Grenze International Journal of Engineering and Technology, Jan Issue

Design of Normally OFF AlGaN/GaN HEMT using Double Quantum Well Structure with Improved Breakdown Characteristics

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***Abstract*—An AlGaN/GaN based high electron mobility transistor (HEMT) is considered as an excellent candidate for future power devices due to its high breakdown voltage, high saturation drain current and low on resistance (R_{on}). The conventional AlGaN/GaN heterostructures are inherently normally ON devices but normally off operation (enhancement mode) is often desired for fail safe operation and ease of design. For safety and OFF mode power saving concerns, it is ideal for a HEMT to be normally OFF device where the channel will not conduct without any gate bias.However, current collapse, i.e., dispersion of drain current or increased dynamic R_{on} is regarded as one of the most critical issue to be solved in normally-off devices. Even though there have been remarkable improvements in growth and device technologies it is still essential to find out the reason behind current collapse and ways to get rid of it. In this work a normally off HEMT using double quantum well has been investigated. In order to suppress current collapse and enhance the breakdown voltage, a field plate structured device along with a SiN passivation layer has been studied.**

***Index Terms*— HEMT, GaN, InAiN, normally off, threshold voltage, trapping, passivation, breakdown voltage.**

I. INTRODUCTION

Nowadays, one of the most important societal challenges is represented by the steady increase of the energy consumption in the world. In fact, the energy consumption is expected to increase by about 40% in the next 20 years. In such a situation power saving is a very big concern for any targeted application. Silicon (Si) has been dominating the electronics industry for the past five decades. The biggest advantage of this semiconductor is its abundance and chemical stability but because of sum inherent structural difficulties it is not a befitting material for high voltage and high power applications. To satisfy the growing need for high voltage, high current and high power applications some new semiconductors have been introduced in the power electronics industry. Wide bandgap semiconductors like Silicon carbide (SiC), Gallium Arsenide (GaAs) and Gallium Nitride (GaN) are considered to be best materials for the future energy efficient electronic devices. AlGaN/GaN high electron mobility transistors are becoming popular nowadays for high frequency, high power application and high voltage power switching application. The pyroelectric properties of group III nitrides open up unique possibilities for their realization of heterostructures with novel electronic characteristics. To make nitride devices applicable in

Grenze ID: 01.GIJET.9.1.504_1

complementary FET based high power digital logic and low power loss circuits, enhancement mode (E-mode) or normally OFF devices are required [2]. Positive threshold voltage (V_{th}), drain saturation current (IDSS), ON-resistance (Ron), breakdown voltage (V_{br}) and subthreshold slope (SS) are key parameters of the E-mode or normally OFF transistors which have been optimized broadly through device physics and process innovations for GaN FET as reported in the literatures [2-6].These kind of structures are having a single AlGaN/GaN interface mostly known as single heterostructure HEMT or SH-HEMT.Although remarkable progress has been achieved for AlGaN/GaN single heterojunction HEMTs (SH-HEMT) due to improved material quality and process techniques, there still remain some obstacles. The device under consideration needs high breakdown voltage (V_{br}) for high power and high voltage applications. Therefore, enhancing the V_{br} while keeping the gate-drain distance short is one of the most important challenges in the current development of AlGaN/GaN based HEMT devices. In the conventional AlGaN/GaN HEMT structure, the two dimensional electron gas (2DEG) induced by the polarization process is confined in an approximately triangular potential well formed at the interface between the AlGaN barrier and GaN buffer layer. The GaN is typically used not only as a buffer layer, but also as a channel to carry the electrons. However, due to the lower potential barrier height of the GaN buffer layer the confinement of the 2DEG in the channel is insufficient. It is easy for the 2DEG to overflow from the potential well to the GaN buffer layer. Thus, a punch through effect will take place at the channel/buffer (GaN) layer and it will cause a significant deterioration in the transport characteristics.

II. Brief Description of the Work

High electron mobility transistors (HEMT) based on AlGaN/GaN heterostructures are inherently normally-ON devices but normally off operation is often required in many power electronics applications. Here the operation of a double quantum well enhancement mode HEMT proposed by Ankush Bag et al. is discussed where the normally off operation is realized by introducing a deeper secondary quantum well along with the primary AlGaN/GaN quantum well. Participation of the concerned quantum well in drain current conduction depends on the applied gate voltage. The effect of positive gate bias on the gate terminal causes energy band bending and the 2DEG modulation. The normally off operation is realized by making the triangular primary quantum well devoid of electrons for v_{th}<0V.Moreover, current collapse in the designed structure due to the virtual gate effect is minimized by adding a SiN surface passivation layer and the breakdown characteristics has been improved by adding a gate field plate.

Figure 1: Double quantum well EMODE structure with GFP and SiN passivation layer

Prime process concern of present heterostructure is limiting the depth of source and drain contact till the heterojunction of first QW, which is almost free of carriers due to its spillover [14]. With such construction, the first QW have insufficient carriers to conduct drain current in absence of any gate bias. Downward conduction band bending occurs only under sufficient positive gate bias and it changes the distribution of the electron wave function to accumulate electrons in the first QW. Thus, the design of this double QW is expected to provide an Enhancement mode operation.

