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ChemTech

International Journal of ChemTech Research
CODEN (USA): IJCRGG ISSN: 0974-4290
Vol.7, No.2, pp 921-927, 2014-2015

ICONN 2015 [4th -6th Feb 2015]
International Conference on Nanoscience and Nanotechnology-2015
SRM University, Chennai, India

Concept of Buffer Doping and Back Barrier in GaN HEMT

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Abstract : This paper presents concept of buffer doping and back barrier to improve the performance (breakdown voltage, leakage current reduction..etc) of III-V wide band gap (WBG) semiconductor device, gallium nitride (GaN) high electron mobility transistor (HEMT). Due to high breakdown voltage, GaN can be used for high voltage applications. Generally for using this type of device for high voltage applications, it is required that the back side of device or buffer area should be properly insulating so that more electrons confined into the channel Area and suppress leakage current path. There are various methods like: Doping in buffer area, back barrier concept to achieve this type of Requirements. In this Paper we Mainly focus on the C and Fe Doping in buffer area of the device and AlGaN/InGaN back barrier concept. By intentionally doping the GaN buffer with deep acceptor dopants such as C and Fe Sub threshold drain leakage can be suppressed in GaN HEMTs. Transistors with an undoped GaN channel layer on top of a doped GaN buffer layer had a small current collapse. In this paper we are using different energy levels and different concentration of C and Fe and do a comparative analysis with undoped buffer . This letter also does a comparative analysis of the effect of AlGaN and InGaN back barriers on the current and breakdown voltage characteristics of $Al_{0.25}Ga_{0.75}N$/GaN high electron mobility transistors grown on sapphire substrates. Compared to the conventional GaN HEMTs, introduction of back barrier significantly improves the breakdown voltage values due to better confinement, while the maximum current decreases due to reduced sheet electron density.

Keywords: Buffer Doping, Back Barrier. GaN HEMT.

Introduction:

