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# Towards Cheaper Solar Cells: A New Path to Grow Silicon Ribbons

A. Augusto, J.M. Serra and A.M. Vallêra

*Centre for Sustainable Systems, Faculty of Science, University of Lisbon, Lisbon 1749-016, Portugal*

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**Abstract:** The silicon wafer accounts nearly half of the photovoltaic module cost, and hence on this issue an important opportunity remains for further decreasing the cost of photovoltaics. It is well known that ribbon technology has a large potential for costs reduction by avoiding kerf losses since no saw processes are used, preventing material losses up to 50% of the initial feedstock. On the other hand we ought to ask ourselves why we should use solid silicon feedstock, which has already undergone a crystallization process 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. The cost cutting strategy that supports the Silicon over Dust Substrate (SDS) technology, here presented, is based on the belief that ribbon technology and the silicon feedstock issue will play an important role on "wafer" cost reduction.

**Key words:** Chemical vapor deposition, silicon dust, silicon ribbon, solar cell.

## 1. Introduction

Cost is the key factor for the success of PV deployment. The increasing installed capacity has been responsible for driving the PV cost down, cutting in average the production costs by 20% each time the production doubles. Taking into account this cost reduction trend (Fig. 1) it is expectable that PV electricity would become economically competitive with utility peak power prices in next years in southern Europe and by 2020 in northern Europe [1].

Current turn-key system prices may vary from ~4 to ~8 €/Wp, depending on system types (roof-top add-on, building-integrated, ground-based), size, country, and other factors. In 2015 the prices may range between ~2 and ~4 €/Wp [2, 3]. Technological progress will enable to decrease the PV price even further, while fossil fuel-based electricity prices are expected to continue their long-term increase (Fig. 1).

**Corresponding author:** A. Augusto, Ph.D., research field: materials for solar cells and sustainable energy systems. E-mail: afaugusto@fc.ul.pt.

## 2. Crystalline Silicon Based Solar Cells

### *2.1 Production Costs*

Crystalline silicon based technology is by far the largest player in the photovoltaic's industry. In a study performed by Michael Rogol et al. [4] where over 80% of the PV industry production was analyzed, the silicon wafer (silicon material plus wafer processing) was clearly identified as the largest contributor to the cost of wafer-based cells, accounting nearly half of the total module cost (Fig. 2).

### *2.2 Energy Payback Time and Greenhouse Gas Emissions*

A PV system can be split in three components: (1) The module, (2) the frame and (3) the inverter/cabling (Balance of System, BOS). As shown in Fig. 3, the energy payback time (EPBT) is largely determined by energy requirements to make the PV module. The EPBTs are between 1.7-4.6 years; the exact figure depends on the level of annual irradiation and type of silicon technology used. Despite the different EPBTs, all are much smaller than the lifetime of PV modules

