# THE EUROPEAN PROJECT FLEXCELLENCE ROLL TO ROLL TECHNOLOGY FOR THE PRODUCTION OF HIGH EFFICIENCY LOW COST THIN FILM SOLAR CELLS

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ABSTRACT: FLEXCELLENCE (www.unine.ch/flex) is a STREP financed by the 6th framework program of the EU. It started on October 1st 2005 and is set to last during 3 years. FLEXCELLENCE aims at developing the equipment and the processes for cost-effective roll-to-roll production of high-efficiency thin-film modules, involving amorphous (a-Si:H) and microcrystalline silicon (µc-Si:H). Eight partners, with extended experience in complementary fields, are involved.
Within the first year of the project, a hot wire chemical vapour deposition system (HW-CVD) has been built; and a roll-to-roll deposition system for microwave plasma enhanced chemical vapour deposition (MW-PECVD) has been further developed and put into operation. In the meantime, the very high frequency (VHF) PECVD pilot line at VHF-Technologies is being upgraded to allow higher throughput. Regarding the optimisation of the VHF-PECVD process, device grade quality microcrystalline silicon has been deposited on 30*30cm$^2$ at 2nm/s and laboratory scale a-Si:H and µc-Si:H cells have been developed in a new double chamber system on plastic substrates: so far, these cells achieve a conversion efficiency of 6.2% and 8.2%, respectively.
In addition, a 2D simulation program developed by the UL-FEE has shown that only 10% total losses from a solar cell to a module are achievable on the flexible VHF-Technologies modules. Finally, a first cost calculation has demonstrated that production costs below 0.8 €/Wp should be reasonably achievable with single a-Si:H cells, and that an important part of this cost is for the encapsulation.

Keywords: Roll-to-roll, thin film silicon, CVD based deposition

## 1 INTRODUCTION

The report “A vision for photovoltaic technology” [1] shows that solar electricity production has the potential to contribute significantly to the energy generation in the next decades. Reasonable scenario targets at a 4% share of electricity production by 2030 worldwide and up to 30% a few decades later. To reach these ambitious objectives, the major issues are to lower the costs of modules from around 3 €/Wp to below 0.5 €/Wp, to have products with a maximum capacity for building integration like roofing elements or façade panels, and to find processes leading to the fabrication of environmentally friendly PV products.
Considering these points, thin film silicon modules have a high potential and start to be actively commercialized. Many well-known companies are now starting new mass production lines or new investments including Ersol, Schott Solar and Q-Cells, who recently invested into VHF-Technologies, a partner of FLEXCELLENCE. Commercial production equipments for glass based products are also commercialised by OC Oerlikon and Applied Materials from the display industry.
However, the investment costs for such production equipment are high and the glass-based products remain heavy and fragile, as is the case for crystalline silicon products too.
Therefore, flexible thin film silicon modules prepared in roll to roll processes are promising. Indeed, they are light, flexible and robust, with a high capacity for building integration and can be fabricated on low cost substrates such as stainless steel or plastics. The roll-to-roll processing gives the possibility to increase the throughput linearly by simply increasing the number of deposition sources or widening the web and it requires less floor place.
In the present paper, the authors give an overview of the European project FLEXCELLENCE, which is a Specific Targeted Research or Innovation Project (STREP) financed by the 6th framework program of the EU. The project is set to last 3 years, starting on 1st October 2005. It deals with roll-to-roll processing and flexible thin film silicon cells or modules. In the following, the objectives and the structure of the project are presented. Then, the work already performed and the first results obtained are discussed.

## 2 OBJECTIVES

The FLEXCELLENCE project aims at developing the equipment and the processes for cost-effective roll-to-roll production of high-efficiency thin-film modules, involving microcrystalline (µc-Si:H) and amorphous silicon (a-Si:H).
According to this goal, the main objectives are: (1) to achieve a final blueprint planning of a complete production line for thin film silicon photovoltaic modules with production costs lower than 0.5 €/Wp, (2) to design and test the equipments necessary for the realization of such lines including the deposition systems for substrate coatings, active layer deposition and series connection, (3) to demonstrate the high-throughput manufacturing technique for intrinsic µc-Si:H layer (equivalent to static deposition rate higher than 2nm/s) and finally (4) to show

that the technology developed in the project is suitable for the preparation of flexible single or tandem junction cells and modules, which satisfy the strictest reliability tests and guarantee long-term outdoor stability.

