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Half wave rectification of inorganic/organic heterojunction diode at the frequency of 1 kHz

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ABSTRACT

An inorganic/organic vertical heterojunction diode has been demonstrated with p-type Poly(3,4-ethylenedioxythiophene) poly(styrenesulfonate) (PEDOT:PSS) deposited by spin coating on n-type Ga-doped ZnO (GZO) thin films. Transparent conducting GZO thin films are deposited on glass substrate by rf-magnetron sputtering. Electrical properties of GZO thin films are investigated depending on the processing temperatures. The resistivity, mobility and carrier concentration of the GZO thin films deposited at processing temperatures of 500 °C are measured to be about 3.6×10^{-4} Ω cm, 23.8 cm^2/Vs and 7.1×10^{20} cm^3, respectively. The root mean square surface roughness of the GZO thin films is calculated to be ~0.9 nm using atomic force microscopy. Current-voltage characteristics of the n-GZO/p-PEDOT:PSS heterojunction diode present rectifying operation. Half wave rectification is observed with the maximum output voltage of 1.85 V at 1 kHz. Low turn-on voltage of about 1.3 V is obtained and the ideality factor of the n-GZO/p-PEDOT:PSS diode is derived to be about 1.8.

1. Introduction

Recently, inorganic/organic heterojunction devices have been investigated so far mainly for their potential application in electronics, such as transistors memory elements, and rectifying devices [1–3]. The rectifying device can be fabricated as a result of a barrier in a semiconductor/semiconductor p–n junction or a metal/semiconductor Schottky contact, as has been demonstrated in many previous reports. Among them, zinc oxide (ZnO) semiconductor based heterojunction with organic materials has been extensively investigated. ZnO is a one of the most attractive transparent oxide semiconductors and has many advantages including high carrier mobility, a wide-bandgap energy (3.3 eV), and a large exciton binding energy (60 meV), making it ideal for transparent thin film transistors, flat panel displays, antistatic windows, optoelectronics devices and solar cells [4–7]. Generally, undoped ZnO thin films have an n-type conduction and a high resistivity due to low carrier concentration. The group-III elements, such as Al, Ga and In have been reported as an effective source for the carrier generation in ZnO thin films as dopants [8,9]. Among these dopants, we have chosen Ga as a dopant because of smaller lattice mismatch between Ga and ZnO lattice. The covalent bond lengths of Zn–O and Ga–O are estimated to be 1.97 and 1.92 Å, respectively [10]. Based on this reason, Ga-doped ZnO (GZO) became one of the most important materials for transparent conducting oxide. Many research groups have investigated the properties of GZO thin films [11–16]. However, the p-type doping on ZnO interrupts the high performance of the ZnO based optical and electrical devices. Many research groups have used a p–n heterojunction with a p-type polymer Poly(3,4-ethylenedioxythiophene) poly(styrenesulfonate) (PEDOT:PSS), which is one of the promising materials for realizing ZnO based p–n heterojunction. The PEDOT:PSS is used as an electroactive polymer due to its high conductivity, transparency and good photo-stability [17–19]. The fabrication of the ZnO/PEDOT:PSS heterojunction has been already reported by Sharma et al. [20]. The resultant value of the ideality factor is much higher than '1' implying that it is necessary to improve the quality of the p–n heterojunction. Moreover, previous studies using the p–n heterojunction have reported DC rectifying I–V characteristics. In this work, we report on the n-GZO/p-PEDOT:PSS heterojunction diodes and their half wave rectification characteristics.

2. Experimental details

Glass substrates (Corning #1737) are cleaned in ultrasonic bath with acetone, methanol, and de-ionized water, sequentially. A 3 wt.% Ga-doped ZnO was used as a target for GZO thin film deposition. The 100 nm thick GZO thin films are deposited by rf-magnetron sputtering method. The sputtering is carried out at different processing

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temperatures. The basal vacuum in the sputtering chamber is lower than 2.7×10^{-4} Pa and pre-sputtering is performed to remove contaminations on the target surface. The electrical properties of GZO thin films are measured using Hall effect measurement (HMS-3000, ECOPIA) with Van der Pauw configuration at room temperature. The surface structure of GZO thin film were characterized using field-emission scanning electron microscopy (FE-SEM) (Inspect F-K11069, FEI, by using 20 kV operating voltage) and atomic force microscope (AFM) (XE-100, Park systems, XY scan range of 10 μm in a non-contact mode).

We have used the p-type polymer (PEDOT:PSS) to fabricate the p–n junctions on GZO thin films. The deposited GZO thin films on the glass substrate are patterned using conventional photo-lithography and wet etching process. The PEDOT:PSS with thickness of 100 nm is spin coated (2000 rpm, 45 s) on the patterned GZO thin films. After spin coating, the devices is annealed at 120 °C on a hot plate for 12 min. In order to fabricate the electrodes, the In and Au are deposited on the top of GZO thin films and PEDOT:PSS layer, respectively by thermal evaporation method. In order to minimize the possible defects that can provide deleterious current paths between electrodes and both GZO thin films and PEDOT:PSS layer, we patterned the contact area of electrodes with 1 mm × 1 mm dimension using metal shadow mask. The current-voltage (I–V) characteristics of the heterojunction diode were measured using a semiconductor parameter analyzer (EL423, ELECS).

