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Mass production of *p*-type Cz silicon solar cells approaching average stable conversion efficiencies of 22 %

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Abstract

Within this work, both the performance and reliability of industrial *p*-type monocrystalline solar cells with dielectrically passivated rear side and corresponding modules are investigated. Results of the mass production of Q.ANTUM solar cells at Hanwha Q CELLS on boron-doped *p*-type Czochralski-grown silicon (Cz-Si) substrates are presented, exceeding 21.5 % average conversion efficiency. Without power-enhancing measures such as the use of half cells, multi-wire approaches or light-capturing ribbons, essentially all currently (as of March 2017) produced Cz-Si Q.ANTUM solar modules exhibit output powers of > 300 Wp with 60 full 4-busbar cells. In terms of reliability, light-induced degradation (LID) is investigated in detail, with conditions relevant for the activation of, both, the boron-oxygen (BO) defect, and, so-called “Light and Elevated Temperature Induced Degradation” (LeTID). While the formation of the BO defect has been considered the most prominent LID mechanism in boron-doped *p*-type Cz-Si, LeTID has so far been discussed mainly as a potential issue for passivated emitter and rear cells (PERC) on multicrystalline silicon (mc-Si) substrates. This work shows that, if not adequately suppressed, LeTID can also occur in *p*-type Cz-Si PERC with a degradation in output power of up to > 6 %, which cannot be suppressed in a straightforward manner by conventional processing steps to permanently deactivate the BO defect. In contrast to conventional PERC, Hanwha Q CELLS’ Q.ANTUM technology is shown to reliably suppress, both, LID due to BO defect formation, *and* LeTID in modules manufactured from, both, *p*-type mc-Si and Cz-Si substrates.

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1. Introduction

Within the last 3 years, the market share of solar cells with dielectrically passivated rear side has increased from less than 5 % in 2013 [1] to about 15 % in 2016 [2], and is expected to further increase in the coming years [2]. The majority of these cells is represented by the passivated emitter and rear cell (PERC [3]) structure and has been processed on boron-doped *p*-type silicon substrates. Besides challenges in process technology, stability issues due to LID have been a key challenge for high-efficiency *p*-type Cz-Si solar cells, which is particularly pronounced in PERC-like solar cells as their performance is more sensitive to bulk electron diffusion length than that of aluminium back-surface field (Al-BSF) solar cells. In particular, two LID mechanisms have significantly contributed to hindering a wider distribution of the industrial manufacturing of PERC-like solar cells on boron-doped *p*-type silicon substrates: LID due to boron-oxygen (BO) defect formation [4–6] and so-called “Light and elevated Temperature Induced Degradation” (LeTID) [7–9], most pronounced for PERC on Cz- and mc-Si substrates, respectively. While Hanwha Q CELLS’ Q.ANTUM technology [9–11] has been shown to suppress LeTID on mc-Si substrates [9], BO defect formation has been discussed as the main reliability issue due to LID in boron-doped *p*-type Cz-Si.

This work reports on results of the mass production of Hanwha Q CELLS’ Q.ANTUM technology on boron-doped *p*-type Cz-Si substrates. Besides device performance upon fabrication, LID of Q.ANTUM and PERC is investigated in detail. It is shown, that, if not adequately suppressed, LeTID can not only occur in *p*-type mc-Si PERC but also in *p*-type Cz-Si PERC. While the BO defect can be permanently deactivated by commercially available processing steps, the suppression of LeTID is shown to not be equally straightforward. In contrast to conventional PERC, Hanwha Q CELLS’ Q.ANTUM technology is shown to reliably suppress, both, LID due to BO defect formation, and, LeTID in modules manufactured from, both, *p*-type mc-Si and Cz-Si substrates.

2. Q.ANTUM solar cells on *p*-type Cz silicon substrates

Fig. 1 shows sketches of a standard Al-BSF and the Q.ANTUM solar cell structure. The Q.ANTUM solar cell resembles a PERC-like structure, i.e., it features a dielectrically passivated rear side with local contacts, front-side junction and screen-printed metallisation. Fig. 2a shows average cell conversion efficiency as a function of time in production and pilot production at Hanwha Q CELLS of *p*-type Cz-Si Al-BSF and Q.ANTUM solar cells, respectively [12]. An increase in average efficiency of +0.6 $\%_{abs}$/year is observed, which for the Al-BSF cell structure is disrupted in the beginning of 2013 leading to a significantly flatter increase compared with the Q.ANTUM solar cell. By switching to the Q.ANTUM solar cell structure, the increase in conversion efficiency of +0.6 $\%_{abs}$/year could be maintained and, therefore, the efficiency curves of both structures are decoupled with an increasing gap between

