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From R&D to Mass Production of Micromorph Thin Film Silicon PV

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Abstract

Developments in small R&D KAI\textsuperscript{TM} systems have resulted in NREL-confirmed stabilised cell efficiencies of 10.09 \% for amorphous p-i-n and 11.91\% for Micromorph tandem devices. Up-scaling of the processes to 1.4 m\textsuperscript{2} R&D equipment has so far lead to modules having initial powers of 139.1 W for amorphous silicon and 163 W for Micromorph tandem respectively. At present Oerlikon customers produced in total more than 4.5 million modules (a-Si:H p-i-n or Micromorph tandem) which all together correspond to a cumulative total power of over 450 MW\textsubscript{p}. Recently Oerlikon Solar introduced its new improved production concept, the so-called ThinFab\textsuperscript{TM}, which brings module production costs down to remarkable 0.5 \texteuro/W\textsubscript{p} at a capacity of 120 MW\textsubscript{p}.

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1. Introduction

Oerlikon Solar entered thin film PV in 2003 as an equipment manufacturer formerly very active in the flat panel display field. Oerlikon Solar’s strategy was to adapt the PECVD KAI™ (Plasma Enhanced Chemical Vapour Deposition) deposition systems, approved in mass production and developed originally for the TFT display industry, to thin film silicon solar cells. The base of Oerlikon’s thin film silicon solar device technology originates from the long-term research carried out at the Institute of Microtechnique of the University of Neuchâtel (IMT, now belonging to the EPFL). This research has included work on the well-known VHF-GD (Very High Frequency Glow Discharge) deposition technique [1, 2], the Micromorph (amorphous/microcrystalline silicon) tandem device concept [3, 4], as well as subjects regarding light trapping [5, 6]. Oerlikon Solar is developing and providing mass fabrication equipment including processes for thin film silicon manufacturing lines for module areas of 1.3 m x 1.1 m (1.4 m²). Recently Oerlikon Solar introduced the ThinFab™ concept which represents a turnkey mass production line for Micromorph modules [7]. The production output of one such a fab is 120 MWp/year at low module panel production costs of 0.5 €/Wp [7].

For the coming years the challenge of thin film silicon PV technology, which has a much higher cost reduction potential than conventional wafer-based PV, will be the improvement of module performance towards crystalline technology, leading the path to low-cost photovoltaic electricity generation. Therefore, in this paper an overview of the improvements in cell and module efficiencies in Oerlikon’s R&D is given with a successful transfer into production (e.g. [8]).

2. Experimental

The heart of Oerlikon Solar’s active silicon absorber layer deposition is the KAI™ PECVD reactor. To improve deposition rates for solar device-quality amorphous, and especially microcrystalline silicon [9-11], the display-type single-chamber reactors were modified to run at a higher excitation frequency of 40.68 MHz. R&D developments are currently carried out in reactors of different substrate sizes, like the KAI™-M (52 x 41 cm²) in Neuchâtel and the KAI™-1200 (substrate size 1.25-1.30 x 1.1 m²) in the pilot line in Trübbach.

The processes for the different layers involved in the device and modules are first explored in small KAI™-M reactors and then transferred to the industrial size 1.4 m² R&D KAI™-1 1200 reactor. Amorphous and microcrystalline layers, cell and module processes have already been successfully transferred to KAI™-20 1200 production systems, e.g. Ref. [8].

In order to obtain efficient light trapping in the thin film silicon cells and modules, an advanced front TCO is essential. It has been demonstrated that ZnO deposited by the LPCVD (Low Pressure Chemical Vapour Deposition) process has excellent light-trapping capabilities [5, 6]. Especially with respect to Micromorph tandem solar cells the silicon absorber layers have to be kept as thin as possible while maintaining the absorption potential, and hence the efficiency, high. In addition, due to the light-induced degradation (Staebler-Wronski effect) in amorphous silicon, efficient light management allowing the reduction of the layer thickness is fundamental for high stabilised performance. Therefore, Oerlikon Solar developed TCO deposition equipment for LPCVD ZnO based on IMT’s former process developments [12, 13]. As-grown surface-textured ZnO layers have been developed in Oerlikon Solar equipment with excellent uniformity, transmission, haze and low sheet resistance. Thanks to the low process temperature of around 200°C, LPCVD ZnO is also suited for the back contact of cells and modules. ZnO back
contacts in combination with a white reflector demonstrate excellent reflector properties [14-17] and have been systematically applied in all cells and modules presented here. The test cells were laser-scribed to well-defined areas of 1 cm².

