Light-induced degradation and regeneration of multicrystalline silicon Al-BSF and PERC solar cells

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Light-induced degradation (LID) is a well-known problem faced by p-type Czochralski (Cz) monocrystalline silicon (mono-Si) wafer solar cells. In mono-Si material, the physical mechanism has been traced to the formation of recombination active boron-oxygen (B–O) complexes, which can be permanently deactivated through a regeneration process. In recent years, LID has also been identified to be a significant problem for multicrystalline silicon (multi-Si) wafer solar cells, but the exact physical mechanism is still unknown. In this work, we study the effect of LID in two different solar cell structures, aluminium back-surface-field (Al-BSF) and aluminium local back-surface-field (Al-LBSF or PERC (passivated emitter and rear cell)) multi-Si solar cells. The large-area (156 mm × 156 mm) multi-Si solar cells are light soaked under constant 1-sun illumination at elevated temperatures of 90 °C. Our study shows that, in general, PERC multi-Si solar cells degrade faster and to a greater extent than Al-BSF multi-Si solar cells. The total degradation and regeneration can occur within ~320 hours for PERC cells and within ~200 hours for Al-BSF cells, which is much faster than the timescales previously reported for PERC cells. An important finding of this work is that Al-BSF solar cells can also achieve almost complete regeneration, which has not been reported before. The maximum degradation in Al-BSF cells is shown to reduce from 2% (relative) to an average of 1.5% (relative) with heavier phosphorus diffusion.

1 Introduction P-type Cz monocrystalline silicon (mono-Si) wafer solar cells are known to suffer from light-induced degradation (LID). The physical mechanism of LID in mono-Si solar cells has been attributed to the formation of recombination active boron–oxygen (B–O) complexes [1–4]. Subsequent studies found that it was possible to permanently deactivate these defects by a process called regeneration [5–10]. When the solar cell is under illumination, it was found that the defect causing degradation scales linearly with the boron concentration and quadratically with the interstitial oxygen concentration. This suggests that the defect is a boron–oxygen complex that has a stoichiometric composition of one substitutional boron and two oxygen atoms. This boron–oxygen complex introduces recombination centres that result in LID. For regeneration, the exact mechanism is still under debate but

is found to occur at elevated temperatures and in the presence of excess minority charge carrier injected by light or forward bias. One proposed explanation is there is a complex of unknown composition that dissociates under illumination and elevated temperature. After dissociation, one component of this complex associates with the oxygen dimer, which reduces the O_{2i} concentration and forms a recombination inactive complex [11]. As a result, the concentration of the boron–oxygen complex responsible for the LID effect is reduced.

Previously, LID in multicrystalline silicon (multi-Si) wafer solar cells was largely unobserved, likely because minority carrier lifetimes were low and largely dominated by other defects like metallic impurities, dislocations and/or grain boundaries. As multi-Si wafer quality started to improve and minority carrier lifetimes increased, LID in

multi-Si solar cells was also observed. In recent years, LID has also become a major problem for multi-Si wafer solar cells, and has been actively studied by various groups [12–18]. Several solar cell manufacturers have reported strong LID in Al-BSF (aluminium back-surface-field) and Al-LBSF (aluminium local back-surface-field) or PERC (passivated emitter and rear cell) multi-Si solar cells that cannot be explained by B–O complexes or iron–boron (FeB) pairs [12–14, 19]. The performed studies found no correlation between LID and the oxygen concentration in the wafers. Also, Ga-doped wafers were found to exhibit LID effects. One thing to note is that none of these works reported regeneration in Al-BSF multi-Si solar cells.

PERC (or Al-LBSF) solar cells are particularly sensitive to the LID effect [12–14]. Kersten et al. published results on multi-Si PERC solar cells which showed degradation and regeneration over a prolonged period of over 1000 hours at a temperature of 95 °C and 300 W/m^2 illumination intensity [13]. Bredemeier et al. recently demonstrated that degradation of carrier lifetime samples terminated within $\sim$100 hours and regeneration was completed after another $\sim$400 hours at a temperature of 75 °C and 1 sun illumination intensity [20].

In this work, we demonstrate that regeneration can occur not only for PERC solar cells, but also for standard Al-BSF solar cells. The entire degradation and regeneration process for Al-BSF cells takes about 200 hours. To the best of our knowledge, this is the first reported case of regeneration for Al-BSF solar cells.

