A lateral ZnO nanowire UV photodetector prepared on a ZnO:Ga/glass template

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Abstract
We report the lateral growth of ZnO nanowires on a ZnO:Ga/glass template. By reducing the oxygen flow ratio, it was found that we could change the growth direction of ZnO nanowires from vertical to lateral. ZnO nanowire-based photodetectors were also fabricated using the laterally grown ZnO nanowires. It was found that the detector current increased by more than 12 times upon ultraviolet illumination. It was also found that the corresponding time constant of our lateral ZnO nanowire photodetector was around 452 ms.

1. Introduction

In the past decade, a significant amount of research and development activities has been focused on the synthesis, structural characterization and physical phenomena of nano-structured materials. Due to their peculiar characteristics and size effect, these materials often exhibit novel physical properties that are different from those of the bulk. This has attracted great interests both for fundamental research and potential nano-device applications [1, 2]. Among the various nano-structured materials, wide band-gap one-dimensional (1D) ZnO nanowire is a promising functional material [3–7]. With a room temperature band-gap energy of 3.37 eV and an exciton binding energy of 60 meV, ZnO emits short-wavelength light, conducts transparently and is piezoelectric. Recently, it has been shown that ZnO nanowires can also be used as (UV) photodetectors [8, 9], chemical sensors [10] and biological sensors [11].

On the other hand, glass substrates are transparent and of low cost. Large-area glass substrates are also commercially available. Thus, glass is an ideal substrate material for large-size optoelectronic devices. If we can grow ZnO nanowires

on glass substrates, we should be able to realize various novel optoelectronic devices, such as ZnO-based light emitters, photodetectors and field emission displays (FEDs). ZnO nanowires can be synthesized by various methods [12–18]. However, it is difficult to grow ZnO nanowires on glass substrates since glass substrates are amorphous and weak at high temperatures. Previously, Huang *et al* [19] reported the successful gas phase synthesis of ZnO nanowires on patterned Au catalyst by vapor–liquid–solid (VLS) reaction at high temperatures (i.e., 900–925 °C). Geng *et al* [20] modified this VLS technology and successfully grew ZnO nanowires on an Si substrate. Very recently, Tseng *et al* developed a low-temperature self-catalyzed VLS process at 550 °C and reported the growth of vertical single-crystalline ZnO nanowires on a $ZnO:Ga/Si_3N_4/SiO_2/Si$ template [21]. Using the same method, Hsu *et al* reported a similar growth of vertical single-crystalline ZnO nanowires on ZnO:Ga/glass template and demonstrated ZnO nanowire UV photodetectors by flipping the sample so that the tips of the vertical ZnO nanowires were contacted directly with a patterned ITO/glass substrate [22]. However, such a simple scheme is not suitable for practical applications since the tips of the vertical ZnO nanowires were contacted softly with the underneath ITO/glass. This work reports the lateral growth of ZnO
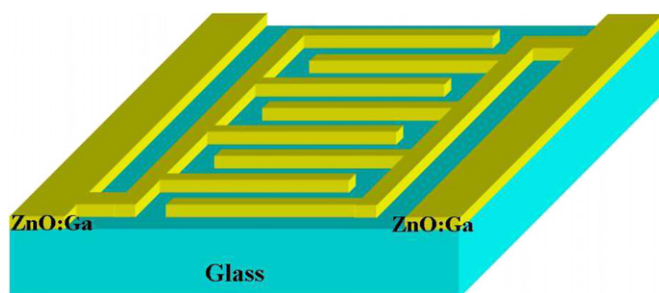
Figure 1. Schematic diagram of the patterned ZnO:Ga/glass template.

(This figure is in colour only in the electronic version)

nanowires on the ZnO:Ga/glass template by the VLS process. A UV photodetector was also fabricated using the laterally grown nanowires. The fabrication process and the properties of the fabricated photodetector will also be discussed.

2. Experimental details

Prior to the growth of ZnO nanowires, we first deposited a 50 nm thick Ga-doped ZnO thin film onto glass substrates by RF magnetron sputtering. X-ray diffraction (XRD) measurement showed that the sputtered ZnO:Ga film was oriented along the (0 0 2) direction. Using four-point resistivity measurement, we found that the sheet resistance of the sputtered ZnO:Ga film was around 200 Ω/sq. We then used standard photolithography to partially etch away the ZnO:Ga film and define the comb-like pattern. During wet etching, the template was dipped in 2% HCl for 3 min to remove the exposed ZnO:Ga. As shown in figure 1, we designed our etching mask so that fingers of the comb-like pattern were 5 μm wide and 80 μm long with a spacing of 5 μm. We subsequently used two small pieces of glass to cover the two electrodes of the patterned ZnO:Ga film so that no ZnO nanowires will be grown in these regions.

