Fabrication and Characterization of DSSC/Si Tandem Solar Cell with PEDOT:PSS/ITO Buffer Layer

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Abstract: In this study, dye-sensitized solar cell (DSSC)/silicon tandem solar cells were fabricated by changing the buffer layer structure. When joining two cells, a buffer layer is important to efficiently transport electrons by suppressing buffer of electrons by a potential barrier. Therefore, we used PEDOT:PSS/ITO as buffer layer structures, and measured their solar cell characteristics. As a result, it was found that the structure in which both PEDOT:PSS layer and ITO layer are stacked as buffer layers is suitable for the buffer layer of DSSC/Si tandem cells. In addition, the characteristics improved each time DMSO was added to PEDOT:PSS, and as a result, the characteristics of tandem solar cells also tended to improve. The maximum conversion efficiency (Voc = 0.78 V, Jsc = 4.87 mA / cm2, FF = 0.62, Eff = 2.35 %) was obtained when the DMSO concentration was 1%. It was suggested that conversion efficiency can be improved by improving the buffer layer.

Keywords: Photovoltaic, tandem, DSSC, PEDOT:PSS, buffer layer.

1. INTRODUCTION

Research on improving the conversion efficiency of silicon (Si) solar cells has attracted a lot of attention, and the conversion efficiency of 26.6% was recorded in 2017 as a single junction solar cell [1]. On the other hand, according to the Shockley-Quisser limit, the theoretical limit efficiency derived from the band gap is about 30% [2, 3], and it is difficult to further improve the conversion efficiency of silicon solar cells. Therefore, a multi-junction solar cell obtained by bonding a plurality of different types of solar cells has been attracting attention. Since it can absorb light of a wide range of wavelengths, it can be expected to greatly improve the conversion efficiency, and many multi-junction solar cells have been studied using III-V compounds, perovskite, etc [4-7]. Two-junction (tandem) solar cells made of III-V/III-V, perovskite/Si, III-V/Si, in particular, have a simpler structure and are easier to manufacture than multi-junctions [8-12]. In this study, we focused on tandem solar cells using dye-sensitized solar cells (DSSC) [13]. DSSC is classified as an organic solar cell [14], and as a principle of power generation, light incident on the solar cell is first absorbed by the dye and electrons are excited. The excited electrons immediately transition to TiO_2 and move to the counter electrode through the electrode and external circuit. The electrons at the platinum counter electrode are injected again into the dye by the redox reaction of the iodine electrolyte (I^-/I_3^-). Electricity is generated by repeating this cycle. The structure is generally glass, FTO, TiO_2 nanoporous (with dye adsorbed), iodine electrolyte and Pt counter electrode from the incident light side. In addition, there are also reports of improving the performance of solar cells by introducing an electron translate layer (ETL) made of TiO_2 [15-19]. By combining a silicon solar cell (Eg ~1.12 eV) as a bottom cell of a tandem solar cell and a DSSC (Eg~1.7 eV) as a top cell, it is expected that an efficiency of about 40% can be reached theoretically [20, 21]. DSSC / Si tandem solar cells using PEDOT:PSS (poly(3,4-ethylenedioxythiophene)-poly (styrenesulfonate)) [22] as a substitute for Pt with low transmittance as a buffer layer for tandem solar cells have been reported and the conversion efficiency of more than 18% has been achieved[23]. However, there is no detailed discussion about the buffer layer near PEDOT:PSS. Therefore, in this study, we experimented and examined the effect of the buffer layer containing PEDOT:PSS on the solar cell characteristics. In particular, we report on the change in properties depending on the concentration of dimethyl sulfoxide (DMSO) [24-26] added as a high-boiling solvent to increase the conductivity of PEDOT:PSS.

2. EXPERIMENTAL

To make the top cell of the tandem solar cell, 0.15M titanium diisopropoxide bis(acetylacetonate) (TiOx, Aldrich) was deposited. Subsequently, TiO_2 (P25, Aerosil) was deposited on the TiOx layer by a doctor blade method to produce an ETL of DSSC. After that, annealing was performed at 450 °C for 30 minutes in a baking furnace, and then Di-tetrabutylammonium cis-bis(isothiocyanato)bis (2,2'-bipyridyl-4,4'-dicarboxylato) ruthenium(II) (N719, Solaronix) for 18 hours to prepare DSSC.

