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Colored a-Si:H transparent solar cells employing ultrathin transparent multi-layered electrodes

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ABSTRACT

We fabricated hydrogenated amorphous silicon (a-Si: H) transparent solar cells using ultrathin transparent multi-layered electrodes (TMEs) as rear-side transparent electrodes for building-integrated photovoltaic (BIPV) windows. Each TME included a bottom layer, thin Ag layer, and optoelectronic controlling layer (OCL). The TMEs were experimentally designed to have high transparency and conductance. The fabricated a-Si:H transparent solar cells showed optimal performance with a 6.36% power-conversion efficiency and 23.5% average transmittance (500–800 nm) when TMEs with a thickness less than 160 nm were incorporated. We demonstrated that the reflection color of the cell could be tuned without serious loss of cell efficiency by varying the thickness of the OCL. The backside colors were predicted to be the coordinates on a CIE 1931 chromaticity diagram using the reflection spectrum from the cell and emission spectrum of a 50 W LED light source. The developed a-Si:H transparent solar cells exhibited high efficiency and show feasibility for incorporating various colors in the photovoltaic and aesthetic functionalities of BIPV windows.

1. Introduction

Human residential areas are the main emitters of greenhouse gases and consumers of electrical power. Recently, zero-energy building (ZEB) technologies have attracted great interest in connection with climate change and the depletion of fossil fuels [1]. As one of the promising candidates among ZEB technologies, building-integrated photovoltaic (BIPV) systems can improve energy-consumption efficiency and reduce environmental side effects by using solar energy on-site to provide electricity without CO_2 emissions [2]. Transparent solar cells can be used, as parts of ZEB technologies, in roofs, facades, and windows. In addition, they can be used in automobile sunroofs [3]. When transparent cells are used as BIPV windows, they can work as bifacial cells, providing the benefit of electrical generation [4,5]. If they are to work well as parts of various building designs, BIPV windows need to appear in various colors to match the aesthetic requirements of those designs.

Hydrogenated amorphous silicon (a-Si: H) solar cells are suitable for semi-transparent or transparent solar windows for several reasons: Si is non-toxic; a-Si:H-based solar cells are easy to fabricate on large-area glass substrates; these cells have proven their long-term stability in the field [2,6]. In a-Si:H solar cells, transparent conducting oxide (TCO) layers are commonly used for front-transparent conducting electrodes (TCEs), where the front color of a cell is determined by the reflection from the TCO layer. To date, indium tin oxide (ITO), fluorine-doped tin oxide and zinc oxide (ZnO) TCEs have been used widely in various optoelectronic devices: flat-panel displays, optical sensors, touch screens, and solar cells [7–9]. Among them, ITO has the best conductivity and transparency, but its higher price, because of the scarcity of indium, and chemical instability are the concerns that arise when considering the use of ITO [10–12]. In our previous reports, we developed transparent a-Si:H cells with enhanced efficiency and transmittance without metal grids [13,14] and showed the possibility of color-tuning by controlling the thicknesses of Cu_2O layers [15,16]. However, in general, controlling the colors of cells by changing the thicknesses of TCO layers results only in variations of the conductivity

Abbreviations: a-Si:H, hydrogenated amorphous silicon; BIPV, building-integrated photovoltaic; EQE, external quantum efficiency; GZO, ZnO:Ga; ITO, indium tin oxide; NW, nanowire; OCL, optoelectronic controlling layer; OMO, oxide-metal-oxide; TCE, transparent conducting electrode; TCO, transparent conducting oxide; TME, transparent multi-layered electrode; ZEB, zero-energy building

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of the TCO layers and, consequently, in variations of cell efficiency. Thus, implementing color in cells with single TCO layers has been limited to a narrow color range.

Multi-structured TCEs also may be available for transparent solar cells. Ag nanowires (Ag NWs) have low resistivity, high optical transmittance, and high flexibility [17–19]. However, Ag NWs have many unfavorable issues for commercial usage, such as non-uniform topography and unstable properties related to corrosion, high haze, and weak adhesion to substrate surfaces [18–21]. Oxide-metal-oxide (OMO) structures [21–23], designed to ensure the electrical stability of the Ag layer between TCO layers, generally have low sheet resistances of 5–15 Ω/sq and high transmittance values of 80–90%, even at thicknesses less than 100 nm [22]. Additionally, OMO structures have other merits: high flexibility and low process temperatures [23,24]. As a result, they have been applied mostly in organic light-emitting diode or organic photovoltaic devices [18,21,24,25]. However, uses of Ag, the common metal in OMO structures, still would benefit from improvements in the deposition process, because of the poor adhesion of Ag [26–28]. Opaque a-Si:H solar cells, using OMO structures of aluminum-doped ZnO and Ag as a TCE, were fabricated at a low temperature of 200 °C and showed an efficiency of only 3.2% [10]. Because the transmittance of an OMO structure and its conductivity vary inversely according to the thickness of the Ag layer, the OMO structure should be designed carefully to obtain high performance for a-Si:H transparent solar cells.

