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Spray coated silver nanowires as transparent electrodes in OPVs for Building Integrated Photovoltaics applications

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ABSTRACT

The application of spray coated silver nanowires (AgNWs) onto OPVs for building Integrated Photovoltaics (BIPVs) is demonstrated. By using AgNWs with PEDOT:PSS, a transparent conductive layer was demonstrated on top of an P3HT:PCBM active layer with a sheet resistance of 30 Ω/□ for 90% transparency. This has been applied to two separate configurations; semi-transparent OPVs for solar glazing applications and OPVs onto an opaque substrate, namely steel. For the latter, a novel technique to planarise the steel substrate with an intermediate layer is also presented, with a substantial decrease in surface roughness reported to ensure that the substrate is smooth enough to use for OPV fabrication. The use of SU-8 as an intermediate layer reduced the surface roughness to $R_A = 10$ nm, which is one of the lowest values reported to date, and was achieved on a low cost substrate (DC01 low carbon steel) using solution processing.

1. Introduction

Building Integrated Photovoltaics (BIPVs) comprises of a group of solar cell technologies that are built into (instead of installed onto) the building structure and can replace some building materials (such as windows or roofs) [1,2]. BIPV's potential to readily integrate into the building envelopes holds aesthetic appeal for architects, builders and property holders. Currently, BIPVs claim a very small share of the PV market, but it is with the emergence of technologies such as organic photovoltaics (OPVs), this proportion could increase [3]. OPV technology does possess numerous advantages over existing solar cell technologies for BIPVs. These include the ability to tune the appearance of the module, low cost of raw materials, low toxicity of materials, low rare metal usage for solar cell construction and low energy payback time [4,5].

Currently, there are two primary BIPV applications sought by users of OPV technology; firstly, semi-transparent OPVs for applications in bus shelters, green houses or solar glazing applications. In the case of a semi-transparent OPV, a transparent substrate of glass or plastic is normally used along with two transparent electrodes [6,7]. The second application is for roof mounted PVs, where an opaque building material is normally used as the substrate. Today, steel remains one of the primary materials used in many external structures such as industrial storage and commercial buildings for use in roofing and facades. Several groups have demonstrated devices on steel including Galagan et al., who laminated OPVs onto steel substrates [8] and Kumar [9] who used high grade steel as an electrode for OPVs.

To create a truly building-integrated PV, as opposed to a building attached PV, compatibility is needed between the substrate and the solar cell materials and process conditions. For this reason, an intermediate layer (IL) must be coated between the steel and solar cell. In the case of OPVs, the requirements for this layer are very demanding as the active layer needs to be deposited onto a low roughness underlying substrate (typically $R_A < 20$ nm). Therefore, this IL layer must planarise the surface, as well as be an insulator to the steel substrate, which is important for large area monolithic cell integration. Typical ILs are composed of single or multi-layers, using ceramic materials such as SiO_x and Al_2O_3 deposited by vacuum (physical vapour deposition (PVD) and plasma enhanced chemical vapour deposition (PECVD)) or non-vacuum (sol-gel, anodization) techniques [10,11]. To date, the best surface roughness achieved is around $R_A = 12$ nm using vacuum-deposited radio frequency PVD onto stainless steel substrates [12].

In the case of these BIPV applications, a transparent top electrode is also needed. To achieve this, Galagan et al. used a silver grid electrode and Kumar et al. used a PEDOT:PSS layer. Other potential alternatives which have been reported include graphene

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[13] and thin metallic layers [14]. Silver nanowires (AgNWs) have also recently emerged as a promising solution to act as transparent electrode for OPVs. This is due to their comparable optical and electrical performance to ITO and have been demonstrated in non-inverted structures [15,16] and inverted structures [17,18]. However, scientific challenges still remain to establish AgNWs as a serious candidate solution due to their processing and high surface roughness leading to electrical shorts.

In this work, we have developed a novel approach to fabricate OPVs onto steel using spray-coated silver nanowires (AgNW) as transparent electrodes. By spray coating, the transparent electrodes possessed a sheet resistance of 30 Ω/□ at 90% transparency. To enable OPVs on steel, a solution processible approach has also been developed whereby a epoxy IL is coated onto steel. The roughness of this IL is one of the best reported on a steel substrate. Furthermore, this has applied to low carbon steel (DC01), which is a low cost, high roughness steel grade and the demonstration of OPV devices on such a substrate could provide a route for low cost module fabrication for BIPV applications. The device configuration can also be used for fabrication of semi-transparent OPVs by using a glass substrate. These were used to create semi-transparent OPVs, which produced an average transparency of 51% from 350 to 800 nm.

2. Experimental

2.1. Device fabrication of semi-transparent OPVs

Solar cells on glass substrates composed of a transparent bottom electrode, a thin-film active layer, and a transparent top electrode have been constructed. The schematic in Fig. 1 (a) provides an overview of the device structure and illumination is possible through the top or bottom electrode. These cells were based on indium tin oxide (ITO) coated glass substrates (R_s = 18 Ω/□, transparency = 84% with glass, transparency = 94% without glass, purchased from Xinyan Ltd.) which were cleaned using deionised water, acetone and isopropanol, then treated in an oxygen plasma for 10 min.