2 Experimental details

2.1 Cell fabrication
Fabrication of Al-BSF multi-Si solar cells involved a standard wet-chemical acidic texturing step performed in an industrial inline wet-chemical process tool (RENA, InPilot) for industrial-grade multi-Si wafers (156 mm square, boron doped, p-type, $\sim$1.5 Ω cm, 160–180 μm thick). For isotropic texturing, a mixture of hydrofluoric acid (HF), nitric acid (HNO$_3$) and de-ionized (DI) water at a temperature of about 7–8 °C was used. This was followed by the removal of parasitic porous silicon produced during the iso-texturing step by 5% potassium hydroxide (KOH) solution at a temperature of 20 °C. The wafers were then cleaned in a hydrochloric (HCl)–HF solution, followed by DI rinsing and drying. Using a Centrotherm furnace, the wafers were n$^+$ diffused by heating to peak temperature of 870 °C to achieve 40–50 Ω/sq sheet resistance (R_{sq}). The 'SERIS etch' [21–23] was performed on diffused wafers for 3 minutes to increase R_{sq} to a targeted value of $R_{sq} \sim$ 80–90 Ω/sq. With an inline plasma enhanced chemical vapour deposition (PECVD) system (Roth & Rau, SiNA-XS), an antireflection and passivation layer of amorphous silicon nitride (SiN$_x$) with thickness of 70 nm and refractive index of 2.05 (at 633 nm) was deposited at a substrate temperature of 400 °C. Using an industrial printer (Applied Baccini), Al paste (Monocrystal, Analog PASE 12D) and Ag paste (DuPont, PV18A) were used for printing the rear and front contacts, respectively.

In the final step, the screen-printed wafers were co-fired under optimized conditions in a fast firing furnace (Despatch, CDF).

The fabrication steps of the PERC (or Al-LBSF) solar cells were similar to those of the Al-BSF solar cells, except for the following steps. During the phosphorus diffusion, the wafers were heated to peak temperature of 830 °C to achieve 80–90 Ω/sq and no etch back was done. On the rear, AlO$_x$ and SiN$_x$ dielectrics were deposited with PECVD and laser ablation was used to locally open up the dielectric stack, so that local rear contacts could be formed.

A second batch of Al-BSF solar cells (A, B and C) was fabricated from wafers grown by another manufacturer. Other than the emitter formation step, the processing conditions for cells A and B were identical to that of the first batch of Al-BSF cells. Cell A has an emitter layer with R_{sh} $\sim$90 Ω/sq and no etch-back. Cell B was diffused to form an emitter layer with R_{sh} $\sim$50 Ω/sq, etched back completely with 'SERIS etch' and re-diffused to R_{sh} $\sim$90 Ω/sq. Cell C's processing conditions were identical to the first batch of Al-BSF with the cell diffused to $\sim$50 Ω/sq and etched back to R_{sh} $\sim$90 Ω/sq using SERIS etch.

3 Results and discussion

3.1 LID in PERC solar cells
For the LID study, a multi-Si PERC solar cell was placed in a light-soaking chamber and illuminated with 1 sun of light intensity while heating it to 90 °C on a hot plate. The cell was removed from the chamber at specific intervals to perform current–voltage (I–V) and external quantum efficiency (EQE) measurements at room temperature. The I–V measurements were performed on a steady-state solar simulator under standard test conditions (AM1.5G spectrum, 1000 W/m^2 light intensity, 25 °C cell temperature).

