Towards High Efficiency Flexible Printed Tandem Solar Modules

T. Offermans, M. Chrapa, J. Schleuniger, L. Mühlebach, R. Ferrini, G. Nisato

The Printable PV activity at CSEM addresses breakthrough, organic and inorganic printable materials and processing technologies that target applications with design added value and reduced environmental impact. The additive technologies developed are aimed at mass customizable manufacturing of PV products with high automation and reduced capital equipment cost. The objective is to provide Switzerland with know-how and technological options at the device design and process development level to support equipment developer, materials researchers and industrial suppliers as well as end users in the emerging field of printed PV.

From small hero cell to large area flexible demonstrator

During the past years, CSEM has developed their printing and device fabrication capability from lab-scale single cells made by spin-coating in an inert gas on small 2.5 × 2.5 cm glass substrates, through Doctor Blade coating in the ambient environment on increasingly larger substrates, to complete modules printed on flexible substrates. In parallel, CSEM developed efficient tandem cells by optimizing the optical stack, the charge transport and light in-coupling structure. Hero tandem cells were reproduced, blade coated in air from non-chlorinated solvents, with efficiencies ranging between 8 and 10%. A light management structure was designed and fabricated specifically for an already optically and electrically optimized homo-tandem cell, which increased the cell efficiency from an average of 9.2% to 10%.

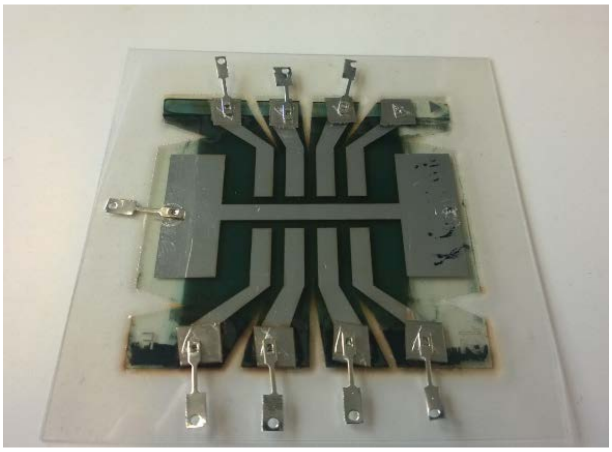

Figure 1: Photograph of the encapsulated flexible tandem solar cells.

These "hero" tandem cells were made on rigid ITO coated glass substrates, with an active area up to 1 cm^2. In order to fabricate tandem cells on large area flexible substrates with the same high efficiency as on glass, in a first step a fabrication process was adapted for the flexible substrate, and in a second step the printing method was changed from blade coating to slot-die coating in order to obtain high uniformity coatings over a large area.

Tandem cells on flexible substrate

The change from rigid to flexible substrate is not trivial. The following two factors have a tremendous impact on the cell performance: 1) the optical properties of the substrate in the total stack, and 2) the roughness of the substrate. Optical simulations predict a 30% lower performance than the hero-tandem on glass. A major reduction in the photocurrent by 10-20% compared to ITO-glass is calculated due to a reduced transmission of the flexible substrate. In addition, a thick smoothening coating on the substrate is needed to ensure a good quality coating of the following six layers in the stack. As a result the maximum obtainable photocurrent drops further, resulting in an efficiency of just over 7% using realistic, electrically non-limiting layer thicknesses. Tandem cells were fabricated accordingly on flexible substrates with a size of 5 × 5 cm^2. In order to demonstrate the robustness of the flexible tandem cells, the cells were encapsulated within ultra-barriers and electrical contacts were attached (photo in Figure 1). All cells, except one, remained functional with similar performance as measured before encapsulation. A slight drop in the V_{oc} is observed, and an improvement of the J_{sc}, resulting in a PCE of the encapsulated device of 6.5%, which is close to the 7% considered possible based on optical simulations.

Slot-die coated flexible tandem cells and modules

In order to demonstrate the upscalability of the tandem cell fabrication using an industrially relevant printing method, we set out to slot-die coat the cells on the flexible substrate. Note that in order to obtain high efficiency, control of layer thickness within 5-10 nm is needed, over the entire coating area. Thus one challenge to be addressed when coating a large area is the flatness of the substrate during coating. In a R2R setup, this is done by adjusting the tension on the web, in the table top S2S setup, used in this work, this required the use of a rigid, flat carrier substrate. Within project Sunflower, CSEM together with its partners could make significant progress in the development of the fabrication process to make large area flexible tandem cells, resulting in two functional 12 × 17 cm^2 homo-tandem modules, slot-die coated in air, using non-chlorinated solvents, encapsulated, with a voltage output of 4-5 V, current output of ~100 mA under solar illumination.

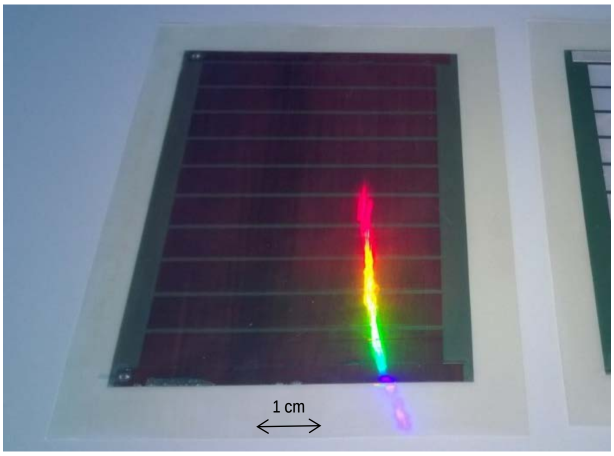

Figure 2: Photograph of one of the final flexible tandem demonstrator modules, encapsulated and laminated with a light management foil.

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