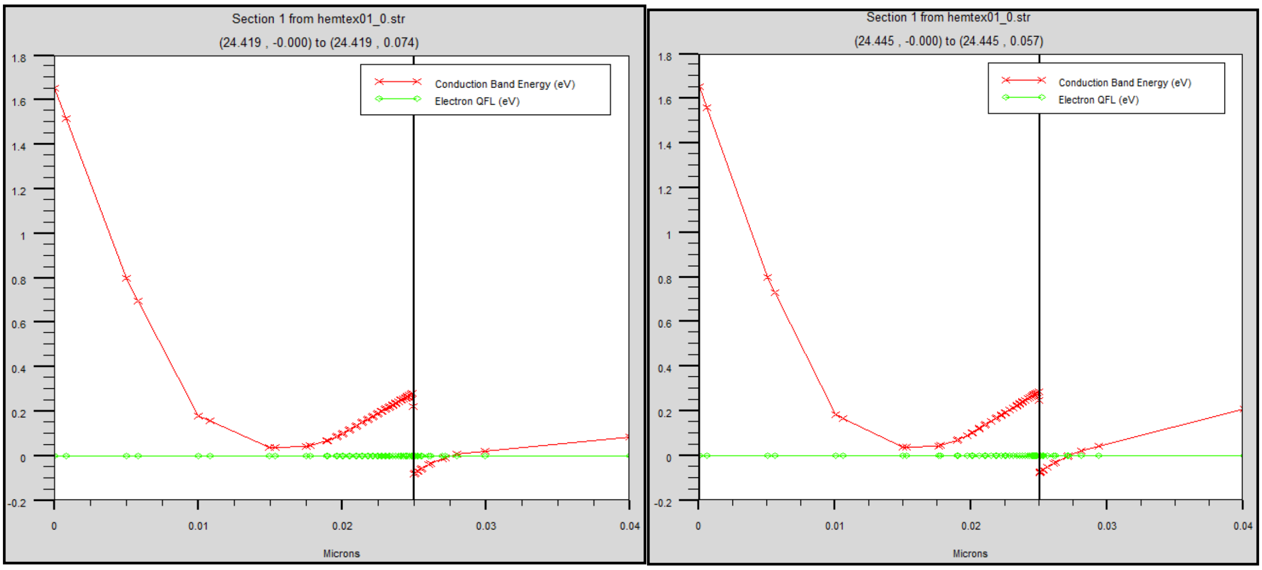
Gallium nitride has been a subject for intensive investigation and emerged as an attractive material for a high power and high frequency applications and a centre of research for the next generation power electronics devices. They have emerged as excellent candidates for power switching applications due to their unique combination of low conduction losses and fast switching. In some recent years there has been made a tremendous progress in GaN power HEMTs. There is a very easy way to increase the breakdown voltage is to scale the gate to drain distance (Lgd). It has been a major challenge to increase the breakdown voltage while scaling L_{gd} in the current developments for GaN based HEMTs. [1,2] Due to the presence of AlGaN barrier layer, the electrons are well confined to the upper side, but poorly confined from the bottom side in standard GaN HEMTs. Generally for using this type of device for high voltage applications, it is required that the back side of device or buffer area should be properly insulating so that more electrons confined into the channel Area and suppress leakage current path so due to better confinement of electrons definitely there is an enhancement in breakdown voltage of device. There are various methods like: Doping in buffer area, back barrier concept to achieve this type of Requirements. In this paper we mainly present how Sub threshold drain leakage can be suppressed in GaN HEMTs by intentionally doping the GaN buffer with deep acceptor dopants such as C and Fe or by using a back barrier. It was found that current collapse is dependent on dopant concentration and is worse with Fe doping than with C doping. Transistors with an undoped GaN channel layer on top of a doped GaN buffer layer had a small current collapse but much a higher drain current. Concept of introducing a back barrier has been proposed, giving rise to a second hetero-structure in the same device providing better confinement to the electrons, resulting in lower sub-threshold leakage currents and providing better breakdown voltages. In this paper we are using different energy levels and different concentration of C and Fe and do a comparative analysis with undoped buffer . In this paper we also present a comparative analysis of the confining capabilities of two kinds of back barriers namely AlGaN and InGaN with a fixed $Al_{0.25}Ga_{0.75}N$ serving as the upper barrier layer and a GaN buffer in between the two barrier layers to serve as the 2-DEG channel.

Experimental setup for simulation:

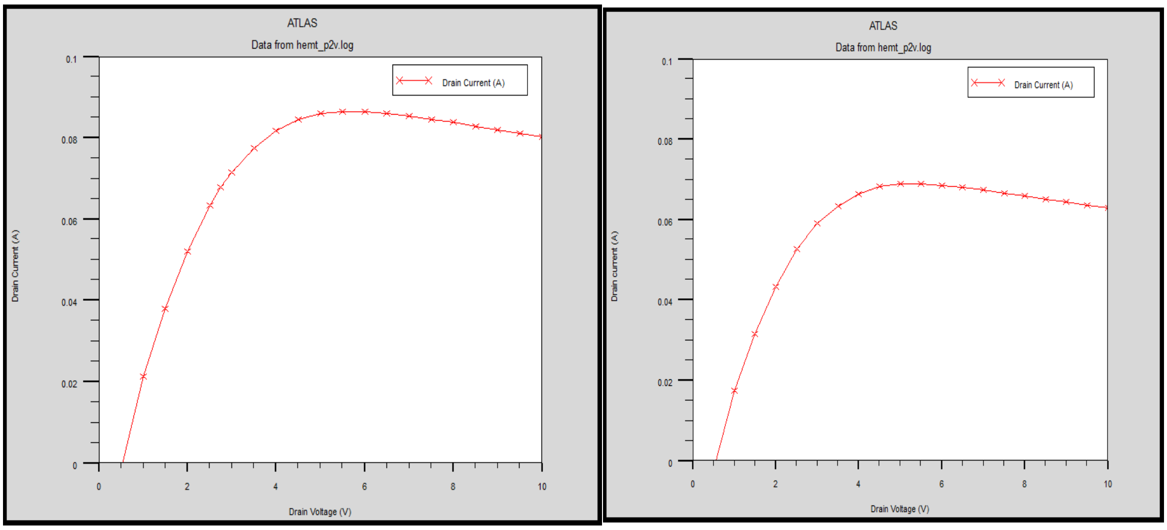
The structure considered for simulation was formulated in Silvaco ATLAS for two-dimensional physical based device simulations. It comprises of a 100 um gate width, followed by 10 nm each of highly doped $Al_{0.25}Ga_{0.75}N$ barrier and supply layer. This is followed by 5 nm of undoped $Al_{0.25}Ga_{0.75}N$ space layer , 3nm of channel layer and 2.697 um of GaN buffer. The bottom of the device comprises of a 30 nm AlN layer for nucleation purposes and a 360 um Sapphire substrate. Gate length of the device has been kept at 1 um. The gate source and the gate drain distances as well have been kept at 1 um and 1.5um respectively. The total width of the device from the drain end to the source end stands at 50 um. A 5.6 eV of work function for the Schottky contact at the gate has been taken throughout the measurements and drain source ohmic contact resistance of $1.6e10^{-6}$ ohm has been considered.