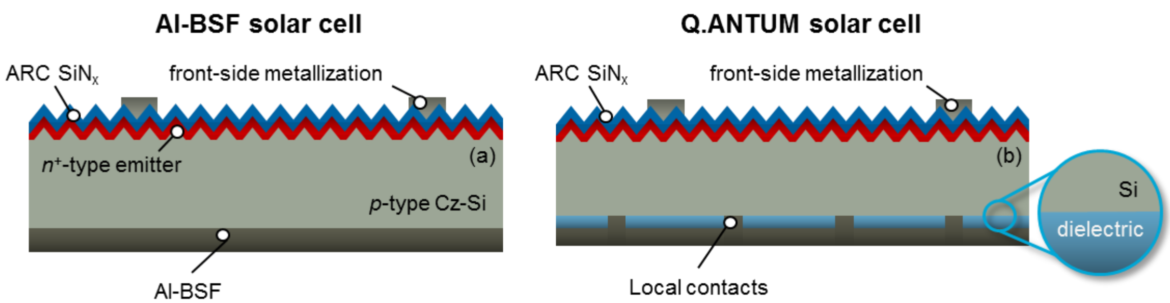

Fig. 1. Sketches of (a) aluminium back-surface field and (b) Q.ANTUM solar cell structures.

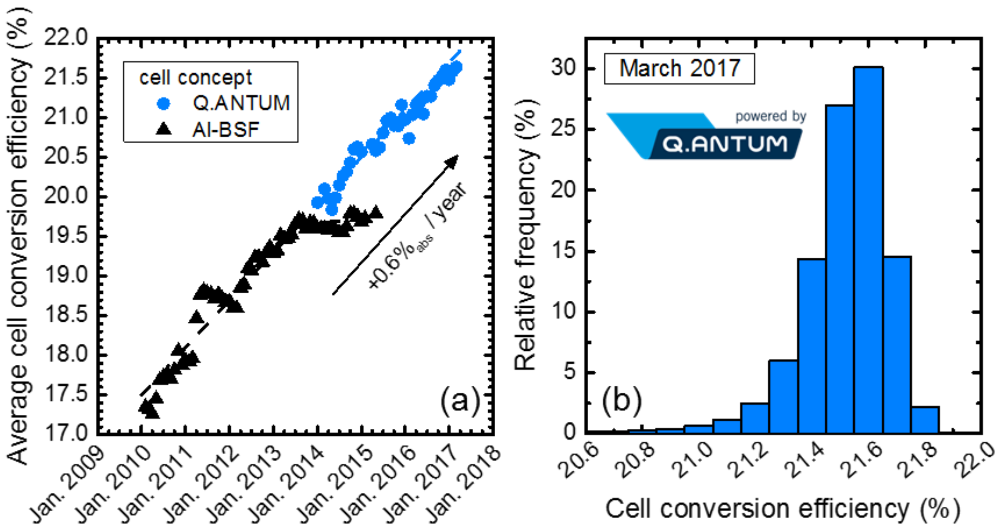

Fig. 2. (a) Solar cell efficiency of mass and pilot production as a function of time at Hanwha Q CELLS. Graph continued from Ref. [12]. (b) Cell conversion efficiency distribution of Q.ANTUM solar cells on *p*-type Cz silicon substrates in mass production in March 2017.

Q.ANTUM and Al-BSF cells. Within the next years, we do not expect a significant slow-down in the yearly efficiency increase of Q.ANTUM solar cells, exceeding 23 % average conversion efficiency while maintaining a lean manufacturing process.

Fig. 2b shows the distribution of cell conversion efficiency of Q.ANTUM solar cells on *p*-type Cz-Si substrates in mass production at Hanwha Q CELLS in March 2017. A tight distribution with maximum frequencies at 21.5 % and 21.6 % can be seen. These cell efficiencies lead to essentially all currently (as of March 2017) manufactured Cz-Si Q.ANTUM solar modules exhibiting power classes of > 300 Wp, utilising 60 6-inch pseudo-square full-area 4-busbar solar cells and standard module interconnection technology, i.e., no power-enhancing measures such as the use of half cells, multi-wire approaches (e.g., soldering of multiple wires [13, 14] or connection of embedded wires during lamination [15, 16]) or light-capturing ribbons have been applied. These output powers are at the same level or even higher than those for modules with industrial PERT-like (passivated emitter, rear totally diffused [17]) solar cells on *n*-type silicon substrates and are further closing the gap to the power classes of modules with comparably complex and, hence, typically higher-cost, highest-efficiency *n*-type Cz-Si solar cell structures such as hetero junction [18–21] and rear-contact solar cells [22–25], at extremely competitive manufacturing cost.