In order to evaluate the stabilised performance, our devices were light-soaked at 50°C under 1 sun intensity and in open-circuit voltage conditions for 1000 hours. Cells were characterised under AM1.5 illumination delivered from double-source sun simulators and large area modules were characterised by flasher measurements. Especially the Micromorph tandems, but also the single-junction a-Si:H devices were characterised based on primary calibrated component reference cells that match the sub-cells well [18].

3. Results and discussion

3.1. R&D development in KAI™-M reactors

The LPCVD process for front ZnO has been carefully optimised with respect to high optical and electrical properties, its as-grown texture adapted for the high performance of the involved device, e.g. the single-junction a-Si:H or the Micromorph tandem.

All silicon deposition processes necessary for the amorphous and Micromorph tandem devices are developed and optimised in smaller R&D KAI™-M systems at Oerlikon Solar-Lab in Neuchâtel representing the research lab of Oerlikon Solar.

Figure 1 represents the I-V characteristics of our best light-soaked amorphous single-junction p-i-n cell measured by NREL (Golden, CO, USA). A remarkably high independently confirmed stabilised efficiency of 10.09% was achieved for this device [19], which demonstrates that Oerlikon Solar’s LPCVD ZnO (front and back contact) combined with amorphous silicon deposited in the industrial single-chamber KAI™ reactor are a very mature and advanced technology. This champion cell of 10.09% was reported in 2009 [19] and still holds the record for such a device [20].

This excellent amorphous single-junction cell forms the basis for the top cell of our Micromorph tandem developments in the KAI™-M. As the amorphous top cell contributes about two thirds to the overall Micromorph tandem cell efficiency, the result represented in Fig. 1 is of great importance. Furthermore, for the Micromorph tandem new doped layers based on microcrystalline silicon oxides have been developed and successfully implemented, especially in an intermediate reflector between the top and bottom cells.

Besides the previously discussed efforts to improve light trapping, we started to investigate the influence of a glass texture. In the framework of a joint research project with Corning Incorporated, glass substrates with new textures have been extensively investigated. Indeed, these new specialty glasses in combination with our LPCVD ZnO front contact improve the light trapping even further.

In the screening phase of this program, a large number of textured glass samples were characterised. Examples of external quantum efficiency (EQE) results are shown in Fig. 2. Typically there is little difference seen in a-Si:H cell EQE between flat glass reference samples and textured glass test cells, but large differences in μc-Si:H cell performance can be observed. The superstrates which have been utilised to fabricate the tandem champion cells reported below (type A) have measured bottom cell current
improvements estimated from the EQE data of about 8% relative to flat-glass references. As can be seen in Fig. 2, other textured glass samples (such as type B) have shown even larger EQE current improvements of at least 12% and are under investigation for further cell efficiency improvements.

Fig. 1. I-V characteristics of the best stabilised amorphous silicon single-junction test cell. The cell was deposited in a R&D KAI™-M system (52 x 41 cm² substrate area). The superstrate is a high-quality flat glass coated with LPCVD ZnO. A special AR concept has been applied which reduces the optical reflection losses at the air-glass interface [19].

Fig. 2. The external quantum efficiency of cells fabricated using two candidate textured glass designs showing significant μc-Si:H cell current gains of 8% (type A) to 12% (type B) relative to flat-glass reference cells.
Optimisation of cells was then carried out on selected textured superstrates. A doped silicon oxide intermediate reflector was also incorporated into the cell. This design takes advantage of the increased $\mu$-Si:H cell current generation capability and maximises overall stable cell efficiency, which has greater value than simply enabling cost reduction through thinning the $\mu$-Si cell. As reported last year, cells were fabricated and characterised as having initial efficiencies of 13.0 % and stabilised ones of 11.9 % without an antireflective coating [21]. The stabilised performance given in Fig. 3 was verified at NREL and reported to be the highest stabilised a-Si:H/$\mu$-Si:H tandem cell performance published to date [20]. The addition of a broad-band anti-reflection coating (ARC) would raise this efficiency to values above 12 % and, hence, the absolute efficiency gain of the Micromorph tandem compared to the record amorphous single-junction is in the range of 2 % absolute in R&D at present.

