Thin Solid Films 516 (2008) 8736–8739

Contents lists available at ScienceDirect

Thin Solid Films

journal homepage: www.elsevier.com/locate/tsf

Characteristics of low doped gallium-zinc oxide thin film transistors and effect of annealing under high vacuum

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ARTICLE INFO

Article history:
Received 6 August 2007
Received in revised form 30 May 2008
Accepted 10 June 2008
Available online 22 June 2008

Keywords:
Zinc oxide
Zinc oxide:metal
Thin film transistor
X-ray diffraction
Electrical measurements and properties

ABSTRACT

We report on the fabrication and electrical characteristics of thin film transistors (TFTs) based on low Ga-doped zinc oxide (GZO). Low Ga-doped (1 wt.%) ZnO thin films deposited as an active channel by radio frequency magnetron sputtering at room temperature exhibit a high transmittance (>80%). The devices show a mobility of ~5.7 cm^2/Vs at low operation voltage of <5 V and a low turn-on voltage of ~0.5 V with a subthreshold swing of ~85 mV/decade. The TFT device performance is significantly affected by vacuum-level and annealing treatment, which is attributed to the chemisorption/desorption of oxygen from the surface of active channel. Low doped GZO is a type of TFT channel material that has potential for high performance, multi-functionality and easy-process.

1. Introduction

Zinc oxide (ZnO) is a transparent and wide band gap (~3.36 eV) semiconducting material that has been extensively studied due to its multi-functionality such as optoelectronic, piezoelectric and pyroelectric with high exciton binding energy of ~60 meV [1–3]. The potential applications include ultraviolet lasers, light emitting devices, transparent conductors and thin film transistors. The intrinsic oxygen defects and Zn interstitials enable good electrical conductivity of ZnO thin films. However, the conductivity of ZnO can be further improved by doping with several elements such as As, In, Ga, Fe, Sb, Al and Li. The minimal resistivity of ZnO achieved by doping was about 10^{-4} Ωcm [4–7]. Of all the elements considered Ga is the best n-type doping element because of its good lattice match with ZnO lattice; the bond lengths of Ga–O and Zn–O are 1.92 Å and 1.97 Å, respectively [8]. Also the Ga atom replaces the zinc ions and acts as substitutional impurity, releasing a free electron in the conduction band at room temperature. High gallium doped zinc oxide (GZO) material has been used for contact electrodes in transparent oxide thin film transistors (TFTs) due to its high conductivity and transparency [9]. Recently, ZnO films with low resistance and high transparency have been obtained with Ga doping concentration range of 2.0–4.0 at.% [10,11]. ZnO with different concentration of gallium has been studied for high mobility and crystalline thin films. Carrier concentration of Ga-doped ZnO increases linearly with increase in Ga concentration [12]. An improved high carrier concentration of ~$10^{21}/cm^3$ can be achieved by Ga doping compared to un-doped zinc oxide thin film which has typical carrier concentration of ~$10^{17}/cm^3$ [12–14]. Recent reports demonstrated that low Ga-doped ZnO down to ~1 wt.% can be grown in single crystal by radio frequency (rf) magnetron sputtering [15]. This material has potential in optoelectronic devices because it can be grown as a transparent single crystal thin film at room temperature and has a wide band gap of ~3.76 eV [16,17].

Since the electrical properties of ZnO surface are affected by gaseous molecules present in the ambient, many researchers have studied the effect of annealing on ZnO film at different ambient conditions [15,18]. However, the choice of annealing atmosphere, temperature and pressure still remains controversial. There is also lack of information about the environmental effects on ZnO thin film grown by rf-magnetron sputtering.

Here we present electrical characteristics of low Ga-doped (1 wt.%) ZnO thin film transistor fabricated at room temperature. Device characteristics with different ambient conditions are studied and the corresponding mechanism is discussed. This letter demonstrates our effort to develop a thin film transistor fabricated at room temperature with low Ga-doped (1 wt.%) ZnO, and its environmental effect.

