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Highly transparent amorphous silicon solar cells fabricated using thin absorber and high-bandgap-energy n/i-interface layers

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ABSTRACT

We used very thin (i.e., ~115-nm-thick) absorbers to fabricate full-penetration (FP) semitransparent a-Si:H solar cells for building-integrated photovoltaic (BIPV) windows and introduced high-bandgap (HB) n/i-interface layers to decrease shunt loss and increase carrier collection. The optoelectronic properties of the fabricated cells showed that the HB layers improved the fill factor by decreasing shunt loss and increased the short-circuit current density by enhancing generated-carrier collection. We used scattering matrix analysis to simulate the transmittance characteristics of the semitransparent solar cells fabricated using the HB layers and showed that the HB layers shifted the transmission peak to longer wavelengths. We used a figure of merit (FOM), the product of the efficiency and the average transmittance in the range 400–800 nm, to represent the performance of the semitransparent solar cells and compared the FOMs of the cells fabricated for application to BIPV windows. The cell fabricated using triple HB layers showed the highest FOM, more than 20% higher efficiency than the reference cell (fabricated without using any HB layers), and its transmittance was similar to that of the reference cell. Fabricating FP semitransparent a-Si:H solar cells with triple HB layers and evaluating their optoelectronic performances will be very useful for implementing high-performance BIPV windows.

1. Introduction

Photovoltaic (PV) energy is a promising renewable energy source because it is environmentally friendly and fulfills the global energy demand while only requiring installation on a small fraction of Earth's surface [1]. In particular, building-integrated PV (BIPV) devices can supply their own electricity to buildings, thereby saving external energy expenses. BIPV technology has recently attracted considerable attention. Further, there is an increasing focus on the emission of greenhouse gases in cities [2], and the use of BIPV devices is being proposed to reduce the use of fossil fuels and to thereby reduce greenhouse gas emission from the major source, i.e., buildings. BIPV systems do not require supplemental areas in order to be installed; for instance, they can replace unproductive façades with handsome windows that generate electricity [3–6]. Architects have applied PV fenestration systems or PV windows to the windows and facades of buildings or to car sunroofs, and related technologies are expected to rapidly grow [6–8]. Although dye-sensitized solar cells (DSSCs) have been studied for application to PV windows owing to their low production cost, various degrees of transparency, and relatively high efficiency [9,10], they show poor stability related to electrolyte leakage and dye degradation at elevated temperatures [9]. Therefore, DSSC reliability should be improved before commercializing DSSC products. Hydrogenated amorphous silicon (a-Si:H) thin film solar cells, on the other hand, may be a viable alternative because Si is abundant and because a-Si:H-based solar cells have shown high reliability, low temperature coefficients, and low production costs, and they can be fabricated on large-area glass substrates [11,12].

Many a-Si:H-based semitransparent solar cells are aperture type, as shown in Fig. 1 (a). Aperture cells are composed of rectangular grids fabricated by complicated patterning processes such as those using a laser to punch through or partly remove a-Si:H films and back contact layers [11,13]. Unlike aperture semitransparent cells, full-penetration (FP) cells, shown in Fig. 1 (b), can generate electricity while simultaneously allowing light to be transmitted through the entire area of the cells [14]. Although FP

Abbreviations: a-Si:H, hydrogenated amorphous silicon; BIPV, building-integrated photovoltaic; DSSC, dye-sensitized solar cell; PT, penetration-type; E_g, bandgap energy; HB, high-bandgap; GZO, Ga-doped zinc oxide; TCO, transparent conductive oxide; S-matrix, scattering matrix; IQE, internal quantum efficiency; *FF*, fill factor; FOM, figure of merit

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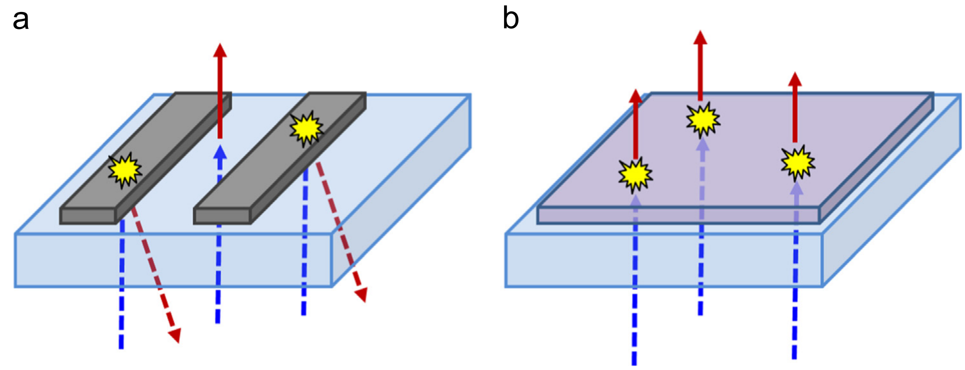

Fig. 1. Schematics of (a) aperture and (b) full-penetration semitransparent a-Si:H solar cells.

cells do not show any opaque patterns and various colors are feasible with them, FP BIPV windows should be highly transparent without showing any substantial loss in conversion efficiency, which can be achieved by increasing absorption but should not involve a consequent decrease in transmittance.

