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Contact Resistance Increase in Ga-Doped Silicon Solar Cells at Current Injection and Elevated Temperature Treatments

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Abstract. PERC solar cells based on Gallium p-type doping were treated at elevated temperatures in the range of 80…160°C and current injection. Current injection is conducted in a current-induced degradation (CID) setup in the dark, measuring voltage while applying a current at 0.06, 0.53 and 1.0 times the short-circuit current – ranging from maximum power point to open-circuit injection conditions. The results of the CID treatment show no significant light and elevated temperature induced degradation (LeTID) behaviour for these Ga-doped PERC cells. PERC cells treated at temperatures above 110°C show an increase in relative voltage during CID starting the earliest at a measurement time of 50 hours. It was found that the voltage increase could be related to increased contact resistance between the front silver metallization and the phosphourus emitter as indicated by comparing electroluminescence imaging before and after CID treatment and confirmed by transfer length method measurements. These measurements on a cut-out stripe showed an increase in contact resistivity and a lateral intensity variation as visible in the post electroluminescence image.

Keywords: Carrier Induced Degradation, Contact Resistance, LeTID, PERC, Gallium-Doped

1. Motivation

Reliability is a key property of solar cells and solar modules to be successfully implemented. Thus, testing devices at the edges of typical operating conditions is necessary. In the past, the phenomenon of light and elevated temperature induced degradation (LeTID) was found [1,2] treating boron-doped PERC solar cells e.g. at 1 sun irradiance at 75°C. Gallium-doped industrial-type PERC solar cells seem to be more stable under the stated conditions, although LeTID behaviour is also reported [3,4]. Therefore, we tested our industrial-type PERC solar cells regarding LeTID-like behaviour in the presented study below.

2. Experimental

In this study industrial-type M2 PERC solar cells made from Gallium-doped Cz Si wafers with a bulk resistivity of about 0.25 – 0.6 Ωcm (acceptor density N_A = 2 – 8 × 10^{16} cm^{-3}) are investigated. The industrial-type PERC process sequence was carried out at ISC Konstanz which exhibit an industrial type, wet chemical saw-damage removal, texturing and rear side polish. A homogenous, about 90 Ω/sq, phosphourus emitter was diffused in an industrial POCL3-diffusion furnace. Rear surface passivation is achieved by a SiON stack deposited via PECVD. The front and back were metallized using a screen-printing process with a commercially available silver paste in an H-grid for the front and a commercially available aluminum paste as a full-surface layer for the back. The cells underwent current-induced degradation (CID) treatment at elevated temperatures in the range of 80…160°C in the dark at current injection. For the CID measurement, a hotplate, a chuck and measuring bars are used as shown in Figure 1 and described in [5].

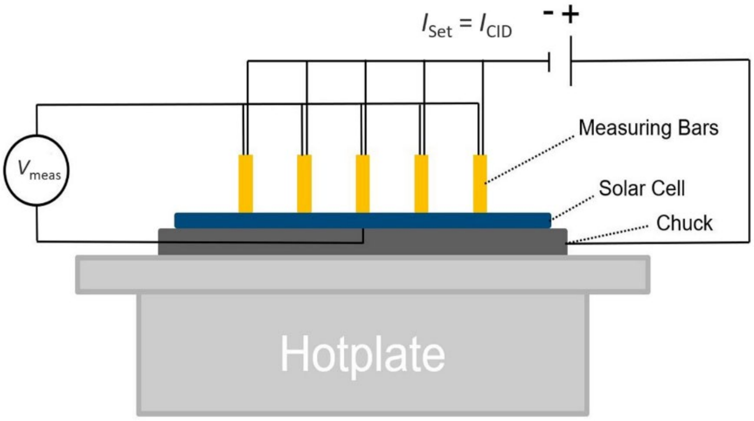

Figure 1. *Schematic of the CID setup.*

The CID current is investigated in the range of I_{CID} = 0.06…1.0 × I_{SC} which corresponds approximately to maximum power point (MPP) to open-circuit voltage (V_{OC}) injection conditions. A design of experiment (DoE) was developed to investigate possible LeTID behaviour. Three temperature levels (80°C, 95°C, 110°C) and three carrier injection levels ([0.06, 0.53, 1.0] × I_{SC}) are chosen. The DoE was changed and extended to higher temperatures up to 160°C after a few first measurement points which showed minor changes.

