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Characterization of ZnO nanowires grown on Ga-doped ZnO transparent conductive thin films: Effect of deposition temperature of Ga-doped ZnO thin films

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Abstract

ZnO nanowires on Ga-doped ZnO (GZO) transparent conductive thin films deposited at different substrate temperatures were demonstrated and characterized. The GZO thin films were deposited at various substrate temperatures ranging from 200 to 600 °C in order to study the influence of deposition temperature of the GZO on the characteristics of the ZnO nanowires. The resistivity of the GZO thin films decreased from 5.11×10^{-4} (200 °C) to 4.83×10^{-4} Ωcm (400 °C) and then increased to 6.12×10^{-4} Ωcm (600 °C). The ZnO nanowires were grown vertically and were highly *c*-axis oriented on the GZO thin films at every deposition temperature without any seed layers. The crystallinity of the ZnO nanowires was improved with increasing deposition temperature of the GZO thin films. In addition, as deposition temperature increased, the diameter of the ZnO nanowires increased, while the density decreased. Photoluminescence (PL) measurement and energy-dispersive X-ray spectroscopy (EDX) proved that the ZnO nanowires on the GZO thin films deposited at higher substrate temperature had less defects and were closer to stoichiometric ZnO. After the growth of the ZnO nanowires on the GZO thin films, the transmittance decreased with respect to that of the GZO only thin films, but the sample was still transparent with an average optical transmittance higher than 70%.

Keywords: Ga-doped ZnO; ZnO nanowires; Transparent conductive oxide

1. Introduction

ZnO nanowires have received considerable attention because of their potential applications in devices such as solar cells, chemical sensors, light-emitting diodes (LED), optical detectors, and so forth. In recent years, the emergence of transparent electronics for next-generation optoelectronics has generated interest in investigating the growth of ZnO nanowires on transparent materials. In particular, ZnO nanowires grown on transparent conductive layers can be applied to various electronic devices. For instance, they can be used to fabricate transparent chemical or optical sensors. In addition, they can play a role as the working electrodes in dye-sensitized solar cells (DSSC) [1–3].

We have already reported on ZnO nanowires grown on Ga-doped ZnO (GZO) transparent conductive layers [4]. GZO has an advantage over conventional transparent conductive oxide (TCO) such as indium tin oxide (ITO) and fluorine tin oxide (FTO) in terms of cost. Furthermore, ZnO nanowires can be grown on GZO thin films directly without any additional seed layers or catalysts due to their shared crystal system. When considering GZO thin films to be used as transparent electrodes, deposition temperature is a key factor in determining the electrical properties. However, to our knowledge, no report exists describing the effect of deposition temperature of GZO thin films on the growth behavior and properties of ZnO nanowires.

In this paper, we report GZO transparent conductive thin films deposited at various substrate temperatures for ZnO nanowire growth. Because the GZO thin films simultaneously play a role as a transparent electrode and a seed layer, we

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investigate the electrical, optical, and structural properties of GZO thin films concretely. In addition, the influence of the GZO thin films deposited at various substrate temperatures on the growth and characteristics of ZnO nanowires is also discussed.

2. Experimental

GZO thin films (100 nm) were prepared by using a pulsed laser deposition (PLD) system. A ZnO target containing 2 wt% Ga_2O_3 was ablated, and the depositions were carried out on pre-cleaned glass substrates at temperatures varying from 200 to 600 °C. During every deposition, the oxygen partial pressure in the chamber was kept at 20 mTorr. X-ray diffraction (XRD) was used to characterize the structural properties of the GZO thin films. The surface morphology and optical transparency were measured by field emission scanning electron microscopy (FE-SEM) and UV–vis spectroscopy, respectively. Hall measurement was also performed by the Van der Pauw method at room temperature to analyze the electrical properties of the GZO thin films.

ZnO nanowire arrays were grown on the GZO thin films described above. The growth was accomplished in a horizontal tube furnace system by vapor transport process. ZnO and graphite powder mixture with a weight ratio of 1:1 was prepared and placed at the center (high temperature zone) of the tube furnace. The GZO-coated glass substrates were located at low temperature zone and the working pressure was kept at 70 Torr in Ar atmosphere. The morphology and structure of the ZnO nanowires grown on GZO thin films were observed by FE-SEM. The structural and optical properties of the ZnO nanowires were studied by XRD and photoluminescence (PL) measurement, respectively. The chemical composition was determined by energy-dispersive X-ray spectroscopy (EDX) analysis.

