COST EFFECTIVE ENCAPSULATION COMPOSITES FOR BUILDING INTEGRATED PHOTOVOLTAICS

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Abstract
A novel multilayer polymer composite material system and process for encapsulation of thin film solar cells into profiled roofing elements were developed in view of building integrated photovoltaic (PV) applications. The multilayer material included texturized hybrid nanocomposites for enhanced light trapping and a glass fiber reinforced composite for structural integration. At production volumes beyond 100'000 parts per year, the financial payback time of the modules was found to be less than 4 years.

1. Introduction

New building integrated photovoltaic (BIPV) roofing markets are estimated to be of 5 b€ in 2015. The general objective of the present project is to develop a materials system and process for profiled encapsulation of flexible thin film PV for structured roofing elements. This opens a new market of profiled roofs with integration solutions easily accepted by the architects. Focus of the research was on the development of cost effective polymer composite processes [1] to increase light-trapping in the thin film device and to integrate flexible PV laminates into preformed fiber reinforced composite structures.

Light-trapping was realized through tailored texturization of the back reflector of the cell using UV nanoimprint lithography (UVNIL) with hyperbranched polymer (HBP) nanocomposites [2]. Particulate polymer nanocomposites show significant improvement in mechanical properties [3] but often lead to processing problems owing to a liquid-to-solid transition at particle concentrations below 10 vol%. Nevertheless, UVNIL has been demonstrated using batch processes [4, 5], and scaling-up to large area using cost-effective roll-to-roll (R2R) remains challenging. Polymer composites can be adapted to any roofing geometry and are thus compatible with BIPV requirements. However, in the case of integration using thin film PV devices, a key concern is the risk of premature cracking of the brittle PV stack during composite forming operations. The development of a composite backing structure is therefore potentially interesting but highly challenging.

The objectives of the work were to analyze and optimize nanocomposite and fiber reinforced composite formulations, scale up the process techniques to R2R, and evaluate the influence of these processes on the PV efficiency and overall pay-back time of conformal PV modules.

2. Roll-to-roll processing of texturized nanocomposite back reflector

Three types of UV-curable nanocomposites based on an acrylated HBP were elaborated, namely by mixing preformed silica nanoparticles with the HBP (*particulate composites*), by mixing tetraethyl orthosilicate (TEOS) within the HBP matrix followed by TEOS condensation (*sol-gel composites*) and by combining the mixing and sol-gel processes (*hybrid composites*). A careful optimization of the mixing step and of the dual-cure photopolymerization and condensation sequence was carried out, the optimal process sequence depending on silica particle loading and associated rheological behavior. Attention was also paid to the internal stress build-up during polymerization and resulting problems such as distortion and cracking. The Vickers microhardness was found to increase by more than 2 times with increasing silica loading for the particulate composites and reached a value of 287 MPa [6] at a silica fraction of 30 vol% However, the huge increase in suspension viscosity limited the processability of the particulate composites [7]. In contrast, sol-gel and hybrid processes allowed maximizing the silica fraction, while keeping a low viscosity, thanks to the liquid sol-gel precursors. The viscosity of hybrid suspensions was one to two orders of magnitude lower than that of their particulate counterparts, as depicted in Fig. 1.

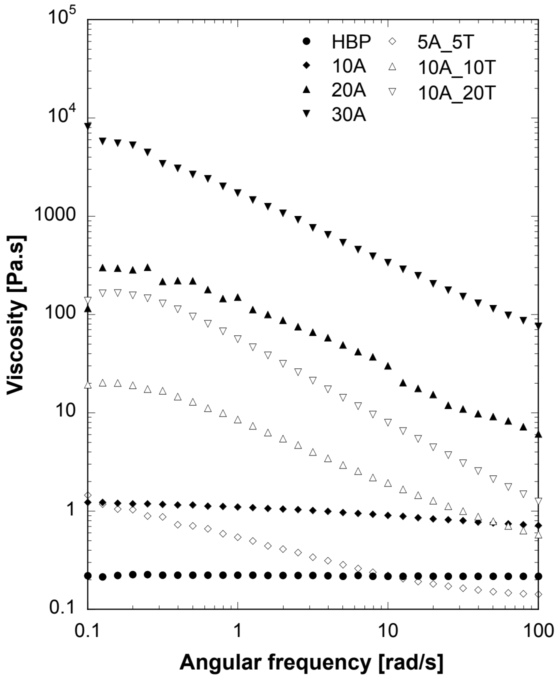

Figure 1: Viscosity of composite suspensions vs. angular frequency. Composites are denominated based on their composition xA and xA_yT, where x and y are the volume fractions of Aerosil nanoparticles 'A' and silica obtained from the condensation of TEOS 'T', respectively.

