Nitride-Based MSM Photodetectors with a HEMT Structure and a Low-Temperature AlGaN Intermediate Layer


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UV metal-semiconductor-metal (MSM) photodetectors (PDs) based on the AlGaN/GaN high-electron-mobility transistor (HEMT) structure with the low-temperature (LT) AlGaN intermediate layer atop were fabricated. A much lower dark current subsequently obtained was in fact benefited by the insertion of the LT AlGaN intermediate layer. In addition, the foregoing structure also rendered PDs with better gate controllability. For the MSM PD structure grown on the LT AlGaN intermediate layer, the resultant responsivity at 360 nm varied from 0.11 to 0.12 A/W when the device was biased from 2 to 5 V while the UV/visible rejection was estimated to be around 104. With a 5 V applied bias, the corresponding noise equivalent power and normalized detectivity (D*) determined were 2.65 × 10−10 W and 1.74 × 1010 cm Hz0.5 W−1, respectively.

Experimental

All samples studied in this paper were grown using metalorganic chemical vapor deposition. Sapphire (0001) was used as the substrate. Trimethyl-aluminum (TMAI), trimethyl-gallium (TMGa), and ammonia (NH3) were used as group III and V source gases, respectively. Immediately after subjecting the sapphire substrate to a thermal annealing treatment with hydrogen in an enclosed chamber at 1120°C, the graphite susceptor was then cooled to 600°C in order to deposit a 30 nm LT GaN buffer layer. HT-GaN was then grown at 1050°C over the LT buffer layer. The thickness of the first HT-GaN layer was kept at 1.75 μm. Then, the LT Al0.3Ga0.7N intermediate layer with thickness of 100 nm was deposited at 500°C, followed by the deposition of a second 0.25 μm HT-GaN layer and a 20 nm Al0.25Ga0.75N layer (epi-structure for PD A). The deposition condition invoked for the first and second HT-GaN layer growth were identical. In comparison, a 2 μm HT-GaN layer and 20 nm Al0.25Ga0.75N layer but without including the LT Al0.3Ga0.7N intermediate layer were also deposited on the LT buffer layer (epi-structure for PD B). Prior to proceeding on the fabrication of MSM photodetectors, the Hall measurement was conducted to determine the mobility and sheet carrier concentration of these two different epi-structures. The measured mobility and sheet carrier concentration for PD A were 948 cm2/V s and 2.92 × 1013 cm−2, respectively, while the corresponding values determined for PD B were 954 cm2/V s and 3.49 × 1013 cm−2, respectively.

Next, the MSM PDs were fabricated using these two epi-structures. The device consists of two interdigitated electrodes with finger width and spacing of 14 and 6 μm, respectively, and also with an optical area of 110 mm2. Schottky contacts deposited thereafter were made up of a Ni (400 Å)/Au (1000 Å) multilayer, patterned by standard lithography and liftoff techniques. Electrical characterization of all the devices included current–voltage (I–V) and capacitance–voltage (C–V) measurements. I–V measurement was conducted at room temperature using an HP-4156 semiconductor parameter analyzer. C–V measurement was carried out using a computer-interfaced HP-4284A LCR meter. An impedance analyzer meter connected to a probe station was operated in parallel mode. The measurement frequency was fixed at 1 MHz. For the spectral response measurement, a xenon lamp filtered by a monochromator was used. The incident power was measured by a calibrated pyroelectric detector. The detectors were biased with a voltage source connected in series with a transimpedance amplifier. The current was measured with the assistance of a chopper and a lock-in amplifier. The responsivity was calculated as the ratio of the photocurrent

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to the power incident on the detector. The noise characteristics were measured using a low noise current preamplifier equipped with a fast Fourier transform spectrum analyzer.

