FLEXCELLENCE : TOWARDS ROLL-TO-ROLL MASS-PRODUCTION OF LOW COST THIN FILM SILICON SOLAR CELLS

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ABSTRACT: We report on the "mid-term" results obtained in the frame of the European FLEXCELLENCE project (www.unine.ch/flex). FLEXCELLENCE aims at developing the equipment and the processes for cost-effective roll-to-roll production of high-efficiency thin-film modules, based on amorphous (a-Si:H) and microcrystalline silicon (µc-Si:H). Eight partners, with extended experience in complementary fields ranging from device simulation to machinery development, are involved.
During this first part of the project several milestones were achieved:
- Setting-up and operation of roll–to-roll systems for deposition of solar cells by micro-wave PECVD, Hot-wire and VHF PECVD.
- Fabrication of high quality nanotextured substrates both on plastic foils and on metal foils with insulation.
- Achievement of high efficiency devices on textured plastic substrates with initial efficiencies of 8.8%, 8.6% and 10.9% for amorphous silicon, microcrystalline and tandem micromorph cells, respectively.
- Improvement in interconnection technologies, module encapsulation and reliability.
- Demonstration of the possibility to reach ultra-low cost (< 0.6 €/Wp) if high efficiency micromorph concepts can be realised in production.
- Successful integration by one of the partners of new high-throughput VHF-electrodes and move to module mass-production.

Thanks to the collaborative nature of the project, important steps towards the goal of mass-production of high efficiency thin film Si modules have consequently been realised.

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

1. INTRODUCTION

Flexible thin film silicon modules prepared in roll-to-roll processes offer a number of advantages. They can be fabricated on moderately priced 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 a minimum amount of floor place. The modules are light, easy to transport, flexible, with a high capacity for building integration. In addition to Unisolar and Fuji, which entered mass production with a-Si:H/a-SiGe:H based products, several compagnies (Nuon, Powerfilm, VHF-Technologies,…) are piloting advanced R&D or small production for consumer products. The EU Flexcellence project (Specific Targeted Research or Innovation Project of the 6th EU framework program, 1.10.2005-31.9.08) aims at strengthening the know-how and technology in the roll-to-roll processing of flexible thin film silicon cells or modules.

In the present paper, the authors give an overview of the major results obtained in the first half of the project. A more detailed description of the project objectives and structure is given in [1].

2. CONSORTIUM AND MAIN ACTIVITIES

Specifically, The FLEXCELLENCE project aims at developing the equipment and the processes for the production of cost-effective and high efficiency flexible photovoltaic modules with a focus on:
- In line roll-to-roll process, plastic and metallic substrates.
- a-Si:H, µc-Si:H, and a-Si/µc-Si micromorph solar cells.
- Si deposition: VHF and MW-PECVD, HW-CVD.

To reach these goals, a collaborative and non-competitive consortium with complementary competences was set-up. It includes two equipment manufacturers, Roth&Rau (R&R) and Carl Baasel Lasertechnik (ROFIN), one module producer, VHF-Technologies (VHF), two research institutions Energy Research Center of the Netherland (ECN) and the Fraunhofer Institut für Electronenstrahl und Plasmatechnik (FEP), and three universities, the University of Barcelona (UBA), the University of Ljubljana (UL-FEE) and the University of Neuchâtel (UniNe), with various expertises in the field of solar cell fabrication, roll-to-roll processing, and opto-electronic simulations. Fig.1 describes the partners and their tasks within the consortium.

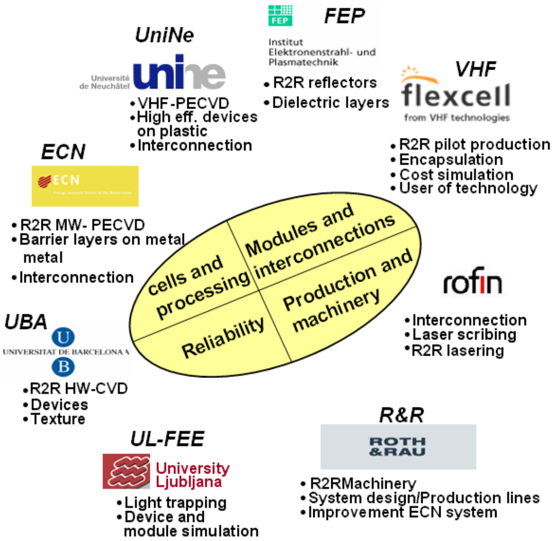

Figure 1: The Flexcellence consortium. The acronyms used in the text are reported on the figure.

