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Performance Analysis of *In AlN/GaNMOSHEMT* for High Power RF Applications

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Abstract

We presents DC and RF performance of 30 nm gate length AlN spacer based In AlN/GaN based MOSHEMT with In GaN back barrier is investigated using Silvaco ATLAS TCAD tool. The proposed MOSHEMT featuring Al_2O_3 oxide layer, heavily doped n+ GaN Source/ drain region exhibits thesheet carrier density (n_s) of $1.66X10^{13}$ Cm^{-2}, drain current density of 1.8 A/mm. drain current density, transconductance (g_m)of 530 mS/mm, low leakage current 10^{-9} A/mm and current gain cut-off frequency (f_t) of $300\ GHz$.The excellent electrical characteristics of proposed MOSHEMTsareattractive candidates for future high power sub millimetre wave applications.

Keywords

HEMT, 2DEG, Leakage current, back-barrier and short channel effects.

1.Introduction

Recently the lattice matched InAlN/GaN based high electron mobility transistors ($HEMTs$) are of great interest for high power switching and RF applications because of their high breakdown voltage, high current density and thermal stability. The limitation of AlGaN/GaNHEMT have been reached now in particular for the bottom part of the mm-wave spectrum (30 to 300 GHz). Furthermore the unavoidable strain caused by the lattice mismatch between GaN and AlGaN limits the Al contents of the barrier to about 30%and therefore the2DEG density to 10^{-13} Cm^{-2}. As a consequence, the maximum current density is limited to 1 A/mm. The presence of strain has been identified as a source of failure for these devices [5,6].

Lattice matched In AlN/GaN HEMTs present several advantages with respect to AlGaN/GaN. They allow for a more efficient downscaling of the transistor dimensions, making easier to achieve cut-off frequencies more than 200 GHZ [4]. InAlN/GaN HEMT have been shown to produce the current density of 2 A/mm [16]. There fore In AlN/GaN based HEMTs are ideal candidates for power applications at frequencies more than 100 GHz.

ISSN:0971-1260
Vol-22- Issue-14-December-2019

Besides the remarkable potential for high power and high frequency applications, In AlN/Ga NHEMT has also demonstrated for good thermal stability at $1000^{\circ}c$ [18]. However, despite the great potentials of the In AlN/GaN HEMTs, are suffering from leakage currents and consequently low breakdown voltages reported [19], as well as strong short channel effects [20]. The ohmic contacts were characterized to reduce the contact resistance of ~0.3 $ohm.mm$ [20]. Devices for high temperature operation on the other hand from high buffer leakage which strongly degrades the operating temperature of HEMT.Finally high performance HEMTs were reported on SiCsubstrate.

In AlN/GaN HEMT Provide a better carrier confinement in the 2DEG than conventional AlGaN/GaN HEMT based HEMT due to larger spontaneous polarization between the barrier and channel [6]. To reduce the alloy disorder scattering at the In AlN/GaN interface, a very thin AlN spacer layer is placed between them which improves the 2DEG density.However due to limitation in schottky barrier height and thin barrier layer device performance is suffered from gate leakage current and poor off state as the gate length is reduced below 70 nm. A thin epitaxial oxide layer is introduced between gate and barrier layer to solve the aforementioned two issues named as Metal Oxide Semiconductor High electron Mobility Transistors (MOSHEMTs). Several progresses have been made to reduce the leakage mechanism by using different dielectric oxide layer such as $SiO_2, Al_2O_3, HfO_2, La_2O_3$ [8-15].

The outstanding microwave performance current gain cut-off frequency of 225 GHzandpower gain cut-off frequency of 300 GHZ AlGaN/GaN HEMT was reported in [1],[2] respectively. However if the device gate length is reduced below 50 nm ,its very challenging task in AlGaN/GaN HEMT to maintain the high aspect ratio (L_g/d)ratio to suppress the short channel effects. The lattice matched new barrier materialInAlN introduced in [3] for better microwave performance of the device. A 55 nm gate length In AlN/GaN HEMT with 11 nm barrier thickness shown f_t of 205 GHz [7] and f_{max} of 245 GHz achieved by 30 nm gate length with 4.5 nm In AlNbarrier layer thickness.