Results and Discussion

The 2 × 2 μm atomic force microscopy (AFM) topographic images were first gathered to inspect the surface morphology of PD_A and PD_B. As shown in Fig. 1, the growth steps and dense pits can be clearly observed from PD_B (Fig. 1b), while surface pits are almost invisible in PD_A (Fig. 1a). These pits are generally thought to be the surface termination of threading dislocations which are accompanied by high leakage current density.\(^\text{18-20}\) Evidently, inserting the LT AlGaN intermediate layer can effectively block the leakage paths, suppressing the leakage current, and ultimately improving the quality of upper AlGaN/GaN heterostructure.

Figure 2 shows room-temperature I-V characteristics of PD_A and PD_B incorporated with the AlGaN/GaN HEMT structure. The magnitude of the dark current generated by this device structure is mainly determined by the cathode depletion region that shares the largest part of the applied voltage. Here we define \(V_p\) as the bias voltage at which the 2DEG channel below the cathode depletion region is being pinched off. From Fig. 2, the dark current exhibits a strong bias dependence at low applied voltages (\(V < V_p\)) and reaches a plateau at high applied voltages (\(V > V_p\)). This I-V characteristic is similar to the gate leakage behavior of the AlGaN/GaN heterostructure HEMT being reported earlier.\(^\text{21,22}\) The origin of this current might be due to the vertical tunneling through two potential barriers occurring at the AlGaN/GaN heterojunction and also at the Schottky contact between the AlGaN barrier layer and the cathode terminal. The values of \(V_p\) were found to be 0.7 and 3.4 V for PD_A and PD_B, respectively. Hence, a lower bias voltage was needed for PD_A to deplete the 2DEG channel, indicating the controllability of Schottky contact was better for PD_A when compared with PD_B. As a bias exceeds \(V_p\), the saturation current amounts only to 10 pA for PD_A but only 1 μA for PD_B. Thus, by incorporating an LT AlGaN intermediate layer it is evident that the leakage current could be reduced by five orders of magnitude as compared to PDs without this layer. In comparison, our devices either perform equally well or even better than other AlGaN/GaN MSM or Schottky barrier PDs, which has already been reported by other groups.\(^\text{6,23-26}\) In fact, one of the significant advantages of choosing PDs with HEMT structure over the other detector candidates is their compatibility with the HEMT fabrication process, which allows a direct monolithic integration with HEMT-based circuits; all can be implemented in one epitaxial step due to their simple planar structure.

The C-V characteristics of both PDs were measured at a frequency of 1 MHz, shown in Fig. 3. The resultant C-V behavior of these two devices is similar to the charge control phenomenon of other AlGaN/GaN HEMT devices being reported previously.\(^\text{27}\) At low applied bias, the measured capacitance initially remains constant. The capacitance is due primarily to the carriers in the 2DEG channel. As bias voltage increases, the capacitance decreases slightly with increasing bias voltage. In a bias region where \(V < V_p\), the applied bias gradually falls on the cathode contact, causing the capacitance to be dominated by the cathode depletion region. As bias voltage increases further, the enlarging depletion region under the cathode contact renders a steep decrease in capacitance. A sharp decrease in capacitance originated from the depletion region penetrating into the 2DEG channel and ultimately extending to the GaN layer underneath. In other words, the 2DEG channel underneath the cathode contact is being pinched off. As the pinch-off condition is satisfied, the 2DEG under the cathode side is depleted due to the flatband condition of the AlGaN/GaN heterojunction. In this region (\(V > V_p\)), the capacitance is dominated by the cathode depletion region and is due primarily to the background donors in the GaN channel layer. As shown in Fig. 3, we again find that the
controllability of the Schottky contact is indeed better for PD_A when compared with PD_B. This result also agrees well with a prior observation result depicted in Fig. 2.

