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16.7% EFFICIENT SOLAR CELL USING ELECTROMAGNETIC CASTING (EMC) MULTICRYSTALLINE SILICON WAFERS IN AN INDUSTRIAL TYPE SOLAR CELL PROCESS

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ABSTRACT: Purpose of the work is to understand the efficiency performance of EMC p-type mc-Si wafers from 18 different positions along the axis of growth of a 2,000kg, 35cmx35cm cross section, 7m long ingot. The 35cm x 35cm mold yields 2x2 or 4 corner 156mm x 156mm size wafers. The multicrystalline wafers have been produced by the electromagnetic casting (EMC) method. This EMC method uses an electromagnetic field to confine the melt from the mold wall by electromagnetic force, F=JxB, and to melt silicon by induction heating. This technique enables semi-continuous casting by melting the charged material at the top and solidifying the molten material at the bottom of the melt without contact to the crucible wall. The solar cells were produced using a state of the art screen-print industrial type solar cell process . A mc-Si group produced by conventional mc-Si production method was included for reference. The average efficiency of the EMC produced wafers from bottom to top was 16,5% with a maximum exceeding 16,7%.

1 Introduction

1.1 History of electromagnetic casting of silicon

The use of cold crucibles and electromagnetic fields for melting by induction of metals and semiconductors has been investigated for many years. The ceramic-free induction melting of metals and their alloys was patented first by the Siemens und Halske Company Germany in 1931. The application of induction heated zone refining process of silicon, using a horizontal water-cooled silver boat was reported in 1957 and 1961 by H.F. sterling and R.W. Warren, UK. Two years later the same Researchers Huff and Sterling reported the growth of high purity silicon crystals from a water cooled cold crucible using the Czochralski (Cz) process. In 1985, T.F. Ciszek, USA, was the first who proposed to apply the cold crucible technique for the silicon melting and casting by using an open bottom type of the crucible for the vertical continuous casting of solar grade silicon for solar cells. He performed the casting of a 25x25mm2 cross sectional ingot with 170mm length [1].

Since then research teams in Japan (SUMCO Solar Corp.)[6], France (EPM Madylam [7], [8], EMIX [11]) and more recently Korea (Korean Institute of Technology) [9] have investigated the use of electromagnetic casting with cold crucible for the production of large sized ingots for the crystalline silicon photovoltaic industry.

1.2 Features of EMC mc-Si ingots

Wafers from EMC mc-Si ingots have a recognizable grain pattern. The wafers have large crystal grains at the centre decreasing in size towards the edge due to more rapid cooling due to proximity to the crucible wall. One advantage of cold wall crucible casting over conventional casting methods is freedom from high levels of C and O [2]. The interstitial oxygen concentration of the EMC ingot used is < $0.5x10^{17}$atoms/cm^3 [3]. The oxygen concentration of EMC mc-Si from Osaka Titanium Company (now SUMCO) was lower than four other mc-Si suppliers as reported in [4].

The low Oi concentration is expected to contribute minimal or no degradation on the long-term EMC solar cell efficiency caused by light induced degradation (LID) through B-O complex formation [5].

Resistivity control within the target ±20% (e.g. 1.5±0.3 Ω .cm) along the p-type ingot length is possible on account of the semi-continuous casting nature of the method [3]. Similar resistivity control for an n-type phosphorus doped EMC ingot is expected from the method. For dopants with a more severe segregation profile like phosphorus, achieving tight resistivity control is one of the challenges facing HEM or Bridgman solidification or block cast mc- Si.

Another feature of the EMC method is the productivity. Unlike conventional mc-Si casting methods the crucible can be reused. High crystallization rates of between 1,6 and 2,2mm/min and significantly larger ingot sizes (2000kg – 3000kg possible) than conventionally cast mc-Si are further advantages of the EMC method [3], [6].

2 Material and Processing

ECN received wafers from Sumco Solar Corp. representing 18 positions along a 7m long 35cm x 35cm p-type multicrystalline ingot produced by EMC production method. The wafers were laser marked for traceability and processed in the ECN baseline process of October 2009 alongside a comparison group of mc-Si p-type wafers. The comparison wafers used were picked from available stock, commercial wafers and were produced by conventional mc-Si production methods. The ECN baseline p-type process uses industrial type equipment.