Subsequently, further optimisation of cells on these same substrates was carried out and additional performance enhancements demonstrated. This has been accomplished by improvements of the two junctions and better-optimised TCOs in combination with the developed textured glass substrate. In Fig. 4 the best cell performance to date is shown, having an initial efficiency of 13.5%, again without an antireflective coating [22].

In summary, all steps (glass texture, LPCVD ZnO processes for front and back contact, amorphous and microcrystalline $p$, $n$ and $i$-layers deposited by PECVD in KAI™-M reactors, control of interfaces, etc.) for the fabrication of high-performance amorphous silicon single-junction and Micromorph tandem devices have been significantly improved on small-area cells and in small-area equipment, as has been demonstrated by the remarkably high stabilised efficiencies independently confirmed by NREL.
Fig. 4. A comparison of the best initial efficiency results obtained to date with a typical best initial efficiency of a cell previously reported. The initial efficiency has been improved from 13.0 % to a new initial efficiency of 13.5 %. Note that this device does not utilise an antireflective coating.

3.2. Up-scaling: R&D development in KAI™-1200 reactors

Next, the results obtained in small-area equipment were transferred as closely as possible to industrial size (1.4 m²) LPCVD reactors (TCO-1200) for the ZnO deposition and PECVD reactors (KAI™-1200). The monolithic series connection of the segments of the 1.4-m² modules was carried out by laser patterning using the laser scribing system LLS-1200 developed by Oerlikon Solar. Figure 5 shows a photograph of an amorphous p-i-n and a Micromorph tandem 1.4-m² module. Note the much darker optical appearance of the Micromorph module (left in Fig. 5) as compared to the amorphous module (right), revealing the enhanced light absorption and, hence, more efficient utilisation of the sunlight.

Fig. 5. Photograph of a 1.4 m² Micromorph tandem module (left) and for comparison (right) a 1.4 m² amorphous single-junction module which both have been fully fabricated in the R&D pilot line at Oerlikon Solar in Trübbach.

Following this transfer strategy, we succeeded in our pilot line in Trübbach to fabricate an amorphous silicon p-i-n single-junction 1.4 m² R&D module with an initial output power of 139.1 W. The present initial output power as given in Fig. 6 has been slightly improved by 1.9 W since our recent publication in September 2010 [23]. Taking into account only the active area this module results in an active large-area
efficiency of a remarkable 10.51%. A relative light-induced degradation of 17.2 % has been determined for corresponding 10 x 10 cm² mini-modules enabling us to estimate the stabilised output power of this a-Si:H module to reach 115 W. This corresponds to a stabilised active-area module efficiency of remarkable 8.7 %. Thus, the transfer from small-area 1 cm² test cells to the 1.4 m² R&D module is linked to a relative loss in efficiency of at present only 13.8 %. Factors responsible for this reduction can be found by, for example, non-uniformities of involved layers, ohmic losses in front and back TCO, ohmic losses in monolithic series connection, etc.

Fig. 6. I-V characteristics and parameters of a 1.4 m² a-Si:H single-junction module fully manufactured in the R&D pilot line of Oerlikon Solar in Trübbach [23].

As in the case of the optimisation in the KAI™-M reactor, the processes used in the single-junction amorphous module serve as a basis for the development of the full-size 1.4 m² Micromorph tandem modules. The a-Si:H absorber layers were further optimised and adapted for implementation as top cells in the Micromorph tandems using flat glass substrates. The goal is similar: a reduced light-induced degradation in combination with a high stabilised Micromorph module power.

Fig. 7. I-V characteristics and parameters of a 1.4 m² a Micromorph module fully manufactured in the R&D pilot line of Oerlikon Solar in Trübbach [23].
Figure 7 represents the AM1.5 I-V characteristics of our record 1.4-m² R&D Micromorph module recently presented [23]. A high initial module output power of 163 W has been achieved, which corresponds to an active-area efficiency of 12.2 %. Large-area indoor light soaking was applied and a stabilised output power of 143 W was obtained for this module. This corresponds to a relative degradation of 12.3 % and leads to an active-area module efficiency of 10.7 % after light soaking.

