Low Dark Current GaN p-i-n Photodetectors With a Low-Temperature AlN Interlayer

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***Abstract*—GaN p-i-n ultraviolet (UV) photodetectors (PDs) with a low-temperature (LT)-AlN interlayer were proposed and fabricated. It was found that the dark current of such detectors is as small as 28pA even at a high reverse bias of 40 V. Although the high potential barrier at the AlN–GaN interface would slightly reduce the responsivity of PD under low reverse biases, the high UV-to-visible rejection ratio of the PD with an LT-AlN interlayer could be achieved under high reverse biases due to its very low dark current. The rejection ratio of the PD with the LT-AlN interlayer is as large as 735 at the reverse bias of 40 V.**

***Index Terms*—GaN, interlayer, low temperature (LT), photodetectors (PDs), p-i-n.**

THE tremendous progress of III–nitride semiconductors in recent years makes these materials promising candidates for ultraviolet (UV) emitting and detecting applications. These kinds of materials are also suitable for working in extreme conditions due to their properties of superior radiation hardness and high-temperature resistance. During the last decade, the fabrication of various types of GaN-based photodetectors (PDs) has been reported [1]–[6]. Among these structures, p-i-n type PDs have high breakdown voltage, low dark current, sharp cutoff, and high responsivity. For a diode operated at reverse bias, like a PD, low leakage current is one of the important characteristics which induce high responsivity and large rejection ratio. Unfortunately, the typical current–voltage (I–V) characteristic of a PD reveals an increase of leakage current with increasing applied voltages. Therefore, lowering leakage current is always a research-worthy issue for a PD. In avalanche PDs, the leakage current can be reduced by scaling down the chip size of devices [7], [8]. The small amount of dislocations should result in less leakage paths in a small area of an epitaxial wafer. The small size of the device, however, also means the small light absorption region. Another way to reducing leakage current is fabricating PDs by the epitaxial lateral overgrown technique [9], but it requires a relatively complicated procedure. Recently, the use of low-temperature (LT)-AlN interlayer between two high-temperature epitaxial layers to reduce threading dislocations and control stress in III–nitride epitaxial system has been reported [10], [11]. Compared to the LT-AlN interlayer, the high-temperature AlN interlayer will induce higher dislocation density in the subsequently grown epitaxial layers [12]. On the other hand, the LT-AlN layer as a cap layer in GaN metal–semiconductor–metal PD has been demonstrated to serve as the passivation layer of a diode [13], [14]. In this letter, we report the fabrication of GaN p-i-n PD with an LT-AlN interlayer. Properties of the fabricated devices with and without the LT-AlN interlayer will also be discussed.

The GaN PDs used in this study were all grown on 2-in c-plane (0 0 0 1) sapphire substrates by a low-pressure metal–organic chemical vapor deposition system. Trimethylgallium (TMGa), trimethylaluminum (TMAl), and ammonia (NH_3) were employed as gallium, aluminum, and nitrogen sources, respectively. Silane (SiH_4) and biscyclopentadienyl–magnesium (Cp_2Mg) were used as the n- and p-type precursors, respectively. Hydrogen (H_2) was used as carrier gas during epitaxy. The fabricated p-i-n PDs consist of a 25-nm-thick GaN nucleation layer grown at 520 °C, a 4-μm-thick Si-doped n-GaN layer grown at 1120 °C, a 0.5-μm-thick undoped GaN layer, a 30-nm-thick LT-AlN interlayer, a 0.5-μm-thick undoped GaN layer, and a 100-nm-thick Mg-doped p-GaN layer. The growth temperature of LT-AlN interlayer was 560 °C. For comparison, samples without the 30-nm-thick LT-AlN interlayer were also prepared. All samples were subsequently annealed *in situ* to active Mg in the p-type layer. GaN p-i-n PDs were then fabricated by conventional photolithography and inductively coupled plasma etching. Ni–Au contact was subsequently evaporated onto the p-type GaN surface to serve as the p-electrode. On the other hand, Cr–Pt–Au contact was deposited onto the exposed n-type GaN layer to serve as the n-electrode. The wafers were then lapped down to 100 μm. We then used scriber and breaker to fabricate the $325 \times 325\ \mu m^2$ chips. After these procedures, we used an HP-4156 semiconductor parameter analyzer to measure I–V characteristics of the fabricated PDs. Spectral responsivity measurements were also performed by a JOBIN-YVON SPEX 1000 M System with a xenon arc lamp light source. All the optical systems were calibrated using a UV-enhanced silicon photodiode.

