

Improved thin film transistor performance of solution-processed-zinc-oxide nanorods with spin-on-glass capping layer

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ABSTRACT

Due to the vulnerability of various organic and oxide materials to the atmosphere, a protective layer is often used to improve device performance and stability. In this study, we use a spin-on-glass (SOG) layer to encapsulate a solution-processed-zinc-oxide (ZnO) film. ZnO loses oxygen very easily to the atmosphere and even loses Zn at relatively low temperatures. An SOG capping layer prevents the loss of oxygen without degrading its crystalline properties. We demonstrate the properties of a bottom-gate transistor with a capping layer; it shows improved electrical properties with a mobility of $0.5 \text{ cm}^2/\text{V.s.}$ and stability. Physical characterization reveals that the defect density with a capping layer is much lower than it is without it. A capping layer can also prevent the loss of oxygen at the annealing temperature of 350°C .

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1. Introduction

In recent years, there has been significant interest in oxide electronics, especially zinc-oxide (ZnO) and its alloys, for various applications [1]. ZnO has long been considered for optical device applications. Recently, significant interest has been shown in the use of ZnO in transparent device applications, both as an oxide electrode and as a semiconductor active channel layer. Most research has focused on large-area, low-cost, flexible and transparent device applications, specifically for electronic paper displays and transparent light-emitting diodes [2,3].

ZnO is mainly deposited by means of various physical vapor deposition methods, including sputter or plasma laser deposition [4]. ZnO nanowires or nanorods have been also constructed at high temperatures using the chemical vapor deposition method; however, there has been recent interest in applying ZnO in inkjet printing and roll-to-roll device fabrication, which requires solubility, good adhesion properties and low synthesis processing temperature and time [5–7]. Good atmospheric stability and easy film growth and morphology are also very important. Above all, the electrical properties also need to be comparable to those of other materials, such as amorphous silicon or organic materials. Even though sputtered-ZnO shows high device performance with mobility close to $15 \text{ cm}^2/\text{V.s.}$ for solution-processed ZnO, this value is near $1 \text{ cm}^2/\text{V.s.}$

The device properties can be controlled by manipulating the physical nature of the oxide. The key factor is to have a proper balance between the defect density and the stoichiometry of the film according to the requirements of the device [8]. Stoichiometric ZnO is an insulator that crystallizes with the wurtzite structure to form transparent needle-shaped crystals and usually shows strong UV luminescence (380 nm). Still, it is virtually impossible to prepare a perfect crystal structure because ZnO tends to lose O_2 quite easily [9,10], and this non-stoichiometric film shows semiconducting or metallic properties depending on the defect properties or defect density. Our interest in this study is the semiconducting property of ZnO as an active channel layer. Semiconducting ZnO is actually a direct band-gap material with a band gap of around 3.4 eV at room temperature [11]. Like many other wide-band-gap oxide materials, ZnO also shows asymmetric doping behavior, and that is why it is difficult to achieve p-type ZnO, whereas it naturally forms n-type semiconducting properties [12].

But the defects present in the material also need to be controlled as they deteriorate the device properties. Defects are responsible for reducing the device lifetime and light-emitting efficiency [13]. For example, dislocations act as nonradioactive recombination centers and surpass the UV emission. Additionally, devices made from the solution process also contain pinholes, and this leads to very poor performance.

We have previously demonstrated a room temperature synthesis process for ZnO solution [14]. ZnO synthesis was carried out at room temperature and in only a few hours, and described in detail in the experimental section. A suitable capping layer is necessary to protect

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the film from the environment. Usually, a single layer or multilayer film is deposited as a protective layer. A capping layer is also very important for organic transistor devices. In this paper, we proposed spin-on-glass (SOG) as a capping layer which is spin-coated on top of the ZnO layer. SOG was purchased from Honeywell USA. It is a solution mixture of silicon oxide with dopants mainly boron or phosphorous and can be applicable in the printing process. It is used mainly as a dopant source in conventional silicon device fabrication. The physical properties of the ZnO films are characterized by photoluminescence spectroscopy (PL) as well as other common tools, such as scanning electron microscopy (SEM) and X-ray diffraction spectroscopy (XRD). The PL source was Ar ion laser with an excitation wavelength of 351 nm and the X-ray source was Cu K α . Studying the ZnO structure by PL is an especially powerful tool to obtain information about the crystal purity and microstructure. It also provides valuable information about the various defect levels in the semiconductor band. The PL spectra of ZnO usually show peak positions at the UV and visible spectrum region.

