P-type Czochralski Silicon Heterojunction Solar Cells with High and Stable Open-circuit Voltage

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Silicon heterojunction (SHJ) solar cells currently hold the world-record 1-sun single junction silicon solar cell efficiency with their remarkably high open-circuit voltages (V_{OC}). This is due to the excellent surface passivation provided by the amorphous silicon films, which imposes a temperature limit of ~250°C for the SHJ solar cell fabrication. As a consequence, SHJ solar cells do not benefit from the gettering of impurities and hydrogenation of bulk defects that naturally takes place at high temperatures (> 700°C) during the fabrication of aluminium back surface field and passivated emitted and rear cell (PERC) architectures. Industrial high-efficiency SHJ solar cells use n-type Czochralski silicon (Cz-Si) wafers with starting lifetimes of at least 1 ms. The replacement of n-type with cheaper p-type wafers is potentially commercially viable if p-type SHJ (p-SHJ) solar cells have an efficiency within 0.4%$_{abs}$ of n-type SHJ (n-SHJ) solar cells.[1] Also, p-SHJ solar cells have to maintain the same stability as their n-type counterparts. Due to the presence of both boron and oxygen, boron-doped Cz-Si is susceptible to boron-oxygen (BO) related light- or carrier induced degradation (LID). Although BO related light induced degradation (BO-LID) can reduce the efficiency by up to 1.5%$_{abs}$ in PERC solar cells, there has been substantial progress in developing industry-suitable solutions for BO-LID in p-type PERC solar cells which minimise this loss to less than 0.5%$_{rel}$.[2] When it comes to p-SHJ solar cells, little work has been done investigating LID.[3] In this work, we identify BO-LID in p-SHJ solar cells and develop defect-engineering processes to mitigate such degradation. We then combine these defect-engineering processes with an industrial SHJ solar cell processing to demonstrate large-area stable p-SHJ solar cells with V_{OC} of 734 mV and efficiency of 21.9%.

In this work, commercial-grade textured p-type Cz-Si wafers with a resistivity of 1.6 Ω·cm were used. All the wafers were pre-gettered using a phosphorus diffusion gettering process (G) with a peak temperature of 840°C for 45 minutes to increase material quality and remove metallic impurities. This was followed by a re-texturing step to remove approximately 2 μm from each side of the wafers including the diffused layers. The deposition of hydrogenated silicon nitride films (SiN_x:H) was performed at a peak temperature of 400 °C on both sides of the wafers for surface passivation. The SiN_x:H films were then removed before SHJ solar cell fabrication. The cell formation at Meyer Burger used the same processing conditions as for n-SHJ solar cells, no optimisation was performed for the p-SHJ solar cell fabrication. The p-SHJ solar cells were then divided into two groups, where one group was treated with an advanced hydrogenation process (AHP) at UNSW using an in-line pilot production tool, and the other group was not treated. The susceptibility of the samples from both groups to BO-LID was tested with 48 hours light-soaking (LS) at 25°C and an illumination intensity of approximately 0.02 W.cm^{-2}. The V_{OC} was in-situ monitored on a Suns-V_{OC} stage during LS. Injection-dependent minority carrier effective lifetime (τ_{eff} versus Δn) curves of the SHJ solar cells were extracted from the Suns-V_{OC} measurements. Current density-voltage (J-V) measurements were performed at Meyer Burger using standard testing conditions, while the champion stable SHJ solar cell was also independently measured at SERIS.

The J-V characteristics of the p-SHJ solar cells are presented in Table I. An average V_{OC} of 735 mV was achieved for the G only group, which resulted in an average efficiency of 21.6%. The average efficiency decreased to 18.5% after LS, representing a 3.1%$_{abs}$ drop in efficiency. The V_{OC} of one sample from the G group was monitored during LS (Figure 1). An enormous V_{OC} drop of 63 mV was recorded, resulting in a final V_{OC} of 658 mV for the G+LS sample. To verify whether the observed degradation was BO-LID, the injection-dependent SRH lifetime ($1/\tau_{SRH}$) was determined by subtracting the inverse effective carrier lifetimes before and after LS (Figure 2). A defect capture-cross-section ratio ($k = \sigma_n/\sigma_p$) of 11.4 was determined, which is in agreement with known values for the BO defect.[4]

Table I. J-V characteristics of the defect-engineered p-SHJ solar cells.

Process	Number of cells	J_{SC} [mA cm^{-2}]	V_{OC} [mV]	FF [%]	η [%]
G	7	39.7 ± 0	735.4 ± 0.9	73.8 ± 0.3	21.6 ± 0.1
G + LS	2	38.7 ± 0.1	658.1 ± 3.9	72.3 ± 0.5	18.5 ± 0
G + AHP	4	39.6 ± 0	736.7 ± 1.4	74.8 ± 0.8	21.8 ± 0.3
G + AHP + LS	2	39.6 ± 0.1	735.4 ± 0.1	74.1 ± 0.5	21.6 ± 0.2
Champion stable cell measured at SERIS					
G + AHP + LS	1	39.1	734.1	76.0	21.9

AHP increased the average efficiency of the G group by 0.2%$_{abs}$, resulting in an average efficiency of 21.8% for the G+AHP group. A stable efficiency of 21.9% (V_{OC} of 734 mV) was achieved for the champion cell after AHP and LS. One sample from the G+AHP also had its V_{OC} monitored during degradation, and after 48 hours of LS, almost no change was observed in V_{OC} (Figure 1). This resulted in an average stable efficiency of 21.6% for the G+AHP+LS group. Therefore, the efficiency loss due to LID was reduced from 3.1%$_{abs}$ (G+LS) to 0.2%$_{abs}$ (G+AHP+LS) with the AHP treatment. It is important to note that the mitigation of BO-LID was achieved without a high-temperature hydrogenation step (> 700°C), which is known to introduce hydrogen from the SiN_x:H films into the silicon wafer's bulk during the fabrication process. This is in agreement with the recent results from Sun et al.[5], which demonstrates hydrogen incorporation into the silicon bulk under the typical SHJ fabrication temperature regime (~250°C).

