Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 77 (2015) 15 – 20

Energy Procedia

5th International Conference on Silicon Photovoltaics, SiliconPV 2015

Temperature coefficients of compensated silicon solar cells – influence of ingot position and blend-in-ratio

Charly Berthod[a]*, Rune Strandberg[a], Jan Ove Odden[b]

[a]Department of Engineering Sciences, University of Agder, Jon Lilletuns vei 9, 4879 Grimstad, Norway
[b]Elkem Solar AS, Fiskaaveien 100, 4621 Kristiansand S, Norway

---

Abstract

Solar-grade silicon made from a metallurgical route presents boron and phosphorus compensation. Earlier work has shown that cells made from such material produce more energy than reference polysilicon modules when the temperature and irradiance is high. In the present study, solar cells from two different ingots with different blend-in-ratios were made from wafers at varying ingot heights in order to investigate how the temperature coefficients vary with compensation level and ingot height. The results suggest that solar modules made with solar cells from different ingot heights will perform differently at high temperature. It was also observed that the compensation level seems to have a smaller impact on the temperature coefficients than the ingot height.

Keywords: Compensated silicon; solar-grade silicon; temperature coefficient; ingot height; multicrystalline solar cells

---

1. Introduction

The ever present need for cost reductions in silicon production suggests replacing the well-established Siemens process [1] by metallurgical refining methods or even chemical routes. These processes offer not only well-known advantages, thanks to a reduction in the energy consumption and a lower carbon footprint of the solar cells [2], but also indications of a better temperature coefficient (TC) and larger specific electricity production in hot and sunny climate [3-6]. Elkem Solar Silicon® (ESS®) is produced by a metallurgical route that gives a low impurity

---

* Corresponding author. Tel.: +47 908 99 243.
E-mail address: charly.berthod@uia.no

doi:10.1016/j.egypro.2015.07.004

concentration [1]. It is a compensated material with both phosphorus and boron present because of the difficulty of removing these elements in metallurgical processes. Gallium can be added to increase the stability of the resistivity along the ingot and to secure an ingot yield not limited by resistivity or p/n changeover. The compensation leads to silicon with slightly different electronic properties, giving rise to differences in cell performance such as a lower short-circuit current (J_{sc}) and a higher open-circuit voltage (V_{oc}) [7].

The recent trend of replacing the Siemens process by cheaper methods in silicon production has led to an increase in the research on compensated silicon in order to determine the electronic properties of the solar cells made by such materials. In particular, the TC is of interest owing to the performance enhancements mentioned above [3-5]. These results on modules have been confirmed on cells, where the TCs of J_{sc}, V_{oc}, *FF* and efficiency of ESS®-cells were all found to be better compared to poly-silicon reference cells [8].

Understanding the variation of the efficiency of solar cells with temperature is important, and until now no comprehensive and general model has been developed that describes the TCs according to cell characteristics such as bulk resistivity, impurity content, dopants concentrations or compensation level. Since variations in the TCs are observed between different cells, it seems logical that a modification or an improvement of these coefficients is possible if the right measures are taken.

In the present study, the TCs were measured on solar cells made from wafers taken from different ingot heights of ingots consisting of compensated material mixed with poly-Si in two different blends. The results reveal information on how the compensation level and ingot height affects the temperature dependency of the solar cell characteristics.

2. Experimental procedure

Solar cells were selected from eight different heights along the ingot from the bottom to the top. The ingots came from the centre of a G5 furnace, and the solar cells were manufactured by the same producer, which is a research institute. This enables position tracking but gives lower efficiencies than compared to the industrial processing of the same wafers. The cells are multicrystalline silicon solar cells (15.6x15.6 cm^2) with a conventional aluminium back surface field (Al-BSF). The IV-characteristics were measured under a standard AM1.5G spectrum with a NeonSee™ AAA sun simulator at STC. The TCs were obtained by measuring the IV characteristics of a cell from 25°C to 50°C with one degree steps, and then performing a linear fitting of each parameter to get the temperature coefficients (as shown by Martin Green [9], over a limited temperature range the four IV parameters are linear with temperature.)

The blend-in ratios, resistivities and dopants of the two blended ingots (BIR-M and BIR-H), both having an ESS® blend-in ratio of >50%, are shown in Table 1.

Table 1. Ingots description.

Ingot name	Blend-in-ratio	Resistivity target (Ω cm)	Mean resistivity (Ω cm)	Dopants
BIR-M	medium	1.25	1.25	B/Ga-P
BIR-H	high	1.25	1.27	B/Ga-P

3. Results

The principal characteristics of the solar cells (J_{sc}, V_{oc} and the efficiency) are presented in Fig. 1. The trends along the ingot can be seen with the highest magnitude of the J_{sc}, V_{oc} and the efficiency near the bottom of the ingot where the lowest defect concentration is expected. Despite the different blend-in-ratios, no significant differences are seen on these cells, making them suited for a TC comparison without considering differences in the principal characteristics.

