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Shaoji Tang, Lingxia Zhang, Hualong Wu, Changshan Liu, and Hao Jiang

AFFILIATIONS
State Key Laboratory of Optoelectronic Materials and Technologies, School of Electronics and Information Technology, Sun Yat-Sen University, Guangzhou 510275, China

*E-mail: stsjiang@mail.sysu.edu.cn

ABSTRACT
We reported the improved performance of ultraviolet two-terminal Al0.1Ga0.9N/GaN npn heterojunction phototransistors with a 10-nm-thick low-doped n-type Al0.1Ga0.9N insertion layer between emitter and base. Optical current gain at 2 V bias was increased from 6.6 × 10^3 to 9.8 × 10^4 by inserting the thin undoped layer. Spectral response measurements showed a high ultraviolet to visible (350 nm/400 nm) rejection ratio of 6.7 × 10^4 under 2 V bias, while that of the control sample without the insertion layer is 2.4 × 10^3. Simulation analysis reveals that the conduction band notch at the interface of the base-emitter (B-E) heterojunction is lowered by the insertion layer, leading to a weakened electric field and a narrowed space-charge region at the interface. This effect can reduce the recombination in the B-E heterojunction and contribute to the improved gain performance of the phototransistor.

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I. INTRODUCTION

Ultraviolet (UV) photodetectors have a wide range of applications both in commercial and military areas, including flame sensing, corona detection, combustion process monitoring, missile plume tracking, and so forth. Most of these applications require highly sensitive devices with a high signal-to-noise ratio. High internal gain and low dark current are, therefore, desired for the UV detectors. In the past decade, III-nitride photodetectors have been actively developed because of their attractive properties as regards high quantum efficiency, low dark current density, sharp wavelength cutoff, and intrinsic visible/solar-blind UV detection. Among a variety of III-nitride based UV photodetectors, heterojunction phototransistors (HPTs) are of particular interest as the HPTs can provide high optical current gain without high operating voltage. To date, efforts have been made to develop AlGaN heterojunction based UV HPTs, and high optical gain and high rejection ratios have been achieved in the npn visible/solar-blind UV HPTs. Generally, the optical gain of HPTs can be enhanced by (1) improving the emitter injection efficiency of the base-emitter (B-E) heterojunction, (2) increasing the base transport factor related to high crystalline quality and proper width of the p-type base, and (3) enhancing the light absorption efficiency, which results similar to large base current I_b in heterojunction bipolar transistors. In the case of the AlGaN/GaN emitter/base heterojunction, the band offset in the valence band appears as a large barrier, which enhances the accumulation of optical generated holes in the base region and thus increases the optical current gain. However, the abrupt AlGaN/GaN heterojunction also exhibits a discontinuity in the conduction band. The band bending at the heterointerface results in an undesired potential notch of the conduction band there. This notch traps the injected electrons and enhances the B-E recombination current, causing a decrease in the emitter injection efficiency and, therefore, a gain reduction of the HPT. As the emitter-base junction is forward-biased under normal operating conditions of the HPT, mostly recombination occurs in the space-charge region (SCR) of this junction. For improving the performance of the HPT, it is crucial to suppress the recombination in the SCR of the B-E heterojunction. So far, device
structures such as compositional grading emitter or composite emitter have been proposed to decrease the carrier recombination in the B-E heterojunction of GaAs-based HBTs. As for the AlGaN/GaN HPT, however, there is still no report on suppressing the SCR recombination of the B-E heterojunction. In this work, a thin lightly doped AlGaN layer, inserted between the emitter and base of the AlGaN/GaN HPT, was employed to minimize the B-E recombination current. The fabricated devices showed significant improvement on the gain and current properties. Experimental characterization and simulation were conducted to understand the mechanism of performance improvement.

II. EXPERIMENT

The AlGaN/GaN UV HPTs presented in this work were grown on c-plane sapphire substrates by the low-pressure metal organic chemical vapor deposition (LP-MOCVD) method. A collector-up structure with a double heterojunction was utilized to minimize the redistribution of a Mg dopant by Mg memory effect.

