COMPENSATED SOG-SI FROM A METALLURGICAL ROUTE: HIGH LATITUDE OUTDOOR PERFORMANCE

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ABSTRACT: We compare the outdoor performance of two polycrystalline-Si PV modules of identical design, but with cells based on different types of solar-grade Silicon. The cells of one of the modules are made of Si feedstock purified in the conventional chemical route, whereas the other module has cells based on solar Si produced from a pyrometallurgical route. Electrical and electronic parameters of the modules are extracted from measured current-voltage data and compared. The two modules perform similarly in the Nordic conditions at which they have been tested. Only minor differences are found between their electrical parameters. Analysis of the electronic parameters related to p-n junction quality reveals the general similarity of the two materials, but also indicate subtle differences.

Keywords: Performance, Polycrystalline Silicon, PV Module

1 INTRODUCTION

1.1 Scope and motivation

This paper presents the results from a direct comparison between the outdoor performances of two polycrystalline-Si PV modules made by Q-Cells. The two modules are identical in design, but their cells are based on different types of solar-grade Silicon (SoG-Si). The first feedstock type is purified in the conventional chemical route, and the second type is produced from the pyrometallurgical route developed by Elkem Solar AS, resulting in the product which is known under the trade mark Elkem Solar Silicon (ESS™). The cell designs are otherwise the same. The modules are tested in Southern Norway by simultaneous recording of I-V curves over a wide range of test conditions. With the term 'performance' we mean the maximum power of a module.

The two modules perform almost equally in terms of maximum power, with only slightly differing electrical parameters (terminal behavior). However, we have probed deeper than this, and have also analyzed electronic parameters related to p-n junction quality, namely the ideality factor and the reverse saturation current of the diffusion diode in the double-exponential model. The analysis of these parameters has revealed both similarities and subtle differences between the two materials studied. The ideality factors of both modules are slightly higher than 1, and vary within a narrow range.

We conclude that, despite subtle differences in the electrical and electronic parameters, the two modules studied have performed similarly under the conditions they have been subject to. One cannot, on the basis of this study, say that one of the modules is better than the other.

1.2 Organization of the paper

The paper first reviews the reasons for the development of SoG-Si from metallurgical routes, a relatively new feedstock type for making polycrystalline-Si PV cells and modules. The major efficiency-loss mechanisms related to feedstock type are then outlined, and we point out the significant progress in the production of high-quality SoG-Si from metallurgical routes.

Thereafter, we describe the test setup used to measure the outdoor performances of the two PV modules. We then compare the electrical parameters (terminal behavior) of the two modules. Later on, we analyze key electronic parameters related to p-n junction quality, namely the diffusion-diode ideality factor and the reverse saturation current from the double-exponential model. Finally, we compare the two modules up against another.

2 SOG-SI FROM METALLURGICAL ROUTES

2.1 Solar-grade polycrystalline Silicon

The drive for lower cost Silicon wafers for terrestrial photovoltaic applications lead to development of polycrystalline ingot casting technologies. Until 1997, the Silicon used in the production of polycrystalline-Si solar cells originated from material rejected by the microelectronics industry [1,2]. Later on, the rapid growth of the PV industry led to a shortage of rejected material, and the manufacturers were forced to purchase ordinary electronics-grade Si (EG-Si), an ultra-pure and very expensive material. Eventually, economic alternatives were developed. The chemical route uses the conventional Siemens process for purification, whereas the metallurgical route transforms metallurgical silicon directly into solar-grade (SoG-Si). This second route can be five times more energy efficient [1].

PV applications are more tolerant than microelectronic applications to higher concentrations of impurities and crystal defects, which abound in polycrystalline Silicon. Grain boundaries are created during the process of solidification. In addition, clustered as well as isolated dislocations are present due to stresses in the material. Impurity atoms (mostly oxygen) contaminate the melt from the crucible at high temperatures. In the case of metallurgical purification, atoms of many other elements remain in the material at relatively high concentrations, phosphorus included. To achieve p-type doping, a proper amount of boron needs to be added, enough to compensate the phosphorus, which is an n-type dopant. Atoms of transitional metals tend to cluster at grain boundaries and dislocations, making them highly recombination-active parts of the solar cell. Techniques are being developed to concentrate
most of the detrimental impurities in large-sized precipitates, thus leaving most of the cell area less affected [3,4].

