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Radiative energy loss in a polysilicon CVD reactor

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This work aims at understanding the energy loss in the polysilicon deposition reactor during the production of solar grade silicon. The radiative heat transfer between the polysilicon rods and the reactor wall in the so-called *Siemens* reactor is studied in detail in this paper. First, the most commonly used reactor configuration, 36 rods in three rings, is explained, detailing the particular radiation transfer of each rod toward the wall. Based on this analysis, some proposals for diminishing the energy loss are proposed: enlarge the reactor capacity, improve the properties of the reactor wall and introduce thermal shields. The impact of each proposal on the energy savings is quantified. If the reactor capacity is enlarged from 36 to 60 rods, the energy savings would be around 11 kWh per kg of polysilicon produced (kWh kg^{-1}). Increasing the reflectivity of the wall, the savings would be around 17 kWh kg^{-1}. And finally, the potential for cost reduction because of the introduction of thermal shields would be 20 kWh kg^{-1}.

1. Introduction

The market for ultrapurified silicon, typically referred to as 'polysilicon', which was traditionally devoted to microelectronics, is currently subject to profound changes due to the expansion of the photovoltaic (PV) industry. In 2009, a total amount of 80,000 t of polysilicon was consumed by the solar industry vs 20,000 t by the semiconductor industry [1], and the share of polysilicon used for solar will certainly increase in the medium and long terms [2], as the perspectives of growth for the PV industry are very solid [3]. The estimates for worldwide silicon production and electronic and solar industry shares of silicon consumption in the following years are presented in Figs. 1 and 2 respectively.

Metallurgical silicon is the raw material for polysilicon production. It is produced by carbothermic reduction of quartz at high temperature (approximately 2000 °C) in an electrical arc furnace. 98–99% pure silicon is obtained in a process that consumes around 10 kWh kg^{-1}.

Further purification is required for the semiconductor and PV industry. To this end, a three step process known as the 'Siemens process' is traditionally performed: metallurgical silicon reacts with hydrogen chloride or silicon tetrachloride ($SiCl_4$) in a fluidized bed reactor to synthesize a volatile silicon hydride, typically trichlorosilane, which can be fractionally distiled in a number of columns, then deposited as solid silicon by chemical vapour deposition (CVD) on slim seed rods heated by the Joule effect. Purities in the range of 99.9999999% are within reach, but at the cost of high energy consumption (in the range of 100–150 kWh kg^{-1}) and low efficiency deposition [4]. It should be noted that more than 60% of the energy used in producing polysilicon is consumed in the decomposition process [5,6].

According to a recent study [7], 14% of the manufacturing cost of crystalline silicon PV modules corresponds to the polysilicon feedstock. However, the energy breakdown in manufacturing the PV modules has different shares, as presented in Fig. 3, and the polysilicon production contribution rises to 30% [8]. Polysilicon companies and R&D centres have been working decades on reducing this energy consumption: by proposing alternatives to the 'Siemens process' or by proposing improvements in the consolidated 'Siemens process'.

An alternative for simplifying the traditional route is to replace trichlorosilane with monosilane, which has advantages in the deposition step because deposition temperatures are lower (800 °C instead of 1100 °C) and productivities can be higher. This process was proposed in the early 80s and industrially exploited, first for the semiconductor industry, and more recently for the solar industry [9]. The drawback is the need for additional steps for redistribution and separation, as monosilane is produced from trichlorosilane, and the need to recycle the chlorosilanes not converted in the redistribution steps.

Another approach is to replace the silicon seed rods by small silicon particles which are continually fed into a fluidized bed reactor. The energy consumption using these reactors can be decreased sevenfold. Because it is a continuous process and not batch-type, the productivity is increased, and the need for crushing the deposited silicon is avoided. However, there are some challenges to using these silicon granules in the following crystallization step that should be addressed.

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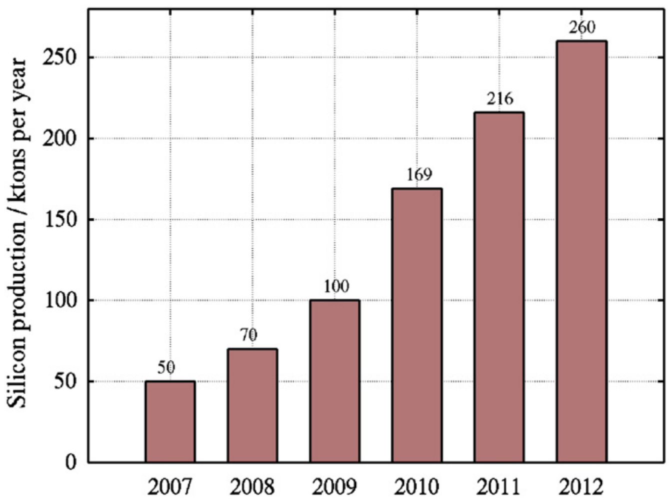

Fig. 1. Thousand tons per year of silicon production. Estimates taken from [1].

