



Tandem amorphous/microcrystalline silicon thin-film solar modules: Developments of novel technologies

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ARTICLE INFO

Keywords:

Solar cell
Solar module
Photovoltaic
Amorphous silicon
Microcrystalline silicon
Thin-film
Tandem

ABSTRACT

Tandem amorphous/microcrystalline silicon thin-film solar modules with large-area panels, high energy yield, low light-induced degradation, and high damp-heat reliability are commercially manufactured. Several novel technologies are researched, developed, and introduced into the production line. These include (1) special passivation to increase the shunt resistance by an order of magnitude and enhance modules' low-light performance; (2) large-area uniformity of transparent-conducting-oxide films and lamination processes to reduce the problem of cells' current and segments' voltage mismatches; (3) segment laser scribing to enable the modules' output voltage to 70 V and 30 V; (4) novel front reflective layers to enable customized color appearance; and (5) special 4-step laser scribing to produce see-through modules of purple, dark blue, light blue, silver, golden, orange, red wine, and coffee colors. Two new types of modules: low-voltage modules and see-through color modules are successfully developed, manufactured, and installed. The performance ratio of a 900 kWp system of 30 V low-voltage modules has been simulated and projected to be 92.1%, which is 20% more than its crystalline silicon and CdTe counterparts. The see-through color modules have been achieved with the highest module power reaching 105 W and the highest visible-light transmittance near 20%.

1. Introduction

There are three major commercial types of thin-film solar modules: silicon (Si), cadmium telluride (CdTe), and copper indium gallium diselenide (CIGS). The efficiency of CdTe and CIGS thin-film solar modules still contend with the wafer-based silicon ones. Nevertheless, they use either precious metals such as In, or toxic and hazardous metals, such as Cd. Certain questions and concerns still exist for their large-scale applications. Especially, the *n*-type cadmium sulfide (CdS) used by both CdTe and CIGS thin-film solar cells contains the Cd element which always poses a safety concern for environmentally conscious applications. Therefore, it is generally believed that Si thin film solar modules still have certain advantages in some cases, though their efficiency still fall behind their counterparts. In addition, they suffer from problems of light-induced degradation (LID). Nevertheless, it is worth reminding that Si thin-film solar modules generally have a lower temperature coefficient and also better low-light performance. As a result, for photovoltaic (PV) systems with the same kilowatt (kW) power rating, Si thin-film ones can produce higher kilowatt-hour (kWh) energy yield. In other words, Si thin-film PV systems usually can generate 5 to 10 percent more electricity than other type of systems due to

their lower temperature coefficient and better low-light performance.

Tandem amorphous/microcrystalline silicon (a-Si/ μ -Si) thin-film solar modules have gradually superseded pure amorphous ones due to their better performance (Keppener et al., 1999; Shah et al., 2002, 2004; Meier et al., 2002; Yamamoto et al., 2000, 2002, 2004; Nakajima et al., 2009), especially in increasing the efficiency and also alleviating the LID problem. Therefore, ongoing efforts are mainly focused on these two issues of improving the efficiency and reducing the LID problem for tandem a-Si/ μ -Si thin-film solar modules. Some interesting issues also attract attention, such as modules' high output voltage (normally around 100 V). High output voltage of regular a-Si/ μ -Si modules will put a stringent demand on the specifications of their associated balance of system (e.g., electrical connection cables) and it could not be compatible with the low output voltage (around 30 V) of the mainstream products of crystalline Si wafer-based solar modules. As a result, it can be expected that this additional cost in balance of systems incurred by regular high-voltage a-Si/ μ -Si thin-film modules can be effectively reduced by low-voltage ones. In addition, low-voltage modules are more suitable for stand-alone applications, for example, conventional 12 V battery chargers for consumer electronics.

A thin-film solar panel is normally laser scribed into cells and these

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cells are connected in series to form a solar module. In order to achieve a low output voltage, a panel needs to be additionally laser scribed into several segments and the segments are then connected in parallel. Conceptually, this segment laser scribing contributes only a few additional processes and the realization of low-voltage modules should be rather straightforward. However, in reality, several technical challenges and hurdles need to be carefully considered, especially in the commercial production line. For example, additional laser scribing will not only decrease the effective illuminated area and thus increase the area of dead zones, but also create many material defects along the edge of the scribed lines. The defects resulting from laser scribing will provide channels for leakage current and hence decrease the shunt resistance of solar modules. Therefore, the first technical challenge in developing low-voltage modules will be to minimize the detrimental effects resulting from the laser scribing processes. Furthermore, because of the connection arrangements of series-connected cells and parallel-connected segments, the module performance will inevitably suffer from mismatch effects that result from the different physical characteristics of individual cells and segments. Due to this mismatch effect, the output current will be determined by the cell with the lowest short-circuit current and the output voltage will be determined by the segment with the lowest open-circuit voltage. The mismatch effects caused by the different physical characteristics of cells and segments mostly result from the non-uniformity of thin films due to the spatial variation from manufacturing processes on large-area panels. These result from the transparent conducting oxide (TCO) films grown by low-pressure chemical vapor deposition (LPCVD) processes in which the non-uniformity of the film thickness can be over 20%. Improving the uniformity of manufacturing processes and thus minimizing the mismatch effects among cells and segments is another technical problem that needs to be resolved in order to develop low-voltage solar modules. In the following, a brief description on the developments of these key technologies and the performance of the low-voltage modules enabled by these technologies will be discussed.