2.2 PV cells based on SoG-Si from metallurgical routes

A number of projects exist for production of solar Si from metallurgical routes [1,5]. Elkem Solar has achieved cell efficiencies of 15–16% with their material, and there is a potential for reaching efficiencies of more than 18% [1,6,7]. It has been found that only parts of the grain boundaries are recombination active, in contrast to standard polycrystalline material [6]. Very good average minority-carrier lifetime has been achieved [7].

Similarly to both Czochralski-grown monocrystalline Silicon (Cz-Si) and polycrystalline-Si from chemical routes, SoG-Si from metallurgical routes is prone to light-induced degradation (LID) due to formation of recombination-active boron-oxygen complexes [8,9]. However, neither light-induced nor long-term degradation effects are studied in the present paper.

3 DETAILS OF THE TEST SETUP

3.1 Design of the modules

The cells and two modules have been manufactured by Q-Cells. The same glass-plastic design with an Al frame is used on both modules. Each module consists of $N_{	ext{cells}}=60$ series-connected, screen-printed square cells of size $15.6 \times 15.6 \text{ cm}^2$. Each cell features 3 main bus bars. Bypass diodes are connected across substrings of 12 cells, resulting in a total of 5 diodes in each module.

3.2 Site and configuration

The modules are installed on a flat roof in the city of Kristiansand, Norway, at latitude N58°09’ facing South, inclined 60° from the horizontal. Each module is connected to an individual variable electronic load, and is maintained at the maximum power point of operation between the current-voltage (I-V) curve measurements. The modules were mounted outdoors for the first time in the autumn of 2009, and systematic in situ measurements have since been performed. In addition, during this period, the modules have twice been demounted and sent to an independent, certified laboratory in Germany for indoor reference measurements.

3.3 I-V curve measurements

Current-voltage characteristics of the modules are simultaneously recorded over constant periods of time. A commercial multichannel electronic load system Dynaload MCL488 is used. Each load is individually controlled by the PC-based I/O board NI PCIe-6363, which is also used to record all measured signals. By varying the load resistance between infinity and nearly zero, an I-V curve is swept starting from open-circuit and almost reaching short-circuit. Due to a non-zero minimum load-resistance of about 0.15 $\Omega$, the modules are never completely short circuited (see Fig. 1). Therefore, the value of the short-circuit current $I_{SC}$ has to be extrapolated from the lower-voltage part of the curve.

Crystalline-Si modules typically have low capacitances. This allows for sweep times as low as a few milliseconds [10,11]. However, the shortest sweep time achievable with the present data-acquisition system is about 300 ms, allowing for some irradiance instability to affect the quality of the recorded I-V curves. Each curve contains about 4000 data points, which allows for efficient filtering of noise and sufficient resolution of the recorded I-V curves.

3.4 Irradiance and temperature measurements

Irradiance and module temperatures are recorded in parallel with the sweeping of the I-V curve. A polycrystalline-Si reference cell SolData 80spc is used as a real-time irradiance sensor. However, self-referenced irradiance from $I_{SC}$ data of the modules is found to be more reliable. Values of $I_{SC}$ and $V_{OC}$ at Standard Testing Conditions (STC) as well as their temperature coefficients for both modules are available, as they have undergone tests at an independent certified laboratory. The difference between the self-referenced irradiances of both modules is less than 1 W/m² in most cases.

