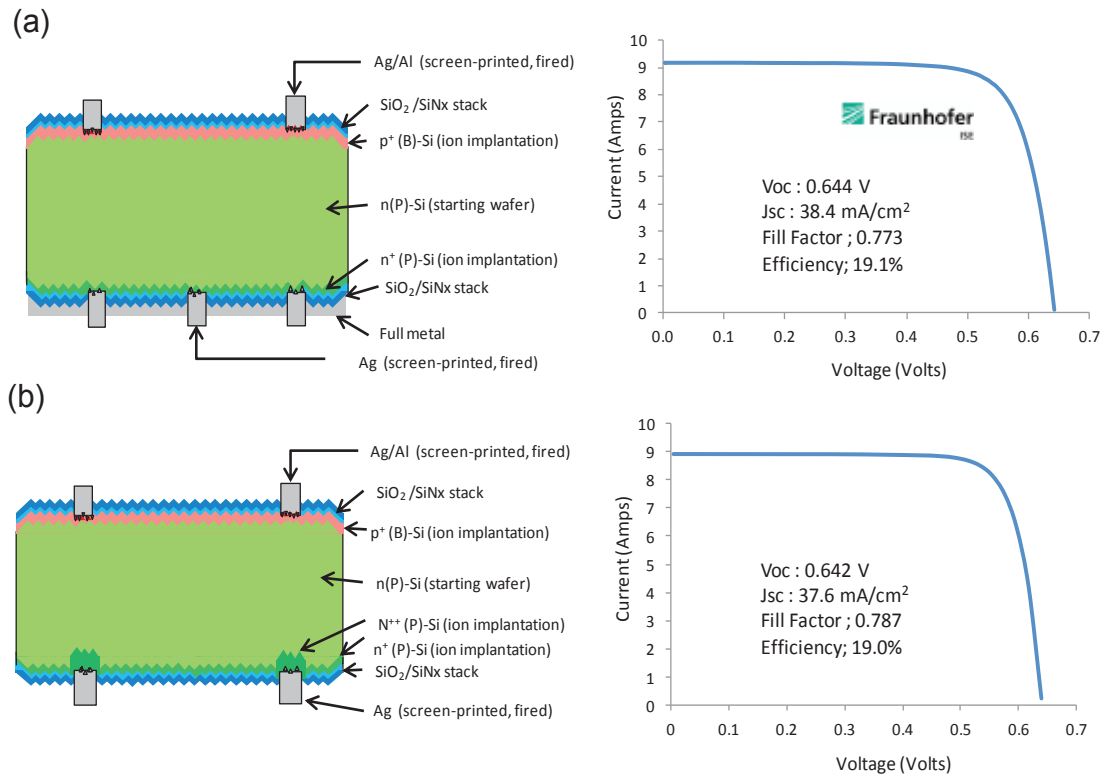

Fig. 7. Structures and performance of ion implanted n-type front junction cells; (a) passivated P BSF with local contacts and full metal back and (b) bifacial cell.

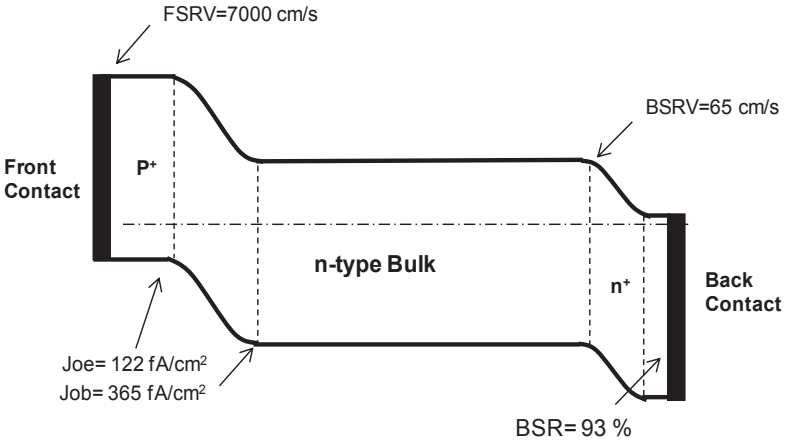

Fig. 8. Quantitative analysis of surface recombination velocities, J_{oe}, J_{ob} of a 19.1 % n-type front-junction cell with full metal back.