2. Experimental

2.1. ZnO synthesis

The sonochemical method was carried out in room temperature without any heat treatment. The process includes dissolving zinc acetate ($\text{Zn}(\text{CH}_3\text{COO})_2 \cdot 2\text{H}_2\text{O}$: 4.43 g) and potassium hydroxide (KOH: 2.22 g) separately in methanol (MeOH). They were mixed and reaction was carried out in ultrasonic bath. The size and shape of the nanorods can be controlled by simply varying the MeOH content. The synthesis process is simply depicted in Fig. 1(a).

2.2. Device fabrication

To make a bottom-gate transistor device, we patterned gate metal on a thick thermal-oxide layer deposited on a silicon wafer.

The thermal-oxide functions as a buffer layer. A titanium/titanium nitride bilayer was deposited as a gate-metal electrode. Consequently, atomic-layer-deposited aluminum oxide (Al_2O_3) was deposited as a gate dielectric. The dielectric constant of Al_2O_3 was 7.3 with a thickness of about ~ 100 nm. Finally, chromium/gold was deposited as a source-drain electrode. The schematic of the bottom-gate structure is shown in Fig. 1(b). The ZnO solution was spin-coated (2000 rpm, 30 s) on this device. The thickness was approximately ~ 150 – 160 nm. Well-aligned ZnO nanorods were achieved by simple hot plate drying at 150°C for 1 h. The source-drain-gate was opened by simply scratching off the solution with a cotton swab or by an etching process. Fig. 1(c) shows the top view optical image of the ZnO-coated device. The channel length (L) and width (W) were $10\ \mu\text{m}$ and $100\ \mu\text{m}$, respectively. After drying, SOG was coated at 3000 rpm and of thickness around 150 nm. For the curing of the SOG capping layer, we have annealed the sample in vacuum atmosphere at 200°C or 350°C .

3. Results and discussion

3.1. Device performance

The device performance of the bottom-gate ZnO transistor with SOG capping layer is demonstrated. Fig. 2(a) and (b) show the transistor characteristics of a device after annealing in a vacuum at 200°C . The transfer data shows an on-current of just below $10\ \mu\text{A}$ with an on-off ratio in the order of 10^4 . The source to drain voltage applied was 20 V. The figure also shows the leakage current (red line), which is also quite low in the order of 10^{-9} A. The threshold voltage found from the linear transfer curve was around +16 V. Output characteristics of the device shows good characteristics with a clear saturation region. The mobility of the device was calculated to be in the region of $0.03\ \text{cm}^2/\text{V.s.}$, which is much lower

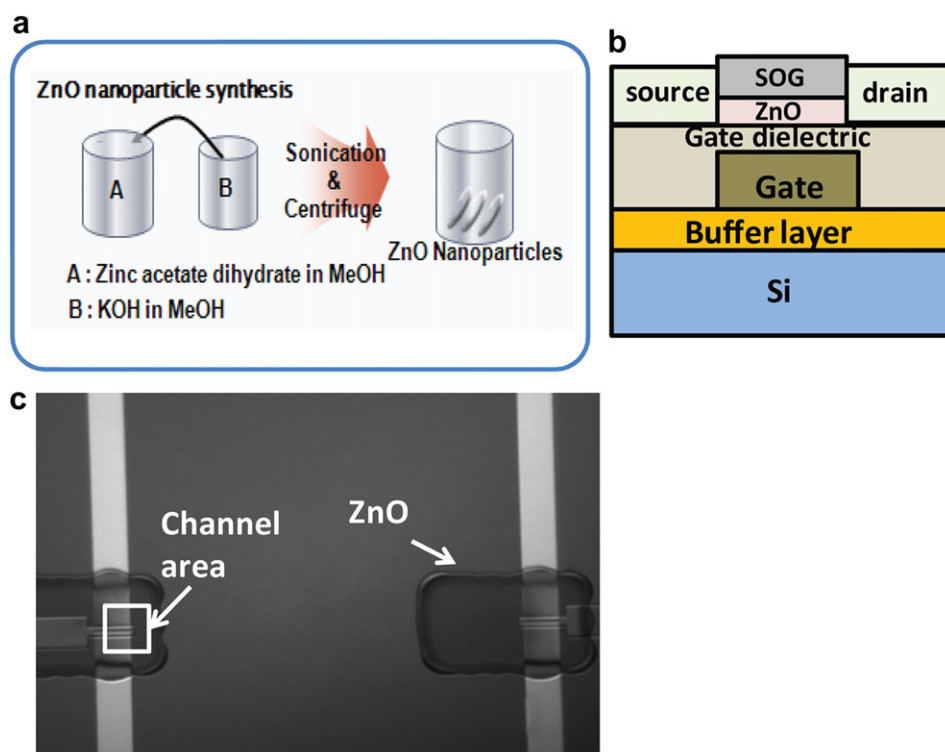


Fig. 1. (a) Schematic of the sonochemical synthesis of ZnO solution. (b) Bottom gate device structure and (c) top view optical image of the ZnO-coated device.

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