Building-integrated photovoltaic (BIPV) is another important application for photovoltaic industry and commerce (Eiffert and Kiss, 2000; Roberts and Guariento, 2009). It not only extends and enriches the versatility and functionality for photovoltaic (PV) applications but also makes solar electricity more accessible and integrated to our daily lives. In BIPV applications, photovoltaic modules or panels are fabricated as an integral part of building materials, such as windows, skylights, facades, roof covers, and exterior walls. As a result, BIPV is an ideal solution for utilizing solar electricity while retaining buildings' architectural functions and aesthetic appearances at the same time. However, the current mainstream commercial PV modules are made from single-crystalline or multi-crystalline silicon wafers. It would be very difficult or even impossible to tailor their functions and configurations for various BIPV applications, for example, the see-through function for BIPV windows or skylights. In addition, the production of wafer-based silicon PV modules comprises of different and separate processes for polysilicon materials, wafers, cells, and modules, it could be rather difficult to commercially coordinate these different production procedures and customize their functions or configurations for designated specifications required by various BIPV applications. On the contrary, material/cell/module manufacturing processes are usually integrated into one production line for thin-film solar modules. As a result, it will be relatively easier to modify these manufacturing processes to commercially customize the functions or configurations of solar modules; especially, different types of large-area substrates, such as glass, plastic, ceramic, graphite, or metal could be employed for thin-film solar modules to meet different BIPV specifications.

Due to the demand for specific BIPV applications, there are conventional methods of making BIPV panels to appear with a specifically designed color, such as the direct attachment of an organic color film outside the module, the spraying or coating of color paint on the front glass, and the utilization of a dyed front glass. These conventional

methods, although straightforward, are usually rather impractical and thus have their limitations and problems for successful commercial BIPV products. For example, organic color films or paints are mostly not durable enough to meet the 20 to 25-year warranty of solar modules. Dyed front glasses usually reflect too much incident sunlight which will make solar modules suffer enormous optical losses and rather worse efficiency. Finally, additional materials used by these conventional methods will inevitably incur additional cost which is against the cost-effective consideration of successful commercial products. As a result, in this work, many innovative technologies are researched, developed, and introduced into the existing production line specifically for BIPV applications. These novel and key technologies, such as front reflective layers and 4-step laser scribing, are required not only to be compatible with the existing manufacturing processes but also to be very cost effective to become successful commercial products. They were successfully introduced into the production line to manufacture see-through BIPV panels with various colors, such as purple, dark blue, light blue, silver, golden, orange, red wine and coffee. The details of these technologies and the resulting products will be discussed in the following.

This article is written to serve the purpose of reviewing the technologies developed and achieved by Auria Solar (Tsai and Tsai, 2011; Tsai and Tsai, 2014a, 2014b). These technologies, in our opinion, could be useful for future developments of tandem amorphous/microcrystalline silicon thin-film solar modules. The contents of this work are organized as follows: In Section 2, Novel technologies for tandem a-Si/ μ -Si thin-film solar modules are introduced. These technologies are listed, presented, and discussed in Section 2.1 for passivation (Moon Technology); Section 2.2 for uniformity of TCO films and lamination; Section 2.3 for segment laser scribing; Section 2.4 for front reflective layer; and Section 2.5 for 4-step laser scribing. By means of these novel technologies, two new types of tandem a-Si/ μ -Si thin-film solar modules: low-voltage modules and see-through color modules are successfully developed, manufactured, and installed. The implementation and installation of these novel types of modules are presented and discussed in Section 3. The conclusion is given in Section 4.

2. Novel technologies

In this work, tandem amorphous/microcrystalline (also called as “micromorph”) silicon thin-film solar modules are produced from the 60 MW production line of Auria Solar. The structure of a cell in a-Si/ μ -Si thin-film solar modules is schematically shown in Fig. 1. In general, the thickness of the front and back glasses is about 3.2 mm, the back reflector 0.5 mm, the a-Si:H cell layer 300 nm, the μ -Si cell layer 1400 nm, the back TCO 1500 nm, and the front TCO 1800 nm. The manufacturing processes of these modules are briefly outlined in Fig. 2 in which a front-glass substrate goes through the LPCVD TCO film growth, plasma-enhanced chemical vapor deposition (PECVD) hydrogen-rich amorphous silicon (a-S:H) and microcrystalline silicon (μ -Si) film growth, and 3-step laser scribing to form the basic structure of solar cells, and then metal ribbon wiring, back-reflector screen printing, abrasive blasting edge isolation, PV foil encapsulation, lamination, and junction-box adhesion to form a finished module.

The size of a panel is 1.3 m \times 1.1 m. A module is usually laser scribed into 99 cells and its output voltage is about 100 V. To produce modules with lower output voltages, several novel technologies, such as the Moon Technology passivation, unprecedented uniformity of TCO films, and novel segment laser scribing, are developed and introduced into the production line. These technologies, when introduced into the existing production line, are strongly demanded to ensure the efficiency of low-voltage modules are better than (or at least not worst than) regular ones. At the same time, the throughput and yield in every production process is strictly required not to be compromised. These novel technologies will be discussed in the following.

On the other hand, the structure of a see-through color BIPV module is schematically shown in Fig. 1(b), where the back reflector in a

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