Two samples per position were processed totaling 36 wafers for 18 positions along the axis of growth of a 35cm x 35cm 7m ingot. Thirty four cells were completed with two samples lost due to handling error. The two damaged samples were from different positions so there is data for each of the 18 ingot positions. A reference group of 15 commercial mc-Si from another supplier were included.

The wafers were processing in the ECN p-type baseline which consists of P-diffusion, Al-Back Surface Field SiN_x:H firing through industrial type process [12]. The ECN baseline is in itself a continuous improvement/kaizen project aimed at pushing up cell efficiency through fine process tuning [10].

The wafers in this case were processed according to the October baseline settings. At that time the ECN baseline consisted of the following process steps as described in Figure 1.

Figure 1, ECN baseline process Oct. 2009

All wafers for the EMC and reference groups were processed concurrently in order to eliminate run to run variation for the two groups.

3 Results

3.1 EMC vs. Ref mc-Si

The EMC wafers average efficiency was 16,5% with a maximum of over 16,7% .

Table I: Average values

	I_{sc} (A)	V_{oc} (mV)	FF (%)	Eta (%)
EMC mc-Si	8,40	614	77,7	16,5
Ref mc-Si	8,34	612	77,1	16,2

Table II: Maximum and minimum cell results

		I_{sc} (A)	V_{oc} (mV)	FF (%)	Eta (%)
EMC	Max	8.48	617	78.1	16.7
mc-Si	Min	8.31	611	77.1	16.3
Ref	Max	8.39	615	77.7	16.4
mc-Si	Min	8.29	610	75.0	15.8

3.2 EMC efficiency performance relative to ingot position

In Figure 2, position 1B represents the portion of the ingot grown at the start of the process and 17T represents the last portion of the ingot to be grown in the production process. Bottom and Top make refers to the positions of the ingot as it stands in the furnace after crystallization.

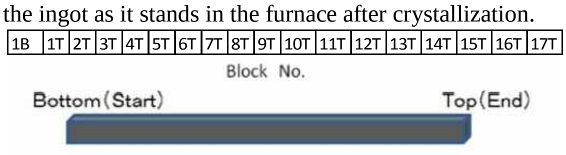

Figure 2, ingot positions

The EMC mc-Si cell results according to ingot position in Figure 2 indicate possible room for improvement in the growing process. The second half of the ingot from position 10T to 16T is better by ~ 0,1% than the first half running from positions 1T to 9T. Further modifications to the growth process in the first half of the ingot may yield an improved overall ingot performance in the future.

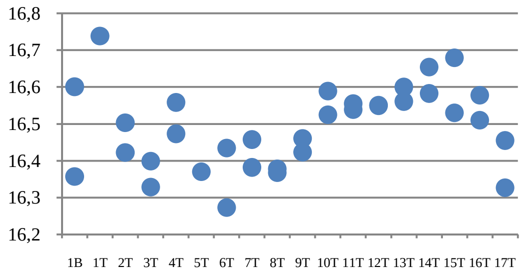

Figure 2, efficiency versus ingot position

4 Discussion

The results show that EMC mc-Si is a viable alternative to conventionally cast wafers for use in p-type mc-Si solar cell production lines. The EMC wafers outperform the conventionally cast mc-Si wafers from another supplier. The results for the EMC wafers were in line with the ECN baseline level for October 2009. The performance of the EMC wafers according to ingot position indicate there is further room for improving the performance through improvement of the crystallization process in the first part of the grown ingot.

The semi-continuous nature of this casting process allows for good resistivity control throughout the ingot as the dopant segregation effect present in batch processing (CZ, HEM or Bridgman ingots) is avoided. Production of ingots using dopants which have a severer segregation coefficient than boron are possible with the EMC method, for example, an n-type phosphorus doped mc-Si ingot.

5. Conclusions

Using industrial type processes, high solar cell efficiencies are possible with p-type EMC mc-Si wafers. Main differences between EMC and conventional mc-Si production methods are larger ingot sizes, tighter resistivity control, higher crystallization rates and lower O_i throughout the ingot.

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