AlGaN/GaN HEMT: C doping-

The DC characteristics for two different configurations of device, namely for basic GaN HEMT without any doping in buffer and GaN HEMT:C doping in buffer with a concentration of 5.5e16 is illustrated in Fig 1. The output drain current reaches a maximum value of 0.86 A/mm for the specified gate width of 100 um for conventional HEMT. The same characteristic value for the GaN HEMTs with 5.5e16 C dopants in buffer with is measured around 0.69 A/mm. It can be seen in fig 1 that Drain current is lower with 5.5e16 C dopants than without any doping in buffer region. The V_{th} is shifts from -1.5V to more positive (-1V) value with C dopants in buffer than a conventional HEMT. The I_d-V_{gs} curves for all these configuration is also illustrated in Fig 2.

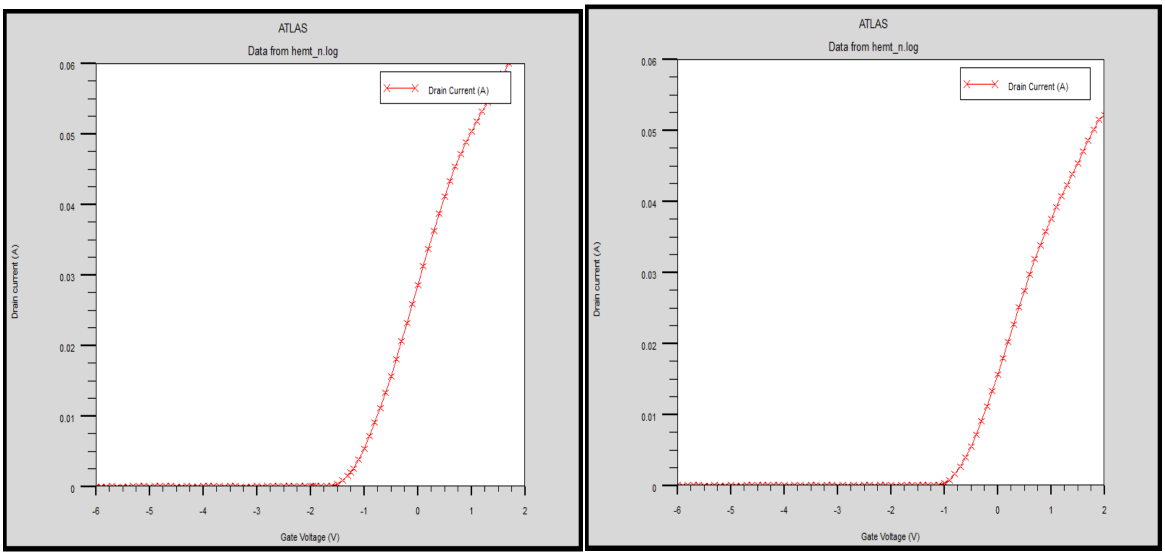


(a) (b)



(c) (d)

Fig 1.(a)Band diagram for AlGaN/GaN HEMTs without any doping (b) Band diagram for AlGaN/HEMT with C dopants in buffer.(c and d) I_d-V_{ds} characteristics for AlGaN/GaN HEMT without doping and with C dopants respectively.