The direct module temperature is available for one of the modules via a Pt100 probe attached on the back metal surface of a central cell. Equivalent Cell Temperatures (ECTs) for both modules were calculated after IEC 904-5 [12] from measured $V_{OC}$ data, using the reference values and temperature coefficients provided by the independent laboratory. The Pt100 reading was systematically higher than the ECT estimate by a few degrees. At conditions close to Nominal Operating Conditions (NOC), both temperature estimates were within the NOC temperature range for glass-plastic crystalline-Si modules found in the literature [13,14]. However, the estimates based on the IEC-procedure were used in this work as the IEC-procedure is an established international standard and since detailed module data provided by a certified lab are available and therefore used in the estimation. It should be noted, however, that an error of 3°C in the cell temperature results in only a 1% error in the values found for the diffusion-diode ideality factor by our procedure; and the estimates of the reverse saturation currents are not affected by inaccuracies in cell temperature estimates.

4 ANALYSIS OF OUTDOOR I-V DATA

4.1 Comparison of electrical parameters

Various procedures for the translation of I-V curve
The factor $k_I$ is similar for both modules and varies range of cell temperatures and irradiances: constant fraction of the short-circuit current over a wide curves, the maximum-power-point current is an almost An interesting observation is that for non-shaded I-V less than a per cent, favoring A10156. However, the maximum-power-point voltage of A10156 difference between the maximum-power-point currents. 2%) compared to its competitor. There is a similar route. The module based on SoG-Si from a metallurgical denoted A10156 is based on SoG-Si from a chemical denoted A10160 is based on SoG-Si from a metallurgical route. The module based on SoG-Si from a metallurgical route has a slightly lower short-circuit current (by about 2%) compared to its competitor. There is a similar difference between the maximum-power-point currents. However, the maximum-power-point voltage of A10156 is higher by 2%, and the open-circuit voltage is also higher. As a result, the maximum powers of the two modules differ by only 0.3%. The fill factors differ by less than a per cent, favoring A10156.

An interesting observation is that for non-shaded I-V curves, the maximum-power-point current is an almost constant fraction of the short-circuit current over a wide range of cell temperatures and irradiances:

$$I_{MP} = k_I I_{SC}$$ (1)

The factor $k_I$ is similar for both modules and varies between 0.93 in summer and 0.94 in winter.

From the electrical characteristics alone, and with the very small sample of modules, one cannot really distinguish the modules from one another. The differences could be attributed to statistical variance. However, it should be mentioned that it may be expected that modules based on SoG-Si from a metallurgical route will have a lower photocurrent due to larger amounts of impurities increasing the bulk recombination. With a larger sample of modules, this could turn out to be a real effect, rather than a statistical coincidence.

Another way of probing deeper into the comparison of the two technologies, even with such a small sample of modules, is to analyze the I-V curves in light of the double exponential model. This is done in the following Sections.

### 4.2 Extracting double-exponential-model parameters

During the course of this study, we have also investigated the applicability of the double-exponential model to industrial polycrystalline-Si PV modules [19,20]. We have concluded that the cells within a high quality module may be expected to be nearly identical. However, we have found that not all variants of the double-exponential model that are available in the literature are applicable to polycrystalline-Si PV devices. Many authors make a priori assumptions for the values of some of the parameters. The diffusion-diode ideality factor $n_1$ is often assumed to be equal to 1, and the recombination-diode ideality factor $n_2$ is sometimes assumed to be equal to 2. We have shown such a priori assumptions to be erroneous in the case of polycrystalline-Si PV modules, at least for the parameter $n_1$, which is larger than 1 and even shows some variation.

Appelbaum et al. (1993) showed that the non-linear curve fitting approaches usually result in wide parameter sets, all achieving good fitting [21]. In order to find unique and physically meaningful parameters for each individual I-V data set, we have applied a method based on semi-logarithmic plots, described in detail in [19,20]. In brief, the method evaluates the parameters one by one, starting with the photocurrent $I_{MP}$ and the module series resistance $R_s$, which is found using an algorithm introduced in [19]. A semi-logarithmic plot is then created. The plot is compensated for the series-resistance effect, and features partial linearity at the higher voltages. The slope of this linear region is used to evaluate the diffusion-diode ideality factor $n_1$, whereas the reverse saturation current $I_{01}$ is extracted from the vertical-axis intercept after linear extrapolation. Only non-shaded I-V curves taken at irradiances above 400 W/m² are analyzed.

