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Novel hybrid electrode using transparent conductive oxide and silver nanoparticle mesh for silicon solar cell applications

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Abstract

Transparent conductive oxides (TCOs) have been widely used as the front electrodes for various solar cell structures, including heterojunction silicon wafer solar cells and the vast majority of thin-film solar cells. For heterojunction silicon wafer solar cells, the front TCO layer not only serves as a top electrode (by enhancing the lateral conductance of the underlying amorphous silicon film), but also as an antireflection coating. These requirements make it difficult to simultaneously achieve excellent conductivity and transparency, and thus only high-quality indium tin oxide (ITO) has as yet found its way into industrial heterojunction silicon wafer solar cells. For thin-film solar cells, in order to provide efficient lateral conductance of the charge carriers, normally a TCO layer of a few hundred nanometers thickness is used which impedes the optical transparency due to the enhanced free carrier absorption. To reduce the conflict between conductivity and transparency, and to separately engineer the electrical and optical properties, a hybrid electrode is proposed and fabricated by us which consists of a TCO layer (optical layer) and a silver nanoparticle mesh (electrical layer). This hybrid electrode is demonstrated to have a 10 times higher lateral conductance compared to a single TCO layer, while maintaining high light transmission in a wide wavelength range. Due to the excellent performance of the hybrid electrode, it is demonstrated that such an electrode is suitable for various solar cell structures.

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Keywords: heterojunction; thin film; transparent conductive oxides; silver nanoparticles; solar cells

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1. Introduction

Transparent conductive oxides (TCOs) are widely used as the front electrode for a variety of solar cell structures. The ideal TCOs to be used as the front electrode should be fully transparent in a wide wavelength range and have metal-like conduction properties; however this is not the case for real TCO materials. Due to the limited conductivity and non-negligible light absorption of TCOs, there is always a trade-off between conductivity and transparency. For heterojunction (HET) silicon wafer solar cells, which feature an amorphous silicon layer stack on the illuminated surface, the use of TCO is not only for lateral carrier transport, but also to provide good antireflection properties. These requirements constrain the carrier concentration and thickness of the TCO, thus making it a challenge to optimize both the electrical and the optical performances. Indium tin oxide (ITO) is the most commonly used TCO material for HET solar cells, due to its excellent electrical and optical properties. Current deposition techniques are able to form ITO films with resistivities in the range of 10^{-5} to 10^{-4} Ωcm while maintaining the optical transmissions in the range of 80-90 % [1-6]. Due to the high cost of ITO, there is increasing interest in more cost-effective materials such as aluminum-doped zinc oxide (AZO) and gallium-doped zinc oxide (GZO). However, the efficiencies of HET solar cells using the cost-effective materials are lower due to the increased resistive losses in the TCO layer [7, 8]. For thin-film solar cells, due to the poor lateral conductance of the thin active layer, a thicker TCO layer of up to 1 μm thickness is normally used which results in low light transmission in the long wavelength range due to the increased free carrier absorption.

One possibility to reduce the sheet resistance of the front electrode is to add a more conductive layer in between of two TCO layers, for example a thin metal layer, to form a multilayer structure [9, 10]. Although the lateral conductance of such structures is greatly enhanced, the overall transmission suffers for large parts of the solar spectrum, making this approach unsuitable for solar cell applications. Another alternative approach is to use the metal mesh networks that are fabricated using either patterning methods or wet-coating processes of nanostructures (i.e. nanoparticles, nanowires). Commonly used patterning methods include lithography [11, 12] and direct writing methods by inkjet printing [13, 14]. The patterning methods are able to form regular and periodic structures, with an accurate control of the network line width down to the nanoscale range; however they are limited to small-area devices due to the complex and time-consuming fabrication processes. The wet-coating methods, including spin coating [15], Meyer rod coating [16] and spray coating [17] are normally solution based. Therefore, they are easier and cheaper to be applied to large-area devices such as solar cells. Given the fact that the optimal sheet resistance of the front electrode used in a solar cell should be below 10 Ω/□ [18], only a few highly transparent materials with comparable sheet resistance are suitable for photovoltaic applications.

In order to enhance the lateral conductance of the front electrode, a silver nanoparticle mesh is used in this study as an electrical layer which exhibits a sheet resistance below 5 Ω/□ and 90 % transparency in the visible range (380-780 nm) of the spectrum. In this work, two hybrid structures (A and B) that are fabricated by superimposing the silver nanoparticle mesh with a TCO layer are proposed for different applications. Hybrid structure A (see Fig. 3a) targets applications in HET silicon wafer solar cells (or substrate thin-film solar cells, e.g. CIGS solar cells). It uses an 80 nm thick TCO layer as an antireflection coating onto which a silver nanoparticle mesh is deposited. This structure allows to separately engineer the electrical and optical properties of the front electrode: the electrical layer (i.e. the silver mesh) provides sufficient lateral conductance for the charge carriers while the optical layer (i.e. the TCO layer) mainly functions as an antireflection coating (but also provides a short-distance lateral conduction path towards the silver mesh) [19]. Hybrid structure B (see Fig. 3b) is not very different from the hybrid structure A. It aims for applications in superstrate thin-film solar cells (e.g. organic solar cells, amorphous silicon solar cells, CdTe solar cells, etc.). The silver nanoparticle mesh is inserted between the glass substrate and the solar cell structure, which forms a hybrid electrode with the TCO layer. Due to the good lateral conductance of the silver mesh, the lateral conductance of a thin TCO layer (around 100 nm) is sufficient for carrier conduction in between of the silver lines. For both structures, cost-effective TCO materials, such as AZO, can be used to further reduce the device cost.