3. Light-induced degradation of PERC

Besides maximising conversion efficiency and output power, the long-term stability of solar cells and modules is of crucial importance. Two key mechanisms that are potential hazards for the reliability of solar cells and modules based on boron-doped *p*-type silicon substrates are the boron-oxygen (BO) defect and so-called “Light and elevated Temperature Induced Degradation” (LeTID). The impact of these mechanisms on PERC cell and module performance is discussed in this section and it is shown that Q.ANTUM technology suppresses LID and LeTID in mc- and Cz-Si.

To separate BO defect formation and the formation of LeTID, different temperatures, excess charge carrier densities and treatment times are applied. The applied nomenclature is as follows: CID describes current-induced degradation, which means that the same excess charge carrier densities are established by current injection in the dark as with LID. Two levels of excess charge carrier density are considered: OC and MPP mode, which correspond to the excess charge carrier concentrations at open-circuit and at maximum power point at an illumination intensity of E_{ill} = 1 kWm^{-2}.

3.1. Boron-oxygen defect

To investigate the impact of BO defect formation on device performance, Q.ANTUM solar cells and PERC without applied permanent deactivation of the BO defect have been processed on boron-doped *p*-type Cz-Si substrates from different industrial suppliers and subjected to light soaking with an illumination intensity of ~1 sun-equivalent for 24 h at a temperature of 25°C. For typical boron and oxygen concentrations, the formation of the BO defect has been shown to be almost independent of illumination intensity in the range of 0.01 $kWm^{-2} < E_{ill} < 1\ kWm^{-2}$ [4, 26] and to typically be close to saturation after 24 h of light-soaking at 25°C [27–29]. Fig. 3 shows values of relative degradation in maximum output power upon light soaking. While a significant degradation of 4 % to 5 % is observed for PERC without BO defect stabilisation, LID can be suppressed to less than 0.5 % by applying Q.ANTUM technology.

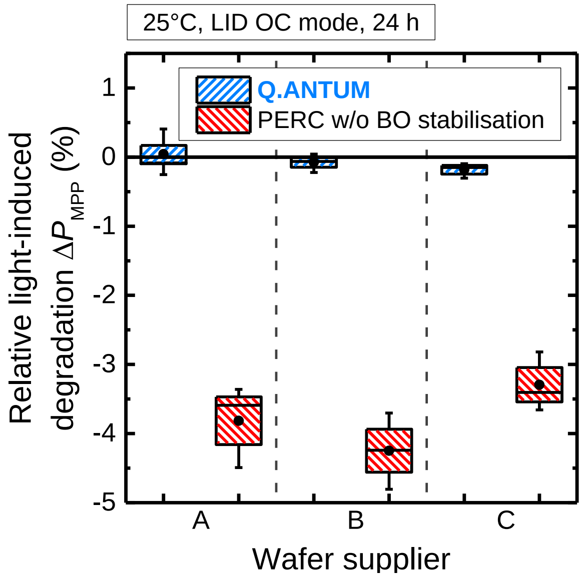

Fig. 3. Light-induced degradation of maximum output power of Q.ANTUM solar cells and PERC without BO stabilisation on Cz-Si substrates from different suppliers (~1 sun-equivalent / 25°C / 24 h).

3.2. Light and elevated Temperature Induced Degradation (LeTID)

In contrast to BO defect formation, LeTID has so far mainly been associated with a potential issue for mc-Si PERC [7–9]. In a previous study by Hanwha Q CELLS [9], solar modules have been fabricated from **mc-Si** PERC with intentionally manipulated LeTID sensitivity ("high LeTID" / "medium LeTID") along with LeTID-suppressing **mc-Si** Q.ANTUM modules, and have been subjected to different treatments. Fig. 4 (right) shows an extract of the results (graph is adapted from Ref. [9]): relative module power degradation as a function of treatment time. A severe degradation of more than 10 % is observed for "high LeTID" PERC modules, which is an order of magnitude in degradation that has been confirmed to also occur in the field [9, 30]. While the "medium LeTID" treatment reduces degradation to about 4 %, Q.ANTUM technology is shown to suppress LeTID. Note, that the applied test conditions are CID in MPP mode at elevated temperature. Compared with OC mode, the lower excess charge carrier densities in MPP mode lead to slower formation of LeTID but to a higher extent since regeneration sets in at a later point in time [9]. Hence, to test worst-case conditions at a reasonable speed, Hanwha Q CELLS suggests the testing conditions of CID in MPP mode at 75°C to evaluate the long-term stability of silicon solar modules in terms of LeTID susceptibility [9].

