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High responsivity ZnO nanowires based UV detector fabricated by the dielectrophoresis method

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ABSTRACT

ZnO nanowires UV photodetectors with different interdigital electrode distances were fabricated by using a dielectrophoresis method in this work. The multiple horizontal nanowires array integrated that photodetectors were composed by lots of paralleled ZnO nanowires. Experimental results showed the responsivity of the detector with the electrode distance of 6.5 μm could reach 40 A/W at 10 V bias. It was also observed that the rising and decaying stages of the time-resolve photocurrent were both two processes, which was possibly attributed to the relaxation processes of the surface states and the deep level traps.

1. Introduction

Due to their unique properties and large surface-to-volume ratios, low-dimensional nano-devices, such as field effect transistor [1,2], lasers [3,4] and photodetectors [5–7], have attracted considerable attention in recent years. Zinc oxide (ZnO) nanowire (NW) has become the most important building block to fabricate the optoelectronic nanodevices because of its wide band gap and facile fabrication properties [8–16]. Lots of foundation works have been done and some exciting results were acquired in aspects of the ultraviolet (UV) nanolaser at room temperature [3], the high internal gain (10^8) UV detectors [6], etc. In order to make a nanodevice with a single nanowire, the electron-beam lithography and focused ion beam microscopy are usually needed. However, the fabrication of nanodevices with the large area and large quantity is still a challenge [17]. Some methods were explored to prepare large area NWs devices, such as the print process [18,19], vapor–liquid–solid (VLS) [20], and dielectrophoresis [21]. Among those, the dielectrophoresis was a controllable and effective method to fabricate large quantity of nanodevices.

In this work, we successfully fabricated the self-assembly ZnO NWs devices by the controllable dielectrophoresis method. To connect the electrodes, the long ZnO NWs were prepared using a low temperature hydrothermal method. The electrical and the responsivity properties of devices with different electrodes distances were measured. To further study the photoresponse properties, the rising and decaying processes of the devices were analyzed.

2. Experimental

The ZnO NWs were grown via a low temperature hydrothermal method. In the first step, a substrate with a ZnO seeds layer was put into the aqueous solution containing 0.01 mol/L Zn $(CH_3COO)_2{\cdot}2H_2O$ and 0.01 mol/L hexamethylenetetramine (HMTA). The reaction was maintained at 90 °C for 24 h in a Teflon-lined stainless autoclave [22]. These processes were repeated three times to obtain the desired length. Then, the sample was rinsed with distill water and dried in air at 90 °C. At last, the ZnO NWs were ultrasonic for 1 h to disperse the ZnO NWs into the ethanol solution.

The interdigital electrodes were prepared on the silicon substrate with a 300 nm thick SiO_2 layer. A 100 nm thick Au film was sputtered on the substrate. The interdigital electrodes with 12 pairs of fingers were obtained by the traditional photolithography and wet etching. The length of the electrode fingers was 500 μm, whereas the intervals between two adjacent electrodes were different from 6.5 μm to 10 μm. An alternating current electric field was applied across the interdigital electrodes with a frequency f = 10 MHz and a peak-to-peak voltage V_{pp} = 15 V. Then, appropriate amounts of ZnO NWs solution were placed between the electrodes.