Prior to the growth of the HPT structure, a 25-nm-thick low temperature GaN nucleation layer and a 1.5-μm-thick unintentionally doped (u) GaN high-temperature buffer layer were grown on the substrate. Then, a 1-μm-thick heavily Si-doped n-GaN layer with n \sim 3.5 \times 10^{18} \text{ cm}^{-3} was deposited as subemitter and Ohmic-contact layer, followed by a 60-nm-thick compositionally graded n-type Al\textsubscript{0.1}Ga\textsubscript{0.9}N (x = 0–0.1, n \sim 1.5 \times 10^{19} \text{ cm}^{-3}) layer. A 120-nm-thick n-type Al\textsubscript{0.1}Ga\textsubscript{0.9}N (n \sim 2.7 \times 10^{18} \text{ cm}^{-3}) was subsequently deposited as emitter. After that, a 10-nm-thick lightly doped n'-type Al\textsubscript{0.3}Ga\textsubscript{0.7}N (3.8 \times 10^{17} \text{ cm}^{-3}) insertion layer (IL) was grown, followed by a 100-nm-thick Mg-doped p-GaN (3.8 \times 10^{17} \text{ cm}^{-3}) base layer and a 200-nm-thick u/Ga\textsubscript{0.9}N (n \sim 8 \times 10^{16} \text{ cm}^{-3}) light absorption layer. Finally, a 30-nm-thick compositionally graded n-type Al\textsubscript{0.1}Ga\textsubscript{0.9}N (x = 0–0.1, n \sim 3.8 \times 10^{17} \text{ cm}^{-3}) layer and a 250-nm-thick n-type Al\textsubscript{0.1}Ga\textsubscript{0.9}N (n \sim 2.7 \times 10^{18} \text{ cm}^{-3}) collector layer were deposited. For comparison, a control sample without the 10-nm-thick n'-Al\textsubscript{0.3}Ga\textsubscript{0.7}N insertion layer was also prepared.

The device fabrication started with a chlorine-based dry-etching process to form the emitter mesa down to the subemitter layer using the inductively coupled plasma (ICP) method. After the mesa definition, the samples were annealed at 650 °C in N\textsubscript{2} ambient for 25 min to activate the Mg dopant and recover the ICP-etching-induced damages. Then, the samples were treated in dilute HCl for 10 min to remove the surface native oxide layer and rinsed in alcohol-based (NH\textsubscript{4})\textsubscript{2}S solution \text{[C\textsubscript{6}H\textsubscript{5}O + (NH\textsubscript{4})\textsubscript{2}S]} at 60 °C for 15 min to passivate the surface. In order to investigate the carrier-transport properties of the base-emitter (B-E) heterojunction, some of the HPTs are fabricated as three-terminal devices in which the base mesa was also formed by the same process as that for the emitter mesa. Ring-shaped contacts deposited by electron-beam evaporation were employed for all the electrodes. Stacked metals of Ti/Al/Ni/Au were used as the Ohmic contacts of the emitter and collector and were alloyed by rapid thermal annealing (RTA) in N\textsubscript{2} ambient at 830 °C for 30 s, while metal bilayers of Ni/Au were used as the Ohmic contacts of the p-type base and were alloyed by the RTA method in O\textsubscript{2} ambient at 550 °C for 120 s. The active-area diameter of the fabricated HPTs is 150 μm. A schematic diagram of the device structure is shown in Fig. 1.

![FIG. 1: Schematic epitaxial structure of the AlGaN/GaN HPTs with a 10-nm-thick lightly Si doped Al\textsubscript{0.3}Ga\textsubscript{0.7}N insertion layer.](image)

Current-voltage (I-V) characteristics of the fabricated AlGaN/GaN HPTs were measured under dark and UV illumination conditions using a Keithley 4200-SCS semiconductor characterization system. The UV illumination was incident from the collector side using a UV lamp with a center wavelength of 357 nm. A Newport optical power meter was used to measure the power density of the incident UV light. The optical power density was measured to be 250 nW/cm\textsuperscript{2}. Each I-V curve was recorded after applying a reverse bias of 5 V to eliminate the accumulated holes at the base region, which may impose a lowering of the quasi-Fermi level and cause an extra gain in the test. Spectral response measurements were performed by using a UV light source consisting of a xenon lamp and a deuterium lamp, a monochromator with 1200 g/mm grating, and a UV-enhanced calibrated Si photodiode.

![FIG. 2: I-V curves of the Al\textsubscript{0.1}Ga\textsubscript{0.9}N/GaN HPTs with and without the IL measured under the dark and illuminated conditions.](image)
III. RESULTS AND DISCUSSION

