AlGaN/GaN heterojunction bipolar transistors with low dynamic $R_{ON,sp}$ and V_{th} hysteresis

Xinyuan Wang[1,2#], Lian Zhang[1#], Zhe Cheng[1], Lifang Jia[1], Zhe Liu[1,2] and Yun Zhang[1,2*]

[1] *Laboratory of Solid State Optoelectronics Information Technology, Institute of Semiconductors, Chinese Academy of Sciences, Beijing 100083, China*

[2] *Center of Materials Science and Optoelectronics Engineering, University of Chinese Academy of Sciences, Beijing 100049, China.*

 # Xinyuan Wang and Lian Zhang contributed equally to this work.

Email: yzhang34@semi.ac.cn.

This paper demonstrates the dynamic characteristics of 150-V-class GaN power HBTs for the first time. At OFF-state collector bias V_{CEQ} = 80 V, the device shows a low dynamic specific on-resistance ($R_{ON,sp}$) of 0.316 mΩ·cm^2, which is only 4.7% higher than static $R_{ON,sp}$, thanks to current conductive path far from the surface. A threshold voltage (V_{th}) of 3.58 V extracted at 1 A/cm^2 is achieved with an on/off current ratio of 2×10^7. The device also shows a large base voltage swing of -7 to 7 V with a small V_{th} hysteresis of 50 mV. The low dynamic resistance degradation, high positive V_{th} with low V_{th} hysteresis, and large base voltage swing all demonstrate the great potential of GaN HBT in power switching applications.

Introduction: Vertical GaN transistors have demonstrated great promise for power switching applications owing to higher voltage, higher current density and lower specific on-resistance ($R_{ON,sp}$) [1-3]. Recently, fin-channel junction field-effect transistor (Fin-JFET) with an avalanche breakdown voltage of 1200 V have been reported [4]. Sub-micrometer fin channels in Fin-JFETs help to achieve superior gate control and normally-off operation. On the other hand, GaN heterojunction bipolar transistors (HBTs) have also been proposed as power switching devices [5-8], which are also vertical structures, with the advantages of low photolithography accuracy, normally-off operations, high current density, strong avalanche breakdown ability and lower $R_{ON,sp}$ due to conductivity modulation effect. Up to date, some promising results have been reported of GaN HBTs, such as high electric field near to 3 MV/cm [7-9] and high current density (141 kA/cm^2 on GaN-on-GaN HBT [10]).

Despite these excellent static performances, the dynamic performance of GaN HBTs have not been demonstrated. In HEMTs or some of vertical devices, full or partial current conductive path distributes near the surface, electrons are trapped by the surface traps, leading to dynamic $R_{ON,sp}$ degration and a shift of the threshold voltage (V_{th}) [11,12]. The current of HBT flows far from the surface, which is expected to have stable dynamic characteristics. In this work, we demonstrates the dynamic characteristics of 150-V-class GaN power HBTs firstly. The device shows a low dynamic $R_{ON,sp}$ of 0.316 mΩ·cm^2 at OFF-state collector bias (V_{CEQ}) of 80 V, which only degrades by 4.7% compared with the static $R_{ON,sp}$. A threshold voltage (V_{th}) of 3.58 V defined at 1 A/cm^2 is achieved with an on/off current ratio of 2×10^7. The device also shows a large base voltage swing of ±7 V with a small V_{th} hysteresis of 50 mV.

Device Design and Fabrication: The AlGaN/GaN HBT is grown on sapphire by metal-organic chemical vapor deposition (MOCVD) system. The schematic of the device is shown in Figure 1. Detailed epitaxial growth techniques and device preparation processes were reported in the previous work [7,13]. The emitter size is 5 (W_E)×10 (L_E) μm^2, and the emitter metal width is 2 μm. The width of the external base on one side is 7 μm, including the base metal width of 2 μm, the distance from base metal to emitter edge (W_{BE}) of 2 μm, and the distance from base metal to base edge (W_{BC}) of 3 μm. Considering that the electron current cannot exceed the W_{BE} length and a 45° current spreading in the n$^-$-GaN collector, the active area is calculated as 95 μm^2 ((2 + 5 + 2 + 0.5) μm × 10 μm).

