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INVESTIGATING THE INFLUENCE OF BORON DIFFUSION TEMPERATURE ON THE PERFORMANCE OF N-TYPE PERT MONOFACIAL SOLAR CELLS WITH REDUCED THERMAL STEPS

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Abstract. *This research work aims to optimise the fabrication of n-based PERT monofacial solar cells of $p^{+}nn^{+}$ structure, using a simplified process and standard-sized n-type Czochralski (Si-Cz) monocrystalline silicon wafers. The aim is to achieve a conversion efficiency of 14.3%, comparable to the best performances reported for similar architectures. The study focused on the influence of the boron diffusion temperature on the emitter sheet resistance and the electrical performance of the cells. A diffusion temperature of 970°C was found to be optimal, offering a good compromise between low sheet resistance and uniform boron diffusion. Surface passivation by a layer of silicon oxide, deposited by dry thermal oxidation at 900°C in a controlled oxygen atmosphere, minimised surface recombination. The incorporation of an 80nm-thick silicon nitride (SiNx) anti-reflection coating (ARC), combined with pyramidal surface texturing, significantly reduced reflectance and optimised the absorption of incident light. The best-performing n-base PERT monofacial solar cell showed a short-circuit current density (Jsc) of 36.8 mA/cm², an open-circuit voltage (Voc) of 635 mV, a form factor (FF) of 0.79 and a conversion efficiency of 14.3%. These promising results confirm the potential of n-based PERT monofacial solar cells to achieve high performance using a simplified manufacturing process and standard wafer sizes, paving the way for low-cost production.*

Keywords: PERT solar cells, n-type silicon, boron diffusion, surface passivation, conversion efficiency, simplified manufacturing

BADANIE WPŁYWU TEMPERATURY DYFUZJI BORU NA WYDAJNOŚĆ JEDNOPOWIERZCHNIOWYCH OGNIW SŁONECZNYCH PERT TYPU N ZE ZREDUKOWANYMI STOPNIAMI TERMICZNYMI

Streszczenie. *Niniejsza praca badawcza ma na celu optymalizację produkcji jednopowierzchniowych ogniw słonecznych PERT o strukturze $p^{+}nn^{+}$, wykorzystujących uproszczony proces i monokrystaliczne płytki krzemowe typu n Czochralskiego (Si-Cz) o standardowych rozmiarach. Celem jest osiągnięcie sprawności konwersji na poziomie 14,3%, porównywalnej z najlepszymi wynikami odnotowanymi dla podobnych architektur. Badania koncentrują się na wpływie temperatury dyfuzji boru na rezystancję obszaru emitera i wydajność elektryczną ogniw. Stwierdzono, że temperatura dyfuzji 970°C jest optymalna, oferując dobry kompromis między niską rezystancją powierzchniową a równomierną dyfuzją boru. Pasywacja powierzchni za pomocą warstwy tlenku krzemu, osadzonej przez suche utlenianie termiczne w temperaturze 900°C w kontrolowanej atmosferze tlenu, zminimalizowała rekombinację powierzchniową. Zastosowanie powłoki antyrefleksyjnej (ARC) z azotku krzemu (SiNx) o grubości 80 nm, w połączeniu z piramidalnym teksturowaniem powierzchni, znacznie zmniejszyło współczynnik odbicia i zoptymalizowało absorpcję padającego światła. Najlepiej działające jednopowierzchniowe ogniwo słoneczne PERT na bazie n wykazało gęstość prądu zwarciowego (Jsc) 36,8 mA/cm², napięcie obwodu otwartego (Voc) 635 mV, współczynnik kształtu (FF) 0,79 i sprawność konwersji 14,3%. Te obiecujące wyniki potwierdzają potencjał jednopowierzchniowych ogniw słonecznych PERT na bazie n do osiągnięcia wysokiej wydajności przy użyciu uproszczonego procesu produkcyjnego i standardowych rozmiarów płytek, torując drogę do taniej produkcji.*

Słowa kluczowe: ogniwa słoneczne typu PERT, krzem typu n, dyfuzja boru, pasywacja powierzchni, sprawność konwersji, uproszczona produkcja

