Progress of Thin Film Silicon PV Developments at Oerlikon Solar

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ABSTRACT

The shortage in crystalline silicon for the PV industry calls for alternative solar cell concepts like thin film solar cells. Various studies have led to the conclusion that thin film PV has due to its considerably reduced quantity of the absorber material a higher potential for cost reduction compared to conventional wafer-based silicon PV. Oerlikon Solar's approach and strategy is to adapt mass production approved PECVD KAI deposition systems, developed originally for TFT display industry, to thin film silicon solar cells deposition and, moreover, build full thin film manufacturing lines for amorphous and Micromorph (a-Si:H/μc-Si:H) tandem silicon modules. Thus, R&D modules of 1.4 m^2 substrate area have been fabricated with initial aperture efficiencies of 9.6% for both amorphous p-i-n single-junction as well as Micromorph tandem devices. This paper summarizes the status of Oerlikon Solar's R&D activities in the field of thin film silicon solar cells and modules.

INTRODUCTION

The crystalline silicon shortage in the PV industry and the tremendous demand of solar cell modules make alternative solar cell concepts very attractive. Especially thin film PV is a strong candidate to solve the shortage problems crystalline PV is facing today and surely in the next years. Although, in the recent years growth rates of PV have been over 30 % and more, the wafer-based PV technology has not achieved further cost reductions: The module prices have even augmented [1] in spite of an increased automation and a massive volume boost of wafer based PV production worldwide, which both usually should lead to lower prices.

Several studies conclude that thin film PV has a higher cost reduction potential compared to the conventional crystalline silicon based PV [2-4]. Due its considerably reduced necessary quantity of the absorber material, herein, especially thin film silicon has a huge potential as its technology is based on non-toxic and highly abundant materials. The introduction of hydrogenated microcrystalline (μc-Si:H) / nanocrystalline (nc-Si:H) as very attractive PV thin film absorber material by the Institute of Microtechnology (IMT of University of Neuchâtel) in 1994 have been opened new perspectives for thin film silicon PV [5]. Thus, the so-called "Micromorph" concept pioneered by IMT [6] consisting of an amorphous silicon top and a microcrystalline silicon bottom cell is today considered as one of the most promising thin film PV solar cell. Using such microcrystalline silicon as low bandgap sub-cell in multi-stacked junctions solar cells module powers in the range of 10 % efficiency and beyond are targeted by several companies. Although high lab cell efficiencies of 15 % have already been achieved [7, 8], it is still very challenging to transfer such small-area record efficiencies to large area modules with high performance. This combined with the high productivities of mass fabrication equipments are important key elements for a successful thin film line.

Just at this point OC Oerlikon entered in thin film PV in 2003 as equipment manufacturer formerly very active in the flat panel display field. Oerlikon Solar's strategy is to adapt PECVD KAI deposition systems, approved in mass production and developed originally for TFT display industry, to thin film silicon solar cells deposition based on amorphous and microcrystalline silicon [9-14]. To complete to a full thin film manufacturing line of amorphous and Micromorph modules additional production equipments like glass cleaning, laser patterning for the monolithic series connection, Low Pressure Chemical Vapor Deposition (LPCVD) of ZnO, wiring, module technique are addressed and developed at Oerlikon Solar as well. Light-trapping by front Transparent Conductive Oxides (TCO) plays a fundamental role in reducing the silicon absorber thickness especially the thicker microcrystalline silicon bottom cell. Thus, Oerlikon focuses on the development of LPCVD ZnO as a high-quality TCO with excellent light-trapping capabilities for the next generation of a-Si:H and Micromorph tandem modules.

In this paper the present status of Oerlikon Solar in the field of thin film silicon solar cells and modules is reported.

EXPERIMENTAL

The basis of Oerlikon Solar's silicon absorber deposition by the Plasma Enhanced Chemical Vapor Deposition (PECVD) is the KAI reactor and production system. To improve deposition rates for amorphous, and especially microcrystalline silicon [15], the display-type reactors were modified to run at a higher excitation frequency of 40.68 MHz. Developments are currently carried out in R&D reactors of different substrate size, like the KAI-M (520x410 mm) and the KAI-1200 (substrate size 1.25-1.30x1.1m^2). In the small reactors we are exploring

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the preparation processes both for the amorphous silicon [16, 17] and microcrystalline silicon cells [18]. The developed recipes are then transferred to the industrial size R&D KAI-1 1200 of 1.4 m^2 module area. For amorphous layers, cells and modules these recipes have already been successfully transferred to KAI-20 1200 production systems.

