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Original Article

Design of a Normally-off HEMT using Double Quantum Well Structure with Improved Breakdown Characteristics

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Abstract *- HEMT "High Electron Mobility Transistor" is very suitable for emerging power devices because of its high saturation drain current, high breakdown voltage, and low on-resistance (Ron). Although normally-off operation (enhancement mode) is frequently preferred for fail-safe operation and ease of design, ordinary AlGaN/GaN heterostructures are, by nature, generally ON devices. A HEMT should be a normally-off device, where the channel will not conduct without any gate bias for reasons of safety and power-saving in the OFF mode. However, one of the most important problems in normally-off devices to be resolved is current collapse, also known as enhanced dynamic Ron or drain current dispersion. The reasons for the present collapse and how to reverse it remains crucially vital even if growth and gadget technologies have significantly improved. This work examines an Al0.2Ga0.8N/GaN/Al0.25Ga0.75N/In0.15Ga0.85N/GaN normally-off HEMT that employs a double quantum well. A field-plated device with a SiN passivation layer was investigated for reducing current collapse and increasing the breakdown voltage.*

Keywords *- Breakdown voltage, GaN, HEMT, InAiN, Normally-off, Passivation, Threshold voltage, Trapping.*

1. Introduction

Today, the world's steadily rising energy consumption is one of the most significant socioeconomic concerns. In the following 20 years, a rise of around 40% in energy usage is anticipated. Power conservation is a major consideration for any intended application in the field of engineering. For the past 50 years, silicon (Si) has dominated the electronics sector. This semiconductor's abundance and chemical stability is by far its most significant advantage. However, due to some inherent structural issues, it is an unsuitable material for high voltage and high power applications. Some novel semiconductors have been created in the power electronics sector to meet the expanding need for high voltage, current, and power applications. The greatest materials for upcoming energy-efficient electronic devices are thought to be wide bandgap semiconductors like GaN (Gallium Nitride), GaAs (Gallium Arsenide), along with SiC (silicon carbide). Today's high frequency, power, and voltage power switching applications all use AlGaN/GaN high electron mobility transistors. Group III nitrides' pyroelectric capabilities present one-of-a-kind opportunities for creating heterostructures with unusual electrical features. Nitride devices require E-mode (enhancement mode) or normally-off devices to operate as a power switch for safety and power saving in the OFF mode [2]. According to the literature [2-6], advancements in device physics and fabrication processes have significantly improved the threshold voltage (V_{th}), drain saturation current (ID_{SS}), breakdown voltage (V_{br}), ON-resistance (Ron of E-mode or normally-off transistors).

These structures are classified as single heterostructure HEMTs or SH-HEMTs since they only have one AlGaN/GaN interface. Due to better material quality and manufacturing methods, AlGaN/GaN single heterojunction HEMTs (SH-HEMT) have made significant progress, but several challenges still exist. The device under consideration requires a high breakdown voltage (Vbr) for high-power and high-voltage applications.

As a result, enhancing the V_{br} while keeping the gate-drain distance as minimal as feasible is one of the primary challenges facing relevant studies on AlGaN/GaN-based HEMT devices. The triangular-shaped potential well formed at the intersection of the AlGaN barrier and GaN buffer layer confines the two-dimensional electron gas (2DEG) generated by the polarization process in the standard AlGaN/GaN HEMT architecture. In addition to acting as a buffer layer, GaN is commonly used as an electron channel. However, the GaN buffer layer's low potential barrier height prevents the 2DEG from being trapped within the channel. The 2DEG will overflow from the primary triangular potential well. As a result, there will be a punch-through effect at the channel/buffer (GaN) layer, significantly worsening the transport characteristics. Under some conditions, such as increased temperature, higher 2DEG density, or larger negative gate voltage, some 2DEG may leak out of the potential well and into the buffer layer, giving rise to 3D electron gas [3]. As three-dimensional electron gas has substantially lower mobility than two-dimensional electron gas, this will reduce the mobility of the electrons. In addition to the causes listed above, some defects are being produced in the buffer layer due to the residual donors like Iron (Fe) or Carbon (c) in the undoped GaN that was purposefully induced to make it a semi-insulating layer. These might make the undoped GaN buffer layer's current collapse effect stronger. Normally-off HEMT technology is necessary to get around the shortcomings of an AlGaN/GaN HEMT that operates normally ON.

