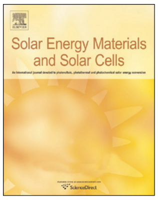
Solar Energy Materials & Solar Cells 143 (2015) 442–449

Contents lists available at ScienceDirect

Solar Energy Materials & Solar Cells

journal homepage: www.elsevier.com/locate/solmat



Design of esthetic color for thin-film silicon semi-transparent photovoltaic modules

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ARTICLE INFO

Article history:
Received 5 February 2015
Received in revised form
25 July 2015
Accepted 27 July 2015

Keywords:
Amorphous silicon
Semi-transparent photovoltaic module
Color design
Laser-scribed patterns

ABSTRACT

Color design for large-area hydrogenated amorphous silicon (a-Si:H) semi-transparent glass-to-glass (GTG) photovoltaic (PV) modules has been studied for the application to building integrated PV (BIPV) modules. Three-dimensional color space of CIE (Commission Internationale de l'éclairage) $L^*a^*b^*$ (CIELAB) is adopted for a systematic color analysis. Three kinds of design configurations are invented by combining the transparency of back contacts and laser patterning techniques. In addition, the realization of emotionally stable and esthetic color is challenged using color back encapsulating materials. Transparent back contact (TBC)-type modules with green color are fabricated via the most simplified processes without sacrificing any active area. Bright and esthetic hybrid-type modules are also fabricated using additional laser-scribed patterns and blue encapsulating film. It is found that opaque back contact (OBC)-type module design is the best way to achieve target color together with the highest conversion efficiency. Because color of the back encapsulating materials does not deteriorate the conversion efficiency, the developed design concepts are promising options for large-area semi-transparent BIPV modules.

1. Introduction

It is well known that global warming caused by excess CO_2 emissions has raised concerns about climate change. Sufficient supplies of clean energy are intimately linked with global stability, economic prosperity and quality of life. Accordingly, clean renewable energy including solar, wind and hydrogen energy has become a prime issue. A photovoltaic (PV) module using solar light is a promising candidate among the renewable energy sources because the sun is our primary source of clean, abundant energy. Furthermore, semi-transparent building integrated PVs (BIPVs) are being proposed to reduce greenhouse gas emissions in cities by generating electricity without using fossil fuels [1]. Since BIPVs can be widely used as curtain walls, façades and roofs [2–6], their market is forecasted to grow rapidly if module design is sustainable and esthetic.

Thin-film silicon (Si) PV technology is one of promising options for semi-transparent BIPVs because of abundant raw materials, industrial-proven mass production, flexible size, easy transmittance engineering and low temperature coefficient [7,8]. Nonetheless, reddish color of the conventional hydrogenated amorphous Si (a-Si:H) semi-transparent BIPV modules produced by Suntech, Schott Solar and Sun Well (see Table 1) [9] could cause emotional instability of workers and residents. Hence, the realization of emotionally stable and esthetic color while keeping an acceptable conversion efficiency is a key technology issue to improve the application of the a-Si:H semi-transparent PV modules to BIPV modules. As described in Table 1, Auria Solar developed a-Si:H/hydrogenated microcrystalline Si (μc-Si:H) double-junction semi-transparent PV modules [10]. Various esthetic colors such as blue, purple, gold and silver were materialized by employing a hydrogenated amorphous silicon-carbide (a-SiC:H) reflective layer between a front glass substrate and transparent electrode. However, a considerable loss of the nominal conversion efficiency (η^*) was inevitable due to the reflection loss from the reflective layer. In this work, a systematical study on a-Si:H semi-transparent glass-to-glass (GTG) PV modules is challenged by avoiding a sacrifice of the conversion efficiency. Aiming to convert red color to blue, green and gray colors, various parameters such as the thickness of the intrinsic a-Si:H (i-a-Si:H) layer (d_i), transmittance (T), opening ratio (X), back contact and color of back encapsulating materials have been adjusted. Color of the fabricated a-Si:H semi-transparent PV modules was analyzed in terms of CIE (Commission Internationale de l'éclairage) $L^*a^*b^*$ (CIELAB) that is the most complete color space specified by the International Commission on Illumination [11]. CIELAB was developed to be used as a reference for all perceivable colors to the human eye. In addition, CIELAB is a device-independent, three-dimensional model comprised of three coordinates. The lightness, L^*, indicates black at $L^*=0$ and diffuse white at $L^*=100$ (specular white may be higher). The color channels, a^* and b^*, yield true neutral gray values at $a^*=0$ and $b^*=0$. Red and green opponent colors are

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http://dx.doi.org/10.1016/j.solmat.2015.07.042
0927-0248/

Table 1
The technical specifications of conventional thin-film Si semi-transparent BIPV products.

Producer	Cell	Size (m^2)	Color	Transmittance (%; 400–800 nm)	η_* (%)
Suntech (MSK)	a-Si:H	0.93	No artificial color	10	4.6
			No artificial color	5	5.4
			Standard	–	5.6
Schott Solar	a-Si:H	1.49	No artificial color	10	5.2
			Standard	–	5.8
Sun Well	a-Si:H	1.43	No artificial color	20	4.9
			Standard	–	5.9
Auria Solar	a-Si:H/μc-Si:H	1.43	Purple	12	5.2
			Dark blue	11	5.2
			Light blue	10	4.2
			Silver	10	3.1
			Gold	6	3.1
			Orange	20	5.6
			Red	16	6.3
			Coffee	6	7.3
			Standard	–	9.3

represented along the a^* axis; negative values indicate green while positive values indicate red. Yellow and blue opponent colors are represented along the b^* axis, with blue at negative b^* values and yellow at positive b^* values. Hereafter, we will discuss the results of module design.

