



Recent advances and remaining challenges in thin-film silicon photovoltaic technology

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This contribution reviews some of the latest achievements and challenges in thin-film silicon photovoltaic (PV) technology based on amorphous and nanocrystalline silicon and their alloys. We address material and device developments, including (i) improved plasma deposition processes to achieve high-quality dense absorber materials; (ii) absorber layers based on silicon tetrafluoride, which lead to enhanced absorption in the near-infrared and yield outstanding short-circuit current densities; (iii) dedicated optimization of the interfaces and device architecture, as well as (iv) enhanced light harvesting by means of multi-scale textured substrates and reduced parasitic absorption in the non-active layers. This paper will describe how, by combining all of these advances along with precise control of plasmas over large areas, key results have been achieved in recent years, at both the cell and large-area module level, with stabilized efficiencies of over 13 and 12%, respectively.

Introduction

Thanks to a continuous and remarkable growth rate over the last 10 years, photovoltaics (PV) have now exceeded 100 GW-peak of worldwide cumulative installed capacity [1]. PV is thus well on its way to becoming a conventional source of electricity, with today's very low module prices making it appealing to investors and private individuals. Crystalline silicon (c-Si) dominates the market, with thin-film technologies based on cadmium-telluride (CdTe), copper–indium–gallium–selenide (CIGS) and silicon taking around 10% of the market. Thin-film silicon technology presents numerous advantages, including: (i) the raw materials are abundant and non-toxic [2], (ii) rigid or flexible – and possibly lightweight – substrates can be used [3], (iii) its uniform appearance is well suited for building integration [4,5]. Thin-film silicon modules can also be easily patterned by laser, allowing various degrees of transparency. The major drawback of thin-film silicon technology is its lower conversion efficiency, which is in the range of 7–10% for commercial modules versus 15–21% for those based on c-Si.

Thin-film silicon devices are based on either amorphous silicon (a-Si:H) or microcrystalline (also called nanocrystalline) silicon ($\mu\text{c-Si:H}$). Because of its amorphous network, a-Si:H is more defective than c-Si and suffers from a performance degradation upon light soaking, known as the Staebler–Wronski effect (SWE) [6]. This degradation phenomenon is much less severe in $\mu\text{c-Si:H}$, which is a mixed-phase material composed of interconnected nanocrystalline grains (usually less than 30 nm in size) embedded in an amorphous matrix. During $\mu\text{c-Si:H}$ layer growth, large conglomerates of nanocrystals form, with typical sizes on the order of hundreds of nanometers. This complicated, still fascinating, material is not yet fully understood. Its microstructural and electronic properties depend in a complex manner on the deposition parameters and on the structure of the substrate. This explains why a major part of the research efforts during the last 10 years has focused on further understanding thin-film silicon material properties and growth. Emphasis was also placed on developing thinner devices, which reduces not only deposition time and thus production costs, but also light-induced degradation (LID) in a-Si:H, since the thicker the absorber layer, the larger the impact of the SWE on solar cell performance. It must also be mentioned that doped layers have poor electronic properties. Hence only intrinsic,

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that is undoped, material can be used as the absorber, with still a modest minority-carrier lifetime. Consequently, the use of p-i-n junctions with an electric field extending throughout the device is required, and not p-n junctions like most other PV technologies [7].

Thin-film silicon solar cells and modules can be made in two different configurations: the superstrate configuration, also called 'p-i-n' in accordance with the sequence of layers, or the substrate ('n-i-p') configuration. In superstrate configuration, light enters through the substrate, typically glass, while in the substrate configuration, light enters through the last layer to be deposited (light always enters through the p-type layer, because of the poorer mobility of holes). Whereas glass is most widely used in the superstrate configuration, a large variety of substrates have been employed for the substrate configuration, including stainless steel and flexible foils such as polyethylene naphthalate (PEN) or polyimide. This latter polymer was, for example used by United Solar Ovonic Corporation, one of the pioneers in the development of flexible thin-film silicon modules, fabricated by roll-to-roll processing [7–9]. Flexible modules present distinctive advantages for building integration (BIPV) with their light weight, a certain freedom in design for, for example curved building parts, and reduced mounting costs. Indeed, these products can be directly bonded to the roof or directly laminated with building elements [10]. However, the BIPV market has not yet developed as expected and many manufacturers of flexible thin-film silicon solar cells had to stop their production.

The goal of this contribution is to describe the latest advances in thin-film silicon PV research, with, first, a review on state-of-the-art efficiencies of solar cells and modules. Then, the paper will depict how a high-quality dense absorber material, together with a dedicated optimization of the interfaces and device architecture, is mandatory to reach high conversion efficiencies. Furthermore, routes on how to increase the short-circuit current density in such thin solar cells will be discussed in view of: (1) the use of silicon tetrafluoride (SiF_4), leading to enhanced absorption in the near-infrared, as well as (2) the development of multi-scale textured substrates and more transparent non-active layers.