5. Ion-implanted n-base n^+-n-p^+ back junction cell with B emitter and P front surface field

Finally, Fig. 9 shows the advanced n-base back junction cell structure fabricated in this paper by ion-implantation. Unlike the previous cell structures, this device has implanted boron emitter on the back side and implanted P front surface field. The process sequence involved a single step anneal which also resulted in thin oxide passivation on the front and back surfaces. After capping the front and back in-situ oxides with SiN_x coating, a laser was used to open vias through the back dielectric stack. Ag grid on the front and fritless Al on the entire back were screen printed and co-fired to obtain ohmic contacts on the front and Al/B selective emitter on the back. Figure 9 shows that we were able to achieve 19 % efficient back-junction cells with V_{oc} of 645 mV and J_{sc} of 37.9 mA/cm^2 on 239 cm^2 Cz wafers.

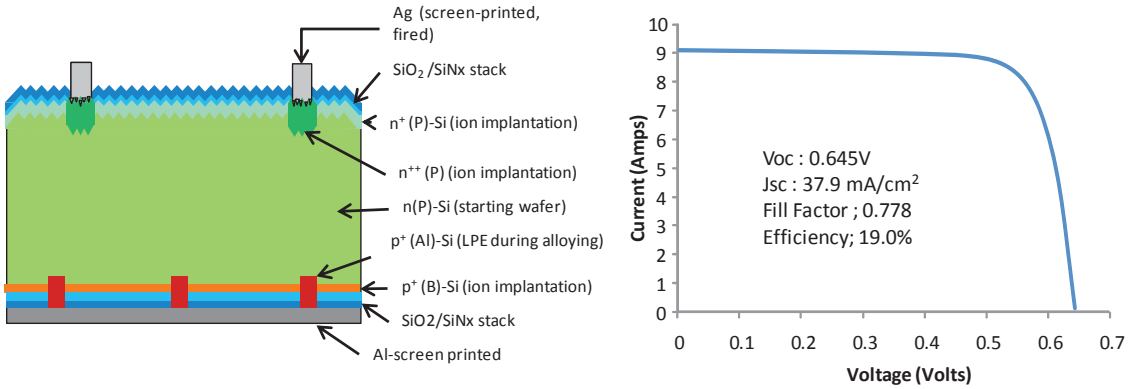

Fig. 9. Structure and I-V data of a 19 % n-type boron back junction cell.

6. Challenges in ion-implantation

Even though ion implantation simplifies the fabrication of advanced cell structures, it poses many challenges and requires good understanding and control of ambient conditions, wet chemistry, interactions between energy, dose and anneal conditions, doping profiles and bulk life time. For example, incomplete amorphisation or dopant in-activation can lead to recombination and higher J_o values. Unlike the conventional $POCl_3$ process, implanted P diffusions are not as effective in gettering impurities. Therefore, the use of contaminated wafers or process induced contaminations can be more detrimental to ion implanted cells. This is especially true for p-type Si which is more sensitive to impurities. Implanted B diffusion is a real challenge due to the formation of B clusters, incomplete activation, low solubility in Si, higher anneal temperatures, formation of B rich layer, passivation of textured B emitters and retention of high bulk life time during high temperature annealing. However, as demonstrated in this paper, a good understanding of these issues can lead to high-efficiency n-type and p-type cells.

7. Conclusion

We have shown that ion implantation provides a great opportunity to simplify the production of advanced solar cell structures. It offers several advantages over conventional $POCl_3$ including a single side dopant incorporation, in-situ oxidation for superior surface passivation, elimination of PSG glass removal and junction edge isolation, precise doping control and novel profiles by varying energy, dose and annealing recipes and patterned implantation. Suniva has pioneered the volume production of high

efficiency screen printed cells with maximum efficiency exceeding 19 % using the first high throughput (≥ 1000 wafers/hr) implanter built by Varian Corporation. In addition, we have demonstrated several promising ion implanted n and p-type advanced cell structures in R&D with efficiencies in the range of 19-20 %. These structures include p-type selective emitter cells with local Al-BSF, n-type front junction p^+-n-n^+ cells with B emitter, passivated P BSF with local contacts and full metal back, n-base B and P implanted bifacial cells, and n-base n^+-n-p^+ back junction cells with implanted and passivated B emitter and P front surface field. Design and process optimisation are expected to drive these efficiencies beyond 20 %.

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