Introduction

Growing energy demand and pressing environmental concerns have put renewable energies at the forefront of the global energy transition [9]. Among these, solar photovoltaic (PV) energy is a promising and sustainable solution for meeting growing energy needs [13]. The photovoltaic industry, historically dominated by p-type monocrystalline silicon solar cells [15], is seeing a growing adoption of n-type silicon technology [12]. This development is driven by the intrinsic advantages of n-type silicon, such as better tolerance to metallic impurities [1, 10, 14], longer minority carrier lifetime [4], and absence of light-induced degradation (LID) related to boron-oxygen complexes [11]. Among solar cell architectures, PERT (Passivated Emitter and Rear Totally Diffused) technology stands out for its high conversion efficiency [16]. The PERT structure, which belongs to the PERC (Passivated Emitter and Rear Cell) family of solar cells, is characterised by high-quality surface passivation and an optimised rear surface field, improving the collection of minority carriers and increasing the open circuit voltage [2].

This research work focuses on optimising the manufacture of n-based PERT monofacial solar cells, with a $p^{+}nn^{+}$ structure, fabricated from n-type Czochralski (Si-Cz) monocrystalline silicon wafers. The main objective is to achieve a conversion efficiency of 14.3% using a simplified manufacturing process and standard wafer sizes. Particular attention is paid to optimising two crucial steps in the fabrication process: boron diffusion to form the p^{+} emitter and surface passivation by a layer of silicon oxide (SiO_2). Boron diffusion is carried out at different temperatures to study its influence on the emitter sheet resistance and the electrical performance of the solar cells. Surface passivation [7], carried out by dry thermal oxidation, aims to minimise surface recombination and improve cell efficiency [3]. In addition, an anti-reflection coating (ARC) of silicon nitride (SiNx) is deposited on the front of the cell to reduce light loss by reflection and increase the amount of light absorbed by the cell [8]. Surface texturing using an anisotropic chemical process is also used to improve light absorption [17]. This paper presents a detailed analysis of the electrical parameters of fabricated solar cells, including short-circuit current density (Jsc), open-circuit voltage (Voc), form factor (FF) and conversion efficiency (η). The external quantum efficiency (EQE) and reflectance of solar cells are also examined to assess their optical performance.

1. Methods and materials

This research work aims to optimise the fabrication of n-based PERT monofacial solar cells, with a $p^{+}nn^{+}$ structure, made from n-type Czochralski (Si-Cz) monocrystalline silicon wafers. The aim is to achieve a conversion efficiency of 14.3% by simplifying the manufacturing process and using standard wafer sizes.

1.1. Silicon substrates

The solar cells were fabricated on n-type, phosphorus-doped, solar-grade, {100} oriented Si-Cz wafers with a thickness of (180 ± 20) μm and a standard surface area of 156 mm × 156 mm (M2, 6 inches). This choice of substrate is motivated by n- type silicon's better tolerance to metallic impurities and its longer minority carrier lifetime, favouring better solar cell performance [6].

1.2. Description of the manufacturing process stages

The manufacturing process for monofacial solar cells, illustrated in Fig. 1 consists of the following steps.

Chemical Texturing with KOH
RCA Cleaning
Deposition of Boron Dopant with Spin-On Technique
Diffusion of Dopants (Boron/Phosphorus) in HF and HCl Chemical (POCl3)
Etching of Silicates (SiO2) and Phosphorus in the Same RCA Chemical Step
Etching of Surfaces with Silicon Oxide (Standard Oxygen Flow)
AR Film (TiO2) on Both Sides by E-beam
Deposition of Metal at N+ Region for Highly Doped n+ Region
Deposition of Ag/Al Metallic Paste on Highly Doped p+ Region
Simultaneous Firing of Metallic Pastes
Edge Isolation – Laser

Fig. 1. Diagram of the manufacturing process for n-type monofacial PERT solar cells

Surface texturing: Silicon wafers are textured in an alkaline solution (isopropyl alcohol, potassium hydroxide and deionised water) at 80°C for 8 minutes. This anisotropic chemical texturing process creates microscopic pyramids on the surface, increasing the effective area exposed to light and reducing reflectance.