Inspite of excellent microwave characteristics the short channel effects of the device degrades the performance of the device when the HEMTscale down below 50 nm. The AlGaN back barrier have the potential to reduce the short channel effects ($SCEs$) and it gives better carrier confinement in the channel [23]. However the use of AlGaN back barrier instead of GaN buffer degrades the thermal conductivity of the HEMT devices.

In this research work, we have investigated the the sheet charge density (n_s), threshold voltage (V_{off}),drain-source current(I_{DS}), transconductance (g_m), gate leakage current, Current gain cut-off frequency$(f_t)$for 30 nm gate length InAlN/AlN/GaNMOSHEMT on siC substrate. The MOSHEMT characteristics are studied by using Al_2O_3 oxide layer. To avoid the short channel effects in the device 3.5 nm In GaN back barrier in introduced below the GaN channel which provides better carrier confinement in the 2DEG region and GaN used as the buffer layer. And also the proposed device threshold voltage variation and current gain cut-off frequency are studied for different gate length varying from 30 nm to 230 nm.

ISSN:0971-1260
Vol-22- Issue-14-December-2019

2. InAlN / AN/ GaNMOSHEMT Device structure and Bandgap Diagram:

The cross section view of Al_2O_3/InAlN/AlN/GaN HEMT with InGaN back barrier is shown in Fig.1. The HEMT having the gate lengthL_g,oxide layer thicknesst_{ox}, $InAlN$barrier thicknessd_d, AlN spacer layer thicknessd_i and the drain to source distance(L_{SD}) is 1 μm. The proposed 1nm AlN spacer based $HEMT$with 3.5 nm $thickness$ $In_{0.15}Ga_{0.85}N$ as a back barrier reducesthe short channel effects and to provide the better electron confinement in 2$DEG$by residing the polarization induced electricfield in the $InGaN$ back barrier which provided effective conduction band offset.The lattice matched 7.5 nm $InAlN$used as barrier layer with GaN channel. The access and output resistance of $HEMT$ limits the performance of the device and as contact resistivity is a major part of such as parasitic resistances.The highly doped $n+$ GaN regrown ohmic contact is allowed a significant reduction of the contact resistivity in our model. Regrown ohmic contacts have thus become a requirement for high speed GaNbased $HEMTs$.To achieve the higher cut-off frequency, it's desirable to reduce the gate resistance. The T-shapedschottky($Ti/Pt/Au$) gate(30 nm $length$) metal stack with small foot print used as gate contact.SiCused as a substrate for good thermal conductivity in this model.A very thin4 nm $Al2O3$ oxide layer is placed between the barrier and gate terminal which helps to reduce gate leakage current in the $HEMT$device.

The energy band diagram of $InAlN/AlN/GaNHEMT$ is shown in figure 2. The presence of AlNspacer layer produced a large effective conduction band offset($\Delta E_{c,eff}$) between barrier and channel. Which helps the $HEMT$ for greater carrier confinement and better mobility for electrons in 2DEG.

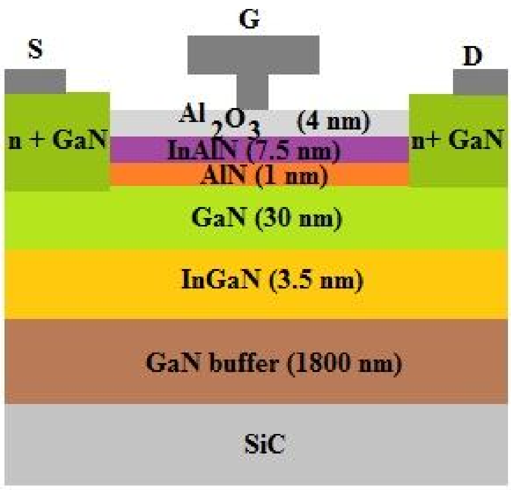


Fig.1. Cross-sectional view (not drawn to scale) of a spacer layer-based $Oxide/InAlN/AlN/GaNHEMT$.