In order to investigate the impact of LeTID on **Cz-Si** devices, three sorts of solar modules have been manufactured: (i) PERC modules without permanent deactivation of the BO defect, (ii) PERC modules with applying a commercially available processing step to permanently deactivate the BO defect and (iii) LID- and LeTID-suppressing Q.ANTUM modules. To separate the formation of the BO defect and LeTID, two different CID treatments have been applied: (i) OC mode at T_{LID} = 25°C, which corresponds to the conditions applied in section 3.1 to test for BO defect formation and (ii) MPP mode at T_{LID} = 75°C, which corresponds to the conditions suggested by Hanwha Q CELLS to test LeTID susceptibility.

Fig. 4 (left) shows values of relative module power degradation as a function of treatment time. In OC mode at T_{LID} = 25°C, the Cz-Si PERC modules without BO stabilisation show a degradation of around 6 %, which is in the same order as for the PERC discussed in section 3.1. By applying a commercially available processing step to permanently deactivate the BO defect (PERC w/ BO stabilisation), this degradation can be reduced to about 1 %. However, when subjecting the PERC modules w/ BO stabilisation to CID in MPP mode at T_{LID} = 75°C, a severe deg-

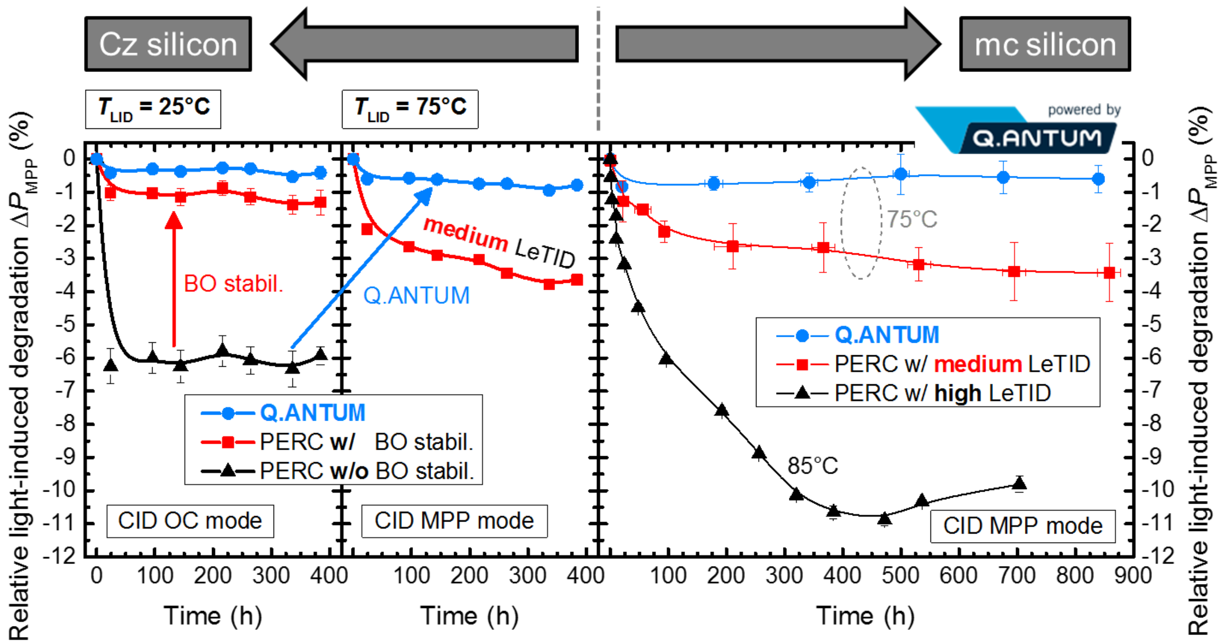

Fig. 4. **(left)** Relative degradation in maximum output power of modules with **Cz-Si** solar cells as a function of treatment time at temperatures of 25°C and 75°C in OC and MPP mode, respectively. Resulting degradation values for modules from PERC with and without BO stabilisation are displayed, along with LID- and LeTID-suppressing Q.ANTUM modules. **(right)** Relative power degradation of modules with **mc-Si** solar cells as a function of treatment time at temperatures of 75°C and 85°C in MPP mode. Resulting degradation values for modules from PERC with maximum and medium LeTID sensitivity are displayed, along with LeTID-suppressing Q.ANTUM modules. Graph (right) is adapted from Ref. [9]. It can be seen that Hanwha Q CELLS Q.ANTUM technology suppresses LID and LeTID for mc- and Cz-Si.

radation of about 4 % is observed. As expected from the discussion in section 3.1, LID due to BO defect formation is close to saturation after 24 h of light-soaking at 25°C while degradation due to LeTID at 75°C continuously progresses in the considered time scale. When comparing Fig. 4 (left) and (right), it can be seen that the extent of LeTID of the Cz-Si PERC modules w/ BO stabilisation and its formation rate approximately correspond to the mc-Si PERC modules w/ medium LeTID. In conclusion, a strong LeTID signal is observed also on *p*-type Cz-Si PERC modules, despite the suppression of excessive LID due to BO defect formation by commercially available BO stabilisation processing. As illustrated in Fig. 4, in contrast to conventional PERC, Hanwha Q CELLS' Q.ANTUM technology not only suppresses LID and LeTID on mc-Si but also on Cz-Si substrates. Since LeTID has been shown to occur in the field to a similar extent as tested by the discussed test at CID MPP mode at 75°C [30], a significant benefit is expected for Q.ANTUM compared with conventional PERC in terms of energy yield and, therefore, LCOE.

