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In-situ characterization of electron-assisted regeneration of Cz-Si solar cells

L. Helmich[a,*], D.C. Walter[a], D. Bredemeier[a], R. Falster[b], V.V. Voronkov[b], J. Schmidt[a,c]

[a] Institute for Solar Energy Research Hamelin (ISFH), Am Ohrberg 1, 31860 Emmerthal, Germany
[b] SunEdison Semiconductor, Via Nazionale 59, 39012 Merano, Italy
[c] Department of Solar Energy, Institute of Solid-State Physics, Leibniz Universität Hannover, Appelstraße 2, D-30167 Hanover, Germany

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ABSTRACT

We examine the regeneration kinetics of passivated emitter and rear solar cells (PERCs) fabricated on boron-doped *p*-type Czochralski-grown silicon wafers in darkness by electron injection via application of a forward bias voltage at elevated temperature (140 °C) in order to discriminate between electronic and photonic effects. Based on these dark regeneration experiments, we address the existing inconsistency regarding the measured linear dependence of the regeneration rate constant on the excess carrier density. Using the method of dark regeneration by current injection into the solar cell, we are able to measure the total recombination current of the solar cell at the actual regeneration temperature under applied voltage, i.e., at the physically relevant regeneration conditions. The direct comparison of the regeneration rate constant as a function of electronically injected carrier concentration in the dark and the regeneration rate constant during illumination clearly shows that the regeneration is a purely electronically stimulated effect and that photons are not directly involved.

1. Introduction

The boron-oxygen (BO)-related defect center limits the efficiency of silicon solar cells fabricated on boron-doped Czochralski-grown silicon (Cz-Si) after light-induced degradation (LID). As previously shown, however, the BO defect can be permanently deactivated, i.e. the efficiency can be fully regenerated, if the solar cell is exposed to illumination or, alternatively, if electrons are injected by application of a forward bias voltage at elevated temperatures [1–4]. For the regeneration under illumination, a dependence of the regeneration rate constant R_{de} on the average excess carrier density Δn_{avg} in the bulk of the silicon base, determined from room-temperature measurements, has been reported by several research groups [5,6]. R_{de} increases proportionally with the illumination intensity [5,6]. However, a proportional dependence of R_{de} on Δn seems to be inconsistent with the strictly mono-exponential decay of the effective defect concentration during the regeneration process, as Δn is expected to increase strongly during the process of regeneration, due to a loss of the BO recombination centers. One possible explanation would be that the lifetime is in fact constant at the increased temperature applied during regeneration [7], which would result in a constant Δn value at the regeneration temperature. In order to examine the regeneration at well-defined Δn and to isolate the impact of electron injection on the regeneration kinetics, we measure the current flow in-situ through PERC solar cells under different constant forward bias voltages in the dark at elevated temperature.

2. Experimental details

In this contribution, we examine passivated emitter and rear cells (PERCs) fabricated on 2.0–2.2 Ωcm boron-doped Cz-Si wafers using an industrial-type screen-printing process [8]. The interstitial oxygen concentration $[O_i]$ is according to the wafer supplier in the range of $(7-8) \times 10^{17}$ cm^{-3}. The 156 × 156 mm^2 sized solar cells have an efficiency in the range of (20.52 ± 0.22)% before they were laser-cut into 25 × 25 mm^2 cells to increase the number of identical cells and to reduce the total current flow through the cell. First, we characterize all cells by measuring their *I-V* characteristics in the fully degraded and the dark-annealed states, respectively. The solar cells are degraded at room temperature using a halogen lamp with an illumination intensity of P_{ill} = 10 mW/cm^2 for 65 h (fully degraded state). Dark annealing is performed under ambient environment on a hot plate at 200 °C for 10 min (annealed state). The measured efficiencies in the fully degraded state are $(19.06-19.35)$%, whereas the efficiencies after dark annealing, which temporarily deactivates the BO defect, are in the range $(19.43-19.85)$%. Directly after dark annealing, we place the solar cell between two brass plates connected with Teflon screws, as shown in Fig. 1.

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[*] Corresponding author.
E-mail address: l.helmich@isfh.de (L. Helmich).

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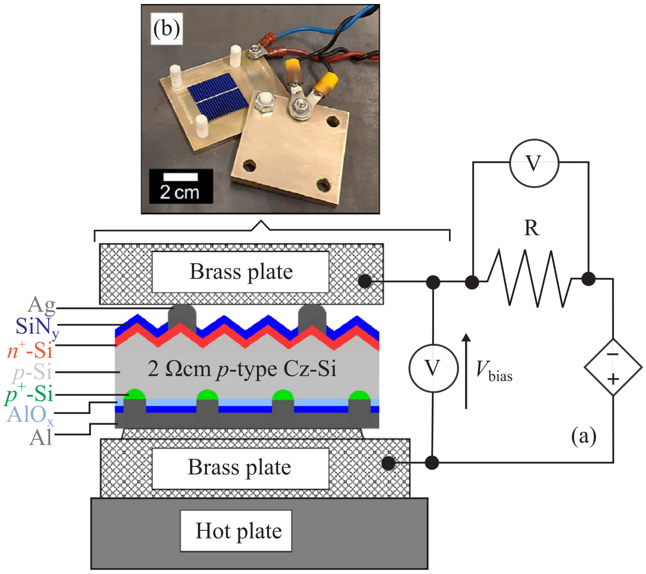

Fig. 1. (a) Schematic of our set-up for the in-situ regeneration experiments in darkness. (b) Photo of the clamped solar cell placed on the hot plate.

