PAPER

Novel super junction technique used in AlGaN/GaN HEMT for high power applications

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Abstract

In this paper, a novel super junction technique in AlGaN/GaN HEMT is proposed and analyzed. The novel super junction is capable of splitting the potential drops to two points rather than a single point in the lateral axis (channel axis). Technology Computer Aided Design (TCAD) physical simulator is used to investigate the proposed GaN HEMT. Analyses of the simulation results, shows that the breakdown voltage of proposed AlGaN/GaN HEMT with super junction is higher than that of a conventional device. Proposed device demonstrated a breakdown voltage improvement of 26%. This is due to the reduction of peak electric field using super junction and it is evidenced in the simulation. Further, the Johnson figure of merit (JFOM) is extracted. The JFOM of proposed and conventional AlGaN/GaN HEMT are 4.89 × 10¹² V s⁻¹ and 3.79 × 10¹² V s⁻¹, respectively. The JFOM in the proposed device is improved by 23%. This improvement is mainly due to the improvement of breakdown voltage rather than cut-off frequency. Overall, the proposed device is a promising candidate for high-power applications as it can withstand higher voltages without compromising the switching-frequency.

1. Introduction

The global power consumption across the world was 21 PWh annum⁻¹ in 2012. It is expected to increase to 35 PWh annum⁻¹ in 2040. This will lead to power crisis in the world. Hence, it is necessary to reduce the power wastage. The Power Converter circuit consumes more power leading to significant power wastage. 100 W power converter with 95% efficiency has a power wastage of 5 W [1–5]. The power wastage largely depends on the power device and its technology used in the converter. The technology could be evaluated using various performance metrics such as high frequency operation, high efficiency, high power level and high operating temperature [6–9]. Because of this enhanced performance, the GaN technology outperforms the Si and SiC technologies [10–14]. The performance enhancement is due to the Group III-Nitride material properties such as higher electron velocity and wide-band gap. Wider band gap facilitates the GaN device to operate in wide range of operating temperatures [15–19].

High electron velocity enhances the saturation current; thus, the device operates at high power level. Further, high electron velocity enables the GaN HEMT to operate in high frequency application. Apart from these material properties, AlGaN/GaN HEMT offers additional features such as higher sheet carrier density and electron mobility. High sheet carrier density increases the saturation current and power level of the device. Higher electron mobility reduces the on-state resistance and knee voltage. All the above are the hetero-structure properties of GaN that increase the conversion efficiency of the power switches thus increasing the overall efficiency of the converter circuits. Apart from these properties, power switches also demand few other figures of merits such as

\[ R_{ON} = V_{BR} \]  \hspace{1cm} (1)

\[ R_{ON} = C_{ISS} \]  \hspace{1cm} (2)
where $R_{ON}$, $C_{ISS}$, $C_{OSSS}$, $V_{BR}$ and $Q_{RR}$ are on-resistance, input capacitance, output capacitance, breakdown voltage and gate charge, respectively. Industries and academia are still working to improve these figures of merits. Super junction is used for SiC MOSFET to improve the performance, however, it is not used for GaN HEMT. Therefore, in this paper, super junction is proposed for GaN HEMT to enhance the figure of merit such as breakdown voltage ($V_{BR}$) and Johnson figure of merit (JFOM). TCAD simulation of proposed technique is carried out to investigate and analyze its performance. The TCAD simulation is validated with experimental data to ensure that the simulation is realistic.

2. Device schematic and simulation models

The proposed AlGaN/GaN HEMT with novel super junction is shown in figure 1. The device consists of AlGaN barrier with thickness of 20 nm, 100 μm-thick silicon substrate and 2 μm-GaN buffer. Gate to drain spacing, gate length and gate-to-source spacing are 5 μm, 1 μm, and 2 μm, respectively. The novelty in the proposed work is the Super Junction (SJ) in the GaN HEMT device. AlGaN barrier is used to induce piezoelectric polarization at AlGaN/GaN interface. A thick GaN buffer is used to reduce the dislocation propagation to the channel from GaN/Silicon interface. Silicon is used as a substrate because the GaN does not have its own native substrate. The device is passivated using SiN which reduces the surface traps compared to other passivation materials such as SiO2, HfO2 and Al2O3. Further, the novelty of the proposed technique is substantiated with comparison of similar designs available in literature. In [20], the super junction is used for MOSFET device. The super junction for GaN HEMT device is not used. Further, the super junction for MOSFET is used in the active semiconductor area. The super junction in the proposed GaN-HEMT is used in the passivation area rather than the active semiconductor area.