Figure 2 contrasts the dark current and photocurrent characteristics of the HPTs with and without the lightly doped Al$_{0.1}$Ga$_{0.9}$N insertion layer (IL). The collector-emitter bias voltage ($V_{CE}$) was swept from 0 to 5 V while the base is left floating. For the HPTs without the IL, the measured dark current ($I_{dark}$) increases steadily with increasing $V_{CE}$ when the $V_{CE}$ is below 2 V. Dark currents of less than 3 pA were obtained in this region. When the $V_{CE}$ rises to 2.0 V, the $I_{dark}$ begins to increase rapidly, indicating a punch through effect. Under the condition of $V_{CE}$ below the punch-through voltage ($V_{pt}$), the bias voltage almost drops on the base-collector (B-C) junction of HPT so that the reverse leakage current of the B-C junction is dominant in the dark current. As the $V_{CE}$ increases, the C-B depletion region expands (i.e., the effective width of quasineutral base decrease), leading to a punch through of the base layer by C-B and E-B depletion regions at $V_{pt}$. Then, the voltage drop on the B-C junction keeps at $V_{pt}$, and further increasing the $V_{CE}$ may result in a larger amount of electrons injected from the emitter to the base because the increment of $V_{CE}$ acts as the forward voltage applying on the B-E junction. The dark current, which increases sharply under this condition, is dominated by the diffusion current of the B-E heterojunction. The $V_{pt}$ increases from 2.0 to 3.5 V with insertion of the 10-nm-thick n-AlGaN layer. The increased $V_{pt}$ is ascribed to the decreased base-side depletion region of the B-E junction, which requires more voltage to reach the punch through condition. In the bias region of $V_{CE} < 2.0$ V, the dark current of the Al$_{0.1}$Ga$_{0.9}$N/GaN HPT with the IL is about one order of magnitude lower than that of the HPT without the IL, due to the decreased reverse current of the B-C junction by the increased width of the quasineutral base. Beyond the $V_{pt}$, the dark current of the HPT with the IL increases higher than that of the HPT without the IL, indicating higher emitter-injection efficiency by the introduction of the thin AlGaN IL. Furthermore, the photocurrent ($I_{ph}$) of the HPT with the IL is about one order of magnitude higher than that of the HPT without the IL in the whole measuring range. At $V_{CE} = 5$ V, the photocurrent of the proposed sample is about $1.3 \times 10^{-6}$ A, while it is about $2.0 \times 10^{-7}$ A for the control sample. Assuming a 100% quantum efficiency, the optical gain was $9.8 \times 10^{4}$ for the HPT with the IL operating at $V_{CE} = 2$ V, which is ~15 times that of the HPT without the IL ($6.6 \times 10^{3}$) and more than one order of magnitude higher than those reported in Refs. 2 and 3.

Figure 3 plots the $I_{ph}/I_{dark}$ ratio of the two structure HPT samples as a function of $V_{CE}$. The maximum ratio of the Al$_{0.1}$GaN/GaN HPT without the IL is approximately $2.0 \times 10^{4}$, while that of the Al$_{0.1}$GaN/GaN HPT with the IL is $3.0 \times 10^{6}$. On the other hand, the maximum operating voltage to guarantee the $I_{ph}/I_{dark}$ ratio $\geq 10^{2}$ is 2.6 V for the HPT without the IL and increases to 4.3 V for the HPT with the IL. Therefore, using the thin lightly doped Al$_{0.1}$Ga$_{0.9}$N insertion, the $I_{ph}/I_{dark}$ ratio and the allowable operating voltage range can be effectively increased.

Figure 4 shows the spectral responses of the Al$_{0.1}$Ga$_{0.9}$N/GaN UV HPTs with and without the IL under the different bias voltages. As can be seen, both the HPTs exhibit a sharp cutoff at the wavelength...
of ∼360 nm, which corresponds to the band-edge absorption of the und-GaN layer. A UV/visible rejection ratio (350 vs 400 nm) of $6.7 \times 10^4$ was obtained under the bias voltage of 2 V for the Al$_{0.1}$GaN/GaN HPT with the IL, which is one order of magnitude higher than that of the HPT sample without the IL. This rejection ratio is greater than the value in Ref. 2 ($\sim 10^3$) and less than that in Ref. 3 ($\sim 4 \times 10^5$), which could be partly due to the different illumination power levels. Under an input optical power of 105 pW, the peak responsivity is 87 A/W at 340 nm and $V_{CE} = 2.0$ V for the device without the IL and increases to 349 A/W with the introduction of the IL.

To understand more clearly the effect of the thin lightly doped insertion layer, we measured the forward I-V characteristics of the B-E heterojunction for the two structure HPTs. As shown in Fig. 5, the values of ideality factor $n$ for the visible-blind HPTs without and with the IL are 3.72 and 2.26, respectively. The relatively large values of the ideality factor ($n > 2$) may partially be attributed to the n-Al$_{0.1}$Ga$_{0.9}$N/und-GaN unipolar heterojunction as well as the p-metal/p-GaN junction. Also, the ideality factor of $n > 2$ implies that the recombination current is dominant in the p-n junction, instead of the diffusion current. The smaller $n$ value of the HPT with the IL, however, suggests a smaller component of recombination current in the B-E junction. Moreover, at $V_{BE} = 3.0$ V, the base-emitter currents $I_{BE}$ are about $2.5 \times 10^{-3}$ A and $7.8 \times 10^{-6}$ A for the Al$_{0.1}$GaN/GaN HPT without and with the IL, respectively. The reduction of $I_{BE}$ is mainly ascribed to the larger vertical series resistance with the extra 10-nm-thick lightly doped AlGaN IL and the smaller recombination current in the B-E heterojunction.

