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Cu_2O thin films as the color-adjusting layer in semi-transparent a-Si:H solar cells

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ABSTRACT

We investigated penetration-type semi-transparent hydrogenated amorphous silicon (a-Si:H) solar cells that incorporated cuprite (Cu_2O) thin films, deposited by radio frequency magnetron sputtering, as the color-adjusting layer. Depending on the arrangement of the Cu_2O and transparent conductive oxide layers in the cells, the cells could be classified as either inner-type or outer-type. By simulating and experimentally measuring the reflectance of both types of cells, it was found that the optical interference in the two cells had a more significant effect on the short-circuit current density than did the thickness of the incorporated Cu_2O films. We fabricated a-Si:H cells whose transparency and color could be controlled simultaneously. This technique of fabricating a-Si:H cells that exploit the phenomenon of interference can be used to realize cells that exhibit different colors.

1. Introduction

As part of the efforts to address global energy concerns, researchers have devoted significant attention to investigating solar cells, with most studies focusing on improving the conversion efficiencies and lowering the costs of such cells. At the same time, though, the need for novel functional solar cells that are flexible and portable or can be used as building-integrated photovoltaic (BIPV) devices is greater than ever. To fulfill the energy requirements in buildings, BIPV windows that can generate heat, light, and electricity, while also simultaneously allowing for cooling are being developed [1]. In addition, since windows are a major component of buildings, BIPV windows need to esthetically pleasing as well and thus should be available in different colors. Dye-sensitized solar cells (DSSCs) have been studied widely for use as BIPVs owing to their low production cost, different degrees of transparency, and ability to exhibit different colors [2,3]. In spite of these advantages, DSSCs suffer from poor stability in outdoor operating conditions, which can be harsh, and undergo a decrease in efficiency with a change in color, which depends on the type of dye used [4]. Therefore, other devices that offer high transparency and can exhibit a number of colors without undergoing a decrease in cell efficiency need to be developed.

Semi-transparent hydrogenated amorphous silicon (a-Si:H) solar cells are a viable alternative owing to their high reliability and the low temperature coefficient of a-Si:H [5]. Most of the a-Si:H-based transparent cells developed are of the see-through type and include grid-like rectangular electrodes with different patterns [6]. There have also been studies on penetration-type (PT) semi-transparent a-Si:H cells (PT a-Si:H cells) that can generate electricity over the entire cell area while also transmitting the incident light. However, until now, only cells reddish in color have been developed because the absorption spectrum of the a-Si:H layer usually determines the cell color [7]. Thus, to realize PT a-Si:H cells that exhibit different colors, optical function layers that allow for the ready control of their color are required.

In general, the reflection spectrum of a cell can be controlled by its interference, which is determined by the refractive index and the physical thickness of the optical function layer; by varying these parameters, the color of the layer surface, and hence that of the cell, can be adjusted [8]. In order to fabricate cells that embody different colors, we introduced a color-adjusting layer (CAL) with a refractive index lower than that of the a-Si:H layer in PT a-Si:H cells during the fabrication process. The CAL, which had a high transparency and low resistivity, helped prevent the cell performance from deteriorating during color change. Transparent conductive oxides (TCOs) such as Al, Ga, In, and B-doped ZnO, commonly used to form the top

Abbreviations: a-Si:H, hydrogenated amorphous silicon; BIPV, building-integrated photovoltaic; DSSC, dye-sensitized solar cell; PT, penetration-type; CAL, color-adjusting layer; TCO, transparent conductive oxide; rf, radio frequency; XRD, X-ray diffraction; GZO, Ga-doped zinc oxide; EQE, external quantum efficiency; S-matrix, scattering matrix; FF, fill factor

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electrode in PT a-Si:H cells, allow one to control the reflection spectra of the cells by simply changing the optical thickness of the TCO layer. However, changing the thickness of the TCO layer can affect the electrical performance of the cells. For instance, the series resistance of the cell increases with a decrease in the TCO layer thickness [9]. Dielectric materials such as TiO_2, SiO_2, and Al_2O_3 exhibit a high degree of interference, but, given their high resistivity, they need to be patterned in order to be able to transport the generated carriers to the electrode.

In order to overcome these disadvantages, we employed a cuprite or cuprous oxide (Cu_2O) thin film as the CAL. Cu_2O is a natural p-type semiconductor with a direct band gap energy of 2.17 eV (for bulk) and a refractive index of 2.55. It has been extensively studied because copper is relatively nontoxic, cheap, and abundantly available [10–12]. In addition, it has a high transparency in the visible region and a resistivity lower than that of other dielectric materials. Therefore, it was assumed that PT a-Si:H cells that exhibit various colors should be realizable without significant electrical loss, owing to the optical interference exhibited by the Cu_2O, TCO, and a-Si:H layers.

