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Low-noise *p*-GaN/*i*-ZnO/*n*-ZnO:Al Ultraviolet Photodetectors using Vapor Cooling Condensation Technique

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1. Introduction

Zinc oxide is an II-VI semiconductor, which belongs to the wurtzite hexagonal structure. ZnO is one of the most attractive semiconductor materials for photonic and electronic applications. It has been studied as the blue/ultraviolet light-emitting diodes [1] due to its properties of wide bandgap of 3.37 eV, large exciton binding energy of 60 meV and strong cohesive energy of 1.89 eV. Moreover, applications of the ZnO ultraviolet photodetectors have been intensively developed due to its simple fabrication and lower cost [2,3]. In general, ZnO films have been grown by sputtering, molecular beam epitaxy (MBE) and metal organic chemical vapor deposition (MOCVD). In this study, a novel vapor cooling condensation technique was used to deposit *i*-ZnO films and to fabricate resulted *p*-GaN/*i*-ZnO/*n*-ZnO:Al (*p*-*i*-*n*) UV photodetectors. In this work, the heterostructed *p*-*i*-*n* photodetectors were measured and analyzed.

2. Experiment

The structure of a *p*-*i*-*n* photodetector is schematically shown in Fig. 1 (a). First, the 800 nm-thick GaN buffer layer was deposited on the *c*-plane (0001) sapphire substrate by using metal-organic chemical vapor deposition (MOCVD) technique. The 1 μm-thick Mg-doped GaN layer was grown on the buffer layer to form the *p*-type layer. To perform the p-type ohmic contact, Ni/Au (20/100 nm-thick) were deposited on the *p*-GaN layer and then annealed at 500°C for 10 min in an air ambient. In this study, we used vapor cooling condensation system, as shown in Fig. 1 (b), to grow high-quality *i*-ZnO layers. ZnO powders were put on a tungsten boat and heated. The sublimated ZnO vapor gases were condensed and deposited on the *p*-GaN layer which was cooled by liquid nitrogen. The 150 nm-thick *i*-ZnO was deposited on the *p*-GaN layer. The 20 nm-thick Al-doped ZnO (*n*-ZnO:Al) was then deposited on the *i*-ZnO layer using a sputter system. The deposited *i*-ZnO layer and *n*-ZnO:Al layer had an electron concentration of 7.6×10^{15} cm^{-3} and 5×10^{19} cm^{-3}, respectively. An 150 nm-thick Al was deposited on the *n*-ZnO:Al layer to perform the n-type ohmic contact.

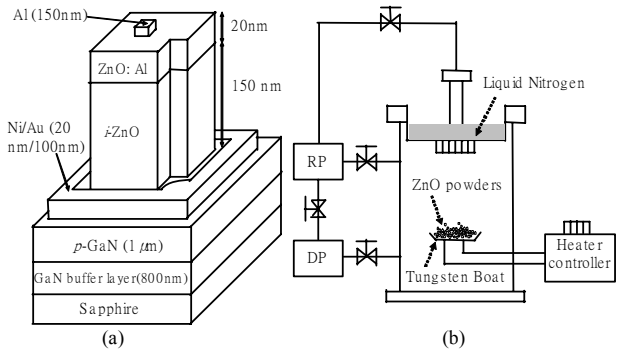

Fig. 1 (a) A schematic of *p*-*i*-*n* heterostructure photodetector and (b) Equipment setup of vapor cooling condensation evaporation system.

3. Results and discussion

The spectral photoresponsivity of the fabricated *p*-*i*-*n* photodetector was measured in the wavelength range from 300 nm to 500 nm using an 150W xenon (Xe) lamp, which was connected to a monochromator via an optical fiber. Each measured device was uniformly illuminated from the top side. By measurements of the spectral photocurrents, the photoresponsivity spectra were calculated according to $R=I_{ph}/P_{opt}$, where R is the photoresponsivity. I_{ph} and P_{opt} are the photocurrent and the optical power, respectively. The photoresponsivity measured results are shown in Fig. 2. As shown Fig. 2, the photoresponsivity was found to slightly increase with the reverse voltage. It can be seen that the photoresponsivities which were unbiased and applied 5V reverse bias are evaluated about 0.030 A/W and 0.092 A/W at 360 nm, respectively. Generally, the photoresponsivity would increase with the increase in photocurrent. The photocurrent increased due to the wider depletion layer, which can accommodate many electron-hole pairs.

The current-voltage (I-V) characteristics of the *p*-*i*-*n* photodetectors were measured by using an Agilent 4156C semiconductor parameter analyzer, as shown in Fig. 3. The leakage current is 6.32 pA for applied 5 V reverse bias. The dynamic resistance (dV/dI) operated at zero bias voltage (defined as R_0) is about 1.82×10^{12} Ω, yielding a dynamic resistance-area product of $R_0A=1.64\times10^{9}$ Ω-cm^2, where A is the photodetector area of 9×10^{-4} cm^2. Without applied bias

and external photo flux, illumination, this high zero bias dynamic resistance R_0 ensures low Johnson-Nyquist noise (thermal noise) component [4, 5]. Substituting the experimental results of R_0=1.82×10^{12} Ω into noise power density formula $S_n=4KT/R_0$ showed a low thermal noise power density of 8.68×10^{-33} A^2/Hz.