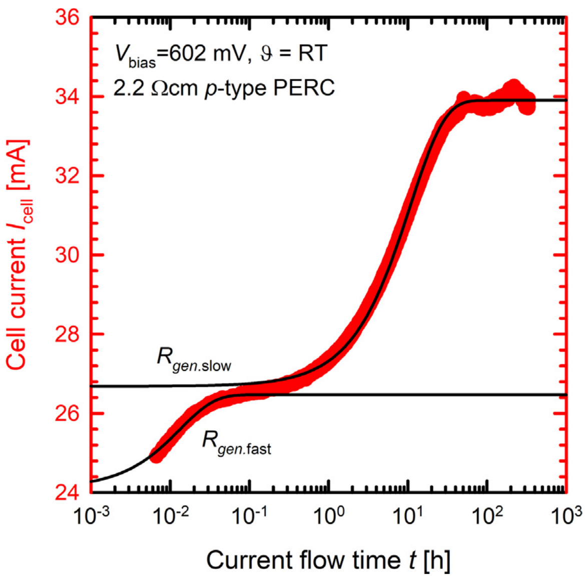

Fig. 2. The typical two-stage degradation, as known from the literature [9], can also be observed in the dark cell current, if a constant forward bias voltage (V_{bias} = 602 mV in this case) is applied to the cell at room temperature.

This sandwich-like structure is then put onto a conventional hot plate. After 30 mins, the thermal equilibrium is reached and a voltage is applied, which is kept constant during the entire experiment. The cell current I_{cell} (red symbols in Fig. 2(b)), which is proportional to the overall recombination rate in the cell, is measured by a voltage-drop over a resistance, which is connected in series (see Fig. 1(a)). We choose the resistance (0.1 Ω or 1 Ω) according to the examined current range. The initial state of the solar cells was after dark annealing and the temperature of the cell temperature on the hot plate was kept constant at 140 °C during regeneration. After complete regeneration, we characterize each solar cell again by illuminated *I-V* measurements (25 °C, AM1.5 G spectrum, 1sun) using the LOANA solar cell characterization tool (pvtools, Hamelin, Germany).

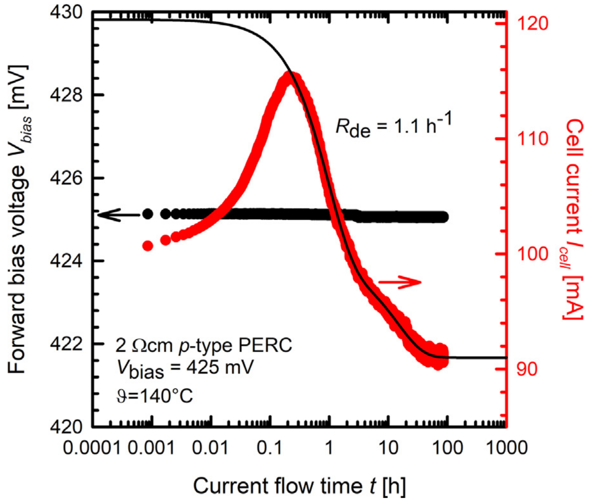

Fig. 3. Evolution of the cell current I_{cell} under constant forward bias voltage V_{bias} = 425 mV at 140 °C in darkness. The solid black line shows a double-exponential decay function. The forward bias voltage V_{bias} is constant during the entire regeneration experiment.

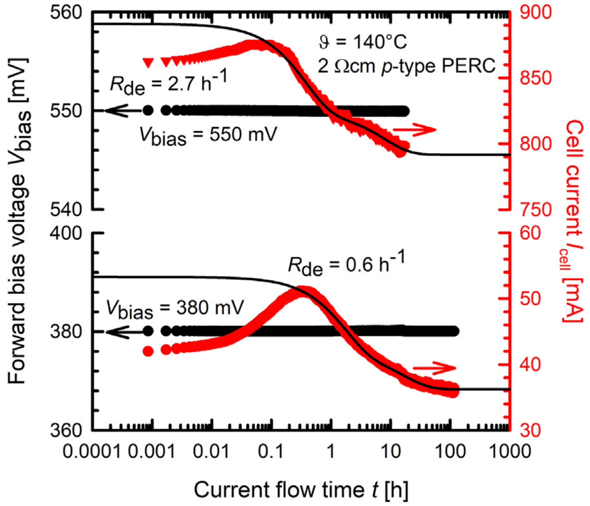

Fig. 4. Evolution of the cell current I_{cell} at two different forward bias voltages V_{bias} at 140 °C in darkness. The solid black lines show fits of double-exponential decay curves. The forward bias voltage V_{bias} is constant during each regeneration experiment.

3. Results and discussion

3.1. In-situ measured degradation and regeneration kinetics

Figs. 2–4 show the time evolution of the dark-injected cell current I_{cell}, which is directly proportional to the total recombination rate versus the logarithmically plotted time at the applied voltages V_{bias}.

In Fig. 2 the typical degradation behavior at room temperature known from the BO defect activation under illumination is observed. For the fast initial increase of the cell current, we determine a rate constant of $R_{\text{gen,fast}}$ = 2.1 × 10^{-2} s^{-1} and for the second, slower rate constant we determine $R_{\text{gen,slow}}$ = 2.6 × 10^{-5} s^{-1}. These rate constants, $R_{\text{gen,fast}}$ and $R_{\text{gen,slow}}$, are in excellent agreement with the fast and slow generation rate constants of the light-induced BO defect