To grow the ZnO nanowires, we placed the patterned ZnO:Ga/glass template and Zn powder on an alumina boat, and inserted them into a quartz tube. The zinc vapor source was Zn metal powder with a purity of 99.9%, obtained from Strem Chemicals. The evaporation process was performed in the quartz tube located in a horizontal tube furnace.

A JEOL JSM-6500 F field emission scanning electron microscope (FESEM) operated at 5 KeV and a MAC MXP18 x-ray diffractometer (XRD) were then used to characterize structural properties of the as-grown ZnO nanowires. The room temperature current–voltage (I–V) characteristics of the fabricated devices were then measured both in dark and under illumination by an HP4156 semiconductor parameter analyzer. It should be noted that the I–V measurements were performed in a box so that the dark currents were measured in total darkness. The transmission spectrum was measured using a high-intensity UV light source (Hamamatsu, 150 W, at wavelengths from 115 to 400 nm).
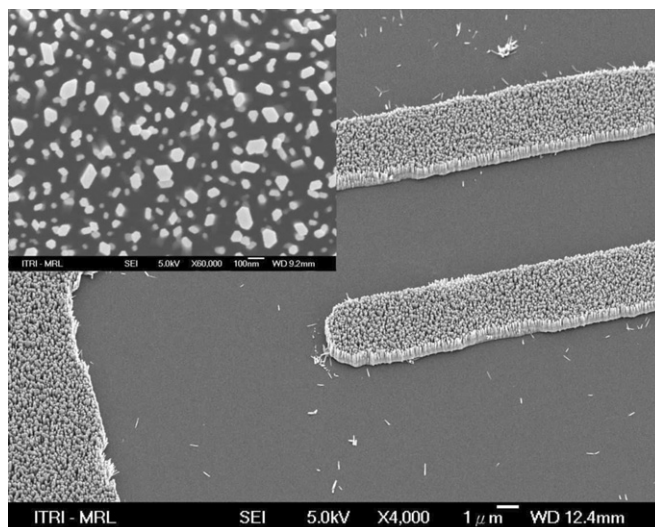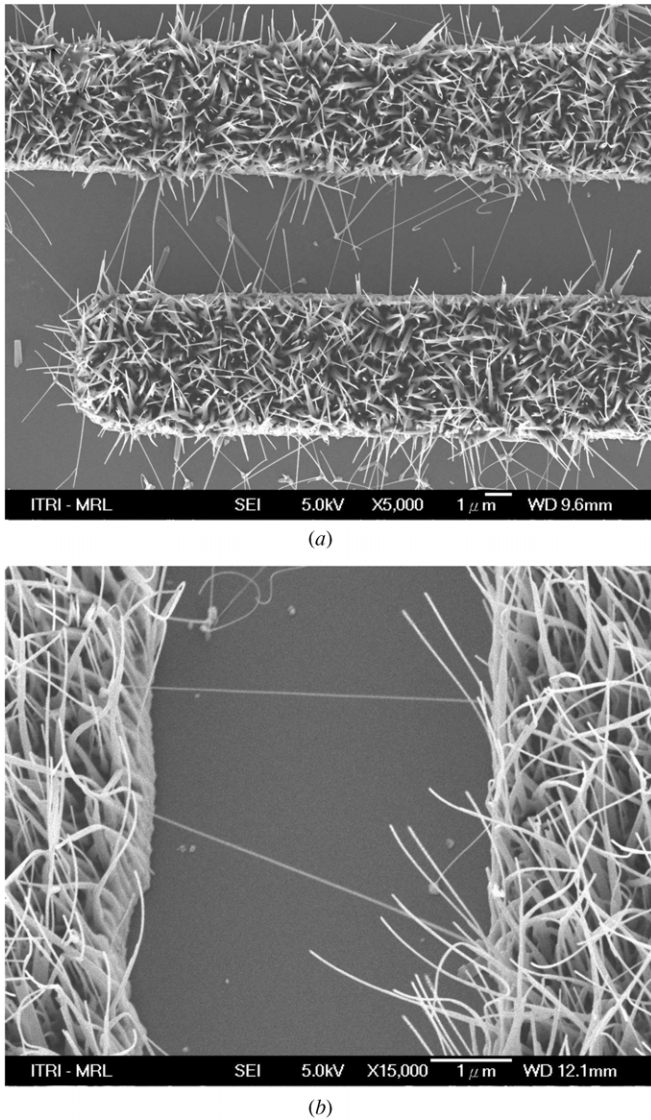

