# INLINE FAST CVD SYSYEM FOR CONTINUOUS PRODUCTION OF SILICON RIBBONS FOR SOLAR CELLS BY THE SDS PROCESS

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## ABSTRACT

The silicon wafer accounts for about half of the photovoltaic module cost. We believe two aspects are essential to reduce considerably the "wafer" costs: the feedstock issue and ribbon technology. In the SDS process the pre-ribbons are grown directly from silane by fast CVD process and followed by zone melting recrystallization (ZMR). In this paper a new generation of fast CVD reactor to grow silicon ribbons in a continuous mode by the SDS process is presented along with results on the CFD modeling that led to the reactor design. To perform the CVD, halogen lamps with elliptical mirrors are used. Due to the existing optics the radiation is focused on the deposition surface, promoting the creation of well defined convection flow cells inside the reactor. The need to increase both the pre-ribbon deposition homogeneity and recrystallization success and the adaptation of the reactor to an inline process, are the reasons for this new generation of the SDS reactor.

## INTRODUCTION

Silicon wafers represent as much as 45% of the total cost of a photovoltaic module, and hence in this factor an important opportunity remains for further decreasing the cost of photovoltaics [1]. In our cost cutting strategy we believe that ribbon technology and the feedstock issue will play an important role on "wafer" costs decrease. It is well known that ribbon technology as a large potential for materials waste reduction since no saw processes are used. On the other hand we ought to ask ourselves why should we use solid silicon feedstock, which has already undergone a crystallization process (Siemens process or another one) with high energy content to recrystallize it again in a crucible spending even more energy, when we can go directly from the gaseous feedstock source to the final ribbon? Those are the reasons that support the vision behind the silicon on dust substrate (SDS) ribbon technology: To develop a new process of silicon ribbon formation for photovoltaic applications using silane as feedstock.

## SDS PROCESS

Silicon sheet formation from the gas phase needs a substrate. Previous R&D has focused on non-detachable silicon films on cheap substrates or on detachable films on high quality substrates with high cost. The SDS technology uses: (i) a bed of silicon dust that is a cheap substrate and a "sacrificial detachment layer", part of it being incorporated into a (ii) thick film obtained by Fast Chemical Vapor Deposition (CVD) at low temperature and ambient pressure; (iii) the detached, free standing film is then crystallized by a floating molten zone technique, known as zone melting recrystallization (ZMR), to increase crystal quality while avoiding impurity contamination.

The SDS process is two-step process (see Fig. 1): In the first step, pre-ribbons are obtained by fast CVD. Their thickness is enough to be self-supported, but due to the its CVD conditions, high pressure (atmospheric pressure) and low temperatures, usually avoided in the CVD processes, their structure have a porous and microcrystalline nature and so they must be recrystallized. The ZMR step is performed using an in-house-developed furnace composed of two elliptical mirrors that concentrate the radiation of two 1000W halogen lamps [2]. The doping is achieved by a recently developed technique [3], where boric acid is sprayed over the pre-ribbon surface prior to the recrystallization step.

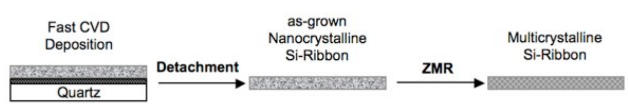


Fig. 1. Main steps of SDS process

We proved the concept and produced test cells with this new material using a batch version of SDS reactor [2]. This new version of the SDS reactor addresses the CVD deposition step since the ZMR step is already suitable for continuous mode operation.

## MOTIVATION FOR THE NEW REACTOR

With the previous reactor, silicon ribbons were successful grown in a static regime and later used in simple test solar cells [4]. However despite the high quality of the pre-ribbons produced, the lack of homogeneity in the deposition and the resulting porosity variability, led often to the collapse of the pre-ribbons during the ZMR process [5]. Therefore a new reactor design was required, first to increase both the pre-ribbons recrystallization success and second to be suitable for an inline process.

The new reactor was designed in order to: Increase the deposition homogeneity and reduce the porosity variability; Increase the silicon deposition rate and finally to adapt the reactor to inline process.

To answers those requirements it was decided to design a reactor with squared cross section and equipped with:

- Motion system to move the silicon dust substrate very smoothly at constant speed along the reactor, forcing all regions of the substrate experience the same deposition conditions along the displacement direction.
- Radiative heating sources (halogen lamps) with elliptical mirrors placed along the reactor, creating convection flow cells to boost the deposition rate. Due to the mirrors action the radiation is focused on the dust substrate, forming narrow and uniform lines of radiation perpendicular to the displacement direction. Such configuration favors the deposition homogeneity along those lines direction.

## EXPERIMENTAL SETUP

The silicon dust substrate is obtained by thermal decomposition of silane and placed on top of a quartz holder plate that is moving inside the reactor. The pre-ribbon grows by thermal dissociation of the silane on the silicon dust placed on top of the quartz that is in motion at constant velocity along the reactor (see Fig. 2) As result a more homogeneous deposition is obtained since all regions of the sample experiences the same deposition conditions along the reactor. The thermal energy needed comes from the radiation of three halogen lamps placed on top of the reactor window. Each lamp has attached an elliptic mirror that is used to focus the radiation on the silicon dust substrate. This allows defining three heating regions (red stripes in Fig. 2 and Fig. 3).