To increase the transmittance, one can reduce the thickness of intrinsic a-Si:H (i-a-Si:H) layers in exchange for reducing the absorption in i-a-Si:H layers. Simply reducing the i-Si thickness from 300 to 150 nm reportedly increased the transmittance by ~20%, resulting in serious efficiency loss (from 5.32 to 3.14%), which worsened the transmittance gain; that is, the fill factor, *FF*, decreased from 69 to 53%, implying that the uncontrolled shunt path in the thin absorber layer had caused serious loss for the thin absorber layers [15]. Accordingly, FP semitransparent solar cells fabricated using very thin i-a-Si:H absorption layers require additional structures in order to simultaneously achieve high efficiency and high transmittance. Interfacial layers between p-type (p-) a-Si:H and i-a-Si:H layers or i- and n-type (n-) layers can be used for such structures. Many methods of fabricating buffer layers at p/i-interfaces have been used to improve the efficiency of conventional opaque a-Si:H and hydrogenated amorphous silicon germanium (a-SiGe:H) solar cells [16–21], and p/i-buffer layers have also been used to reduce efficiency loss and achieve high transmittance in FP semitransparent solar cells [14].

Highly resistive n/i-interface layers could reduce the loss of shunt resistance for opaque a-Si:H-based single or tandem solar cells [22,23], where the thickness and bandgap energy (E_g) of the n/i-interface layers considerably affects the open circuit voltage (V_{OC}) and *FF* of opaque a-SiGe:H solar cells [20]. Since the interfacial layers could affect both the electrical and optical properties of FP solar cells, designing and characterizing the interfacial layers are very important for fabricating BIPV windows. Materials showing intrinsically high E_g and low resistivity can be good candidates for the interfacial layers; for example, Cu_2O thin films have been used to form a heterojunction with a-Si:H films and to tune the colors of FP a-Si:H solar cells [24]. The E_g of i-a-Si:H films can be controlled by adjusting the hydrogen dilution ratio (R, the ratio of H_2 to SiH_4 flow rates) while depositing a-Si:H films. The use of E_g-engineered i-a-Si:H films as interfacial layers provides more freedom to control optical and electrical properties when fabricating semitransparent solar cells.

We used a very thin (i.e., ~115-nm-thick) i-a-Si:H absorber layer to fabricate highly transparent, highly efficient FP semitransparent a-Si:H solar cells, and we used high-bandgap (HB) layers as n/i-interface layers to reduce the shunt loss in the thin absorber. We investigated the electrical properties of the FP semitransparent a-Si:H solar cells for various configurations of HB layers and used scattering matrix analysis to analyze the changes in the transmission spectra. We also developed a method of estimating the cell efficiency and transmittance of the FP semitransparent solar cells and demonstrated that properly configuring HB layers could improve the cell efficiency while maintaining the transmittance required for BIPV windows.

2. Materials and device fabrication

The FP a-Si:H solar cells were fabricated using inductively coupled plasma chemical vapor deposition (ICP-CVD) at 250 °C. ICP-CVD can increase the plasma density and dissociation rate of source gases to reduce the ion-bombardment impact; it can be used to grow high-quality films at low temperatures [25]. P-i-n a-Si:H layers were deposited using i-a-Si:H HB layers and SiH_4, PH_3 (1.5% diluted in H_2), and B_2H_6 (0.1% diluted in H_2) gases at 0.2 Torr in a single chamber. The i-a-Si:H layers were grown at lower R (<5) for the HB interfacial layers, and the E_g (as measured using the Tauc plot and 100-nm-thick layer [14]) of the layers was higher than that of the main i-a-Si:H absorber grown at higher R ($=10$); however, the E_g was recalibrated for this study. The E_g of the a-Si:H films slightly increased to a maximum with increasing R and subsequently decreased with further increase in R, indicating that the transition of the films had shifted to a more ordered structure. In this case, a transition can shift according to the variation in the plasma frequency and temperature [26]. E_g also reportedly increased with decreasing R in a certain R range at a low working pressure of 0.2 Torr [14,27]. Therefore, process variables such as temperature, plasma conditions (power, frequency, and generation method), and working pressure can influence the increasing/decreasing behaviors of E_g for any given R.

Table 1 summarizes the structure of our fabricated FP semitransparent a-Si:H solar cells. Radio frequency (RF) magnetron sputtering was first used to deposit ~1200-nm-thick gallium-doped zinc oxide (GZO) film at 200 °C for the front transparent conductive oxide (TCO) layer [28], which was chemically etched using diluted acid to form a textured surface so that the front TCO layer thickness was reduced to ~1025 nm. A p-a-Si:H layer and triple p/i buffer layers were subsequently deposited onto the front TCO layer. The triple buffer layers were sequentially grown using R=0.5, 2, and 5. The buffer structure fabricated in our previous study demonstrated that V_{OC} and *FF* were enhanced by the internal electric field formed at the p/i interface [12,14]. Hence, we used a very thin (i.e., 115-nm-thick) i-a-Si:H absorber to achieve high transparency. We noted that this absorber was only ~1/3 as thick as the conventional ones used to fabricate a-Si:H thin film solar cells. Instead, we used various configurations of HB layers for n/i-interface layers. The details of the HB layers are listed in Table 2. We expected that the HB layers could enhance the shunt resistance and current flow at the n/i-interface. RF magnetron sputtering was also used to deposit ~450-nm-thick GZO film as the rear TCO under the same conditions used to deposit the front TCO film.