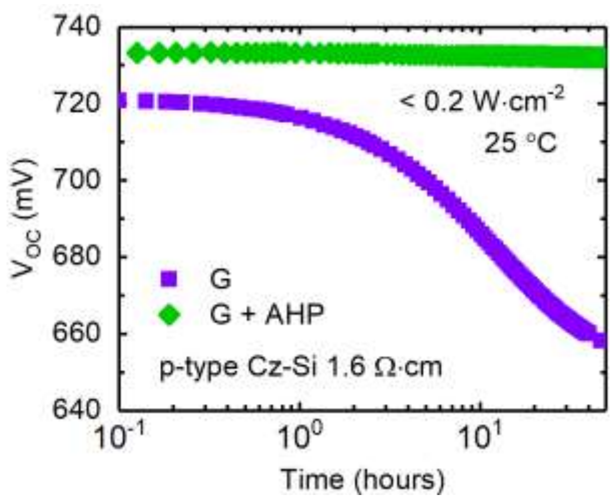

Figure 1. V_{OC} as a function of time under illumination for the AHP treated (G+AHP) and non-treated (G) p-SHJ solar cells.

While the instabilities related to BO-LID were mitigated and the stable V_{OC}s demonstrated here are comparable with the V_{OC} of the 26.7% solar cell from Yoshikawa et al. (738 mV, n-SHJ)[6] and higher than the V_{OC} of the 26.1% interdigitated back contact solar cell featuring tunnel oxide-doped polycrystalline silicon contacts from Haase et al. (727 mV, p-type)[7], the FF is still a limiting factor. Although the average FF also increased with AHP, from 73.8% (G) to 74.8% (G+AHP), it is still ~6%$_{abs}$ lower than the recent p-SHJ solar cells from Descoeudres et al.[8] The low FF in p-SHJ is expected to be caused by surface-related effect rather than a bulk effect.[9] Olibet et al. suggested that the lower τ_{eff} at low-Δn on p-type than n-type is caused by to the discrepancy between the capture-cross-section for electrons and holes at the a-Si:H/c-Si interface.[10] N-SHJ can also be susceptible to this reduced τ_{eff} at low-Δn, and the issue can be solved by optimizing the a-Si passivation layers.[11] Therefore, the optimization of the a-Si passivation layers for a p-type silicon base could reduce the Δn dependency of τ_{eff} on p-SHJ. This is critical to enable higher FF in p-SHJ solar cells, such as the FF of 80.8% demonstrated by Descoeudres et al.[8]

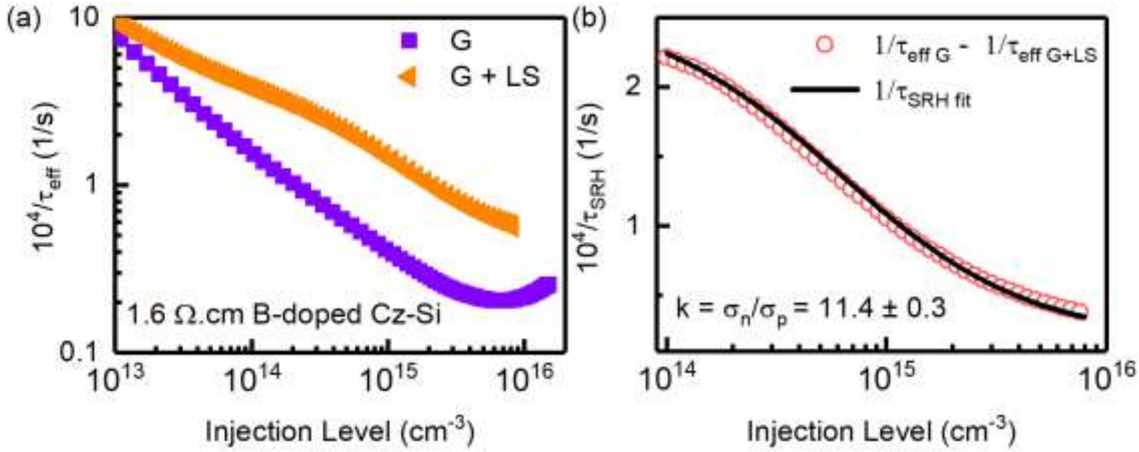

Figure 2. (a) Δn over $1/\tau_{eff}$ of the p-SHJ solar cell before (G) and after (G+LS) LS and (b) injection dependent SRH lifetime curve and model fit.

In this work, large-area p-SHJ solar cells were fabricated with pre-gettered wafers, which demonstrated to be susceptible to significant BO-LID (3.1%$_{abs}$ efficiency loss after LS). A post-fabrication AHP process not only increased the average efficiency of the solar cells by 0.2%$_{abs}$ but also reduced the extent of degradation to 0.2%$_{abs}$. A stable V_{OC} of 734 mV was achieved (21.9% efficiency), without the need of a high-temperature hydrogenation step. Future work is required to enhance the FF of the p-SHJ. The results presented here demonstrate the possibility of fabricating stable industrial SHJ using commercial-grade low-cost p-type silicon wafers.

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