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Transparent conductors with an ultrathin nickel layer for high-performance photoelectric device applications

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ABSTRACT

A thin nickel (Ni) layer of thickness 5 nm was inserted in between the indium tin oxide (ITO) layers of thickness 50 nm each so as to increase the conductivity of ITO without affecting much of its transmittance nature. ITO layers with and without Ni film were prepared by reactive DC sputtering on both Si and glass substrates. The influence of Ni layer on the optical and electrical properties of prepared devices was investigated. Due to the insertion of thin Ni layer, the resistivity of ITO/Ni/ITO sample ($3.2 \times 10^{-4}\ \Omega$ cm) was reduced 10 times lesser than that of ordinary ITO layer ($38.6 \times 10^{-4}\ \Omega$ cm); consequently it increased the mobility of ITO/Ni/ITO device. The external and internal quantum efficiencies (EQE and IQE) of ITO/Ni/ITO device exhibited better performance when compared to ITO layer that has no Ni film. At wavelengths of 350 and 600 nm, the photoresponses of ITO/Ni/ITO device were predominant than that of reference ITO device. This highly conductive and photoresponsive Ni inserting ITO layers would be a promising device for various photoelectric applications.

1. Introduction

The use of transparent conductive oxide (TCO) layer in photoelectric devices enhances transparency, conductivity and thereby the overall performance of the devices [1–5]. ITO is widely used in optoelectronic devices as electrodes, passivation layer and anti-reflector proficiently because of its unique properties of high transparency, low resistivity, high carrier concentration ($\sim 10^{21}$ cm^{-3}), wide energy band gap ($\sim$3.9 eV) and eminent work functions ($\sim$4.5 eV) [6–8]. The high optical transparency and low electrical resistivity of ITOs are the main reasons to retain this in device fabrications. However, the ITO films deposited at room temperature exhibit relatively high electrical resistivity in the order of $10^{-3}\ \Omega$ cm [9] due its amorphous nature. Therefore, in order to increase the conductivity, thin metal layers are inserted in between ITO layers [10]. Though this method helps to improve the conductivity of ITO films, consequently it reduces the transparency due to opaque nature of metal particles. To solve this, heating the substrates during deposition or annealing the samples after deposition is carried out to retain the trade-off between conductivity and transmittance of the metal embedding ITO structures [11]. Thickness of metal film is also an important entity to define the efficiency of the devices. In order to obtain an optical transmittance of above 60% and low resistance, metal films between ITO layers should be uniform, continuous and ultrathin [10]. Park et al. [12] have analyzed the influence of Ni thickness on the properties of TCO materials. The optical properties of ITO/Ni/ITO samples have been characterized with respect to different annealing temperatures by few researchers [10,13–17].

In this work, the enhanced electrical properties and photoresponsive characteristics of ITO/Ni/ITO device are

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emphasized. The structural, optical and electrical properties of ITO/Ni/ITO sample were characterized and compared with those of ordinary ITO layer. Both ITO/Ni/ITO and ITO single layer samples were annealed at 300 °C for 10 min by rapid thermal process. It was reported that the conductivity, carrier concentration, internal and external quantum efficiencies (IQE and EQE) and photo-response of Ni embedding ITO layers were superior to those of a single ITO layer.

2. Experiment details

ITO layers of 50 and 100 nm thicknesses were deposited on both Si and glass substrates using DC sputtering system (SNTEK, Korea). A DC power source (3.70 W/cm^2) was applied to a 4-in. ITO target (In_2O_2 containing 10 wt% SnO_2) at room temperature (RT) under Ar atmospheric condition. The ITO film of 100 nm thickness was used as reference film. A thin Ni layer of 5 nm thickness was then deposited on ITO of 50 nm thickness. Above thin Ni layer, another ITO layer of 50 nm thickness was deposited to produce ITO/Ni/ITO sample. Rapid thermal annealing (RTA) was subsequently performed at 300 °C for 10 min under vacuum condition. A field emission scanning electron microscope (FESEM, FEI Sirion) was used to observe the cross-sectional and top view images of prepared samples. The crystalline phases of ITO and Ni were determined from high resolution transmission electron microscope (HRTEM) and selected area electron diffraction (SAED) images. The samples deposited on glass substrates were used to measure the optical properties of the ITO/Ni/ITO and single ITO films with a UV spectrophotometer (Scinco, Neosys-2000). A quantum efficiency measuring system (McScience, K3100) was used to measure the quantum efficiencies of prepared samples. Electrical characteristics were obtained using a probe station with measuring instruments (Keithley 2400).