In order to achieve high efficiency a-Si:H and µc-Si:H/a-Si:H tandem devices, effective light trapping schemes should be implemented on flexible substrates and high efficiency solar cells and modules should be developed on these new surfaces. Laboratory scale solar cells and mini-modules with 11% and 10% efficiency, respectively are to be fabricated in order to demonstrate that tandem junction µc-Si:H/a-Si:H can compete with current technologies for electricity output par square meter.

The deposition rates of the intrinsic µc-Si:H layers should be increased from typically 0.1nm/s to 2nm/s: three of the most promising techniques for high rate deposition are investigated (Very High Frequency Plasma Enhanced Chemical Vapour Deposition VHF-PECVD, Hot Wire Chemical Vapour Deposition HW-CVD and Microwave Plasma Enhanced Chemical Vapour Deposition MW-PECVD). A benchmarking of the different deposition techniques will indicate which method emerges as the most cost-effective and could be implemented in the different pilot production lines of the partners. In parallel, the system aspects going from the cells to the modules will be studied; the critical aspect of monolithic cell integration with minimum electrical and optical losses should be solved by using scribing/screen printing techniques. New concepts for more cost-effective encapsulation materials and processes should be established.

All the innovative results, hardware developments, concepts and designs worked out in the project will lead to new systems and will be used for the final blueprint of multi-megawatt production lines that can achieve the production of modules with production costs of less than 0.5 €/Wp.

## 3 PROJECT STRUCTURE

FLEXCELLENCE gathers the extended experience of 8 partners coming from the four complementary fields of solar cell processing, reliability, modules and interconnection, production and machinery:

- The Institute of Microtechnology (IMT), University of Neuchâtel, Switzerland, is one of the leading institutes in the field of thin film silicon solar cells.
- VHF-Technologies, Switzerland, is on the way to become a major European supplier of flexible thin film silicon modules.
- The Energy Research Centre of the Netherlands (ECN), has proven that MW-PECVD can be used to deposit µc-Si:H at high rate and in device grade quality. A pilot line is running now for deposition of thin film Si solar cells on metal foils.
- EXITECH (EXI), United Kingdom, is a system integrator specialised in the manufacturing of industrial laser and micromachining tools for a wide range of applications such as thin-film and wafer-based photovoltaic cells.
- The Fraunhofer Institute for Electron Beam and Plasma Technology (FEP), Germany, has developed a strong know-how in industrial processes for high quality coating of metal foils and plastic webs, and in the roll-to-roll processes.
- Roth and Rau (R&R), Germany, is a leading provider of system solutions for plasma technology and photovoltaics. R&R fabricated the pilot line for ECN.
- The University of Barcelona (UBA), Spain, is the first European group reporting intrinsic and doped µc-Si:H by HWCVD.
- The University of Ljubljana (UL-FEE), Slovenia, brings in its expertise in the field of numerical simulation both for the electrical and optical properties of solar cells and modules.

The WP are organized in a logical way, starting from substrate preparation (WP2), to cells with increased complexity (WP3-5), to the monolithic interconnection issues (WP6). The complete modules including packaging are tested (WP7) and the detailed cost assessments for multi-megawatt roll-to-roll production lines are planned in WP8.

Finally, the exploitation panel formed by the representatives of the industries will optimize the exploitation strategy of the project.

## 4 RESULTS AND DISCUSSION

In the following, the status of the different aspects of the project are presented, especially the first results concerning the three high-throughput manufacturing techniques (MW-PECVD, VHF-PECVD and HW-CVD), the progresses realized in the development of new high quality substrates, and the results obtained in cells. Finally, the status of the monolithic interconnection and preliminary results on cost assessment will be discussed.

### 5.1 High throughput manufacturing techniques

In the frame of the project, a wider VHF electrode has been designed and is now been tested in the pilot line at VHF-Technologies (figure 1). An improved homogeneity over a web width of 50cm is targeted, which will translate into significant throughput improvement compared to the current 30cm web.

**Figure 1**: Roll-to-roll production line at VHF-Technologies.

As already mentioned, the deposition time of the µc-Si:H layer is presently the bottleneck for high-throughput production of devices involving µc-Si:H.

In FLEXCELLENCE, the electronic quality and the deposition rates of the µc-Si:H layers on flexible substrates is being improved by studying simultaneously the VHF-PECVD, MW-PECVD and HWCVD methods [2-4 ].