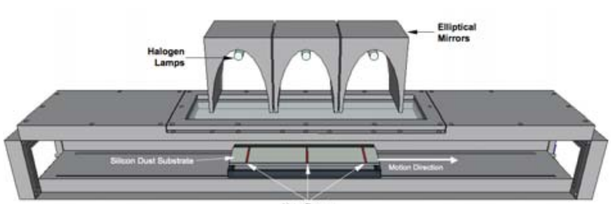


Fig. 2. Cut view of the CVD system schematic

## RESULTS

In the batch version of the SDS reactor, process conditions to achieve measured deposition rates around 8 micron/minute have been obtained. Considering the expected 20 μm/minute deposition rates at 900ºC we need 15 minutes to achieve a 300 μm thick pre-ribbons. With a constant advance speed of 10mm/min, we need a high temperature zone (~900ºC) of only 150 mm in length (See Fig. 2).

### CFD simulations

Computational fluid dynamics modeling (CFD) is a powerful simulation tool that used together with the know-how acquired with the previous reactors help us to find the best design options for the new reactor. The CFD analysis is very useful, because as simulation tool we are free to run innumerous scenarios with different parameterizations, obtaining valuable information for our design. It was observed by CFD simulations that the three heated zones create convection flows (Fig. 3), with a pattern that is strongly dependent of the reactor geometry. To adjust the convection patterns to achieve an intensive use of the gaseous feedstock (silane) and the transversal deposition homogeneity, an extensive study using CFD simulations was performed [6]. On those simulations the heated zones were submitted to a constant radiative heat flux (enough to maintain the temperature at predefined values).

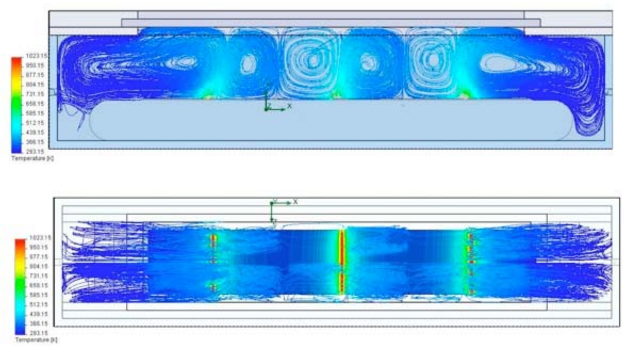

Fig. 3. Computational Fluid dynamics (CFD) analysis of the convection flows inside of the reactor. The convection flows result from the heating zones (red stripes) and the geometry of the reactor. Reactor side view (top) and top view (bottom). The ratio between the distance from the sample to the quartz window and the distance between hot regions is 1/2.

For the fluid, gaseous hydrogen was chosen since the silane represents only 10% of the silane/hydrogen mixture that will be used in the reactor (as in the previous reactor). For the silicon dust substrate were considered the thermal conductivity of porous-silicon [7], the specific heat of native silicon oxide ($c_p$ =1000 $J.Kg^{-1}.K^{-1}$) and two orders of magnitude below for the density when compared to crystalline silicon. The material in the reactor walls was aluminum maintained at 293.15K. In all simulations the gas enters to the reactor at turbulent regime with a flux of 0.4 l/min, and exits through a similar orifice (4mm of diameter) in the opposite extreme of the reactor.
In order to understand the dependency of the convective flows patterns on the reactor geometry were tested different ratios between the distance from the sample to the quartz window and the distance between consecutive heat zones. Was observed that if the distance between consecutive heat zones should was the double of the distance between the sample and the quartz window,

convection flows with cylindrical shape were obtained (see Fig. 3), two for each heat zone. This effect allows the silane to flow over and over on top of the growing pre-ribbon surface increasing the deposition rate and the silane conversion to silicon. If this ratio is greater them 0.5 the cylindrical flows distort vertically (see Fig. 4) until they are lost and become unexpected (see Fig. 5). In the other way if the ratio is lower them 0.5 the convective flow cells tend to distort in length (see Fig. 6), until they cease and the flow become similar to a flow in a rectangular section duct.

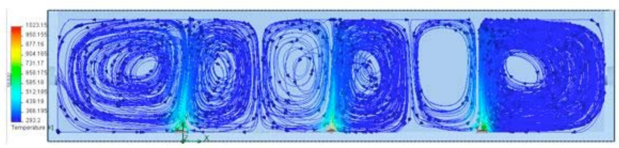

Fig. 4. Computational Fluid dynamics (CFD) analysis of the convection flows inside of the reactor. The reactor cavity dimensions are 60 mm x 60 mm x 300 mm. The ratio between the distance from the sample to the quartz window and the distance between heat regions (80 mm) is 3/4. The fluid injection is made from the orifice on the left wall. (Reactor side view)