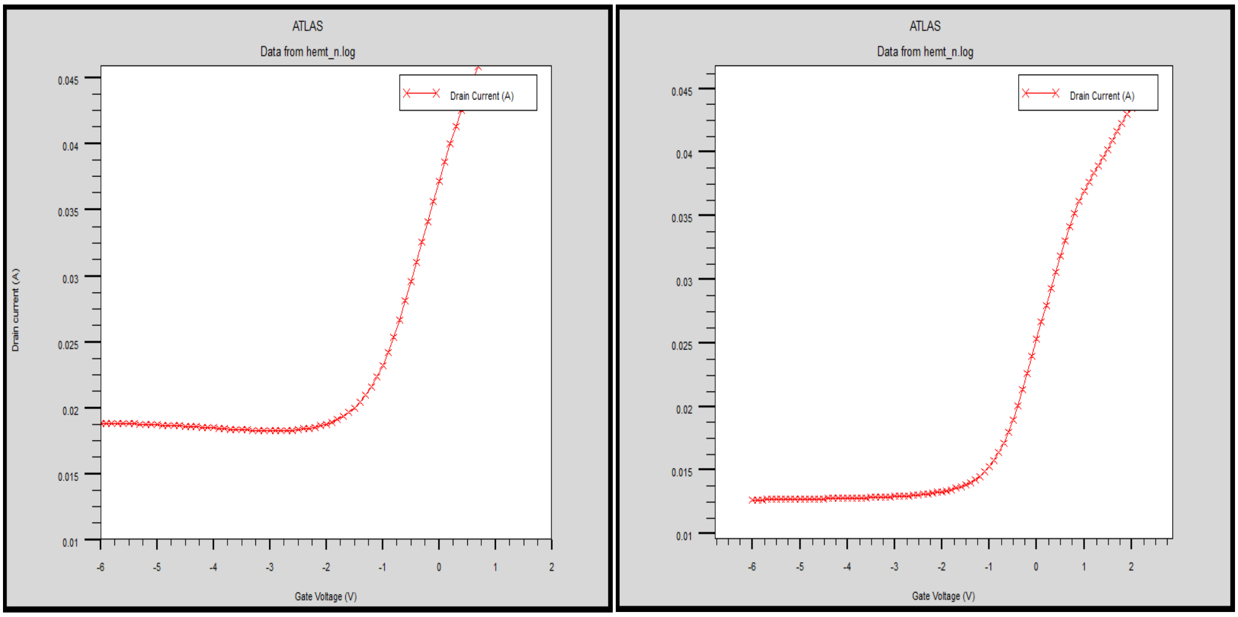
(a) (b)

Fig 2.(a) Id-Vds characteristics for AlGaN/GaN HEMTs without doping (b) Id-Vds characteristics for AlGaN/GaN HEMTs with C dopants in buffer.

These results can be explained by considering the trapping behavior of C impurities. The traps created by C dopants in the GaN buffer capture electrons from the 2DEG channel. Therefore, the electron density is lower which results in a lower drain current. With more dopants, more electrons from the channel are trapped in the buffer. Therefore, the drain current decreases as the C concentration increases.

Leakage Effects on AlGaN/GaN HEMTs:

The leakage effects for two different configurations of device, namely for basic GaN HEMT without any doping in buffer and GaN HEMT:C doping in buffer with a concentration of 5.5e16 is illustrated in Fig 3. These effects are measured by using pipinys models which is formulated in silvaco atlas. It can be directly seen that in case of without doping there is large leakage current so device is pinch off at lower voltages. But in case of C doping leakage current value is decreased so device is pinch off at higher voltages than in case without doping. Due to this suppressed leakage current definitely there is an enhancement in breakdown voltage is expected.