3. MAIN AXES AND ACHIEVEMENT

3.1. Substrates

The goal is to fabricate high quality and cost-effective substrates by roll-to-roll processing with a focus on:

- Metal foils with insulating layers, light-trapping, nanotexture, high quality reflector,
- Plastic webs (PET/PEN) with light-trapping, nanotextures, high-quality reflector,

Sprayed SiO_x based insulating layers are developed by ECN. High breakdown voltages up to 900V on A4 metal foils (4*4mm^2 contacts) are achieved. The sprayed layers fabrication is compatible with roll-to-roll and suitable for embossing, as shown by Fig.2.

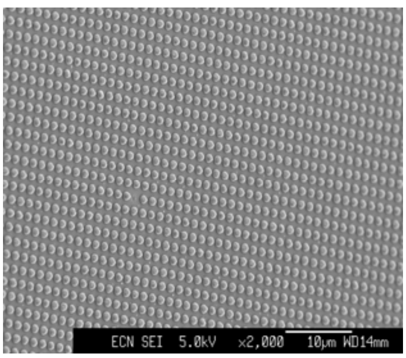

Figure 2: Insulating layer textured by hot embossing before curing (embossing performed at UBA)

Textured PEN and PET plastic substrates fabricated by roll-to-roll at OVD-Kinegram are coated at FEP with various high quality Ag/ZnO or Al/ZnO stacks. Reliable back-reflector on plastic are achieved on which short-circuit J_{sc} gains up to 20% are measured in a-Si:H and μc-Si:H cells (see section 3.3).

3.2. Deposition processes

The focus is set on the development and comparison of three different deposition techniques for the intrinsic a-Si:H and μc-Si:H layers: MW-PECVD, HWCVD and VHF-PECVD. Besides achieving device quality layers, high deposition rates are targeted for intrinsic μc-Si:H. At that stage of the project, a "fair" assessment of the deposition techniques in terms of μc-Si.H deposition rates and cost effectiveness is still not possible, as the VHF process is at a far more advanced stage of development.

i) Deposition by MW-PECVD
A new pilot roll-to-roll system built by R&R in partnership with ECN was installed and ramped-up at ECN. The doped layers are obtained by using RF-linear sources (see [2, 3]), whereas the i- layer are deposited by MW-PECVD. The roll-to-roll system is fully operational, and several doped layers are now of satisfying quality [3]. The development of device quality intrinsic a-Si and μc-Si layers is underway.

ii) Deposition by HW-CVD
At the moment, the new chamber, designed and taken into operation by the University of Barcelona, is being used to perform HWCVD deposition of cells and layers in static mode. Currently, a roll-to-roll charger is being designed and will be installed in the system. More details are given in [4].

iii) Deposition by VHF-PECVD
VHF-PECVD deposition is performed in batch static process at UniNe and in the pilot roll-to-roll line at VHF.
As shown in section 3.3, VHF deposition allows high quality devices fabrication on PEN plastic substrates. μc-Si:H intrinsic layers have been deposited successfully on PEN foil in the roll-to-roll system at VHF.
Besides, intrinsic μc-Si:H layer deposition at 2nm/s are obtained in batch deposition but low compatibility with plastic substrates such as PEN is observed, associated in large part to substrate overheating. A deposition regime at 0.8nm/s in a new low-flow low-power regime compatible with low cost plastic substrates allows the fabrication of device quality layers.

3.3. High efficiency solar cell fabrication on plastic

So far cell fabrication has been performed mostly on plastic foils. Table I reports the best laboratory cell results obtained for n-i-p a-Si:H, μc-Si:H and micromorph structures, deposited on PEN substrates. The current values are obtained from EQE measurements. More details are given by T. Söderström et al [5]. Remarkable initial efficiencies of 8.8% and 10.9% are obtained for single junction a-Si:H and tandem micromorph cells respectively with a i-layer thickness of 270 nm. The high J_{sc} values for the μc-Si:H cells (close to 24 mA/cm2) indicates that the nanostructured substrates fully plays its role of light scatterer. Noticeably no light induced degradation is observed for the μc-Si cell which reaches an efficiency of 8.6%.