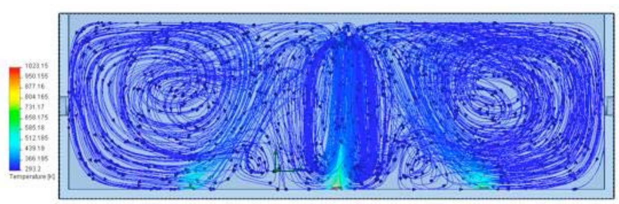

Fig. 5. Computational Fluid dynamics (CFD) analysis of the convection flows inside of the reactor. The reactor cavity dimensions are 90 mm x 60 mm x 300 mm. The ratio between the distance from the sample to the quartz window and the distance between heat regions (80 mm) is 9/8. The fluid injection is made from the orifice on the left wall. (Reactor side view)

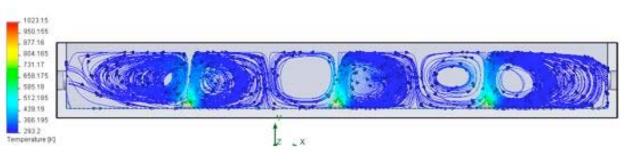

Fig. 6. Computational Fluid dynamics (CFD) analysis of the convection flows inside of the reactor. The reactor cavity dimensions are 20 mm x 60 mm x 300 mm. The ratio between the distance from the sample to the quartz window and the distance between heat regions (80 mm) is 1/4. The fluid injection is made from the orifice on the left wall. (Reactor side view)

The idea of performing CVD in a continuous regime is intended to avoid the lack of homogeneity in the deposition and the resulting porosity variability verified in the previous SDS reactor that operated in a static regime. This continuous regime only ensures homogeneity along the displacement direction of the pre-ribbon. In the width direction, the deposition homogeneity depends on the fluid movement velocity and direction at the heat zones. It was observed that the reactor width and the walls material are important parameters to control the convective flows for the transversal homogeneity of the pre-ribbon. As it can be seen in the next figures, the trajectory lines of the fluid becomes almost parallel if the aluminum walls (see Fig. 7) are replaced by adiabatic walls (see Fig. 8), cancelling the heat exchange between fluid and walls, reducing the variation of flow direction promoted by density variations. The parallel trajectories effect is achieved by combining the maximum possible reduction of reactor width with the use of adiabatic walls (see Fig. 9). Since the material inside of the reactor cannot be itself a source of contamination, we decided to use lateral plates of quartz (amorphous silicon dioxide) as a feasible approximation of an adiabatic material.
The following figures show the effect of quartz walls as a step towards adiabatic material in the CFD simulation for the typical velocity and temperature profiles along the deposition region.

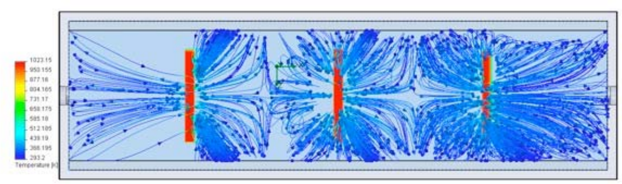

Fig. 7. Computational Fluid dynamics (CFD) analysis of the convection flows inside of the reactor. The reactor cavity dimensions are 40 mm x 70 mm x 300 mm. Whole the cavity is from aluminum cooled at 293.15K (Reactor top view)

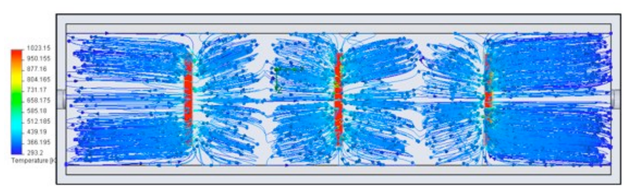

Fig. 8. Computational Fluid dynamics (CFD) analysis of the convection flows inside of the reactor. The reactor cavity dimensions are 40 mm x 70 mm x 300 mm. The long lateral walls are adiabatic. (Reactor top view)

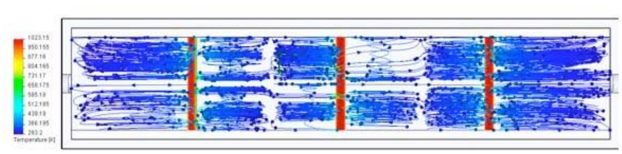

Fig. 9. Computational Fluid dynamics (CFD) analysis of the convection flows inside of the reactor. The reactor cavity dimensions are 40 mm x 50 mm x 300 mm. The long lateral walls are adiabatic. (Reactor top view)

Results regarding the deposition dynamics at the heat zones and radiative distribution analysis on sample surface will be addressed in further publications.

## CONCLUSIONS

The new generation of fast CVD reactor to grow silicon ribbons in a continuous mode by the SDS process is demonstrated. The necessity to upgrade the existent SDS reactor is associated with the need to increase both the pre-ribbon deposition homogeneity and recrystallization success, as well to adapt the reactor to an inline process. The inline requirement is by itself underneath the design and operation mode of the new reactor. Concerning the first two issues, the CFD analysis clear shows good perspectives regarding the deposition homogeneity both in length and in width. This considerable increasing of homogeneity will reflect positively in the recrystallization success.

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