Figure 2. FESEM image with a 30° tilt angle of the ZnO nanowires grown with an oxygen flow rate of 0.8 sccm.
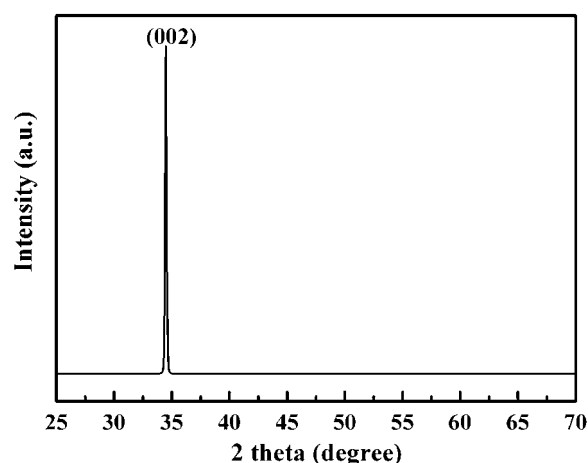
Figure 3. XRD spectrum of the vertically well-aligned ZnO nanowires.
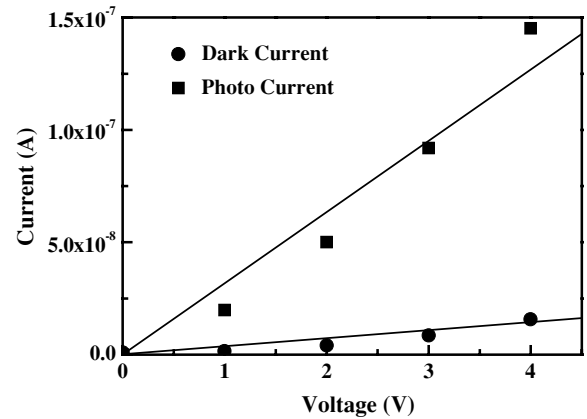
3. Results and discussion

Figure 2 shows the FESEM image with a 30° tilt angle of the ZnO nanowires grown with an oxygen flow rate of 0.8 sccm. The inset in the upper-right corner of this figure shows the top-view FESEM image of the same sample. With an oxygen flow rate of 0.8 sccm, it was found that vertically well-aligned ZnO nanowires were grown on ZnO:Ga/glass templates. It was also found that the average length and diameter of these ZnO nanowires were around 1 μm and 80 nm, respectively. It should be noted that the ZnO nanowires were grown only on top of the patterned ZnO:Ga film while no nanowires were grown directly on the glass substrate. Similar selective growth has also been reported by Hsu *et al* [21]. As shown from the inset, it was found that the tops of these ZnO nanowires were well-defined hexagon, which is probably due to the wurtzite structure of ZnO single crystal. Figure 3 shows the XRD spectrum of these vertically well-aligned ZnO nanowires. It was found that only one strong ZnO (0 0 2) XRD peak with small line width was observed in the spectrum. Such a result

Figure 5. *I–V* characteristics of the sample with lateral ZnO nanowires.

electrical paths. With these lateral ZnO nanowires, the two neighboring electrodes were no longer electrically open. We could thus determine the resistivity of the sample by applying a constant voltage across the two electrodes and measure the corresponding current. Figure 5 shows the *I–V* characteristics of the sample with lateral ZnO nanowires measured in dark (dark current) and under illumination (photocurrent). During photocurrent measurements, a 150 W deuterium (D_2) lamp was used as a UV light source. It can be seen that the measured current increased linearly with the applied bias. It was also found that the resistivity of the crabwise ZnO nanowires that bridged the two neighboring electrodes was as high as 226 Ω cm. With a 2 V applied bias, it was found that dark current and photocurrent were 4.1×10^{-9} and 5.0×10^{-8} A, respectively. In other words, the detector current was increased by more than 12 times upon UV illumination. It is known that oxygen chemisorption plays a central role in regulating the photosensitivity of ZnO [24–27]. In the dark, oxygen molecules adsorb on the nanowire surface as negatively charged ions by capturing free electrons from ZnO, thereby creating a depletion layer with low conductivity near the surface:

$$O_2(g) + e^- \rightarrow O_2^-(ad). \qquad (1)$$
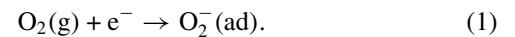
The current increase upon UV irradiation can be explained by photo-excited holes captured by the oxygen ions (O^-, O^{2-}, or O_2^-) on the surface of ZnO nanowires:

$$h^+ + O_2^-(ad) \rightarrow O_2(g). \qquad (2)$$

This will result in an enhanced carrier concentration in the nanowires and a narrower depletion width on the nanowire surface.