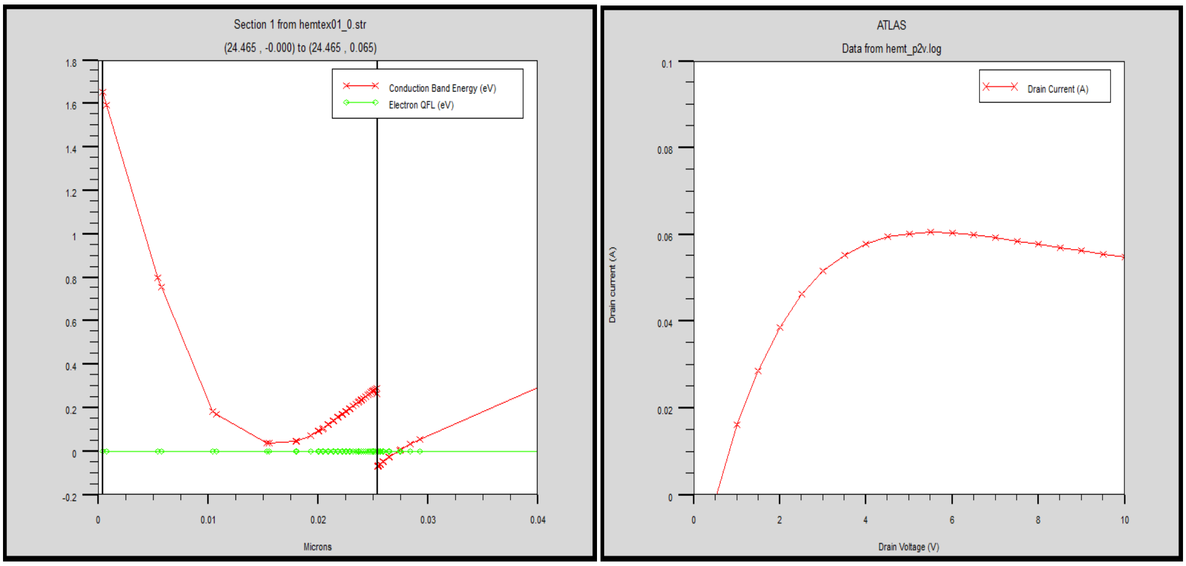


(a) **(b)**

Fig 3.(a) Leakge effects for AlGaN/GaN HEMTs without doping **(b)** leakage effects for AlGaN/GaN HEMTs with C dopants in buffer.

AlGaN/GaN HEMT: Fe doping-

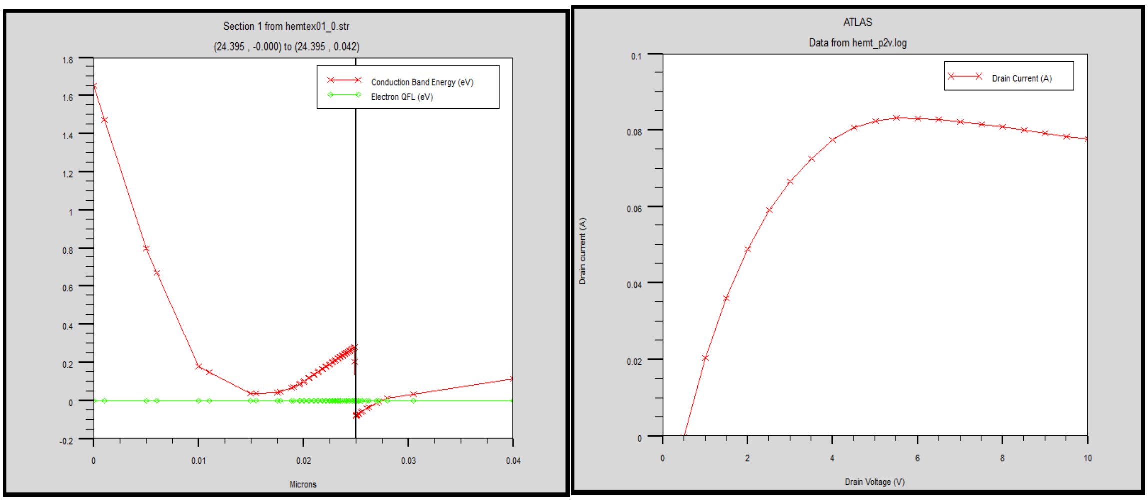
The DC characteristics for the device for GaN HEMT with Fe dopants in buffer with a concentration of 5.5e16 is illustrated in Fig 4. [3] The structure considered for simulation was formulated in Silvaco ATLAS for two-dimensional physical based device simulations. In this the acceptor level for Fe is 2.5ev have been kept. It can be seen in fig 3 that the drain current is decreases with this concentration level of Fe atoms than with the C dopants in buffer region of GaN HEMTs which is not match with the literature. Generally literature says that Fe has deep acceptor level near to the valence band so drain current should be increase than in the case of C dopants in buffer.