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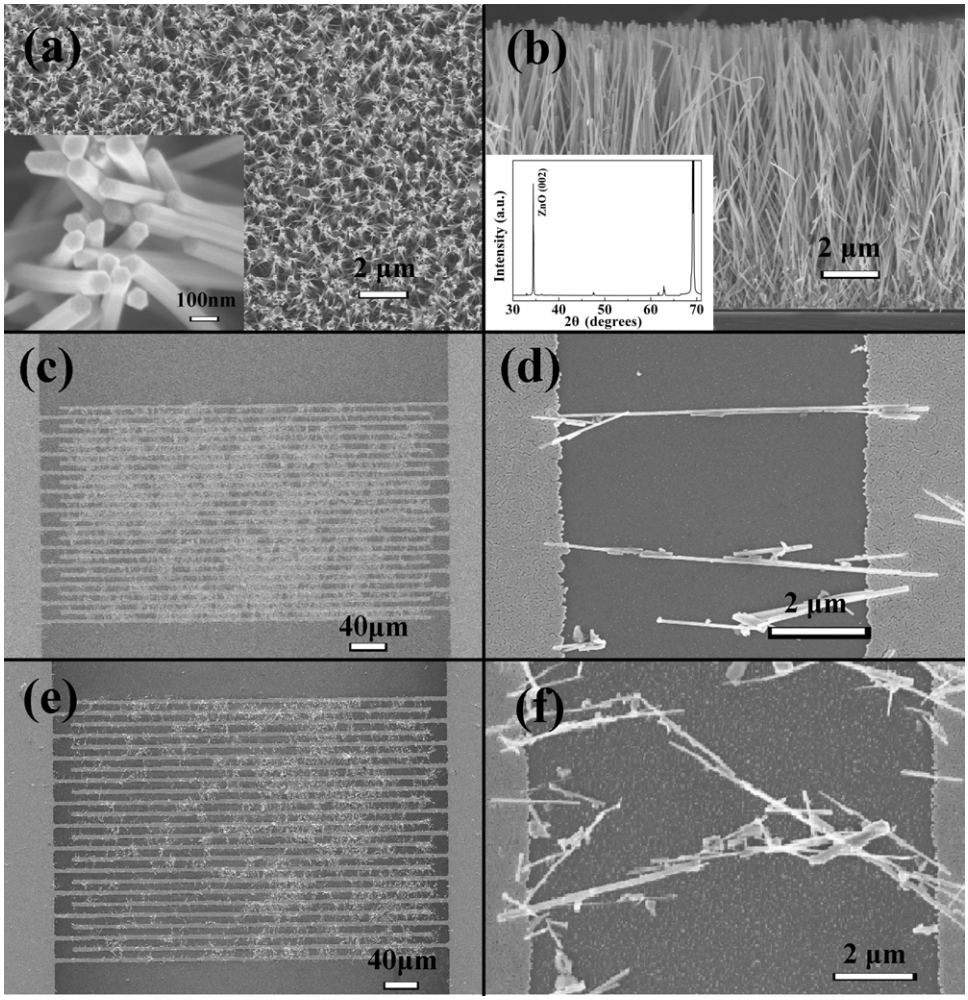

Fig. 1. (a) Typical SEM image of ZnO nanowires (inset is a high-magnification image of nanowires), (b) the profile image of ZnO nanowires (inset is the XRD pattern of ZnO nanowires), (c)–(f) shows the SEM images of the ZnO NWs on the Au electrodes with different finger distances arrayed by dielectrophoresis method, the finger distances of (c) and its high-magnification image (d) is 6.5 μm, the finger distances of (e) and its high-magnification image (f) is 10 μm.

After 5 min, the sample was rinsed with ethanol and drying in air, the contact between the ZnO NWs and the gold electrodes is stable and reliable. At last the power was turned off.

The morphologies of the devices were observed by a field emission scanning electron microscopy (FESEM, Hitachi S-4800). The AC current was measured by a Keithley 2611A System SourceMeter. To measure the photoresponse property, a 150 W Xe lamp was used as the excitation source. The spectrum response was measured by a lock-in amplifier.

3. Results and discussions

From Fig. 1(a), it could be observed that the diameter of the ZnO NWs is around 100 nm and the top of the nanowire is hexagonal-shaped. The profile image (Fig. 1(b)) shows the length of the ZnO NWs is about 8 μm. The inset of Fig. 1b is the XRD $\theta-2\theta$ scans of the as grown sample. A strong XRD diffractive peak located at 34.42° could be ascribed to the ZnO (0 0 2) peak.

ZnO nanowire could be arrayed under the electric field between the interdigital electrodes by using the dielectrophoresis method. Fig. 1(c)–(f) shows the SEM images of the ZnO NWs on the Au electrodes with different finger distances. When the distance of the fingers is 6.5 μm, a single nanowire could span across the two adjacent electrodes as shown in Fig. 1(d). When the distance being to enlarge to 10 μm, the quantity of the nanowires lied on the electrodes decreased a lot (as shown in Fig. 1(c) and (e)). Because the interval is larger than the nanowires length, several nanowires have to join each other to connect with the adjacent electrodes (Fig. 1(f)).

