Fabrication of ZnO nanowall-network ultraviolet photodetector on Si substrates*

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Abstract: ZnO nanowall networks were prepared by plasma-assisted molecular beam epitaxy without a catalyst on Si (111) substrates. The nanostructures have preferred orientation along the *c* axis. The nanostructures are about 10 to 20 nm thick and about 50 nm tall. The planar geometry photoconductive type metal–semiconductor–metal photodetector based on the ZnO nanowall networks exhibits a high and wide response spectrum, and no decrease from 250 to 360 nm. With the applied bias below 5 V, the dark current was below 6 μA, and the peak responsivity of 15 A/W was achieved at 360 nm. The UV (360 nm) to visible (450 nm) rejection ratio of around two orders could be extracted from the spectra response.

Key words: ZnO; detector; MBE
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1. Introduction

With a wide direct band gap (3.37 eV) and high exciton binding energy (60 meV) at room temperature, zinc oxide (ZnO) attracts much attention as an excellent candidate material for ultraviolet (UV) laser applications. Optically pumped stimulated emission with excitonic gain at room temperature has been demonstrated in ZnO films and nanostructures[1−4]. Recently, much attention has been paid to low dimensional ZnO nanostructures, including one-dimensional nanostructures such as nanowires[5], nanobelts[6], nanorods[7], and nanotubes[8], due to the ability to enhance device performance through nanostructuring. The photodetectors based on nanostructure materials usually present high responsivity, which is attributed to the large surface-to-volume ratio, and photoconductive gain. ZnO-based nanostructures are also regarded as one of the most promising materials for UV photodetectors[9, 10]. While the vast majority of these photodetectors are fabricated from epilayers grown on sapphire or SiO_2 substrates[11, 12], a few utilize Si as the substrate[13, 14]. Nevertheless, silicon is particularly important for its reduced cost and possibility of integration with Si-based microelectronics. To the best of our knowledge, only a small amount of information can be found on ZnO nanostructures UV photodetectors on Si substrates.

In this work, we obtained ZnO nanowall networks on Si (111) by plasma-assisted molecular beam epitaxy (p-MBE). ZnO nanowall network metal–semiconductor–metal (MSM) photodetectors on Si (111) are fabricated. A high and wide response spectrum of MSM photodetectors were obtained in UV spectra. The optical and electrical properties of the photodetectors are also discussed.

2. Experiments

The growth of the nanowalls was carried out using a V80H p-MBE system equipped with Knudsen-cells for a Zn (99.9999%) element source as well as a radio frequency (RF)-plasma cell for an oxygen source (O_2, 99.999%). The background pressure in the growth chamber was about 1×10^{-9} mbar. A mass flux controller was used to control the oxygen flow rate. During growth, the RF power of the oxygen plasma was 300 W. The oxygen flow rate was 1.0 sccm. The pressure in the growth chamber was about 1×10^{-5} mbar. The Si (111) substrates were kept at 350 ℃ in the growth process.

X-ray diffraction (XRD) spectra were collected by a D/max-RA X-ray spectrometer (Rigaku International Corp, Japan) with Cu Kα radiation of 0.1543 nm to obtain structural information. The sample morphology was investigated by a filed-emission scanning electron microscope (FE-SEM) (Hitachi S4800).

3. Results and discussion

Figures 1(a) and 1(b) show the FE-SEM images of the as-grown sample. The sample has nanowall-like structures, which are composed of nanowalls interconnecting with each other that thus form networks. The nanowall networks can be seen more clearly in the higher magnification SEM image shown in Fig. 1(b). As can be seen, the nanowalls are perpendicular to the substrate. The wall thickness is 10–20 nm; the average height of the nanowall is about 50 nm. One can observe a typical feature that the roots of the walls are markedly thickened.