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Next, a pn junction Si wafer (D6FL-CAOK, Delsolar, hereinafter referred to as pnSi) silicon was prepared for the production of the bottom cell. After sufficient hydrofluoric acid treatment, an ITO layer was sputtered to a thickness of 80 nm on the n-type side of the pnSi with the sputtering system (CS-200, ULVAC). Thereafter, an Al electrode was formed on the back surface (p-type side) of the Si wafer by thermal evaporation using a vacuum deposition apparatus (VPC-1100, ULVAC). Further, PEDOT:PSS (PH1000, Heraeus) added with DMSO was formed on the ITO layer by spin coating. Finally, an iodine electrolyte was injected between the DSSC produced above and a DSSC/Si tandem solar cell having the structure of Figure **1** was produced. The performance of the produced tandem solar cell was measured by a solar simulator (AM1.5, 100 mW/cm^2, CEP-25BX, BUNKOUKEIKI).

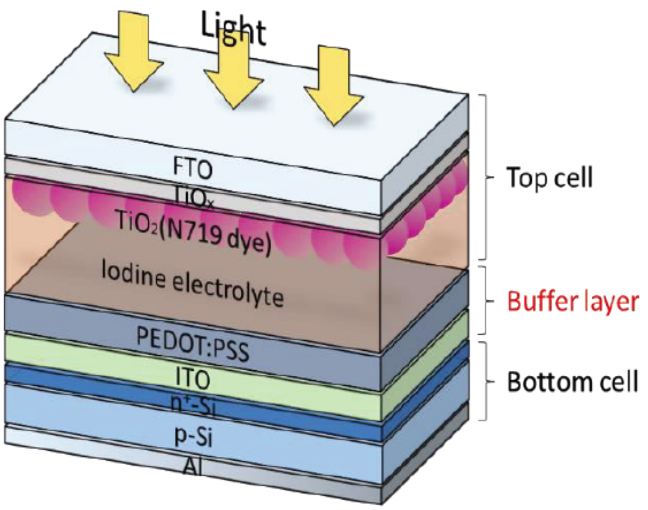

Figure 1: Outline of the fabricated DSSC / Si tandem solar cell.

3. RESULT AND DISCUSSION

3.1. Evaluation of PEDOT: PSS Film

Figure **2** shows the reflectance and transmittance at each wavelength of PEDOT:PSS deposited on Eagle XG measured by ultraviolet-visible absorption spectroscopy (UV-vis, V-570, Jasco). Since PEDOT:PSS has high transmittance, it is suitable for transmitting light to the bottom cell in the buffer layer of the tandem solar cell. Even when the DMSO concentration was changed, neither the transmittance nor the reflectance was significantly changed. Figure **3** shows the sheet resistance of PEDOT:PSS layers for various amount of DMSO concentration. It can be seen that the sheet resistance decreases drastically with the DMSO concentration, and when the DMSO concentration is 2% or more, the sheet resistance saturates at around 100 Ω/□. Therefore, when about 2% DMSO is added to PEDOT:PSS, it is expected that PEDOT:PSS linear connection will be satisfied and the contribution to conductivity will not be improved furthermore.

3.2. Fabrication of Tandem Solar Cells with Varying Buffer Layers

A buffer layer for a tandem solar cell is required that has a high conductivity and a suitable work function (WF). First, a tandem solar cell was fabricated using only PEDOT:PSS as the buffer layer without using ITO in Figure **1**. Figure **4** shows the results of J-V measurement. In the case of a PEDOT:PSS only buffer layer, FF was lost greatly, and stable characteristics could not be obtained. It is considered that the electron flow from n-Si to PEDOT:PSS layer was suppressed by the built-in potential. Therefore, in order to improve the

