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Achievements and challenges in thin film silicon module production

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ABSTRACT

This paper addresses the achievements and challenges in a-Si:H/μc-Si:H tandem solar cell technology including production aspects. As an example we show figures of the module production at Masdar PV, with module conversion efficiencies reaching 10%. The process integration was supported by PVcomB, namely, by developing improved PECVD processes and transferring them to Masdar PV. The important role of the TCO substrate for producing high-efficiency modules at lowest possible costs is discussed. We show the results of tandem cells on thermally annealed ZnO:Al substrates, resulting in an improvement of 0.4–0.5% (abs) as a result of the TCO annealing, reaching a stable efficiency of 12.1% for a 1 cm² solar cell and 11.6% for a mini module. The challenges in developing thin film silicon solar modules with higher efficiency than presently reached are discussed.

1. Introduction

The photovoltaic (PV) market has grown continuously over the past years with a cumulated capacity installed worldwide reaching 100 gigawatt-peak to date [1]. As a consequence, module sales prices have dropped tremendously. A trend that is expected to continue, driving module prices and production costs further down. Crystalline silicon (c-Si) based modules are dominating the market with a share of more than 85% [2]. Thin film modules based on amorphous silicon (a-Si:H) and microcrystalline silicon (μc-Si:H), copper–indium–gallium–diselenide (CIGS), or cadmium–telluride (CdTe) are considered an alternative to reduce costs, energy pay-back time, and the consumption of raw materials. With conversion efficiencies of commercial modules being in the range of 8–13% as compared to 14–20% for c-Si based modules, however, these modules need lower production costs in order to compensate for higher PV system mounting costs.

Thin-film silicon modules, such as a-Si:H based modules, are an ideal option for a future terawatt PV market since such modules are based on non-toxic materials and all raw materials are available in practically unlimited quantities [3]. They are ideal for application in large-scale power plants, preferably in hot regions. The lower mounting costs for such power plants are more favorable for modules with lower efficiency. For application in hot regions with higher module operating temperatures the energy output of a-Si:H based module is favorable with respect to c-Si based modules due to the lower temperature coefficient [4]. Additionally, the light-induced degradation of such modules is lower at elevated temperatures [5,6]. Moreover, thin film silicon modules are ideal candidates for building-integrated photovoltaics (BIPV) due to the homogeneous, dark appearance and the flexibility in module size up to 5.7 m^2. The low temperature coefficient favors high output in BIPV applications. The possibility in producing semi-transparent modules by laser scribing, and the use of non-toxic raw materials make thin film silicon attractive for BIPV.

This paper addresses a-Si:H/μc-Si:H tandem junctions. An introduction and overview to this technology can be found in [7–9]. After the first a-Si:H/μc-Si:H ("micromorph") solar cells were reported in 1996 by Meier et al. [10], Kaneka was the first company developing high efficiency tandem and triple cells with currently up to 12.3% stable efficiency [11–13] and started large-scale module production around ten years ago [14]. In the past few years many companies established production lines with module efficiencies continuously being increased to currently up to 9–10% in production average and module size up to 5.7 m^2 [15]. Prototype modules on production scale reach stabilized efficiencies close to 11% based on a tandem junction [16,17] or a triple junction [18]. These values are remarkably close to the best solar cell efficiencies of up to 12.3% obtained in laboratories with tandem junctions [11,19–23] and, recently reported by LG Electronics, 13.4% with an a-Si:H/μc-Si:H/μc-Si:H triple junction [18,24]. It demonstrates the mature processes and production equipment benefitting from the flat panel display industry, on the one hand side, but also the urgent need to push up the laboratory efficiencies on the other hand side. The low module efficiency is the most severe restraint and a potential show stopper for this technology if no new concepts for higher efficiencies are developed.

As one of the largest producers of a-Si:H/μc-Si:H tandem modules, Masdar PV GmbH operates a sunfab-type production

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line from Applied Materials with a name plate capacity of 95 MW_p. With a-Si:H single junction based modules reaching stabilized efficiencies of 8% produced first, the production was changed to a-Si:H/μc-Si:H tandem modules in August 2011. As a cooperation partner of Masdar PV the Competence Center Thin-Film and Nanotechnology for Photovoltaics Berlin (PVcomB) offers a platform for technology development and process transfer for thin-film PV modules. For this purpose two R & D lines for a-Si:H/μc-Si:H and CIGS based modules on $30 \times 30\ cm^2$ are operated. In this paper we present results from process transfer of a-Si:H/μc-Si:H modules from PVcomB to production at Masdar PV yielding modules with 10% stable efficiency on 5.7 m² size. As an example for joint R & D work on solar cells with higher efficiency we present results of tandem cells on thermally annealed aluminum doped zinc oxide (ZnO:Al). We conclude with discussing the perspectives for a-Si:H/μc-Si solar cells and modules.

2. Process transfer from PVcomB to Masdar PV

The silicon deposition equipment of the a-Si:H/μc-Si:H tandem lines at PVcomB and Masdar PV are plasma-enhanced chemical vapor deposition (PECVD) cluster tools from Applied Materials, AKT1600 (Gen 2) and AKT60K (Gen 8.5), respectively. Both are operated at a plasma excitation frequency of 13.56 MHz. The production line consists of four AKT60K cluster tools with seven deposition chambers each and a substrate size of 5.7 m^2. Generally, one tool is used for deposition of the a-Si:H top cell and three tools are used for the μc-Si:H bottom cell. The use of similar PECVD platforms facilitates fast process transfer from PVcomB to the production at Masdar PV.