Light-trapping textures for the back reflector of thin film amorphous silicon solar cells were produced with the 3 types of composites through a UVNIL replication method. A random pyramidal nickel template was used to imprint nanocomposites containing up to 25 vol% of silica on a polyethylene naphthalate (PEN) substrate in a batch process. Large area (several 10 m^2) HBP coatings were also textured on a 18 cm wide PEN web R2R line. Fig. 2 shows the UVNIL tool built in-house, the nickel template used to imprint the polymer composites and the R2R pilot line also built at LTC. The influence of nanoparticle fraction, imprint pressure and R2R process on the shape fidelity of the replicates was studied using scanning electron microscopy and optical analyses.

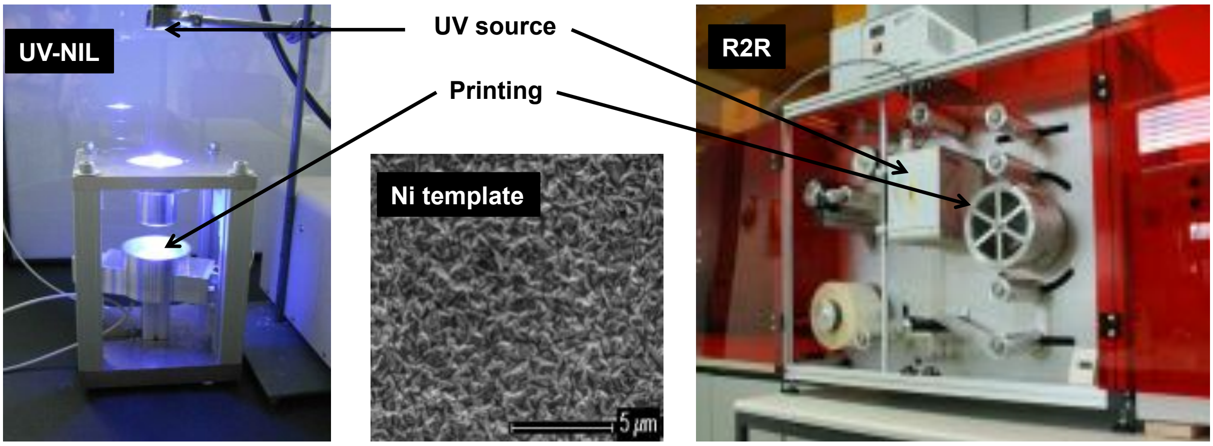

Figure 2: Picture of the UVNIL tool (left), electron micrograph of the nickel template (center) and picture of the 18 cm wide web R2R pilot process (right).

In all cases a replication fidelity better than 90% was obtained, even at a pressure as low as 1 bar and at nanoparticle loading as high as 20 vol%. The electron micrographs in Fig. 3 show the morphology of a HBP and hybrid composite replicas. The texture was replicated as a negative image of the Ni template with no visible difference between the different materials. Fig. 3 also shows the data for angle-resolved scattering (ARS) and haze (ratio of scattered light to total reflected light). A haze above 99% over the visible light spectrum and a very effective light scattering performance in a broad angular exposure was reached, especially for hybrid composites. In order to test the limits of the R2R pilot line, different imprinting speeds were also tested (from 20 cm/min to 2 m/min). Even at the highest speed, the same haze and ARS performance were achieved.

