FINAL RESULTS OF 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: This paper reports on the final main results of the Flexcellence project. The project was running for 3 years and its goal was the development of equipments and processes for cost-effective roll-to-roll production of high-efficiency flexible thin-film silicon solar cells and modules. All aspects necessary for the successful implementation of the technology could be considered simultaneously and at the end of the project, worldwide level results could be achieved; Indeed, the feasibility of wide web coating of amorphous and microcrystalline layers by roll-to-roll Very High Frequency (VHF) Plasma Enhanced Chemical Vapour Deposition (PECVD) was demonstrated with a new 50cm width VHF PECVD electrode developed during the project, nano-textured substrates with very specific and advantageous optical properties were produced, the three most promising Chemical Vapor Deposition processes for thin film silicon were investigated, solar cells up to 9.8% stabilized efficiency were deposited on low cost plastic substrates and laboratory-scale VHF PECVD reactors, new insulating and conductive inks, new parameters for laser scribing and a better-optimized laser patterning design led to improved series connection process and higher module’s output power. Finally the work made on the encapsulation processes and reliability testing led to significant breakthrough in the field of long-term outdoor stability of flexible modules on plastic foils.

Most of these developments were either directly industrially exploited by the partners or subjects of further investigations for commercial use.

1. INTRODUCTION

Photovoltaics has the potential to play an important role in the future energy mix and to become a major source of sustainable energy within the next years. The European Photovoltaic Industry association (EPIA) foresees that the international annual PV market should more than quadruple by 2013, if favourable energy policies are set. Crystalline modules represent today around 85% of the market, but the silicon feedstock shortage of the last years limited the growth of this technology and opened new opportunities for thin films.

Thin film silicon presents many advantages like the low material quantity necessary for the fabrication, the abundance and non-toxicity of silicon as well as the reduced energy payback time. For some years, turn-key production lines are available on the market and many companies produce already amorphous or micromorph modules with stabilized efficiency up to 9%. However, in order to establish thin film silicon as one of the major photovoltaic technologies, ambitious development must still be realized to further increase the conversion and cost efficiency.

The project Flexcellence (www.unine.ch/flex) [1] was initiated with exactly this objective. Its goal was to develop the equipments and processes for cost-effective roll-to-roll production of high-efficiency thin-film modules, involving amorphous (α-Si:H) and microcrystalline (μc-Si:H) silicon. Flexible modules produced on plastic or metal are light, flexible and robust, with a high capacity for building integration. The roll-to-roll processing gives the possibility to increase the throughput linearly by simply increasing the number of deposition sources or widening the substrate webs. The equipments require also less floor space than more usual batch-processing equipments. Finally, the combination of the high band gap α-Si:H (1.7 eV) and low band gap (1.1 eV) μc-Si:H creates an almost ideal tandem device [2].

During the project, the different steps and aspects of the roll-to-roll industrial production of single and tandem cells and modules could be addressed on two different substrates. The main final results and their industrial exploitation are presented in this paper.

2. MAIN FINAL RESULTS

2.1. NEW SUBSTRATE CONCEPTS

New and mature solutions for the production by roll-to-roll process of high quality and cost effective flexible substrates were investigated and developed. At the end of the project, two different substrates were available:
- Metal substrates, involving an insulating layer to enable monolithic interconnection,
- Low cost plastic substrates with high optical reflecting and scattering properties i.e. nanostructured surface.
For metal substrates, the insulating layer was applied by means of a wet spraying process and subsequently embossed in order to achieve the high light-scattering properties necessary for light-trapping. On plastic foils, the nano-structures were produced either by hot embossing directly in the PEN substrate, or by UV nano-imprint lithography roll-to-roll process in an interlayer. Different texture shapes and sizes could be produced and are shown in Figure 1.

![Figure 1: SEM images of periodically ordered pyramidal texture on PEN (bottom) and of the embossed insulting layer (top).](image)

Regarding the production costs, calculations have shown that less than 7€/m² for substrates including back reflectors is achievable on plastic; the same calculation made for metal substrates leads to production costs around 10€/m² for steel foils.

### 2.2. HIGH THROUGHPUT TECHNOLOGIES

The deposition rate of the intrinsic \( \mu \text{c-Si:H} \) layers needs to be increased to at least 1nm/s. Therefore, the three most promising technologies for the deposition of high rate device grade quality \( \mu \text{c-Si:H} \) layers were investigated: VHF-PECVD, Radio Frequency/MicroWave Plasma Enhanced Chemical Vapour Deposition (RF/MW-PECVD), and Hot Wire Chemical Vapour Deposition (HW-CVD).

