Characterization of AlGaN/GaN Metal-Semiconductor-Metal Photodetectors With a Low-Temperature AlGaN Interlayer


Abstract—AlGaN/GaN metal-semiconductor-metal photodetectors (MSM PDs) with a low-temperature (LT) AlGaN interlayer (IL) were fabricated. Compared with the conventional AlGaN/GaN MSM PD, it was found that leakage current can be suppressed by insertion of a LT AlGaN IL due to the reduction of surface pits and improvement of crystalline quality. It was also found that larger photoresponsivity can be achieved due to the enhanced electric field strength as a result of inserting a LT AlGaN IL. Furthermore, suppressed photoconductive gain, lower noise level, and larger detectivity of MSM PD can also be achieved by using a LT AlGaN IL.

Index Terms—LT AlGaN IL, MSM PDs.

I. INTRODUCTION

AlGaN/GaN heterostructures have recently attracted much attention. The large band offset and strong piezoelectric effect in this material system have been shown to induce a high sheet density two-dimensional electron gas with an enhanced electron mobility and make them very promising for high-frequency/high-power applications [1]–[3]. In the past few years, various nitride photodetectors (PDs) have been demonstrated, such as Schottky barrier PDs [4], p-i-n PDs [5], and metal-semiconductor-metal (MSM) PDs [6]. Among them, MSM PDs have the superior advantages of easy fabrication and application to optoelectronic integrated circuits (OEICs) [7]. These characteristics made AlGaN/GaN MSM PDs a much attracting device. However, the growth of device quality heterostructures remains difficult due to the lack of suitable substrates for GaN growth [8]. The large differences in the lattice constant and thermal expansion coefficient of GaN and sapphire inevitably lead to defect generation in nitride epitaxial layer. Previously, Iwaya et al. [9], [10] reported that insertion of a second low-temperature (LT) grown buffer layer between the high-temperature (HT) grown GaN was determined to reduce the etch pit density (EPD) to a great extent as an effective way to limit the defects propagation. Similar material analysis and original mechanism of crystalline quality improvement and defect reduction by using LT interlayer (IL) have been widely studied and established [11]–[15]. Nevertheless, the effect of a LT IL on the characteristics of optoelectronic devices has been limited, especially in Schottky-type PDs [16]. In this paper, AlGaN/GaN MSM PDs with a LT AlGaN IL have been prepared. The characteristics of leakage current, spectral photoresponsivity, and low-frequency noise of the fabricated devices will be reported.

II. EXPERIMENTS

Growth of the epilayers in this study was carried out using metal-organic chemical vapor deposition (MOCVD). Samples were grown on c-plane sapphire substrates using a GaN LT nucleation layer, followed by the growth of AlGaN/GaN heterostructure consisting of a 2 μm GaN layer and a 20 nm Al0.25Ga0.75N layer (PD A). In order to obtain high-quality AlGaN/GaN heterostructure, we inserted a LT Al0.25Ga0.75N IL into the the HT GaN layer (PD B). Notice that the total thickness of the HT GaN layer was kept at 2 μm.

Ni (40 nm)/Au (100 nm) contact electrodes were subsequently deposited onto the surfaces of both samples. The fingers of the contact electrodes were 10 μm wide and 100 μm long with 10 μm spacing. The finger number was 12 and the active area of the device was 110 × 230 μm². The room temperature current-voltage (I-V) characteristics of these devices were measured using an HP 4156 semiconductor parameter analyzer. The top-illuminated spectral responses of these devices were also quantified using a 250 W Xe arc lamp with a calibrated monochromator as the light source. The effective power of the light received by the devices was around 1 ~ 10 μW. The monochromatic light, calibrated with an optical power meter, was collimated onto each PD via an optical fiber. The noise characteristics were measured using a low noise current preamplifier equipped with a fast Fourier transform spectrum analyzer.