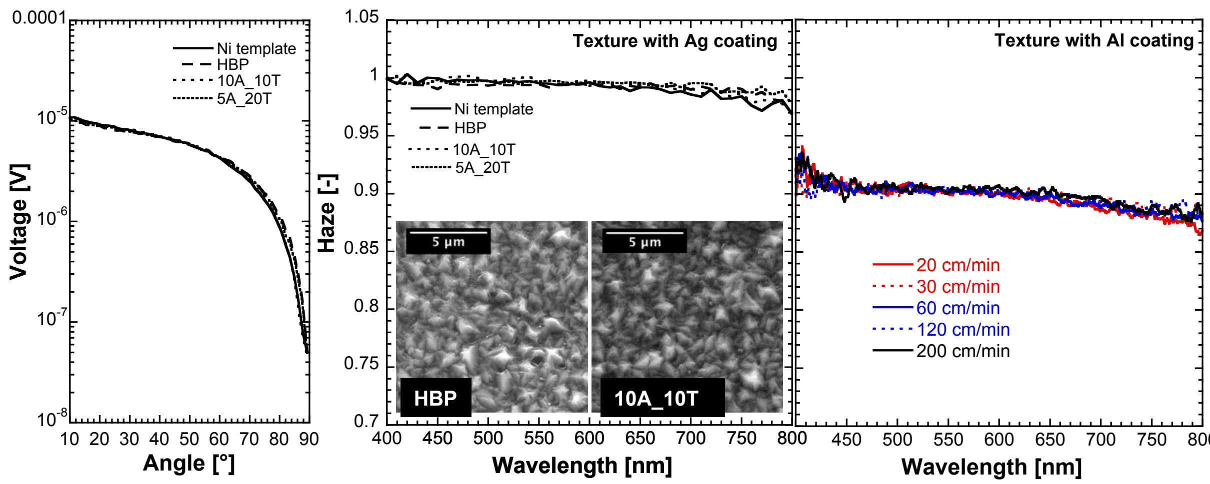

Figure 3: ARS (left) and haze (center) data for nickel template, texturized HBP and hybrid composite replicas. The figure on the right corresponds to the haze of HBP replicas produced at different R2R line speeds. SEM images of HBP and hybrid composite replicas are shown as insets.

Thin film amorphous silicon solar cells were deposited on large area unfilled HBP textured substrates [8]. Table 1 summarizes the performance of the devices. The highest photocurrent density achieved with the present R2R process was 13.5 mA/cm^2 [9], which was 23% higher than the reference photocurrent of 11.0 mA/cm^2 of a flat cell. The cost of the nanocomposite texture was only few euro cents per m^2, which makes such materials very attractive when combined with cost-effective R2R technology.

Substrate	V_{oc} [V]	J_{sc} [mA/cm^2]	FF [–]	Efficiency [%]	Texturization cost [c€/m^2]
Flat PEN (stable)	0.91	10.71	65.1	6.38	0
Texturized HBP (stable)	0.86	13.16	61.6	7.00	5

Table 1. PV parameters of roll-to-roll processed cells on flat PEN and texturized HBP coated PEN substrates, after 1000 h of light induced degradation (stable state). V_{oc} open circuit voltage, J_{sc} short circuit photocurrent, FF fill factor.

3. Conformal modules

The multilayer PV device (transparent electrode, a-Si, aluminium electrode) was deposited on a 50 µm thick polyethylene naphthalate (PEN) substrate and laminated at 150°C with a fluorinated polymer top foil and a thermoplastic back sheet, using an ethylvinyl acetate adhesive. The laminate was subsequently thermoformed into a standard Montana® roofing profile (Fig. 4). A glass-reinforced polyester backing structure was molded on the backside of the preformed laminate using light resin transfer molding (RTM). The choice of the thermoset composite route was for demonstration purposes, whereas a thermoplastic composite route was considered for large volume production as detailed in Section 4.

A fracture mechanics model was developed in a first to predict the influence of temperature and mechanical stress on the failure of the active PV layers [10]. This information was essential to calculate the critical radius of curvature of the fragile device and enable forming the PV laminate. A thermoelastic analysis of the position of the neutral axis was carried out in a second step to optimize the thickness and tailor the temperature-dependent stiffness of the thermoplastic backing layer. A polyester fiber reinforced polypropylene ethylene–propylene rubber with excellent dielectric and waterproof properties was identified, which enabled forming the 1 mm thick laminate to radii of curvature down to 8 mm. However, the admissible flexural rigidity (2.8 N.mm^2) and heat deflection temperature of the polymer (70°C) were insufficient for use as a structural backing. A glass/polyester composite was thus developed in a third step, with 30%vol fibers for optimal processability and mechanical performance. A light RTM technology was used, in which vacuum in the mold pulls the resin into the glass mat reinforcement. The vacuum was set at 0.8 bar to avoid evaporation of the polyester resin solvent at higher vacuum levels. The temperature cycle and formulation of the polyester resin, accelerator and catalyst were also optimized using chemorheological analyses with attention paid to the gel time, which limits the time for the injection step.