Under these conditions, the cell showed light-induced degradation during the initial phase (first $\sim$20 hours) and subsequently exhibited regeneration. The room-temperature values for the 1-sun short-circuit current density (J_{sc}), open-circuit voltage (V_{oc}), fill factor (FF), and efficiency of a representative PERC solar cell are shown in Fig. 1a–d, respectively, whereby the solid lines are guides to the eye. The maximum drop in efficiency is $\sim$4.3% (relative) after 21 hours, just before the start of regeneration. After another 300 hours of regeneration, the efficiency is at $\sim$99.4% (relative) of its original value. During the degradation phase, a large drop in J_{sc} (Fig. 1a) and FF (Fig. 1c) was observed, which is consistent with the observation in [13]. Kersten et al. found that there was increased lifetime degradation at lower injection levels compared to higher injection levels, which increased the ideality factor of the solar cell, resulting in a drop in FF. The generally decreased lifetime also decreased the base effective diffusion length and thus the J_{sc}. The shorter degradation and regeneration times for PERC solar cells observed in our work could be attributed to the higher light intensity of 1 sun used in this study, compared to 300 W/m^2 light intensity used in Kersten's work. It has been demonstrated that
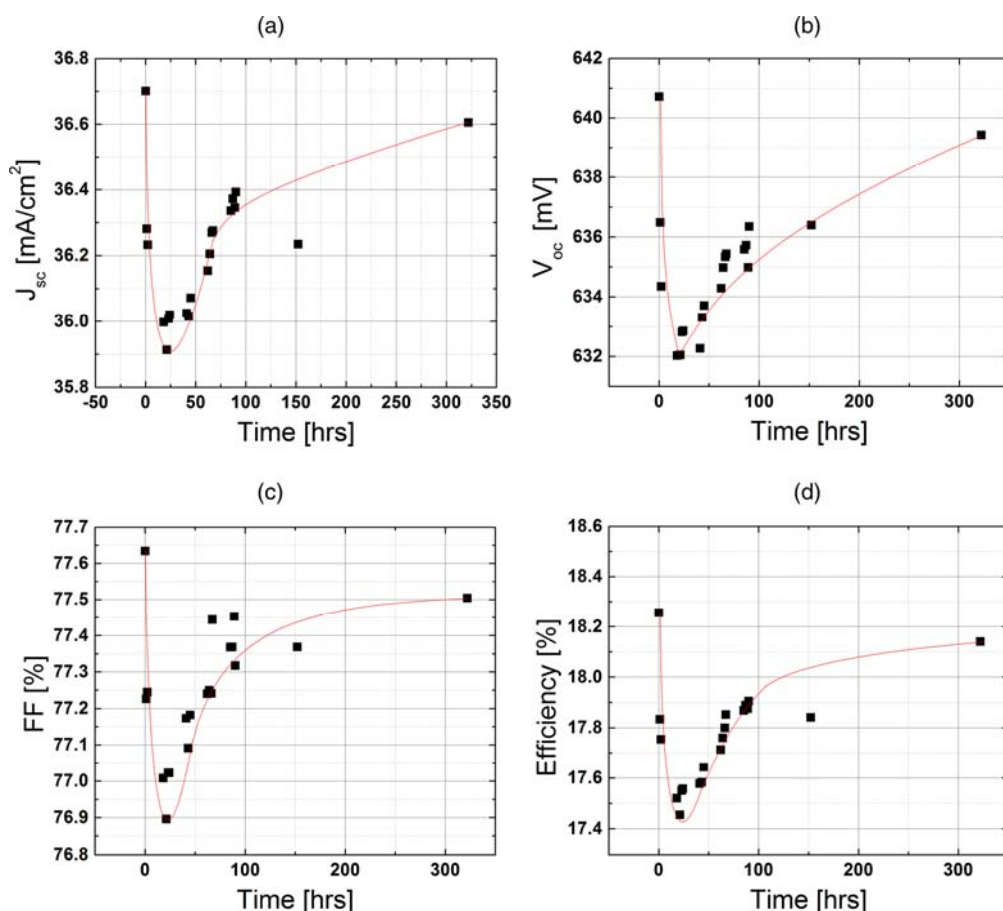
Figure 1 Measured LID and regeneration behaviour of a multi-Si PERC solar cell at 90 °C. (a) J_{sc}, (b) V_{oc}, (c) fill factor and (d) efficiency measured at STC.

higher degradation rate occur at higher light intensity for multi-Si [15].

External quantum efficiency (EQE) of the PERC cell is shown in Fig. 2(a). By plotting the EQE at 950 nm wavelength vs. time in Fig. 2(b), we observe a similar trend as

for the efficiency and J_{sc} in Fig. 1. This shows that the degradation and regeneration are caused by bulk and/or rear surface effects, which influenced the base effective diffusion length and thus the EQE in this particular wavelength range.
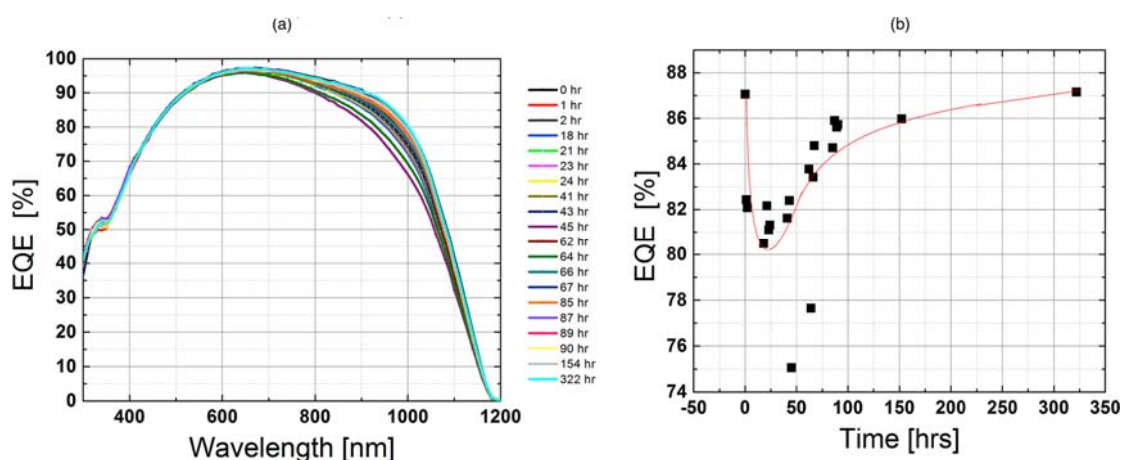