III. RESULTS AND DISCUSSION

Fig. 1(a) and (b) depict SIMS profiles of Ga, N, and Al for PD A and PD B. The SIMS profiles clearly show that Al exists parallel to the GaN layer and a 20 nm Al0.25Ga0.75N layer (PD A). In order to obtain high-quality AlGaN/GaN heterostructure, we inserted a LT Al0.25Ga0.75N IL into the the HT GaN layer (PD B). Notice that the total thickness of the HT GaN layer was kept at 2 μm.
that the presence of Al in PD B was till the depth of 370 nm, conforming well to our design of LT AlGaN IL.

Fig. 2(a) and (b) show the EPD images of both samples. The wet etching experiment was conducted in H₃PO₄ solution at 160°C for 3 min to estimate the EPD with an optical microscope. It was observed that the EPDs of PD A and PD B were around 5.3 × 10⁸ and 3.8 × 10⁷ cm⁻², respectively. This observation agrees well with the result of Iwaya et al. [9], indicating that LT AlGaN IL is effective in eradicating etch pits. These etch pits might be the origin of the surface states, which generally considered as trapping centers or leakage paths [17]. The lower EPD in PD B thus indicates that the surface states density could be suppressed by using a LT AlGaN IL. Furthermore, it was well known that the origin of the etch pits might be related to screw dislocations [18], [19]. Therefore, insertion of the LT AlGaN IL might stop threading of the screw dislocations. Further research is necessary to clarify the relationship between etch pits and dislocations.

Fig. 3 presents the I- V characteristics of both fabricated devices in a dark environment. It was found that dark current reached saturation faster for the PD B. We believe this observation should be related to the enhanced internal electric field strength in the depletion region of the active layer after a LT AlGaN IL being inserted. When ~5 V applied bias was administered, the measured dark currents of PD A and PD B were 2.46 × 10⁻⁶ and 6.86 × 10⁻¹² A, respectively. The five orders of magnitude lower dark current for PD B might be attributed to the reduction of the crystal defects and the improvement of the crystalline quality of epitaxial films. Furthermore, a larger Schottky barrier height was obtained for contact electrode deposited on the epitaxial film of PD B. In general, the presence of surface states tends to lower the Schottky barrier height [20]. Furthermore, the point defects are an efficient way to inject carriers across the barrier and decrease the Schottky barrier value [21]. Since the Schottky barrier height of PD B is larger compared to that of PD A, the insertion of a LT AlGaN IL could effectively bring about a reduction on the surface states. The result of I- V measurement can respond to the EPD results.

Fig. 4(a) and (b) show the cross-sectional schemes of the electric field distribution at reverse bias. The electric field distribution schemes are according to the simulation results proposed by Carrano et al. [21], who presents two-dimensional electrostatic simulation showing the difference in depletion region growth with and without the underneath buffer layer included. In MSM-type PD, the magnitude of the electric field strength falls off rapidly with increasing depth from the electrodes in the absorption layer [22], as shown in Fig. 4(a). The photo-carriers generated in the deep absorption region have to travel a long distance under a weak field and need more time to reach the contact electrodes on the sample surface. On the other hand, as shown in Fig. 4(b), we suggest that the electric field is mostly localized in the region above the LT AlGaN IL owing to the discontinuity of different interface regardless of penetration of minor electric field lines. Like buffer layer, it has
been reported that undoped LT AlGaN IL has no conductivity [23]. Due to its high resistivity, the currents between two contacts are forced to flow above the LT AlGaN IL as a result of more dense electric field strength. Furthermore, the lateral component of electric field in PD B may be stronger than that in PD A because of the deformation of potential contours [21]. This provides an enhanced electric field to separate the photogenerated carriers.

