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Research paper

Light-activated humidity and gas sensing by ZnO nanowires grown on LED at room temperature

Cheng-Liang Hsu [a,*], Li-Fan Chang [a], Ting-Jen Hsueh [b,*]

[a] Department of Electrical Engineering, National University of Tainan, Tainan 700, Taiwan, ROC
[b] National Nano Device Laboratories, Tainan 741, Taiwan, ROC

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ABSTRACT

ZnO nanowires were hydrothermally synthesized on a silicone layer of an ultraviolet (UV) light-emitting diode (LED). The ZnO nanowires/LED combination was used to fabricate a device that can perform humidity sensing, gas sensing, and UV detection. Under UV, blue, and green LED illumination, the humidity and ethanol gas response of the device showed its unique physical characteristics. The ethanol gas response characteristics of the device were enhanced when the input power was increased.

1. Introduction

Gas sensors have attracted attention due to their wide application in medical diagnostics, military and industrial applications, environmental monitoring, food safety, and internet of things (IoT) [1,2]. According to an IT research agency (International Data Corporation), IoT will become a $7.1 trillion market in 2020. In recent years, IoT devices have been embedded with a variety of sensors to create portable electronic devices, such as wearables and smart phones [3]. Metal oxide nanostructure (NS) gas sensors have become the focus of intense research due to their advantages such as high sensitivity, small size, low cost, and quick response [4–8]. Metal oxide NSs such as SnO_2 [4], TiO_2 [5], Ga_2O_3 [6], In_2O_3 [7], and ZnO have been reported to have novel physical and chemical properties for gas sensing [8], owing to their large surface-area-to-volume ratio compared to that of thin films [4–8]. Among these metal oxide materials, ZnO is the most important semiconductor, with a wide band gap of 3.4 eV and a large exciton binding energy of 60 meV, due to its superior optical [9], electrical [10], and magnetic properties [11]. ZnO NS gas sensors have been reported with various morphologies, such as nanoparticles (NPs) [12], and one-dimensional (1-D) and two-dimensional (2-D) structures [13,14].

Optimal sensing performance of metal oxide NS gas sensors is achieved at high temperatures of 100–450 °C [4–14]. The elevated temperature provides energy for the chemisorption and reaction of gaseous species on the surface. Heating accounts for most of the energy of these sensors. Energy consumption is thus a challenge in the development of portable IoT products. Furthermore, high temperature may ignite flammable or explosive gases. The grain boundaries of a metal oxide also have taken risk on diffusion and sintering effect when operated for a long time at high temperature, leading to reliability issues [15]. Several methods have been proposed to reduce the sensor operating temperature, such as noble metal doping or decoration [16–18], micro-electromechanical systems (MEMS) fabrication [19], application of an electrostatic field [20], use of nanosensing materials [21], and use of ultraviolet (UV) illumination [22–24]. Among these techniques, UV activation has attracted attention due to its potential for allowing room-temperature operation [22–24]. ZnO under UV illumination was generated that photocatalytic to degrade and decompose the organic gases in the air [25,26]. The present study integrates a ZnO nanowire (NW) gas sensor and an UV light-emitting diode (LED) to fabricate a device that exhibits excellent humidity and gas sensing performance. The device can also be used for UV detection. The ZnO NW sensors were hydrothermally synthesized on a silicone layer of the LED. The ethanol gas sensing

* Corresponding authors.
E-mail addresses: clhsu@mail.nutn.edu.tw (C.-L. Hsu), tingjen1123@yahoo.com.tw (T.-J. Hsueh).

