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20.8% industrial PERC solar cell: ALD Al_2O_3 rear surface passivation, efficiency loss mechanisms analysis and roadmap to 24%

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ABSTRACT

PERC cell is currently entering the industrial crystalline silicon solar cell production lines. While there has been many reports focusing on research PERCs, this paper aims to present a cost-efficient PERC roadmap at fully industrial level, i.e. beyond the research and pilot lines. We present a systematic experimental study on the most important material and cell parameters for PERC, for instance, the key processes of ozone based ALD Al_2O_3 rear surface passivation and screen printed aluminum local back surface field are discussed in detail, especially highlighting the importance of the process integration. Industrial PERC cells using this roadmap have demonstrated average efficiency of 20.5% and champion efficiency of 20.8% with open circuit voltage of 660–666 mV. Light-induced degradation analysis shows that the PERC cells are subject to bulk degradation and not to surface degradation. An anti-LID treatment processed by simultaneous applying forward voltages and anneal can drastically decrease LID. The cell efficiency loss mechanisms are analyzed based on the quantum efficiency measurement, suns-V_{oc} tests and series resistance loss calculations. These are combined with PC1D and PC2D simulations to analyze recombination loss mechanisms present in the cells in order to promote viable solutions to extend the current industrial PERC cell efficiency to 24%.

1. Introduction

PERC (Passivated Emitter and Rear Cell) structure was initially developed in 1989 by University of New South Wales in lab scale [1] and redeveloped in 2002 by Fraunhofer ISE by using the pilot-line laser fired contact process [2]. In recent years, there has been continuous development to achieve cost-efficient processes [3–13], e.g. surface passivation by dielectric films using low temperature processes [3–8], laser ablation [9,10], and screen-printed Al local back surface field (LBSF) [11]. As a result, PERC cell is gradually becoming the most cost-efficient choice for mass production of crystalline silicon solar cells.

Al_2O_3 passivation was first successfully applied on boron emitter passivation of n-type Si solar cell by Benick and Hoex in 2008 [14]. Al_2O_3 passivation can achieve the lowest surface recombination velocity (SRV) on p-type Si (p-Si) due to excellent field effect passivation by the negative fixed charges (Q_f) and superior chemical passivation due to the low interface defect density (D_{it}) [7,8]. Furthermore, its good low-light performance, anti-ultraviolet radiation and the resistance to humidity leads to outstanding and stable module performance in different environments [6]. In general, Al_2O_3 passivation on p-Si has the highest potential to become the mainstream technology for surface passivation of high efficiency Si solar cells. Among all the techniques to synthesize Al_2O_3, atomic layer deposition (ALD) is very promising due to advantages such as mono-layer film growth control, pinhole-free coating, good step coverage and low substrate temperature [6].

Until now, most of the research on Al_2O_3 passivation has mainly focused on the Al_2O_3 process itself [5–8], while its integration into the cell processes (e.g. PERC) has not been studied in detail. Moreover, the research on industrial PERC is still limited. Typical studies on industrial PERC are found in the Ref.s [15–18], among which Trina Solar holds the record cell efficiency (η_{cell}) of 22.13% and 21.25% on mono-and multi- crystalline Si PERC, respectively, achieved in pilot line in December 2015 [18]. Meanwhile, some theoretical studies have attempted to analyze the η_{cell} loss mechanisms of the lab-scale, pilot-line or industrial PERC [19–24]. However, the η_{cell} loss mechanisms (especially the recombination losses mechanisms) of the industrial PERC still need to be further understood. This paper aims to present a

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cost-efficient industrial PERC roadmap based on the experimental data obtained in mass production. In Section 2, we discuss in detail the key processes of ozone-based ALD Al_2O_3 rear surface passivation and screen-printed Al LBSF, highlighting the importance of process integration. Then we analyze the efficiency loss mechanisms based on some key characterization methods and discuss the light-induced degradation (LID) behaviour of such industrial PERC cell. In Section 3, we systematically analyze the recombination loss mechanisms on current industrial PERC cell through PC1D and PC2D simulations and promote a future technology roadmap to extend the η_{cell} to 24%.

2. 20.8% industrial ALD Al_2O_3 PERC cell

2.1. Experimental methods

In this study, both minority carrier lifetime (in the following shortened as lifetime) and solar cell experiments were carried out to effectively investigate into each sub-topic. For these experiments, we used p-type (boron (B) doped), Czochralski silicon (Cz-Si) wafers, with resistivity from 1 to 4 Ω cm and a starting thickness of 190 µm. The wafers are industry-standard, pseudo-square 6-in. (cell area=242.2 cm^2) and are taken from the same Cz-Si ingot.

The structure and the corresponding process flow of the industrial PERC cell used in this study are shown in Figs. 1 and 2, respectively. After saw damage removal (SDR) and random-pyramids-texturing using NAOH solution, front n^+ emitter with 90 Ω/□ sheet resistance ($R_□$) was formed via $POCl_3$ diffusion. Then edge isolation and rear side polishing were processed in a RENA's wet bench using HNO_3-HF-H_2SO_4 solution. The rear polished surface is beneficial to both light trapping and rear surface passivation. The cell rear side was passivated by ALD Al_2O_3 and plasma enhanced chemical vapor deposition (PECVD) SiN_x stacks and then locally patterned using laser ablation with 532 nm ps-laser. Finally, screen printing and co-firing were used for front and rear side metallization to form front Ag/n^+-Si ohmic contact, Al LBSF and rear local Al/p^+-Si ohmic contact.