Figure 2 (a) External quantum efficiency vs. wavelength, (b) external quantum efficiency vs. time at wavelength of 950 nm for a PERC solar cell.
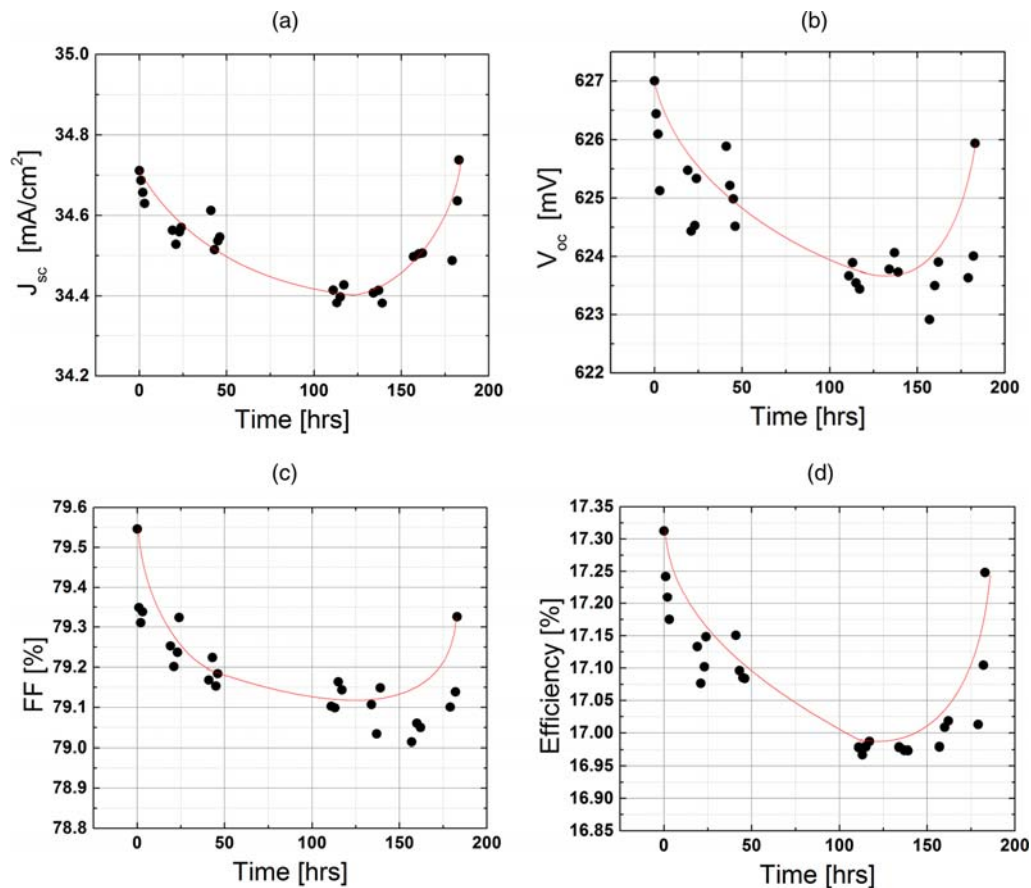
Figure 3 Measured LID and regeneration behaviour of a multi-Si Al-BSF solar cell at 90 °C. (a) J_{sc}, (b) V_{oc}, (c) fill factor and (d) efficiency measured at STC.