2. Normally-Off GaN HEMT Technology

Because of the occurrence of 2DEG at the interface, AlGaN/GaN heterostructures operate normally as ON devices (i.e., the transistor remains in the ON state even with a negative gate voltage). Minimizing a device's power consumption in this era of high voltage and high power gadgets is difficult. Nowadays, many favour normally-off devices because they provide more power-efficient and fail-safe functioning with a straightforward circuit [7]. Due to this, several industrial manufacturers and academic groups are recently focusing on the manufacturing and commercialization of normally-off semiconductor technology. A positive change in the V_{th} (threshold voltage) is necessary for producing E-mode operation, and the region close to the gate must be adjusted for that purpose utilizing methods like fluoride-based plasma treatment or band engineering technology. The first approach to achieving regular off-HEMT operation was the "recessed gate" idea. Local AlGaN barrier thickness reduction occurs beneath the gate using this technique [24]. For a specific AlGaN thickness, the contact's Fermi level will be below the conduction band minimum. As a result, the 2DEG under the gate will be depleted, and the threshold voltage (V_{th}) will move in the right direction [10]. Yong Cai, Yugng Zhou, and others [4] have also suggested the "Flourine gate" HEMT as a potential solution. In this method, fluorine ions that are negatively charged are implanted either through plasma or ion implantation under the gate electrode. The increased negative charge reduces 2DEG and a favourable change in the V_{th} [11].

Additionally, the gate leakage current is reduced significantly by the negative fixed charges (i.e., the included Fluorine ions) [12]. The most attractive candidate for normally-off HEMT is the p-GaN gate method due to its good figure-of-merit and reliable enhancement mode operation [13]. Theoretically, The AlGaN layer's conduction band is widened by the p-GaN cap layer, giving the device a positive threshold voltage and enabling correct operation [17]. Due to the existence of the P-GaN layer, the 2DEG is depleted below the gate electrode, and the channel's electron density must be restored with a positive gate bias. A normally-off operation is achieved in this manner. Despite being the only actual normally-off HEMT method that has been marketed to this day, the p-GaN gate has specific reliability difficulties [13]. Gate leakage current frequently affects the normally-off p-GaN gate HEMTs when the gate is stressed at forward voltages more significantly than 5–6 volts [13]. These are some of the techniques that were suggested for producing enhancement mode HEMTs. Each method has drawbacks, one of which is the instability of the threshold voltage as the working temperature rises. HEMTs based on AlGaN/GaN heterostructures usually are ON devices, even though power electronics applications always need a normally-off operation. Ankush Bag et al. [14] have proposed a new kind of HEMT that would function in an enhancement mode based on a pair of quantum wells, and that idea is examined herein; this mode, a deeper secondary quantum well is introduced along with the primary AlGaN/GaN quantum well for achieving the normally-off operation. The applied gate voltage determines whether the concerned quantum well participates in the conduction of the drain current. Energy band bending and 2DEG modulation are effects of positive gate bias on the gate terminal. The triangular primary quantum well's electrons are removed to achieve the normally-off operation for V_{gs}=0V. Additionally, the SiN surface passivation layer minimizes current collapse in the planned structure caused by the virtual gate effect, and adding a gate field plate improves breakdown characteristics.