Figure 4: Montana® roofing profile and full size profiled composite a-Si solar module (1.8 m x 1 m, 6.3 kg, 60 W).

A full-scale 1 m x 1.8 m demonstrator replicating a commercial SP44/333 Montana® roofing profile was produced using three individual 50 cm wide laminate PV foils (Fig. 4). The demonstrator module weights 6.3 kg and provides an output power of 60 W. Comparison of the current-voltage characteristics of the individual flat laminates (prior to forming) and of the final module ensured that no degradation occurred during forming process (fill factor equal to 62% in all cases) [11]. The long-term endurance of the conformal PV laminates with composite backing was also validated using standard damp-heat cycling tests.

4. Cost analysis

The overall cost for renovation of an industrial roof (1'000 m^2) was calculated as a function of production volume with either roof integrated solar modules [11] or standard rack mounted modules. Calculations were made in case of CIGS thin film technology for the integrated modules (efficiency 14.6%) with a 3 mm thick glass-reinforced thermoplastic composite backing formulated for roofing standards (instead of the polyester composite, which was less cost-effective). Crystalline Si modules (c-Si, efficiency 22%) were used as a reference. For both PV technologies an active area equal to 90% of the module area was assumed. The cost was calculated using the data in Table 2 (production of the composite backing, assembly of the solar modules and roof renovation in Switzerland). The results displayed in Fig. 5 show that the integrated technology is considerably less costly compared to the reference c-Si owing to the cost-effective manufacturing process for the composite backing [12] and to its integrated nature. The total cost for the roof renovation (preparation of the roof, production and mounting of the modules) was estimated to be close to 174 CHF/m^2, compared with 390 CHF/m^2 for standard rack-mounted c-Si modules (a cost saving of 55% for an annual production volume of 1 million modules).

Production duration [years]	10
Hours per shift per day	8
Working days per year	233
Shift efficiency [%]	85
Reject [%]	5
Max number of shifts per day	3
Scrap per part [%]	1
Depreciation time [years]	10
Plant operating cost [CHF/m^2/yr]	190
Plant area [m^2]	100
Energy cost [CHF/kwh]	0.13 *
Cost of labor per person [CHF/hr]	33 **
Number of direct persons	1
Indirect labor cost per person [CHF/hr]	48 **
Direct/indirect labor ratio	3/1
Consumable cost per direct labor person [CHF/hr]	1

(*) http://www.elcom.admin.ch/
(**) http://www.ggba-switzerland.ch. *2. Workforce and Labor Costs*. 2011.

Table 2. Parameters of the costing model.

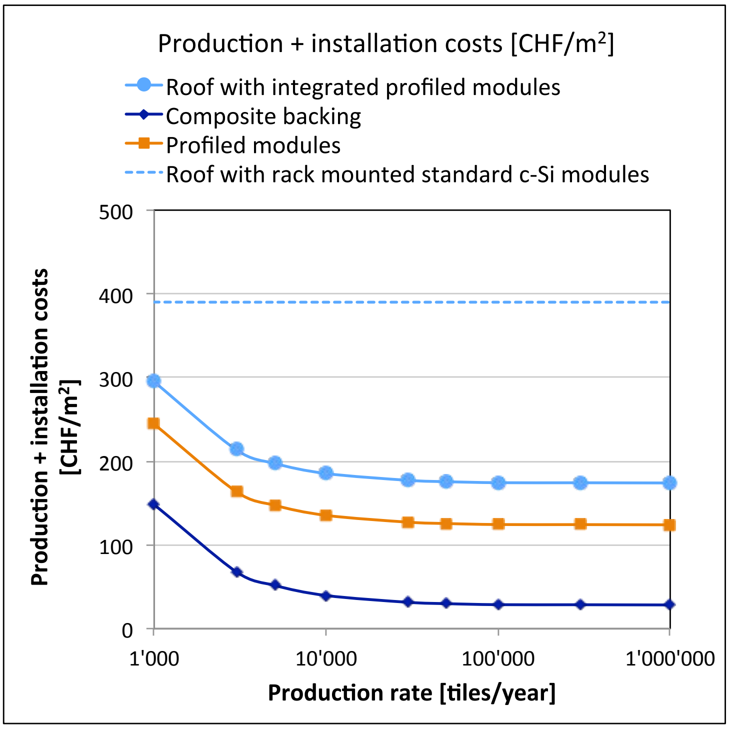

Figure 5. Costs for composite backing, profiled modules and overall costs for roofing renovation using integrated CIGS modules. The corresponding cost for standard rack-mounted c-Si modules is shown as a reference.

