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Improved adhesion of multi-layered front electrodes of transparent a-Si:H solar cells for varying front colors

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ABSTRACT

A low temperature deposition process was developed to fabricate ultra-thin, transparent, multi-layered electrodes (TMEs) suitable to be used on variously shaped flexible substrates, as those utilized in the transparent solar cells of building-integrated photovoltaic (BIPV) systems. The fabricated TMEs consisted of a bottom layer (BL) of gallium doped zinc oxide (GZO), an Ag-layer, and optoelectronic-controlling layers (OCLs) of GZO; and exhibited a high transmittance of 90% at 550 nm, and a low sheet resistance of 9.4 Ω/sq. at the thickness of ~ 100 nm. Because the Ag of TMEs easily detach from inorganic or amorphous surfaces, the GZO-BL was chemically treated in a diluted acetic and nitric acid mixture (10:2) to generate changes in its surface energy and improve the Ag adhesion. To quantitatively evaluate the Ag adhesion of TMEs, we proposed and conducted a tape pull-out adhesion test, and found the optimum GZO-BL texturing condition. The developed TMEs were used as the front transparent conductive electrodes of transparent a-Si:H solar cells to tune their reflection colors. By changing the thickness of the OCL, a wide range of colors was obtained without serious efficiency variations, as was predicted by optical simulations. The fabricated transparent cells show a high efficiency of 4.8%, as well as a high average transmittance of ~ 20% in the visible range. The developed TME structure, using the proposed deposition process, can be fabricated on various substrates and can be applied to devices that require a variety of colors such as BIPVs, wearable PVs, and the PVs of moving vehicles.

1. Introduction

Most residential energy consumption comes from metropolitan areas, which is also where most greenhouse gases are emitted. Thus, the construction of net zero-energy-buildings (ZEB) would be an ideal solution to these problems. Since the 1970s, net ZEBs that use renewable energy, instead of power from fossil fuels or nuclear sources, have been developed in various areas [1,2]. In this regard, solar energy photovoltaics could be the most effective renewable energy source for ZEBs (in comparison to other sources such as wind, geothermal, and solar thermal energy) because buildings use electricity, which can be directly obtained from photovoltaic devices. Transparent solar cells can be used as parts of ZEBs in building-integrated photovoltaic (BIPV) systems (e.g. roofs, façades, and windows), and therefore, solar cells need to be fabricated on various substrate shapes, such as rounded and flexible substrates, and not only on flat glasses.

In particular, hydrogenated amorphous silicon (a-Si:H) transparent solar cells are suitable for BIPV systems because, besides being inorganic solar cells, they are only thin- films solar cells with proven long-term stability, comparable to that of the common parts of buildings. Although organic or dye-sensitized thin film solar cells could also be used as transparent solar cells, their reliability has not been proven [3–5]. Moreover, a-Si:H transparent solar cells also offer other numerous advantages to BIPV systems [6–9]. For example, Si is a low-cost, abundant, and nontoxic material [8–12], and the fabrication technology of a-Si:H is mature enough to be commercially used in the production of flat panel displays on glass substrates, or on flexible substrates of several square meters in area.

In a-Si:H solar cells, transparent conducting oxide (TCO) layers are used for the front or rear transparent conducting electrodes (TCEs). To date, by simply providing good conductivity and transparency, indium tin oxide (ITO), fluorine-doped tin oxide, and zinc oxide (ZnO) TCOs have been generally used on the glass substrates of solar cells and flat panel displays. For BIPV applications, however, other features are also important for the production of TCEs: thinness, flexibility, and durability on various metal foil or plastic substrates [13–15]. Likewise, a reliable process, depositing thin TCEs at low temperatures, is not only required to release the thermal stresses of the flexible substrates

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