3.3. KAI™-20 1200 production tool

Finally, the developed processes for amorphous and microcrystalline layers and modules from the R&D pilot line in Trübbach were transferred to the KAI™-20 1200 production systems of Oerlikon’s customers. Such a system is schematically shown in Fig. 8. KAI™-20 1200 systems are already well-proven in mass production for both a-Si:H p-i-n as well as Micromorph tandem modules and are running 24 hours a day, 360 days a year with a high uptime [8]. This system consists of two PECVD process towers, 2 load-locks, one central transfer chamber and an external robot for glass loading from cassettes. Each process tower is equipped with a stack of 10 plasma-box reactors. The layers are processed, as developed in the KAI™ R&D systems, in parallel in both stacks (2x10 reactors) at a plasma excitation frequency of 40.68 MHz. The whole KAI™-20 1200 PECVD production system has one common gas delivery system including the mass flow controllers and a process pump system. The annual production capacity for amorphous modules of such a system having a footprint of only 6 m x 8.6 m is 20 MW/y. Up to now, Oerlikon customers manufactured in total more than 4.5 million amorphous and/or Micromorph 1.4 m² modules in their fab lines using such KAI™-20 1200 deposition systems. All modules produced by KAI systems at different customer’s sites have a cumulative total module power of > 450 MWp [24].

Fig. 8. Footprint (left) and side view (right) of a production KAI™-20 1200 PECVD system.

Recently at the 25th EU-PVSEC at Valencia (2010), Oerlikon Solar introduced its new generation module production line. The so-called ThinFab™ [7] leads, at a 120 MWp output capacity, to a reduced production cost structure of only 0.5 €/Wp due to many optimisations (e.g. by an increased throughput, improved flow of material, rebuilt and revised KAI™ production system, small footprints, etc.) learned from our previous installed production lines.
4. Conclusions

The KAI™ single-chamber reactors have demonstrated high-performance cells and modules. In small-area KAI™-M reactors a stabilised champion cell efficiency of 10.09% for a single-junction amorphous cell has been achieved thanks to our LPCVD ZnO with its excellent light-trapping properties as front and back contacts [19]. On the basis of the excellent amorphous cell process and by the use of textured glass substrates developed by Corning Inc. in the frame of a common project, a Micromorph tandem champion cell with a stabilised efficiency of 11.91% was realised [21]. It is noted that both stabilised cell efficiencies have been independently confirmed by NREL. Meanwhile, by further optimisation, we have improved the initial efficiency from 13.0 to 13.5% for a Micromorph test cell [22] and we expect a stabilised efficiency of above 12% [25]. As the present Micromorph test cells have been obtained without an AR coating, we believe we can soon reach the benchmark of 13% for the stabilised test cell efficiency with the Micromorph tandem concept. The subsequent up-scaling of the small-area processes in the R&D pilot line led to a 1.4 m² amorphous module with an output power of 139.1 W and of 163 W for a Micromorph tandem module before light soaking. Taking the module area into account, high active-area efficiencies of 10.51% and 12.2% have been achieved for the amorphous and the Micromorph large-area module [23]. Based on the known degradation behavior of small modules, we estimate a stabilised module output power of 115 W for the amorphous single-junction 1.4 m² module (corresponding to a module efficiency of 8.0%). A stabilised output power of 143 W has been obtained for the 1.4 m² Micromorph module after large-area indoor light soaking, which corresponds to a stabilised overall module efficiency of 10.0%. These remarkable module results clearly demonstrate the high potential of the processes and systems of Oerlikon Solar. The high productivity of Oerlikon KAI™ PECVD machines has the strength to minimise cost and risk of a thin film silicon PV production line. Oerlikon manages all process steps from glass cleaning up to the fabrication of large-area modules. At present, customers using Oerlikon Solar systems have produced altogether more than 4.5 million modules, which represent a cumulative power of more than 450 MWp. Recently Oerlikon Solar introduced its new improved production fab concept, the so-called ThinFab™, which brings total module production costs down to remarkable 0.5 €/Wp at a 120 MWp output capacity [7]. Just this month Oerlikon Solar announced a first order of a 120 MWp ThinFab™ [24].

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