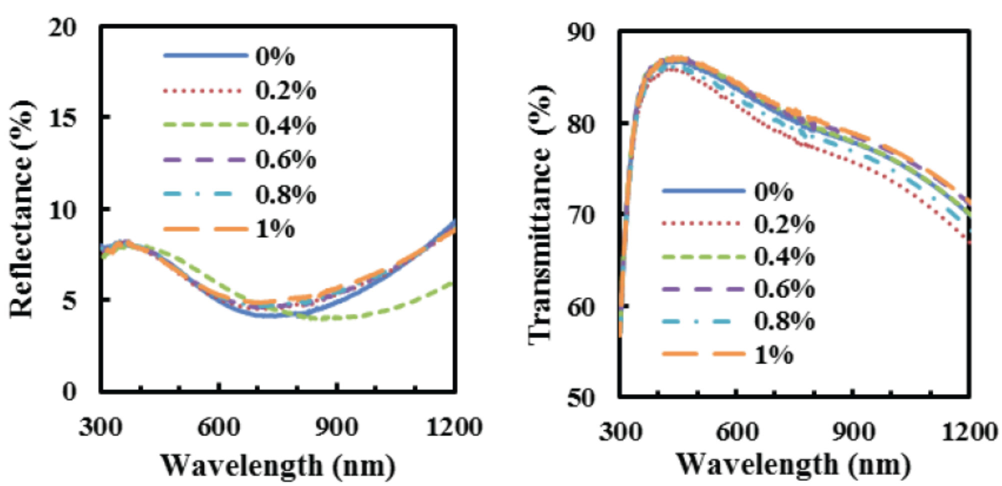

Figure 2: DMSO concentration dependence of PH1000 reflectance and transmittance.

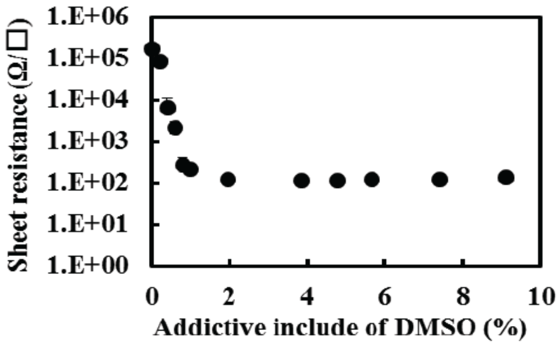

Figure 3: Dependence of sheet resistance of PH1000 on DMSO concentration.

electron flow from n-Si towards the electrolyte, a tandem solar cell was manufactured by using only ITO without using PEDOT:PSS as a buffer layer in Figure **1**. The measurement results are also shown in Figure **4** as above. In the buffer layer made only of ITO, both Jsc and Voc decreased, and good characteristics could not be obtained. From the decreasing of Voc, it is surmised that the ability of reduction from I_3^- ion to $3I^-$ ions is low at the ITO layer. Since the J-V curve is stable as compared with PEDOT:PSS alone, it is considered that the ITO layer is uniformly formed by sputtering, while PEDOT:PSS is considered to have unevenness in film formation.

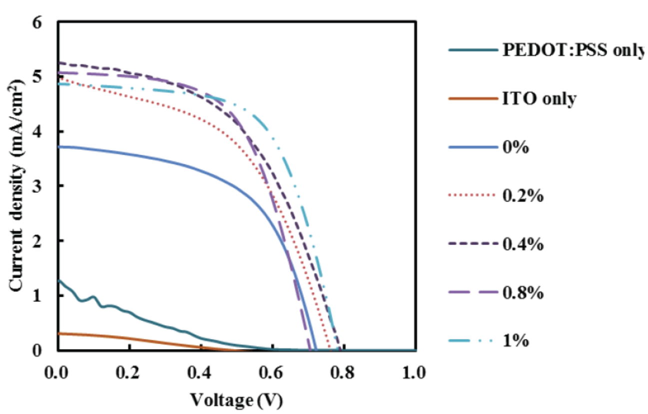

Figure 4: J-V characteristics of the buffer layer structure of DSSC/Si tandem solar cell and DMSO concentration dependence in ITO/PEDOT:PSS buffer layer.

Subsequently, a tandem solar cell was measured with a two-layer structure in which an ITO layer and PEDOT:PSS layer were formed as a buffer layer. The measurement results are shown in Figure **4**. In the tandem cell using pnSi, a clear J-V curve was obtained, Voc was 0.7 to 0.8 V, and Jsc was 5 mA/cm^2 or more. Although Voc did not change greatly, the improvement of Jsc was confirmed when the DMSO concentration was changed. The FF also improved as the DMSO concentration increased, and as a result, conversion efficiency tended to increase by adding DMSO in PEDOT:PSS layer. But there is not much difference for various amount of DEMO up to 1%. Figure **5** shows the J-V characteristics of the tandem cell, the top cell (DSSC) and the bottom cell (Si cell). The open circuit voltage of tandem solar cell is the sum of those for DSSC and Si, suggesting that the DSSC/Si tandem solar cell was successfully fabricated. But this figure suggests that Voc of the silicon bottom cell is low, and little benefit can be gained by improving Voc due to tandemization. In order to investigate the cause of the characteristic deterioration in this silicon solar cell, the solar cell of ITO/pnSi/Al structure was measured.