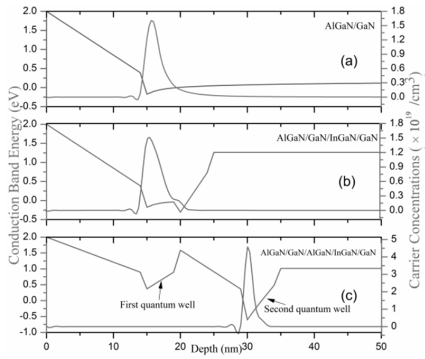


Figure 2: Conceptualization of DQFET. Energy band diagram and carrier population in heterojunction of a) conventional AlGaN/GaN, (b) AlGaN/GaN/InGaN/GaN [14] and (c) AlGaN/GaN/AlGaN/InGaN/GaN double QW heterostructure for E-mode operation by separating carriers in anon-conducting secondary low energy quantum valley at zero gate bias[23]

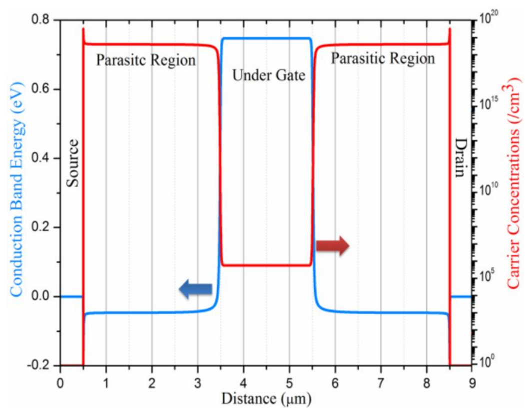


Figure 3: Carrier Concentration and Conduction band energy profile of the EMODE HEMT Structure with positive gate bias [23]

Among several technical requirements of an efficient power switch, a critical one is obtaining a very low ON resistance (R_{ON}) immediately after switching from a high voltage OFF state to a low voltage ON state [28]. As an enhancement mode device is normally being used as a switch, a low ON resistance immediately after switching ON the device is a very important criterion.

The virtual gate effect: The RF power performance of a GaNFET can be largely affected due to a significant reduction in the drain current during large signal RF biased operation compared to that expected from DC measurement. This phenomenon is referred to as current collapse. One major cause of this current collapse is the virtual gate effect. When the gate is under large negative bias (reverse biased condition) electrons can be injected, from the gate onto the surface of the device at the drain side gate edge changing the occupation of the surface states. The virtual gate formed on the surface depletes the 2DEG formed in the channel and increases the parasitic source and drain resistance of the device which results into an increased dynamic ON resistance (R_{ON}) [25]. In addition, many studies have shown that the electric field distribution in HEMT has a decisive influence on device performance and reliability. Therefore, electric field optimization is important for HEMTs. Field Plate (FP) technology is considered as one of the technologies that significantly improves the power performance of HEMT. Using the field plate technology, the depletion region can be effectively expanded, and the single peak electric field can be replaced by multiple peaks, making the electric field distribution more uniform. Thus, the breakdown voltage (v_{br}) performance and current collapse effect can be improved [32]. However, FP structure does not increase the ON resistance of HEMT [34].

Several kinds of field plates have been proposed till date to improve the dynamic characteristics and increase the off state break down voltage, e.g. source field plate (SFP), gate field plate (GFP) and drain field plate (DFP). Among all these structures, GFP has shown better performance than the others which can be explained by two reasons: one is the 2DEG compensation during the ON state and less negative charge trapping during the OFF state [29].

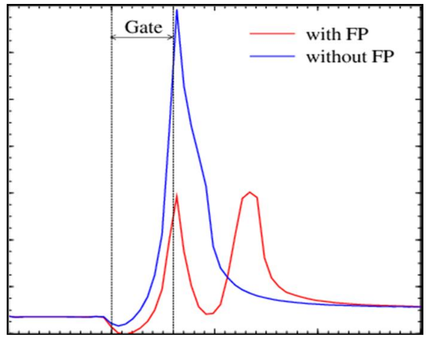
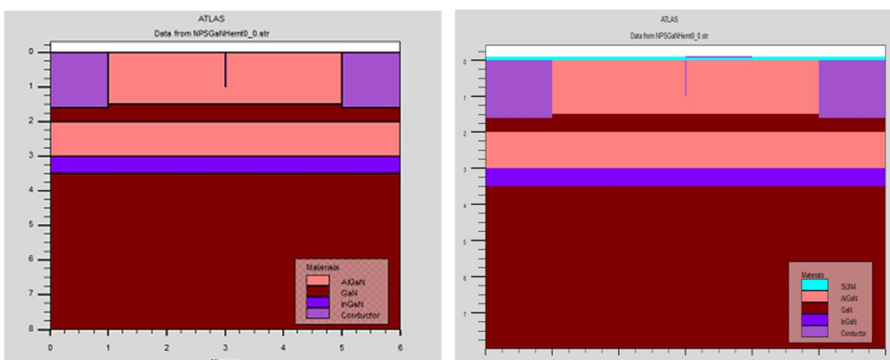