In this work, we present a-Si:H transparent solar cells employing ultrathin transparent multi-layered electrodes (TMEs) at rear TCEs, as shown in Fig. 1. The TME structure is composed of a bottom layer, metal (Ag) layer, and optoelectronic controlling layer (OCL). Unlike conventional OMO structures, the TME design includes both an Ag layer and OCL to achieve high transmittance and high conductivity simultaneously. In addition, the OCL plays the special role of modifying colors using optical interference. We also show how the color of the cells can be represented by the color coordinates on a Commission Internationale de l'Eclairage (CIE) 1931 chromaticity diagram using the spectral measurements of the cells and light sources. This method will be useful for obtaining high performance in a-Si:H transparent solar cells showing various colors with small variations of the OCL.

2. Material and methods

The proposed structure of the color-controlled a-Si:H transparent solar cell using ultra-thin TMEs is presented in Fig. 1; a front TCE layer of ZnO:Ga (GZO), *p-i-n* a-Si:H layers, and a rear TCE layer were grown sequentially on a glass substrate. The *p-i-n* a-Si:H layers were continuously grown in a single chamber of a conventional 13.56 MHz plasma-enhanced chemical-vapor-deposition system at 200 °C, where SiH_4, CH_4, PH_3 (1.5% diluted in H_2 gas), and B_2H_6 (0.1% diluted in H_2 gas) gases were used. The *p*-layer was a dual layer of a-Si: H(8 nm)/a-SiC: H(7 nm), and the *n*-layer was a normal a-Si:H layer of 20 nm [29]. These layers have shown good performance in our previous laboratory conditions [30], although other oxide-based or microcrystalline-based Si-thin films can be used for *p*-/*n*-type layers.

Based on our previous experiments, the thicknesses of the front GZO TCO layer and *i*-a-Si:H layer were selected to be ~1000 nm and 150 nm, respectively, to obtain high transparency.

The TME layer was deposited on the *p*-i-*n* a-Si:H/GZO/Glass by the RF magnetron sputtering method at room temperature and then used as the rear transparent electrode to control the color of the a-Si:H transparent solar cells. In the TME appearing in Fig. 1, the thicknesses of the bottom GZO layer and Ag layer were fixed at 30 nm and 12 nm, respectively, and those of the OCLs were varied in a search for the optimum condition. The OCL also was GZO and was prepared by the RF magnetron sputtering method. For comparison, a reference a-Si:H transparent solar cell with a single GZO of 200 nm for a rear TCE was also fabricated.

The fabricated a-Si:H transparent solar cells were ~0.25 cm^2. We characterized the cells in several ways. The sheet resistance was measured with a four-point probe; the film thicknesses were measured by α-step and scanning electron microscopy. The reflectance and transmittance were measured by ultraviolet-visible spectroscopy in the wavelength range of 400–800 nm. For an illuminated current density-voltage (*J–V*) analysis, a solar simulator of AM 1.5 G was used at room temperature. For the measurement of quantum efficiency, an IQE-200 Quantum Efficiency Measurement System (Oriel Instruments, Irvine, CA, USA) was used.

3. Results and discussion

3.1. Characterization of TME layers

Because one of the important roles of the TME depicted in Fig. 1 is to control the color of the cell using the OCL, the TME should have both high transparency and conductivity. Its conductivity and opacity are mainly dependent on the thickness of the Ag layer. Therefore, we first checked the optical and electrical properties of the TME layers with variations of the Ag-layer thickness in the range of 8–12 nm, where the thicknesses of the bottom GZO and top OCL layers were fixed at 30 nm and 50 nm, respectively. For comparing the performances of transparent electrodes, reflecting transparency, and conductivity, the figure of merit *FOM* for TCO can be used to evaluate TCE films, just as in display, touch panel, and solar cell applications. The *FOM* is related to sheet resistance R_S and optical transmittance *T* as described in Eq. (1) [31]:

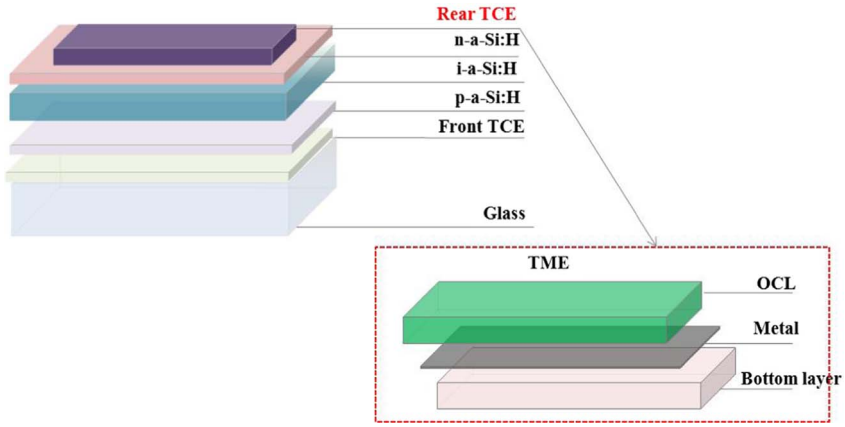

Fig. 1. Structure of transparent a-Si:H solar cells employing ultrathin TME for rear TCE; TME consists of three layers: bottom GZO, Ag metal, and OCL.