2. Experimental details

GZO-TFTs were fabricated with the use of a thermally grown SiO_2 thin film on Si substrate. The alignment marks and patterns were generated by standard electron beam lithography process. A 35 nm of GZO thin film was deposited with a growth rate of 3.5 nm/min at room temperature by rf-magnetron sputtering system using (1 wt.%)

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0040-6090/$ – see front matter
doi:10.1016/j.tsf.2008.06.054

gallium doped GZO target. The deposition of active channel was done in Ar ambient at 75 W of rf power, 0.67 Pa pressure and room temperature. Gate insulator of SiO_2 (100 nm) and Ti (10 nm)/Au (70 nm) electrodes were also deposited by same method and conditions (Fig. 1A). The channel length and gate width were 1 µm and 5 µm, respectively, corresponding to a width-to-length ratio of 0.2 (Fig. 1B). Device image was taken by field-emission scanning electron microscopy (FE-SEM; JEOL-JSM-7000F) operated at 3 kV. Structural characterization of the thin film was investigated by high resolution X-ray diffractometry (HRXRD) using Panalytical X' Pert PRO diffractometer equipped with monochromatic copper anode (CuKα 1.54056 Å), operated at 40 kV and 30 mA in $\theta/2\theta$ mode. Atomic force microscopy (AFM) (PSIA XE-100) in contact mode was used to analyze the surface features and surface roughness of the thin film. An etched Si tip (length 130 µm, width 35 µm) with the resonance frequency of 75 kHz and force constant of 0.60 N/m was used for the measurement under ambient condition. Photoluminescence (PL) and transmittance of thin film was measured at room temperature using 325 nm line of a He–Cd laser at various excitation powers and optical spectrometer (VARIAN CARY 5000) in the range of 200 to 1600 nm, respectively. Electrical measurements for the device characteristics were performed by using four-probe system and precision semiconductor parameter analyzer (HP 4156C).

The bottom-gated field effect transistors (FETs) were vacuum annealed at 475 K under vacuum (~3.3×10^{-3} Pa) to investigate the environmental effect on the device characteristics. Several current–voltage measurements with different ambient conditions were performed to investigate the role of absorbed gaseous molecules in the thin film and the stability of device performance.

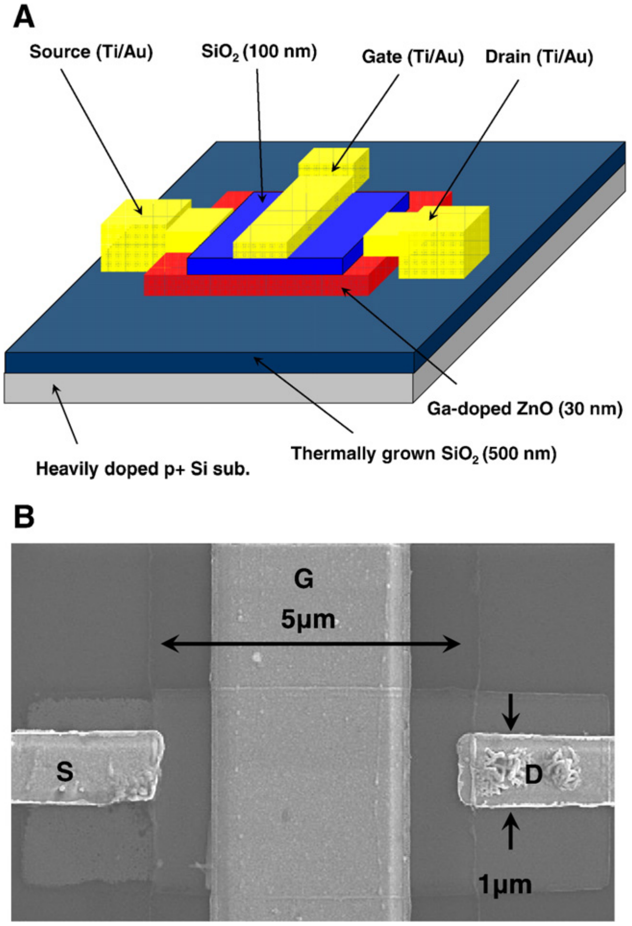

Fig. 1. (A) Schematic side view of top-gate TFT and (B) FE-SEM image of top-gate TFT fabricated on SiO_2/Si substrate. Length and width of GZO channel were 5 µm and 1 µm. A gate oxide of SiO_2 (100 nm) was deposited over GZO thin film. Metal electrodes of (Ti/Au) were deposited for source (S), drain (D) and gate (G).