(a) **(b)**

Fig. 4 (a) Band diagram for GaN HEMTs with Fe dopants with the concentration level of e16,(b) I_d-V_{ds} curve for GaN HEMTs with Fe dopants with the concentration level of e16.

To match the results with literature or with the theoretical aspects this is very challenging task. Now we change the concentration level of Fe atoms from e16 to e15 for the same acceptor level. For this type of configuration the simulation was again formulated in Silvaco ATLAS. The DC characteristics for this configuration is illustrated in fig 5. As per comparison of fig.1(d) with fig 5(b) it can be directly seen that drain current is increased in case of Fe doping with a concentration level of e15 than C doping which follows the literature aspects also.



(a) (b)

Fig.5 (a) Band diagram for GaN HEMTs with Fe dopants with the concentration level of e15,(b) I_d-V_{ds} curve for GaN HEMTs with Fe dopants with the concentration level of e15.

AlGaN/GaN HEMT with back barrier:

Generally by increasing the gate to drain distance there is an increment in breakdown voltage but by increasing L_{gd}, the on state resistance is increase and also it degrades the output power efficiency. [4] To minimize the on-resistance, it is therefore desirable to select hetero-structures with a high sheet charge density. Breakdown in GaN HEMTs, characterized by sudden punch-through of electrons due to sub-threshold leakage from the high resistive buffer layer at high off-state drain voltage leads to an increase in off-state current. Due to the presence of AlGaN barrier layer, the electrons are well confined to the upper side, but poorly confined from the bottom side in standard GaN HEMTs. With the concept of introducing a back barrier has been proposed , giving rise to a second hetero-structure in the same device providing better confinement to the electrons, resulting in lower sub-threshold leakage currents and providing better breakdown voltages. The general structure with this type of concept is shown in fig 6. In this structure AlGaN serving as the upper barrier layer, AlGaN or InGaN serving as back barrier layer and a GaN buffer in between the two barrier layers to serve as the 2-DEG channel.

