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GZO/GaN Schottky barrier ultraviolet band-pass photodetector with a low-temperature-grown GaN cap layer

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Aluminum gallium nitride (AlGaN) alloys are most promising materials for the fabrication of high-sensitivity solar/visible-blind photodetectors (PDs), since it has a wide direct band gap (3.4~6.2 eV at room temperature) and a high saturation electron drift velocity. In the past years, various types of GaN-based photodetectors have been demonstrated, such as *p-n* junction photodiodes, *p-i-n* PDs, *p-π-n* PDs, Schottky barrier PDs, andmetal-semiconductor-metal (MSM) PDs [1-5]. The most important key point to fabricate Schottky barrier PDs with high responsivity and low leakage current is the performance of Schottky contacts (SCs). It has been reported that various metals and transparent conducting oxide films deposited on GaN could achieve high performance SCs. In addition to the choice of contact metals, leakage current of SCs also depends strongly on the threading dislocation (TD) density of the GaN layers. In this study, we grew a LTG GaN cap layer on conventional high-temperature-grown GaN layer associated with the use of GZO films deposited on the LTG GaN to form the SB PDs.

In this work, the samples used in this work were grown on c-face sapphire (0001) substrates by metal organic chemical vapor deposition. As shown in Fig. 1, a 30-nm-thick GaN nucleation layer was grown first at 550 ^{o}C, and followed by a 3-μm-thick Si-doped *n*-GaN and a 1-μm-thick un-doped GaN layer grown at 1050°C. Finally, the wafers were capped with a 30-nm-thick un-doped GaN layer grown at temperature of 550°C. It should be noted that the LTG GaN cap layer behaves in a kind of insulator with a sheet resistivity larger than 10^9 Ω/□. To fabricate the GaN SB PDs, Cl_2-based plasma dry etching was applied to expose the *n*-GaN underlying layer. A GZO film with a thickness of about 200 nm was deposited on top of the samples by DC magnetron sputtering. The GZO target used in the DC magnetron sputtering containes 97% ZnO and 3% Ga_2O_3, in terms of weight percentage. The deposited GZO thin films exhibited a typical transmittance of over 80% at an incident wavelength of 360 nm, which implies a potential alternative to replace the conventional transparent contact layers, such as Ni/Au bilayer metal, which are used to serve as a transparent Schottky and Ohmic contact on GaN-based PDs and LEDs [6], respectively. Samples were then annealed at 700°C for 1 min in N_2 ambient by rapid thermal annealing in order to reduce resistivity of the GZO films. The typical resistivity of the GZO films after annealing was measured to be around 5×10^{-4} Ω-cm determined by Hall-effect measurement [7]. Then, a Cr/Au (50/200 nm) bilayer was deposited on the exposed *n*-GaN and the GZO served by e-beam evaporator to serve as *n*-type Ohmic contacts and anode electrodes, respectively. The diameter of the circular devices fabricated in this work was maintained at 500 μm. Here, PD-I and PD-II are corresponding to the sample with and without the LTG GaN cap layer, respectively. The current-voltage (I-V) characteristics were measured at room temperature using HP4156C semiconductor parameter analyzer. Spectral responsivity of these SB PDs was measured using a Xe arc lamp and a calibrated monochromator as the light source. The monochromatic light was calibrated by Si photodiode and then illuminated onto the front side of SB PDs.

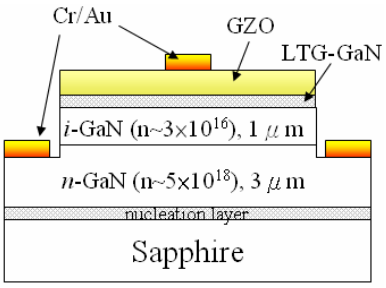

FIG. 1. Schematic structure of the GZO/LTG GaN/*i*-GaN Schottky barrier diode (PD-I).

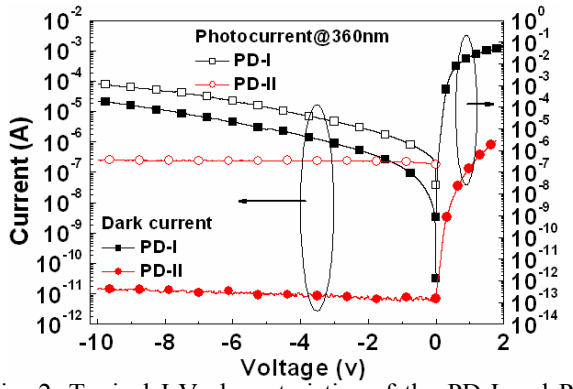

Fig. 2. Typical I-V characteristics of the PD-I and PD-II, respectively. The power and the wavelength of the incident light are 1μW and 360 nm, respectively.