In this study, we investigated the feasibility of using a Cu_2O thin film as a CAL that allows the backside colors of PT a-Si:H solar cells to be controlled. By changing the thickness of the Cu_2O layer and the arrangement of the layer structure (TCO/Cu_2O or Cu_2O/TCO), we could achieve variously colored solar cells while maintaining the cell efficiency.

2. Materials and methods

We investigated the optical, electrical, and structural properties of Cu_2O thin films for use as the CAL in solar cells. First, Cu_2O thin films were deposited on a glass substrate at room temperature by the radiofrequency (rf) magnetron reactive sputtering method using a copper target (99.99% purity). During the deposition process, Ar was used as the sputtering gas, and O_2 and N_2 were used as the reactive gases. N_2 helps the preferential formation of stable Cu_2O films with the (200) orientation [13]. The flow rates for O_2 and N_2 were fixed at 2.2 sccm and 25 sccm, respectively. The pressure within the deposition chamber during the deposition process was 20 mTorr. The thicknesses of the deposited layers ranged from 20 to 540 nm. The structural properties of the layers were characterized through X-ray diffraction (XRD) analyses performed in the $\theta-2\theta$ mode. The sheet resistances of the deposited layers were measured using a four-point probe. The thicknesses of the layers were measured with a stylus-based surface profiler (Alpha-Step IQ, KLA-Tencor) and scanning electron microscopy (SEM). The reflectances and transmittances of the layers were measured through ultraviolet–visible spectroscopy over wavelengths ranging from 400 to 900 nm.

P-i-n-type a-Si:H solar cells were fabricated on textured Ga-doped zinc oxide (GZO)-coated glass at 250 °C using a conventional plasma-enhanced chemical vapor deposition system at 13.56 MHz. All deposition steps were performed in the same chamber, and 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. The GZO coating was deposited at 200 °C by rf magnetron sputtering. Wet texturing was performed on the TCO layer to increase light scattering. In order to make the cells sufficiently transparent for use as PT-type BIPVs, we employed GZO films as the top and bottom TCO layers and used an intrinsic (*i*-) a-Si:H layer with a thickness of only ~140 nm. However, these factors had a detrimental effect on the efficiency of the resultant cells, which was lower than that of conventional opaque a-Si:H thin-film cells with a thicker *i*-layer [14].

The Cu_2O films used to adjust the reflection and transmission colors of the cells were inserted in two configurations: they were either incorporated under the top TCO layer (resulting in an inner-type cell) or above the top TCO layer (resulting in an outer-type cell), as shown in Fig. 1. The colors of the cells were observed at the upper surface of the top TCO layer, i.e., at the surface where the incident light transmits through the device. To perform current density–voltage (*J*–*V*) analyses under illumination, a solar simulator with a global Air Mass 1.5 (AM1.5) spectrum was used at room temperature. The aperture area of the solar cells was measured to be 0.25 cm^2. To measure the quantum efficiencies of the cells, an IQE-200 (Newport) quantum efficiency measurement system was used.

3. Results and discussion

3.1. Characteristics of the Cu_2O thin films

When employing a Cu_2O thin film as the CAL in a PT a-Si:H solar cell, the thickness of the film should be as low as possible in order to reduce the absorption loss. However, Cu_2O films deposited by rf magnetron reactive sputtering undergo structural changes during the initial stage of the deposition process, and these changes are accompanied by variations in the electrical and optical properties of

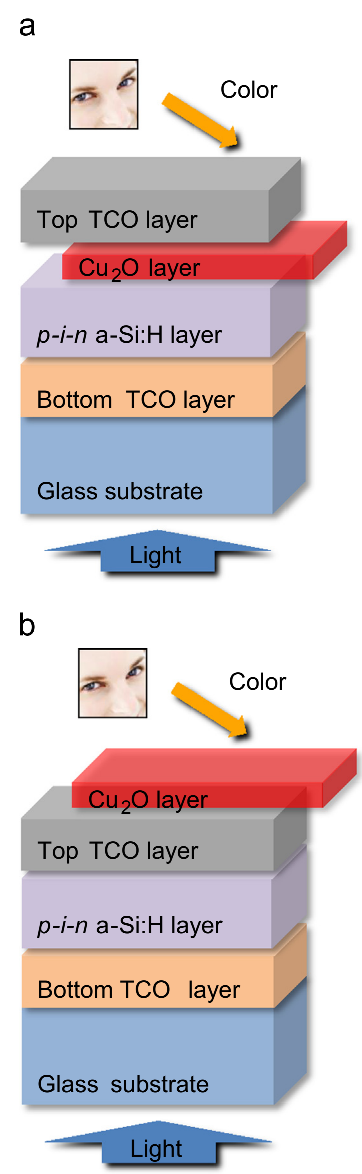

Fig. 1. Structural view of a penetration-type hydrogenated amorphous silicon (a-Si:H) single cell with (a) the inner-type structure and (b) the outer-type structure. TCO: transparent conducting oxide, and a-SiH: hydrogenated amorphous silicon.