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High Spectrum Selectivity Ultraviolet Photodetector Fabricated from an n-ZnO/p-GaN Heterojunction

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Undoped n-ZnO films have been deposited onto p-GaN to form a pn heterojunction, and the current−voltage curve of the heterojunction shows obvious rectifying behaviors. A photodetector is fabricated from the heterojunction. Under back-illumination conditions, the GaN layer on one hand acts as a p-type counterpart for the n-ZnO layer, on the other hand as a "filter" that is transparent to the illumination light with wavelength longer than 360 nm. Because of the GaN "filter", the photodetector shows a narrow band-pass response of only 17 nm in width. The results reported in this paper may provide a facile route to photodetectors with high spectrum selectivity.

Introduction

Zinc oxide (ZnO) is a promising candidate for application in ultraviolet (UV) photodetection due to its large and direct band gap, which ensures a high absorption coefficient in the UV spectrum range and a high UV−vis rejection ratio.[1,2] Moreover, photodetectors fabricated from ZnO-based materials excel in high resistance to irradiation compare with that from other wide band gap semiconductors like diamond, SiC, and GaN.[3] Furthermore, the cheap price and biocompatibility characters make ZnO more attractive. ZnO-based photodetectors can be divided into three types according to their operating mode, that is, photoconductive type, metal−semiconductor−metal (MSM) type, and pn junction type.[4−7] In comparison with photoconduction- and MSM-type photodetectors, pn junction photodetectors have several advantages such as low dark current, fast response speed, and high responsivity, etc.[8] However, up to now most of the reports on ZnO-based photodetectors are focused on the photoconductive or MSM type,[9−12] whereas the reports on pn junction photodetectors are very limited.[5,6] This is mainly due to the serious fact that there are still huge difficulties in realizing stable and reproducible p-ZnO.[13] As an alternative, some groups tried to combine other available p-type materials, such as Si, 6H-SiC, NiO, $SrCu_2O_2$ with n-ZnO to form pn heterojunctions, and some photodetectors based on these heterojunctions were demonstrated.[14−17] However, such kind of photodetectors usually show response to UV light as well as visible light, namely, the spectrum selectivity is very poor.[11] Even in ZnO-based photoconductive, MSM or pn junction structured photodetectors, the response in the UV range is frequently a very broad peak.[4−12] In some cases, it is necessary to monitor the light in a very narrow spectrum range; thus, photodetectors with high spectrum selectivity are greatly wanted. To realize such high spectrum selectivity, a fragile and bulky optical filter is usually needed. However, such a filter will inevitably increase the complexity and cost of the photodetector.

In this article, n-ZnO has been combined together with p-GaN to form a heterojunction diode, and a photodetector is fabricated from this diode. In this structure, GaN and ZnO share the same crystalline structure and have very small lattice mismatch, which ensures a high-quality heterojunction can be achieved. Furthermore, the band gap of GaN (3.4 eV) is slightly larger than that of ZnO (3.37 eV). Under back-illumination conditions, the GaN layer on one hand acts as a p-type counterpart for the n-ZnO, on the other hand as a "filter" that is transparent to the light with wavelength larger than 360 nm. Since ZnO has a sharp cutoff absorption edge at about 390 nm, the photodetector based on the ZnO/GaN heterojunction should have very narrow response span within 360−390 nm. In our experiment, the photodetector fabricated from the heterojunction shows a narrow response "window" of only 17 nm, namely, a high spectrum selectivity photodetector has been obtained.

Experimental Section

The heterojunction structure was prepared by depositing undoped ZnO films onto commercial available GaN/Al_2O_3 templates using a plasma-assisted molecular beam epitaxy (MBE) technique. The growth details can be found in our previous publication.[18] The GaN layer was 2 μm in thickness and showed p-type conduction with a hole concentration of $3 \times 10^{17}/cm^3$ and a hole mobility of 10 $cm^2\ V^{-1}\ S^{-1}$. The as-grown ZnO film had a thickness of about 500 nm and showed n-type conduction with an electron concentration of $1 \times 10^{17}/cm^3$ and an electron mobility of 24 $cm^2\ V^{-1}\ S^{-1}$. The electrical properties of the films and the dark current of the photodetector were measured by a Hall measurement system (Lake Shore 7707). A Rigaku O/max-RA X-ray diffractometer (XRD) with Cu Kα radiation ($\lambda = 0.154$ nm) was used to evaluate the crystalline properties of the films. Both optical transmission and absorption spectra were recorded using a Shimadzu UV-3101PC spectrophotometer. Photoluminescence (PL) measurement was carried out in a JY-630 micro-Raman spectrometer employing the 325 nm line of a He−Cd laser as the excitation source.

