Low-Pass and Bandpass Alternative Ultraviolet Photoconductor Based on Zinc Oxide Nanoparticles on Intrinsic Gallium Nitride-Based Substrate

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***Abstract*—Zinc oxide (ZnO) nanoparticles created by top-down wet-chemistry synthesis were deposited onto intrinsic epitaxial grown gallium nitride-based substrates. Aluminum (Al) was evaporated through a shadow mask to form photoconductors. Visible-blind ultraviolet (UV) response has been recorded as high as 0.8 A/W at 375 nm. Experiments demonstrated that the photoconductors exhibited either a low-pass or bandpass spectral response depending on the illumination directions.**

***Index Terms*—Polyvinyl-alcohol (PVA) coated ZnO nanoparticles, spectrally selective response, top-down wet-chemical etching, ultraviolet (UV) photoconductor.**

I. Introduction

ULTRAVIOLET (UV) detectors have a wide range of applications, such as flame sensing, biological and chemical analysis, optical communications, astronomical studies, missile launch detection, and emitter calibration [1]. Wavelength selective detectors are particularly desirable for specific source and range recognition in order to eliminate false alarms, as well as increase communication capacity in short distance nonline-of-sight optical communication systems. Device structures for narrow bandpass detection include resonant cavity enhancement schemes and quantum well structures for high performance detectors in near infrared and infrared wavelength ranges [2], [3], and absorptive epitaxial filter layers in aluminum gallium nitride (AlGaN) systems designed for UV wavelengths detection [4]–[6].

Zinc oxide (ZnO) is a promising direct wide bandgap semiconductor material in UV detection since it has large exciton binding energy (60 meV), high radiation hardness, and relatively low growth temperature [7], [8]. In this work, high responsivity UV photoconductors based on polyvinyl-alcohol (PVA) coated ZnO colloidal nanoparticles on epitaxially grown AlGaN and gallium nitride (GaN) substrates are demonstrated. The photoconductors exhibit either low-pass or bandpass spectral response by illuminating the light from front side or back side.

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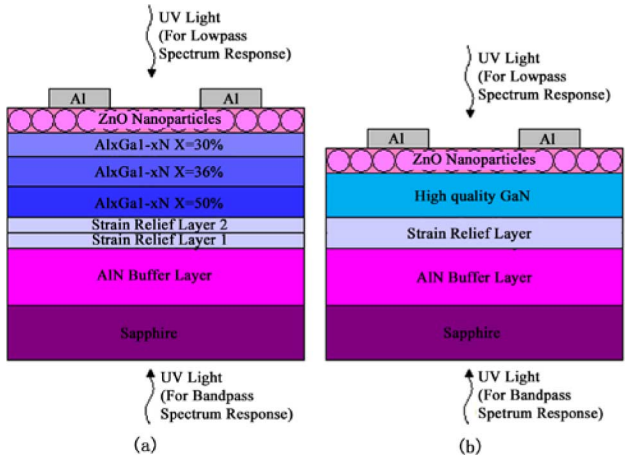

Fig. 1. Structure of (a) ZnO nanoparticles-AlGaN substrate and (b) ZnO nanoparticles-GaN substrate photoconductors.

Spectrally selective performance in specific wavelength ranges was achieved. To our knowledge, this is the first demonstration of a multilayer heterostructure device comprised of solution processed ZnO colloidal nanoparticles on GaN-based semiconductor substrates.

II. Experiment

ZnO nanoparticles were created by a top-down wet-chemistry synthesis process and then coated with PVA [9]. The nanoparticles were dispersed in ethanol to form a 30 mg/ml suspension and spin-casted onto the substrates. The samples were annealed in air at 150°C for 5 minutes. Two irregular 100-nm thick aluminum (Al) contacts (2 mm^2) were deposited by electron beam (e-beam) evaporation through a shadow mask to create photoconductors. The schematic diagram of the photoconductors is shown in Fig. 1. Wires were bonded by a conductive epoxy to the Al contacts.

III. Results and Discussion

The AlGaN and GaN epitaxial substrates were grown by Sensor Electronic Technology Inc. (SET Inc.) The components of AlGaN and GaN substrate are indicated in Fig. 1. The AlGaN structure targeted a cutoff wavelength of 300 nm. The GaN structure is similarly designed, with a targeted cutoff wavelength of 360 nm. These substrates were cleaned and then characterized through absorption, photoluminescence,

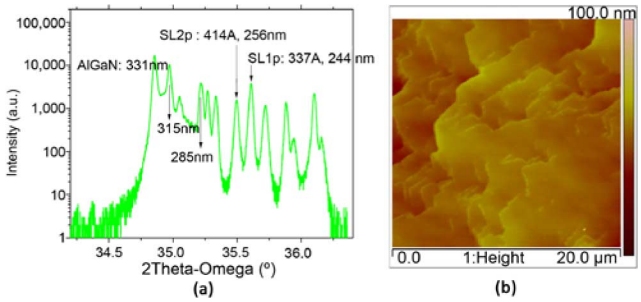

Fig. 2. (a) XRD and (b) AFM of AlGaN substrate.