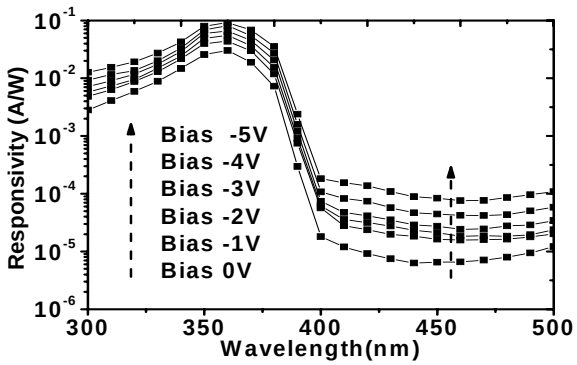

Fig. 2 The spectral photoesponsivity of *p*-GaN/*i*-ZnO/*n*-ZnO:Al photodetectors.

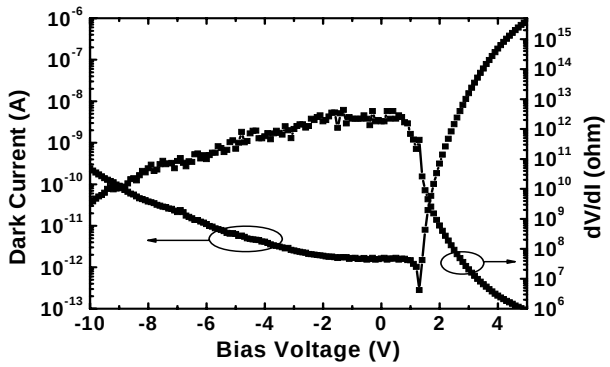

Fig. 3 Current-voltage characteristics and dynamic resistance of *p*-GaN/*i*-ZnO/*n*-ZnO:Al photodetectors.

The spectra of noise power density which were applied different bias were shown in Fig. 4. It was found that the each noise power density S_n, which was about from 3.42×10^{-27} A^2/Hz (at -1 V) to 4.89×10^{-26} A^2/Hz (at -5 V) at 1 Hz is larger than the thermal noise power density. It indicated that the device which was applied bias is not dominated by the thermal noise. Flicker (1/*f*) noise is main contribution to noise power density [6]. For a bandwidth of Δf, the total square noise current can be determined by integrating the noise power density:

$$<i_{1/f}^2>=\int_0^{\Delta f} S_n(f)df \qquad (1)$$

Where the noise detectivity D^* is obtained from the relation:

$$D^* = R\sqrt{A\Delta f}\Big/\sqrt{<i_{1/f}^2>} \qquad (2)$$

Where R and A are the photoresponsivity and the photodetector area, respectively. With a reverse of bias 5 V, a large large detectivity of 1.66×10^{11} cmHz$^{1/2}$W^{-1} was obtained. Therefore, the fabrication technology incorporated with the vapor cooling condensation technique can produce a photodetector with a large value of detectivity. The large detectivity was attributed to low noise power density of *p-i-n* photodetector.

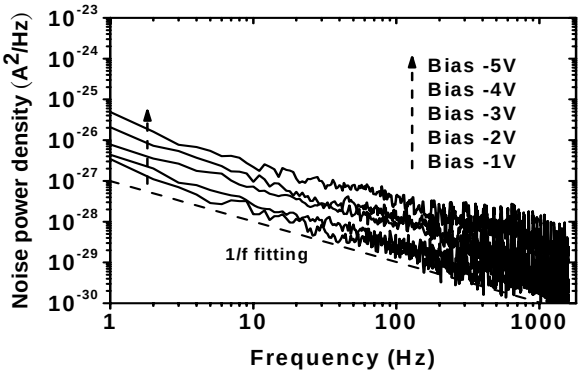

Fig. 4 Noise power density measured as a function of frequency for different bias voltage.

4. Conclusion

The vapor cooling condensation technique was used to grow high quality *i*-ZnO film. Thus fabricated photodetector exhibits a small dark current of 6.32 pA at 5 V reverse bias. The peak photoresponsivity are 0.03 A/W(0 V) and 0.092 A/W(-5 V) at 360 nm. The noise power density of 8.68×10^{-33} A^2/Hz is thermally limited at zero bias. Being 1/*f*-type limited under bias, the noise power density of the device is 4.89×10^{-26} A^2/Hz at 5 V reverse bias. The detectivity (D^*) of 1.66×10^{11} cm Hz$^{1/2}$W^{-1} can be determined by low 1/*f* noise power density. So high performance *p-i-n* photodetectors can be obtain by employing vapor cooling condensation technique to deposit high-quality *i*-ZnO film.

Acknowledge

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