The proposed AlGaN/GaN HEMT in figure 1 is realized by using ATLAS TCAD physical simulator. Mesh, region and electrode syntax are used in the simulator to realize the physical device. In order to perform realistic simulation, various physics-based models are used in the simulation. Reported data in [21–26] are used to calibrate the TCAD simulation. Hole and electron transport is governed by drift-diffusion model. Shockley Read Hall model (SRH) is used to facilitate the carrier recombination and generation process. The SRH generates the electron and hole pairs by means of thermal conductivity. Impact ionization model is used to enable avalanche breakdown process. In addition to SRH and impact ionization model, light beam is induced at the bottom of the GaN layer. This light beam generates the optical electron-hole pairs; thus, improving the convergence in the wide band-gap material. Further, as it is breakdown simulation, the drain contact is changed from voltage boundary to current boundary at the initial phase of the avalanche process. This boundary change has been done using current contact.

Apart from the models discussed so far, polarization is one of the important models in TCAD simulation. Polarization model is used to mimic the asymmetric crystal nature and strain in III-Nitride materials. Polarization models are used as the source to confine the electron along the AlGaN/GaN channel interface. In AlGaN layer, both piezoelectric and spontaneous polarization is used. In GaN layer, only spontaneous polarization model is used. The ATLAS TCAD determine the total polarization (PT) using the equation,

\[
P_T = P_{SP} + P_{PZ}
\]

where, $P_{SP}$ and $P_{PZ}$ are the spontaneous and piezo-electric polarization. The piezoelectric polarization is determined by the equation,
where, the $a_0$ and $a_1$ are lattice constant and average lattice constant, respectively. The $c_{13}$ and $c_{33}$ are elastic constants. The $\epsilon_{31}$ and $\epsilon_{33}$ are piezoelectric constants. These spontaneous and piezoelectric model places the positive and negative charges at top and bottom surface of AlGaN barrier layer. Due to the charge balance in a semiconductor device, the positive charge at the AlGaN bottom surface induces the 2-Dimensional Electron Gas (2DEG) at the AlGaN/GaN interface. The 2DEG acts as channel in GaN-HEMT simulation. The gate is fixed as Schottky contact using a work function of 5.2 eV. The drain and source are fixed as ohmic contacts using a work function of 3.93 eV. The material parameters considered in the simulation are given in table 1.

In order to enable the impact of higher electric field on electron velocity, high field mobility is incorporated in the simulation and it is expressed as

$$\mu_H = \frac{\mu_0 + \nu (F_{a}^{a-1}/F_{c}^{a})}{1 + c \left( \frac{F_{a}}{F_{c}} \right)^x}$$

where, $a_0$ and $a_1$ are lattice constant and average lattice constant, respectively. The $c_{13}$ and $c_{33}$ are elastic constants. The $\epsilon_{31}$ and $\epsilon_{33}$ are piezoelectric constants.

### 3. Results and discussion

In order to validate and benchmark the simulation in this paper, the reported data in [21] is used. The reported pinch-off voltage and drain current at $V_{GS} = 0$ V in [21] are $-3.3$ V and 12.2 mA, respectively. The simulated transfer characteristics also exhibits pinch-off voltage and drain current at $V_{GS} = 0$ V are $-3.3$ V and 12.2 mA, respectively. The simulated pinch-off and drain current fits well with that of one reported in [21]. This ensures the validity of the simulation. Further, simulated energy profile is verified. Figure 2 shows the conduction band energy with fermi-energy level at on-state. As it can be seen, conduction band energy goes below Fermi energy. The region of conduction band below fermi energy is called as quantum well. The formation of quantum well also ensures that the simulation is correct. The well height is $-3.25$ eV and it is also a nominal value. Further, In simulated data the conduction band energy with fermi-energy level at off-state. As it can be seen, the quantum well is not formed at off-state. It is due the fact that the conduction band is above Fermi energy level.