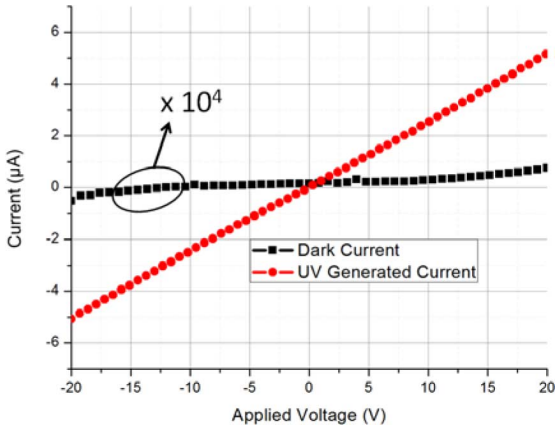

Fig. 3. I–V plot of PVA coated ZnO nanoparticles-AlGaN substrate photoconductor shows a UV photo-generated current (red circle) to dark current (black square, multiplied by 10^4 of its real value) ratio as high as 5 orders.

x-ray diffraction (XRD) and atomic force microscopy (AFM) measurements. The XRD and AFM results as shown in Fig. 2 indicate the good quality of the AlGaN substrate.

The PVA coated ZnO nanoparticles exhibited enhanced UV optical performance compared to their uncoated counterparts. A sharp cutoff at 375 nm in absorption spectrum and a strong band edge UV emission with a peak at 377 nm with diminished parasitic green emission were achieved [9]. The good optical performance of PVA coated ZnO greatly contributes to the good photoresponse performance of reported detectors

Point contacts current–voltage (I–V) characteristics of samples were measured under darkness and illumination of 340-nm UV light-emitting diode (LED) with intensity of 45.58 mW/cm^2. The results of the photoconductor based on PVA coated ZnO nanoparticles spin-casted onto intrinsic AlGaN are shown in Fig. 3. Linear I–V curves were obtained, indicating ohmic behavior between the ZnO nanoparticles and the Al contacts occurred. At -20 V bias, the dark current is 50 pA and the UV photo-generated current is 5 μA, corresponding to a UV photo-generated current to dark current ratio (on/off ratio) of 10^5.

The spectral response of a front illuminated PVA coated ZnO nanoparticles-AlGaN substrate photoconductor under 20-V bias is shown in Fig. 4. A low-pass response with a sharp cutoff wavelength at 380 nm is observed. This visible-blind characteristic conveniently allows for UV detection to be facilitated under normal environment without the use of filters. The responsivity of the PVA coated ZnO nanoparticles-AlGaN substrate device

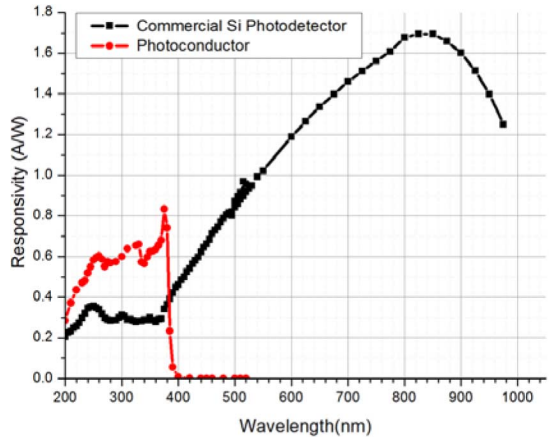

Fig. 4. Spectral response of commercial UV enhanced Si photodiode (black square) and PVA coated ZnO nanoparticles-AlGaN substrate photoconductor (red circle).

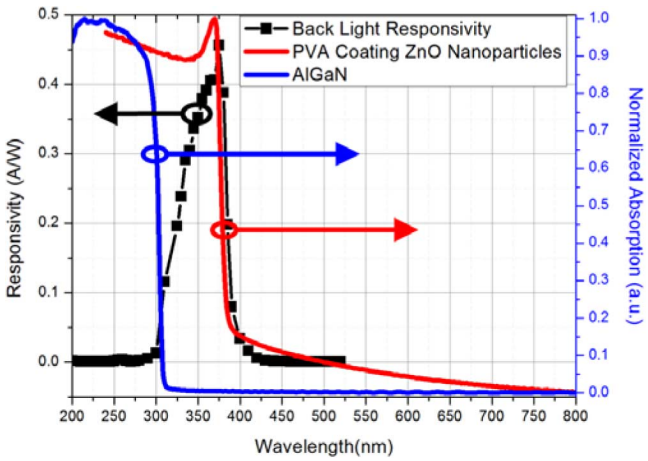

Fig. 5. Back illuminated PVA coated ZnO nanoparticles-AlGaN substrate photoconductor, exhibiting bandpass (black square: 300–380 nm) responsivity as it relates to the absorption spectra of AlGaN (blue line) and PVA coated ZnO nanoparticles (red line).