Based on IMT's modified Low Pressure Chemical Vapor Deposition (LPCVD) process we developed large-area R&D equipment (1.4 m^2) for the deposition of ZnO [19, 20]. ZnO layers have been deposited with excellent transmission, haze and low sheet resistance. Standard front TCO like Asahi U-type SnO_2, our in-house ZnO and commercial available large area SnO_2 has been used for our cells and modules. Due to the low process temperature involved, LPCVD ZnO is also suited for the back contact of cell and module developments. ZnO back contacts in combination with a white reflector reveal excellent light-trapping properties [9, 12, 13] and have been systematically applied in cells and modules presented here. The test cells were laser scribed to areas of well-defined 1 cm^2.

In order to evaluate the stabilized performance cells and mini-modules were light-soaked at 50°C under 1 sun illumination for about 1000 hours. Cells and mini-modules were characterized under AM 1.5 illumination delivered from double-source sun simulators and large area modules were characterized by flasher measurements in accordance with ESTI Laboratories of the JRC (Ispra) [14, 17]. The large area Micromorph tandem modules were characterized on the basis of large area space multi-junction modules.

Laser-scribing equipment for large-area modules (1.4 m^2) has been developed for all three pattern steps for each type of TCO [9]. Our laser processes are running at industrial relevant high speed, throughput and precision. Module stringing and encapsulation have been developed for 1.4 m^2 substrate area as well.

RESULTS AND DISCUSSION

Amorphous silicon R&D results

Figure 1 shows the absorption coefficient of a 2 μm thick amorphous silicon layer deposited in KAI PECVD system at a typical deposition rate of 3.5 Å/s in function of the photon energy. The measurements and analysis have been carried out by the internationally recognized Institute of Physics in Prague. The low defect absorption (α at 1.2eV) of around 0.1cm^{-1} and the Urbach energy of 44 meV reveal an excellent a-Si:H material quality that is usually obtained after intensive optimization in small area laboratory R&D PECVD systems. The defect absorption is a direct measure for the defect density of the layers and the Urbach energy is a rough indication for the disorder present in the amorphous network [21]. The optical gap E_{03} of 1.73 eV (which is close to the Tauc's gap) demonstrates that these layers consist not of wide bandgap low defect density material as often obtained by strong hydrogen dilution. The utilization of a low bandgap intrinsic amorphous material is an important issue to obtain high efficiency Micromorph tandem cells as the stabilized efficiency is strongly linked to a maximal a-Si:H top cell photocurrent. Such intrinsic amorphous layers with its low defect densities and low Urbach tail energies are incorporated in our cells and modules.

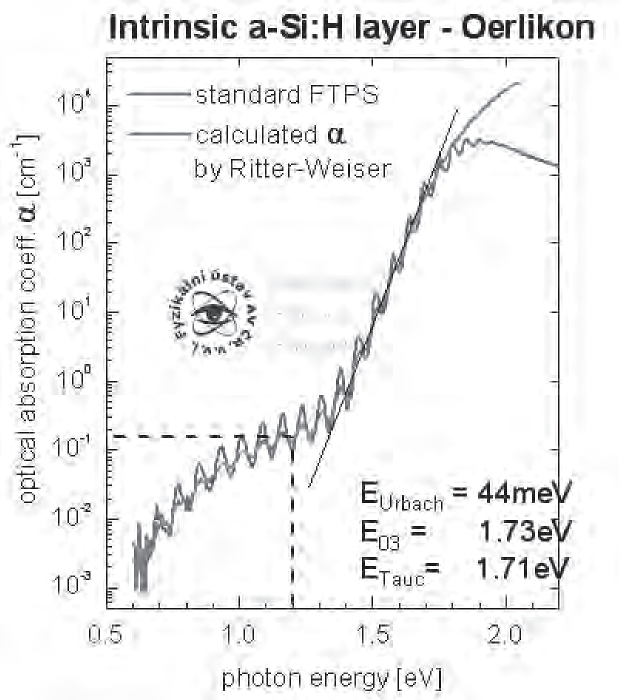

Figure 1: Optical absorption coefficient as a function of the photon energy measured for amorphous silicon layers deposited in R&D KAI PECVD systems. The Fourier Transform Photocurrent Spectroscopy measurements and analysis have been carried out by the Institute of Physics in Prague [22].