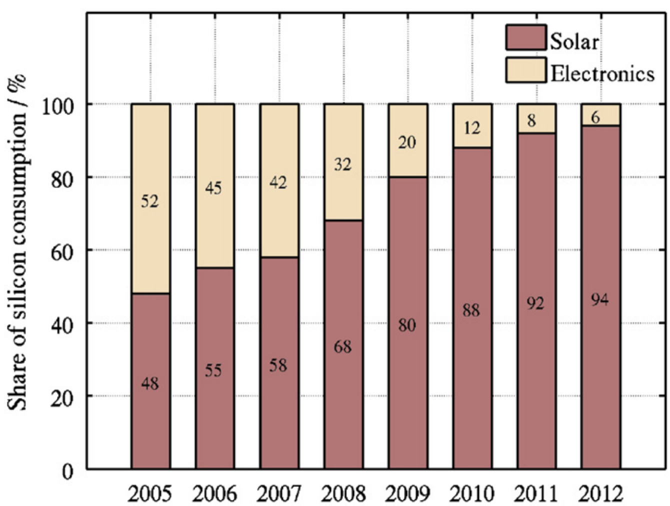

Fig. 2. Electronic and solar shares of silicon consumption. Estimates taken from [2].

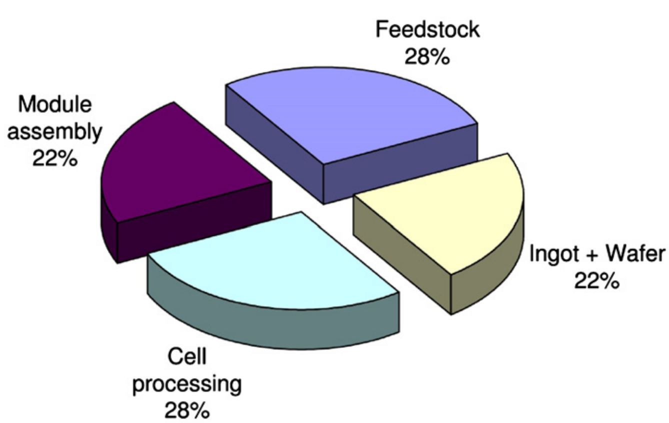

Fig. 3. Breakdown of energy consumed in producing c-Si PV modules. Estimates taken from [8].

A combination of silane and fluidized bed deposition has been in production since 90s [4], and the use of trichlorosilane is being evaluated as an alternative [10]. When using silane, the main disadvantages are silicon powder formation and the porous morphology of the polysilicon produced. The other alternative, the utilisation of trichlorosilane, is characterised by difficulty of heating, lack of powder formation, and better morphology of the granules obtained [11].

A radically different alternative is called the metallurgical route. It refers to processes that avoid the conversion of metallurgical silicon into a volatile compound, decreasing to a great extent the energy consumption in the deposition step [12–14]. The purity usually reached with these processes is much lower than that of the traditional route, but that does not necessarily mean that the material cannot be used for solar cells. In fact, by introducing some changes to the crystallisation and solar cell processing steps, similar solar cell efficiencies have been achieved with this lower quality material as have been achieved with semiconductor grade material [15].

Despite the existing alternatives, the tremendous expansion of the polysilicon industry returned the research on the conventional process to the foreground since around 80% of the polysilicon is produced by means of this consolidated process [16]. It has motivated to systematically investigate the process parameters of the CVD reactors [17] and the way to reduce the production cost, in a new and more competitive market. The energy consumed in depositing polysilicon in a CVD reactor can be reduced by increasing the productivity (kg/h) and/or reducing the power loss. In this paper some alternatives are explored for reducing the power loss in such reactors.

The CVD reactor for polysilicon production consists of a chamber where several high-purity silicon slim rods are heated by Joule effect, and the polysilicon is deposited in these seed rods, thickening them [18–20]. Typically, the rods are made of two vertical parts, parallel to each other so that their free ends do not touch, and a silicon rod bridge that connects these ends. Then, the rods have a U-inverted shape. For clarity, two terms are defined, and they will be used hereinafter in this paper: the term rod will stand for the vertical part, and U-rod will stand for the U-shaped combination of rods.

The total energy consumption in the CVD reactor has three contributions: the energy loss by convection, the energy loss by radiation and the energy consumed in the chemical decomposition of trichlorosilane (TCS). The energy given to the gases by convection heats them up, and leaves the reactor with the exhaust gases or is exchanged with the reactor cold wall. The energy radiated is emitted by the polysilicon rods toward the reactor cold wall. The energy consumed in the chemical decomposition of TCS, compared to the other two contributions, can be disregarded. The energy loss by radiation is around 70% of the total energy loss [21], that is supplied to the silicon rods by means of electric energy.

This paper deals with the radiation loss, analysing how the hot polysilicon rods radiate toward the reactor wall, and how to decrease this energy loss. Two paths can be followed to reduce the radiation loss:

- Increasing the number of rods within the reactor vessel. When increasing the number of rods part of the radiation of one rod does not leave the reactor, since it can fall on another rod.
- Introducing a high reflectivity reactor wall and/or thermal shields. Increasing the reflectivity of the reactor wall by making it of silver or silver-plated steel, as presented in Ref. [19], reduces the amount of radiation energy absorbed by the wall. Also thermal shields can be used to reduce the radiation loss [22].

The temperature of the rods is roughly 1100 °C and the reactor wall is cold. Some questions arise: are all the rods radiating in the same manner? how different radiates a rod in the inner ring in comparison to a rod in the outer ring? how much power is required