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LIFE CYCLE ASSESSMENT OF AN INGOT MANUFACTURING PROCESS USING SILICON POWDERS FROM RECYCLING

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Silicon ingot and wafer production by rapid hot pressing processes

Within the Horizon 2020 innovation action "Implementation of a circular economy based on recycled, reused and recovered indium, silicon and silver materials for photovoltaic and other applications" with the acronym "CABRISS" opportunities for innovative photovoltaic (PV) materials are assessed. In this paper an innovative process for the production of silicon (Si) wafer equivalent and highly doped wafers from Si powders coming from the PV modules recycling process or from kerf of the diamond wire sawing process is presented. The core motivation is the reuse of Si waste as pure Si powder (purity of 99,5 – 99,9 % and with tailored particle size distribution) as a basis for the production of new Si-based PV wafer material.

A rough process scheme is presented in Figure 1 resp. Figure 2. The incoming Si powder is mixed with doping powders in a wet processing step (a). The mixture is dried in process (b) and consumables are separated and led back to process (a). The doped Si powder afterwards is filled in a pressing mold with slight excess ingot measures and pre-compressed in a cold pressing process (c). Afterwards it is hot pressed at temperatures close to the melting point to a material density of >98 % and cooled down in a defined way. After adjusting the block to the Ingot measures of 156 x 156 mm^2 it is cut to wafers via slurry or diamond wire sawing process (d).

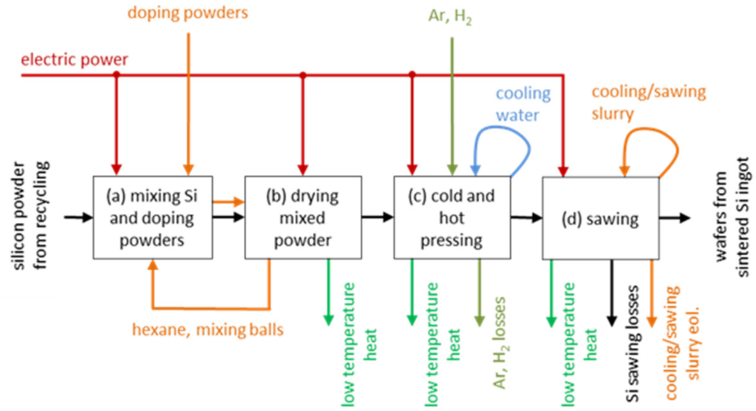

Figure 1: Structure of silicon wafer production via hot pressing process and the usage of silicon powder from photovoltaic recycling process.

Figure 2: From left to right: (1) filling of the pressing mold with doped Si powder (2) setup of hot pressing (3) hot pressed Si ingot 156 mm x 156 mm x 40 mm (Photo: Peter Biermayr and Erich Neubauer)

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Assessment of technical parameters of the sintered ingot and wafers

After a series of 5 hot pressing experiments where ingots were sintered the following findings can be described:

- One of the five of the sintered ingots showed major reactions with the pressing die and therefore these ingots were not/restricted useable.
- The average material density was 97 %
- Sawing processes showed that the typical roughness of wafer surface was up to 100 microns what is distinctly higher than in case of multi cSi or mono cSi materials (typically 10 to 20 microns) but this is subject to further optimization
- On certain areas inhomogeneities were observed which are mainly a result of the feedstock/powder used. New milling concepts have been meanwhile applied in order to minimize the effect of impurities and inhomogeneities coming from milling.
- Electrical conductivity of the doped wafers is sufficiently high to be used for further processing.

Selected aspects of life cycle assessment (LCA) and life cycle cost analysis (LCC)

The hot pressing process described above was investigated in the view of the essential LCA and LCC aspects: (i) greenhouse gas (GHG) emissions (ii) embedded primary energy (iii) energy payback time and (iv) life cycle costs. Several calculations were carried out for the existing lab scaled process constellation and for an industrial sized production model.

The final energy consumption for pressing and slicing one kg ingot was 72.9 kWh_{el} in case of lab scale and 23.4 kWh_{el} in case of industrial scale process. Thus, specific final energy consumption for the lab scale process is 3.1 times higher than for the optimized process. Under consideration of a technically feasible heat recovery in the industrial process (at the minimum useful heat > 600 °C can be recovered) the factor increases to 3.5. Therefore, the production of one wafer needs 1.4 kWh_{el} in case of lab scale process and 0.4 kWh_{el} in case of industrial process. Assuming a cell efficiency of 15 % and Q_G = 1400 kWh/(m^2a) the contribution to the EPBT of this wafer material would be 0,08 years what is a very promising result.

Cost analysis considers i) investment and depreciation, ii) materials, iii) energy and iv) workforce. The wafer costs in case of lab scale production are 1.48 € per wafer and in case of industrial scale they decrease to 0.48 €. The cost structures of the two production scenarios are significantly different. The specific Investment costs and workforce costs are much lower in case of industrial production. A sensitivity analysis shows that the specific costs of the Si/B powder mix have the highest impact on the total wafer price in case of industrial scale wafer production. A comparison with the current multi cSi wafer spot market price (0.62 €/wafer) shows that lab scale hot pressing process will not be competitive even if the input powder costs are zero. The calculated industrial scale wafer production costs are lower by 0.14 €/wafer than the present spot market price for multi cSi wafers. But this difference is not equal to a potential profit because the empirical proof of the feasibility to process PV cells without any additional effort is missing up to now.

Conclusions

The innovative approach of processing Si wafers from Si kerf or PV recycling Si sources via hot pressing shows some promising results for LCC and LCA attributes. But it also shows some challenges for material improvements and the need of an empirical proof of PV cell production on the original or modified surface of the sintered wafer.