R&D results of KAI-M reactor

The deposition process of the amorphous p-i-n solar cell device has been developed and optimized in the KAI-M reactor. Meanwhile similar stabilized cell efficiencies to best lab Asahi U SnO_2 of around 8.6 % could be obtained even on in-house developed LPCVD ZnO, as given in Figure 2. These stabilized efficiencies demonstrate clearly that our single-chamber KAI process is state-of-the-art and fully equivalent to a multi-chamber p-i-n process.

R&D module results of 1.4 m^2 KAI-1 1200 reactor

The optimized KAI-M processes of single-junction a-Si:H p-i-n cells, as of Figure 2, have now been successfully transferred to the R&D KAI-1 1200 reactor (substrate area of 1.4 m^2). Since Asahi U is just available for R&D purposes and on small surfaces only commercial large area SnO_2 has been used. The use of a commercial TCO instead of Asahi U requires an adaptation of the i-layer thickness for highest stabilized efficiencies as demonstrated in a previous publication [17].

After a careful optimization we obtained a module with an initial output power of 128.8 W. Figure 3 reveals the AM1.5 I-V characteristics of this best single-junction p-i-n module resulting in an initial aperture efficiency of remarkable 9.63 %. Based on former results on mini-modules assuming a degradation of about 20 to 25% we extrapolate a stabilized output power of around 100 W after light-soaking for this R&D a-Si:H module.

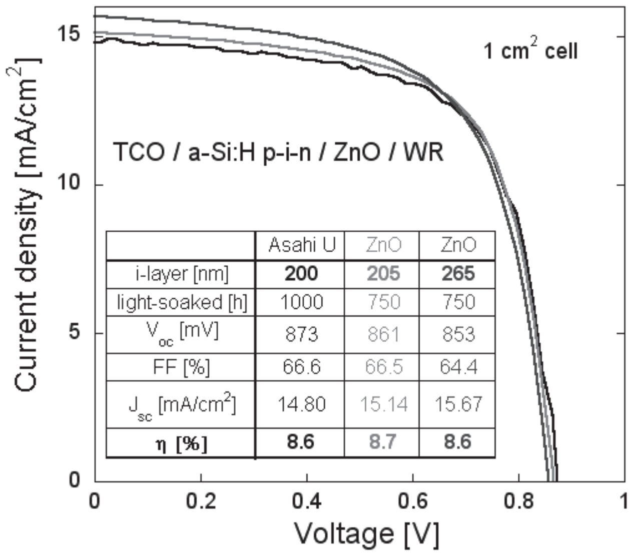

Figure 2: Best stabilized a-Si:H p-i-n test cells (1 cm²) on different front TCOs. The cells were developed in the KAI-M and light-soaked at 50°C and 1 sun [14, 17].

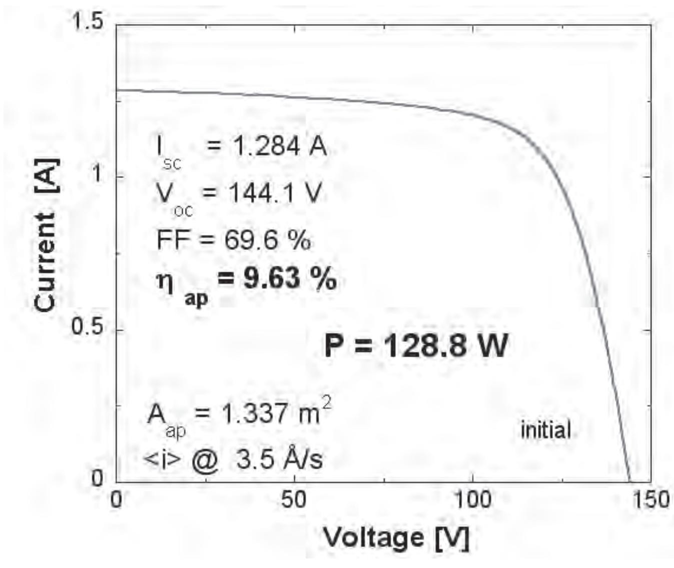

Figure 3: AM1.5 I-V characteristics of the best R&D 1.4 m² a-Si:H single-junction p-i-n module deposited on commercial front TCO. In the KAI-1 1200 system the intrinsic a-Si:H layer is deposited at a rate of 3.5 Å/s.