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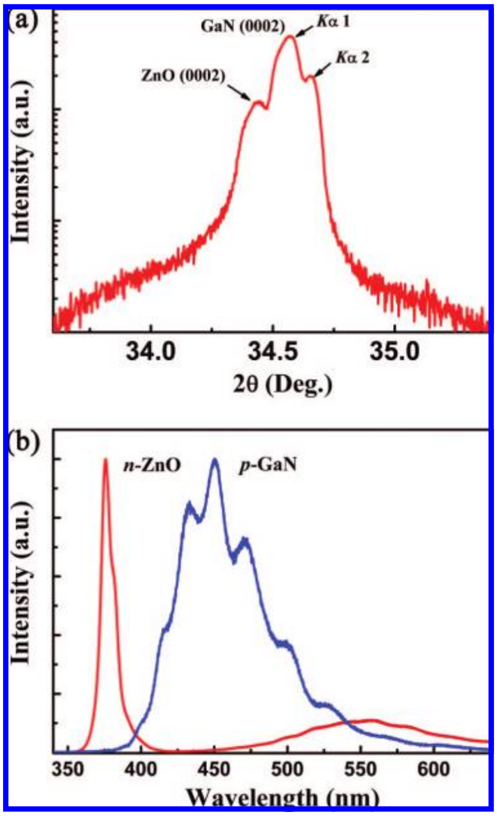

Figure 1. (a) XRD pattern of the ZnO/GaN heterojunction, in which Kα1 and Kα2 label the diffractions from the two Cu Kα lines. (b) Room-temperature PL spectra of the ZnO and GaN layer.

Ohmic contacts were achieved by vacuum evaporation of In and Ni/Au metal layers on n-ZnO and p-GaN layers, respectively. The photoresponse of the n-ZnO/p-GaN heterojunction photodetector was studied using a 150 W Xe lamp, monochromator, chopper (EG&G 192), and lock-in amplifier (EG&G 124A).

Results and Discussion

Figure 1a shows an XRD pattern of the ZnO/GaN heterojunction. There appear three peaks in the pattern, and the peak at 34.44° is the diffraction from the ZnO (0002) facet, whereas the other two peaks at 34.57° and 34.66° are from the Kα1 and Kα2 diffraction from the GaN (0002) facet. The appearance of the ZnO (0002) peak indicates that the ZnO layer is hexagonal structured and highly *c*-axis oriented. Shown in Figure 1b are the room-temperature PL spectra of the n-ZnO and p-GaN layer. As shown in the figure, the spectrum of the ZnO layer shows a dominant sharp peak at 375 nm, which is typically attributed to the free-exciton emission of ZnO,[13] and the deep-level emission at about 550 nm is very weak. The PL spectrum of the GaN layer is dominated by a broad peak at about 450 nm, which is frequently observed in Mg-doped p-GaN, and can be attributed to the transition from conduction band electrons or shallow donors to Mg acceptors.[19] The fringes observed in the spectrum are due to the interference between interfaces in the film.

Figure 2 shows the absorption and transmission spectra of the n-ZnO and p-GaN layer. It is clear from the spectra that the GaN layer has a sharp transmission edge at 360 nm. The absorption spectrum of the ZnO layer shows a free-exciton absorption peak at 366 nm. One can see from the figure that the transmission of GaN and the absorption of ZnO have an overlap in the region from 360 to 390 nm. This narrow "window" promises that high spectrum selectivity photodetectors can be realized in the ZnO/GaN heterojunction.

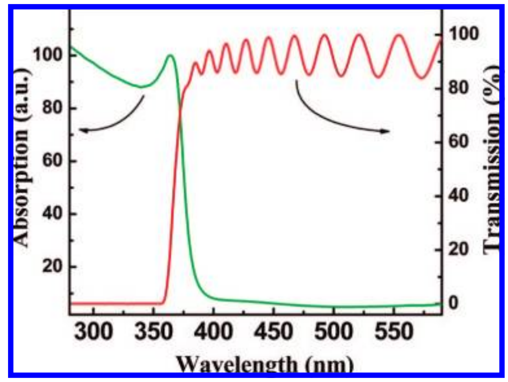

Figure 2. Transmission spectrum of the GaN layer and absorption spectrum of the ZnO layer.

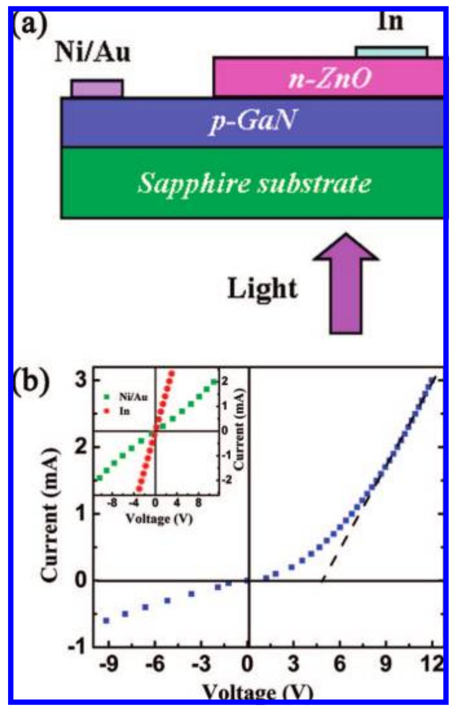

Figure 3. (a) Schematic illustration of the ZnO/GaN photodetector. (b) Typical rectification characteristics of the pn heterojunction; the dashed line is a guide to the eyes. The inset illustrates the $I-V$ curve of the Ni/Au contact to the p-GaN and the In contact to the n-ZnO layer, revealing good ohmic behaviors have been obtained in both contacts.

