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Temperature dependent quantum efficiencies in multicrystalline silicon solar cells

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Abstract

Several field studies comparing modules based on Elkem Solar Silicon® (ESS®) cells with reference modules based on non-compensated virgin polysilicon show that the compensated ESS® modules outperform the reference modules with comparable installed capacity under certain operating conditions. At high temperatures and high irradiation conditions the modules based on compensated silicon produce more energy than the reference modules. In order to increase the understanding of the observed effect cells are studied at different temperatures by the means of IV-characteristics as well as quantum efficiencies. Quantum efficiency measurements show that the main difference between ESS® cells and polysilicon cells when increasing the temperature occurs in the 800 nm to 1100 nm wavelength range. Changes in this wavelength region are typically attributed the bulk properties of the material, i.e. the minority carrier lifetime and the carrier mobility.

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1. Introduction

PV energy production is growing and an increase in the demand for silicon for solar cell production can be expected in the future. By minimizing the energy consumption in the silicon feedstock production the energy pay-back time of installed solar modules can be reduced. Solar grade silicon (SoG_M-Si) produced through the metallurgical route is one of the most energy effective production methods for PV [1, 2]. A reduction in the greenhouse emissions follows the reduced energy consumption [3]. Elkem Solar Silicon® produced through the proprietary metallurgical process contains slightly higher concentrations of doping elements, both boron and phosphorus, compared to conventional polysilicon. Typical levels for [B] and [P] are 0.20 ppma and 0.60 ppma, respectively. In order to keep the resistivity in ingots in a range suitable for solar cell production phosphorus and gallium are added in order to compensate for the phosphorus present. Despite the additional doping elements the performance of cells based on such compensated silicon or blends containing both virgin polysilicon and compensated silicon rival those made from virgin polysilicon only [2, 4]. It has been reported that the increased total dopant concentration leads to a reduction of the carrier mobility in compensated silicon [5-8]. However, reduced recombination activity of defects in compensated silicon may counterbalance the reduced mobility by an increase in the minority carrier lifetime [9]. Typically lower short-circuit currents (and slightly higher open-circuit voltages) is observed in solar cells based on compensated silicon [5].

Field studies where modules consisting of Elkem Solar Silicon® are compared to reference modules with comparable specifications at standard test conditions show that the modules based on 100% ESS® solar cells outperform the reference modules under high temperature and high irradiation operating conditions [2]. Similar results where modules based on upgraded metallurgical silicon perform better than the references at summertime has also been reporter for other feedstock suppliers [10]. A test system at BVRIT in Hyderabad, India, containing 14 ESS® modules and 14 polysilicon reference modules, demonstrate that the modules based on Elkem Solar Silicon® produce more energy than the reference modules at elevated temperatures and irradiance [11, 12]. During the first year the ESS® modules produce more energy than the reference modules in most months of the year, despite a slightly lower installed capacity. This beneficial effect of temperature and/or irradiation intensity favoring ESS® cells has also been demonstrated on cells in more controlled laboratory experiments [13, 14]. Temperature dependent illuminated IV-measurements in a solar simulator show favorable temperature coefficients in ESS® cells for the short-circuit current (J_{SC}), open-circuit voltage (V_{OC}), fill-factor (FF) and efficiency (η) [13]. A higher operating temperature as well as high irradiance will benefit the modules based on Elkem Solar Silicon® [14].

In the present study the quantum efficiencies in cells containing ESS® as well as the reference cells based on conventional polysilicon will be studied in order to gain more insight into the observed effect favoring ESS® based cells. Quantum efficiencies will be evaluated at 25°C and 50°C.

2. Experimental details

Solar cells are chosen from the same batches as used in the field studies in Hyderabad. The wafers and cells are produced in 2011 under as identical conditions as possible; by the same producer in identical furnaces and in the same cell production line. Cells produced from the top 200 wafers of each block yield average efficiencies of 16.86% (range 16.43-17.33%) for ESS® and 16.96% (range 16.34-17.34) for the poly references. Cells from the bottom 200 wafers yield average efficiencies of 17.18% (range 16.20-17.56%) for ESS® and 17.27% (range 16.34-17.50%) for the references. Although differences in material quality between blocks and even within the same block may arise in multicrystalline wafers, the main differences in the cells are attributed the different silicon feedstock. Prior to measurements all cells were subject to annealing at 200°C for 20 minutes followed by a light soaking in order to stabilize the degradation caused by BO-related defects. The IV characteristics are measured using a commercially available AAA sun simulator. The temperature dependence of the IV data is found by taking measurements at even temperature intervals between 25°C and 70°C. Internal and external quantum efficiencies (IQE and EQE) are measured at 25°C and 50°C using a setup from PV-tools/LOANA.

Minimal temperature changes in reflection with the temperature increase are assumed and contacting properties are assumed to be identical for ESS® and poly cells. An estimate for the J_{SC} can be obtained by integrating Eq. 1 from 300 nm to 1200 nm.