3. Conceptual Framework

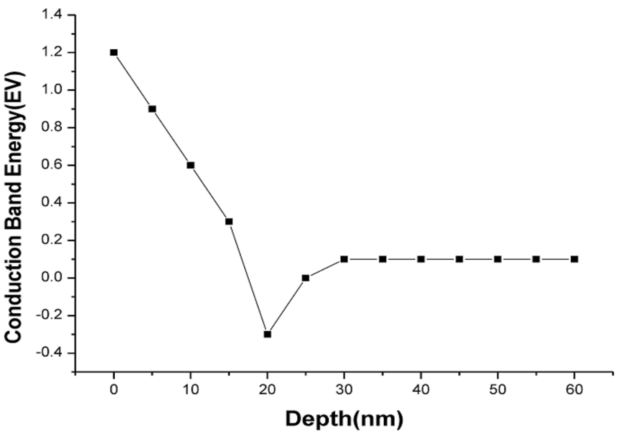
In this type of heterostructure, the InGaN layer has an opposite piezoelectric polarization field from that of the AlGaN layer that causes the conduction band to rise very sharply below the 2DEG channel [14]. This phenomenon changes the shape of the potential triangular well formed in a conventional heterostructure. The confined electrons are located occupying a larger area than the conventional heterojunction. Here, the GaN channel potentials are lowered by the InGaN notch, converting the triangle quantum wells to rectangular quantum wells (as given in fig 2). The InGaN back-barrier heterostructure undergoes a new two-step alteration in the current study to create two distinct QWs with various energy properties. It is suggested that the first step is to introduce a potential barrier between the two wells of electron confinement to separate them. Two isolated QWs with dissimilar energies will be produced as a result. A secondary goal is to increase the energy gap between the two QWs.

Polarizations and band-offsets primarily influence the distribution of electron wave functions and carriers in QWs. Carrier concentration can be distributed differently with the externally provided potential to the QWs.

The needed energy is further increased by lowering the second QW channel's conduction band energy. The source and drain contacts should be submerged in the 1st quantum well, which remains almost free of 2DEG due to electron spillover at zero gate bias [14]. Because of a lack of carriers, the first QW in this design cannot conduct drain current without a gate bias. With a high enough positive gate bias, electrons may be collected in the first quantum well (QW) by bending the conduction band downwards.

Fig. 1 Double quantum well EMODE structure with GFP and SiN passivation layer

As a result, it is envisaged that this double QW HEMT will operate in enhancement mode. One of the many technical criteria for a successful power switch [16] is the ability to quickly transition from a high-voltage OFF state to a low-voltage ON state with a very low ON resistance. It is one of the many technical criteria for an efficient power switch. A low ON resistance right after turning the device ON is necessary because an enhancement mode device is typically utilized as a switch. The maximal electric field in an AlGaN/GaN HEMT is often seen close to the drain side gate edge [17]. During the OFF state of the device, the high electric field causes mobile charges to become trapped in the areas near the gate electrode. These trapped charges increase dynamic ON resistance and, as a result, a decline in performance.



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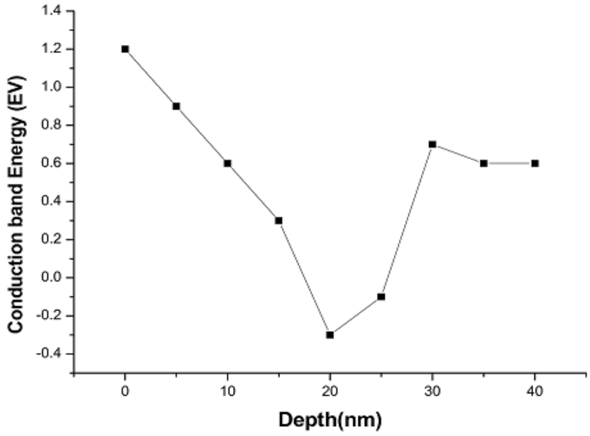