State-of-the-art efficiencies

Nowadays, mainstream thin-film silicon research deals with multi-junction solar cells, as obtained by the monolithic interconnection of at least two sub-cells. The 'micromorph tandem' [11] is, for example obtained by combining an a-Si:H top cell with a $\mu\text{c-Si:H}$ bottom cell, as sketched in Fig. 1 in the superstrate configuration. Transparent conductive oxide (TCO) materials – typically tin oxide (SnO_2), zinc oxide (ZnO) or indium tin oxide (ITO) – are used as front electrodes. A metallic electrode or a TCO material and a dielectric white reflector are used in the back. An intermediate reflecting layer (IRL) is typically implemented between the top and bottom cells as sketched in Fig. 1. This layer, generally based on silicon oxide (SiO_x) material, reflects light into the top cell, thanks to its lower refractive index (typically $n \sim 1.7\text{--}2$ at 600 nm) compared to that of silicon ($n_{\text{Si}} = 3.8$), allowing for a thinner top cell. However the IRL needs to be conductive enough and as transparent as possible to reduce absorption losses. As will also be discussed later in this contribution, certain SiO_x layers fulfill these conditions and furthermore can be mixed-phased, with the alloying

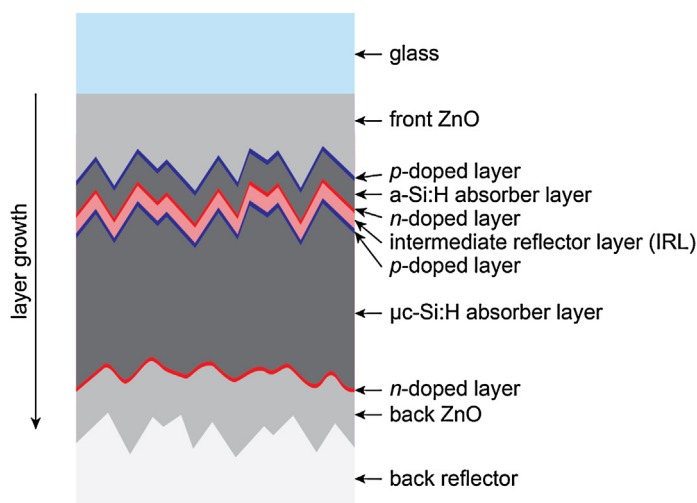


FIGURE 1

Schematic of a typical amorphous (a-Si:H)/microcrystalline silicon ($\mu\text{c-Si:H}$) (micromorph) tandem in the superstrate configuration. Light enters through the glass and front electrode, here composed of zinc oxide (ZnO). The a-Si:H cell is the top cell, whereas the bottom cell is composed of $\mu\text{c-Si:H}$. An intermediate reflecting layer (IRL) is typically implemented between two cells to increase the current density of the top cell. ZnO is then used as the back electrode in combination with a reflector.

taking place in the amorphous phase of the layer, while silicon crystallites evolve as filaments [12]. Much work has been undertaken on the topic of IRLs (see, e.g. [13–15]), with the latest developments focusing on asymmetric morphologies in both the superstrate [16,17] and substrate [18] configurations, to optimize both light trapping and absorber layer growth.

Thin-film silicon is particularly suitable for multi-junctions as it offers a wide range of bandgaps (see, e.g. [19] for a-Si:H). Multi-junctions, also widely used in other PV technologies such as those based on III-V compounds (see, e.g. [20]), enhance efficiency by either extending or more efficiently using the absorbed light spectrum [21,22]. For thin-film silicon, the use of the multi-junction configuration also generally leads to reduced LID of the solar cell performance, thanks to the use of thinner a-Si:H absorber layers. Furthermore, the multi-junction configuration not only increases open-circuit voltage (V_{oc}) values through the monolithic interconnection, it also reduces resistive losses in the electrodes – and therefore increases the fill factor (FF) – because of the lower short-circuit current density (J_{sc}). Multi-junctions thus allow for the use of more resistive, and hence more transparent, electrodes.

The intense research efforts of the last years have recently led to novel record certified stabilized device efficiencies for both single-junction [23–25] and multi-junction solar cells [26], as reported in Table 1. The highest stabilized certified efficiency now stands at 13.4% for a small-area cell in the triple-junction configuration [27], while the best micromorph tandem modules now reach over 12% stabilized efficiency [28], an impressive result on 1.4 m^2 . Furthermore, it was already demonstrated that conversion efficiencies of over 10% could be maintained, in superstrate configuration, over areas as large as 5.7 m^2 [29]. Table 1 hence demonstrates that the continuous progress achieved over the last years has permitted to reduce the gap between the efficiencies of solar cells ($\sim 1\text{ cm}^2$) and modules ($>1\text{ m}^2$). Still, commercial

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