Figure 2 shows a typical rectified I-V characteristic of the PD-I and PD-II. Under reverse biasing, PD-I was nearly independent in bias voltage and well below 20 pA as the bias voltages was lower than -10 V. In contrast, the dark

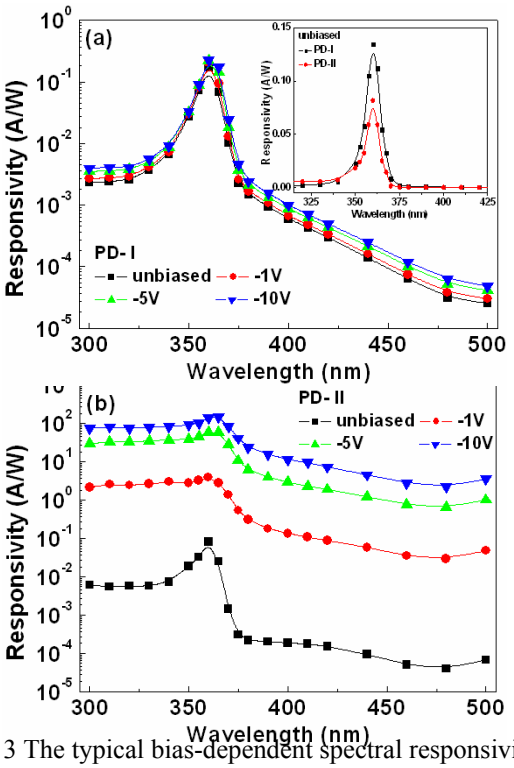

Fig. 3 The typical bias-dependent spectral responsivity of (a) PD-I and (b) PD-II measured at different reverse biases. The inset of Fig.4 shows the PD-I and PD-II all exhibited a narrow band-pass spectral response from 330 to 380 nm.

current of PD-II was large and increased rapidly as the reverse bias increased. This behavior of low dark current in PD-I could be attributed to the fact that the high resistivity LTG GaN cap layer could result in a higher Schottky barrier height at the GZO/*i*-GaN interface and hence a low leakage current in the SB PDs. [8,9] Under forward bias, the high turn on voltage observed in PD-I could be attributed to its high barrier height and the fact that injected carriers are compensated by poor crystal quality related trap levels within the band gap of LTG GaN. Under illumination at 360 nm, the contrasts of photocurrent and dark current are around 2.7×10^4 and 7.8 for PD-I and PD-II, respectively, when the samples were biased at -1 V, as shown in Fig.2. These results revealed that the PD-I with a LTG GaN cap layer could significantly exhibits less leakage current and more photocurrent to dark current contrast compared to PD-II without a LTG GaN cap layer. Figures 3 (a) and 3 (b) shows bias-dependent spectral responses of PD-I and PD-II, respectively. The peak responsivities of PD-I show a slightly increase with an increase of bias voltage implying that a small internal gain. However, PD-II without the LTG-GaN cap layer exhibited stronger bias-dependent responsivity and larger internal gain when reverse bias was increased. The internal gain would lead to a decrease of the UV-to-visible spectral rejection ratio because the below band gap response will be more effectively intensified by the gain than the above band gap spectral response. In this study, PD-I exhibited UV-to-visible spectral rejection ratios (360 nm to 450 nm) all around ~10^3. The results could be attributed to the fact that PD-I with a LTG GaN cap layer could reduce dark current and suppress internal gain effectively because the LTG GaN cap layer with high-resistivity property may passivate the charged surface states and thereby reduce the trap states at the GZO/*i*-GaN interface. The inset of Fig. 4 shows the PD-I and PD-II all exhibited a narrow band-pass spectral response from 330 to 380 nm. The long-wavelength cutoff is an inherent characteristic resulting from the band-edge absorption of the GaN layer. The short-wavelength cutoff is attributed to the surface absorption of the GZO top layer [7] when incident photon energies were above the band-gap of the GZO films. The results were very different from the behaviors of typical PDs which have a flat spectral response at the short- wavelength region, which have transparent metal contacts.

In conclusion, GZO films were deposited onto LTG GaN/*i*-GaN (PD-I) and *i*-GaN (PD-II) epitaxy layer to form Schottky barrier UV band-pass PDs. The UV PDs exhibited a narrow band-pass spectral response ranging from 330 to 380 nm. It was found significantly reduce the leakage current and achieve a much larger photocurrent to dark current contrast ratio by using a LTG GaN on top of the conventional nitride-based UV PDs. The short-wavelength cutoff at around 330 nm can be attributed to the marked absorption of the GZO top contact layer. When the reverse biases were below 10 V, the dark currents of PD-I were well below 20 pA.

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