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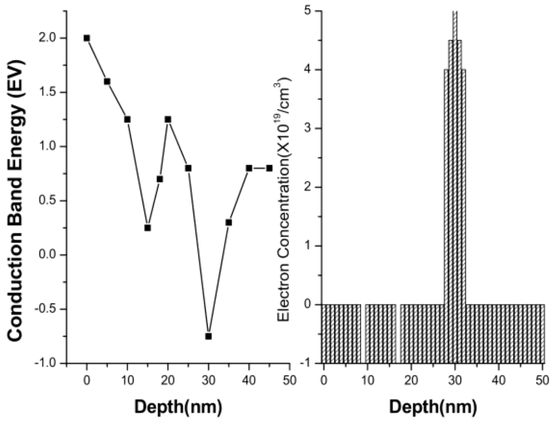

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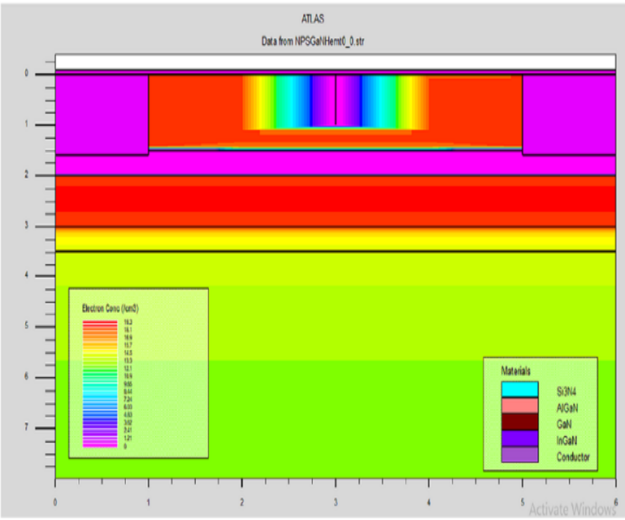
Fig. 2 Energy band diagram and carrier population in (a) Original AlGaN/GaN heterostructure (b) AlGaN/GaN heterostructure with InGaN back-barrier layer" (c)Al0.2Ga0.8N/GaN/Al0.25Ga0.75N/In0.15GaN/GaN double quantum well-based structure (at VGS = 0V)

3.1. The virtual gate effect

Due to a considerable decrease in the drain current compared to that anticipated from DC measurement, the RF power performance of a GaN-FET may be significantly impacted. Current collapse is the term used to describe this phenomenon. The virtual gate effect is a significant contributor to the current collapse. When the device's gate is reverse biased, electrons can be inoculated from the gate onto the device's surface at the drain side gate edge, changing the surface states' occupation. The virtual gate established on the surface depletes the 2DEG produced in the channel, increasing the device's parasitic source and drain resistance and the dynamic ON resistance (R_{ON}) [15]. After an OFF-ON switching event, the concept called "current collapse" or "dynamic R_{ON}" describes a condition where the transistor's R_{ON} stays high for an extended time. The significant electron trapping that takes place during the OFF state is what causes the transiently elevated R_{ON} values [15]. As per reports, the present drop in AlGaN/GaN HEMT may be due to the virtual gate impact. The current collapsed, and contact resistance increased when the gate was stressed by a very negative bias, which led electrons to migrate to the ungated regions of the device. Si_3N_4 can be used as a surface passivation layer to reduce the virtual gate effect. This layer's insertion allows for the prevention of lowering the device's transconductance and the transport of electrons onto the surface, and the subsequent development of a virtual gate [15]. Additionally, numerous articles have described that the distribution of the electric field in HEMTs significantly affects the device's efficiency and dependability. So, for HEMTs, it is crucial to optimize the electric field. FP (Field plate) technology is one method that helps HEMTs provide better power efficiency. The field plate technique may enhance the electric field distribution's uniformity by effectively expanding the depletion zone and replacing the single-peak electric field with numerous peaks. Therefore, breakdown voltage (V_{br}) is increased while the current collapse impact is reduced [20]. However, the field-plated structure does not improve the ON resistance of HEMT. [22].