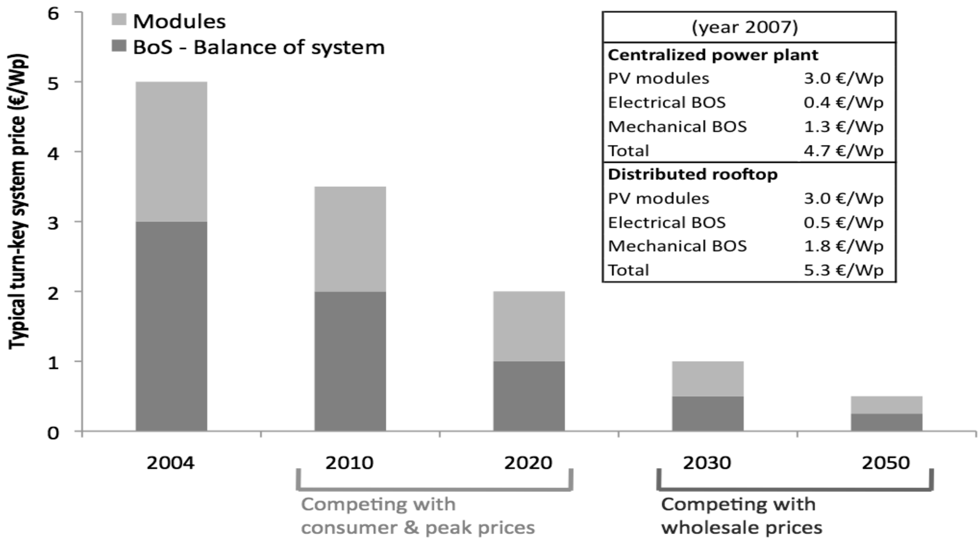


**Fig. 1 Evolution scenario of turn-key PV system [1, 3].**

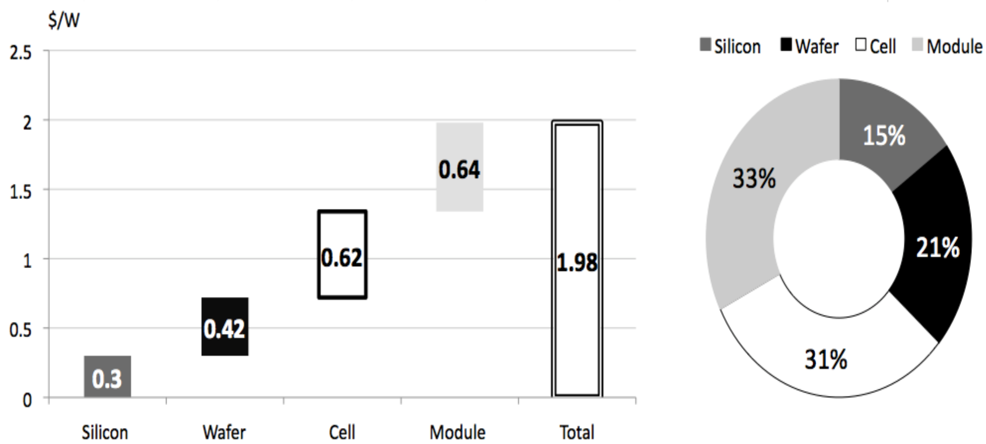


**Fig. 2 c-Si module average cost: sum of the average costs at each step of the supply chain.**

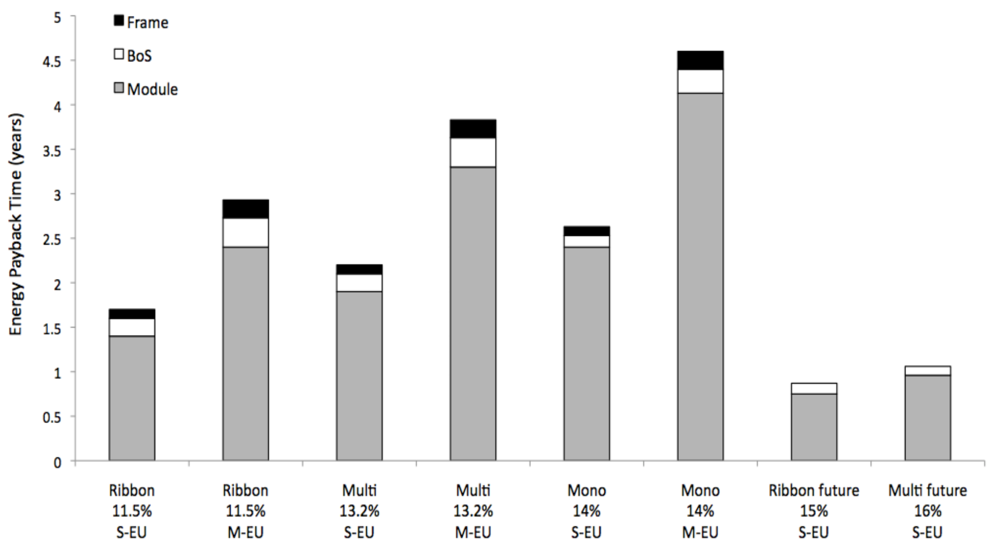


**Fig. 3 EPBT (yr) for a grid-connected PV-system under an irradiation of 1700 kWh/m$^2$/yr (Southern-Europe) and 1000 kWh/m$^2$/yr (Middle-Europe) [5].**

based on crystalline silicon (i.e. << 25 years).

Comparing the technologies the ribbon option is the one that has the lowest energy payback time.