The structure and illumination geometry of the photodetector are schematically illustrated in Figure 3a. Illumination light is shed onto the heterojunction from the GaN side. The absorption coefficient of GaN is larger than 10^5 cm^{-1} in the UV range;[20] considering the thickness of the GaN layer is about 2 μm, the spectrum with wavelength shorter than 360 nm (the transmission edge of GaN) will be absorbed totally by the GaN layer, and only the light with wavelength longer than 360 nm can pass through the GaN layer and reach the ZnO layer. Furthermore, the carriers generated in the GaN layer cannot reach the depletion region in the time scale of their lifetime for the large thickness of the GaN layer and thus will not contribute to the photoresponse. Meanwhile, ZnO has an absorption edge at about 390 nm. Consequently, the photodetector fabricated from the ZnO/GaN heterojunction will only have a response in a narrow

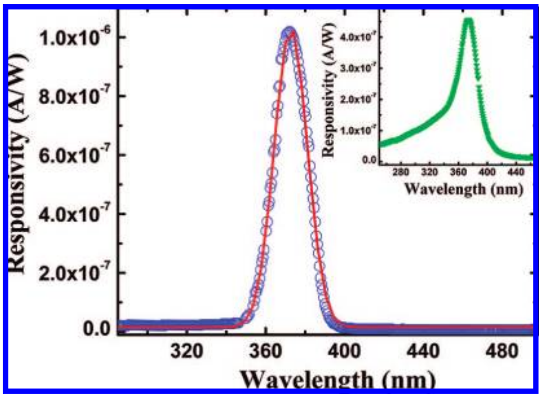

Figure 4. Room-temperature photoresponse of the n-ZnO/p-GaN photodetector under back-illumination at 0 V bias. The inset shows the response of the photodetector under front-illumination at 0 V bias.

spectrum window within 360−390 nm. Therefore, in this photodetector, the GaN layer acts a p-type material to form a pn heterojunction with ZnO, as well as a "filter" that ensures a high spectrum selectivity photodetector can be obtained. Figure 3b shows the current−voltage ($I-V$) curve of the n-ZnO/p-GaN heterojunction diode. The $I-V$ curve of the heterojunction shows obvious rectifying behavior with a turn-on voltage of about 4.6 V. The linear $I-V$ curves for both Ni/Au on p-GaN and In on n-ZnO reveal that good ohmic contacts have been obtained for both electrodes.

The photoresponse of the photodetector under back-illumination at 0 V bias is shown in Figure 4. The spectrum shows a narrow band centered at 374 nm with a full width at half-maximum (fwhm) of only 17 nm, revealing that the responsivity of the photodetector is highly selective. For comparison, the photoresponse spectrum of the photodetector under front-illumination at 0 V bias is shown in the inset of Figure 4. In this case, no "filter" is available for the photodetector; thus, the response selectivity should be poor. Our experimental results reveal that, under front-illumination, the photodetector shows obvious response in the high-energy tail. That is, the spectrum selectivity of the photodetector has degraded due to the lack of a "filter". The above fact confirms unquestionably the validity of the GaN "filter" in our photodetector.

The thermally limited detectivity (D^*) of the photodetector can be expressed by the following formula:[21]

$$D^* = R_\lambda (R_0 A/4kT)^{1/2} \quad (1)$$

where R_λ is the responsivity at 0 V bias, R_0 is the differential resistance, and A is the area of the device. A detectivity of 1.41 $\times$ 10^8 cm $Hz^{1/2}/W$ can be obtained at 374 nm for the photodetector under back-illumination, which corresponds to a noise equivalent power (NEP) of 9.5 $\times$ 10^{-8} $W/Hz^{1/2}$ at room temperature.

Conclusions

In summary, an n-ZnO/p-GaN heterojunction photodetector has been fabricated by depositing n-ZnO layer onto a p-GaN template. Under back-illumination conditions, the photodetector shows an enhanced UV photoresponse in a narrow spectrum range of only 17 nm in width. The high selectivity is due to the fact that the GaN layer that acts as a "filter" for the photodetector. The results shown in this paper reveal that the n-ZnO/p-GaN heterojunction can be a promising candidate for high spectrum selectivity UV photodetector applications. Furthermore, the results may provide a facile route to photodetectors with high spectrum selectivity by employing two or more semiconductors with different band gaps acting as "filters".

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