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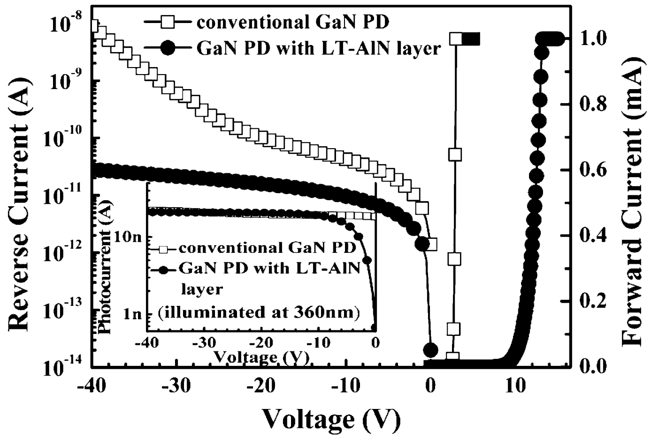

Fig. 1. Room-temperature dark I–V characteristics of the fabricated p-i-n PDs with and without an LT-AlN interlayer. The inset shows the I–V characteristics of both detectors under 360-nm light illumination.

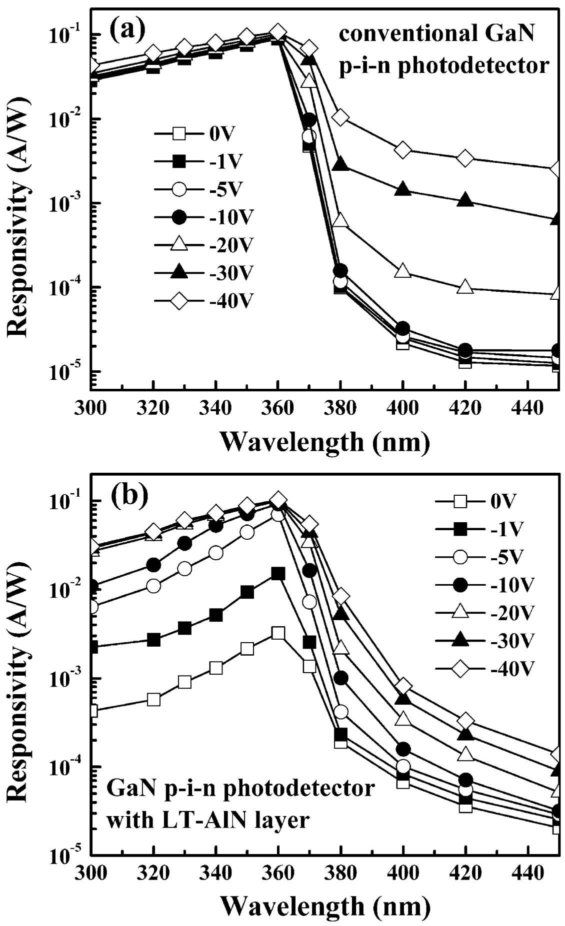

Fig. 2. Responsivities measured under various applied reverse biases for the fabricated GaN p-i-n PDs (a) without and (b) with the LT-AlN interlayer.

Fig. 1 shows the dark I–V characteristics of the two GaN p-i-n PDs. It can be seen that the dark leakage current is significantly low for the PD with LT-AlN interlayer. Under reverse bias, it was found that the dark current of the PD with LT-AlN interlayer was 2–3 $\times 10^{-11}$ A. In contrast, the dark current of the conventional PD was much larger and increased rapidly with increasing reverse voltage. The measured results of these samples are repeatable. We measured at least ten samples with an LT-AlN interlayer and ten samples without an LT-AlN interlayer and always achieved the same results. It should be noted that the dark current of the PD with an LT-AlN interlayer was over two orders of magnitude lower than that of the conventional PD at the reverse bias of 40 V. The origin of high dark current in conventional PD is attributed to the leakage current paths formation from the threading dislocations and related defects. It has been reported that threading dislocations can be suppressed from extending to the following high-temperature epitaxial layers (top p-GaN and upper i-GaN layers) by inserting an LT interlayer [10], [11]. Amano *et al.* showed that both LT-AlN and LT-GaN interlayers can reduce the dislocation density of GaN layers by about one order of magnitude [11]. However, the crystalline quality of the bottom n-GaN and i-GaN layers cannot be improved by an LT-AlN interlayer. On the other hand, the GaN p-i-n PDs with an LT-GaN interlayer showed a dark current of 147 nA at the reverse bias of 40 V [15], which is larger than the dark current of detectors with an LT-AlN interlayer. Thus, comparing the results of these two structures, the less dislocations effect of the LT interlayer should not be responsible for dark current reducing in our GaN p-i-n detectors. It was also known that the bandgap of AlN is larger than that of GaN. The energy gap discontinuities of conduction and valence band at AlN–GaN heterointerface are 2.0 and 0.7 eV, respectively [16]. Thus, the traveling carriers (electrons/holes) would be blocked by this high energy barrier, which results in a very low dark current. This should be the main cause for such low dark current of the device. On the other hand, the very slight increase of dark current at high voltage was observed in the PD with LT-AlN interlayer. This may be due to the current tunneling mechanism at high reverse bias. The influence of high potential barrier at the AlN–GaN interface also shows in the forward-bias I–V characteristics. It was found that the turn-on voltages of the PDs with and without LT-AlN interlayer were 9.4 and 2.5 V, respectively. This high turn-on voltage can be attributed again to the blocking effect of the high potential barrier at AlN–GaN interface on carriers transport. Similarly, the photogenerated carriers also need the same large bias ($\sim$10 V) to overcome this AlN–GaN interface barrier. The inset of Fig. 1 shows the I–V characteristics of both detectors under 360-nm wavelength light illumination. It was found that the photocurrent of the detector with an LT-AlN interlayer reached to the current level the same as that with the conventional PD while the applied voltage was larger than 10 V.