- New "clever" designs, which will reduce the cost of ownership, are currently developed and the preliminary tests are ongoing,
- New deposition parameters and processes are studied and optimized.

**Figure 2:** New MW-PECVD roll-to-roll system built by the system manufacturer R&R and shipped to ECN

For that purpose, a new MW-PECVD roll-to-roll system (Figure 2) has been built by the system manufacturer R&R and shipped to ECN for the optimization of the intrinsic a-Si:H and μc-Si:H layers.

The commissioning is still under way at ECN but first promising results were already obtained with growth rates up to 3nm/s for intrinsic a-Si:H layers.

A new large area (30*30 $cm^2$) HWCVD system (Figure 3) was built at the UBA and is now ready for deposition. The UBA is now carrying out the next steps to incorporate the roll-to-roll deposition process in the system.

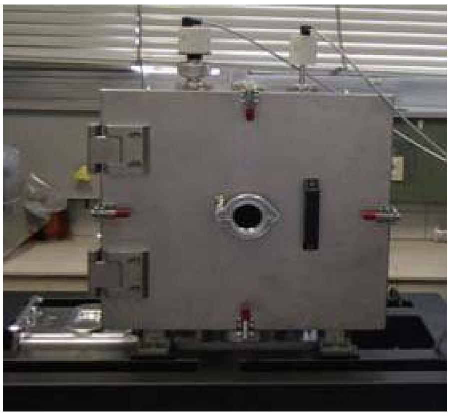

**Figure 3:** New large area HWCVD system at the UBA

Finally, high rate intrinsic μc-Si:H layers have been deposited in a static process by VHF-PECVD onto 30*30$cm^2$ substrates at the IMT. A KAI-S system from Unaxis was used [5].

For the characterisation, dark conductivity measurements (σ dark), the Raman microscopy and the Fourier Transform Photocurrent Spectroscopy (FTPS) were performed on 1 to 1.2 μm thick layers (Table I):

- σ dark measurements were used to determine the activation energy (Eact) and dark conductivity at room temperature ($\sigma_{RT}$).
- Raman spectroscopy was performed with a HeNe laser excitation beam to evaluate the crystalline fraction (ϕc) of the intrinsic layer. It was measured from the top and the bottom of the samples and averaged (to study the nucleation and gradients in crystallinity).
- The FTPS technique was used to evaluate the quality of the layers in term of material disorder (Urbach Tail Slope (UTS) and remaining sub-gap absorption).

**Table I:** Microcrystalline layers deposited on glass in a parallel plate reactor. The Raman crystallinity factor, the dark conductivity at room temperature, the activation energy and the UTS have been measured

| | Rate | ϕc | $\sigma_{RT}$ | Eact | UTS |
|---|---|---|---|---|---|
| | (nm/s) | | S | eV | meV |
| Standard | 0.5 | 0.41 | $2.10^{-6}$ | 0.48 | 51 |
| New #1 | 2 | 0.69 | $2.9.10^{-6}$ | 0.39 | 59 |
| New #2 | 2 | 0.59 | $2.1.10^{-7}$ | 0.47 | 53 |

These results show that high deposition rates up to 2nm/s are achievable for the deposition of high quality μc-Si:H on glass.

Layer #2 in table I has electrical properties comparable to the properties of the standard layer, whose quality has been proven in cells. The next step of this work will be to develop other new layers, with comparable high rate but lower crystalline fraction and lower sub-gap absorption which are still high in layer "#2".

3.2 New substrate concept

One goal of FLEXCELLENCE is to develop a new and mature solution for cost-effective substrates, which must be totally compatible with the roll-to-roll process developed at VHF-Technologies.

Therefore, two types of substrates are being developed:

- Metallic substrates, involving an insulating layer to enable the monolithic interconnection. The first results on these substrates were published in the following reference [6 ].
- Nano-structured plastic PET and PEN substrates with high quality light trapping properties, which are discussed in this paper.

Two texturing methods for PET and PEN have been tested so far:

- The hot embossing technique, which gives the possibility to deposit the cells directly on the PET or PEN surface, is currently developed at the UBA [7 ],
- The roll-to-roll proprietary technique of OVD-Kinegram A.G is currently used at the IMT.

With both methods, different texture shapes and sizes have been achieved [7 ].