To further investigate LeTID in *p*-type Cz-Si solar cells, PERC with high LeTID sensitivity have been fabricated, one group without permanently deactivating the BO defect and one group with applying a commercially available processing step to permanently deactivate the BO defect, similarly to the experiment described in the previous paragraphs. Furthermore, LID- and LeTID-suppressing Q.ANTUM solar cells have been fabricated. The three cell types have been subjected to LID in OC mode for 24 h under two conditions: (i) at T_{LID} = 25°C and (ii) at T_{LID} = 75°C. In analogy to the previous paragraphs, this approach is chosen to separate LID due to BO defect formation and LeTID. While, again, BO defect formation is expected to be close to saturation after 24 h, compare Fig. 4 (left) and Refs. [27–29], the degradation at T_{LID} = 75°C after 24 h includes BO defect formation and a "snapshot" of LeTID. Hence, in terms of LeTID, the power degradation value at T_{LID} = 75°C after 24 h represents only a certain extent of LeTID with the maximum degradation value being expected to be higher than the one given. Fig. 5 shows the relative degradation in maximum output power of the different groups. Without BO stabilisation, the PERC show a degradation of around 5 % at 25°C, which is in the same order as the results discussed in section 3.1 and Fig. 4 (left). When applying "standard" BO stabilisation, the corresponding PERC show a degradation of about 1 %, which, again, is in the same order as observed in Fig. 4 (left), reducing BO defect formation significantly. However, when subjecting the PERC to LID at 75°C, the power of the PERC w/o BO stabilisation degrades by over 12 % and, when applying "standard" BO stabilisation, by about 6 %. Hence, the degradation at elevated temperature occurs on top of the degradation at 25°C, which has been confirmed by other experiments, also on longer time scales. When comparing the results of the groups PERC with BO stabilisation in Figs. 4 and 5, two observations are highlighted: (i) After 24 h of treatment at 75°C in OC mode, LeTID of the "high LeTID" PERC with BO stabilisation is already significantly higher than the corresponding values of the "medium LeTID" PERC modules with BO stabilisation after 400 h in MPP mode discussed in Fig. 4. Hence, the extent of LeTID in Cz-Si PERC can be manipulated in a similar manner as in mc-Si PERC. (ii) Despite the significantly differing LeTID sensitivity of groups "high" and "medium LeTID" PERC with BO stabilisation, both groups shows very similar LID at 25°C. Hence, this finding would result from a typical LID test targeting BO defect formation in Cz-Si despite their significantly different risk in terms of long-term stability in the field. This difference in risk can be reliably resolved by applying the suggested test sequence by Hanwha Q CELLS to evaluate the long-term stability of silicon solar modules [9].