The financial payback time (FPBT) was calculated for Switzerland (average irradiation on a roof 1'000 kWh/m^2/year [13]), using present feed-in-tariff data for installations between 100 and 1'000 kW (0.290 CHF/kWh for roof integrated modules and 0.235 CHF/kWh for roof mounted modules). As shown in Table 3 the roof with integrated CIGS and rack-mounted c-Si modules are expected to deliver 131 and 198 MWh/year, respectively. The FPBT data show that the integrated technology is more effective, in spite of the reduced efficiency of the CIGS cells compared with the c-Si cells.

The addition of a light trapping texture on the back reflector of the thin film device would potentially increase the efficiency of the cell by a relative 20%, i.e. from 14.6% without texture to 17.5% with texture. The production cost of the texture was estimated to be below 1 CHF/m^2 owing to the cost-effectiveness of the material precursors (0.05 €/m^2, see section 2) and of the R2R process, which represents less than 0.6% of the overall module cost. The increased efficiency with negligible cost would further decrease the FPBT of the CIGS module to 3.8 yrs, a major improvement compared with the standard rack-mounted technology.

Technology	Texturized back reflector	Cell efficiency [%]	Energy produced [kwh/year/roof]	Total renovation cost [CHF]	Feed-in-Tariff [CHF/kwh]	FPBT [years]
Rack-mounted (c-si)	–	22	198'000	389'997	0.336	8.5
Integrated (CIGS)	No	14.6	131'400	174'020	0.290	4.6
Integrated (CIGS)	Yes	17.5	157'700	175'064	0.290	3.8

Table 3. Financial payback time (FPBT) in Switzerland for a 1000 m^2 roof renovated with conformal modules based on CIGS technology, with and without texturized back reflector (597 tiles required for 1000 m^2) and with standard rack mounted c-Si modules.

5. Conclusions

A materials system and process for the encapsulation of thin film silicon solar cells into profiled BIPV modules with improved efficiency was developed, which comprised a R2R processed nanocomposite texturization, a thermoformed PV laminate and a resin transfer molded polyester composite backing.

Hybrid nanocomposite suspensions with tailored rheology were elaborated using a combination of silica nanoparticles and sol-gel precursors. The viscosity of hybrid suspensions was found to be one to two orders of magnitude lower than that of their particulate counterparts. An optimized dual-cure photopolymerization and condensation sequence was devised, where the condensation time before polymerization was decreased for compositions with increasing TEOS to avoid distortion and cracking problems. The hybrid nanocomposites were transparent and their hardness reached values up to 287 MPa at a silica fraction of 30 vol%. Light-trapping textures with sub-micron random pyramidal features for the back reflector of the cells were produced with the nanocomposites by means of UVNIL. Perfect replication fidelity was obtained for composites up to 25 vol% of SiO_2. The resulting haze was found to be above 99% in the visible light range and the light scattering performance was also very high in a broad angular exposure. A R2R process was moreover developed for cost-effective production of large area texturized coatings. High fidelity textures were produced on large areas at a rate of 2 m/min. Thin film a-Si cells were deposited on the R2R produced textured substrates. The achieved photocurrent density of 13.5 mA/cm^2 was 23% higher than the reference photocurrent of 11.0 mA/cm^2.

A profiled module demonstrator was manufactured in a two-step operation, starting with the preforming of a PV laminate followed by a light RTM of a polyester composite backing. Attention was paid to develop a laminate structure and process compatible with the severe thermomechanical limits of the fragile active PV layers. An evaluation of the life-cycle costs of such BIPV modules using a CIGS thin film device with was carried out. The estimated financial payback times were found to be less than 5 years (without texturized back reflector) and less than 4 years (with texturized back reflector). The polymer composite backing enables fast profiling into stable and complex shapes, and offers a low-cost and energetically robust alternative to standard building-integrated PV products based on crystalline silicon.

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