Figure 6 shows the transient response of the measured current by turning off the UV excitation. It should be noted that the current decreasing rate is determined by the speed of oxygen molecules absorbed on the ZnO nanowire surface to capture excess electrons. As shown in figure 6, it was found that the turn-off transient can be fitted well by the exponential curve [28, 29] shown as follows:

$$I(t) = I_d + (I_p - I_d)\exp[-(t/\tau)], \qquad (3)$$

Figure 4. (*a*) Top-view SEM micrograph of the ZnO nanowires grown with an oxygen flow rate of 0.4 sccm. (*b*) presents a partially enlarged photograph of the same sample.

again indicates that these ZnO nanowires were all well oriented with pure wurtzite structure [17].

Figure 4(*a*) shows the top-view SEM micrograph of the ZnO nanowires grown with an oxygen flow rate of 0.4 sccm while figure 4(*b*) is an enlargement. It was found that the growth direction changed from vertical to lateral as we decreased the oxygen flow rate from 0.8 to 0.4 sccm. It was also found that the average length and diameter of these lateral ZnO nanowires were 6 μm and 30 nm, respectively. It has been reported previously that the diameter of the ZnO nanowires will become smaller and thinner when grown at a low oxygen flow ratio [23]. With a smaller diameter, the growth direction of the ZnO nanowires will become more sensitive to the airflow in the furnace tube. In other words, the ZnO nanowires can no longer be grown vertically at a low oxygen flow ratio. It is even possible that some nanowires will be bent and thus grown laterally. As shown in figure 4, it can be clearly seen that some of the lateral ZnO nanowires bridged across two neighboring fingers to provide
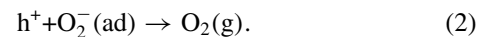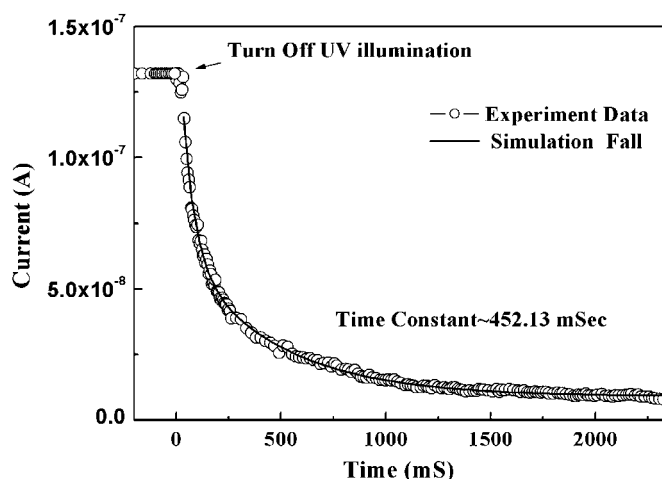
Figure 6. Transient response of the measured current by turning off the UV excitation.

where $I(t)$ is the transient current, I_d is the current measured in dark, I_p is the current measured under UV illumination, t is the time after turn off and τ is the corresponding time constant. From the data plotted in figure 6, it was found that the corresponding time constant for our lateral ZnO nanowire photodetector was around 452 ms. It should be noted that the 452 ms time constant observed in this study was much smaller than that reported by Keem *et al* [30]. The faster response indicates that the lateral ZnO nanowire photodetector is suitable for high-speed operation.

4. Conclusions

In summary, we reported the lateral growth of ZnO nanowires on a ZnO:Ga/glass template and the fabrication of a UV photodetector. With a 2 V applied bias, it was found that dark current and photocurrent of the fabricated detector were 4.1×10^{-9} and 5.0×10^{-8} A, respectively. It was also found that the corresponding time constant of our lateral ZnO nanowire photodetector was around 452 ms.

Acknowledgments

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