In AlGaN/GaN HEMT based hetero-interface at off-state structure for the conduction band profile is shown in figure 3. As this paper is focused on off-state breakdown voltage, validity of the simulation is also verified by

| Material Property | AlGaN | GaN | Unit |
|-------------------|-------|-----|------|
| Electron affinity | 3.41  | 4.0 | —    |
| Energy band gap   | 4.9   | 3.5 | (eV) |
| Conduction band state density | 2.71  | 2.23 | ($10^{18}$ cm$^{-3}$) |
| Electron saturation velocity | 1.1   | 2.5 | ($10^7$ s$^{-1}$) |
| Valance band state density | 2.06  | 2.51 | ($10^{18}$ cm$^{-3}$) |
| Electron mobility  | 300   | 1200| (cm$^2$ v s$^{-1}$) |
| Permittivity      | 8.8   | 8.9 | —    |

### Table 2. TCAD parameters of mobility model.

| Parameter | Value |
|-----------|-------|
| $E_c$ (kV cm$^{-1}$) | 220.89 |
| $\nu$ ($10^7$ cm s$^{-1}$) | 1.9094 |
| $a$ | 7.2044 |
| $b$ | 0.7857 |
| $c$ | 6.1973 |

$$P_{PZ} = 2\frac{a_1 - a_0}{a_0} \left( \frac{\epsilon_{31}}{\epsilon_{33}} - \frac{c_{13}}{c_{33}} \right)$$

(6)

In order to enable the impact of higher electric field on electron velocity, high field mobility is incorporated in the simulation and it is expressed as

$$\mu_H = \frac{\mu_0 + \nu (F_{a}^{a-1}/F_{c}^{a})}{1 + c \left( \frac{F_{a}}{F_{c}} \right)^x}$$

(7)
off-state characteristic analysis. Figure 4 depicts the off-state conduction and valence band profile along the channel. As it can be seen, the energy band is uplifted in gate region and it is called as energy barrier. This energy barrier prevents the electron flow from source to drain in off-state condition. Further, the off-state electron concentration is analyzed, which is shown in figure 5. It is very clear that the electrons are depleted under the gate region. Under off-state condition, the formation of energy barrier and depletion of electrons below the gate region ensures that the simulation is correct.

The breakdown voltage is a high voltage phenomenon; therefore, potential distribution and electric field is analyzed at higher drain voltage. The potential distribution along the channel at drain voltage of 100 V is depicted in figure 6. Both the conventional and proposed device show a potential gradient at the gate corner of the drain side. However, compared to the conventional device, the proposed device demonstrates a dissimilar potential distribution under super junction region. A two-step potential gradient is observed for the proposed
device. It is necessary to analyze the observed potential distribution. In the conventional device, the potential drops at a single point. On the other hand, the potential drops at two points in the proposed device. This is due to the presence of the novel super junction.

The breakdown voltage, device reliability, junction temperature and gate-edge degradation depends on electric field distribution. Hence, electric field is analyzed in figure 7. The peak electric field for the proposed device with super junction and conventional device is $2.75 \times 10^6$ V cm$^{-1}$ and $3.4 \times 10^6$ V cm$^{-1}$, respectively. The peak electric field in the proposed device is lower compared to the conventional device. It is due to the presence of super junction in the proposed device that effectively suppresses the electric field. The lower field in the proposed HEMT makes it a promising device for higher operating temperature and higher voltage applications. Further, the lower field in the proposed device is also necessary to enhance the device reliability and reduce the gate edge degradation.

In order to extract the breakdown or blocking voltage of conventional HEMT and proposed HEMT with super junctions, output characteristics are analyzed. The output drain current versus output drain voltage is analyzed and depicted in figure 8. For this analysis, the drain voltage is swept from 0 V to 500 V and the drain
Figure 6. Potential distribution along the channel for conventional and proposed AlGaN/GaN HEMT.