RF/MW-PECVD and HW-CVD were intensively investigated; in the following, we describe a few of the key developments carried out in the project:

Significant modifications in the design of the HW-CVD reactor were realized in order to be make it compatible with the roll-to-roll low temperature process required for deposition on plastic web; finally, a new filament holder system was developed to prolong the life time of the catalysts, a new 12 filaments deposition source could be demonstrated (Figure 2) and a multipurpose gas shower to be used simultaneously as deposition source and cleaning system was implemented [3].

![Figure 2: The 12-filament deposition source for large area roll-to-roll HWCVD](image)

In parallel, the first MW/RF-PECVD roll-to-roll equipment was built and taken into operation during the first half of the project. The equipment uses a MW-PECVD source for the intrinsic layer and two recently patented linear RF sources (2004, R&R) for the doped layers.

At the end of the project, device quality layers could be produced with both systems. However, the goal of deposition rates up to 2nm/s, as foreseen at the beginning of the project could not be achieved within the time-frame of the project.

The possibility to produce high quality and high rate \( \mu \text{c-Si:H} \) layers was investigated by VHF-PECVD in a batch static process. Here, the goal of 2nm/s was achieved but in a regime that was not compatible with plastic substrates, because of substrate overheating. Consequently, a new low-flow low-power deposition regime was investigated and led to device grade quality layers deposited at 0.8nm/s with no damage on the plastic substrate. Other parameters which should improve both the layer quality and deposition rate could be identified at the end of the project, but important structural modifications are needed for further investigation which could not be done in the framework of the project.

### 2.3. BEST FLEXIBLE SOLAR CELLS

Different strategies were investigated in order to demonstrate high efficiency devices using the different technologies discussed above [4, 5, 6, 7, 8, 9].

At this time, the best cells were produced by VHF-PECVD. The best amorphous cells on PEN have a stabilized efficiency of 7% and further investigations are underway to increase the photocurrent generated in the blue part of the solar spectrum, which was particularly low.

Regarding tandem cells, excellent results could be obtained on nano-structured plastic substrates produced by roll-to-roll. For 2.5 \( \mu \text{m} \) thick \( \mu \text{c-Si:H} \) bottom cells on textured substrates, initial efficiencies of 10.1 and 11.2% have been achieved on flexible plastic substrate and on a rigid reference substrate, respectively. After 1000 h light soaking, these cells stabilized at 9.8% and 10.1%, respectively [2, 10, 11]. The performance parameters of these devices are summarized in Table 1.
Table 1: Latest tandem cells with 2.5 μm bottom cells and intermediate reflector. Initial values are given in parentheses.

<table>
<thead>
<tr>
<th>Material</th>
<th>Voc (mV)</th>
<th>FF (%)</th>
<th>Jsc (top) (mA/cm²)</th>
<th>Jsc (top) (mA/cm²)</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZnO/text -Ag/glass</td>
<td>1.35</td>
<td>65</td>
<td>11.7</td>
<td>11.5</td>
<td>10.1</td>
</tr>
<tr>
<td></td>
<td>(1.32)</td>
<td>(66)</td>
<td>(12.4)</td>
<td>(11.9)</td>
<td>(10.3)</td>
</tr>
<tr>
<td>ZnO/Ag/Plastic PEN</td>
<td>1.29</td>
<td>64</td>
<td>11.9</td>
<td>12.1</td>
<td>9.8</td>
</tr>
<tr>
<td></td>
<td>(1.34)</td>
<td>(68)</td>
<td>(12.3)</td>
<td>(12.3)</td>
<td>(11.2)</td>
</tr>
</tbody>
</table>

2.4. MONOLITHIC SERIES CONNECTION

Significant developments could be achieved on all necessary steps towards monolithic series interconnection of flexible thin film silicon modules in n-i-p configuration [12, 13]:
- A new water based lift-off process could be implemented in production at VHF.
- A new process for screen printing of low-temperature curing silver and insulating inks was significantly improved and is also already partly implemented in the production of VHF.
- The necessary depth selective laser scribes could be demonstrated with state of the art production compatible solid state YAG lasers.

