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Rapid passivation of carrier-induced defects in p-type multi-crystalline silicon

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ABSTRACT

A slow forming carrier-induced degradation effect has previously been reported for p-type multi-crystalline silicon (mc-Si) solar cells and has been observed to be most severe in passivated emitter and rear contact (PERC) designs. The as yet undetermined defect (or defects) responsible for this degradation is typically described as being light-induced. However, in this work we confirm that a directly equivalent degradation also occurs when subjecting a cell to current injection, thus the effect can therefore be more accurately described as being carrier-induced. The defect can take years to form under normal operating conditions, but acceleration of this formation and an apparent subsequent passivation through the use of high intensity illumination at elevated temperatures has recently been demonstrated. In this work we further investigate this approach, analyzing the effects of temperature and time on degradation, regeneration, and resulting stability, as well as the variations in treatment response for mc-Si materials from two different manufacturers. Susceptibility to carrier-induced degradation after 225 h of light soaking at 70 °C is shown to be reduced by 80% using a rapid, 10 s treatment with an illumination intensity of 44.8 kw/m^2 at 200 °C. Stability is shown to further improve by extending treatment time but is reduced with increasing treatment temperature.

1. Introduction

In recent years, there have been an increasing number of reports of a slow forming, light-induced degradation (LID) effect observed in multi-crystalline silicon (mc-Si) solar cells [1–4]. The effect has been shown to be most severe in passivated emitter and rear contact (PERC) cells [1,3] which are predicted to become the dominant device structure in industry within the next few years [5,6]. With mc-Si currently accounting for around 65% of the PV market [5], and the PERC structure rapidly increasing in popularity, the understanding and mitigation of this degradation effect is of critical importance.

The exact defect (or defects) responsible for this degradation has not yet been determined, but it has been shown that the degradation cannot be wholly attributed to the intensively studied B-O complex or Fe_i-B pair dissociation known to be the primary causes of LID in Czochralski (Cz) silicon solar cells [1]. Evidence of this has been presented through observed degradation in gallium-doped wafers [1] and through a lack of correlation with interstitial oxygen concentration [4]. Additionally, the degradation observed in mc-Si occurs on significantly longer timescales than those reported for B-O or Fe_i-B effects on Cz silicon, with mc-Si typically requiring hundreds of hours of light soaking for full defect formation, even when accelerated using elevated temperatures [4]. The defect responsible is likely produced from one or several of the various impurities typically present in mc-Si due to contamination in the material feedstock or the crucible walls/coating. Copper is one such impurity, which has recently been shown to lead to LID in both Cz and mc-Si materials, however, the timescales reported for Cu related LID appear to be too rapid to explain the degradation recently observed in mc-Si PERC cells [7,8]. Further investigation is therefore required in order to determine the root cause in this case.

The lengthy timescales required to observe the full extent of degradation in mc-Si have led to the necessity to increase defect formation rates in order to make experimental studies and rapid mitigation feasible. Hanwha Q-cells have therefore advocated an elevated temperature of 75 °C whilst light soaking to be used as standard and the terminology of ‘light and elevated temperature induced degradation’ (LeTID) to be used [4]. Whilst such terminology is useful for isolating this defect from others, such as the

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B-O complex, it has the potential to mislead as the degradation can occur at temperatures lower than the 75 °C recommended for studying LeTID and can be induced without light [1,4]. Furthermore, the formation rates of other defects, including the B-O complex can also be increased using elevated temperatures and illumination [9,10]. Throughout this work we have therefore used the broader terminology of carrier-induced degradation (CID), this is further discussed in Section 2.

In mc-Si solar cells, this CID manifests as a reduction in V_{oc}, I_{sc} and *fill factor* (*FF*) leading to diminished power output and efficiency, with absolute efficiency losses of up to 2.1% recently observed in mc-Si PERC cells [4,11]. Kersten et al. have reported that symmetrically passivated mc-Si wafers exhibited CID as a reduction in effective minority carrier lifetime with a strong injection level dependence. Furthermore, this degradation was observed to occur when passivating with either silicon nitride (SiN_x) or aluminium oxide (AlO_x) layers, indicating that the CID was primarily within the bulk [4]. However, studies on solar cell structures with differing sensitivity to bulk diffusion length have been shown to exhibit a similar extent of degradation, suggesting that bulk defects alone may not fully account for the degradation [3,12].