Figure 7. Electric field distribution along the channel for proposed and conventional HEMT.

Figure 8. Drain current versus drain voltage under off-state condition ($V_{GS} = -4$ V).
current is observed. This analysis is carried out with off-state condition by applying $V_{GS} = -4$ V. As it is seen in figure 8, the drain current for conventional and proposed device shows a small increase with drain voltage till the breakdown point. Beyond the breakdown point both devices exhibit a sudden increase in drain current. It is due to the avalanche process. To extract the breakdown voltage from the output characteristics, the compliance current of 0.5A is used. At the compliance current of 0.5A, the extracted breakdown voltage for conventional device and proposed device with super junction are 368 V and 462 V, respectively. Compared to the conventional HEMT, the proposed HEMT improves the breakdown voltage by 26%. It is due to the lower electric field in the proposed device (See figure 7). The proposed device with super junction exhibits significant enhancement in the breakdown voltage, and it can be used as a device for high power applications.

The avalanche breakdown mechanism that causes the sudden increase in off-state drain current has been analyzed in figure 9. As it can be seen, under gate edge, conduction and valence band shows a steep decrease in energy levels. It is due to higher potential difference between gate and drain electrode. Under this condition, a large electric field could build up at the gate edge. This large electric field is able to provide great energy to electrons. Electrons with high energy, breaks the junction and avalanche breakdown occurs.

The avalanche process generates more free carriers which contribute the off-state conduction. The avalanche induced impact generation for conventional and proposed device is shown in figure 10. The impact generation rate for the proposed device is lower than that of the conventional device. It is due to the suppression of the electric field by super junction in the proposed device.

Figure 11 shows the current gain ($h_{21}$) of the proposed and convention device. For this current gain analysis, the gate voltage and drain voltage is fixed at $-2.5$ V and 5 V, respectively. The cut-off frequency is extracted at unity current gain. The extracted cut-off frequency of the proposed device and conventional device are 10.59 GHz and 10.35 GHz. The cut-off frequency for both device is almost the same. Although the breakdown voltage is improved in the proposed device, the cut-off frequency is not compromised. This is a unique feature of the proposed device.

Using breakdown voltage and cut-off frequency, the Johnson figure of merit (JFOM) is extracted, as it is an essential parameter. The JFOM is the product of cut-off frequency and breakdown voltage. The extracted JFOM is shown in figure 12. The JFOM of the proposed and conventional AlGaN/GaN HEMT are $4.89 \times 10^{12}$ V s$^{-1}$ and $3.79 \times 10^{12}$ V s$^{-1}$, respectively. The JFOM in the proposed device is improved by 23%. This improvement is mainly due to the improvement of breakdown voltage rather than the cut-off frequency.

In table 3, various devices that uses super junction is listed. In most of the works in the literature, the super junction is used in diode and MOSFET. In this work, the super junction is used in GaN HEMT.

4. Conclusion

AlGaN/GaN HEMT with novel super junction is investigated in this paper. Investigation of the device is carried out using the TCAD simulation. Simulated transfer characteristic is matched with the reported data to validate
Figure 10. Impact generation rate along the channel for conventional and proposed AlGaN/GaN HEMT.

Figure 11. Current gain versus frequency at $V_{DS} = 5\, \text{V}$ and $V_{GS} = -2\, \text{V}$.

Figure 12. Johnson figure of merit calculation at $V_{DS} = 5\, \text{V}$ and $V_{GS} = -2\, \text{V}$.
the simulation. Potential distribution, electric field field spread and impact generation rate of the proposed device is benchmarked with that of the conventional device to provide qualitative analysis. The breakdown voltage of proposed device is higher than that of the conventional device. In the proposed device, 26% improvement in the breakdown voltage is achieved which is due to the electric field suppression in the proposed device using novel super junction. Further, the Johnson figure of merit of the proposed device is also improved by 23% which is due to the enhancement of the breakdown voltage in the proposed device. Thus, the proposed device with super junction is an excellent device for high voltage applications. Further, it is suggested that the GaN HEMT with proposed technique could be used in future power converters.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Conflict of interest

The authors declare that there are no conflicts of interest.

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