RCA chemical cleaning: A standard RCA2 cleaning is performed to remove metallic and organic impurities from the surface, ensuring a clean silicon surface for the doping and passivation steps.

Boron deposition by spin-coating: A liquid boron solution (PBF20, Filmtronics) is deposited on the front side of the silicon wafers using a spinner (Laurell, model WS-650MZ-23NPP) at a rotation speed of 3500 rpm for 30 seconds. The solvent is then evaporated in an oven at 180°C for 15 minutes, forming a thin, uniform layer of boron source.

Boron diffusion: Boron diffusion is carried out in a horizontal quartz tube furnace (Bruce Technologies, Inc.) at 970°C for 20 minutes under a nitrogen atmosphere. This step creates the p^+ emitting region on the front face of the wafer.

Boron silicate etching and RCA cleaning: The boron silicate formed during diffusion is etched with a solution of hydrofluoric acid (HF 10%) for 1 minute. RCA2 cleaning is then carried out to remove etching residues and prepare the surface for passivation.

Surface passivation: A silicon oxide (SiO_2) passivation layer is deposited by dry thermal oxidation at 900°C for 25 minutes in a controlled oxygen atmosphere.

Deposition of the anti-reflective coating (ARC): An 80 nm-thick layer of silicon nitride (SiNx) is deposited on the front side of the wafer by plasma- enhanced chemical vapour deposition (PECVD) at a temperature of 380°C. The SiNx acts both as an anti- reflective layer and as an additional passivation layer, improving the efficiency of the solar cell.

Screen printing and drying of metal contacts: A silver (Ag) metal grid is screen printed onto the front of the wafer (MSP 485, Affiliated Manufacturers Inc.) using a silver-based conductive paste. The grid is then dried in a conveyor belt oven (AllW21 Accu Thermo AW610) at 280°C for 8 minutes.

Firing the metal contacts: The silver-plated metal is baked in a conveyor belt oven at 840°C for 2 minutes to form contacts ohmic contacts with the heavily doped p^+ region.

Edge insulation by laser cutting: The edges of the solar cells are insulated by laser cutting (4000 Series YAG Laser Systems, US Laser Corporation).

1.3. Characterisation of solar cells

After manufacture, the solar cells are characterised to assess their performance:

Sheet resistance: The sheet resistance of the p^+emitter layer is measured using a four-point system.

Current-voltage (I-V) characteristic curve: I-V curves are measured under standard irradiance (1000 W/m², AM1.5G) and temperature (25°C) conditions using a solar simulator (class AAA) to extract short-circuit current density (Jsc), open-circuit voltage (Voc), form factor (FF) and conversion efficiency (η).

Reflectance: The reflectance of the cell is measured using a UV-visible-NIR spectrophotometer.

External quantum efficiency (EQE): The EQE of the cell is measured as a function of wavelength.

By optimising these parameters, we were able to obtain a conversion efficiency of 14.3% for n-based PERT monofacial solar cells.

2. Results and discussion

2.1. Analysis of emitter sheet resistance

Influence of boron diffusion temperature on sheet resistance table 1 shows the sheet resistance values of the boron p^+ emitter (RSQ-B) for monofacial solar cells fabricated on Si-Cz wafers.

Table 1. Sheet resistance of boron p^+ emitter (RSQ-B) as a function of boron diffusion temperature (TB) for Si-Cz wafers

TB (°C)	RSQ-B (Ω/sq)
950	105 ± 4
960	90 ± 3
970	80 ± 3

As expected, the sheet resistance of the emitter decreases with increasing TB. This decrease is consistent with deeper boron diffusion at higher temperatures, increasing the concentration of majority carriers and reducing the resistivity of the emitter layer.

Uniformity of diffusion

The low standard deviation observed for RSQ-B, particularly at 970°C, suggests uniform boron diffusion. The temperature of 970°C was chosen for solar cell manufacture because it offers a good compromise between low sheet resistance and good diffusion uniformity.

2.2. Influence of boron diffusion temperature on the electrical parameters of solar cells

The electrical performance of n-base PERT monofacial solar cells fabricated on Si-Cz wafers was evaluated as a function of boron diffusion temperature. Table 2 shows the values of Jsc, Voc, FF and η obtained for cells fabricated at different temperatures.