In addition to these improvements on the interconnection process, the most suitable geometric parameters for the interconnection were calculated for different configurations and partially implemented in production at VHF; the interconnection losses for single junction amorphous silicon cells could thus be reduced down to values slightly higher than 10% and the calculation shows that the same geometric parameters should yield around 10% interconnection losses as soon as tandem cells are produced.

2.5. ENCAPSULATION

The developments on encapsulation and reliability testing have led to significant breakthrough in the field of long-term outdoor stability especially of flexible modules on plastic foils, with the certification of the first BIPV product from VHF according to CE-EN61646 norm (Figure 3).

The cost of the encapsulation was evaluated on the basis of a model for a production capacity of 200MW and 8% stabilized efficiency μc-Si:H/a-Si:H tandem modules; it was shown that the encapsulation represents 48% of the total production price for flat roof membranes.

2.6. WIDE WEB COATING ELECTRODE

One objective of FLEXCELLENCE was to demonstrate the feasibility of wide web coating of a-Si:H and μc-Si:H layers by roll-to-roll VHF-PECVD process.

For this purpose, a new 530mm wide VHF-PECVD electrode prototype was designed, developed and successfully tested during the first year of the project. Rapidly, complete a-Si modules could be processed with equivalent performances as those prepared in the narrow web reactor.

Figure 3: Installation of VHF’s products on a flat roof, grid connected installation in Bellinzona/Switzerland

The possibility and cost of roll-to-roll lamination process were investigated. The first trials were very encouraging but have shown that considerable efforts of optimization are required and that the cost advantages are quite small since the 48% reported above are mainly driven by the material costs.

Figure 4: New product of VHF with 530mm substrate widths compared to the original products

The development of this new electrode went well beyond the initial objective of the project; it was successfully used for the set up of the 25 MW photovoltaic factory of VHF/Flexcell at Yverdon les Bains. The commercial production of 530 mm wide products started in August 2008 (Figure 4) and the new electrode was also tested for the deposition of μc-Si:H. The first μc-Si:H-based single and micromorph cells have shown that the newly developed electrode is compatible with the requirements of μc-Si:H device fabrication.
2.7. LCA ANALYSIS
Life cycle analysis was also performed for flat roof membranes with 30 years guarantees; the energy payback time calculated for systems installed southern Europe is only 0.6 years i.e. about 3 times lower than those of today’s multi-crystalline standard PV modules, the major contribution coming from the encapsulation materials and the electricity used for the manufacturing of the photovoltaic films and modules.

3. EXPLOITATION OF THE RESULTS
Many high potential outcomes for industrial applications were identified at the end of the project. Some of these results are already in production at VHF/Flexcell:
- Commercial production of 530 mm wide products started already in 2008, with the wide web electrode,
- The new encapsulation process passed the certification (CE-EN 1646 norm) required for BIPV products,
- The water based lift-off process,
- The new low temperature curing Ag conductive paste for screen printing as well as a new connecting scheme, which reduces the dead area losses to the range of 10%.

Other outcomes are in the testing phase to be implemented in production in the near future, like the linear RF electrode patented by R&R in 2004, the low curing temperature insulating pastes developed for the interconnection, or the selective laser scribes which could be demonstrated with state of the art solid state YAG lasers.

Finally, the cost calculations realized during this project, mainly based on VHFs concept, i.e. modules on plastic foil have shown that production costs in the same order of magnitude as the targeted costs of 0.5€/Wp are achievable. Indeed, if we consider two successive generations of flexible μc-Si:H/a-Si:H tandem PV modules, a first generation with efficiency of 8% and production costs reduced by 50%) for the backend/encapsulation (from 7Å/s to 15Å/s ) and lower material prices (ETFE membranes with 30 years guaranties; the energy payback time calculated for systems installed southern Europe is only 0.6 years i.e. about 3 times lower than those of today’s multi-crystalline standard PV modules, the major contribution coming from the encapsulation materials and the electricity used for the manufacturing of the photovoltaic films and modules.

4. CONCLUSION
The FLEXCELLENCE project was a successful and collaborative project. Even though the technological developments took in some cases more time than expected, the different aspects necessary for the production of high efficiency thin-film modules by roll to roll could be investigated. Very good results were achieved, both on the equipment side and on the cell processing side, some of the results achieving world-record level. Furthermore, the implementation of novel processing steps into the production shows the successful dissemination. Also, production cost assessment has shown that the market requirements are reasonably achievable. The project was always very well represented in conferences, workshops and public events and some of the project results were reported as one of the highlights in the closing session of the 23rd EU PVSEC.

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