For lifetime experiments, ALD Al_2O_3 and PECVD SiN_x stacks were symmetrically processed on both sides of the samples. Processes of ALD Al_2O_3, post ALD anneal and PECVD SiN_x capping were varied. In this study, we focused on ozone (O_3) and $Al(CH_3)_3$ trimethylaluminum (TMA)-based thermal ALD process, which was implemented by Beneq's industrial P800 batch ALD tool (throughput:1600 wafers/hour). The post anneal process was implemented in a tube furnace or in an RTP firing furnace. Effective minority carrier lifetime (τ_{eff}) and implied V_{oc} at 1 sun were determined by a Sinton WCT-120 lifetime tester [25]. By combining the Sinton tester with iodine passivation [26], the measured wafer bulk lifetime is ~ 250 µs (at $5 \cdot 10^{15}$ cm^{-3} injection level) with the implied V_{oc} at 1 sun of ~ 720 mV. Thickness and refractive index (n_k) of the dielectric films were determined by a Suntech ellipsometer at a wavelength of 633 nm. Q_f and D_{it} were measured by Semilab SDI PV2000 using the contactless COCOS (corona oxide characterization of semiconductors) method [27].

Cell performances and IV-curves were tested on a HALM I-V tester, which was calibrated with a reference PERC cell previously tested by Fraunhofer ISE under the standard global AM1.5 spectrum, 1000 W/m^2, at 25 °C. Note that the given cell performances were measured before LID except in Section 2.5. Quantum efficiency (QE), electroluminescence (EL), suns-V_{oc} were measured before LID on the completed cells. The LID experiments were carried out under 1-Sun illumination intensity and at 25 °C. The total illumination time was 4 h and the degraded cell parameters reported in Section 2.5 were measured after saturation.

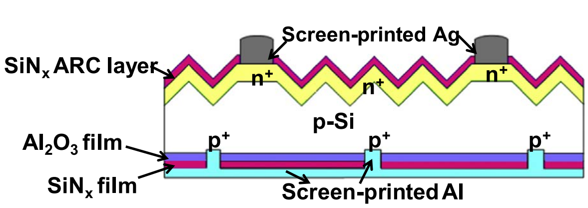

Fig. 1. Schematic drawing of the industrial PERC cell structure.

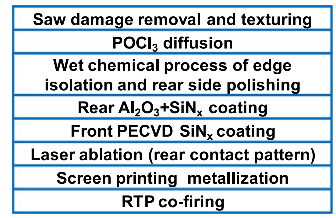

Fig. 2. Process flow of CSUN's industrial Al_2O_3 PERC cell.

2.2. Al_2O_3 rear surface passivation

2.2.1. The basic research foundations

Based on our previous research [28], the baseline process conditions used in the study presented in Section 2.2 are as follows: 1) SDR: ~20µm; 2) pre-ALD clean: HCl and HF clean; 3) ALD temperature: 200°C; 4) Al_2O_3/SiN_x: 10 nm/100nm; 5) deposition pressure: 150–500Pa; 6) RTP firing: ~760 °C (the real peak temperature T_{peak}) in compressed air for 2–3 s.

The relevant experimental information in Section 2.2 is as follows: 1) Effective lifetime, film thickness, n_k, D_{it}, Q_f are measured on the lifetime samples with (100)-oriented Si surface after SDR. 2) The basic settings of Sinton WCT-120 tester: generalized mode, specified minority carrier density (MCD) equal to $5 \cdot 10^{15}$ cm^{-3}; optical constant selected depending on the reflectance and transmittance of the Si surface and the dielectric stack [25] (i.e. 0.7 for (100)-oriented Si surface, 0.7–0.95 for Al_2O_3/SiN_x stack); 3) The number of lifetime and cell samples are 5 and 25–30 for each group, respectively; 4) Due to technology confidentiality, some process parameters are given as relative values. The procedure of the lifetime experiments in Section 2.2 is shown in Fig. 3.

2.2.2. Effect of ozone parameters

The ALD process, as a mono-layer growth-controlled and surface self-limited reaction, is achieved by alternating two chemical precursors into the vacuum chamber. Therefore, process parameters of the chemical precursors are crucial to the ALD process. In this study, the effect of O_3-related parameters (see Table 1) on Al_2O_3 passivation was studied.

Effective lifetime with different O_3 concentrations is shown in Fig. 4, where the relevant procedure and process parameters can be referred to Section 2.2.1. Note that the lifetime samples did not undergo a post-ALD anneal, they were coated with SiN_x films and then underwent the RTP firing step. Effects of O_3 concentration, O_3 dosing time and O_2 flow on the open circuit voltage (V_{oc}) are shown in Fig. 5. As shown in these figures, the Al_2O_3 passivation quality

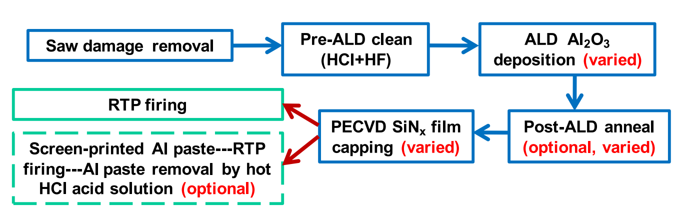

Fig. 3. The procedure of the Al_2O_3 passivation lifetime experiments in Section 2.2. Note: Because lifetime cannot be measured after metallization, we separated two groups in the lifetime experiments: one group went directly into the RTP firing step without screen-printed Al paste, while the second group (optional) was measured after screen printing the Al paste, RTP firing, and Al paste removal.