Table 2. Electrical parameters of n-based PERT monofacial solar cells as a function of boron diffusion temperature (TB)

TB (°C)	Jsc (mA/cm²)	Voc (mV)	FF	η (%)
950	35.2	625	0.77	13.5
960	36.1	630	0.78	14.0
970	36.8	635	0.79	14.3

2.3. Analysis of electrical performance

Increasing the diffusion temperature of boron leads to an improvement in the electrical performance of solar cells. An increase in Jsc, Voc and FF is observed with increasing TB, leading to an increase in conversion efficiency. Fig. 2 Current-voltage (I-V) characteristic curve of the best performing n-based PERT single-facet solar cell (TB = 970 °C).

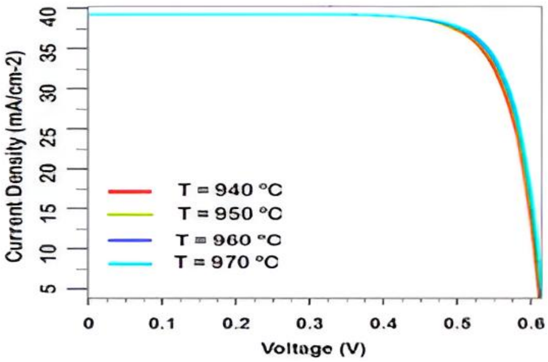

Fig. 2. Current-voltage (I-V) characteristic of n-type silicon-based monofacial PERT solar cells as a function of voltage for different boron diffusion temperatures

Fig. 2 shows the current-voltage (I-V) characteristic curve of the best-performing solar cell, manufactured with a TB of 970°C. This cell has Jsc of 36.8 mA/cm², a Voc of 635 mV, a FF of 0.79 and a conversion efficiency of 14.3%.

3. Discussion

The improvement in solar cell performance with increasing boron diffusion temperature can be attributed to several factors:

- Increased concentration of majority carriers in the emitter: Deeper boron diffusion leads to a higher concentration of majority carriers (holes) in the emitter, which improves the conductivity of the layer and reduces the series resistance of the solar cell.
- Improved p-n junction quality: A higher diffusion temperature can lead to better p-n junction quality, reducing recombination at the interface and improving minority carrier collection.
- Improved surface passivation: Silicon oxide passivation is more effective at higher temperatures, helping to reduce surface recombination and improve minority carrier lifetime.

3.1. Reflectance analysis

The reflectance of the solar cell was measured to assess the effectiveness of the SiNx surface texturing and anti-reflective coating (ARC).

Fig. 3 reflectance of the n-base PERT monofacial solar cell as a function of wavelength.

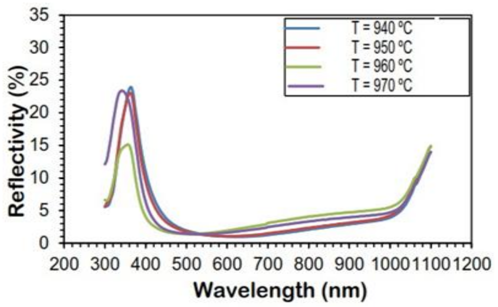

Fig. 3. Reflectance of the p+ emitting surface of n-type silicon-based monofacial PERT solar cells, as a function of wavelength, for different boron diffusion temperatures

Fig. 3 shows the reflectance of the solar cell as a function of wavelength. A minimum reflectance of around 3% is observed in the visible region of the spectrum, centred around 400 nm, indicating excellent performance of the SiNx surface texturing and ARC layer. The combination of the pyramidal texturing and ARC layer minimises light loss through reflection, thereby increasing the amount of light absorbed by the solar cell and contributing to improved efficiency.

3.2. External quantum efficiency (EQE) analysis

EQE measures the ability of the solar cell to convert incident photons into electrons as a function of wavelength. Fig. 4 shows external quantum efficiency of the n-based PERT monofacial solar cell as a function of wavelength.