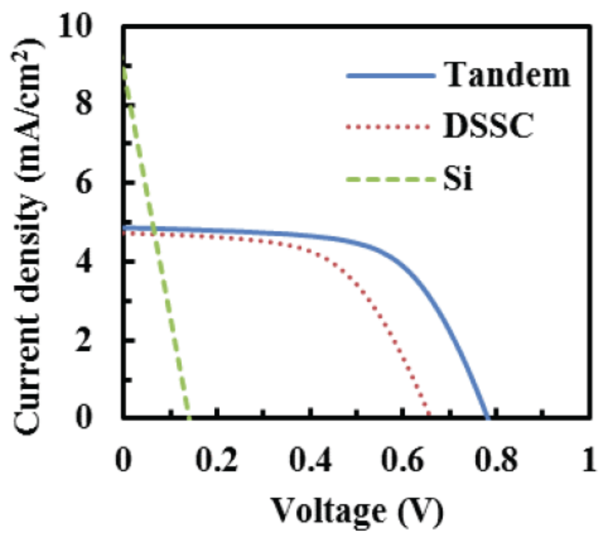

Figure 5: J-V characteristics of DSSC/Si tandem cells.

3.3. Evaluation of ITO/Silicon Cells

Figure **6** shows a scanning electron microscopy (SEM, JSM-6510, JEOL) image of a solar cell with an ITO/pnSi/Al structure. It can be confirmed that n+-Si of texture is formed on p-Si, and that ITO is deposited to cover the texture when ITO is sputtered. However, the J-V characteristics of the ITO/pnSi/Al structure solar cells showed the low performance as shown in Figure **5** even without a top cell. From this result, it is surmised that the contact at the n+-Si interface with ITO deposited by sputtering was poor, which caused the characteristics to deteriorate. Even in a silicon cell in a tandem structre, it is considered that this contact has affected the characteristics of the tandem cell.

4. CONCLUSION

DSSC/Si tandem solar cell was fabricated by using PEDOT:PSS and ITO layers to connect the top cell and bottom cell. The open circuit voltage of tandem cell was the sum of that of the top cell and that of bottom cell. It

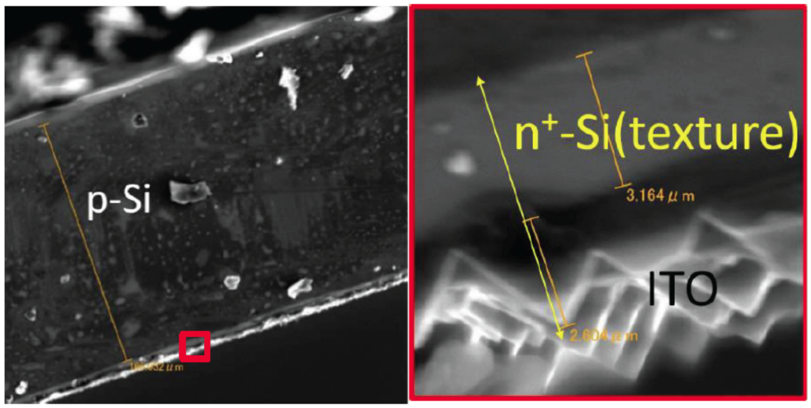

Figure 6: SEM image of solar cell with ITO/pnSi/Al structure.

suggests that the PEDOT:PSS/ITO layer is suitable for the buffer layer of DSSC/Si tandem cell. The addition of DMSO to PEDOT:PSS improved the conductivity of the PEDOT:PSS layer without changing the optical properties, which improved the performance of DSSC/Si tandem solar cell. As a result, the characteristics of the tandem solar cell showed a tendency to improve, and the conversion efficiency reached the maximum (Voc = 0.78 V, Jsc = 4.87 mA/cm^2, FF = 0.62, Eff = 2.35 %) when the DMSO concentration was 1%.

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