Before and after the CID treatment the solar cells are characterized on the same chuck without removing the measurement bars by electroluminescence (EL) imaging using an adjusted ‘Canon EOS RP’ camera with removed infrared filter in a closed dark surrounding box applying 10 A current.

For the transfer length measurements (TLM), stripes of thicknesses between 3 to 10 mm were cut out of M2 solar cells and a stripe of 3 mm thickness is presented below. A laser system was used to scribe from the cell’s back side approximately into half the wafer depth. Finally, the cells were cleaved manually. The stripes were measured in a Cascade S300 semi-automatic wafer prober using a switch-matrix and a Keithley 4200-SCS. The resistance is determined in four-point probe setup at 2 mA current for all combinations of eight equidistant needle pairs contacting the fingers of the TLM stripe.

3. Results

For CID, the derived voltage changes over time for the investigated PERC cells during temperature and current treatment is shown in Figure 2.

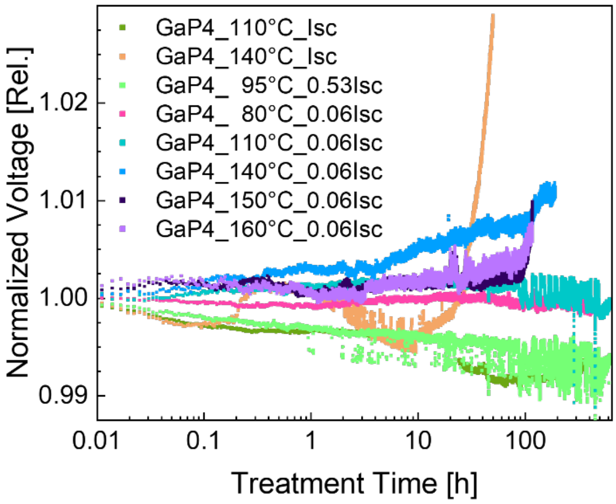

Figure 2. *Normalized change of voltage of the investigated PERC cells during temperature and current treatment in a CID setup.*

From the measurements, we derived that none of the samples showed a pronounced and significant voltage drop during treatment time. For cells treated at temperatures of above 110°C, an increase in relative voltage towards the end of treatment time is observed. From the carried out EL measurements before and after, we show the cell “GaP4_140°C_Isc” as an example in Figure 3.