3. Results and discussion

Fig. 1 shows the XRD θ–2θ spectra of the GZO thin films deposited at 200, 400, and 600 °C. As already reported, the only diffraction peak of ZnO (0002) is detected in θ–2θ scan ranging from 20 to 60°. As deposition temperature increases, the intensity of the (0002) peak increases, and the full width at half maximum (FWHM) decreases. The FWHM is reduced from 0.46 to 0.25°. The change in the FWHM according to deposition temperature is also given in Fig. 1. From these results, it can be realized that *c*-axis oriented GZO thin films were grown because of the lowest surface free energy of (0002) plane in wurtzite ZnO structure [5]. In addition, the improvement of the crystallinity and the degree of orientation with increasing deposition temperature can also be noticed.

The electrical properties of the GZO thin films determined by Hall measurement are shown in Fig. 2. The resistivity decreases from 5.11×10^{-4} to 4.83×10^{-4} Ωcm with increasing deposition temperature from 200 to 400 °C. Obviously, the Hall mobility of the GZO thin films increases at 400 °C, whereas the carrier concentration slightly decreases. The Hall

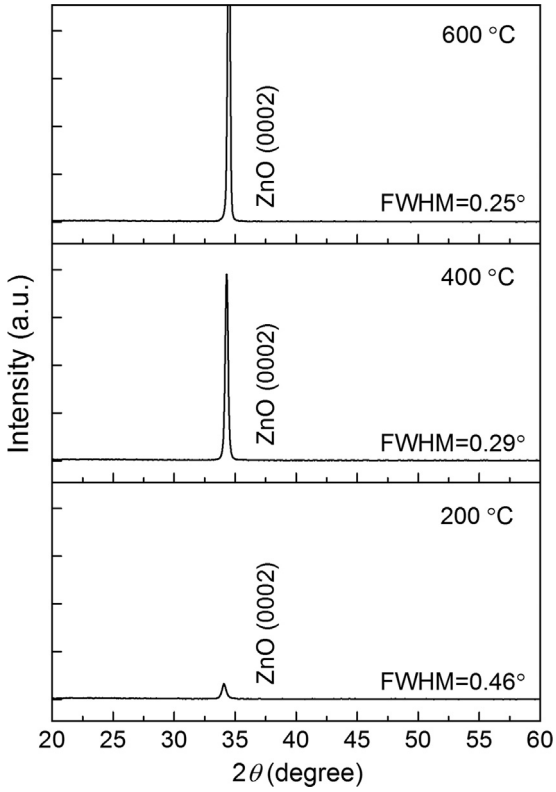

Fig. 1. XRD θ–2θ spectra of the GZO thin films deposited at 200, 400, and 600 °C.

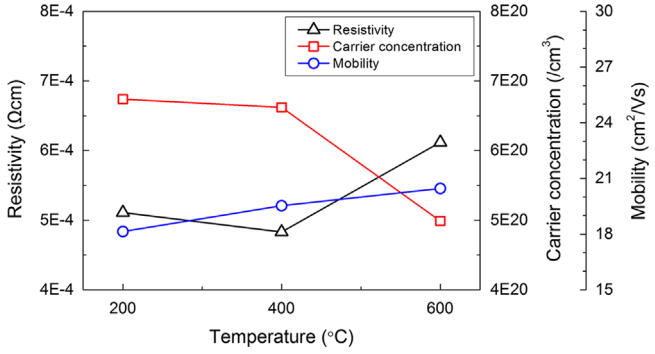

Fig. 2. Electrical properties of the GZO thin films deposited at 200, 400, and 600 °C.

mobility increases continuously above 400 °C. However, it can be confirmed that the carrier concentration decreases dramatically, and as a result, the resistivity increases remarkably to 6.12×10^{-4} Ωcm at 600 °C. The persistent increase in the Hall mobility in the whole temperature range is due to higher crystallinity of the GZO thin films at higher deposition temperature, which was already mentioned in XRD analysis. Meanwhile, the continuous decrease in the carrier concentration might be due to increasing chemisorbed oxygen which acts as an electron trap [6]. In terms of resistivity, as shown above, 400 °C can be regarded as the optimal deposition temperature for the GZO thin films. However, it is also clear that the resistivity of the GZO thin films is low enough even at 200 and 600 °C.