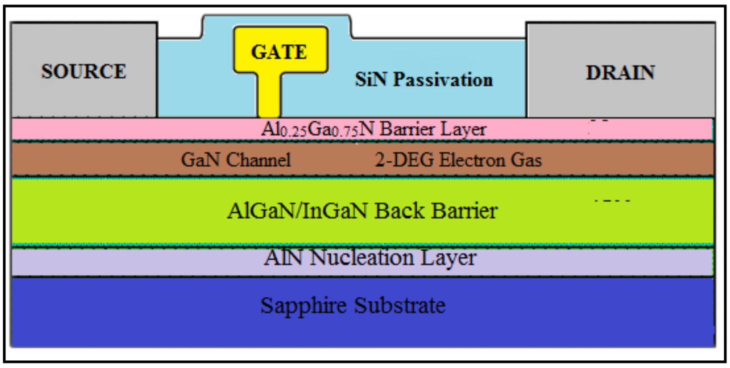
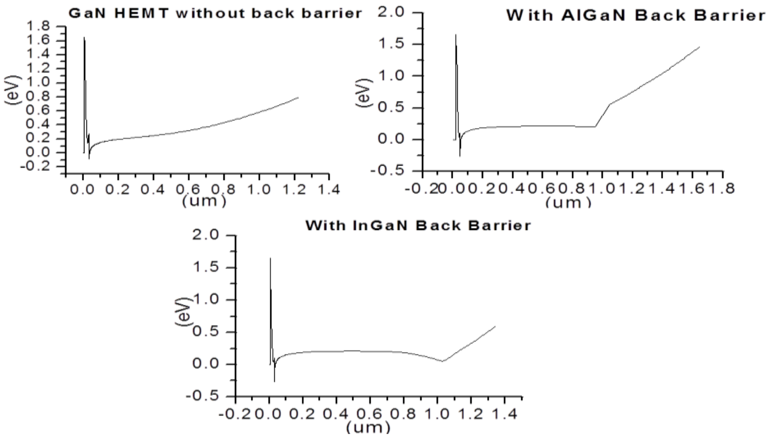
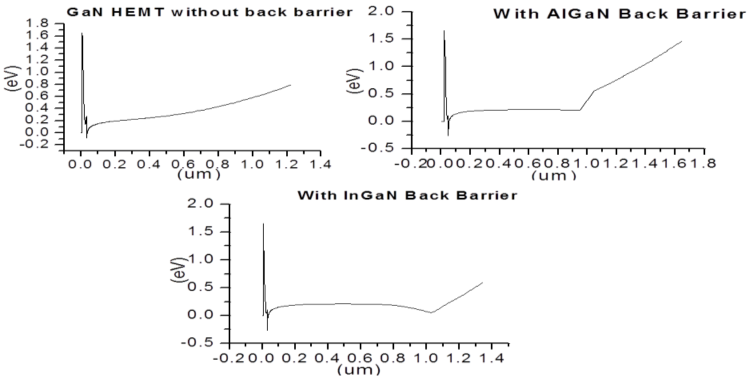


Fig.6 General structure of GaN HEMTs with concept of back barrier.

Fig 7 a and b shows the results of back barrier on the breakdown voltage and band bending. AlGaN back barrier proved to be the best choice for high breakdown voltages.



(a)



(b)

Fig.7 (a) Band Bending (b) Breakdown voltage.

Results:

The DC characteristics for the device for three different configurations, namely for basic GaN HEMT without any doping in buffer and GaN HEMT:C doping in buffer with a concentration of 5.5e16 ,and GaN HEMTS with Fe dopants in buffer are measured. In this paper we also use different concentration level for the Fe dopants. The maximum drain current for conventional GaN HEMT is measured around 0.86 A/mm. The same characteristics value for GaN HEMT with C dopants is measured around 0.69 A/mm. It directly shows that the maximum drain current value was decreased in case of C dopants than conventional HEMT. In this paper we also measured the value of maximum drain current for GaN HEMT with Fe dopants with the same concentration value as C and which is around 0.60 A/mm. we are also changed the concentration level of Fe atoms from e16 to e15 and found drain current is increased up to 0.83 A/mm which is desired as the experimental results.

Discussion:

For high voltage applications, it is required that the back side of device or buffer area should be properly insulating so that more electrons confined into the channel Area and suppress leakage current path. The DC characteristics obtained for the configurations mentioned above follow the experimental results which have been obtained earlier. This is due to reduction in sub threshold drain leakage by intentionally doping in the GaN buffer with deep acceptor dopants such as C and Fe in GaN HEMTs. With the concept of introducing a back barrier has been proposed , giving rise to a second hetero-structure in the same device providing better confinement to the electrons, resulting in lower sub-threshold leakage currents and providing better breakdown voltages AlGaN/GaN DH-HEMTs also studied as remarkable increase in the breakdown voltage values and decrease in off-state drain leakage current on introduction of a back barrier due to improved carrier confinement as a result of increased back barrier height.

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