INNOVATIVE CRYSTALLISATION OF MULTI-CRYSTALLINE SILICON

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ABSTRACT

A new, innovative crystallisation process and furnace for the growth of multi-crystalline Silicon ingots is presented. Important key features of the furnace and process include a newly designed, thermally anisotropic quartz crucible and a very uniform inductive heating and cooling system. This thermal configuration allows for a perfect lateral and vertical temperature control during crystallisation so that high temperature gradients can be obtained, which are especially beneficial for the segregation of remaining impurities in lower quality silicon. Solar cells have been processed on wafers from multi-crystalline Silicon ingots that were crystallized with this new process and furnace, using doped electronic grade silicon and purified metallurgical silicon. The resulting efficiencies were 14.3% in case of the purified metallurgical Silicon and 15.0% in case of the doped electronic grade Silicon.

1. CRYSTALLISATION FURNACE DESIGN

The objectives for the new crystallization furnace were to arrive at a thermal configuration that allows to create high temperature gradients (>10K/cm) and planar isotherms at the solid/liquid interface during crystal growth. The control of the heat exchanges involved during the crystallization process is extremely important in order to maintain the stability of the solid/liquid interface and to assure an efficient segregation of remaining impurities with low segregation coefficients at high solidification velocities. A strong vertical heat flux through the liquid silicon and the bottom of the crucible in combination with a lateral thermal insulation allows for columnar crystal growth, while avoiding equiaxed crystallization (see also [1] for more details).

A schematic overview of the furnace design is shown in Figure 1. The heating is assured by two water cooled induction coils, located above and below the crystallisation chamber which are used to heat a graphite susceptor. The lower heating element serves two additional purposes: (i) as mechanical support for the crystallisation crucible, (ii) as heat exchanger for the controlled extraction of energy during crystallisation. Inductive heating has been selected because of two major advantages: (i) the direct heat transfer in close proximity to the material to be heated and (ii) the absence of water cooled power lines (as in the case of resistance heating) that might disturb the thermal insulation and provide non wanted heat sinks.

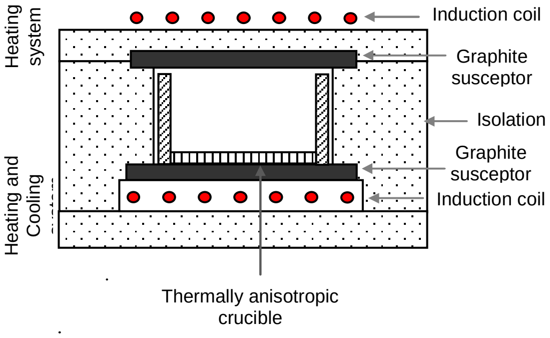

Figure 1: Schematic view of the principal elements of the new crystallisation furnace.

An important element of this crystallisation process is a newly designed crystallisation crucible with anisotropic thermal behaviour [2], as shown in Figure 2. Conventional fused silica crucibles impose relatively important thermal resistances, due to the low thermal conductivity of 2 W/m.K of silica. This thermal resistance obstructs an efficient heat evacuation through the crucible bottom by conduction. On the other hand the thermal insulation properties of silica work in favour of the required lateral insulation of the crucible walls.

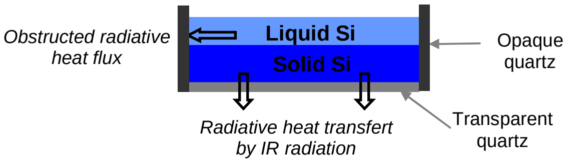

Figure 2: Schematic drawing of the newly developed thermally anisotropic crystallisation crucible.

The newly developed anisotropic quartz crucible allows for a preferred heat extraction through its transparent bottom via infrared radiation, whereas the opaque crucible walls block radiative heat transfer via and thus support lateral insulation. As has been shown in [1] the maximum emittance of Silicon coincides with the transmittance window of the transparent quartz. Figure 3 shows a photo of an anisotropic crucible.

Figure 4: Photo of a 200x200x100mm^3 anisotropic quartz crucible with transparent bottom and opaque side walls.

2. EXPERIMENTAL RESULTS

Comparative crystallisation experiments have been carried out, using two different types of Silicon: (i) Electronic grade (EG) Silicon which was doped with 1ppma of Boron in order to obtain p-type Silicon with a resistivity of 0.5Ωcm; (ii) Purified metallurgical grade (SoG) Silicon from the PHOTOSIL project [3].

Figure 4: 6kg ingot from doped electronic grade Silicon, inside the crucible (left) and after chemical cleaning (right).

The two 6 kg ingots have been cut into wafers which have been electrically characterised in terms of resistivity, Hall mobility and minority carrier lifetime, the latter one was determined by QSSPC with methanol/iodine passivated surfaces and the light bias function in order to correct for trapping effects. The characterisation results are summarised in Table 1.

As can be seen the resistivity of the SoG ingot increases from the bottom to the top, whereas it is uniform around 0.5 Ωcm in the EG ingot. This phenomenon is usually observed in compensated Si and gives an indication that phosphorous was still present in the SoG silicon and has segregated during crystal growth towards the top region of the ingot, resulting in a region of high resistivity starting from 75% of the maximum ingot height. This region is n-type and characterised by a very low minority carrier lifetime. In general minority carrier lifetime and Hall mobilities are lower in the SoG ingot which is also due to the compensation effect and a higher defect density. These defects might have been induced by remaining impurities acting as nucleation centres.

Table 1: Minority carrier lifetimes and Hall mobilities and resistivities of the ingots realised from EG Silicon and purified MG (SoG) Silicon.

	Hall Mobility (cm^2/V.s.)		**Minority carrier Lifetime** (µs)		**Resistivity** (Ωcm)	
	SoG	EG	SoG	EG	SoG	EG
Bottom	160	180	2	2	0.3	0.5
Middle	160	280	4.5	7.5	0.8	0.5
Top	50	180	-	3	1.5	0.4

Solar cells have been processed on wafers from both ingots using an industrial type standard process at the CEA Restaure pilot line [4]. Cells from the p-type region of the SoG Silicon ingot have reached an average efficiency of 14.3% including a best cell with 14.5%, see also Table 2. The cells from the EG Silicon ingot have reached average efficiencies of 15%, which are uniformly distributed from the bottom to the top of the ingot.

Table 2: Results of solar cells from the SoG Silicon ingot.

	J_{sc} [mA/cm^2]	**V_{oc}** [mV]	**FF** [%]	**η** [%]
SoG av.	30.6	612	76.4	14.3
SoG best	30.5	611	77.6	14.5

REFERENCES

[1] F. Lissalde et al.: “Innovative Crystallisation Process and Furnace for Solar Grade Silicon”, *Proceedings of the 22nd European PVSEC 2007, to be published.*

[2] R. Einhaus et al.: “Crucible for a device used for the production of a block of crystalline material, and production method”, *International Patent, No. WO2004/094704, 2004.*

[3] R. Einhaus et al.: “PHOTOSIL – Simplified Production of Solar Silicon from Metallurgical Silicon”, *Proceedings of the 21st European PVSEC, Dresden 2006,pp. 580-583.*

[4] Référence Restaure