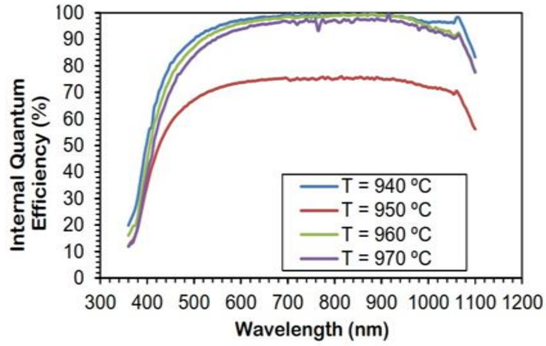

Fig. 4. External quantum efficiency (EQE) of n-type silicon-based monofacial PERT solar cells as a function of wavelength for different boron diffusion temperatures

A maximum EQE of around 95% is observed in the visible region of the spectrum, which means that the solar cell converts photons in this wavelength range very efficiently into electrons. The EQE decreases progressively for shorter and longer wavelengths, due to the low absorption of silicon in these regions of the spectrum. A slight decrease in EQE is observed around 400 nm, which corresponds to the wavelength where reflectance is minimal. This suggests that surface recombination in the p^+ emitter region could be a factor limiting the efficiency of the solar cell.

3.3. General discussion

By optimising the fabrication process parameters, a conversion efficiency of 14.3% was achieved for n-based PERT monofacial solar cells fabricated on standard-sized Si-Cz wafers. This performance is comparable to the best efficiencies reported in the literature for n-base PERT solar cells with a unilateral architecture.

- Several factors contributed to this result: Optimum boron diffusion: Boron diffusion at 970°C resulted in low emitter sheet resistance (80 ± 3 Ω/sq) and good diffusion uniformity, contributing to improved electrical performance.
- Efficient surface passivation: Surface passivation with silicon oxide at 900°C in a controlled oxygen atmosphere reduced surface recombination and improved minority carrier lifetime.
- Minimising optical losses: The 80 nm-thick SiNx ARC layer and surface texturing minimised light losses through reflection, thereby increasing the amount of light absorbed by the solar cell. The minimum reflectance in the visible region of the spectrum (Fig. 4) confirms the effectiveness of these processes.

These results demonstrate the potential of n-based PERT monofacial solar cells to achieve high performance using a simplified fabrication process and standard wafer sizes. The simplification of the unilateral architecture, compared with a bifacial architecture, reduces manufacturing costs and simplifies the manufacturing process.

3.4. Perspectives

Future studies could focus on optimising surface passivation by exploring other passivation materials, such as aluminium oxide (Al_2O_3) or hydrogenated amorphous silicon nitride (a-SiN:H). In addition, numerical simulations could be used to optimise the solar cell structure, including the geometry of the metal grid and the back surface field, to further improve conversion efficiency.

4. Conclusion

This study has demonstrated the feasibility of achieving a conversion efficiency of 14.3% for n-base PERT monofacial solar cells of p^+nn^+ structure, fabricated from standard size Si-Cz wafers. This performance, comparable to the best efficiencies reported for single-sided n-base PERT cells, was achieved through careful optimisation of the manufacturing process. Boron diffusion at 970°C was found to be optimal, providing low emitter sheet resistance (80 ± 3 Ω/sq) and good diffusion uniformity, confirming the significant influence of this parameter on cell performance. Increasing the diffusion temperature led to a significant increase in short-circuit current density (Jsc), open-circuit voltage (Voc) and form factor (FF), resulting in improved conversion efficiency. Surface passivation by a layer of silicon oxide, carried out at 900°C in a controlled atmosphere of oxygen, minimised surface recombination, thus contributing to improved efficiency. The use of a SiNx anti-reflective layer and surface texturing also played a crucial role in reducing optical losses, as confirmed by reflectance and external quantum efficiency (EQE) measurements. This simplified manufacturing approach, using standard wafer sizes and a one-sided architecture, opens the way to low-cost production of high-performance n-base PERT solar cells. Future research could explore the optimisation of passivation layer thickness and the influence of base doping to further improve conversion efficiency.

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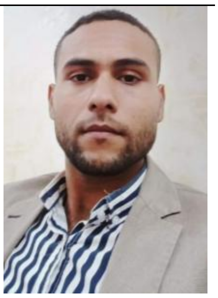

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