In Fig. 4 the greenhouse gas emissions (GHE) per kWh of electricity from PV systems based on three silicon technologies are compared against other energy technologies. Concerning the PV technologies, ribbons perform always better. Wind energy is the one among renewables with fewer emissions, and only ribbons with an improved efficiency can get closer [5, 6]. Comparing the overall technologies, nuclear has the lower GHE per kWh, however problems from other nature cannot be neglected to do a fair assessment.

Regarding the EPBT and the GHE it is clear that solar cells based on ribbon technologies perform better than the established wafer based technologies.

## 3. Silicon over Dust Substrate Technology

The idea is to develop a ribbon technology using gaseous silicon precursors as feedstock, short cutting in the way several high-energy content and costly processes, see Fig. 5.

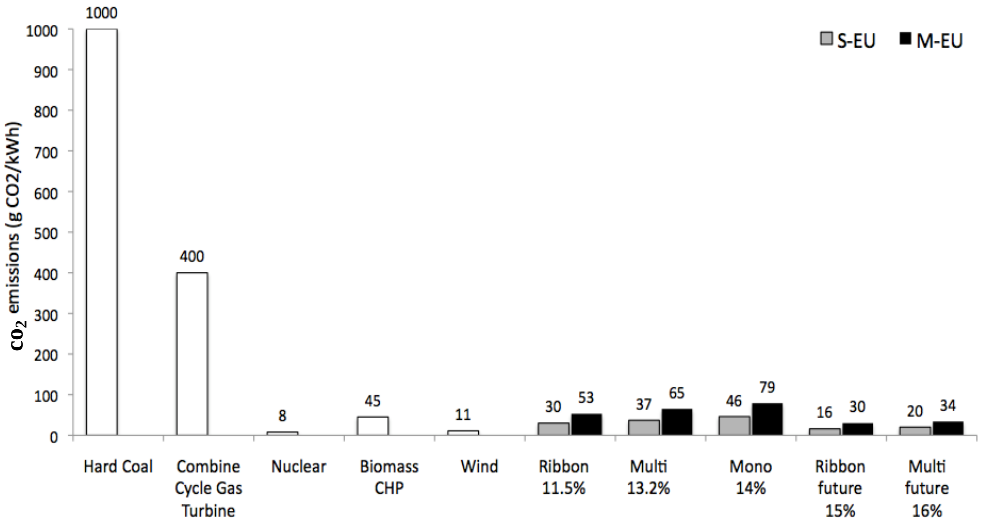


**Fig. 4 GHE of silicon PV systems compared to a number of other energy technologies [5, 6].**

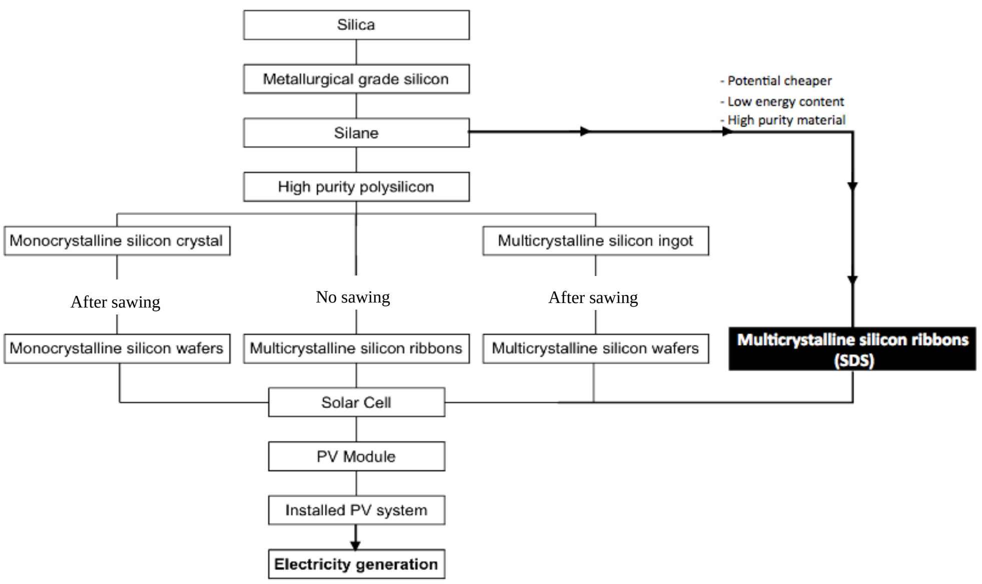


**Fig. 5 Basic producing steps of a c-Si PV systems.**

Furthermore, Silicon over Dust Substrate technology (SDS) uses as substrate (and sacrificial layer) a bed of silicon dust (the reason of its name). It is well known that silicon deposition from a gas phase needs a substrate. Previous R&D focused their efforts on non-detachable silicon films on cheap substrates (with poor results for material quality and final efficiency) or on detachable films on high quality substrates (with resulting good quality films but high cost). The innovative step of using a powder layer or a dust substrate presents a cheap and easily detachable solution (a small part is incorporated but no contamination occurs because the powder itself comes from the thermal dissociation of silane).

### *3.1 Ribbon Growth*

For good crystalline quality, the epitaxial crystalline silicon film growth rates are typically low. For instance, using silane in the low temperature regime (< 900 ºC), the growth rates are typically 10's of Å/min [7]. In the SDS process this problem is addressed by decoupling the deposition from the crystallization