Figure 4 shows the device spectral responsivity measured with various applied biases. A sharp cutoff around the absorption band-edge of GaN (i.e., 360 nm) is expected to be observed from both PDs. Under the illumination of a xenon light source with an incident light wavelength of 360 nm at room temperature, as bias voltage was increased from 2 to 5 V, the responsivities thus measured varied from 0.11 to 0.12 A/W for PD_A, but a larger range from 0.03 to 4.08 A/W was observed for PD_B. Figure 5 depicts the measured responsivities at 360 nm as a function of applied reverse bias for both PDs. It was found that the measured responsivity was almost bias-independent for PD_A, while a steep increase in responsivity was observed for PD_B. In addition, the measured responsivity at voltage above 1 V was abnormally large for PD_B. Such a result suggested that a larger internal gain in fact existed in PD_B. An excessively large internal gain is expected to influence the device performance; for example, its impact on PD bandwidth can hardly be avoided. Previously, it has been reported by Carrano et al.\textsuperscript{26} that the internal gain can be induced by interfacial defects. This kind of trap level is generally thought to be related to the TDs in the GaN film. Brazel et al.\textsuperscript{18} suggested that metastable acceptor- and donor-like states coexisted in the vicinity of TDs and were responsible for the locally occurring high reverse leakage current in GaN-based devices. Consequently, it is reasonable to speculate that comparably fewer TDs must have existed in PD_A, which directly contributes to a much slower increment in responsivity with respect to an increase in bias voltage. Hence, our proposed growth scheme effectively reduces TD density, and this in turn helps to enhance the crystalline quality of AlGaN/GaN epitaxial layers by inserting an extra LT AlGaN intermediate layer. Furthermore, we define UV/visible rejection as a ratio between different responsivities measured at 360 nm and also at 500 nm. The resultant UV/visible rejection ratio was about 2 orders of magnitude larger for PD_A within a specified voltage range as compared with PD_B. The finding indicates that a less bias-dependent responsivity, high UV/visible rejection, and a much less internal gain can all be realized by incorporating an extra LT AlGaN intermediate layer into the overall PD structure.

Figures 6a and b show noise power spectra of the PD_A and PD_B gathered by applying different biases. The noise characteristics of devices were measured in the frequency range 10–500 Hz. The bias was varied from 2 to 5 V with a step of 1 V. The spectral density of noise power $S_n(f)$ can be expressed by\textsuperscript{13}

$$S_n(f) = K f^\alpha$$

where $f$ is the dark current, $f$ is the frequency, $K$ is a constant, and $\alpha$ and $\beta$ are two fitting parameters. As shown in Fig. 6, it was found that $\alpha$ was close to 2 for PD_A and 1 for PD_B throughout the measured frequency range. In other words, the low-frequency noise was dominated by 1/f-type noise in PD_A, as compared to 1/f^2-type noise domination in PD_B. The insets of Fig. 7a and b show the noise power density of our devices as a function of dark current measured at 100 Hz. The $\beta$ value was estimated to be two for both.

Figure 3. C-V characteristics of both fabricated MSM PDs.

Figure 4. Spectral responses at different bias of (a) PD_A and (b) PD_B.

Figure 5. Measured responsivity at 360 nm as a function of applied bias for both PDs.
NEP increases while $\alpha = 2$ decreases and $D^*$ increases with the applied bias. As already depicted in Fig. 5, the internal gain was directly responsible for the abnormally large responsivity obtained from PD_B, and what contributed to this internal gain was most likely due to the unwanted noises generated within the device, which were evidently related to interfacial defects$^{30}$ of the device under study. Without an extra LT AlGaN intermediate layer into the buffer multilayer structure, the presence of interfacial defects is expected to contribute to the unusually large responsivity obtained from PD_A. Therefore, it is reasonable to suggest that both NEP and $D^*$ of PD_B are dominated by the fluctuation in responsivity. With a 5 V applied bias, NEP and $D^*$ measured for PD_A were $2.65 \times 10^{-10}$ W and $1.74 \times 10^7$ cm Hz$^{-0.5}$ W$^{-1}$, respectively. At the same bias, NEP and $D^*$ for PD_B were $1.62 \times 10^{-9}$ W and $2.85 \times 10^7$ cm Hz$^{-0.5}$ W$^{-1}$, respectively. The resultant detectivity ($D^*$) of PD_A is noticeably better compared with other previously reported AlGaN-based MSM or Schottky barrier PDs.$^{34,35}$ These findings indicate that a lower noise level and a larger detectivity can be realized by introducing an additional LT AlGaN intermediate layer into the buffer multilayer structure.