3.2 LID in Al–BSF solar cells Al-BSF cells were fabricated with wafers from the same manufacturer and similar ingot section. Analogously to what was done for the PERC solar cell, a multi-Si Al-BSF solar cell was placed under 1 sun illumination and heated to 90 °C. For Al-BSF solar cells, degradation and regeneration trend were also observed. Figure 3(a–d) show the fall and rise of the room-temperature measured J_{sc}, V_{oc}, FF and efficiency with time, respectively, whereby the solid lines are guides to the eye. The EQE plot is shown in Fig. 4(a). The EQE vs. time plot at a wavelength of 950 nm is shown in Fig. 4(b). The extremely low EQE value at 113 hours is likely due to a
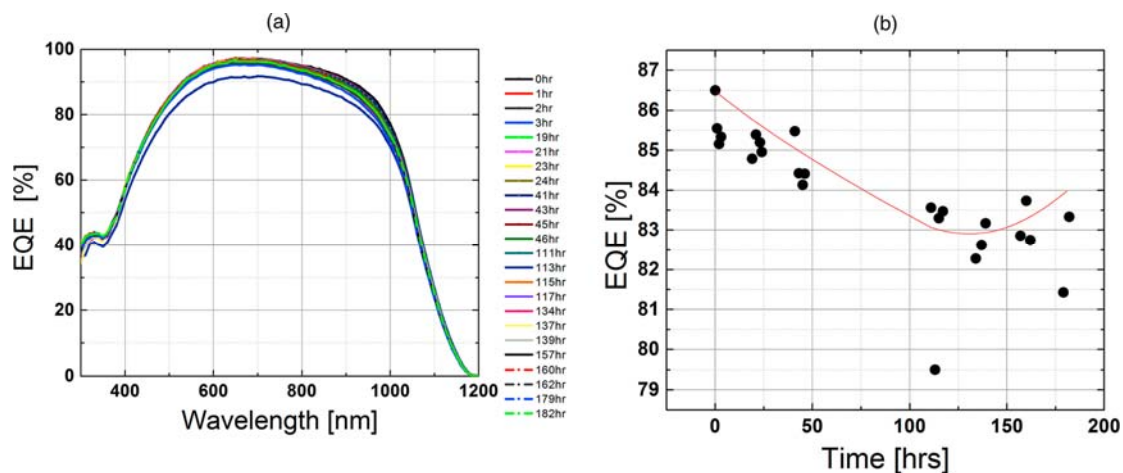

Figure 4 (a) External quantum efficiency vs. wavelength, (b) external quantum efficiency vs. time at wavelength of 950 nm for an Al-BSF solar cell.
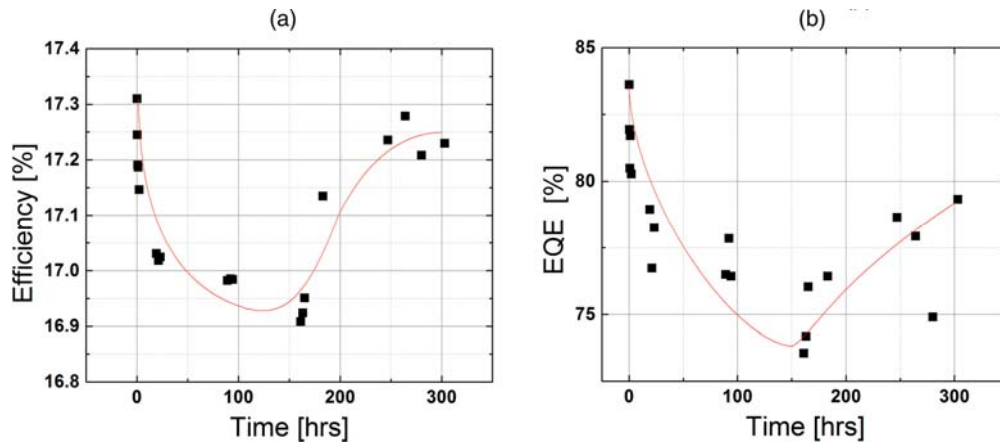
Figure 5 Measured LID and regeneration behaviour of a multi-Si Al-BSF solar cell at 90 °C. a) efficiency measured at STC and b) external quantum efficiency vs time at wavelength of 950 nm.

