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Effect of depth of traps in ZnO polycrystalline thin films on ZnO-TFTs performance

Maria I. Medina-Montes [a,*], Leonardo A. Baldenegro-Perez [b], Raul Sanchez-Zeferino [c], Lizeth Rojas-Blanco [a], Marcelino Becerril-Silva [d], Manuel A. Quevedo-Lopez [b], Rafael Ramirez-Bon [a]

[a] *Centro de Investigación y Estudios Avanzados del IPN, Unidad Querétaro, Apdo. Postal 1-798, Querétaro, Qro 76001, Mexico*
[b] *Department of Materials Science and Engineering, The University of Texas at Dallas, Richardson 75083, TX, USA*
[c] *Departamento de Física, Universidad de Sonora, Apdo. Postal 1626, Hermosillo, Sonora 83000, Mexico*
[d] *Centro de Investigación y Estudios Avanzados del IPN, Departamento de Física, Apdo. Postal 14-740, México, D.F. 07360, Mexico*

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ABSTRACT

ZnO thin films were processed by radio frequency magnetron sputtering at room temperature on p-Si/SiO_2 substrates under pure argon ($Ar:O_2 = 100:0$ vol.%) and argon–oxygen mixture ($Ar:O_2 = 99:1$ vol.%) gas environment. Morphological, optical and electrical characteristics of the ZnO films are reported, and they show a clear relationship with the gas mixture employed for the sputtering process. Scanning Electron Microscopy revealed the formation of grains of 15.3 and 19.9 nm average sizes and thicknesses of 59 nm and 82 nm for films growth in pure argon and argon–oxygen, respectively. Photoluminescence measurements at room temperature showed the violet emission band (centered at 3 eV) which was only detected in the ZnO film grown under pure argon. From thermally stimulated conductivity measurements two traps with 0.27 and 0.14 eV activation energies were identified for films grown in pure argon and argon–oxygen mixture, respectively. The trap at 0.27 eV is associated with a level located below the conduction band edge and it is supported by the PL band centered at 3 eV. Both types of ZnO films were used as the active channel layer in thin film transistors with thermal SiO_2 as gate dielectric. Field effect mobility, threshold voltage and current ratio were improved in the devices with ZnO channel deposited with the argon–oxygen mixture (99% Ar/1% O_2 vol.). Threshold voltage decreased from 25 V to 15 V, field effect mobility and current ratio increased from 0.8 to 2.4 cm^2/Vs and from 10^2 to 10^6, in that order.

1. Introduction

Zinc oxide (ZnO) is an *n*-type semiconductor with a direct band gap energy of 3.37 eV and it is a promising material to be used in electronics (thin film transistors) [1] and optoelectronics devices (solar cells) [2], because it possesses attractive characteristics such as high optical transparency and tunable electrical conductivity. ZnO films can be obtained by several deposition techniques. One of them, radio frequency magnetron sputtering, is a well-known technique that produces high quality polycrystalline ZnO thin films, even at room temperature and without post-thermal annealing [3,4].

ZnO polycrystalline thin films can be easily grown with a defect-rich non-stoichiometry structure [5–7]. Oxygen vacancies (V_O) and interstitials zinc (Zn_i) are the most representative native shallow donor defects in the ZnO crystalline lattice, and several reports attribute the *n*-type conductivity of ZnO to these defects [8]. However, first principle calculations indicated that the oxygen vacancies cannot cause such conductivity because are deep donors [9]. Indeed, there is a well-known level found very frequently in ZnO samples grown by different techniques, that is, an electron trap localized around 0.3 eV below the conduction band (E3 electron trap) [10,11], and the oxygen vacancies have been associated to this defect [12].

ZnO polycrystalline thin films are used as active channel layers in TFTs. Unfortunately, the electrical parameters such as field effect mobility, off current and threshold voltage, are degraded by trapping charge in the grain boundary region of the polycrystalline films [13–15], and the presence of traps can be observed in a large reduction in the drain current of family curves of TFTs [16]. In addition, oxygen vacancies concentration in the ZnO film structure impacts the TFT performance. A report in the literature showed

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* Corresponding author.
E-mail address: lebasi_tresm@hotmail.com (M.I. Medina-Montes).

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that the exposure of ZnO TFTs to plasma treatments in oxygen environment enhanced the current ratio in the devices [17].

The aim of this manuscript is to present a proposal for the origin of the anomalous electrical response of TFTs in terms of depth of traps in the structure of ZnO thin films. ZnO layers were deposited by rf magnetron sputtering at room temperature changing the gas flux during film deposition. The influence of argon and argon–oxygen gas flux on the morphological, optical and electrical properties of ZnO films is reported. Furthermore, the native defects in the ZnO films were analyzed by photo luminescence spectroscopy (PL) [18–20] and thermally stimulated conductivity (TSC) [21–23], which are typical characterization techniques to detect defects in semiconductor materials. Finally, the ZnO sputtered films were applied to assemble TFT devices and the dependence of their main electrical parameters, such as channel mobility, threshold voltage and current ratio on gas flux was investigated. The intent of this paper is to provide some insight on the relation of native defects in the ZnO sputtered films, identified by PL and TSC, with the electrical response of the ZnO-based TFTs in terms of the trap depth in the structure of ZnO thin films. We found that the presence of traps by native defects in the ZnO crystalline lattice results in some anomalous electrical response of the assembled ZnO-based TFTs.