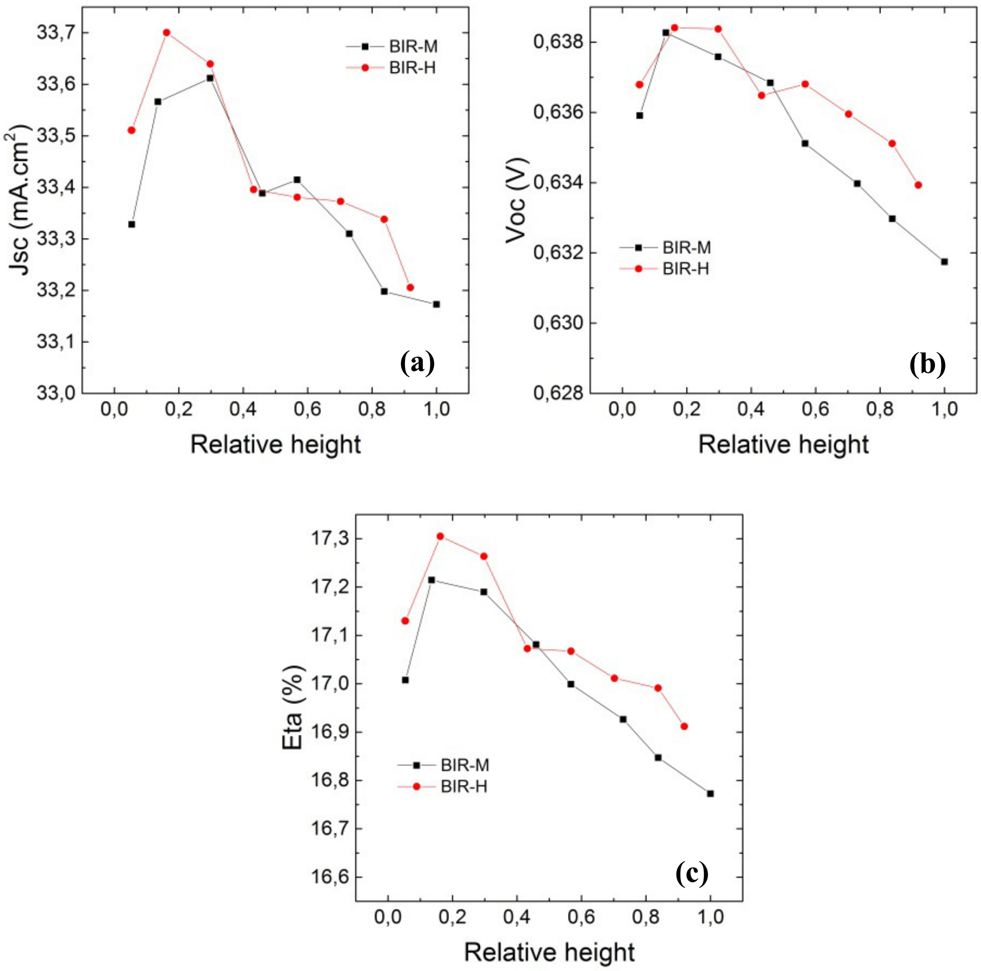

Fig. 1. (a) The short-circuit current density, (b) the open-circuit voltage and (c) the efficiency of the two different ingots taken on eight different locations along the ingots.

The relative TCs of the I_{sc}, V_{oc}, FF and the efficiency of the solar cells from both ingots are found to improve towards the top of the ingots, as shown in Fig. 2. The variation of these coefficients along the ingot is significant because earlier research has reported differences in the relative TC of the efficiency between compensated material and standard polysilicon in the range of 0.03%/°C ± 0.01 [5,8,10]. This work shows a difference of similar magnitude between a top and a bottom cell for both ingots (see Fig. 2d). The main contributing factor of the height-dependent variation of the TC for the efficiency is the variation of the TC of the I_{sc}, which increases at least $0.015\%_{abs}$/°C from bottom to top (see Fig. 2a).

Another observation to be made from Fig. 2 is that no particular discrepancy (or improvement) can be seen between ingots with different blend-in-ratios (i.e. different compensation levels). The variation along the ingot predominates over the difference between the two blend-in-ratios studied here. Reasons for this TC augmentation together with its implications will be discussed in the next part.