At PVcomB the fully automated AKT1600 cluster tool is equipped with three process chambers for a substrate size up to $30 \times 30\ cm^2$. This allows for separation of the deposition of doped and intrinsic materials and processing of 6–8 tandem modules per day. In-situ and remote plasma cleaning by NF_3 is used for chamber cleaning. To support the PECVD process development, a number of in situ diagnostic tools are installed, such as optical emission spectroscopy (OES) and mass spectrometry (residual gas analyzer, RGA). Aluminum doped zinc oxide (ZnO:Al) front and ZnO:Al/Ag back contacts are deposited in an in-line sputter tool from Leybold Optics (A600V7). A laser patterning system from Rofin-Baasel is used for scribing of 1 cm^2 cells and mini modules. For *I–V* measurements of laser scribe defined solar cells and modules, carefully calibrated dual-source class AAA solar simulator (Wacom WXS-155 S-L2) and a class AAA Xenon flasher (h.a.l.m.) are used. The flasher is equipped with halogen lamps to bias the Xenon lamp spectrum for accurate tandem measurements. Solar cells and modules are light soaked in a temperature controlled (50 °C) light-soaking bench at 1 sun, with a light source calibrated to obtain the AM1.5 a-Si:H top cell current. Generally, cells and mini modules are light soaked for one week (168 h), after which they are close to stabilization.

In order to keep track on the performance of the equipment and processes and for having a stable reference process for experiments, an a-Si:H/μc-Si:H baseline process is maintained at PVcomB. For this baseline commercial SnO_2:F (FTO) coated 3.2-mm-thick low-iron float glass, the same as used in production at Masdar PV, is used as the transparent conducting oxide (TCO) substrate material. Intrinsic a-Si:H and μc-Si:H layers for solar cells are deposited at substrate temperatures of approximately 200 °C at rates of 0.22 and 0.45 nm/s, respectively. The i-layer thickness of the top and bottom cells is 270 nm and 1800 nm, respectively. The *IV* parameters of solar cells made with the baseline process are shown in Fig. 1. The efficiency is distributed in a narrow range around 11.5% (initial), and 10.0% after light soaking. The results shown in Fig. 1 will be further discussed in Section 3. Encapsulated $30 \times 30\ cm^2$ baseline modules (756 cm² aperture area) are routinely made with an initial efficiency of 10.6% (J_{sc}=10.6 mA/cm², V_{oc}=1414 mV, FF=70.5%) and 9.5% (J_{sc}=10.3 mA/cm², V_{oc}=1385 mV, FF=66%) after light soaking. Recently, we optimized the baseline process introducing 230 nm and 1600 nm as the top and bottom i-layer thickness, respectively, yielding slightly improved performance. On ZnO:Al front TCO such $30 \times 30\ cm^2$ modules reach an initial efficiency of 11.7% and 10.3% after light soaking (Fig. 2). Here, a textured light trapping anti reflection (AR) foil from DSM (former Solarexcel) [25] was applied on the front side of the glass.

At Masdar PV the stabilized total-area efficiency of 1.4 m² modules could be increased from below 9% to close to 10% in

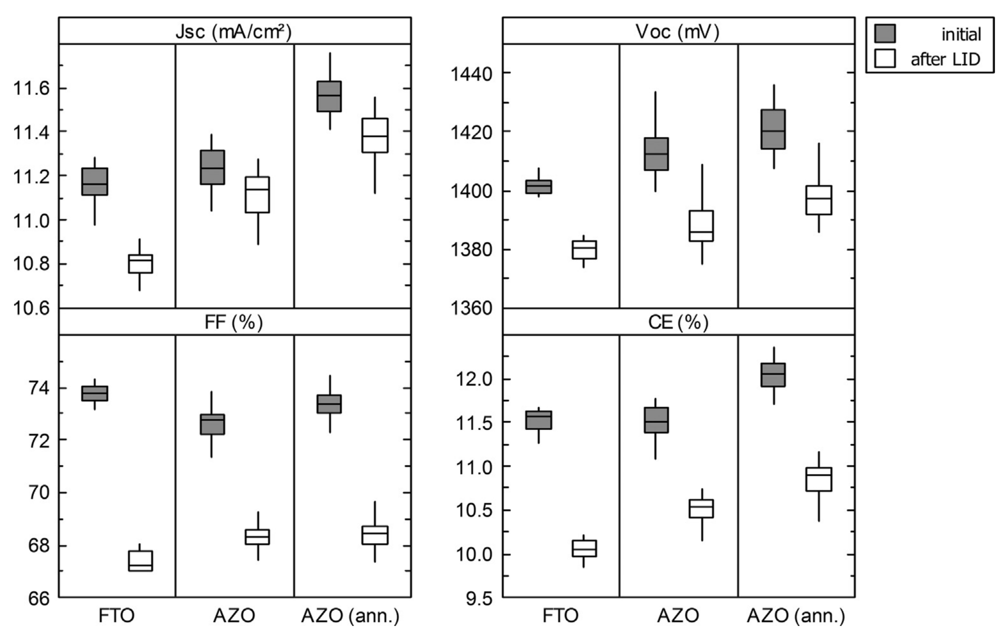

Fig. 1. *IV* parameters of a-Si:H/μc-Si:H 1 cm^2 solar cells on different TCOs (compare Table 1): Commercial FTO, industrial AZO type 1, annealed AZO type 1. The same silicon layer thicknesses and deposition rates as indicated in the text are used for cells on all TCOs. Data is shown initially and after one week of light soaking (1 sun, 50 °C). Boxes contain 50% of the data points around the median value (indicated by a line), the whiskers cover 80% of the data points.