The *I*–*V* curves of the ZnO nanowires based on a metal–semiconductor–metal (MSM) structure are shown in Fig. 2. Both of the devices present the Schottky contact (Fig. 2(a)). The current of the device with the 6.5 μm finger distance (denoted as D1) is almost one order of magnitude larger than the one with the 10 μm finger distance (denoted as D2). The nanowires lied on the electrodes could be regarded as the parallel resistance. The parallel resistance of the device should be decreased with increasing of the ZnO nanowires. Due to this reason, the current of D1 is higher than that of D2. The photo-illuminated *I*–*V* characteristic of D1 is shown in Fig. 2(b). The wavelength and the power of the illuminated light are 365 nm and 0.5 mW/cm^2, respectively. Under the illumination the *I*–*V* curve presents almost a linear shape, which means the device varied from Schottky contact to Ohmic contact.

Fig. 3 shows the photoresponsivites of the two devices. The cut-off edges for both devices are at 400 nm. And the ratio of R (370 nm)/R (400 nm) is 10^2, which shows the good visible-blind property. For device D1 the responsivity is as high as 40 A/W at 370 nm under 10 V bias, and 1.2 A/W under 5 V bias. For device D2

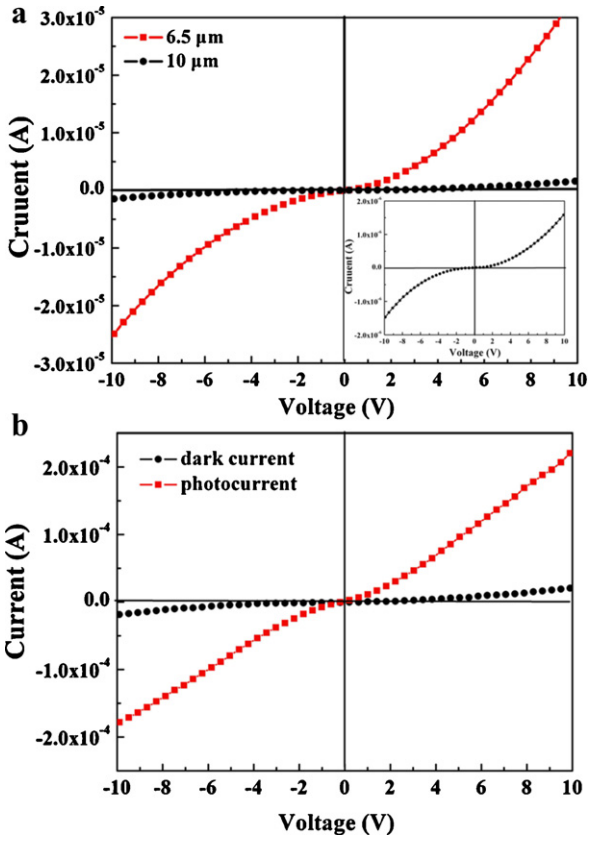

Fig. 2. (a) The *I–V* curves of the ZnO nanowires devices with the 6.5 μm and 10 μm finger distance (inset is an enlarge image of the *I–V* curve with 10 μm finger distance), (b) the photoilluminated *I–V* characteristic of the ZnO nanowires devices with the 6.5 μm finger distance.