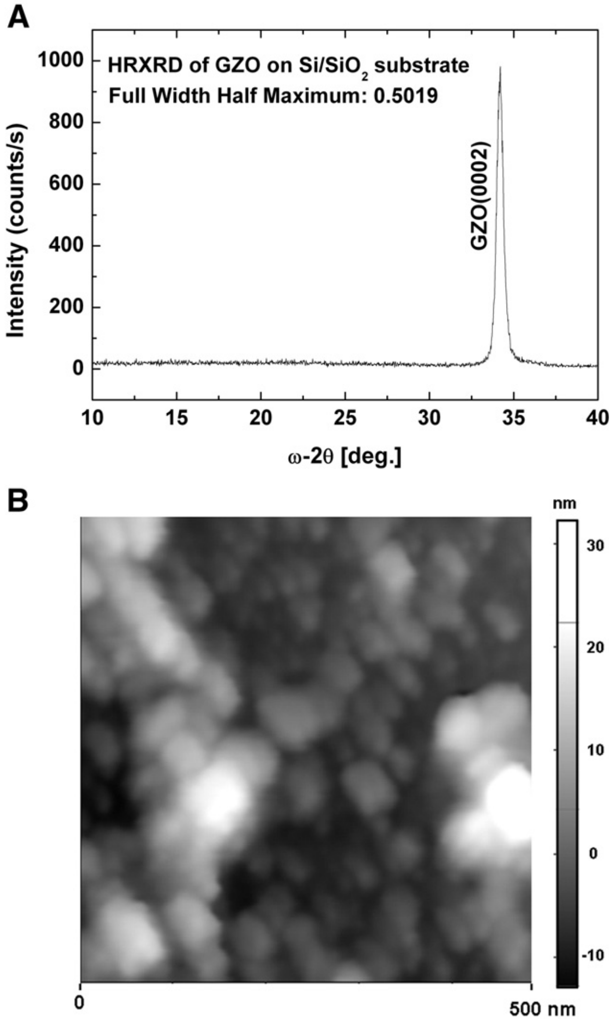

Fig. 2. (A) High resolution X-ray diffraction spectrum (Cu Kα radiation) of GZO thin film and (B) AFM image of GZO thin film as-deposited on SiO_2/Si substrate shows a roughness of 5 nm and grain size of 30 nm (root mean square).

3. Discussion

The structural quality of GZO thin film was investigated by HRXRD scan in $\theta/2\theta$ mode (Fig. 2A). Diffraction pattern revels that the film is strongly oriented in c-plane. A relatively broad peak, full width half maximum of 0.5019, from (0002) plane at $2\theta=34.21°$ was observed in HRXRD measurement. The broadening of the peak is attributed to the high mosaicity of the sample. The lower diffraction angle compared to ZnO (with reference to JCPDS file number 89-1397 of ZnO powder) suggested that the incorporated Ga atoms result in expansion of wurtzite ZnO lattice [19]. Fig. 2B represents the surface morphology of thin film investigated by the AFM. The thin film grown at 75 Watt power in Ar (10 sccm) shows high crystalline and smooth surface structure. Surface morphology in a scan area of the 500 nm×500 nm of the thin film shows a roughness of 5 nm and grain size of 30 nm (root mean square). A considerable roughness features a typical three dimensional growth mode of film at room temperature [20]. As the field effect characteristics depend on grain boundary conduction and hence grain size, the results indicate that structural and surface morphology of thin film grown by magnetron sputtering produces high quality thin film for device fabrication at room temperature.