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Development of a large area n-type PERT cell with high efficiency of 22% using industrially feasible technology

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ABSTRACT

A high-efficiency front junction n-type passivated emitter and a rear total diffusion (n-type PERT) solar cell with the front boron diffusion passivated by a Al_2O_3/SiN_x stack layer deposited by plasma enhanced chemical vapor method and the rear with phosphorus total diffusion and Al evaporated local contact are presented in this paper. The main purpose of this study was to develop industrially feasible front junction n-type PERT solar cells with high-efficiency; these were realized on a large area of n-type industrial 5- and 6-in. wafers. An average of 21.85% cell efficiency was achieved on 5-in. wafers, and the highest cell convert efficiency of 21.98% was achieved with V_{oc} of 683.8 mV, J_{sc} of 40.13 mA/cm^2, and *FF* of 80.11%. For 6-in. cells, we get Fraunhofer independently confirmed efficiency of 21.49% with a V_{oc} of 674.1 mV, a J_{sc} of 39.77 mA/cm^2, a *FF* of 80.18%. Details of cell fabrication and results are presented, followed by a best cell power loss analysis on V_{oc}, I_{sc} and *FF*.

1. Introduction

N-type silicon base solar cells have high potential for applications in the photovoltaic industry. Fabricating high-efficiency devices with higher n-type wafer bulk lifetime is the main trend in photovoltaic industry. N-type Si based devices have been found to be promising candidates since interdigitated back contact (IBC) cells were reported to have achieved an efficiency of 25% [1]. Heterojunction back contact (HBC) cells were reported to have achieved efficiencies of 25.6% [2–4], and recently, front junction tunnel oxide passivation contact (TOPCon) cells were reported with efficiencies of 25.1% [5]. Trina solar cells achieved 22.9% efficiency in a large area 6-in. n-type wafer with industrial IBC technology [6]. However, because of complex processes and high costs involved, these high-efficiency cells cannot be widely applied in the industry. P-type passivated emitter and rear contact (PERC) cells have been mass produced, but when the efficiency is increased, the bulk and front emitter recombination dominates power losses, and the n-type CZ wafer has a much higher minority carrier lifetime than the p-type. The reverse saturation current density of the boron diffused emitter (J_{0e}) is lower than the phosphorus emitter because of less inactive doping [7,8]. Furthermore, the n-type silicon does not suffer from boron–oxygen (B–O) pair related light induced degradation (LID). The front junction n-type PERT cell combines the advantages of p-type PERC and n-type cell, has excellent short wave spectral response and better bulk lifetime, with better scope for increasing efficiency. Fraunhofer reported front junction n-type PERT cells with 22.7% efficiency on 4 cm^2 wafer with fully implantation process [9]. Front junction n-type PERL cell with 23.4% efficiency on 4 cm^2 wafer was also reported by Fraunhofer also [10]. For large area front junction n-type PERT cells, Georgia Institute of Technology reported 20.7% efficiency on a 6-in. CZ silicon wafer [11]. N-type rear junction passovation emitter and rear total diffusion (RJ-PERT) cell, IMEC got the best cell efficiency 22.5% on 6 in. CZ wafer, with front Ni/Cu plating and rear Al sputtering [12]. Hanwha Q cells reported the best efficiency 20.7% [13]. This is also the best rear-junction n-PERT cell efficiency on large area wafer with paste metallization solution. In mass production, it is no value compare with p-PERC. In the same paper, Hanwha Qcells reported 21.3% efficiency with rear PVD process.

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N-type silicon solar cells with lower fabrication costs (that can compete with traditional p-type silicon solar cells), large area (larger than 5-in.), and higher convert efficiency (higher than 22%) is needed in industrial production. The objective of our study is to find this kind of low cost, high-efficiency, easy to manufacture solar cell that can replace the traditional silicon solar cell. Front junction n-type PERT is a good candidate for meeting all these conditions.

In this study, large area and high-efficiency front junction n-type PERT cells were developed. Industrially feasible cell technologies such as plating, physical vapor deposition of Al film coating, boron diffusion, plasma enhanced chemical vapor deposition (PECVD) for Al_2O_3/SiN_x coating were applied to fabricate real front junction n-type PERT cells. Boron and phosphorus doping profiles were modified to reduce Auger recombination and passivate metal contact area, and an excellent average V_{oc} of 684 mV was achieved. Front and rear side laminated SiN_x layer was modified to enhance light trapping, and a near-band gap effective optical path length factor Z_0 of 33.3 was achieved. All of these technologies can be realized in mass production. Power loss analysis was carried out to analyze the potential for higher efficiency and the possibility of industrial production.

2. Device fabrication and measurements

To show that the front junction n-type PERT cell is a good candidate, solar cells were fabricated on commercial 3 Ω cm, 5-in. (125 mm × 125 mm, area 156.25 cm^2), CZ, n-type silicon wafers with a thickness of 190 μm. They feature a front surface with a random pyramids texture and a boron thermal diffused emitter. Al_2O_3/SiN_x stack layers were used for front passivation and anti-reflection. After rear single etching and front masking process, rear phosphorus diffusion for back surface passivation (BSF) and metal contact was carried out. An industrial thermal diffusion machine (Tempress, Holland) was used to diffuse boron and phosphorus, doping source is BBr_3 and $POCl_3$. After removing BSG (boron silicate glass) and PSG (phosphorus silicate glass), the thermal oxidation process was implemented for rear surface passivation with 5 nm-thick SiO_2, front SiO_2 was removed by HF single side etching.