Table I: Best n-i-p laboratory cells obtained at UniNe by VHF-PECVD on plastic foils.

	J_{sc} (mA/cm^2)	V_{oc} (mV)	FF %	η %
µc-Si:H	23.85	510	70	8.6
a-Si:H	14.3	888	70	8.8
a-Si:H/µc-Si……..	11.3………	1.35.	71.5	10.9

Figure 3 gives an example of results obtained when comparing the internal quantum efficiency (IQE) and external quantum efficiency (EQE) of µc-Si:H solar cells on textured and flat plastic substrates in the spectral range from 350 to 1000nm under short circuit conditions. The thickness of the µc-Si:H n-i-p stack amounts to 1.55 µm. When compared to cells on non-textured substrate coated with Ag and ZnO (80 nm), the light conversion of textured cells is enhanced in the spectral region above 700 nm. We find current densities (Jsc) of 17.9 mA/cm^2 and 22.8 mA/cm^2, respectively, revealing a gain of 27%. Figure 3 also includes the IQE's where the external data have been corrected by data from reflection measurements of the different solar cells. It is observed that the textured cell suffers from some loss in the spectral region between 650 and 800 nm. A possible origin could be an increased absorption in the reflective back contact; Indeed, surface textures have been reported to increase the absorptive losses in silver and other metallic layers [6].

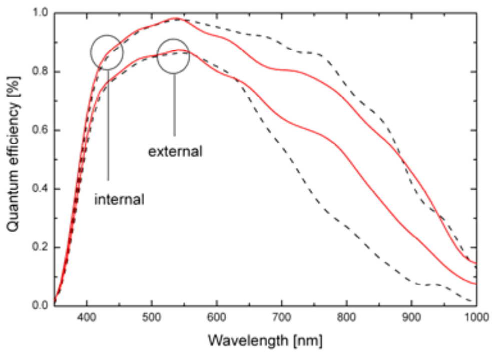

Figure 3: External and internal quantum efficiency (IQE) of 1.55 µm thick µc-Si:H cells on textured PEN (full) and flat reference (dashed lines).

The J_{sc} of the micromorph tandem cells (11.3mA/cm2) will be further increased by introducing additional optical features such as an intermediate reflector (IR) between the a-Si:H and µc-Si:H cells. Preliminary tests of intermediate reflector have been performed. When introducing an SiO_x based IR, a J_{sc} gain around 1mA/cm^2 is found in the top a-Si:H cell, as shown in Figure 4. The IR is prepared by PECVD and can potentially be integrated into a production line. The last developments on SiO-based intermediate reflectors are reported by Buehlmann et al. [7].

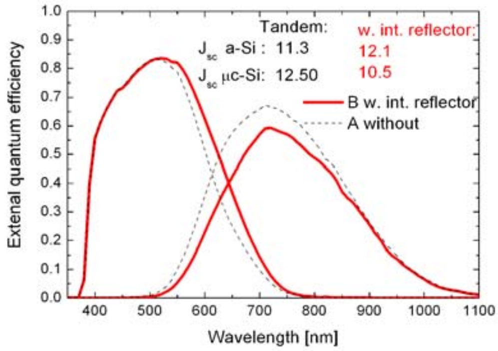

Figure 4: EQE of a tandem micromorph solar with (dashed lines) and without intermediate reflector (full lines). The µc-Si intrinsic layer thickness is only 1.2 µm in this example (check ref. [5] for details).

3.4. Interconnection

Electrical and optical modelling performed at UL-FEE, taking into accounts the improvements of pastes and TCO, demonstrates that interconnection losses below 10% should be achievable in a close future. More details are reported by K. Brecl et al. [8]. In parallel, the Ag paste technology is being improved at VHF and ECN. Also, screen printing with insulating inks is under development at ECN and a large number of laser scribing tests on various cells and substrates are performed at ROFIN. For laser scribing, the target is to achieve selective removal of Al/Ag rear contact and of front ITO (see Figure 5). Details of progress in interconnection will be reported by J. Löffler et al [9].