The XRD patterns of the ZnO nanowall networks are shown in Fig. 2. The film shows a sharp peak at 34.4°, which can be attributed to the ZnO (002) plane. No other peak is observed, which indicates the preferred orientation of the

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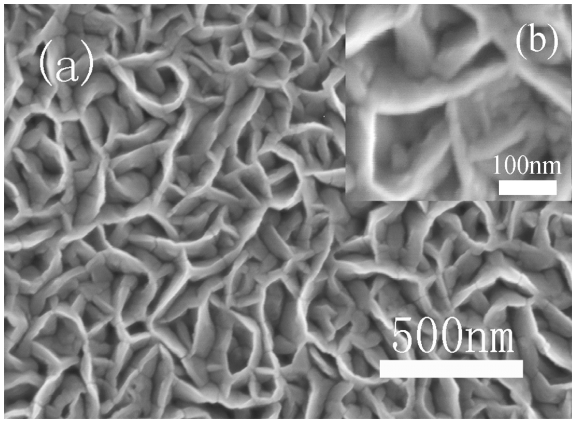

Fig. 1. FE-SEM image of P-MBE-grown ZnO nanowall networks on Si (111) substrate. (a) Low-magnification image. (b) High magnification image.

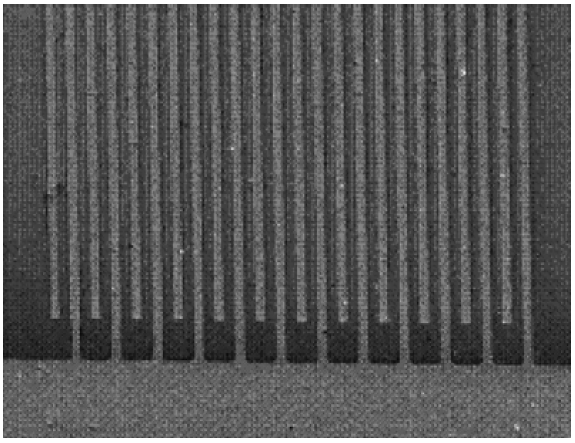

Fig. 3. SEM picture of a ZnO UV detector with MSM structure. The Au fingers are 500 μm long, 5 μm wide and have an interelectrode spacing of 5 μm.

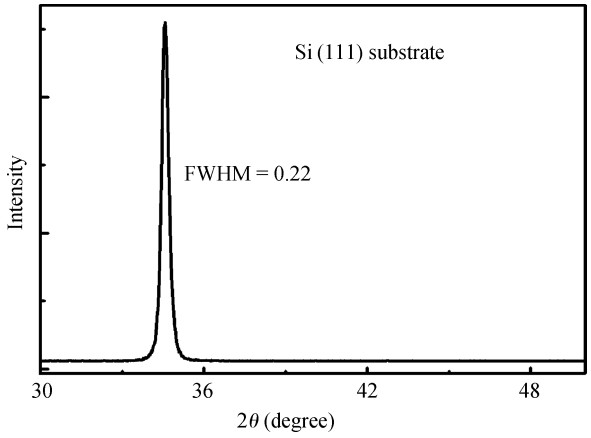

Fig. 2. XRD spectra of the ZnO nanowall networks on Si (111) substrate.

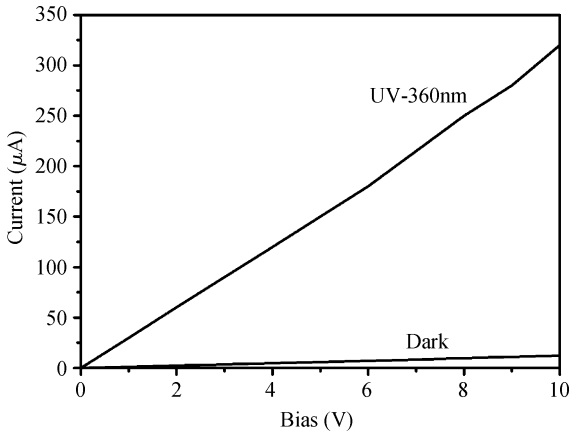

Fig. 4. I–V curves show dark current and photocurrent under 360 nm, 1 μW UV light illumination.

film. The full-width at half-maximum (FWHM) of the (0002) diffraction peak is 0.22, which indicated that the ZnO nanowall networks on Si (111) have good crystal quality. The formation mechanism of the ZnO nanowall was attributed to the Zn/O[15].