Results of KAI-20 1200 production system

Amorphous layers and modules have also been deposited in a production system KAI-20 1200 under production relevant conditions. This system consists of two process towers, 2 load-locks, one transfer chamber and an external robot for glass loading from cassettes (Figure 4). Each process tower is equipped with a stack of 10 plasma-box-reactors. The layers are processed in parallel at the same time in both stacks (2x10 reactors) at plasma excitation frequencies of 40.68 MHz as developed in the KAI R&D systems. The annual production capacity for amorphous modules of such a system having a footprint of only 6 m x 8.6 m is about 20 MW.

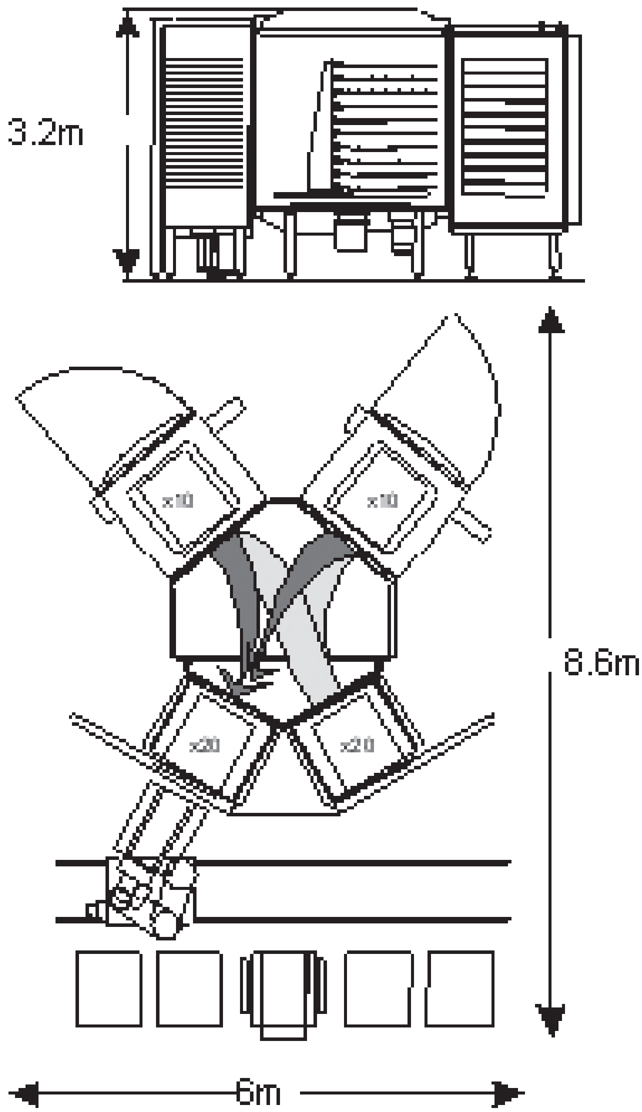

Figure 4: Schematic side and top view of a production KAI-20 1200 system (20MW/y production capacity for a-Si:H p-i-n modules).

Figure 5 represents results of amorphous silicon layers and modules obtained from the 2 stacks by using the parallel processing concept of the KAI-20 1200 production system. All box-to-box variations in both stacks of the deposition rates (top of Figure 5), the layer thickness uniformities (middle of Figure 5) defined as U=|(max-min)/(max+min)|, and the normalized amorphous silicon module powers (bottom of Figure 5) for the 1.4 m^2 substrates fall very close together. Hence, these results demonstrate clearly the high potential of the parallel processing KAI-20 1200 PECVD concept for PV mass production.