is 0.8 A/W at 375 nm when the total optical power on the active area is 22.32 nW. In the UV range, this spectral response is twice that of a typically unbiased commercial UV-enhanced Silicon (Si) photodiode measured using the same setup. This high UV response attributes to the high surface area to volume ratio of nanoparticles which increases the absorption of light over traditional bulk or epitaxial grown materials and the enhanced UV diminished defects performance of PVA coated ZnO nanoparticles.

As shown in Fig. 5, bandpass (300–380 nm) responsivity with a peak at 375 nm can be observed when light penetrates the detector through the substrate or backside of the PVA coated ZnO nanoparticles-AlGaN substrate photoconductor. This wavelength selective response is due to the absorptive properties of the substrate and the ZnO nanoparticles. When the wavelength of incident light is shorter than 300 nm, the cutoff wavelength of AlGaN substrate, that light is absorbed by the AlGaN. Electron-hole pairs generated within the AlGaN substrate do not generate current since these carriers do not have a conduction path to the contacts deposited on top of ZnO

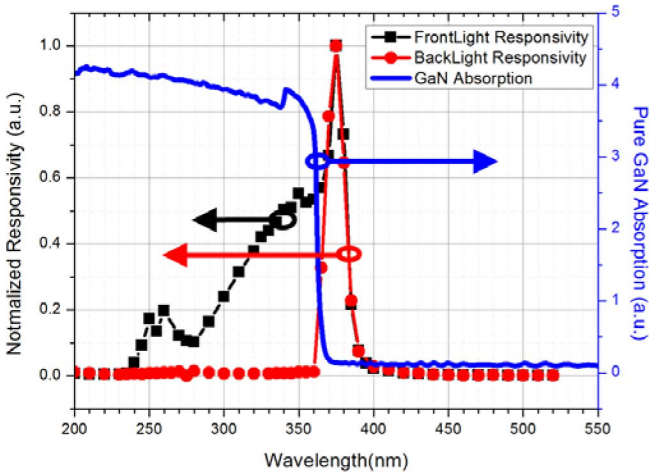

Fig. 6. Front and back illuminated PVA coated ZnO nanoparticles-GaN substrate photoconductors, low-pass (black square) and bandpass (red circle: 360–380 nm) responsivity as it relates to the absorption of GaN (blue line).

nanoparticles. When the incident light wavelength is longer than 300 nm but shorter than 380 nm, the bandgaps of AlGaN and ZnO dictate this light penetrates the AlGaN substrate and reaches the ZnO active layer to generate current. If the incident light wavelength is longer than the 380-nm, cutoff wavelength of ZnO, that light pass through both the AlGaN and ZnO layer and therefore no current generated. This bandpass responsivity can be applied for detecting specific wavelengths without the use of external filters, thus making such a system simpler and further minimizing spectral noise in applications requiring sensitivity to select wavelengths. For example, these devices demonstrated an increased signal-to-noise ratio over a commercial UV enhanced Si photodiode for an intrinsic fluorescence based biohazard detection system. Details are presented in another paper [10].

Wavelength selectivity can be tuned by the material properties of the substrate. Fig. 6 is the spectral response of PVA coated ZnO nanoparticles deposited onto a GaN substrate that has a cutoff wavelength at 360 nm. Under front illumination, the photoconductor exhibited a normal low-pass responsivity corresponding to the cutoff wavelength of ZnO. Under back illumination, the detector exhibited a bandpass responsivitiy from 360 nm to 380 nm, corresponding to the absorption of ZnO nanoparticles and GaN substrate.

Currently carriers generated in the substrate are not being used. Therefore, ZnO nanoparticles and doped AlGaN/GaN heterojunction photodetector is being designed such that the spectral responsivity could be controlled by both the illumination direction and the polarity of the applied voltage between the AlGaN and the ZnO layer.

IV. Conclusion

In conclusion, spectral selective photoconductors were created by depositing PVA coated ZnO nanoparticles onto epitaxially grown AlGaN and GaN substrates. The responsivity of the photoconductor with an AlGaN substrate in the UV range is twice that of a commercial UV enhanced Si photodiode when illuminated on the front side. The absorption cutoff of AlGaN and GaN created a bandpass response when the detector is illuminated on the substrate or backside. With careful design of the bandgap energy of the active material and the substrate, specific wavelength response detectors can easily be achieved.

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