Fig. 2(a) and (b) shows responsivities measured under various applied reverse biases for the fabricated GaN p-i-n PDs without and with an LT-AlN interlayer, respectively. It was found that the maximum responsivity occurred at 360 nm for both detectors, which corresponds to the GaN absorption bandgap. The peak responsivity of the conventional PD was observed in a value of around 0.1 A/W from 0- to 40-V reverse biases. Under high reverse bias ($>$20 V), it was found that the responsivity

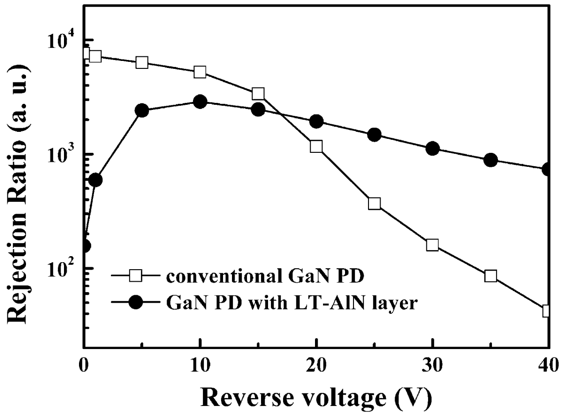

Fig. 3. UV (360 nm)-to-visible (450 nm) rejection ratios of PDs with and without LT-AlN interlayer.

in the long wavelength region (i.e., $\lambda > 400$ nm) increased significantly, as shown in Fig. 2(a). We believe this phenomenon should be attributed to the fact that the dark current of the conventional PD increased markedly with the reverse bias, as shown in Fig. 1. In contrast, no such large responsivity in the long wavelength region was observed in the PD with an LT-AlN interlayer, as shown in Fig. 2(b). This can be attributed to the fact that the defect-generated currents were blocked at AlN–GaN heterointerface by using an LT-AlN interlayer. On the other hand, the small peak responsivity of the detector with an LT-AlN interlayer under low reverse bias (<10 V) can be predicated from the small photocurrent observed at the same bias range, as shown in the inset of Fig. 1. From Fig. 2(b), it was found that the peak responsivity of the PD with an LT-AlN interlayer can reach to 0.1 A/W at the reverse bias larger than 10 V. Here, we define the UV-to-visible rejection ratio as the responsivity measured at 360 nm divided by the responsivity measured at 450 nm. Fig. 3 shows the rejection ratios of both detectors under different reverse biases. It was found that the rejection ratio of the conventional PD reduces significantly when the reverse biases exceed 15 V. This observed behavior is consistent with the dark I–V characteristics of the conventional PD, as shown in Fig. 1. In contrast, although the rejection ratio of the PD with LT-AlN interlayer is smaller than that of the conventional PD under low reverse bias range, it was found that the rejection ratio of the PD with an LT-AlN interlayer only reduces slightly under high reverse biases. The rejection ratios of detectors with and without an LT-AlN interlayer at the reverse bias of 40 V are 735 and 40, respectively. This larger UV-to-visible rejection ratio observed from the PD with an LT-AlN interlayer should be attributed to its much smaller dark current.

In summary, GaN p-i-n UV PDs with an LT-AlN interlayer were proposed and fabricated. Compared with conventional GaN p-i-n PD, it was found that the dark current is significantly low for the PD with an LT-AlN interlayer. Although the high potential barrier at the AlN–GaN interface would slightly reduce the responsivity of PD under low reverse biases, the high UV-to-visible rejection ratio of the PD with an LT-AlN interlayer could be achieved under high reverse biases due to its very low dark current. It should be noted that the rejection ratio of the PD with an LT-AlN interlayer was 18 times larger than that of the conventional PD at the reverse bias of 40 V.

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