PD_A and PD_B. Knowing the values of $\alpha$ and $\beta$, and with data shown in Fig. 6, the $K$ value can be determined from Eq. 1 to be $1.16 \times 10^{-7}$ for PD_A and $2.09 \times 10^{-7}$ for PD_B. It has been reported that $K$ is approximately proportional to the TD density.$^{32}$ A smaller $K$ obtained for PD_A indicates that the TD density is effectively suppressed thanks to the incorporation of an LT AlGaN intermediate layer. For bandwidth $\Delta f$, the total square noise current can be estimated by integrating $S_n(f)$ over the frequency range from zero to $\Delta f$

$$i_n^2 = \int_0^{\Delta f} S_n(f)df = \int_0^1 S_n(1)df + \int_1^{\Delta f} S_n(f)df$$

[2]

where the $S_n(f)$ in the bandwidth range from 0 to 1 is assumed to be the same and equals $S_n(1)$ at 1 Hz. Thus, the noise equivalent power (NEP) and normalized detectivity ($D^*$) can be calculated by

$$NEP = \frac{\langle i_n^2 \rangle^2}{R}$$

[3]

$$D^* = \frac{R}{i_n \sqrt{\Delta f}}$$

[4]

where $R$ is the responsivity, $i_n / \sqrt{\Delta f}$ is the power spectral density of the noise signal, and $A$ is the area of the detector. For a given bandwidth of 100 Hz, we can thus determine NEP and $D^*$ as functions of applied voltage, as shown in Fig. 7. As presented in Fig. 7b, an opposite trend for PD_B is observed when compared with PD_A. Thus, NEP decreases and $D^*$ increases with the applied bias. As already depicted in Fig. 5, the internal gain was directly responsible for the abnormally large responsivity obtained from PD_B, and what contributed to this internal gain was most likely due to the unwanted noises generated within the device, which were evidently related to interfacial defects$^{30}$ of the device under study. Without an extra LT AlGaN intermediate layer included for PD_B, the presence of interfacial defects is expected to contribute to the unusually large responsivity as the applied bias is increased. Therefore, it is reasonable to suggest that both NEP and $D^*$ of PD_B are dominated by the fluctuation in responsivity. With a 5 V applied bias, NEP and $D^*$ measured for PD_A were $2.65 \times 10^{-10}$ W and $1.74 \times 10^7$ cm Hz$^{-0.5}$ W$^{-1}$, respectively. At the same bias, NEP and $D^*$ for PD_B were $1.62 \times 10^{-9}$ W and $2.85 \times 10^7$ cm Hz$^{-0.5}$ W$^{-1}$, respectively. The resultant detectivity ($D^*$) of PD_A is noticeably better compared with other previously reported AlGaN-based MSM or Schottky barrier PDs.$^{34,35}$ These findings indicate that a lower noise level and a larger detectivity can be realized by introducing an additional LT AlGaN intermediate layer into the buffer multilayer structure.
Conclusions

In summary, UV MSM PDs based on an AlGaN/GaN HEMT structure with a LT AlGaN intermediate layer were successfully fabricated. These particular PDs are compatible with the HEMT fabrication process (i.e., allowing a direct monolithic integration with HEMT-based circuits in one epitaxial step) due to their simple planar structure. The subsequent measurement results concluded that a reduction in the dark leakage current and a simultaneous enhancement in gate controllability could be achieved with a modified HEMT epitaxial structure when compared to conventional PDs. For the PDs with the LT AlGaN intermediate layer, the responsivity at 360 nm and UV/visible rejection were respectively obtained as 0.12 A/W and 10^3 at a bias voltage of 5 V. Finally, with the same applied bias, NEP and D* of these very devices obtained were 2.65 × 10^{-10} W and 1.74 × 10^4 cm Hz^{0.5} W^{-1}, respectively.

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