step, looking for higher deposition rates up to 20 micron/min. Thus the SDS is a two-step continuous process (Fig. 6): first a self-standing pre-ribbon is grown by Fast CVD on top of a silicon dust (sacrificial layer) using silane and then, in a second step, the pre-ribbon is crystallized by a floating zone method, acquiring a proper (multi) crystalline structure for solar cell use. The pre-ribbon term is applied instead of just ribbon, because the grown ribbon has a porous and microcrystalline structure, as result of a fast deposition process at atmospheric pressure and low temperature.

The feasibility of the SDS concept was proofed in the past [8] using in the step 1 a batch CVD reactor. However due to the need to overcome some fundamental issues, such as: increase the pre-ribbons deposition homogeneity and evolve from a batch system to a continuous system ideal for inline production, a continuous CVD reactor as being developed allowing to have full integrated inline system suitable for industrial scale up. As a process the SDS has the following advantages: (i) no substrate (therefore no cost and no contamination); (ii) low thermal budget (ambient pressure, low temperature CVD); (iii) high quality and self-standing crystalline silicon ribbon (float zone crystallization, no contact with foreign materials, and so no impurity contamination); (iv) inline process leverages over other technologies regarding its future deployment in industry.

### *3.2 Experimental Procedure*

To perform the first step an in-house-developed CVD reactor that operates in continuous mode in opposition to the previous batch CVD reactor [8] is used. The silicon dust substrate is placed on top of a quartz holder plate that moves inside the reactor at a constant speed of 10 mm/min. The pre-ribbon grows on top of the silicon dust substrate by thermal dissociation of silane (see Eq. (1)). The thermal energy for the deposition is supplied through radiation by halogen lamps. Each lamp has attached an elliptic mirror that focuses the radiation on the silicon dust substrate, creating well defined deposition regions in the substrate, see Fig. 7. These heating regions, where