3. Results and discussion

The resistivity, Hall mobility and carrier concentration of the GZO films deposited on the glass substrates at different processing temperatures are shown in Fig. 1. The rf power and working pressure are fixed at 100 W and 0.67 Pa, respectively. The resistivities of the GZO thin films deposited at processing temperatures of 200 °C, 300 °C, 400 °C and 500 °C are measured to be about 3.3×10^{-3} Ω cm, 1.2×10^{-3} Ω cm, 5.4×10^{-4} Ω cm, and 3.6×10^{-4} Ω cm, respectively. Low resistivity of the GZO thin films is obtained at 500 °C. This is due to the increase of carrier concentration and Hall mobility. We have observed that the Hall mobility increases from 7.5 to 23.8 cm^2/Vs as increasing deposition temperature from 200 °C to 500 °C since the high growth temperature can improve the crystallinity of the GZO thin films. As the deposition temperature increases from 200 °C to 500 °C, the carrier concentration increases from 2.4×10^{20} cm^3 to 7.1×10^{20} cm^3. The increase of carrier concentration is mainly due to the increase of the diffusion of Ga atoms from interstitial locations or grain boundaries into Zn cation sites [21]. Fig. 2 shows the morphology and the grain of GZO thin films processed at 500 °C observed by FE-SEM and AFM. As shown in Fig. 2(a), the grain size of the GZO thin film grown at 500 °C is measured to be about 20 nm. Fig. 2(b) shows the AFM image of the GZO thin films deposited on

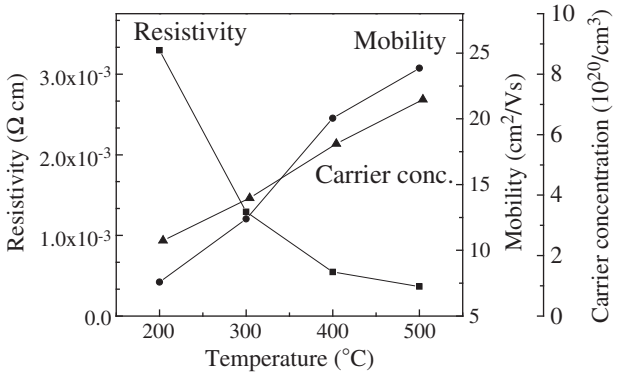

Fig. 1. Resistivity, Hall mobility and carrier concentration of GZO thin films depending on the processing temperatures.

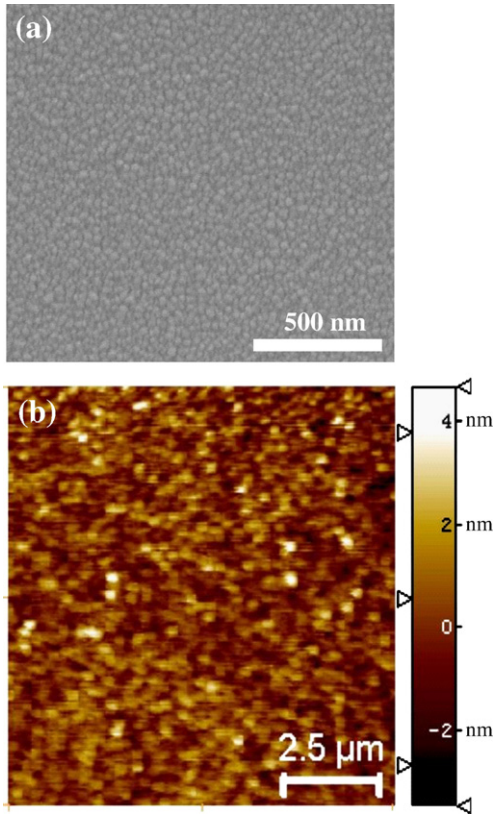

Fig. 2. (a) FE-SEM and (b) AFM images of GZO thin films deposited at 500 °C on glass substrate.

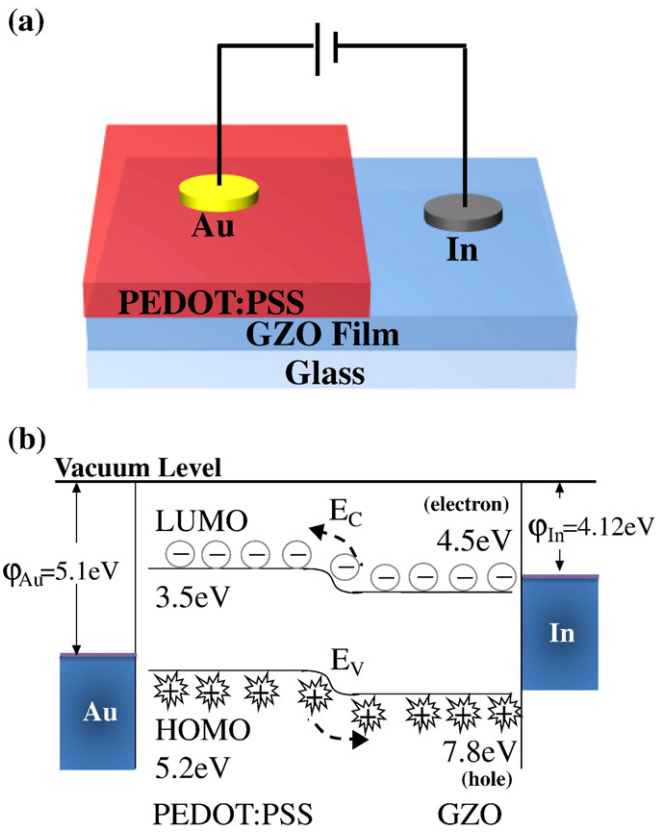

Fig. 3. (a) Schematic diagram of vertical GZO/PEDOT:PSS heterojunction device, and (b) the energy band diagram of the GZO/PEDOT:PSS device.