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Results on performance and ageing of solar modules based on Elkem Solar Silicon (ESS™) from installations at various locations

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ABSTRACT

The present study aims to present the current status of the results obtained using Elkem Solar Silicon (ESS™) as feedstock basis for solar cell and modules. It is shown that solar cells based on ESS™ are able to follow the development of the solar industry obtaining comparable efficiencies to standard polysilicon based cells. The characteristics of ESS™ based solar cells, having normally higher V_{oc} and FF and lower I_{sc}, seem to give clear advantages in the field for solar modules located at high irradiance areas. Results from several locations show enhanced electricity production of ESS™ based solar modules compared to polysilicon at increasing solar irradiance. This is explained by beneficial temperature coefficients for ESS™ based solar cells. Lower electrical loss for ESS™ modules is also expected to contribute to the same beneficial performance under conditions of high solar irradiance.

1. Introduction

Elkem Solar Silicon (ESS™) is a feedstock dedicated solely for the solar industry produced by Elkem Solar AS situated in Kristiansand, Norway. ESS™ has been on the market since 2009 as an alternative to the conventional polysilicon mainly produced through Siemens-type processes involving silicon containing gases, like trichlorosilane or monosilane, and decomposition there from at elevated temperature in bell-jar reactors. The starting point of both types of processes is the metallurgical grade (MG) silicon of approximately 99% purity. The Elkem Solar process route, however, avoids going via gaseous products and purifies the MG-silicon through steps like slag treatment and leaching. Therefore, when producing ESS™, less energy is consumed and also emissions of CO_2 from the process are greatly reduced compared to the conventional polysilicon processes. In fact a reduction by up to 75% on both energy consumption and CO_2 emissions is possible [1,2] and additionally the production cost of the ESS™ is also normally lower. Being a rather new feedstock material on the market it is important to show that ESS™ fulfills the requirements of the industry all the way from the ingot and wafer production, and most importantly to the solar cell and module level, where the capacity and possibilities of the material is realized as increased energy output. In this manuscript we will therefore compare cell characteristics and performance in solar modules for solar cells based on 100% ESS™ with conventional polysilicon as reference where all the production steps including ingot, wafering, cell processing and module assembly have been the same.

2. Material and methods

The main difference between ESS™ and conventional polysilicon is the content of the dopant elements boron (B) and phosphorus (P). While polysilicon is low in B and P, ESS™ as a compensated material contains both elements in typical concentrations of 0.20 ppmw B and 0.60 ppmw P. An ingot based on purely polysilicon will, however, be doped with B in order to meet the resistivity requirements necessary. A typical resistivity profile for a B-doped polysilicon ingot is shown in Fig. 1 with decreasing resistivity from bottom to top.

In the ESS™ case one has to consider the fact that both B and P are already present in the material when calculating the amount of B to be added. An example of a resistivity profile for an ESS™ ingot only doped with boron is shown in Fig. 2a. Here the resistivity

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0927-0248/

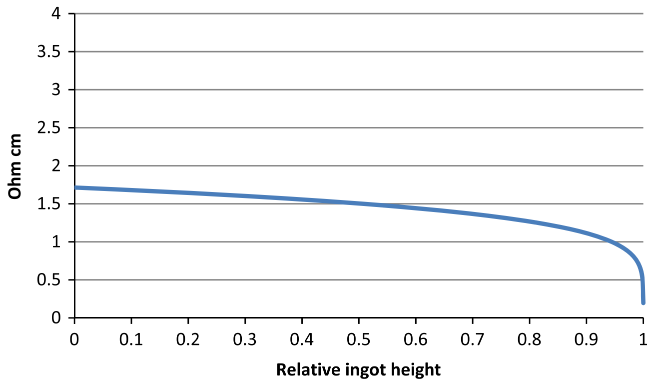

Fig. 1. Resistivity profile of a typical polysilicon ingot doped with boron as a function of relative ingot height.

