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Cell performance of a-Si:H translucent solar cells with various buffers utilizing light reflected by a backside mirror

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ABSTRACT

a-Si:H translucent solar cells with various n/i- buffer layers were fabricated. We employed single buffer and double buffers with different thickness in the fabrication of translucent cells. Compared to the cell without n/i- buffers, cell efficiency increases from 5.7% to 6.5% when double buffer layers were used. For further increase of cell efficiency for translucent cells, a backside mirror that reflects the transmitted light was installed and re-absorption of the reflected light was feasible. Interestingly, it was revealed that the thin double buffered cell was the most effective configuration, acquiring approximately 21% higher efficiency. Proper design of optical thickness and arrangement of buffer layers is required to effectively utilize incident and reflected light.

1. Introduction

In order to utilize buildings as energy generating plants, building-integrated photovoltaic (BIPV) systems have been developed [1–3]. In particular, translucent PV windows are a viable solution to maximize energy benefits from the utilization of daylight [4]. To date, PV windows have mainly been based on dye-sensitized solar cells. However, they are hindered by poor stability due to electrolyte leakage and dye degradation and also undergo a decrease in efficiency with a change in color [5,6].

As an alternative material, a-Si:H translucent solar cells are expected to be a good candidate for a stable solar window [7]. Most a-Si:H translucent cells developed thus far are an aperture type or grid-connected type, including grid-like rectangular electrodes with different patterns [1,3,8]. An aperture type cell is schematically illustrated in Fig. 1(a). An aperture type cell, however, does not offer the feasibility of embodying various colors and opaque grid patterns are shown. To overcome these disadvantages, we fabricated penetration type (PT) translucent cells that can simultaneously generate electricity and transmit incident light over the entire cell area [7,9]. The PT type cells are also advantageous in that they enable enhancement of transparency with less reduction of efficiency compared to aperture type cells [7]. To ensure high transparency, transparent conductive oxide (TCO) layers are used as both electrodes. Another advantage of PT cells is the feasibility of fabricating colored translucent solar cells. Different colors were embodied using Cu_2O films which were deposited by a reactive sputtering method with the addition of nitrogen gas [10,11].

In PT type translucent solar cells, it is crucial to find a method to enhance efficiency while maintaining transparency. Multiple buffer layers are potentially a good solution to enhance open circuit voltage (V_{OC}) as well as fill factor (FF) [12,13]. Among opaque a-Si:H thin film solar cells, research has largely focused on buffers at p/i- interfaces (p/i- buffers). However, when thin amorphous films were used as an absorber, n/i buffers considerably impacted cell performance [13].

In the present study, the thickness of the absorber was reduced to as low as 110 nm to ensure high transparency. By optimizing the process conditions of the buffer layers, it was feasible to obtain efficiency over 6% despite the very thin intrinsic Si absorber. Additionally, we explored another approach to increase cell efficiency that is associated with the reuse of transmitted light. As shown in Fig. 1(b), a backside mirror was installed to reflect transmitted light. We expected that the reflected light would be re-absorbed within the absorber, resulting in an increase of cell efficiency. This improvement of efficiency using reflected light is impracticable, however, in conventional translucent cells that contain an opaque metal grid. Therefore, PT cells are beneficial to improving the cell performance with the reuse of transmitted light.

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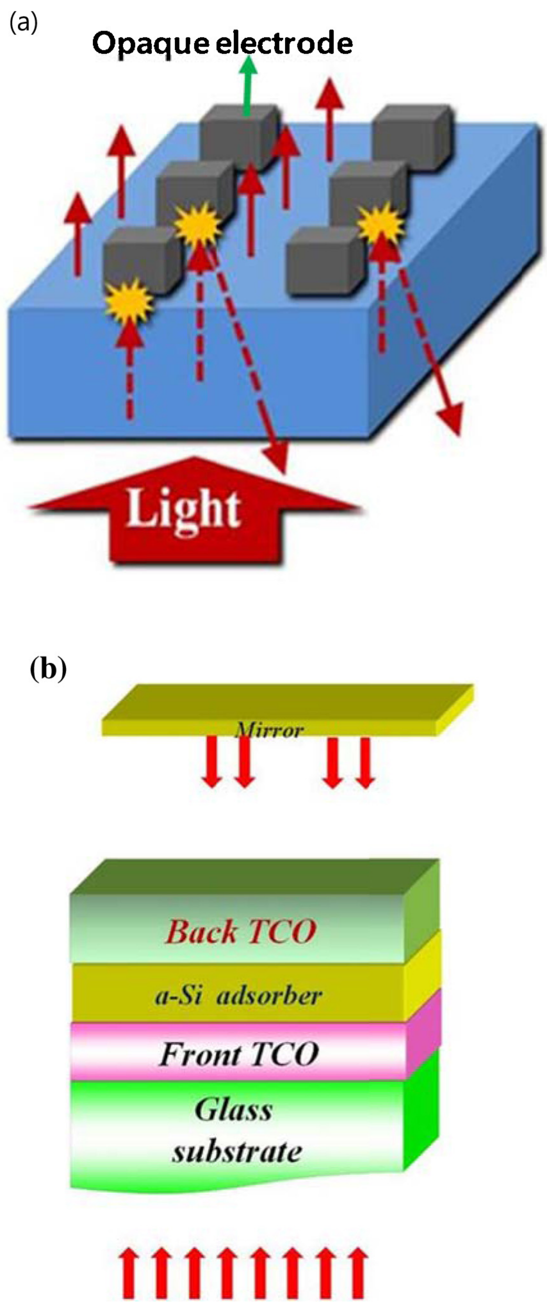

