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A high-sensitivity, fast-response, rapid-recovery UV photodetector fabricated based on catalyst-free growth of ZnO nanowire networks on glass substrate

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ABSTRACT

Here, we report for the first time the fabrication of metal–semiconductor–metal ultraviolet photodetector based on catalyst-free growth of ZnO nanowire networks on ITO seeds/glass substrates by thermal evaporation method. The morphological, structural, and optical properties of the sample were studied by using field emission scanning electron microscopy, X-ray diffraction, photoluminescence, and UV–Vis spectrophotometer. Upon exposure to 365 nm light (1.5 mW/cm^2) at five-bias voltage, the device showed 2.32×10^3 sensitivity. In addition, the photocurrent was 1.79×10^{-4} A, and the internal gain of the photodetector was 24.2. The response and the recovery times were calculated to be 3.9 and 2.6 s, respectively, upon illumination to a pulse UV light (365 nm, 1.5 mW/cm^2) at five-bias voltage. All of these results demonstrate that this high-quality detector can be a promising candidate as a low-cost UV photodetector for commercially integrated photoelectronic applications.

1. Introduction

Zinc oxide (ZnO) has great attention in different applications due to its wide band gap of 3.37 eV, large binding energy of 60 meV, low cost, ease of fabrication, non-toxicity, and its capability to operate in high temperature and harsh environments [1,2]. Moreover, the fact that ZnO exhibits the most versatile and abundant configurations of nanostructures with various shapes and sizes as well as its high optical gain of 300 cm^{-1} makes it the material of focus in many applications, especially optoelectronics and sensing [3]. ZnO based UV photodetectors (PDs) has attracted great interest in comparison to those fabricated from other semiconductors such as AlGaN, SiC, and Si [4,5]. The ZnO based UV detector are important devices which can be used in various applications including environmental monitoring, astronomy, flame sensing, secure chemical/biological analysis, and space-to-space communications. Therefore, numerous studies in the literature have been focusing on ZnO as a promising semiconducting material for possible UV detector [6,7]. Specifically, one-dimensional (1D) ZnO nanowire (NW) have received the most attention because of their electron confinement properties, large surface-to-volume ratio, good crystallinity, and polar nature of the 1D nanostructure [8,9]. In addition, 1D ZnO demonstrated potential applications as next-generation of UV detector, due the quantum effect in these structures results in a density of state at the band edges and enhances the radiative recombination as result of carrier confinement [10,11]. However, UV PD based on ZnO-NWs have a long recovery time in the second scale because that the oxygen-related hole-trap states at the nanowirs surface [12,13]. Therefore, many researchers have been focusing on fabricating UV PD based on ZnO-NW with a lot of efforts in order to promote the response speed. For example, Prades, et al. [14] reported that the surface coating of polymer can reduce the response time of photodetector ZnO-NWs. Zhou et al. [15] reported to the possibility of reducing the recovery time from 417 s to 0.8 s using schottky contact instead of ohmic contact in UV photodetector device fabrication. Recently, it has been reported by Yan et al. [16] that the UV photodetector based on Zn_2GeO_4 NW networks lead to promotion of response speed because that the NW–NW barrier dominated conductance.

On the other hand, many technologies have been used to fabricate a UV detectors based on ZnO nanostructures using a glass substrates. For example, Bai, et al. [17] reported a ZnO-NWs UV detector has been fabricated by using spin-coating a solegel

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precursor on the glass substrate with a rise time constant of 68 s upon 0.47 mW/cm^2 UV illumination. Mohite et al. [18] reported a ZnO UV detector which prepared by using spray pyrolysis technique onto glass substrates with rise and fall time of 11.35 and 17.9 s respectively upon 10 μW/cm^2 UV illumination. Recently, it has been reported by Shewale et al. [19] that the ZnO based UV detector onto glass substrates using chemical spray pyrolysis technique with slow recovery time of 135 s upon 2 mW/cm^2 UV illumination. All those reports have provided the photodetectors often operate under UV irradiation with high light intensity, and the slow photoresponse speed still needs to be improved. However, a systematic study of fabrication UV photodetector based on ZnO nanowires grown on glass substrates by thermal evaporation method has not been published yet.

In this report, we have successfully fabrication of a fast-response MSM-structured UV photodetector based on catalyst-free growth of ZnO nanowires on ITO seeds/glass substrates by thermal evaporation method. Sputtered ITO thin film as a new seed layer coated glass substrate, followed by seed annealing temperature using a CW CO_2 laser, employed here for the first time to grow ZnO-NW networks by the use of thermal evaporation method, in accordance with our previous study [20]. This study aims to manufacture a UV detector on a cost effective glass substrate with a fast-response, rapid-recovery and that exhibits high sensitivity.

The surface morphology and crystal structure of growth ZnO-NW networks were investigated through field-emission scanning electron microscopy (FESEM) and X-ray diffractometer (XRD). The photoluminescence (PL) and electrical characteristics of the UV-sensing device were also investigated.