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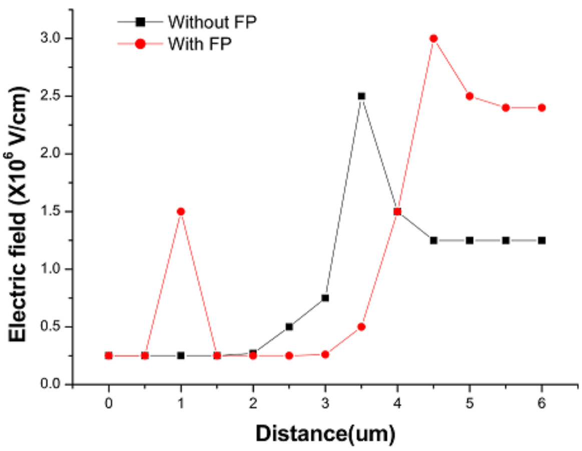


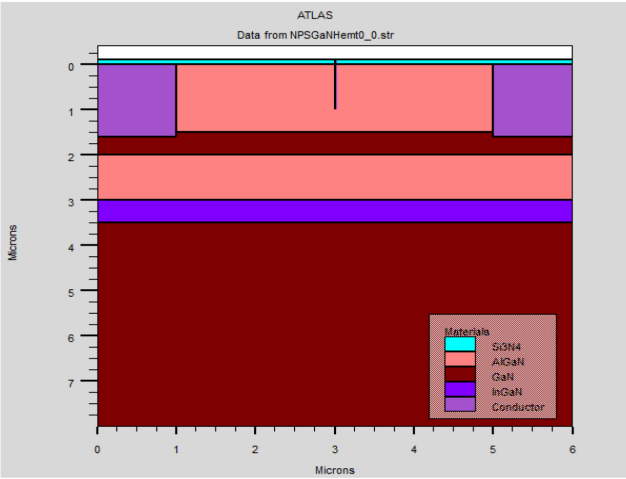
(b)

Fig. 3 (a) Extension of the depletion region with the inclusion of a field plate (b) Variation of the electric field along the channel of the normally-off AlGaN/GaN HEMT with and without field plate

GFP (gate field plate), SFP (Source field plate), and drain field plate are a few examples of the several types of field plates that have been proposed so far to enhance dynamic features and raise the off-state breakdown voltage. GFP's superior performance may be traced to two features that set it apart from the other structures: first, 2DEG compensation throughout the ON state; second, reduced negative charge trapping in the OFF state [17]. The gate-drain distance (L_{dg}), insulator thickness (t), FP length (l), and two material variables—the channel electron constant across L_{dg} and the insulator's dielectric constant; all play a role in how well a HEMT device with a GFP performs. The breakdown voltage performance is greatly influenced by the length of the field plate (l), yet it has been noted that a field plate that is too long may result in more current leakage routes [22]. After a certain point, the value of l will no longer cause the V_{br} to grow. This is because the field distribution along the 2DEG has a cross-like form, with two triangular lobes that reach their maximum values at the FP edge along with the gate edge. (as presented in Fig 6). The entire area beneath the lobes for the specified peak breakdown field is known as V_{br}. The decrease in lobe overlap with an increase in l will cause the rise in this area to saturate [19]. The thickness of the insulator is another crucial factor for properly scaling the electric field (t). An ideal value of t will result in the greatest possible V_{br}. It is because the field distribution at large t involves a single triangular lobe at the edge of the gate, and the effects of GFP diminish. As a result, even for a lower drain to source voltage, a large electric field is obtained, and V_{br} drops. Since the FP lengthens the gate by l, the field distribution at t=0 is the same as at big t; the only difference is that it is now located along the gate's new edge. Therefore, for an ideal value of t, the greatest value of V_{br} can be reached.