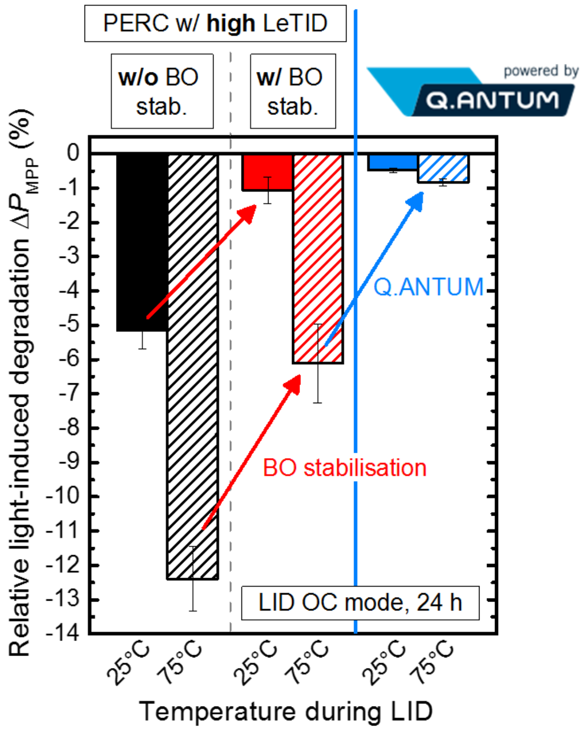

Fig. 5. Light-induced degradation of maximum output power of Cz-Si PERC with and without BO stabilisation and high LeTID sensitivity, and of LID- and LeTID-suppressing Q.ANTUM solar cells (~1 sun-equivalent / 25°C or 75°C / 24 h).

In analogy to the findings discussed previously along with Fig. 4, Fig. 5 shows that Q.ANTUM technology suppresses LID and LeTID also on Cz-Si substrates in contrast to conventional PERC.

4. Summary and conclusion

This work addresses both the performance and light-induced degradation (LID) behaviour of industrial solar cells with dielectrically passivated rear side fabricated on boron-doped *p*-type Czochralski-grown silicon (Cz-Si) substrates and corresponding modules. By applying Hanwha Q CELLS' Q.ANTUM technology, average solar cell conversion efficiencies exceeding 21.5 % are achieved in mass production, which leads to essentially all currently (as of March 2017) produced Cz-Si Q.ANTUM solar modules exhibiting output powers of > 300 Wp with 60 full 4-busbar cells applying standard module technology. We still see significant efficiency headroom for the Q.ANTUM technology and expect to exceed 23 % average conversion efficiency within the next years while maintaining a lean manufacturing process.

One key concern for the long-term stability of Cz-Si passivated emitter and rear cells (PERC) in the field has been LID due to boron-oxygen (BO) defect formation. By applying a "standard" commercially available processing step for the permanent deactivation of the BO defect, LID due to BO defect formation is shown to reduce from 4 % to 6 % to about 1 % in conventional PERC. However, despite this BO defect stabilisation, this work shows that, if not adequately suppressed, so-called "Light and elevated Temperature Induced Degradation" (LeTID) can be a severe issue for the long-term stability of PERC not only on multicrystalline silicon (mc-Si) but also on Cz-Si substrates.

Similarly to mc-Si PERC, the extent of LeTID in Cz-Si PERC can be manipulated, showing power degradation values of 4 % to 6 % on top of LID due to BO defect formation for different scenarios, despite "standard" permanent BO defect deactivation. Hence, the suppression of the BO defect by "standard" commercially available measures is not sufficient to stabilise the performance of Cz-Si PERC modules at elevated temperatures. By typical LID testing of Cz-Si PERC modules, which is targeted for BO defect formation testing, this severe risk of LeTID to the long-term stability in the field may remain undetected. Hence, in analogy to previous publications by Hanwha Q CELLS, current-induced degradation at excess charge carrier densities corresponding to maximum-power-point conditions at a temperature of 75°C is suggested to evaluate the long-term stability of silicon solar modules in terms of LeTID susceptibility.

In contrast to conventional PERC, Hanwha Q CELLS' Q.ANTUM technology is shown to reliably suppress, both, LID due to BO defect formation, and, LeTID in modules manufactured from, both, *p*-type mc-Si and Cz-Si substrates. This enables superior long-term stability and field performance of Q.ANTUM compared with conventional PERC modules.

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