Fig. 1. Schematic structure of (a) aperture type a-Si:H transparent solar cells and (b) penetration type a-Si:H translucent solar cells with a back mirror.

In order to make maximum use of back reflected light, we present the optimal conditions of n/i buffers.

2. Experiment

The a-Si:H films were prepared by inductively coupled plasma (ICP-CVD) at 250 °C with a power of 80 W and working pressure of 0.2 Torr. The ICP process is known to be advantageous due to the high dissociation capacity, which leads to high-density plasma, low ion bombardment and the feasibility of growing high quality films at low temperature [14]. To prepare a-Si:H p-i-n layers, SiH_4, PH_3 (1.5% diluted in H_2 gas) and B_2H_6 (0.1% diluted in H_2 gas) gases were used and all layers were grown in a single chamber. To secure high transparency, a thin absorber layer of 110 nm was used. In our process, p/i and n/i buffers are a-Si:H films having lower hydrogen dilution ratios (R; ratio of H_2 flow rate to SiH_4 flow rate) than that of an intrinsic absorber. The buffers with a low R have a higher band gap than intrinsic absorbers [7].

As described in Fig. 1(b), a front TCO layer and a back TCO layer are used as electrodes to ensure transparency. Gallium doped zinc oxide (GZO) grown by the rf-magnetron sputter method at 200 °C was prepared as a TCO layer. The overall quality of the GZO film was described in our previous report [15]. After deposition of a front TCO layer, this layer was slightly textured to provide the desired light scattering conditions.

For measurement of the transmittance and quantum efficiency, a UV-visible spectrophotometer and an IQE-200 (Newport) measurement system were used, respectively. For the illuminated I–V analysis, a solar simulator at AM 1.5 was also used at room temperature and the measured area of the cell is 0.25 cm^2. The distance between the cell and the backside mirror is about 3 cm.

3. Results and discussions

In the fabrication of a-Si:H translucent solar cells, triple buffer layers were located at p/i- interfaces to enhance the V_{OC} and FF. The R values of p/i- buffers were 0.5, 2, and 5 from p-Si to i-Si sides. The conditions of the p/i- buffers for all samples are identical. In order to investigate the effects of n/i- buffers on the cell performance, four configurations were adopted, as shown in Fig. 2. In typical opaque a-Si:H solar cells, n/i- buffers have a smaller effect on cell performance than p/i- buffers. However, the role of n/i- buffers is not expected to be negligible in a-Si:H translucent cells with a thin intrinsic absorber. In the present experiment, the R value of the intrinsic absorber was 10 and a-Si:H films with lower R values showed a higher energy band gap [7]. The conditions of the buffer layers were as follows: bufferless, a single buffer with R values of 0.5 and two double buffers with different thickness and identical configuration (R = 4/0.5). The thickness of the single buffer layer was 9 nm and the thick and thin double buffer layer had thickness of 18 nm and 12 nm, respectively.

Table 1 shows the cell performance of all samples. The V_{OC} values are almost invariant for various n/i- buffers. This result differs from the case of varying p/i- buffer conditions where V_{OC} increases with increasing band gap of p/i- buffers in a previous study by the authors [7]. On the other hand, the FF and short circuit current density (J_{SC}) were considerably improved with the use of n/i- buffers in most cases. However, the single buffered cell was not effective in terms of improving J_{SC}. The buffer layers may effectively strengthen the internal field within intrinsic layers, which can be verified by the increase of the FF.

Fig. 3 shows the transmission curves over wavelengths from 400 nm to 1000 nm for a-Si:H translucent cells with various types of n/i- buffers. At wavelengths below 700 nm, the bufferless cell shows the highest transmittance among all samples. This indicates that the absorber does not provide sufficient light absorption. Interestingly, at longer wavelengths near 750 nm, the thin double buffered cell shows higher transmission than the single buffered cell. The double buffered cell is thus believed to be advantageous for obtaining high quality translucent cells having high transmittance as well as high efficiency. This result may be due to the effects of optical interference resulting from proper arrangement of buffers with different refractive indices. In the case of the thick double buffered cell, transmission curves shift to longer wavelength.

As presented in Table 1, the thick double buffered cell shows the highest J_{SC}. In order to investigate the spectral response in detail, internal quantum efficiency (IQE) curves in the visible region are provided in Fig. 4. In the green and red region of the spectrum, the spectral response of the cell with thick double buffers is increased substantially compared to the cell with thin double buffers.