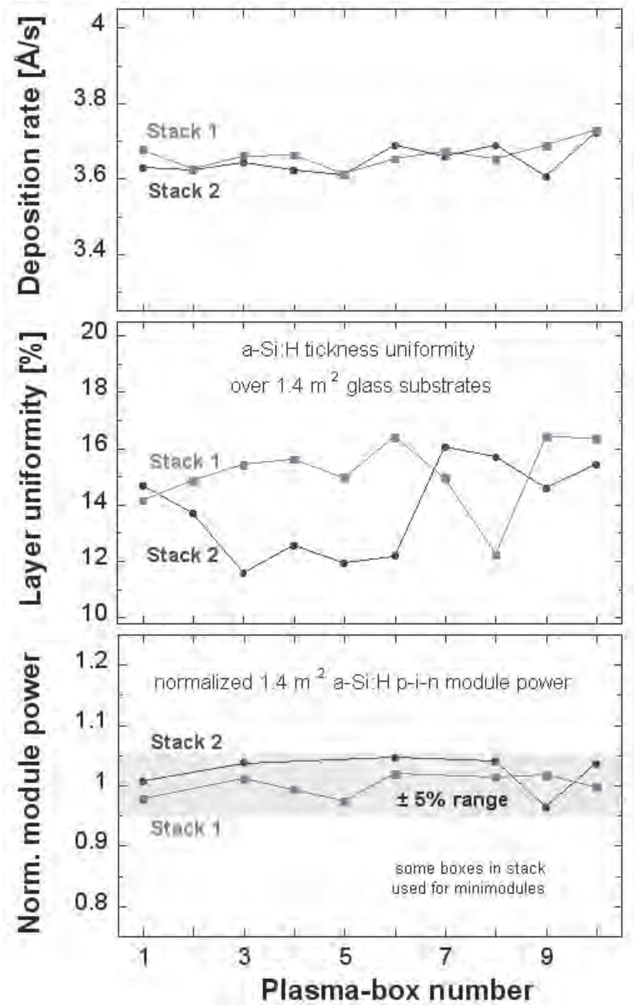

Figure 5: Distribution of deposition rates, amorphous silicon layer uniformities and normalized module output powers over the 20 plasma-boxes in the two stacks deposited in parallel in a KAI-20 1200 PECVD production system.

MICROMORPH TANDEM CELLS AND MODULES

R&D results of KAI-M reactor

a-Si:H / µc-Si:H Micromorph tandem test cells were developed with µc-Si:H bottom cells deposited at rates of around 5 Å/s. As light-trapping for µc-Si based solar cells is fundamental to minimize the Si absorber thickness the focus is on next-generation of front TCO, the LPCVD ZnO. In recent studies it has been reported that LPCVD ZnO has superior light-trapping capabilities for the µc-Si bottom cell compared to today available Asahi U and other commercial front TCO's [15, 23].

The present best stabilized Micromorph test cell efficiency on LPCVD ZnO is given by the AM1.5 I-V characteristics in Figure 6. These cells were developed in the KAI-M reactor whereas the bottom cell was deposited at a rate of around 5 Å/s. The front ZnO has been fully developed in-house and adapted to the Micromorph tandem cell.

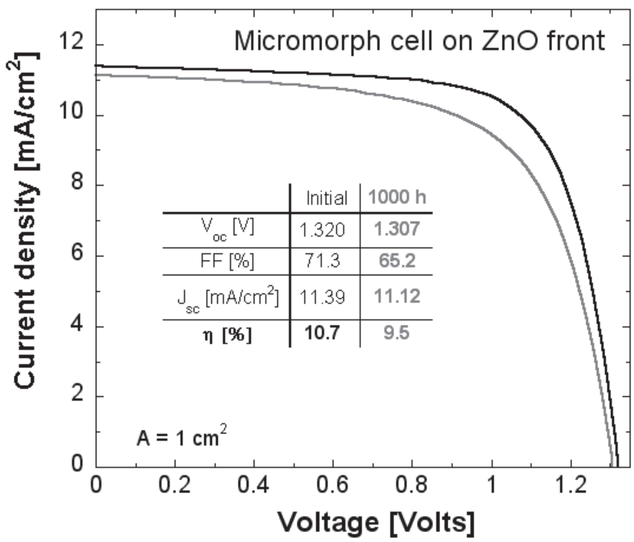

Figure 6: Micromorph tandem solar cell deposited on in-house developed LPCVD ZnO front TCO with a stabilized efficiency of 9.5 % (results of KAI-M reactor). Note, due to the enhanced light-trapping of LPCVD ZnO the µc-Si:H layer thickness can be kept below 1.5 µm for such a device.

Up-scaling in R&D KAI-1 1200 reactor

By up-scaling the small area KAI-M reactors processes and by improvements of the R&D KAI-1 1200 PECVD reactor system microcrystalline silicon layers with an excellent i-layer thickness uniformity of 9 % over the whole area of 125 cm x 110 cm (Figure 7) could be achieved at deposition rates of around 5 Å /s.