4. Simulation Result

The Silvaco Atlas simulation was run under the presumption that the source and drain electrodes are linked through ohmic contacts, and the gate electrode makes shottky contact. The source and drain contact should be submerged in the first quantum well. The parameters and material models were taken from the references provided. To improve the accuracy of breakdown analysis, simulation now includes recombination models and a particular statement for impact ionization in addition to all the models that have been specifically mentioned. In order to assess the contribution of fixed charges and mobile charges to the device characteristics, three fundamental equations, including Poisson's equation, are solved using the Silvaco Atlas simulator. The continuity and transport equations are included in the drift-diffusion and hydrodynamic models. Thermionic field emission (TFE), which takes tunneling into account, models the current flowing through the contacts. Additionally, SRH and Auger recombination models are used to simulate dynamic traps. Utilizing the SELBERR model, impact ionization is modelled. Drain current conduction for the above-stated enhancement mode structure starts with V_{th}> 0.5 V.



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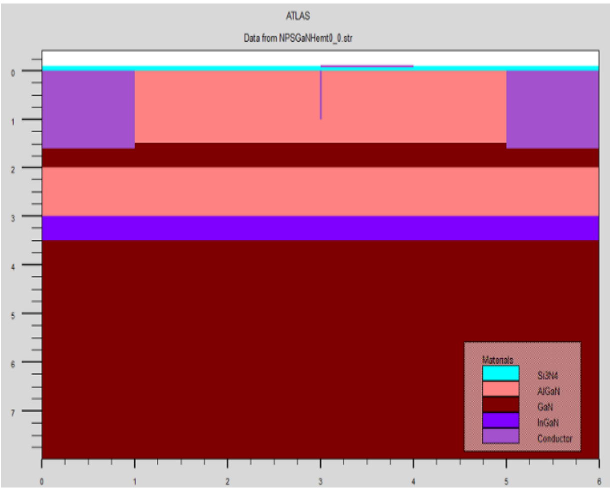


(b)

Fig. 4 Simulated structure of normally-off DH-HEMT a) with field pate and b) without field plate

Figure 6 displays the output features of a standard HEMT, a HEMT with an FP, and a HEMT with a passivation layer. When Vg = +5V, the maximum drain current for a conventional HEMT is 510.24 mA/mm, and the HEMT with FP may achieve 744.9mA/mm maximum drain current (for Vg = +5V). As a result, compared to a regular HEMT, the HEMT's drain current with FP and passivation layer has increased dramatically.

Figure 6 displays the transfer characteristics of conventional HEMT and HEMT having FP and passivation layers. The drain current has virtually remained the same in both cases despite adding performance enhancers like the field plate and passivation layer, which caused the threshold voltage to decrease slightly. A few surface charges might be briefly caught by impurity in the passivation layer or by AlGaN/GaN HEMT structure's electric field, which is strongest near the gate's drain edge [21]. When the switch is switched on, trapped charges will function as a "virtual gate". Therefore, 2DEG will be utilized. The current will cease to flow as a result, and the ON resistance will rise. The G-FP makes the electric field more uniform at the gate. The loss of 2DEG may be reduced by lowering the number of trapped electrons.