3. Results and discussions

The cross sectional and top view images of ITO/Ni/ITO and single ITO reference films were recorded using FESEM as shown in Fig. 1(a) and (b). The intersection layer of Ni between top and bottom ITO layers (50 nm thickness each) is presented in Fig. 1(a) whereas in the reference film (shown in Fig. 1(b)), continuous growth of 100 nm thick ITO layer is observed. The crystalline structure of ITO layers and thin Ni film were identified from HRTEM and SAED images. The formation of ITO/Ni/ITO combination, poly-crystalline nature of ITO and Ni layers are clearly represented in Fig. 2(a), (b) and (c) respectively. It was found that there is no trace for NiO formation which will

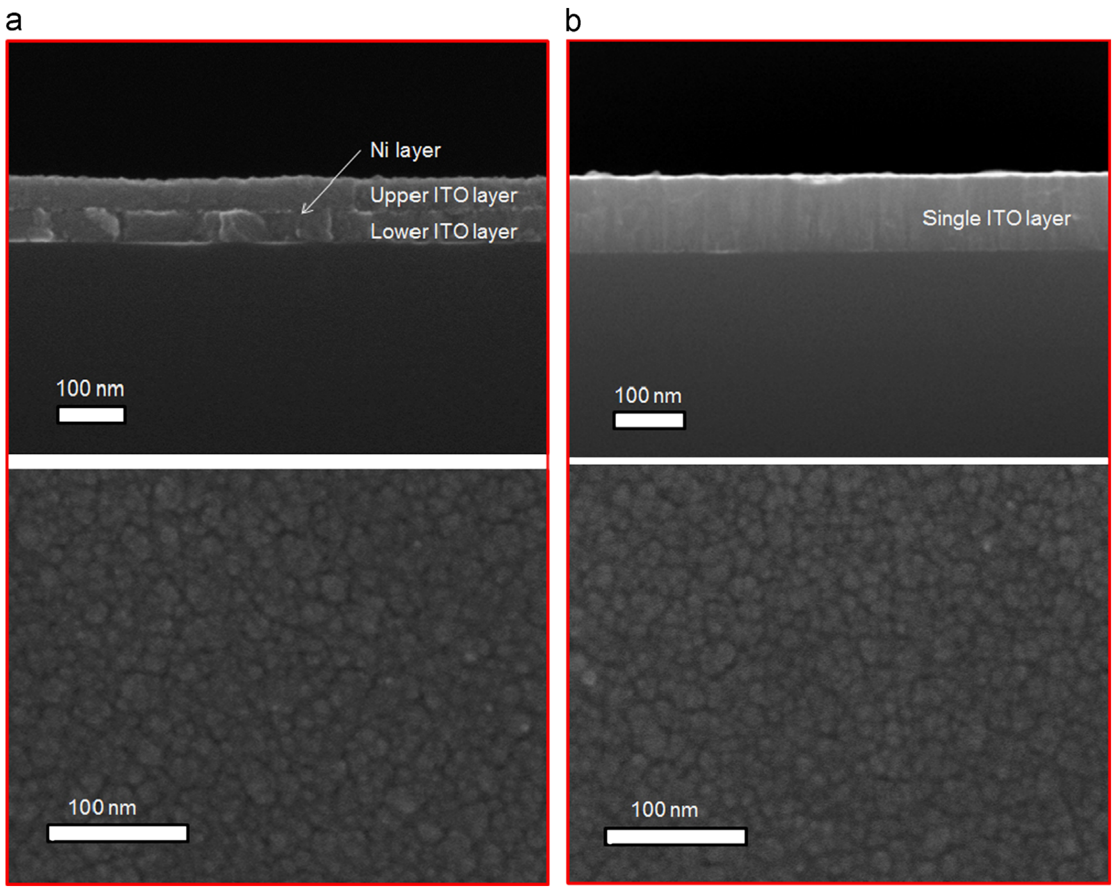

Fig. 1. Cross sectional and surface morphology FESEM images of (a) ITO/Ni/ITO (50–5–50 nm) and (b) single ITO layer (100 nm) samples.