4. Discussion

It was noted above that the relative TC of the I_{sc} is the main contributor to the increase of the relative TC of the efficiency. This is the case although the relative TC of the I_{sc} is smaller in magnitude than the TCs of both the V_{oc} and the *FF* (Fig. 2). The I_{sc} increases slightly with temperature since the bandgap decreases with temperature and more photons are absorbed. Therefore, a rise in the TC of the I_{sc} along the ingot might be explained by an even stronger narrowing of the bandgap due to compensation. However, no difference between the ingots is visible, which discredits this hypothesis.

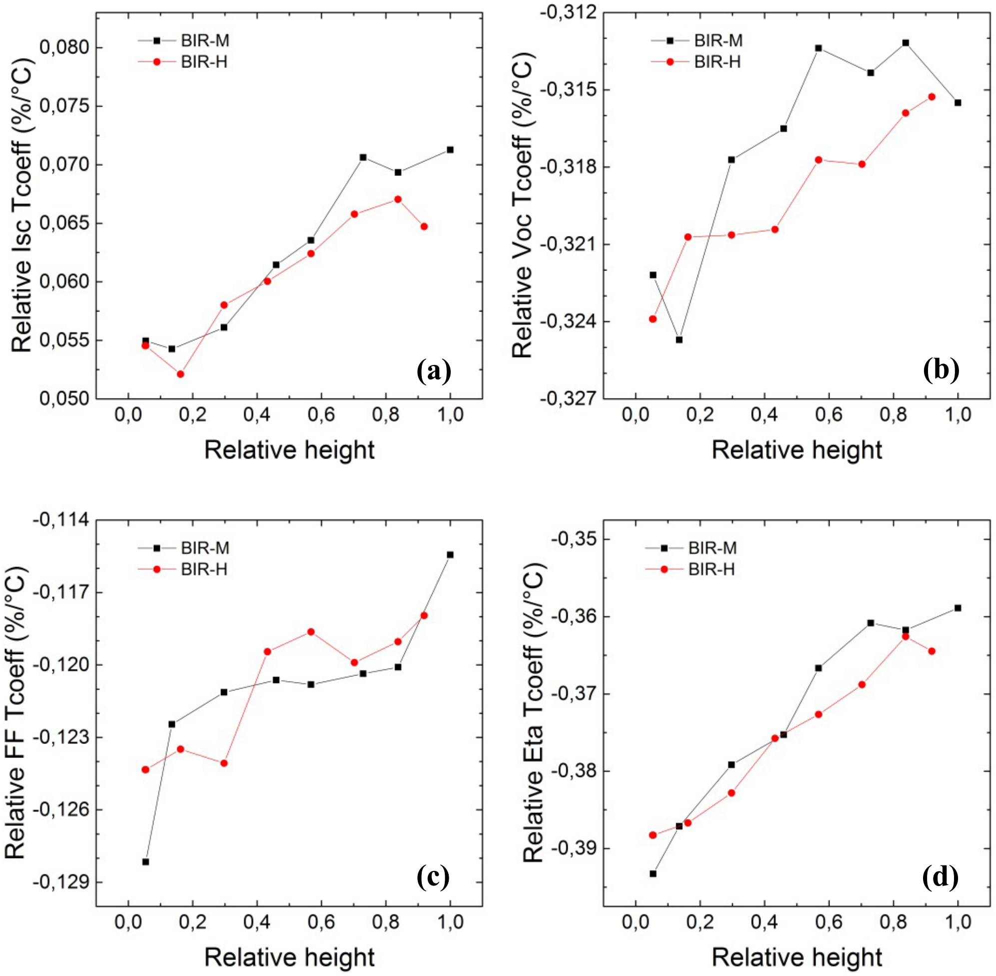

Fig. 2. The relative TCs of: (a) the short-circuit current, (b) the open-circuit voltage and (c) the fill factor and (d) the efficiency of the two different ingots taken on eight different locations along the ingots.

The relative TC of the V_{oc} is also increasing toward the top of the ingot (Fig. 2b), despite the fact that the V_{oc} decreases (Fig. 1b) mainly due to the increase in dislocation concentration towards the top. According to Ref. [9], the relative TC of the V_{oc} can be expressed as

$$\frac{1}{V_{OC}}\frac{dV_{OC}}{dT}=\frac{1}{T}-\frac{\frac{E_{g0}}{T}+k\gamma}{qV_{OC}}\,, \tag{1}$$

where E_{g0} is the bandgap extrapolated linearly from the temperature of interest to 0 K, k is the Boltzmann's constant, γ is a constant equal to 3 and q is the elementary charge.