2. Experimental details

Two ZnO-based TFTs were fabricated using a bottom-common gate configuration as is shown in Fig. 1a from Ref. [24]. The fabrication of TFTs started with the exposure of *p*-Si (1 0 0) substrates to RCA standard cleaning [25]. After cleaning, the SiO_2 dielectric layer was thermally grown on the Si substrates. Two different ZnO layers were deposited on SiO_2/p-Si by radio frequency magnetron sputtering at room temperature. The rf power, deposition time and working pressure were maintained at 100 W, 30 min and 10 mTorr, respectively. One of the films was deposited in pure argon gas environment ($Ar:O_2 = 100:0$ vol.%) and the other in argon–oxygen gas mixture ($Ar:O_2 = 99:1$ vol.%). In order to create the source and drain electrodes, an aluminum blanket of 100 nm thickness was deposited by electron-beam evaporation and patterned by photolithography and lift-off processes. Dimensions of TFTs were defined by channel lengths of $L = 10$, 20, 40 and 80 μm and a channel width of $W = 450$ μm. Finally, the back side of the Si substrate was cleaned with diluted hydrofluoric acid and coated with chromium (10 nm) and gold (100 nm) films, deposited by electron-beam evaporation, as the gate layer.

Surface and cross sectional morphology images of the ZnO films were acquired with a Zeiss Supra 40 Scanning Electron Microscopy (SEM). The crystalline structure was determined using a Rigaku Ultima III diffractometer. Native defects in the films were determined by Photoluminescence (PL) and Thermally Stimulated Currents (TSC). For PL measurements, a He-Cd laser of 325 nm wavelength (Science Tech monochromator 9040) and 150 mW was used. TSC measurements were carried out with a cryogenic refrigeration system under vacuum (10^{-4} Torr) and an electrometer. Finally, electrical measurements of the TFT devices were performed with a Keithley 4200 semiconductor parameter analyzer.

3. Results and discussion

3.1. ZnO films characterization

Fig. 1 shows surface and cross-sectional SEM images of the ZnO films deposited on *p*-Si/SiO_2 substrates. They are labeled as sample A and sample O, indicating the films deposited in pure argon ($Ar:O_2 = 100:0$ vol.%) and gas mixture ($Ar:O_2 = 99:1$ vol.%), respectively. Surface images show compact granular morphologies with grains clearly defined and uniformly distributed. The average grain size in the samples A and O are 15.3 nm and 19.9 nm, correspondingly. Cross sectional images show the growth of columnar structures which are perpendicular to the substrate surface. Films thicknesses were measured from cross sectional SEM images from Fig. 1. The estimated values are ∼59 nm and ∼82 nm in samples A and O, respectively. X ray diffraction patterns (XRD), revealed the preferred orientation of the ZnO films along (0 0 2) in the well-known wurtzite hexagonal crystalline structure, as is shown in Fig. 2.

Fig. 3 shows the PL spectra of the ZnO films measured at room temperature. They are composed by two emission bands centered at ∼2.2 eV and ∼3.0 eV, which are related to defects in the film structure. There are many reports of the green–yellow PL around 2.2 eV in ZnO [26–29], however, its nature it is not clearly understood yet. Kröger related it with a transition between the conduction band and deep donors (oxygen vacancies) [5], Egelhaaf and Oelkrug attributed this emission with a transition between shallow donors (oxygen vacancies) and deep acceptors (Zn vacancies) [30], Reshchikov et al. associated it with a transition between a shallow donor and an acceptor with an energy level ∼0.4 eV above the valence band, and possibly due to a defect complex that may include a Zn vacancy [26].

The main characteristic observed in the PL spectra is the band centered at 3.0 eV (violet emission). Unlike the film deposited in pure argon, this emission is not detected in the film deposited in argon–oxygen environment. This band has been already reported [27,29,31,32]. For example, this feature was found in an oxygen-deficient ZnO_x film [32]. The references mentioned above,

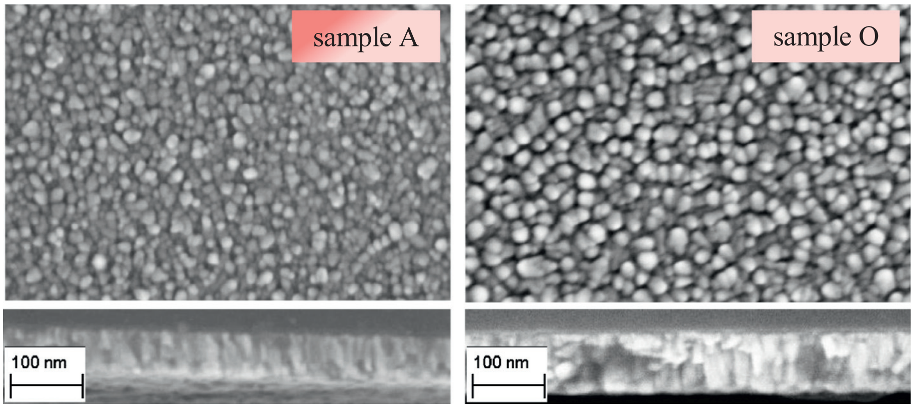

Fig. 1. Surface and cross-sectional SEM images of the ZnO films deposited on p-Si/SiO_2 substrates. They are labeled as samples A and sample O, indicating the films deposited in pure argon ($Ar:O_2 = 100:0$ vol.%) and gas mixture ($Ar:O_2 = 99:1$ vol.%), respectively.