The energy band diagram of $metal/oxide/InAlN/AlN/GaNHEMT$ is shown in figure 2. The presence of AlNspacer layer produced a large effective conduction band offset($\Delta E_{c,eff}$) between barrier and channel. Which helps the $MOSHEMT$ for greater carrier confinement

ISSN:0971-1260
Vol-22- Issue-14-December-2019

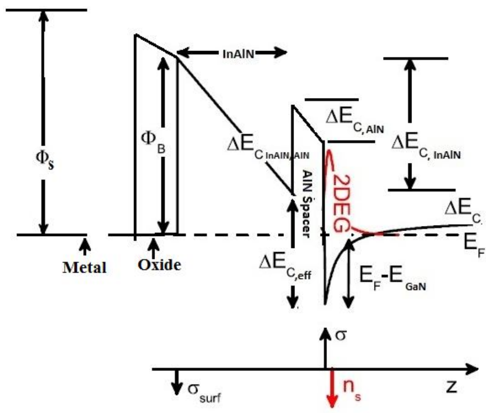


Fig. 2.Conduction band diagram for $metal/oxide/InAlN/AlN/GaN$Heterostructure.

From the energy band diagram the total conduction band offset can be written as follows:

$$\Delta E_{c,eff} = \Delta E_{c,AlN/GaN} + \Delta E_{c,AlN} - \Delta E_{c,InAlN/AlN} \qquad (1)$$

The sheet charge carrier density model in the $2DEG$ for$AlGaN/GaN$interface for all regimes (weak, moderate and strong inversion) as follows [23]:

$$n_s = DV_t\left\{ln\left[exp\left(\frac{E_f - E_o}{V_t}\right) + 1\right] + ln\left[exp\left\{\frac{E_f - E_1}{V_t}\right\} + 1\right]\right\} \qquad (2)$$

Where E_f fermi energy, E_o and E_1 are first and second sub band respectively. $D = \frac{4\pi m^*}{h^2}$is conduction band density of states of $2D$ system. $m^* = 0.22m_e$is electron effective mass of GaN.Where h is the planck constant and m_e is the free electron mass.

3. Result and Discussion

In this work, we have demonstrated the performance of $In_{0.17}Al_{0.83}N\ /AlN/GaNMOSHEMT$ device with $In_{0.15}Ga_{0.85}N$ back barrier by using Silvaco ATLAS$TCAD$ tool. In Fig.1 we discussed about $MOSHEMT$ device structure with various layer. In Fig.2 with the help of conduction band diagram, we discussed about the improvement in two dimensional electron gas ($2DEG$) by introducing AlN spacer between the barrier and channel. Fig.3 shows the variation of sheet carrier density n_s with $InAlN$ barrier thickness. From this plot, we observed that the higher the value of $n_s$for $MOSHEMT$for higher the thickness of $InAlN$ barrier layer.The drain current variation with drain voltage is shown in Fig.4. The gate voltage is sweeps from $0V\ to -7V$. The maximum drain current I_d of $1.8\ [A/mm]$ is achieved at gate source voltage$V_{gs} = 0V$.The transconductance variation with gate-source voltage is shown in Fig.5. The peak transconductance (g_m) of$530\ ms/mm$is obtained at

ISSN:0971-1260
Vol-22- Issue-14-December-2019

$V_{ds} = 4V\ and\ V_{gs} = -3V$. The variation of current gain cut-off frequency with gate-source voltage is depicted in Fig.6. The highest cut-off frequency of $300\ GHz$ is recorded.

To analyze the leakage current mechanism, PF emission model is considered above room temperature. Fig.7. Shows the $TCAD$ Simulation result of $I_g/I_d - V_{gs}$ characteristics of $In_{0.17}Al_{0.83}N\ /AlN/GaN MOSHEMT$ with gate length and width of $30\ nm\ X\ 50\ \mu m^2$ in log-scale plot. The on/off drain current ratio $> 10^7$ is obtained. The combination of $InAlN$ barrier layer with $InGaN$ back barrier suppresses the short channel effects in our proposed device structure Fig.8.A $0.3\ V$ threshold voltage roll-off is observed when the gate length reduced from $230\ nm\ to\ 70\ nm$. However, the rapid reduction in the threshold voltage for below 50 nm gate length showing the evidence of short channel effects suppression in the device.