measurement error. The maximum drop in efficiency is ~2% (relative) which happens at ~110 hours, just before the start of regeneration. After another ~70 hours of regeneration, the efficiency is at ~99.6% (relative) of its original value. As can be seen from a comparison of Figs. 1 and 3, the dependence of J_{sc}, V_{oc}, FF and efficiency with time are totally different for PERC and Al-BSF multi-Si solar cells. For the Al-BSF multi-Si cell, the degradation process is slow while regeneration is fast. In contrast, the opposite is true for the PERC multi-Si solar cell. There is a drop in J_{sc} and FF that can be explained by the increased injection dependence of the minority carrier lifetime at low injection levels, as discussed in [13]. For BSF solar cells, there is a smaller degradation in V_{oc} compared to PERC solar cells, which is consistent with what was observed by other groups. In [12], degradation of V_{oc} was found to be less
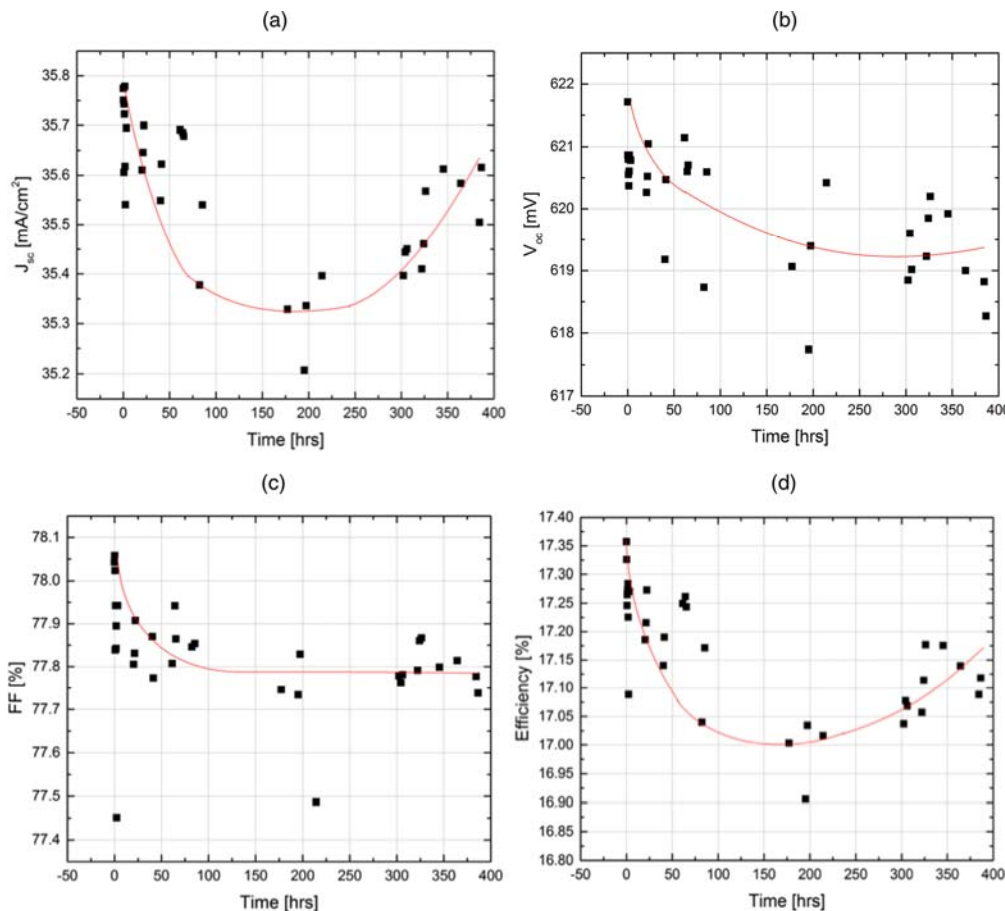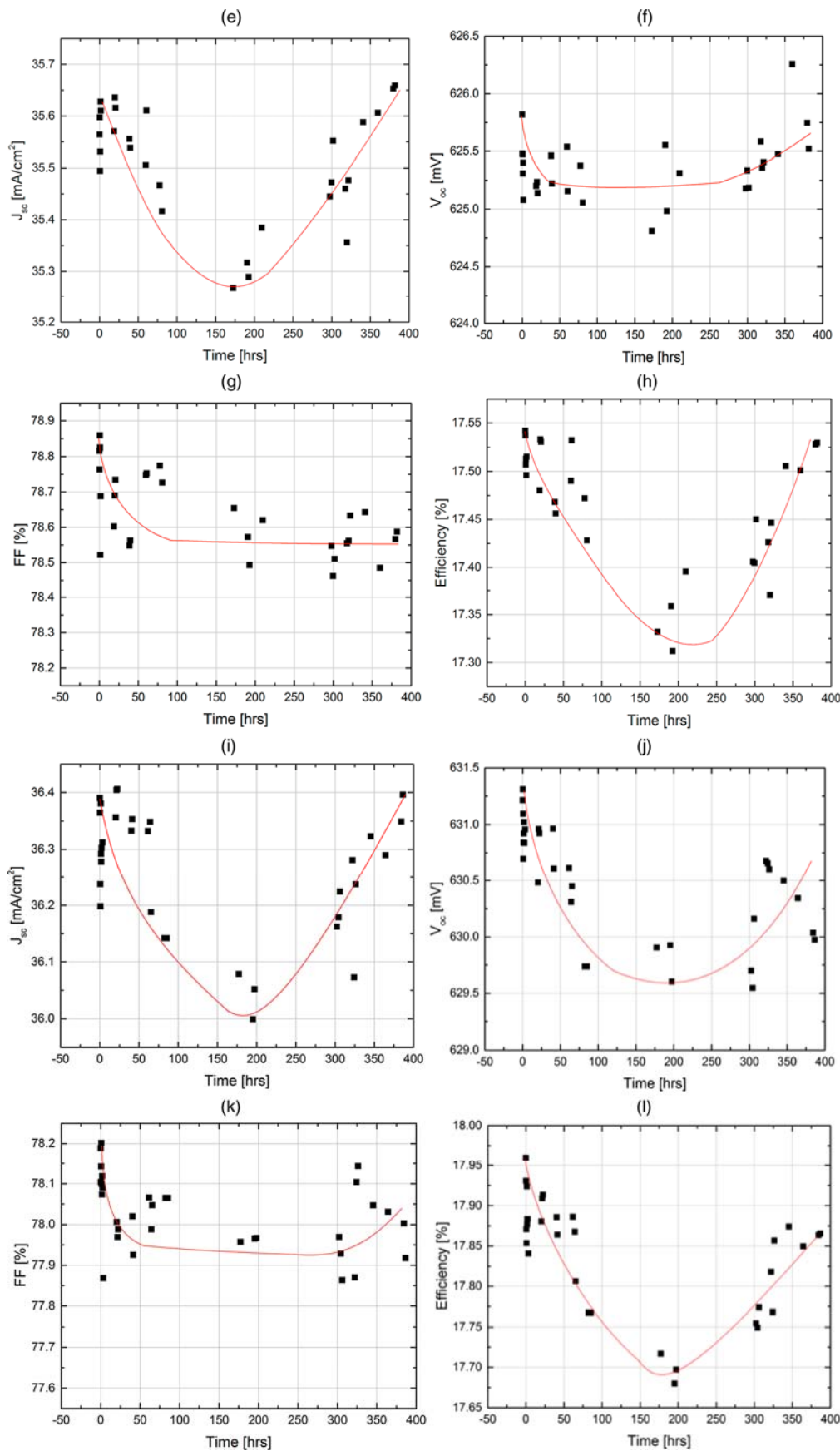