Interdigitated Au ohmic metal contacts were deposited on the ZnO nanowall networks on Si (111) substrate by vacuum evaporation in order to fabricate the MSM photoconductive detector. An SEM picture of the ZnO UV detector with MSM structure is shown in Fig. 3. The fingers were 500 μm long and 5 μm wide with a pitch of 5 μm. The thickness of the Au electrodes is 200 nm. There are 12 pairs of fingers in the interdigitated structure[16].

Figure 4 shows the dark and photoilluminated I–V characteristics of the ZnO nanowall network MSM planar device. The wavelength and power of the illuminated light are 360 nm and 5 μW, respectively. Such a linear relation indicates the ohmic behaviour of Au-electrode on ZnO nanowall network contact. Under 5 V bias, the measured average dark current is 6 μA, which is close to the calculated dark current based on the resistivity of ZnO.

A standard lock-in amplifier technique was employed for the spectral response measurements, where a 150 W xenon lamp was used. The photodetector was illuminated from the front side. Using an intensity-modulated optical signal, which was produced using a mechanical chopper in the beam path of the xenon light, the response time of the photodetector was also measured.

Figure 5 shows the responsivity as a function of wavelength for a ZnO nanowall network UV photodetector. The incident optical power was measured with a calibrated UV-enhanced Si photodetector. In the UV spectral region, the detector showed a high responsivity and wide spectrum, with no decrease from 360 to 250 nm. The responsivity of a photoconductive detector is generally determined by the quantum efficiency and the photoconductive gain[17]. The maximum responsivity of our detector was measured to be 15 A/W at 360 nm with a 5 V bias. The responsivity of our device was higher than that observed from other ZnO film UV photodetectors on Si substrate[14]. This high responsivity may be attributed to its high photoconductive gain[18]. The cutoff wavelength occurred at 385 nm. Meanwhile, the visible rejection (R360 nm/R450 nm) was more than two orders of magnitude. To further characterize the photodetectors, the inset of Fig. 5 is the responsivity as a function of bias voltage. A linear relationship was obtained between 1 and 5 V, indicating no carrier mobility saturation or sweep-out effect up to the applied bias.

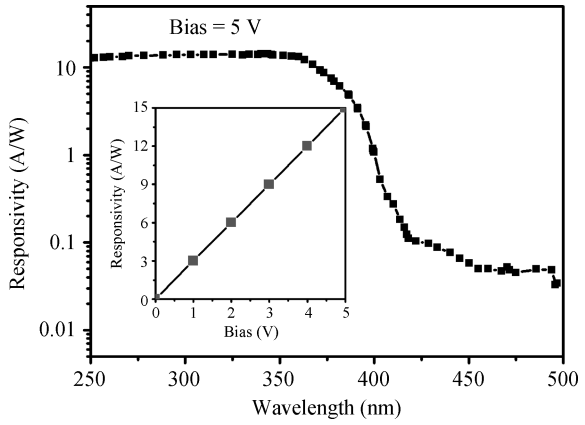

Fig. 5. Spectral response of the ZnO nanowall networks UV photodetector with the reverse of 5 V. The inset shows the responsivity at 360 nm as a function of reverse bias.

This result is consistent with the I–V characteristics shown in Fig. 4.

4. Conclusion

In summary, the ZnO nanowall network UV photodetector has been fabricated on Si (111) by MBE. The photodetector exhibited a sharp cutoff wavelength at 385 nm. The peak responsivity of 15 A/W at 360 nm was measured at 5 V bias. In the UV spectral region, the detector showed a high responsivity and wide spectrum, with no decrease from 360 to 250 nm. The visible rejection (R360 nm/R450 nm) was obtained more than two orders of magnitude from the fabricated photodetector.

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