The crystalline fraction analysis by Raman spectroscopy mapping (Figure 8) reveals remarkable homogeneous microcrystalline layer over the whole substrate size. It has to be pointed out that the crystallinity varies just from around 50% to 65%, typical for material deposited close to the amorphous-microcrystalline transition zone and generally used in high-performance Micromorph tandem cells and modules.

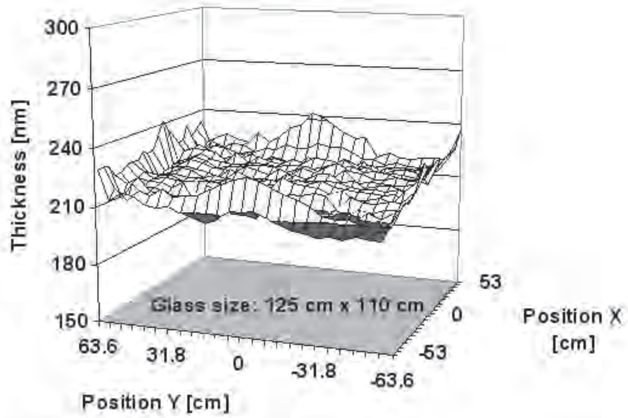

Figure 7: Thickness uniformity scan of a microcrystalline silicon layer over the entire glass substrate deposited in a KAI-1 1200 at rates of around 5 Å /s.

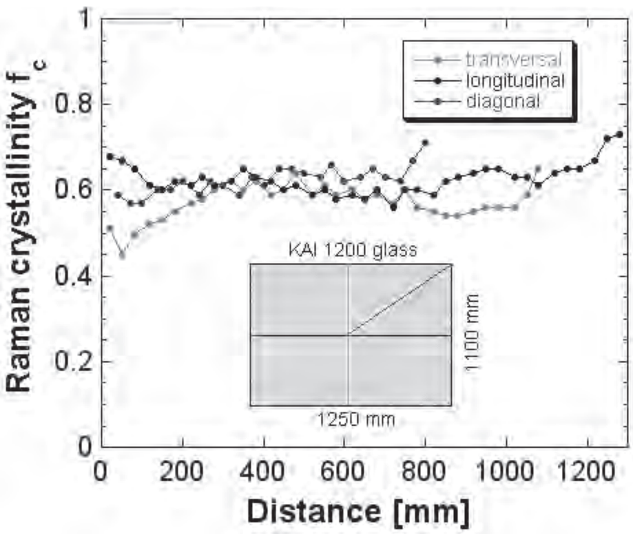

Figure 8: Raman crystallinity of microcrystalline layers over glass substrates of 1.4 m². The layer has been deposited at rates of around 5 Å/s in a R&D KAI-1 1200 reactor.

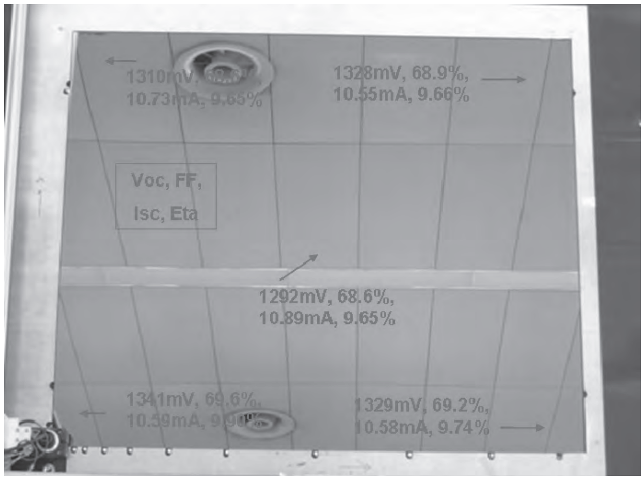

Figure 9: Photograph of a microcrystalline layer deposited on a 1.4 m² glass substrate. The achieved distribution of the open-circuit voltage, short-circuit current, fill factor and efficiency for Micromorph test cells of 1 cm² are added in red.