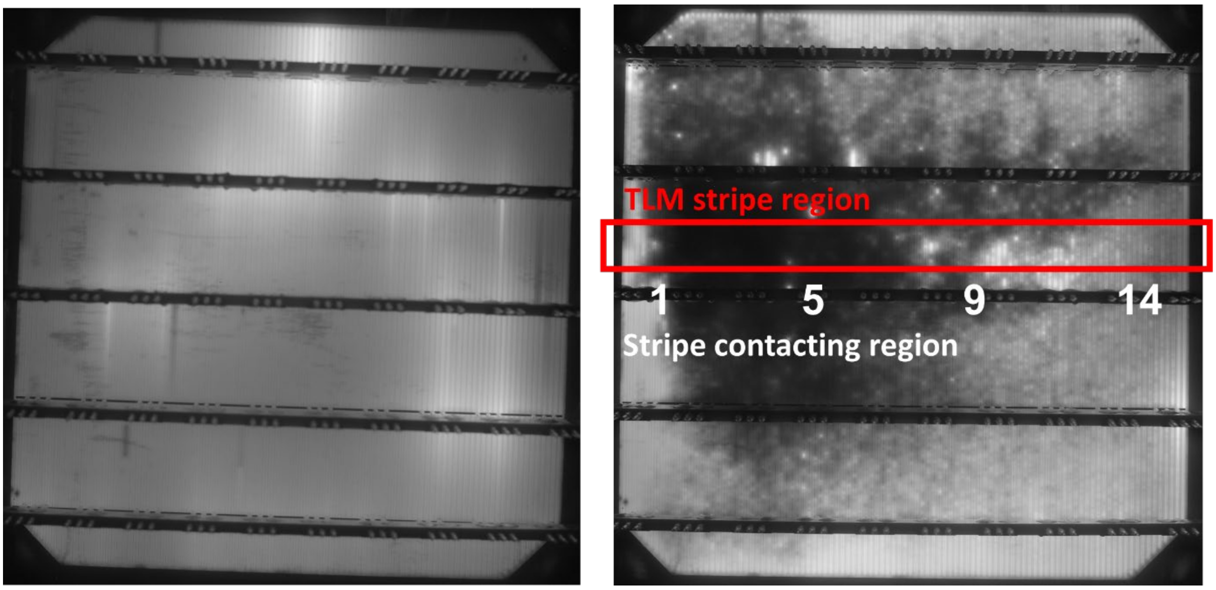

Figure 3. *Comparison of the EL measurement of cell “GaP4_140°C_Isc” before (LEFT) and after (RIGHT) 50h CID treatment at 140°C and at short-circuit current injection conditions in the dark. The red rectangle indicates the area where a stripe was cut out to perform TLM measurements and the white numbers indicate approximate locations of the corresponding stripe contact regions.*

A fairly homogeneous EL image (except for some finger interruptions and visible contact quality differences) before CID treatment turned into an inhomogeneous EL image showing areas of low EL signal intensity and some spots of high EL signal intensity after CID treatment. This indication made us prepare TLM stripes out of the shown cell after 50h of treatment and to perform TLM measurements along the indicated area (stripe) in Figure 3 (RIGHT). The results of subsequent TLM measurements along the stripe of 8 fingers at a time is shown in Figure 4.

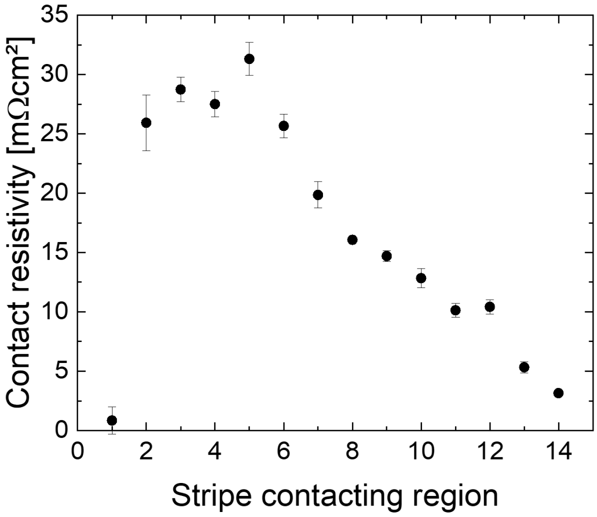

Figure 4. *Contact resistivity against stripe contacting region for a 3 mm wide stripe indicated in Figure 3 (Right). The stripe was subsequently TLM measured along the stripe with 8 fingers at a time contacted dividing the stripe in contacting regions, i.e. "region 1" contacts fingers 1…8, "region 2" fingers 9…16, etc. Note, that the contact resistivity varied strongly indicated by the uncertainty of the fitted coefficients using OriginPro software [6].*

The measured contact resistivity along the stripe shows a sharp increase from region "1" of typical contact resistivity below 5 mΩcm² to values above 30 mΩcm² followed by more steady decrease towards the end of the stripe (region "14").