The Al_2O_3 and SiN_x layers were deposited by the PECVD method at a temperature of 400 °C using MIMA equipment (Meyer Burger, Switzerland). On the rear side, 80-nm thick PECVD SiN_x capping layer was deposited on a thermal silicon oxide surface to provide sufficient hydrogen to enhance the passivation effect of silicon oxide, and to enhance the internal optical reflection [14]. In the next step, a green light picosecond laser was used to ablate the rear stack film; then, the rear side contacts were defined and realized by the e-beam evaporation of a 2 μm-thick aluminum layer. Here, we used a picosecond laser to reduce the laser induced damage, a deeper UV laser is better. The forward bias plating process for front side Ni/Cu/Ag electrode was used [15]. The front surface layers were opened by a UV nanosecond laser. To ensure the electrical contact, the cells were annealed in forming gas ambient (FGA). The final structure of the cell is shown in Fig. 1.

The emitter boron and rear phosphorus dopant profiles were measured by electrochemical capacitance–voltage (ECV) using a CVP21 from Ingenieurbüro WEP, following the measuring procedures described in Ref. [16]. The ECV technique monitors the active dopant concentration [17], regardless of the ionization fraction, and the substrate is an n-type wafer with resistivity of 3 Ω cm. The reverse saturation current density J_0 was measured to evaluate the recombination. The front J_0 emitter monitor was measured on a symmetrical structure of both side boron diffused n-type monitor wafers, bulk resistivity of 8 Ω cm, surface passivated by PECVD Al_2O_3/SiN_x stack layers, before and after oxidation. The reverse saturation current density J_0 was extracted from lifetime measurements performed with a Sinton WCT-120 lifetime tester, applying the method developed by Kane and Swanson [18]. For the extraction of J_0 from lifetime measurements, an intrinsic carrier density of $n_i = 8.6 \times 10^9\ cm^{-3}$ was used. The lifetime was monitored at an injection density Δn of $5 \times 10^{15}\ cm^{-3}$ for J_0 extraction [19]; hence, the resulting J_0 values were not underestimated and were therefore relevant for the one-sun condition. The rear $J_{0\ BSF}$ monitor was measured on a symmetrical structure of n-type monitor wafers with both side phosphorus diffusion, bulk resistivity of about 8 Ω cm, surface passivated by 5 nm-thick thermal SiO_2, and 80 nm-thick PECVD SiN_x stack layers.

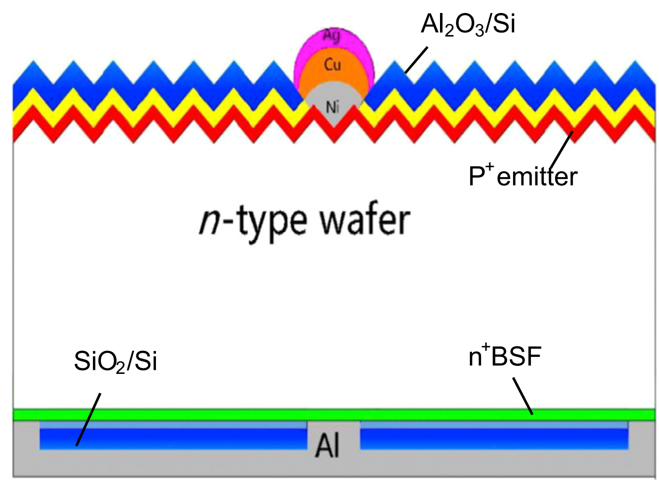

Fig. 1. Schematic cross section of the front junction n-type PERT cell structure.

Table 1
One-sun parameters of high-efficiency front junction n-type PERL solar cells, the best cell was independently confirmed at Fraunhofer ISE CalLab.

	V_{oc} (mV)	J_{sc} (mA/cm^2)	FF (%)	η (%)
AVE.	683.8 ± 1	40.09 ± 0.09	79.76 ± 0.28	21.85 ± 0.1
Best cell	683.8	40.13	80.11	21.98

3. Results and discussion

3.1. Realizing high-efficiency for front junction n-type PERT cell

The one-sun measurement parameters for this kind of front junction n-type PERT solar cells are summarized in Table 1. Due to the effective front side passivation by the Al_2O_3 and rear side thermal SiO_2 passivation, very high open-circuit voltages with an average of 684 mV for 20 processed solar cells have been achieved. For 5-in. cells, the best cell exhibits a V_{oc} of 683.8 mV, a J_{sc} of 40.13 mA/cm^2, and a *FF* of 80.11%, resulting in an independently confirmed solar cell efficiency of 21.98%. Fig. 2a gives the measurement *I–V* curve, independently confirmed at Fraunhofer ISE CalLab. The exceptionally high values for V_{oc} and J_{sc} in a large area front junction n-type PERT cell that were fabricated without any complicated processes. In our lab, small batch (almost 20–30 pc) of cells can reach stable average V_{oc} higher than 680 mV, which indicates proves that the n-type PERT cells maybe well suitable for high-efficiency silicon solar cell mass production. The quantum efficiency of the best cell is shown in Fig. 3b, it shows good bulk response. Over a wide wavelength range (400–1000 nm) the internal quantum efficiency (IQE) is nearly 100%. IQE in short wave