According to Equation (1), a decrease in the V_{oc} should actually decrease the relative TC of the V_{oc}. Thus the increase in the relative TC of V_{oc} is due to another mechanism. Our main assumption is that the increases of the relative TCs of the I_{sc} and V_{oc} are due to a recombination process that happens at larger rates in cells made from top wafers, due to impurity segregation, and that becomes less active with increasing temperature. If so, the lifetime and diffusion length would be longer at high temperature, improving the relative TC of the I_{sc} and V_{oc}. Since the impurity concentrations rises along the ingot, and the capture cross-sections of certain impurities decrease with temperature [11,12], this assumption seems plausible.

The relative TC of the *FF* is also rising with the ingot height (see Fig. 2c). This is caused by the increase of the relative TC of the V_{oc} which can be seen in the following equation from Ref. [9].

$$\frac{1}{FF}\frac{dFF}{dT}=\left(1-1{,}02FF_0\right)\left(\frac{1}{V_{OC}}\frac{dV_{OC}}{dT}-\frac{1}{T}\right). \tag{2}$$

Finally, the relative TC of the efficiency, which is the sum of all three factors, is also increasing with the ingot height (see Fig. 2d). Solar cells made from the top part of the investigated ingots will thus perform better under high temperature conditions compared to cells made from bottom material.

We conclude that the ingot position must be taken into account when comparing the TCs of cells made by different production routes or from different feedstock.

5. Summary

The temperature coefficients of solar cells made of different blends of compensated silicon and poly-Si show rather large variations within an ingot. The ingots included in this study have almost identical resistivities, despite the different blend-in ratios, as well as comparable performances which allow us to rule out differences in the resistivity and material quality as reasons for the observed differences between them. All four temperature coefficients (i.e. I_{sc}, V_{oc}, *FF* and efficiency) improve towards the top of the ingot. The reason for this is not yet determined, but a probable mechanism seems to be an impurity-related recombination process that has a capture cross-section diminishing with temperature (such as B-O complexes, or Fe and FeB for electrons).

References

[1] Søiland AK, Odden JO, Sandberg B, Friestad K, Håkedal J, Enebakk E, Braathen S. Solar silicon from a metallurgical route by Elkem Solar- viable alternative to virgin polysilicon. in: CSSC 6, Aix-les-bains, France, 2012.

[2] Gløckner R, De Wild-Scholten M. Energy payback time and carbon footprint of Elkem Solar Silicon®. 27th EUPVSEC, Frankfurt, Germany, 2012.

[3] Tayyib M, Odden JO, Ramchander N, Prakash MB, Surendra TS, Muneeshwar R,... & Saetre TO. Two years performance comparison of Elkem Solar multicrystalline silicon with polysilicon in a PV grid-connected system. 40th IEEE Photovoltaic Specialist Conference, Denver, Colorado, USA, 2014, pp. 3230-3233.

[4] Tayyib M, Odden JO, Ramchander N, Prakash MB, Surendra TS, Muneeshwar R, ... & Sætre TO. Performance assessment of a grid-connected mc-Si PV system made up of silicon material from different manufacturing routes. 39th IEEE Photovoltaic Specialist Conference, Tampa Bay, Florida, 2013, pp. 0109-0114.

[5] Tanay F, Dubois S, Enjabert N, Veirman J. Low temperature-coefficient for solar cells processed from solar-grade silicon purified by metallurgical route. Progr Photovolt: Res Appl 2011;19(8):966-72.

[6] Ponce-Alcántara S, Connolly JP, Sánchez G, Míguez JM, Hoffmann V, Ordás R. A statistical analysis of the temperature coefficients of industrial silicon solar cells. Energy Procedia 55 (2014), pp. 578-588.

[7] Cuevas A. The paradox of compensated silicon. Optoelectronic and Microelectronic Materials and Devices, 2008. COMMAD 2008. Conference on. IEEE, 2008, pp. 238-241.

[8] Tayyib M, Odden JO, Sætre TO. Effect of temperature and sun intensity on multicrystalline silicon solar cells. 28th EUPVSEC, Paris, France, 2013, pp. 1595-1598.

[9] Green MA. General temperature dependence of solar cell performance and implications for device modelling. Progress in Photovoltaics: Research and Applications 2003;11(5), pp. 333-340.

[10] Cai L, Ren X, Fan B, Zheng J, & Chen C. Effect of temperature on crystalline silicon solar cells processed from chemical and metallurgical route. Optik-International Journal for Light and Electron Optics (2014).

[11] Xiao C, Xuegong Y, Deren Y, & Duanlin Q. Impact of solar irradiance intensity and temperature on the performance of compensated crystalline silicon solar cells. Solar Energy Materials and Solar Cells 128 (2014), pp. 427-434.

[12] Paudyal BB, McIntosh KR, & Macdonald DH. Temperature dependent electron and hole capture cross sections of iron-contaminated boron-doped silicon. 34th IEEE Photovoltaic Specialist Conference (2009): pp. 1588-1593