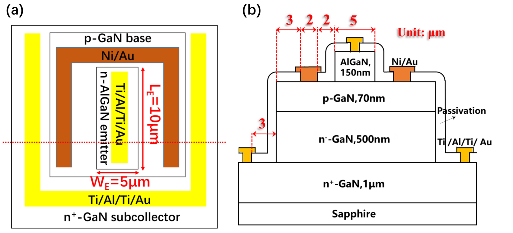

Fig 1 *The vertical (a) and cross-section (b) views of the HBT.*

Results and discussion: Figure 2 shows the current collapse characteristics of a HBT with breakdown voltage (BV_{CEO}) of 160 V. In this measurement, the pulse width and pulse period are 700 μs and 70 ms, respectively. As shown in the insert in Figure 2(a), there are three main phases: (1) On the OFF-state phase, a high quiescent V_{CEQ}, which is set up to 80 V with 20V/step, is applied to the device; (2) During the transient transition from OFF to ON, I_B switches from 0 to 100 μA, while V_{CE} decreases from V_{CEQ} to a low bias; (3) On the ON-state phase, the device is biased with low V_{CE} at I_B=100 μA. The V_{CE} is swept from 0 V to 5 V.

At non-stressing condition ((I_{BQ}, V_{CEQ}) = (0A, 0V)), the HBT shows a static $R_{ON,sp}$ of 0.302 mΩ·cm^2 and a current density J_C of 11.2 kA/cm^2. The relatively low $R_{ON,sp}$ is mainly due to the lower base contact resistance, thanks to the realization of the ohmic contact using emitter regrowth process [13]. At high-voltage-stressing condition ((I_{BQ}, V_{CEQ}) = (0A, 80V)), the maximum J_C is 11.4 kA/cm^2, and the dynamic $R_{ON,sp}$ is 0.316 mΩ·cm^2, which is 4.7% more than the static $R_{ON,sp}$, as shown in Figure 2(b). This value is relatively low among the reported values of GaN HEMTs [14,15]. We attribute the improved dynamic $R_{ON,sp}$ degradation to the vertical current path far from the surface [1]. Slight dynamic $R_{ON,sp}$ degradation may results from defects in the collector and external sub-collector surface traps. Fully vertical GaN-on GaN HBTs can avoid surface traps and reduce the defects in the collector, which is expected to further reduce current collapse.

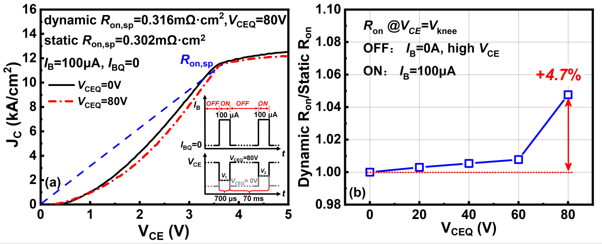

Fig 2 *(a) Pulsed I-V characteristics; (b) The ratio of dynamic $R_{ON,sp}$/static $R_{ON,sp}$ at different V_{CEQ}.*

Figure 3 (a) shows the transfer characteristics of the HBT at V_{CE} of 3 V. A V_{th} of 3.58 V is measured at 1 A/cm^2 with an on/off ratio over 2×10^7. The V_{th} hysteresis is low to 50 mV between the up- and down- sweep of V_B from −7 to 7 V. This value is relatively low compared with GaN HEMTs, owing to almost eliminated surface state trapping [12,16]. A subthreshold swing (*SS*) is 190 mV/dec. The base current is also plotted in Figure 3 (a). The base leakage current is below 10 nA at V_B of -7 V. In the forward operating voltage range of 0 to 7 V, I_B has a very low growth trend to 100 μA, suggesting a sufficient margin for "base" overdrive [4]. As a result, degradation is prevented, even if overshoot voltage occurs during switching. The large voltage margin is important for improving the reliability in power supply circuits. Figure 3(b) gives the transfer curve of the HBT in linear scale. A V_{th} of 4.93 V is evaluated by linear extrapolation of the I_C−V_B curve. The peak current transconductance of the HBT is 6.7 mS.

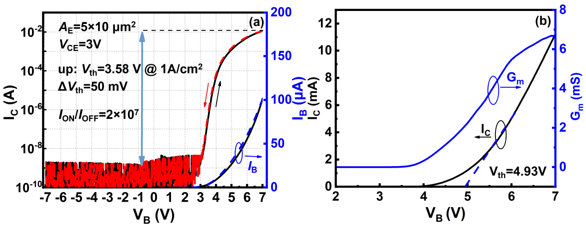

Fig 3 *(a) transfer curve* in semilog scale *and I_B of the HBT; (b) transfer curve* in *linear scale and* transconducation curve.

Conclusion: In summary, we demonstrate the dynamic characteristics of an AlGaN/GaN HBT with BV_{CEO} of 160 V. A low dynamic $R_{ON,sp}$ of 0.316 mΩ·cm^2 at V_{CEQ}=80 V is obtained, showing a degradation of 4.7%. The device also exhibits a high V_{th} of 3.58 V with on/off current ratio over 2×10^7 and low V_{th} hysteresis of 50 mV. The base voltage shows a large swing of ±7 V. These results demonstrate the potential of HBT devices for switching device applications.

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