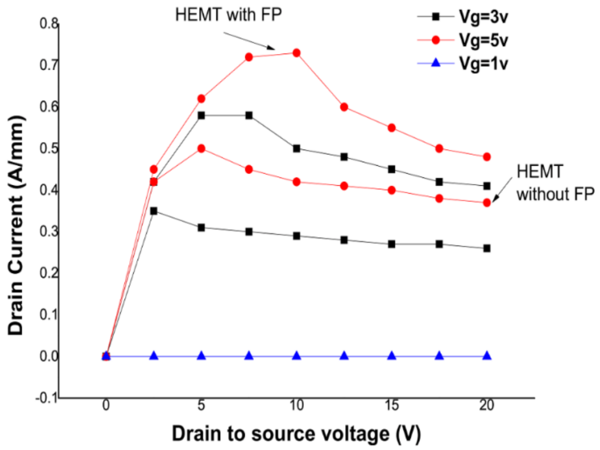


Fig. 5 HEMT with a gate field plate and typical HEMT output characteristics

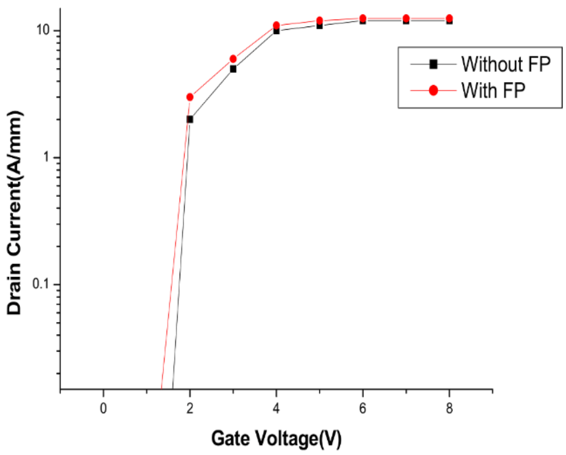
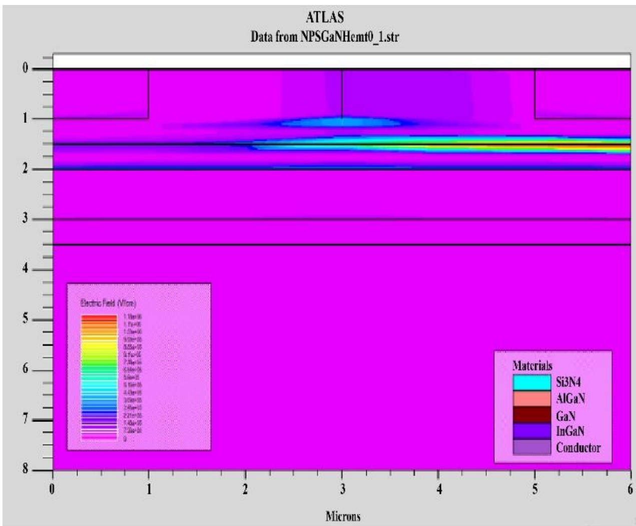


Fig. 6 Transfer characteristics of HEMT with a GFP and a regular HEMT



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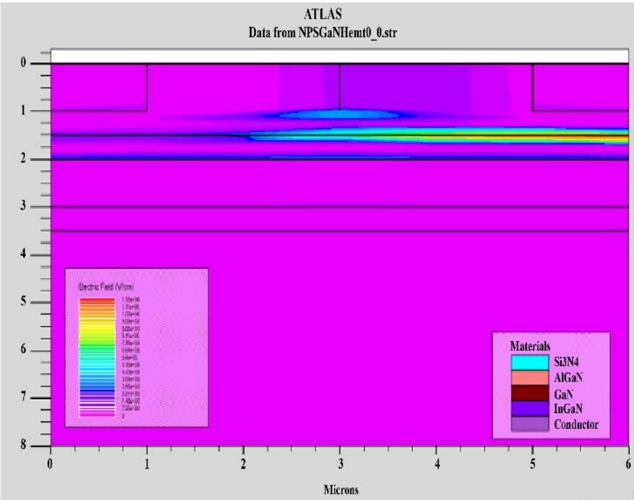

(b)

Fig. 7 Distribution of electric field around the gate electrode (a) without and (b) with a GFP