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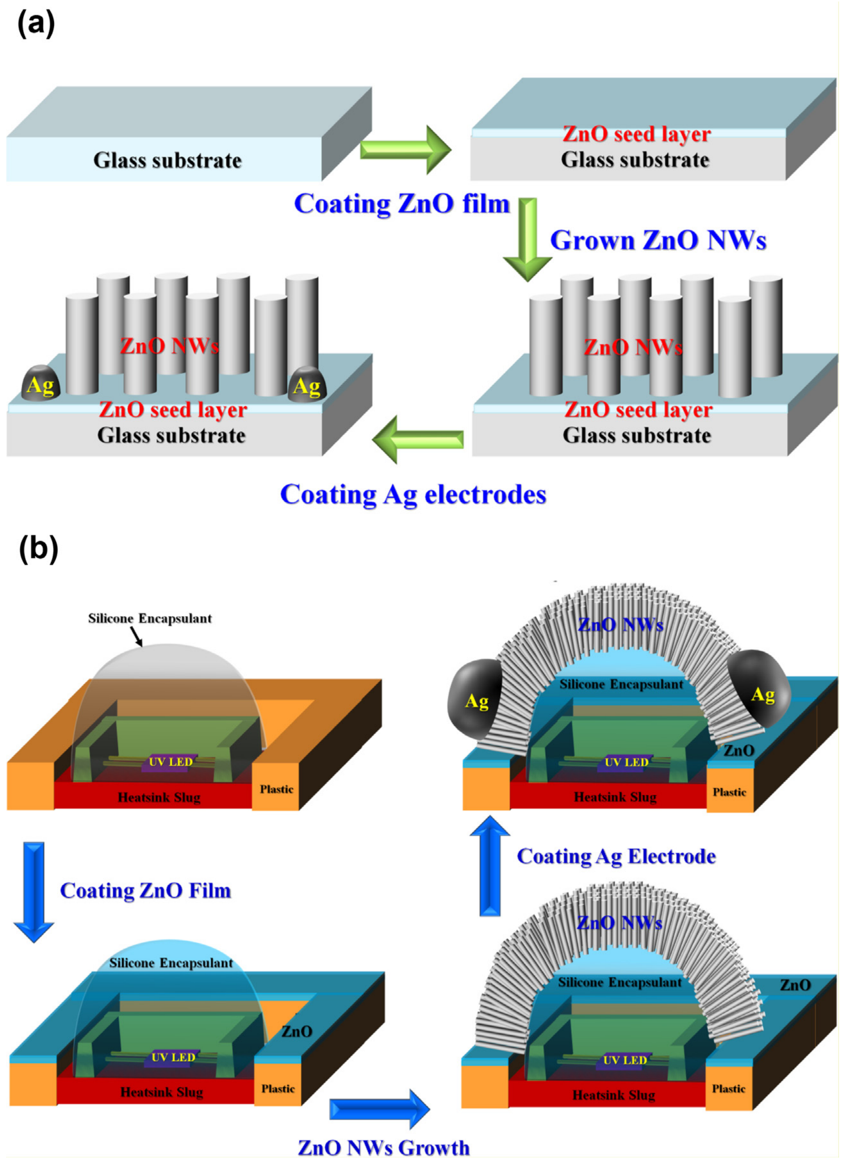

Fig. 1. Schematic diagram of processes and steps of fabrication of ZnO NWs on **(a)** glass and **(b)** silicon layer of LED.

characteristics of the ZnO NWs were activated by UV, blue, and green LED illumination. Details of ZnO NW growth on the silicone layer of the LED and the properties of the light-activated gas and humidity sensing characteristics are discussed.

2. Experimental

Fig. 1 **(a)** and **(b)** schematically depict the processing steps of the ZnO NW sensor fabricated on a glass substrate (Corning® Eagle XG) and LED chips (Nichia). Acetone and deionized (DI) water were used to rinse the glass substrate twice. After a baking process at 80 °C for 2 mins, radio-frequency (RF) magnetron sputtering was used to deposit a 50-nm-thick ZnO seed layer on the glass substrate. ZnO NWs were hydrothermally synthesized on the ZnO seed layer with 0.06 M zinc nitrate hexahydrate ($Zn(NO_3)_2{\cdot}6H_2O$) and 0.06 M hexamethylenetetramine ($C_6H_{12}N_4$) solution at 95 °C in a sealed autoclave for 6 h. The optimization condition of NWs synthesized is that concentration of $Zn(NO_3)_2{\cdot}6H_2O$ is same with $C_6H_{12}N_4$. The $Zn(NO_3)_2$ and $C_6H_{12}N_4$ are hydrolyzed in DI water solution to produce Zn^{2+} and OH^- ions with the increasing temperature. *Li* et al. has reported that highly magnified HR-TEM images of ZnO buffer layer and hydrothermal synthesized ZnO NWs [27]. The columnar grains of ZnO seed layer act the nucleation sites of ZnO NWs. ZnO grows epitaxial from the columnar grains of ZnO seed layer to construct a continuous ultra-thin film. Subsequently, the ZnO NWs were homoepitaxially grown along the columnar grains of ultra-thin film. The reaction mechanism and hydrothermal synthesis equations are discussed in detail in the previous reports [27,28]. The nanostructure of ZnO NWs has a large surface-area-to-volume ratio for enhance humidity and gas sensing ability of sensor. Because the electrodes of the LED are a metal alloy, which may be eroded by the chemical liquid, before ZnO NW synthesis on the silicon layer of the LED, a photoresist (PR) was manually placed on the electrodes to protect them. Exclude above PR coating process, the fabrication process of LED and glass substrate are the same process and steps.

The physical properties and morphology of the ZnO NWs were examined using field-emission scanning electron microscopy (FE-SEM, JEOL-7000F), photoluminescence (PL) spectroscopy (Jobin-Yvon SPEX System) and X-ray diffraction (XRD, MAC-MXP18). A schematic illustration of gas sensing measurement under LED illumination is shown in Fig. 2**(a)**. The distance from