Fig.9. shows the variation in current gain cut-off frequency with different gate length of $In_{0.17}Al_{0.83}N\ /AlN/GaN MOSHEMT$ device. From this plot we can clearly say that the drastic reduction in the gate length results in greater current gain cut-off frequency.

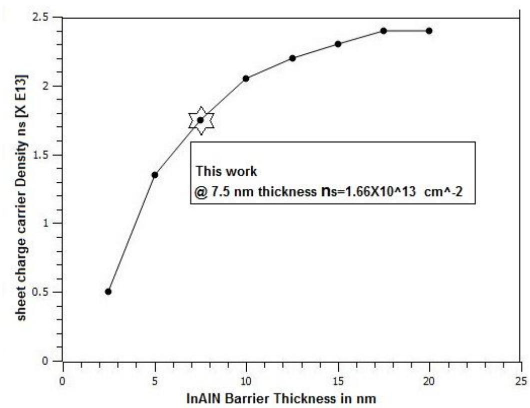
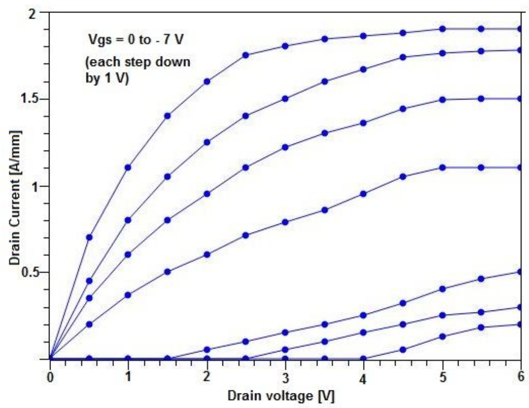


Fig. 3. Variation of sheet charge density n_s with respect to $InAlN$ barrier thickness.



ISSN:0971-1260
Vol-22- Issue-14-December-2019

Fig.4. $I_d - V_d$ characteristics of $Al_2O_3/In_{0.17}Al_{0.83}N\ /AlN/GaNMOSHEMT$ with gate length and width of 30 $nm\ X$ 50 μm^2.

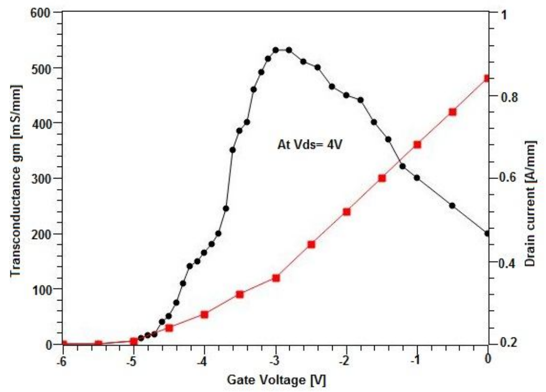


Fig.5. The variation of transconductance and drain current with various values of gate voltage for the device $Al_2O_3/In_{0.17}Al_{0.83}N\ /AlN/GaNMOSHEMT$ with gate length and width of 30 $nm\ X$ 50 μm^2.

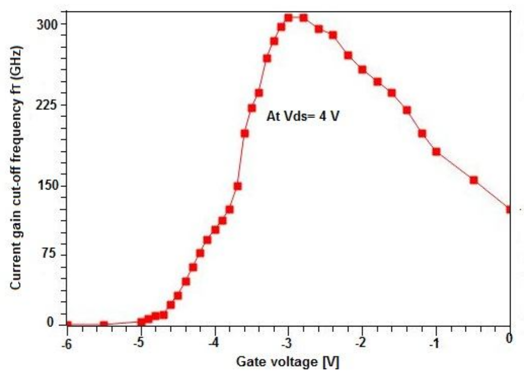


Fig.6. The variation of current gain cut-off frequency with various values of gate voltage for the device $Al_2O_3/In_{0.17}Al_{0.83}N\ /AlN/GaNMOSHEMT$ with gate length and width of 30 $nm\ X$ 50 μm^2.