Figure 6(a–d)

Figure 6 Measured LID and regeneration behaviour of multi-Si Al-BSF solar cells at 90 °C. (a–d), (e–h) and (i–l) show the evolution of I–V parameters (J_{sc}, V_{oc}, FF and efficiency) measured at STC for cells A, B and C respectively.

than 5 mV which is similar to what we observed for our Al-BSF cell.

To verify our observation, the experiment was repeated on a second Al-BSF solar cell from the same process batch. This solar cell exhibited similar degradation and regeneration trend (slower degradation and faster regeneration than PERC cell) and efficiency regenerated to ~99.6% (relative) of its original value after less than 230 hours (Fig. 5a), similar to what was observed for the first Al-BSF solar cell (Fig. 3(a–d)). EQE vs. time plot at a wavelength of 950 nm is shown in Fig. 5(b) and it also shows degradation up to ~150 hours and regeneration begins after that.

Our Al-BSF solar cells degraded to their lowest STC efficiency after ~110 hours, which is much longer than what we observed for our PERC solar cells (~21 hours). One possible reason is that the processing for the Al-BSF and PERC solar cells was different, which means that the impurity type, concentration and/or distribution could be different in the two types of solar cell structures. Another possible reason is that the presence of the AlO_x film at the rear of PERC solar cells could lead to a different degradation mechanism. It has been shown by other groups that LID could be caused by a change in the AlO_x passivation layer [12], i.e. a back surface recombination effect. Although, it was recently shown that AlO_x/SiN_x stack versus SiN_x passivated wafers did not exhibit higher degradation [24]. A third reason for the faster degradation in PERC vs. Al-BSF cells could be due to the higher injection level in PERC cells. Higher injection level has been postulated to be a possible reason for the larger LID in PERC compared to Al-BSF cells [25].