Furthermore, we simulated the energy-band diagrams and electric field distributions for the Al$_{0.1}$GaN/GaN HPTs with and without the IL under the zero bias using a one-dimensional Schrödinger-Poisson equation solver. The simulation results were illustrated in Fig. 6. As shown Fig. 6(a), there is an energy band discontinuity at the interface of the Al$_{0.1}$Ga$_{0.9}$N emitter/GaN base heterojunction, at which appears the undesired notch in the conduction band causing electron trapping. Under normal operating conditions, the top illumination incident on the device passes through the wide-bandgap collector and is absorbed in the collector-base depletion region, creating photogenerated electron-hole pairs. The photogenerated electrons and holes are swept to the collector and base regions, respectively, by the electric field of the reverse-biased B-C junction. The large valence band barrier ($\sim 3.57$ eV) at the base region results in accumulation of photogenerated holes, which causes electric disequilibrium as well as quasi-Fermi level lowering in the base region, allowing electrons to be injected from the emitter to the base. While passing through the E-B heterojunction, the electrons are trapped in the notch of the conduction band and recombining with holes. The inset of Fig. 5(a) highlights the conduction band profiles at the E-B heterojunction interface of the both HPTs. Compared with the HPT without the IL (black line), the potential energy of the conduction-band notch in the HPT with the IL (red line) is significantly raised. Therefore, the trapped electrons need less energy to escape from the
notch. Besides, the slope of notch edge at the base region side is lessened by introducing the IL, corresponding to a weaker electric field in the base SCR as shown in Fig. 5(b). This means that the injected electrons encounter less hindrance during transporting through the base.

On the other hand, Fig. 5(b) also shows that the widths of E-B junction SCR ($W_{BE}$) for the HPTs without and with the IL are 137 nm and 132 nm, and the maximum electric field strengths ($E_{MAX}$) are 1.45 MV/cm and 1.35 MV/cm, respectively. Both $W_{BE}$ and $E_{MAX}$ are decreased by inserting the 10-nm-thick low-doped AlGaN layer between the emitter and base. The thickness of such an IL is critical because a too thick IL may result in an increased $W_{BE}$ instead of a decreased $W_{BE}$, leading to increased recombination current. The recombination current at the B-E junction, $J_{RE}$ can be expressed as

$$J_{RE} = \frac{qN_i}{2\tau} W_{BE} \left( e^{\frac{qE_{BE}}{kT}} - 1 \right),$$

where $\tau$ is the minority carrier lifetime. The other variables, such as $n_i$, $q$, $E_{BE}$, and $T$, take their usual physical meanings. The expression means that the decrease in $W_{BE}$ leads to the reduction of the recombination current at the E-B junction, leading to enhanced current gain that is consistent with our experimental results showing decreased recombination current in the HPT with the IL.

Furthermore, it is known that the dc common-emitter current gain ($\beta_0$) can be given in terms of the dc common-base current gain ($\alpha_0$) as

$$\beta_0 = \frac{\alpha_0}{1 - \alpha_0}.$$  

Since this relation holds for both dc and small-signal conditions, the $\alpha_0$ in the relation can be replaced by the small-signal common-base current gain $\alpha$, which is defined as

$$\alpha = \frac{J_{SC}}{J_{SE} + J_{SP} + J_{RE}},$$

where $J_{SC}$ and $J_{SE}$ are the diffusion current densities at the E-B junction of electrons and holes, respectively, and $J_{SC}$ is the diffusion current density of the electrons reaching the collector. These expressions indicate that the introduction of the low-doped AlGaN IL may reduce the recombination current $J_{RE}$ and then make the common-base current gain closer to 1, leading to enhanced current gain $\beta_0$ and increased photocurrent.

IV. CONCLUSION

In summary, the performance of Al$_{0.1}$Ga$_{0.9}$N/GaN visible-blind UV HPTs has been improved by introducing a thin low-doped Al$_{0.1}$Ga$_{0.9}$N insertion layer between the emitter and base. The thin insertion layer can lower the conduction band notch at the E-B heterojunction interface and raise its potential energy, leading to reduced recombination in the E-B junction and the improved gain performance of the Al$_{0.1}$Ga$_{0.9}$N/GaN UV HPT. As a result, an optical current gain of $9.8 \times 10^4$ was obtained at $V_{CE} = 2$ V. The UV-to-visible (350/400 nm) spectral rejection ratio was increased by one order of magnitude to reach $6.7 \times 10^4$.

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