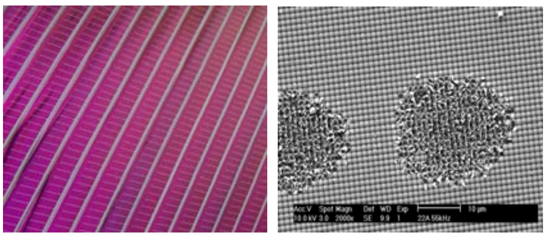

Figure 5: Left: details of monolithically integrated contacts at VHF. Right: selective removal of ITO by pulsed laser ablation for cells on plastic gratings.

3.5. Pilot line at VHF-technologies

On flat plastic substrates, stable single junction a-Si:H modules (30x60cm^2) with efficiencies higher than 4.7% have been obtained. Preliminary tests have shown that it is possible to process textured substrates, and first a-Si:H cells with 6.8% initial efficiencies have been achieved.

3.6. Modules reliability and testing

Complete processes for the fabrication of low-cost and reliable flexible modules have been implemented at VHF. VHF's products were successfully tested with internal tools and are currently in process to obtain the independent IEC certification. Monitoring of outdoor modules are performed by UBA, UL-FEE and VHF. A

2.4 kW system mounted on a corrugated roof in Yverdon (Figure 6) yielded 1135 KWh/Wp in the last year, which is a high value for this location.

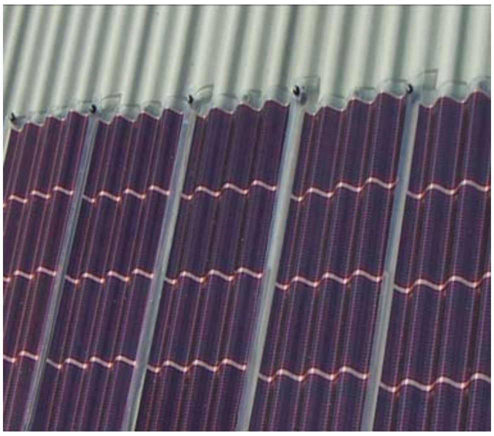

Figure 6: Monitoring of outdoor modules produced by VHF. The 2.4 kW system yielded 1135 KWh/Wp in the last year.

3.7 Towards low costs

Costs estimates based on realistic assumption have been performed by the different industrial partners, FEP and ECN, with the following assumptions:

- Standard EVA/ETFE front lamination (major cost item)
- BIPV model used for the added costs
- No junction box cost
- Rent, energy, insurance, maintenance not considered
- 5 years depreciation, production site Europe.

The calculation are based on a reference plant producing 1 Mio sqm/y of flexible encapsulated modules for building integrated PV in 2008-2010. As a main results, a direct production cost lower than 0.8 €/Wp is calculated for a-Si:H single junction reference solar modules (efficiency ~5%) and a first approximation of the cost of a project plant to produce 1 Mio sqm/y of 10% efficient a-Si:H/μc-Si:H modules leads to a significant improvement and would result into cost < 0.6€/Wp.

3.6 Towards mass production

Multi-pass single chamber at VHF-Technologies based on new electrodes developed within the project have been installed. This allows an enhanced throughput and improved process reliability. Based on these advanced electrode designs, a pilot line for 2MW-5 MW capacity is built at VHF. In parallel, the setting-up a 25 MW production plant is underway.

In addition, other developments in the project could lead to added exploitations impacts:

- "Turn-key roll-to-roll deposition systems", or even turn-key full production lines by R&R,
- Laser tools for roll-to-roll PV,
- Advanced substrates and processes for high efficiency thin film silicon modules.

Figure 7: Multi-pass single - chamber processing at VHF-Technologies.

4. CONCLUSIONS

The essentially collaborative nature of the project ensures a dynamic exchange of know-how, samples and technological advices among the partners. Improvements in virtually every sector pertaining to the technology development could be achieved. Considering the promising cost calculation and the results achieved in the first part of the project, Flexcellence clearly brings flexible thin film Si PV one step closer to cost-effective mass production in Europe.

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