On the electrode, an zinc oxide electron transporting layer was prepared from zinc acetate dehydrate (109 mg) dissolved in 2-methoxyethanol (1 mL) and ethanolamine (0.03 mL) solution, which was spin-coated at 2000 rpm on the metal electrode. The samples were then annealed in the presence of atmospheric air at temperatures of 150 °C for 30 min so that the zinc acetate to calcinate into zinc oxide [19]. After annealing, the thickness of the ZnO was measured at 30 nm using AFM. Active layer blends using poly(3-hexylthiophene) (P3HT) and [6,6]-Phenyl-C_{61}-butyric acid methyl ester (PCBM) with weight ratios 5:4 were prepared and mixed with chlorobenzene solvent with a concentration of 30 mg/mL. Samples were stored in a nitrogen atmosphere glovebox ($[O_2]$, < 1 ppm; $[H_2O]$, < 100 ppm), where the active layers was applied by spin-casting from the 60 °C solution. The active layer were annealed at 140 °C for 60 min before the hole transport layer i.e. Clevios HTL PEDOT:PSS, was spin-coated at 4000 rpm. The transparent top electrode was fabricated by spray coating of PH1000 PEDOT:PSS (purchased from Ossila) and 0.5 mg/mL silver nanowire (Ag NW) (L-50, purchased from ACS Materials) in ethanol subsequently onto the HTL in fume hood through a shadow mask with an air brush. The PH1000 was modified by dimethyl sulfoxide (DMSO) at different concentration, from 5 vol% to 40 vol% (see detail in next section). Both AgNW and PEDOT mixtures were sonicated for 10 min before applying.

2.2. Steel preparation

In this work, four grades of steel have been selected for trials. Different types of steels were identified; stainless steel (AISI430), galvanised/aluminized cold rolled low carbon steel (DX51D+Z and DX51D+AS), uncoated low carbon steel (DC01). AISI430 possessed the lowest initial roughness, but the highest cost, whereas DC01 exhibited the highest roughness and the lowest cost. All the steels were subjected to a high steel speed cold rolled process in order to decrease their thickness to 0.3 mm and roughness at MK Metalfolien GmbH, Hagen, Germany. After rolling, the roughness of the DC01 steel reduced and exhibited the smoothest surface finish (see Table 1), although the level of the roughness (R_A = 0.10 μm, R_{MAX} = 0.71 μm) was too great to use for OPV fabrication. The substrates were cut to 2 × 2 cm sizes and cleaned by subsequent sonication in DECON, DI water, followed by solvent cleaning using. After cleaning and characterisation, an IL epoxy layer of SU-8 2050 (Chestech ltd., UK) was doctor bladed and spin coated at 2000 rpm onto the cleaned substrate, and cured at 150 °C for 15 min and then hard baked at 250 °C for 10 min.

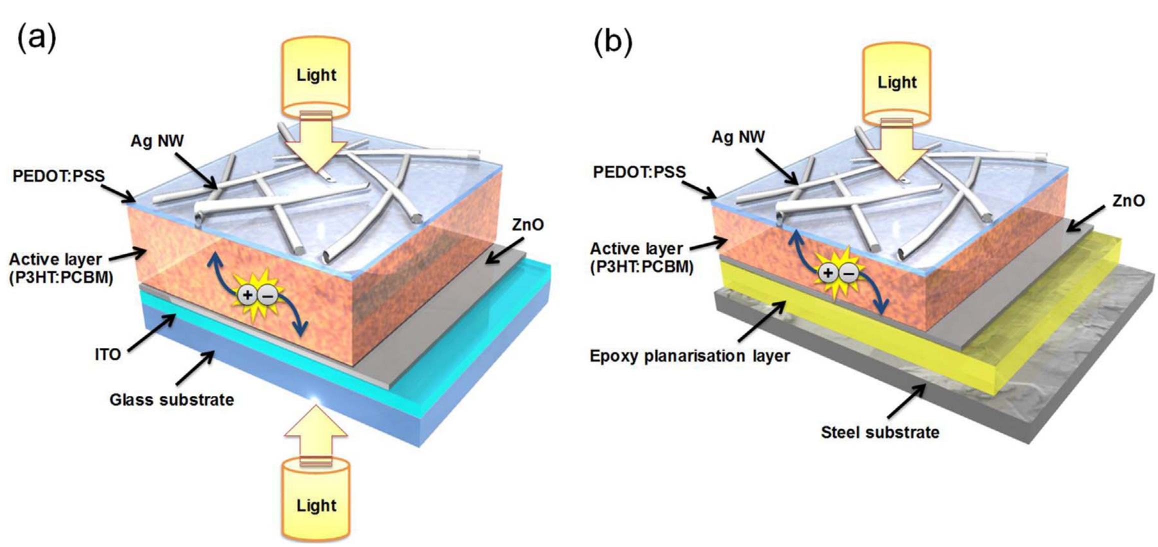

Fig. 1. Schematic of the (a) semi-transparent OPV where photocurrent can be achieved bifacially and (b) of the OPV manufactured onto steel. Planarization of the underlying substrate is imperative to ensure no electrical shorts are present.