2. Experimental

Fig. 1 shows the photograph of the so-called "solar cube" constructed by installing a-Si:H semi-transparent GTG BIPV modules developed by KISCO. A series of pin-type a-Si:H PV modules was fabricated using a 13.56 MHz radio-frequency (RF) plasma-enhanced chemical vapor deposition (PECVD) technique. Randomly textured F-doped tin oxide (SnO_2:F)-coated soda lime glasses with the area of 1.43 m^2 were used as substrates. Fig. 2 illustrates planar and cross-sectional schematics for the fabricated GTG PV modules. As shown in Fig. 2(a), a transparent back contact (TBC)-type PV module has the cell structure of glass/SnO_2:F/p-type a-SiC:H (p-a-SiC:H) window layer/p-type buffer layer (p-buffer)/i-a-Si:H absorber (70-200 nm)/hydrogenated n-type a-Si:H (n-a-Si:H)/B-doped zinc oxide (ZnO:B) back contact (500 nm). For the deposition of the Si layers, cluster-type PECVD system was used. Each type of layers was deposited at the substrate temperature around 200 °C in a separated chamber to minimize the dangling bonds [12] and residual impurity cross-contamination. The p-a-SiC:H window layer was deposited using a mixture of SiH_4, B_2H_6, H_2 and CH_4 reactant gases. In order to reduce the carrier recombination loss at the p/i interface, the layer of p-buffer is carefully selected and inserted between the p-a-SiC:H window layer and i-a-Si:H absorber [13]. For the deposition of the i-a-Si:H absorber, H_2 and SiH_4 were used as reactant gases. For the deposition of n-a-Si:H, a mixture of SiH_4, PH_3 and H_2 reactant gases was used. The ZnO:B back contact was prepared at the substrate temperature of 170 °C using a metal organic chemical vapor deposition (MOCVD) technique [14]. Bubbled diethylzinc (DEZ) and water (H_2O) vapor were introduced into a reaction chamber via high purity Ar (99.99%) carrier gas. B_2H_6 gas was used as a doping source. The monolithic series integration was materialized via the plurality of three parallel laser-scribed patterns (P1, P2 and P3 patterns). The Q-switched infrared (IR) laser with the wavelength of 1064 nm was used for P1 patterns, while the Q-switched green laser with the wavelength of 532 nm was used for P2 and P3 patterns. All the lasers were illuminated from the glass substrate side to prevent the damage on the stacked layers. The conditions for the pulse overlap and laser power were determined not to generate any burr and flake [15]. In our experiments, the cell width of 9.8 mm is selected considering the open-circuit voltage (V_{oc}) and series resistance (R_s) [16,17]. As the final process, the module encapsulation was performed by laminating a back glass with a transparent polyvinyl butyral polyvinylbutyral polyvinylbutyral (PVB) film at 170 °C.

Fig. 1. Solar cube installed by the fabricated a-Si:H semi-transparent GTG PV modules.

As shown in the Fig. 2(b), an opaque back contact (OBC)-type PV module has the similar planar structure to the TBC-type PV module, with the exception of the additional laser-scribed patterns and back contact structure. After the laser scribe of P3 patterns, plurality of P4 patterns were formed perpendicularly to the P1, P2 and P3 patterns using the Q-switched green laser in order to increase T. The X value (=laser-patterned area/aperture area) is controlled by changing the number of the P4 patterns. The OBC-type PV modules have a 80-nm-thick ZnO:B back reflector prepared by MOCVD and 300-nm-thick Al back contact [18] prepared at the substrate temperature of 100 °C via RF magnetron sputtering with a high purity Al (99.999%) target. Hybrid-type PV modules have the same cell structure with the TBC-type PV modules. However, the P4 patterns were formed in the hybrid-type PV modules to enhance T. In addition, blue PVB films were employed as the back encapsulating film. Both the transparent and blue PVB films are Dupont's standard products. Although the cost of the blue PVB film (=8.8 \$/m^2) is more expensive than that of the transparent PVB film (=7.1 \$/m^2), both the PVB films are considerably reliable. The a-Si:H semi-transparent PV modules encapsulated with the transparent and blue PVB films were subjected a climatic chamber for 1000 h at 85 °C and 85% relative humidity. As a result, both the modules passed the International Electrochemical Commission (IEC) 61646 damp heat test. The performance of the a-Si:H semi-transparent PV module fabricated using the transparent PVB film was deteriorated by 0.2% (from 91.1 W to 90.9 W), whereas the performance of the counterpart fabricated using the blue PVB film was deteriorated by 0.3% (from 89.3 W to 89.0 W). Hereafter, transparent PVB was used as the back encapsulating film, unless commented otherwise.

Color of the fabricated a-Si:H semi-transparent PV modules was monitored using a Minolta CM 3700D spectrophotometer. The total transmittance spectra of back glasses and PV modules were measured using a Perkin Elmer, Lambda 950 UV/Vis spectrophotometer. T is the average total transmittance in the wavelength range of 360–750 nm. The photo current–voltage (I–V) characteristics for the