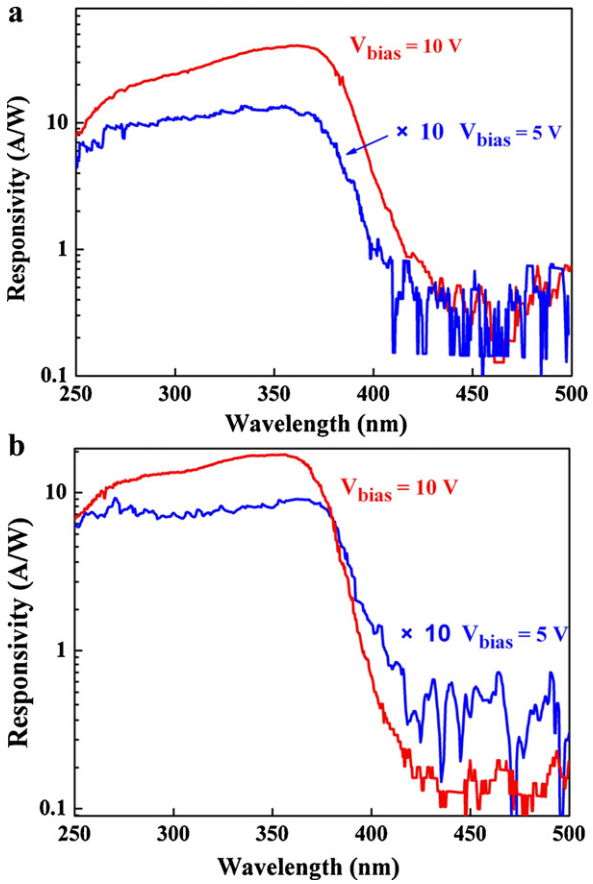

Fig. 3. The photoresponsivites of the ZnO nanowires devices with the (a) 6.5 μm and (b) 10 μm finger distance at 5 V and 10 V bias.

the responsivity is 18 A/W at 370 nm under 10 V bias, and 0.8 A/W under 5 V bias. The responsivities of both devices are much higher than the values of some literature reported. For example, L. Luo et al. have reported the responsivity of ZnO NWs detector was only 0.07 A/W under 20 V bias in 2006 [23], Lei Luo et al. reported the responsivity of ZnO NWs detector is 0.39 A/W under 2 V bias in 2010 [24].

Usually, the responsivity of a detector is defined as:

$$R\ (\mathrm{A/W}) = \frac{I_p}{P_{opt}} = \eta\left(\frac{q\lambda}{hc}\right)G \tag{1}$$

where I_p is the photocurrent, P_{opt} is the incident optical power, η is the quantum efficiency, h is Planck's constant, c is the speed of light, λ is the incident light wavelength, q is the electron charge, and G is the photoconductive gain. According to this equation, it could be deduced that the large photoresponsivity of the devices originated from the large internal photoconductive gain. Under the illumination the device trends to be a photoconductive detector. The photoconductive gain for device D1 is calculated at about 10^2 by assuming $\eta = 1$ for simplicity. For the one dimensional ZnO nanostructures, the large internal gain is attributed to the absorption of the oxygen by the surface trap states. In the dark case, a mass of oxygen is adsorbed on the ZnO NWs surface. The electrons in ZnO NWs are captured by adsorbed oxygen to form negatively charged ions. Then, a depletion layer is formed in the surface. Under the UV illumination, the electron–hole pairs are generated in the ZnO NWs. In this case, the photogenerated holes diffuse to the surface, recombine with the electrons of the absorption oxygen, to release the oxygen at the same time [25]. Reduction of the depletion layer thickness and the photogenerated electrons increased the major carriers, which increased the conductivity.

To further study the mechanism of the response, the decaying and rising of the photocurrent are fitted biexponentially with the following equation [26,27]:

$$I = I_0 + Ae^{-t/\tau 1} + Be^{-t/\tau 2} \tag{2}$$

where $\tau_{off,1}$ and $\tau_{off,2}$ are two relaxation time constants. At 5 V bias for device D1 the decaying time are $\tau_{off,1} = 1.23$ s and $\tau_{off,2} = 18.29$ s, the rising time are $\tau_{on,1} = 1.06$ s and $\tau_{on,2} = 16.28$ s (as shown in Fig. 4(a)). With increasing the applied voltage to 10 V the decaying and rising times are shortened. The time is decreased to 0.67 s, 3.77 s, 1.02 s and 14.16 s for $\tau_{on,1}$, $\tau_{on,2}$, $\tau_{off,1}$, $\tau_{off,2}$, respectively (as shown in Fig. 4(b)). Because the nanowires have large surface-to-volume ratio, the surface states of ZnO nanowires play an important role to the fast decaying and rising times ($\tau_{on,1}$ and $\tau_{off,1}$) [26]. The slow times process could be attributed to a carrier relaxation process in the deep defect states. When increasing the applied voltage, the carriers have more energy to escape from the trap states, which results in the relaxation time shortening.