By using this procedure, we have made the important finding that the series resistances of the two modules are practically equal (approximately 0.4 Ω). Furthermore, there is only a slight variation of the series resistance with cell temperature. This parameter, therefore, seems to be mostly related to cell and module technology used by the manufacturer, and is not so affected by the type of SoG-Si feedstock used.

Two other parameters, that are also extracted using the procedure described above, are related to the p-n junction; these are the diffusion-diode reverse saturation current $I_{01}$ and the ideality factor $n_1$. These parameters are discussed in the following Section. It should be noted, however, that the methodology used to determine the parameters is still under development, and the results must therefore be regarded as preliminary and approximate. In particular, input I-V data is imperfect, and the data is processed by both statistical and numerical algorithms implemented in LabView and Matlab computer codes. We cannot rule out neither imperfection in the choice of algorithms nor in the computer codes that we have developed in the project. However, we do consider the values obtained for the parameters to be good approximations already at this stage.

### 4.3 Comparison of p-n junction parameters ($n_1$ and $I_{01}$)

![Figure 2: Evolution of the diffusion-diode ideality factor $n_1$ in the course of a sunny day for the two polycrystalline-Si modules tested.](image)

The evolution of the diffusion-diode ideality factor $n_1$ for each module in the course of a sunny summer day is
presented in Fig. 2. The values do not correspond to an ideal diffusion diode (i.e. they are larger than unity), and vary to some degree. Plots over cell temperature are given in Fig. 3. The ideality factor for the module based on SoG-Si from the metallurgical route is systematically slightly lower (i.e. closer to the ideal value of 1) than the ideality factor of the module based on SoG-Si from a chemical route. As this parameter is known to affect the fill factor [22], the slightly higher fill factors of the former module can be attributed to its slightly better ideality factor, given the fact that the series resistances of both modules are practically the same.

![Figure 3](image)

**Figure 3:** Diffusion-diode ideality factor $n_1$ over cell temperature. Plots are based on I-V data from 27 June 2010 recorded at irradiances above 400 W/m².

The temperature dependency of the reverse saturation current $I_{01}$ for both modules is shown in Fig. 4. There is a relatively large spread of values in both plots, something which reflects the imperfect I-V data, and maybe also imperfect statistical and numerical processing. Otherwise the plotted temperature dependencies correspond well with theory [15,23]. The module based on SoG-Si from the metallurgical route systematically has the lowest reverse saturation current, something which explains its slightly higher open circuit voltage.

![Figure 4](image)

**Figure 4:** Temperature dependency of the reverse saturation current $I_{01}$ for both modules tested. Values are extracted from I-V data recorded on 27 June 2010 at irradiances above 400 W/m².

In terms of parameters related to p-n junction quality, the two SoG-Si types compared qualitatively behave similarly, but the actual values obtained for the parameters differ somewhat.

5 CONCLUSION

We have measured and compared the high-latitude outdoor performance of two polycrystalline-Si PV modules of the same design but with cells based on different SoG-Si feedstock types. One type is purified by a chemical route, and the other type is produced from a metallurgical route.

The power output of the modules differs by less than 1%. The module based on SoG-Si from a metallurgical route has a somewhat lower short-circuit current but slightly higher open-circuit voltage and fill factor. The series resistances of the modules are practically equal.

We have performed a detailed analysis of module parameters related to p-n junction quality. The values of the ideality factor $n_1$ and the reverse saturation current $I_{01}$ have been extracted from semi-logarithmic plots of I-V data. The module produced from a metallurgical-route SoG-Si has lower reverse saturation current values as well as lower ideality factor values, which could indicate a somewhat better quality of the p-n junctions.

To our knowledge, this is the first detailed parameter analysis of p-n junctions based on SoG-Si from Elkem Solar’s metallurgical route. Our results indicate that cells made from SoG-Si produced from this particular metallurgical route become quite similar to cells made from SoG-Si produced from a chemical route, and can perform equally well when assembled in a module.

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7 REFERENCES