4. Discussion

The CID treated Gallium-doped PERC solar cells didn't show a significant drop in voltage during treatment at higher temperature and injected current in the investigated range (compare Figure 2). Although LeTID behaviour is observed for Ga-doped PERC [3,4] under these conditions, we cannot confirm any sign of LeTID behaviour for the cells in our experiment. Surprisingly, we found an increase in voltage for solar cells treated above 110°C starting the earliest at a measurement time of 50 hours. Revising all our data of all CID experiments, we found CID treated similar PERC cells doped by Boron and/or Aluminum which show a similar voltage increase (not shown). By EL image comparison before and after treatment, the Ga-doped cells showed areas of low EL signal intensity which we attributed to a local increase in series resistance. It also explains the voltage increase in Figure 2 towards the end of their treatment time as higher voltages are related to higher ohmic losses, i.e. to a higher voltage drop. We derived a typical dark lumped series resistance of about 0.5 ± 0.2 Ωcm² fitting the dark IV curve with a two-diode model with variable second diode ideality factor before CID treatment (not shown). A derived typical contact resistivity of 5 mΩcm² contributes to about one fifth to the total lumped series resistance based on typical equations [7] for the determination of the contact resistance contribution. A strong increase in contact resistivity as observed in the TLM measurements can be then estimated to double the lumped series resistance. The observed EL patterns in Figure 3 (Right) seem similar to non-optimal fired front side metallization [8,9], which justified stripe preparation for TLM measurements. The exemplary TLM measurement shown in Figure 4 confirmed that the series resistance increase is caused by increased front side metallization contact resistance. Unaffected areas stay at typical contact resistivities below 5 mΩcm² whereas affected areas reach values above 30 mΩcm². Additionally, we find a corresponding lateral variation of contact resistivity and EL intensity signal as visible in the post EL image in Figure 3 (Right).

The increased contact resistance is thought to be related to hydrogen movement within the PERC cell as LeTID typical treatment conditions are applied [10]. We see similarities of our results to the phenomena of "hydrogen induced contact resistance" [11,12]. Thus, we follow the hypothesis that hydrogen migrates during CID treatment from the silicon bulk towards the surfaces and accumulates also at the screen-printed silver contacts, altering the contact behaviour. In comparison, our treatment temperatures (≤160°C) are lower than the range of around 250...400°C investigated in [11,12]. As we treated our samples for much longer times, it is thinkable that the same mechanism is activated.

5. Conclusions

In our investigations, we treated Gallium-doped PERC solar cells at elevated temperatures and injected currents. LeTID-like behaviour could not be observed. However, we found an increased contact resistivity of the front silver metallization at the end of treatment time. We attributed it to hydrogen movement towards the front contacts, altering the contact behaviour. The effect is observed in the temperature range above 110°C to 160°C which is already at temperatures closer to outdoor conditions. Therefore, we recommend for reliability testing of industrial screen-printed solar cells fired at higher temperatures besides bulk degradation to additionally look at contact degradation.

Data availability statement

The data that support the findings of this study are available from the corresponding author, Matthias Müller, upon reasonable request.

Author contributions

Matthias Müller: conceptualization (lead); data curation (equal); formal analysis (equal); funding acquisition (lead); investigation (equal); methodology (lead); software (equal); supervision (lead); validation (equal); visualization (equal); writing—original draft (lead); writing—review & editing (equal). **Mahsa Mohammadi:** data curation (equal); investigation (equal); methodology (equal); visualization (equal); writing—review & editing (supporting). **August Weber:** data curation (supporting); investigation (equal); methodology (equal); visualization (equal); writing—review & editing (equal). **Jonas Kern:** data curation (supporting); investigation (equal); methodology (equal); software (equal); visualization (equal); writing—review & editing (equal). **Matthias Trempa:** conceptualization (equal); formal analysis (supporting); resources (equal); writing—review & editing (supporting). **Thomas Buck:** conceptualization (equal); formal analysis (supporting); resources (equal); writing—review & editing (supporting). **Johannes Heitmann:** conceptualization (equal); formal analysis (equal); project administration (equal); resources (equal); supervision (equal); writing—review & editing (supporting).

Competing interests

The authors declare that they have no competing interests.

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