Although degradation of Al-BSF solar cells takes longer than for PERC solar cells, regeneration of Al-BSF solar cells occurs much faster than for PERC solar cells, as can be seen from a comparison of Figs. 3(d) and 1(d). Again, this can be due to differences in impurities, or there are different dominating LID mechanisms in our Al-BSF and PERC solar cells. Another possible reason is that the efficiency drop is lower for Al-BSF cells than for PERC cells, and thus the recovery can take place faster.

An important point to note is the observation of LID and regeneration in both our PERC and Al-BSF multi-Si solar cells. The different rear surface structures strongly indicate that the underlying reason has a strong bulk effect (and not just a rear surface effect). A contribution from the AlO_x layer could still be possible for PERC solar cells, and more studies need to be done to determine this.

As LID in our multi-Si PERC and Al-BSF solar cells occurs at a much longer time scale than LID by B–O complexes [26, 27] or by Fe–B pairs [28], it is possible that another mechanism dominates the LID behaviour of our solar cells.

In order to investigate the role that heavy phosphorus diffusion has on LID and regeneration rates on Al-BSF cells, cells A, B and C with different emitter formation were exposed to 1 sun light intensity at 90 °C. Details of the cell fabrication can be found in Section 2. The evolu-

tion of I–V parameters versus exposure time for cells A, B and C are shown in Fig. 6(a)–(d), (e)–(h) and (i)–(l), respectively.

As can be seen from Fig. 6, cell A's efficiency degraded by up to 2% (relative), cell B's efficiency by up to 1.3% (relative), and cell C's efficiency by up to 1.6% (relative). The lower maximum degradation of cells B and C (average of ~1.5% (relative)) compared to cell A can be explained by the enhanced gettering achieved with heavier phosphorus diffusion (R_{sh} ~50 Ω/sq) compared to cell A (R_{sh} ~90 Ω/sq) [23]. The lower initial efficiency of cell A compared to cells B and C also supports the theory that cell A possesses a larger amount of impurities due to the lack of enhanced gettering. For the samples studied herein, the observation suggest that bulk impurities are contributing to the LID effect, which can be reduced by gettering of bulk impurities.

Compared to cells made from the first manufacturer, cells A, B and C took a longer time to reach maximum degradation (~200 hours) and regeneration (another ~200 hours). After ~400 hours, cells A, B and C recovered up to 99.0% (relative), 99.9% (relative), and 99.5% (relative) respectively.

4 Conclusion This study is the first report of nearly complete regeneration of LID-treated Al-BSF multi-Si wafer solar cells, which strongly suggests that LID has a bulk defect contribution. Using 1-sun illumination and 90 °C cell temperature, the combined degradation and regeneration process takes place within ~320 hours and ~200 hours, respectively, for PERC and Al-BSF multi-Si solar cells. The maximum drop in STC efficiency was ~4.3% (relative) and occurred after ~21 hours for the PERC cells. For Al-BSF cells, the maximum drop in efficiency was ~2% (relative), which occurred after about 110 hours. After another ~300 hours of regeneration, the PERC cell efficiency was at ~99.4% (relative) of its original value. For Al-BSF cells, the STC efficiency was at ~99.6% (relative) of its original value after about 70 hours of regeneration. This is an interesting finding, as the degradation of the PERC solar cells took place much faster than that of Al-BSF solar cells and, in contrast, regeneration took place much faster for the Al-BSF solar cells. The large differences in degradation and regeneration rates of PERC and Al-BSF multi-Si solar cells point to the possibility of different LID defect properties (e.g. different processing can lead to differences in impurity type, distribution and/or concentration), different dominant degradation mechanisms in these structures (e.g. AlO_x in PERC solar cells could cause another type of degradation) or that PERC and Al-BSF solar cells operate at different injection levels.

LID and regeneration were also observed in Al-BSF cells made from wafers from another manufacturer and the total degradation and regeneration took a longer time (~400 hours). Since the wafers were from different manufacturers, this could be due to the differences in impurity concentrations. Gettering with a heavier phosphorus diffu-

sion has been shown to reduce the LID effect in multi-Si Al-BSF solar cells from 2% (relative) to an average of ~1.5% (relative) and enable almost full regeneration within ~400 hours of light soaking at elevated temperatures.

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