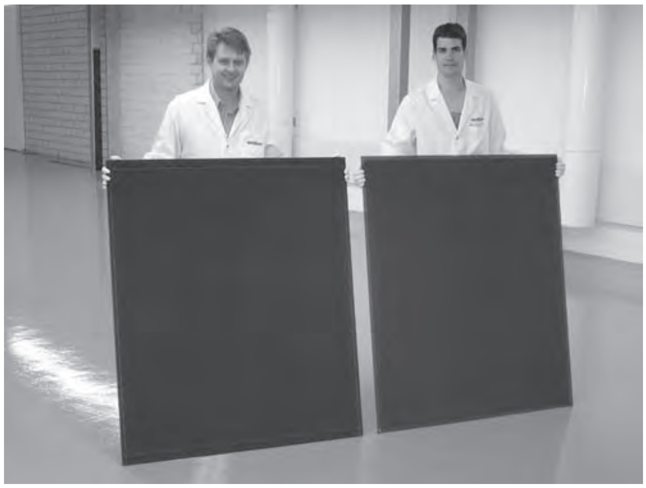

Figure 10: Photograph of a 1.4 m² Micromorph tandem module (left) and for comparison (right) a 1.4m² amorphous single-junction one.

Such microcrystalline layers have been then incorporated in Micromorph test cells of 1 cm². The uniformity of the test cell performances over the substrate of 1.4 m² is represented in Figure 9.

By further careful optimization and properly adapted current matching between top and bottom cells the tandems cells could be further improved. In a next step first 1.4 m² Micromorph tandem modules have been manufactured. Note the much darker optical appearance of a Micromorph tandem module (left side of Figure 10) as compared to an amorphous module (right side) indicating the enhanced light absorption and, hence, more complete utilization of the sunlight.

Figure 11 presents the I-V characteristics of our best 1.3x1.1 m² module reaching an initial output power of 128.4 W. This corresponds to an aperture efficiency of 9.6 %. Taking into account previous light-soaking results of mini-modules we assume a degradation of around 10 to 15% for this module. Therefore, we expect a stabilized output power for this Micromorph module of around 113 W.

Compared to the present small area status our 1.4m² Micromorph modules have still much room for further improvements. In the next step we will address this issue and optimize the module to higher output powers.

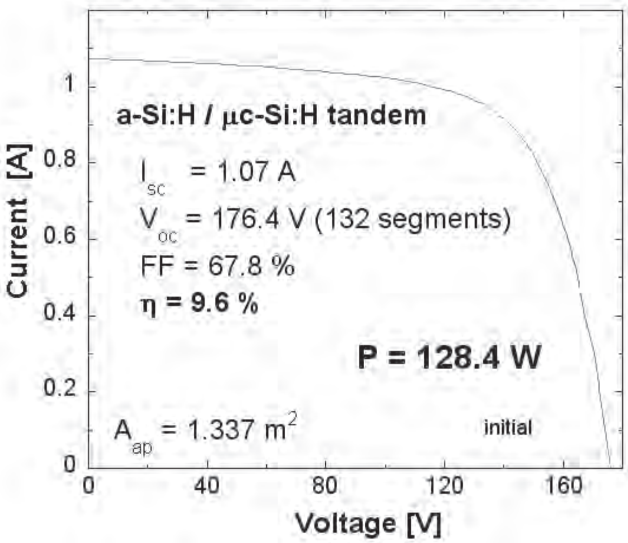

Figure 11: AM1.5 I-V characteristics of the best R&D 1.4 m^2 Micromorph tandem module deposited in the R&D KAI-1 1200 on commercial front TCO.

CONLUSIONS

Oerlikon Solar has demonstrated the capability of the KAI systems in obtaining high performance amorphous single-junction p-i-n modules on commercial TCO. On R&D level an amorphous module with an initial power of 128.8W has been realized on a 1.4m^2 substrate. This corresponds to a remarkable aperture efficiency of 9.63% for this amorphous single-junction module. The KAI 20-1200 production system has proven that the parallel processing concept is capable to obtain very narrow layer and module power distributions.

Moreover, for the first time full Micromorph large area 1.4 m^2 tandem modules have been fabricated in a R&D KAI-1 1200 resulting in a module power of 128.4 W, respectively an initial aperture efficiency of 9.6%. To obtain this result the microcrystalline uniformity of the thickness and crystallinity over the entire substrate has been considerably improved. Additional optimisation of deposition processes, cells and modules and the incorporation of LPCVD ZnO will further improve these efficiencies in the near future.

Looking at these R&D results and results of the mass production equipments thin film silicon PV lines of Oerlikon Solar will have a pronounced impact on cost reduction of future PV modules. Therefore, thin film silicon PV based on PECVD deposition technology can pave the path to economical large-scale application of PV.

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