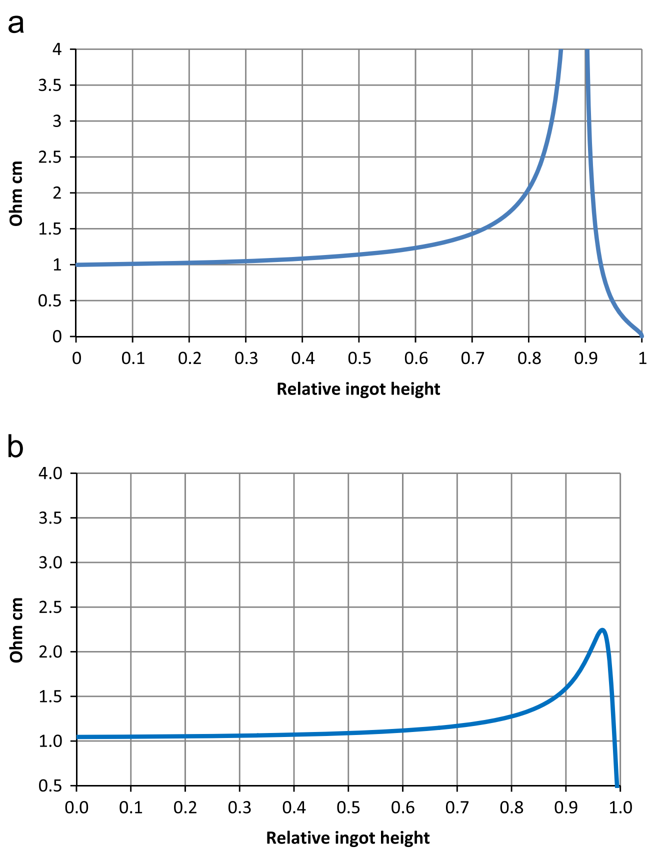

Fig. 2. (a) Resistivity profile as a function of relative ingot height for the case of doping 100% ESS™ with boron only. (b) Resistivity profile as a function of relative ingot height for the case of co-doping 100% ESS™ with gallium.

profile is influenced by the P content giving a profile of increasing resistivity from bottom to top. Another difference is the p/n changeover seen towards the top for ingots based on 100% ESS™, where the P concentration gets higher than the B concentration due to different segregation. An area with n-type material would normally have constituted a yield loss in the ingot process for the 100% ESS™ case compared to polysilicon. However, it is possible to do gallium (Ga) doping when using ESS™. The effect of Ga doping of ESS™ on the resistivity profile is shown in Fig. 2b. In this case the ingot is p-type all the way from bottom to top similar to the polysilicon case. Hence the yield will not be limited by n-type or resistivity issues.

For the wafer and cell processing no additional precautions or steps are necessary compared to the industrial standards when using ESS™ material. All the results presented on general cell characteristics in this manuscript are taken from reports made by key industrial players from China, Taiwan, other Asian countries and Europe. In all cases the original ingots have been produced in industrial size (G4 or G5) solidification furnaces and the cell processing is also done in industrial lines, as is also the case with the solar module production. Additional experiments were conducted on the cell level for some cells, and temperature responses through IV measurements were obtained for both ESS™ and polysilicon solar cells. The IV scans were made using a NeonSee™ AAA sun simulator while increasing the temperature from 25 to 70 °C with measurements every second degree, from which the temperature coefficients were calculated. The temperature interval chosen reflect normal operating temperatures for solar cells in the field.

2.1. *Test facilities*

In the present manuscript we consider solar module results from 3 different locations. These are India, Japan, and Australia. For all the test stations normalized data, hence the kW h/kW p, will be compared since the different batches may differ slightly in number of modules installed or in the internal matching of the modules in the arrays.

2.1.1. *India*

The test station in India is a roof top installation at the B.V. Raju Institute of Technology (BVRIT) near Hyderabad in the southern part of India. A total of 28 solar modules are installed—14 based on 100% ESS™ and 14 on polysilicon reference. The modules are made by Titan Energy Systems Ltd. in India using cells originating from wafers taken from the exact same brick positions (one corner, one centre and two side/edge bricks in the same positions were chosen from each ingot to reflect the total composition of a G4 size ingot) in the initial ingots—hence everything is set as equal as practically possible except for the original feedstock. The Wp of the different arrays installed is 3.337 kW p in total for the ESS™ based arrays and 3.371 kW p for the polysilicon arrays. The installation is grid connected through Power One-Aurora-PVI-6000-OUTD string inverters. Real-time data in-terms of energy fed to the grid by each string and environmental parameters as well as data from DC energy meters are measured continuously, monitored and stored at 5-min intervals (from August 2012 till January 2013), and from February 2013 onward 1-min intervals, with the help of a special software developed in-house. Environmental parameters like wind speed/direction, temperature, irradiance (Horizontal & Plane of Array measured by Kipp & Zonen pyranometers) are also measured, synchronized with the production data and stored.

2.1.2. *Japan*

While the Indian test station has a more research focus, the system installed on the roof top of Ishinomaki Commercial School in Ishinomaki near Sendai, and in the Miyagi prefecture, on the north east coast of Japan is a donation installation by Mitsui, Kyocera, and Elkem. However, also for this grid connected system we monitor both production and environmental parameters like temperature and in plane solar irradiance—but with a resolution of 1 h. Here we also compare 100% ESS™ based solar modules with polysilicon reference modules all made by Kyocera for this project. The installed capacity is 4.865 kW p for the 100% ESS™ arrays and 4.922 kW p for the polysilicon arrays.

2.1.3. *Australia*

The third test facility generating results on 100% ESS™ vs polysilicon reference is an installation in Alice Springs. Elkem Solar had no part in establishing this facility. The results are kindly