2. Experimental details

2.1. Preparation of ITO seed layer on glass substrate

Glass slides (Marienfeld Co.) with the dimensions of 10 × 10 mm are used as substrates in the preparation of ZnO-NW networks. ITO seeds were deposited on substrate by RF/DC sputtering system (Auto HHV 500) using target of In_2O_3 90 wt % and SnO_2 10 wt %. The thickness of the ITO seed layer was approximately 75 ± 5 nm, followed by an annealing treatment using a CW CO_2 laser beam at wavelength (λ) = 10.6 μm. This ITO seeds were annealed over a 1 cm^2 area on glass substrate at annealing temperatures of 450 °C and at power of 25 W in the air for 15 min, in accordance with our previous study [21]. This heat treatment has been used to obtain the optimum properties of the seed layer, which are in agreement with Zhu et al. [22] and A.B. Yadavet al. [23]. The crystal structure, surface morphology and optical properties of sputtered ITO seed layer were studied in our previous work [20].

2.2. Growth of ZnO-NW networks

The ITO seeds-coated glass substrate was cleaned, according to the literature [24]. Thermal evaporation method was used to growth ZnO-NW networks through heating of Zn powder in the presence of O_2 gas in a horizontal two-zone tube furnace with a length of 70 cm, a diameter of 4 cm, and a 40 cm reaction zone. The growth conditions of ZnO-NW followed our previous procedure [20]. High purity zinc powder was used as a first source material and placed in a quartz boat. This Zn powder with boat was inserted into the center of the furnace. The glass substrate was placed horizontally at the end of quartz tube in front of the gas flow stream. In the first zone, the Zn powder is gradually heated up from room temperature to 650 °C at a rate of 10 °C/min, while the temperature of the substrate in the second zone was at 425 °C. High-purity Ar gas was used during the growth process as a carrier gas inside the quartz tube during thermal evaporation. High purity O_2 was employed as a second source material which was fed into the reaction zone after the temperature reached 650 °C. The pumping of O_2 gas into the reaction zone continued for 90 min. White material formed on the glass substrate after the evaporation process was completed. The quartz tube cooled naturally to room temperature.

The structure and morphology of the growth of ZnO-NW networks were characterized and analyzed using a field emission scanning electron microscopy (FESEM) model (FEI/Nova Nano SEM450) with energy dispersive X-ray spectroscopy (EDX). Structural analysis was performed using an X-ray diffractometer (PANalytical X'Pert PRO) equipped with Cu-Kα a radiation (λ = 1.5418 Å). The transmission curve was obtained using spectrophotometer type; a Varian, Cary system 5000 UV–Vis–NIR spectrophotometer was used to determine the optical transmission spectrum. The photoluminescence spectroscopy of the ZnO-NW at room temperature was obtained using a PL spectroscopy system (HR 800 UV system, Jobin Yvon- USA) with a He–Cd laser operating at 325 nm. Finally, the UV-PDs response was conducted using UV (365 nm) illumination with a power of 1.5 mW cm^2 coupled to an Auto-lab. The current-voltage (I–V) characteristics were measured using Keithley Source Meter model 2400 (200 V, 1 A, 20 W).

3. Results and discussion

3.1. FESEM analysis

The morphologies of the catalyst-free growth of ZnO-NWs network on ITO seed by thermal evaporation method with laser annealing of 450 °C were measured by FESEM. Fig. 1 shows high and low magnification images of the morphology of ZnO-NWs network, where reveals that the nanowires of the ZnO network were grown in the form of semi-straight lines, aligned with the base, uniform dimensions, size, and spatial distribution on the substrate. The diameter of these nanowires was estimated to be 80–95 nm and their length was several hundred micrometers.

The EDX spectrum of ZnO-NW networks indicated the presence of Zn and O atoms in addition to the In and Sn atoms of seed layers, as shown in Fig. 2. The EDX showed that this sample contains 45.86 At.% Zn, 50.8At.% O, 2.56 At.% In and 0.78 At.% Sn. These ratios are in agreement with the optimal stoichiometry for the ZnO.

3.2. XRD study

The XRD pattern of the catalyst-free growth of ZnO-NW networks onto ITO seed layer glass substrate by thermal evaporation method are shown in Fig. 3. The scanning Bragg angle was within the 2θ range of 20–80. Apart from the diffraction peaks of ITO seed layer, all peaks of the film could be indexed to the hexagonal phase with a wurtzite structure of ZnO. The sharp and strong diffraction peak of (002) direction indicates ZnO-NW networks grow along the *c*-axis direction. Seven diffraction peaks with 2θ values of 31.4°, 34.3°, 36.1°, 47.3°, 56.4°, 62.6, and 72.4° correspond to (100), (002), (101), (102), (110), (103) and (104) planes of the ZnO. These results are according to ICSD 01-089-1397. An extensive XRD pattern of sample appeared extending from 31.4° to 72.21° in the 2θ region due to the typical of diffraction patterns for a glass substrate [25].

3.3. Optical properties

The UV–vis optical transmission spectrum of the catalyst-free growth of ZnO-NW networks on ITO seeds/glass substrate in a wavelength range of 200–800 nm are presented in Fig. 4, and the absorption spectra of the samples are shown inset of Fig. 4. The average optical transmission in the visible light region is estimated