In addition, the FEP has developed high quality back reflectors on them (highly reflective ZnO/metal stacks) in the large scale area roll-to-roll production line (coFlex® 600) and promising results have already been obtained with these new substrates incorporated into solar cells (see "Solar cells).

3.3 Solar cells

Flexible substrates offer many advantages. However, the cell processing has to be adapted to new particularities,

like outgazing, thermal expansion or strong mechanical stresses to which the active layers are exposed.
In order to demonstrate high efficiency devices, a-Si:H and μc-Si:H cells in the n-i-p type configuration were prepared and optimized in a recently implemented double chamber laboratory scale system at the IMT. This system allows to avoid any contamination of the intrinsic layer by the dopant gases.
At the moment, all substrates incorporated into the cells had the same roughness, which was much better adapted to the μc-Si:H cells than to the a-Si:H ones. All substrate back electrode were deposited supplied by the FEP (see Substrates).
The electrical characteristics of the best cells obtained so far are presented in the table II.

**Table II:** Electrical characteristics of μc-Si :H and a-Si :H cells deposited on PEN substrates in a two chamber laboratory scale system.

| | $J_{sc}$ (mA/cm$^2$) | $V_{oc}$ (mV) | FF % | η % |
|---|---|---|---|---|
| μc-Si:H | 22.19 | 531 | 69.9 | 8.2 |
| a-Si:H | 11.07 | 874 | 64.7 | 6.2 |

8.2% efficiency μc-Si:H solar cells have already been obtained on the PEN substrates prepared with the FEP's roll-to-roll process.
Regarding the amorphous cells, the optimization in the new double chamber system is at its early stage and the highest efficiency obtained so far is 6.2%. Based on the previous experiences reported by J. Bailat at al [8 ], there is still considerable room for improvement.

### 3.4 Monolithic series connection

The conventional scribing technique for a-Si:H cells on glass is well mastered. However, in the case of flexible cells deposited on opaque substrate, the usual technique can not be used.
For this purpose, the project aims at developing a new interconnection technology, which will minimize the optical and electrical resistive losses.
The UL-FEE already succeeded in developing a 2D electrical model, which already gives information about suitable designs of the front metallic finger contact on the VHF's modules and shows that 10% total losses from a solar cell to a module are achievable.
At the moment, a large number of tests are ongoing at VHF, EXI and ECN to reach this goal by:

- Reducing the re-melting zones induced by the laser scribing,
- Developing the process to remove the ITO from the top of the p-doped layer of the cells,
- Improving the screen printing technology for contact grids.

### 3.5 Encapsulation and cost simulations

Finally, VHF-Technologies conducted a first cost simulation for a hypothetic reference plant fabricating 1 Mio m$^2$ per year of flexible encapsulated modules for building integration. The calculation was performed for different type of cell technologies on polymer substrates. Preliminary interesting results have shown that:

- The encapsulation materials dominate the bill, whatever the cell configuration,
- For 5% efficient a-Si:H modules and 50 MW annual capacity, the production costs could be reduced to below 0.8 €/Wpeak.

## 4 CONCLUSION

The breakthrough expected in FLEXCELLENCE is the development of a complete technology for the production of flexible, cost-effective and high efficiency PV modules.
Therefore, promising results have already been achieved. The comparison of the 3 most promising deposition methods is ongoing. Two new roll-to-roll MW-PECVD and HWCVD have been built and commissioned. The IMT has demonstrated high quality μc-Si:H layers deposited by VHF-PECVD at 2nm/s. The experiments were realised on glass by means of a batch process. The next step will be a transfer of the results onto plastic substrates.
μc-Si:H and a-Si:H solar cells have been developed in a new laboratory scale double chamber system at the IMT. These solar cells are totally compatible with mass-production, since the PEN substrates were prepared by means of a large scale area roll-to-roll process at the FEP. 8.2% efficiency μc-Si:H cells and 6.2% efficiency a-Si:H cells have been obtained so far. Based on previous results, further optimisation should lead rapidly to higher efficiencies.
The UL-FEE succeeded in developing a 2D electrical model, which has shown that 10% total losses from a solar cell to a module are achievable on the VHF-Technologies modules and finally, the cost calculation conducted by VHF-Technologies has shown that (1) the encapsulation cost is one of the major issues for cost reduction , and (2) production costs below 0.8 €/Wp should be reasonably achievable with realistic assumption.

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