Fig. 5 shows spectral responses of both fabricated MSM PDs. It indicates that the responsivities measured from both PDs exhibit sharp cutoff at the absorption edge. Since energy band gaps of AlGaN and GaN are 4.03 and 3.4 eV, respectively, the cutoff occurred at around 360 nm should be related to the absorption of the GaN layer and not the AlGaN layer above. With a −2 V applied bias and an incident light wavelength of 360 nm, it was observed that measured responsivities were 0.031 and 0.105 A/W for PD A and PD B, respectively. The larger responsivity for the PD B could be attributed to the enhanced electric field strength as a result of inserting a LT AlGaN IL. This agrees well with the illustration in Fig. 4. As we increased the bias to −5 V, the measured results showed that responsivities increased to 4.079 and 0.119 A/W for PD A and PD B, respectively. It should be noted that the 4.079 A/W responsivity corresponds to an external quantum efficiency larger than 100%. Such a result suggests that there exists a large photoconductive gain in PD A. Previously, it has been shown that photoconductive gain in GaN-based PDs is originated from trapping of minority carriers at metal/semiconductor interface [24]–[27]. The surface states at the metal/semiconductor interface could trap photogenerated holes, and they would lower the Schottky barrier height and produce additional gain in the photoresponse. The smaller photoconductive gain in PD B could be attributed to the effective reduction of surface states and improvement of crystalline quality of active layer by inserting a LT AlGaN IL.

Fig. 6 depicts the measured low-frequency noise power densities of PD A and PD B, respectively. The measured frequency range was from 10 Hz to 10 kHz at −5 V bias. The noise curves obey the Hooge-type equation with a fitting parameter γ (i.e., 1/2γ). Notice that the measured low frequency noise of both PDs could be regarded as a superposition of the 1/f and 1/f² noise. It was found that 1/f noise is dominant in PD A, while 1/f² noise is dominant in PD B. The larger 1/f noise level in PD B than that in PD A might be related to the material imperfections [28]. A high dislocation density strongly increases the level of 1/f noise in certain cases [29], [30]. The other theory [31] predicts that the level of 1/f noise should be proportional to the density of the tail states near the band edges. On the other hand, the larger 1/f² noise level in PD B than that in PD A might be related to somewhat complicated origin of this noise, due to many generation-recombination centers [32]. For a specified bandwidth B, the overall sum of the square of noise current \( \langle i_n^2 \rangle \) can be determined [33] by integrating the noise power density \( S_n(f) \)

\[
\langle i_n^2 \rangle = \int_0^B S_n(f)df.
\]

Noise equivalent power (NEP) and normalized detectivity (D*) can be determined by [34], [35]

\[
\text{NEP} = \frac{\sqrt{\langle i_n^2 \rangle}}{R}
\]

\[
D* = \frac{\sqrt{A\sqrt{B}}}{\text{NEP}}
\]

where \( R \) and \( A \) is the responsivity and device area of the PDs.

Besides, the overall noise level was lower in PD B than that in PD A, indicating the better characteristics of low-frequency
noise could be achieved with insertion of a LT AlGaN IL. With a given bandwidth of 1 kHz and a given bias of −5 V, the calculated NEP of PD A and PD B were 1.62×10^{−8} and 2.65×10^{−10} W, respectively. These values, in turn, led to the corresponding D* of 2.85×10^{10} and 1.74×10^{9} cmHz^{1/2}W^{−1}, respectively. The values realized for the noise and detectivity of PD B with a LT AlGaN IL show that our PDs are well suited for low noise applications. The performance of our devices are compatible or even better than other AlGaN/GaN or AlGaN-based UV detectors reported previously [36–40].

IV. CONCLUSION

In summary, AlGaN/GaN MSM PDs with a LT AlGaN IL were fabricated. Compared with the conventional AlGaN/GaN MSM PDs, it was found that good characteristics can be achieved, including lower dark leakage current, larger photoreponsivity, suppressed photocurrent gain, lower noise level, and larger detectivity, by using a LT AlGaN IL. This provides a simpler way to improve the crystalline quality of AlGaN/GaN heterostructure and makes the high performance monolithic integratable PDs possible. Furthermore, a LT AlGaN IL structure can also be used in fabrication of AlGaN/GaN heterostructure field effect transistors to enhance the device performance.

REFERENCES


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