Because the UV detector usually needs to work in a rough environment, it is important to know the operation state in this condition. The temperature dependent photoresponse properties of device D1 are shown in Fig. 5. In this measurement a UV lamp with the emission peak at 365 nm and the power of 0.5 mW/cm^2 was used at room temperature. As shown in the figure, at 100 °C the device D1 still shows a good UV photoresponse. Because at high temperature the recombination probability of photo-generated carriers increases, the photocurrent at 100 °C is almost one-third

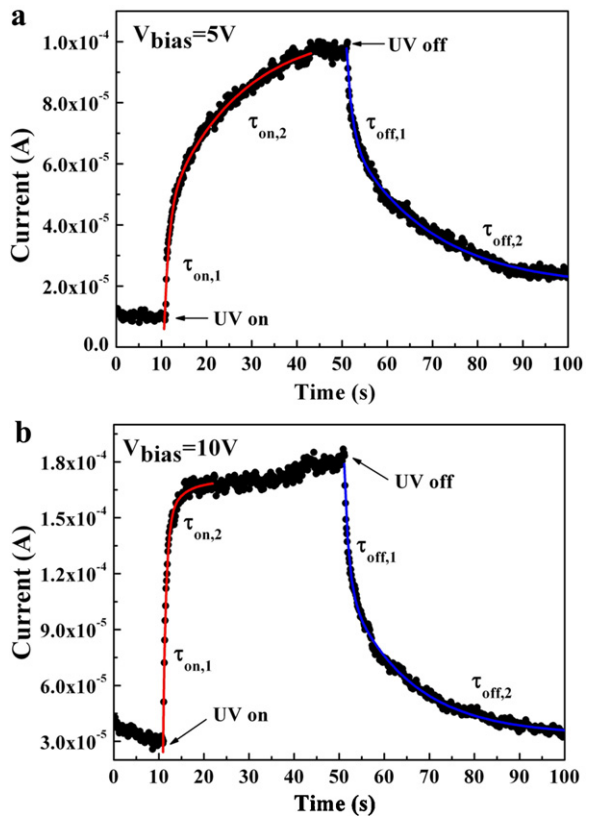

Fig. 4. The decaying and rising of the photocurrent curves and the fitted biexponentially curves of the ZnO nanowires devices with the 6.5 μm finger distance at (a) 5 V and (b) 10 V bias.

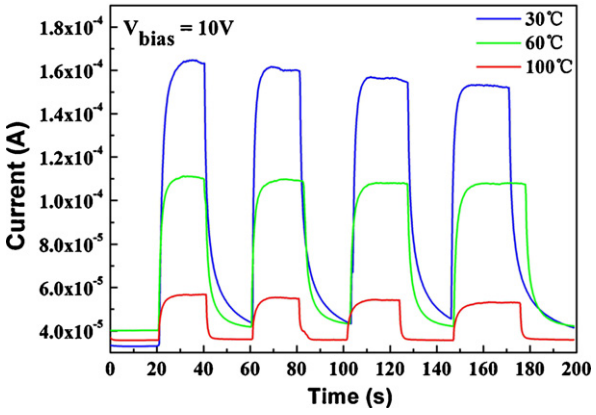

Fig. 5. The photocurrent curves of the ZnO nanowires devices with the 6.5 μm finger distance at 10 V bias at various temperature.

of that at room temperature. And compared with the photoresponse curve at room temperature the rising and decaying times are shortened at high temperature.

4. Conclusions

In summary, UV photodetectors using ZnO nanowires have been fabricated via a dielectrophoresis method. The responsivity of the detector was 40 A/W at 10 V bias with the electrode distance of 6.5 μm. Due to the devices were composed by lots of ordered parallel ZnO NW arrays, the large photocurrent and responsivity could be realized. And at high temperature the device still presented good UV photoresponse, which meant the dielectrophoresis was a proper method to fabricate the high performance nanowires based nanodevices.

Acknowledgments

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