ISSN:0971-1260
Vol-22- Issue-14-December-2019

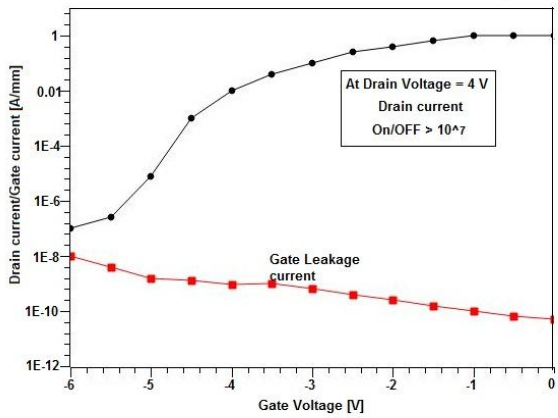


Fig.7. $TCAD$ simulation of $I_d/I_g - V_{gs}$ of $Al_2O_3/In_{0.17}Al_{0.83}N/AlN/GaN MOSHEMT$ with gate length and width of 30 nm X 50 μm^2 in log plot.

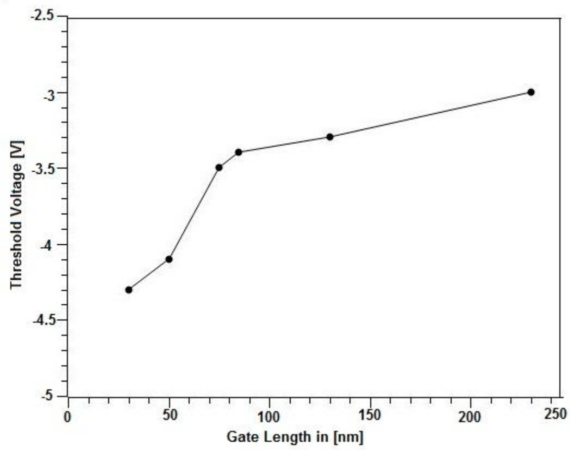


Fig.8. $Threshold\ voltage\ variation\ with\ gate\ length$ of $Al_2O_3/In_{0.17}Al_{0.83}N/AlN/GaN MOSHEMT$.

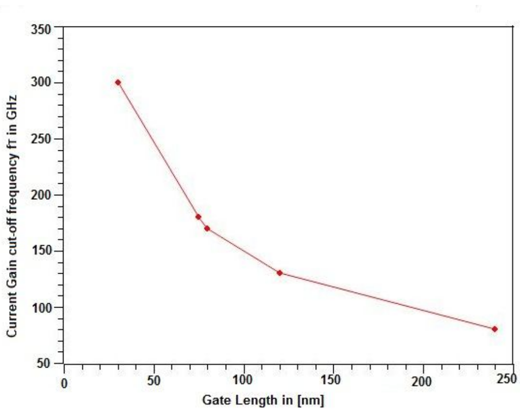


Fig.9. Variation of Current gain cut-off frequency with gate length of $Al_2O_3/In_{0.17}Al_{0.83}N/AlN/GaN MOSHEMT$.

ISSN:0971-1260
Vol-22- Issue-14-December-2019

5. Conclusion

DC and Microwave characteristics of of $In_{0.17}Al_{0.83}N/AlN/GaN MOSHEMT$ with $InGaN$ back-barrier. The device future is heavily $n + GaN$ doped source/ drain regions which reduce the source and drain contact resistance and this helps to increase the speed of the device. $30\ nm\ MOSHEMT$ exhibits a current gain cut-off frequency (f_t) of $300\ GHz$. The outstanding high frequency performance is achieved by reducing the parasitic associated effects by using $n + GaN$ regrown ohmic source and drain contacts. The current driving capability of the proposed $HEMT$ is improved ($I_{ds} = 1.8\ A/[mm]$) by $In_{0.15}Ga_{0.85}N$ back-barrier which reduces short channel effects and better electron confinement in $2DEG$ region. This property makes the $InAlN/AlN/GaN\ MOSHEMT$ device for high RF applications.

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