Continued exposure to conditions that induce degradation has been shown to lead to an eventual recovery of minority carrier lifetime, often termed 'regeneration' [4,13]. Under typical field conditions for a solar cell this could take several years. However, we have recently demonstrated that significant acceleration of the defect formation and subsequent recovery rate can be achieved with the use of elevated temperatures (140–320 °C) and very high irradiance illumination (44.2 kW/m^2) [11]. Similar approaches have previously been proven to be effective for accelerating reaction rates of other defects, such as the B-O complex [10,14]. The state of the system after this degradation/recovery process is significantly more stable than the initial state, strongly indicating that the process has led to passivation of the defect, with the resulting material being less susceptible to CID. In this work, we further investigate the effects of this passivation technique by firstly examining the variability of results across mc-Si material from different manufacturers and ingot positions. In addition, the effect of treatment time on mc-Si PERC cells is investigated in order to gauge the minimum time required for effective stabilisation.

2. Methods for inducing degradation

The gradual degradation of mc-Si based solar cells has typically been reported in the literature as being light-induced or, more recently, as light and elevated temperature induced. However, whilst incident photons are obviously present under typical operating conditions, it is in fact the *excess carriers* generated by the photons that induce the degradation effect. The distinction between light-induced and carrier-induced is important as the commonly used terminology of LID neglects that current can also be used to study these effects. Evidence that the degradation in mc-Si PERC cells is carrier-induced has previously been presented by Kersten et al. who show similar degradation for modules exposed to light or current injection [4]. The carrier-induced nature of the degradation is further supported by the differing rates of degradation that have been observed for cells under identical illumination conditions but operating in either V_{oc} or I_{sc} mode, with those operated at V_{oc} showing a significantly faster decline [4]. In this section we aim to verify these results at the cell level using mc-Si PERC solar cells from neighboring ingot positions in order to confirm that degradation induced by either current or light is directly equivalent.

2.1. Experimental methods

For this experiment, mc-Si PERC solar cells known to exhibit CID effects were sourced from an industrial manufacturer (*Manufacturer A*). Two cells from neighboring ingot positions (sister cells) were subjected to approximately equivalent degradation conditions using illumination or current injection. In both cases the cell was placed on a hotplate with the cell temperature maintained at 70 °C as confirmed by an IR thermometer. For the light soaking case, the cell was illuminated with 0.46 kW/m^2 of broadband light from a halogen source. For the current injection case, the cell was kept in the dark and connected in forward bias to a source measure unit (SMU) power supply operating in current control mode. In order to achieve similar carrier injection levels between the two experiments, the V_{oc} was measured in the illuminated case and the current of the SMU was adjusted to provide a matching voltage drop in the dark case. In both arrangements the cells were removed at regular intervals for Suns-V_{oc} (Sinton Instruments) measurements in order to track the degradation.

2.2. Results and discussion

The resulting change in V_{oc} for each cell with time is shown in Fig. 1. The two degradation curves show excellent agreement, verifying that the degradation effect is in fact carrier-induced and can be equally triggered by current or light.

Whilst light is logically the primary concern for solar cells, fundamentally it is the carriers generated by the incident photons that induce the degradation effect. Alternative methods for carrier injection are therefore applicable and should not be neglected as they may lead to new methods to study or alleviate the problem, as demonstrated by Hyundai's recent use of current injection to avoid destabilisation of the passivated B-O complex in Cz silicon solar cells during the lamination process [15].

3. Rapid passivation, variability and stability

Accelerated passivation of carrier-induced defects in *p*-type mc-Si has recently been demonstrated through the use of high intensity illumination and elevated temperatures [11]. It was shown that identically diffused and SiN_x passivated mc-Si wafers, sourced from three different manufacturers, exhibited significant variance in CID susceptibility when light-soaked for several hundred hours. However, in all cases, substantial passivation was achieved within 120 min at 140 °C, with the results showing

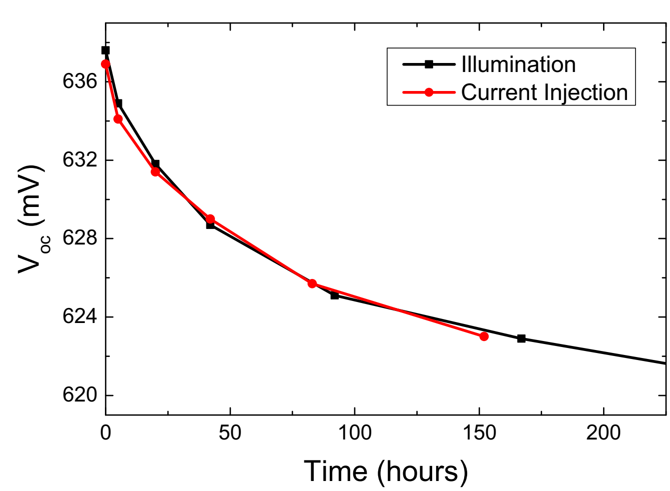

Fig. 1. Change in V_{oc} with time for sister mc-Si PERC cells subjected to equivalent carrier injection using light and current.