Meandering Gate Edges for Breakdown Voltage Enhancement in AlGaN/GaN High Electron Mobility Transistors

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Herein, a unique device-design strategy is reported for increasing the breakdown voltage and hence Baliga figure of merit (BFOM) of III-nitride high electron mobility transistors (HEMTs) by engineering the gate edge toward the drain. The breakdown of such devices with meandering gate-drain access region (M-HEMT) are found to be 62% more compared with that of conventional HEMT whereas the on-resistance suffers by 76%, leading to an overall improvement in the BFOM for by 28%. The 3D technology computer-aided design simulations show that the decrease in the peak electric field at the gate edge was responsible for increased breakdown voltage.

1. Introduction

The continuous research and development in the field of III-nitrides in the past three decades had enabled the technologies which were difficult to realize with conventional semiconductors. One of the promising technologies realized by nitride semiconductors is high-power HEMT switches. The desired properties for a switch are low on-resistance and high breakdown voltage. Highly conducting 2DEG and wide bandgap III-N (AlGaN/GaN) enable low on-resistance and high breakdown voltages, respectively. As the HEMTs are lateral devices, the electric field distribution is not uniform in the off-state condition. The electric field attains maxima at the gate edge toward the drain which leads to breakdown and current collapse. Several field plate designs (gate field plate, source field plate and slant field plate) were implemented to reduce the peak electric field at the gate edge which had resulted in improved uniformity of electric field distribution and hence increased breakdown voltage. In addition to field plates engineering, Schottky drain contacts, lightly doped drain, recessed gate edge, and floating metal ring were also found to increase the breakdown voltage. Currently, to push the breakdown voltage further, high Al composition AlGaN channels are being investigated. Here, we report a novel approach to increase the breakdown voltage by engineering the gate edge (meandering) toward drain.

2. Device Fabrication

The ≈5.5 μm-thick HEMT stack on 1 mm p-type Si(111) was grown by metal organic chemical vapor deposition (MOCVD). The unintentional C-doped GaN buffer layer of thickness ≈1500 nm was grown prior to overgrowth of the top 2D electron gas (2DEG) structures. The top HEMT layers consist of a 300 nm GaN channel layer, a thin ≈1.0 nm AlN spacer, ≈19 nm AlxGa1−xN barrier layer with x = 24%, and a ≈1 nm thin GaN cap. Hall measurements on the epiwafer center to edge regions showed an average sheet resistance of 377 ohm □−1 with a sheet carrier concentration of about 1.1 × 1013 cm−2.

Device fabrication started with e-beam evaporation of Ti/Al/Ni/Au metals for ohmic layer, which was then annealed at 850 °C for 30 s in N2 ambient. Mesa isolation was done using Cl-based reactive ion etching. Device fabrication process ended with e-beam evaporation of Ni/Au metals for gate layer. Two types of devices were fabricated: 1) conventional/regular device (C-HEMT) and 2) meandered gate edge-engineered device (M-HEMT) (Figure 1) on the same samples side by side. For the fabrication of M-HEMT, the AlGaN barrier and GaN channel were etched out in a particular meandering geometry during mesa etching step, as shown in Figure 1C.

3. Device Characterization and Analysis

The devices were characterized for transfer characteristics, as shown in Figure 2. Both types of devices exhibited the same threshold voltage (VTH) as the 2DEG density below the gate remains the same for both devices; however, the reduction in the on-current in the M-HEMT device should be attributed to an increase in the reduction of the effective gate width or periphery. The theoretically estimated value of VTH (VTH = qn_s/C_bar) was found to be −4.64 V (for 21 nm of barrier with barrier dielectric...
constant of 9) which was much less than the experimentally observed $V_{TH}$ ($\approx 2.5 \text{ V}$). The observed difference in $V_{TH}$ should be attributed to the partial depletion of 2DEG below the Ni/Au Schottky gate.[15]

The output characteristics of the devices are shown in Figure 3. The $R_{ON}$ in ohm mm and ohm cm$^2$ for both the devices were calculated using the expression $W/($slope of line fitted to output characteristics) and $W \times L_{GD}/($slope of line fitted to output characteristics), respectively, where $L_{GD}$ and $W$ are gate drain access region and gate width, respectively. The static $R_{ON}$ was found to increase by $\approx 1.7 \times$ for the M-HEMTs compared with C-HEMT. Gate width of 100 $\mu$m was used for both the devices.