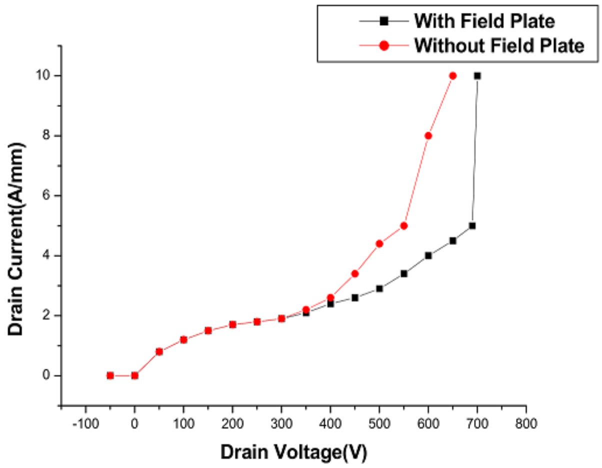

Fig 8. Breakdown characteristics of the device with and without field plate

As mentioned in [14], the low OFF state breakdown voltage is a major problem with the above architecture. A surface passivation layer (SiN) and field plate can be combined to increase the device's breakdown performance and decrease the current collapse effect. The localized manipulation of the electric field has caused the device's breakdown voltage to rise from 550 V to 690 V. (Fig.8). The device's breakdown voltage can be altered by changing the field plate's length [19]. Because of the electric field's dispersion, drain leakage current can be reduced by utilizing a gate field plate. There is a reduction in the strong electric field. One advantage of lengthening the GFP is less space between it and the drain, which allows the passivation layer to withstand higher voltages. A substantial current leakage will be anticipated if the dielectric film's thickness and quality are not properly maintained.

On the other hand, the closer proximity of the drain electrode to the GFP electrode may enhance the surface leakage current. As a result, the length of GFP is a crucial consideration. If the field plate's length is optimal, the breakdown voltage value can reach its highest point (l).

Beyond a certain point, an increase in "l" will not result in an increase in the V_{br}. Six steps make up this simulation. The suggested device topology has been simulated using a loop using six possible GFP length values. This is how the effect of "l" on the device's breakdown performance has been investigated.

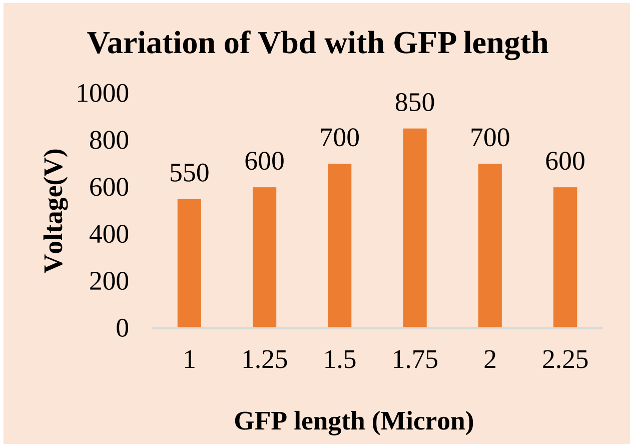

Fig. 9 Variation of breakdown voltage with the increasing length of GFP

Figure 9 is a bar chart that shows the variation of the breakdown voltage (V_{bd}) with field plate length(l). The 1.75 micron FP length can achieve the maximum breakdown voltage in this instance. As previously indicated, another important parameter that affects how much GFP influences breakdown voltage is the insulator layer thickness(t). The GFP modulates the electric field such that it is significantly greater near the edge of the field plate than at the edge of the gate. Hence, the breakdown voltage rises as t increases in magnitude. However, the modulated effect of GFP gets less intense as t continues to rise. Hence, the electric field moves toward the gate edge, resulting in a decrease in V_{bd}.

5. Conclusion

Wide bandgap semiconductor gallium nitride is being used in various power electronics applications. In terms of power density, resilience to high temperatures, and operation at high switching frequencies, the material outperforms Silicon (Si) in these areas. The demand for ever-more-efficient solutions in industries including automotive, telecommunications, cloud systems, voltage converters, electric vehicles, and more is propelling the market penetration of GaN-based power devices. In many wireless fast chargers, the power switch is a normally-off HEMT. The current work uses a double quantum well HEMT to implement the normally-off operation. After applying a positive gate voltage, shottky contacts beneath the electrode mentioned above depleted charged carriers below the gate contact, allowing the device to be switched ON.

Additionally, a gate field plate and a passivation layer were used to achieve an improved breakdown voltage (690V) hence the electric field's redistribution between the gate along with drain electrodes. It was also demonstrated that the combination mentioned above could reduce the current drain collapse due to the virtual gate effect. According to the results, a double heterojunction nitride-based HEMT with a field plate can be exploited as a good structure for business applications.

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