Figure 4: Variation of electric field along the channel of AlGaN/GaN HEMT with and without field plate [31]

III. Simulation of the Normally Off Structure

The simulation was performed (in Silvaco Atlas simulator) with the assumption that the source and the drain forms perfect Ohmic contact and the gate forms Shottky contact. The depth of the source and drain contact is assumed to be up to the first quantum well. The material models and the parameters used were adopted from the references included. Apart from all specified models, simulation also includes recombination models and special statement for impact ionization for increasing accuracy of breakdown analysis. Silvaco simulations are done solving three basic equations such as poisson's equation to estimate the contribution of mobile and fixed charges to the device characteristics. The drift diffusion models and the hydro dynamic models include the continuity equation and the transport equation. Current through the contacts is modeled by thermionic field emission (TFE) including tunneling. In addition to this dynamic traps are modeled by SRH and Auger recombination models. Impact ionization is modeled by using SELBERR model.



(a) (b)

Figure 5: Simulated structure of double quantum well Emode HEMT a) Without field plate and surface passivation b) With Field Plate and surface passivation

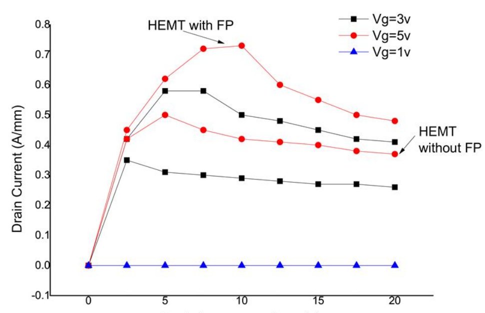


Figure 6: Output characteristics of conventional HEMT and HEMT with FP

Figure 6 shows the output characteristics of the conventional HEMT and HEMT with FP and passivation layer. When V_g = +5V for the conventional HEMT, the maximum drain current is 510.24 mA/mm. In case of the HEMT with FP, the maximum drain current obtained is 744.9 mA/mm(for V_g = +5V).

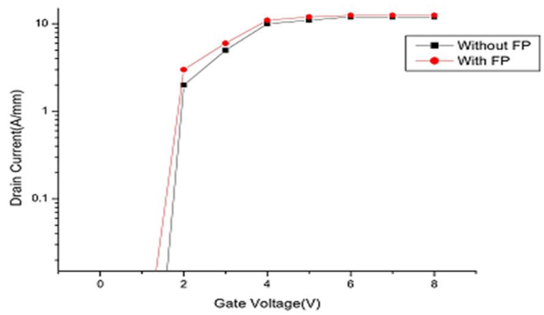


Figure 7: Transfer characteristics of conventional HEMT and HEMT with FP

Figure 7 shows the transfer characteristics conventional HEMT and HEMT with FP and passivation layer. The threshold voltage has decreased slightly after adding the performance boosters like field plate and passivation layer whereas, the drain current remains almost same for both of the cases. The AlGaN/ GaN HEMT structure causes the electric field to be the strongest near the drain edge of the gate, which will trap a part of the surface charge, and the impurities in the passivation layer on the device surface will temporarily trap the charges [33]. When the device is in the ON state, the trapped charges will act as a "virtual gate" and consumes 2DEG which will cause the current to collapse and increasing the ON resistance. Due to the G-FP, the electric field at the gate is homogenized. The trapped electrons are reduced, reducing the loss of 2DEG.

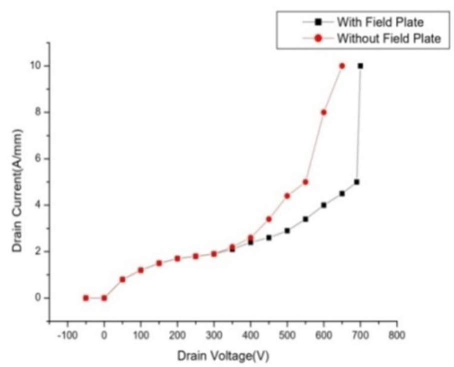


Figure 8: Breakdown characteristics of the device with and without field plate

As stated in [23] low OFF state breakdown voltage is a key issue of the above stated architecture. The breakdown performance of the device can be improved and the current collapse effect can also be minimized by adding a combination of a surface passivation layer (SiN) and a field plate (Fig. 1). The breakdown voltage of the device has been increased from 550 V to 690 V due to localized modulation of the electric field (Fig.8).

IV. Application Areas and Conclusion

Normally off HEMTs are widely used as a power switch in wireless fast chargers. In the present work normally off operation is realized using a double quantum well HEMT. Charged carriers below the gate contact was depleted by means of a shottky contact beneath the above mentioned electrode and the device can be switched ON after the application of a positive gate voltage. Furthermore, an enhanced breakdown voltage (690V) was obtained using a gate field plate and a passivation layer due to redistribution of the electric field between the gate and the drain electrode. It was also shown that drain current collapse which occurs due to the virtual gate effect can also be minimized using the above mentioned combination. Through the results obtained it can be concluded that a double quantum well based nitride enhancement mode HEMT with a field plate can be used as promising structure for commercial applications.

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