The devices were further characterized for three terminal breakdowns (Figure 4). During the measurements, silicone oil (S D Fine Chem Limited) was poured on the sample to avoid contact arcing at high drain biases. The leakage current (gate and drain current) of C-HEMT and M-HEMT were found to reach $10 \mu$A mm$^{-1}$ at drain bias of 400 and 650 V, respectively, indicating that M-HEMTs offer a substantially higher breakdown voltage. The leakage currents of both the devices were normalized with 100 $\mu$m of device width. The drain-gate leakage current at low drain bias was found higher in the M-HEMT compared with C-HEMT, and it should be attributed to etched surface-related effects. The superior breakdown characteristics of M-HEMT were quantitatively investigated by the estimation of BFOM which can be defined for 2DEG as:

$$V_{BD}^2 = R_{ON} \left(\frac{q n_s \mu N}{E_C^2}\right),$$

where $V_{BD}$ is breakdown voltage, $R_{ON}$ is on-resistance, $q$ is electronic charge, $n_s$ is 2DEG density, $\mu$ is electron mobility, and $E_C$ is critical electric field. For the estimation of on-resistance of the M-HEMT, the access region includes the etched-out region and 2DEG region. The BFOMs of both the devices were estimated using the expression $V_{BD}^2/R_{ON}$ (here experimentally observed breakdown voltages...
and on-resistances were used). The estimated BFOM of C-HEMT and M-HEMT were found to be $9.3 \times 10^7$ and $1.3 \times 10^9 \text{V} \cdot \text{cm}^{-1} \cdot \Omega^{-1}$, respectively. The BFOM for M-HEMT was found to be higher by 28% in comparison with the C-HEMT. Although these are not record numbers—primarily due to a large gate length—the new design for M-HEMT is expected to push the records when implemented on HEMT samples with lower sheet resistance, ohmic regrowth, and with scaled gate lengths. The superior breakdown characteristics of M-HEMT were further investigated using the 3D technology computer-aided design (TCAD) simulation, which is discussed in Section 4.

4. TCAD Simulations

Silvaco-ATLAS TCAD tool was used for 3D device simulation. To reduce the computation load, a unit device width (Figure 1C, shown in the gray dashed box) with a thin HEMT stack (≈424 nm) was used for simulation. The material properties were defined by the default parameter lists kp.set2 and pol.set2 of Silvaco ATLAS. The simulated device structure consisted of 24 nm AlGaN barrier, 200 nm GaN channel, and 200 nm of GaN buffer. The barrier and channel were unintentionally doped ($1 \times 10^{15} \text{ cm}^{-3}$), whereas an acceptor trap density of $1 \times 10^{15} \text{ cm}^{-3}$ at 3.28 eV (with respect to conduction band) was considered in the GaN buffer.\[16\] The simulated electric field profiles of the devices at drain bias of 600 V, gate bias of $-7 \text{ V}$, and source bias of $0 \text{ V}$ are shown in Figure 5A,B. The electric field was found to attain a maximum value at the gate edge for both HEMTs; however, the electric field profiles along the device width (Z–Z’ line) were significantly different for both devices. The Z–Z’ line was drawn at the gate edge along the gate width, and it was 25 nm away from the AlGaN/GaN interface in the GaN channel. The electric field profile along the device width (Z–Z’ line) for the C-HEMT had not shown any variation, whereas for the M-HEMT, it was found decreasing (Figure 5C). Also, the peak electric field in the M-HEMT was found lower than that of C-HEMT at the gate edge. The increase in breakdown voltage of M-HEMT in comparison with C-HEMT should be related to the reduction of peak electric field. The simulation overestimates the peak electric field in M-HEMT as in the actual device etched region lies on the both sides of current channel.

5. Conclusions

A new type of HEMT device was demonstrated which had exhibited superior breakdown characteristics and BFOM compared with a conventional HEMT device with reduced current carrying capability. The increase in breakdown voltage should be attributed to decrease in electric field strength at the gate edge due to the unique device structure. As the M-HEMT devices had exhibited promising results further analysis on both the experimental and simulation front are needed to find the optimum device geometries. Optimizing the geometries (in meandered region) may help in reducing the on-resistance of M-HEMT. Also, the application of field plates and/or dielectric passivation needs to be explored to boost the device performance. The simulation presented here was done for ≈400 nm-thick HEMT stack which is very low compared with the practically used stack due to computation constraints. Hence, a rigorous simulation is also required for thick HEMT stacks.

Acknowledgements

The authors acknowledge the funding support from MHRD through NIEIN project, from MeitY and DST through NNetRA. This publication is an outcome of the Research and Development work undertaken in the project under Ph.D. scheme of Media Lab Asia. The authors acknowledge the National NanoFabrication Centre (NNFC) and Micro and Nano Characterization Facility (MNCF) at CeNSE, IISc for device fabrication and characterization.

Conflict of Interest

The authors declare no conflict of interest.

Keywords

Baliga figure of merit, high electron mobility transistors, 2D electron gas, 3D technology computer-aided design

Published online: January 13, 2020
Received: September 18, 2019
Revised: November 10, 2019

Figure 5. Electric field profile in the off-state of device at drain bias of 600 V, gate bias of $-7 \text{ V}$, and source bias of $0 \text{ V}$ for A) C-HEMT, B) M-HEMT. C) The electric field profile along the Z–Z’ line for C-HEMT and M-HEMT.
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