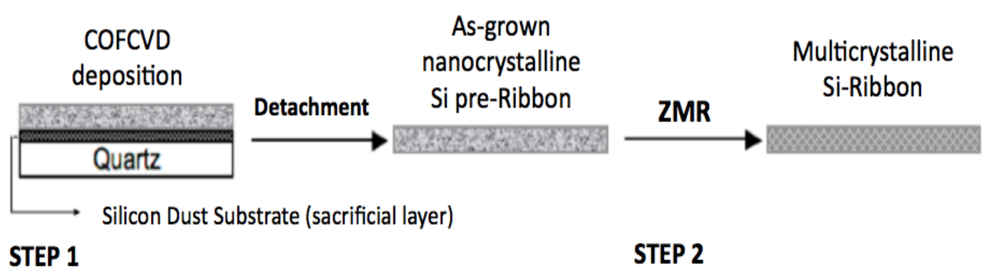


**Fig. 6 Diagram of SDS process.**

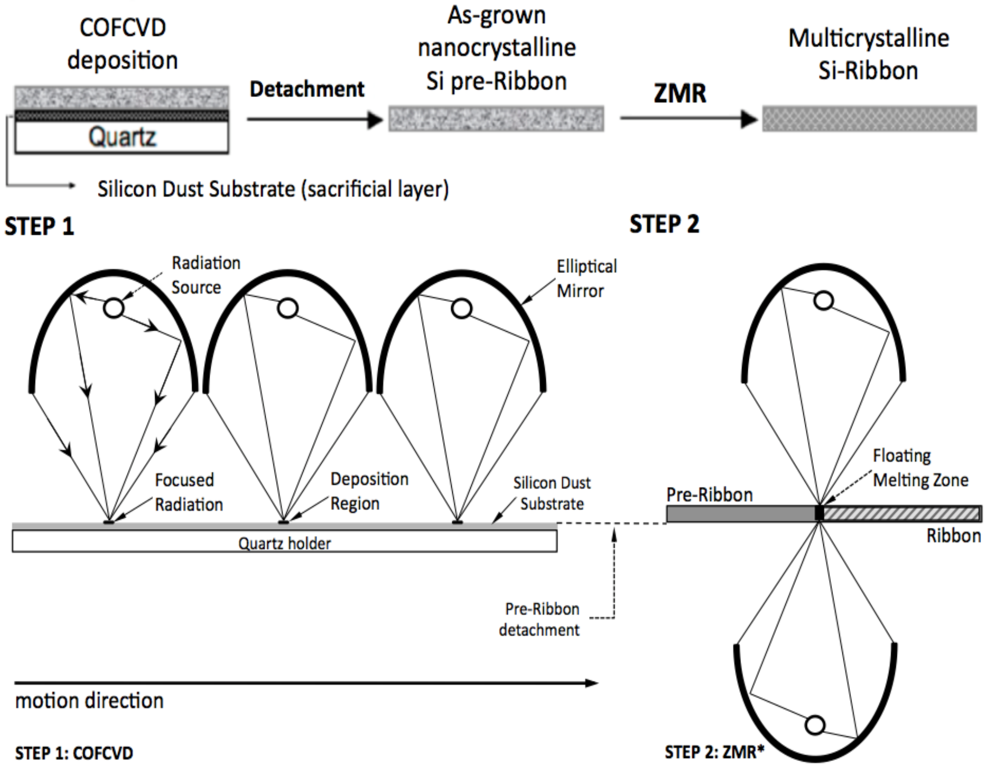


**Fig. 7 Schematic of SDS setup. (*The actual crystallization reactor operates in vertical mode. The future version will operate as in the scheme in horizontal mode).**

the deposition preferentially takes place, promotes the formation of well confined convection cells inside the reactor [9] that boost the deposition rate and the silane conversion to silicon.

$$SiH_4\,(g) \rightarrow Si\,(s) + 2H_2\,(g) \qquad (1)$$

Due to the unique characteristics of this new CVD deposition process: a continuous process, with high deposition rates (up to 20 micron/min), that uses halogen lamps and optics to establish deposition regions; was decided to name the deposition process Continuous Optical Fast CVD (COFCVD) [10]. This new deposition process aims to solve the limitations of the batch reactor previously explored. In step 2 the pre-ribbon is crystallized by a floating molten zone technique, known as Zone Melting Recrystallization (ZMR) [11], increasing its crystal quality while avoiding impurity contamination. The ZMR step is performed using an in-house-developed furnace composed of two elliptical mirrors that concentrate, on the pre-ribbon, the radiation of two halogen lamps. The doping is achieved by a recently developed technique [12] where boric acid is sprayed over the pre-ribbon surface prior to the crystallization step.

## 4. Conclusions

The SDS technology based on a continuous process shows a clear potential for “wafering” cost reduction. Being a ribbon technology no sawing into wafers is involved, avoiding this costly process and the main source of kerf losses. As a gaseous to solid technology several steps of the standard production chain that are costly and energy intensive are also prevented. Furthermore, since the feedstock used (silane) is highly pure, and there is no contact with any foreign material and the fact that float molting crystallization step (ZMR) it is intrinsically an impurity segregation process, the material obtained through the SDS technology is potentially free of contamination. From a scale up point of view as continuous process SDS it is a strong candidate for inline production. Regarding the environmental concerns the SDS as all advantages of ribbons technologies (lower EPBT and lower GHE) plus the fact that several steps with intensive use of energy are removed from the production chain.

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