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AN INVESTIGATION OF NOVEL CHARACTERISTICS OF ULTRATHIN $Al_{0.2}Ga_{0.8}N$/GaN MOSHEMT HAVING 20nm GATE LENGTH AND SiO_2 GATE DIELECTRIC

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ABSTRACT
In this paper the novel attributes of an ultra thin, high speed and high power sub nanometre AlGaN /GaN Metal Insulator Semiconductor High Electron Mobility Transistor (MISHEMT) has been depicted. The enhancement mode device displays a V_{th} of 2.87 V at a V_{ds} of 8V. Along with the complete DC analysis, CV characteristics using small signal analysis and 2DEG transport phenomenon are also portrayed. The best chosen gate dielectric for this highly scaled device was decided as SiO_2 for its superior material properties such as high breakdown field, high band gap and high dielectric constant. The results obtained using ATLAS tool in SILVACO TCAD show that the device has promising potential to become a high speed, high power RF amplifier.

I. INTRODUCTION

Development of gate insulators for GaN-based semiconductors has been the active topic of research for high frequency device researchers for the last decade or so. Analog applications of HEMTs are mainly limited by gate-drain breakdown mechanism as well as by forward bias current drawn by Schottky barrier gate [1, 2-6]. A number of methods have been utilized for finding a possible solution to the problem among which one is increasing the channel doping resulting in higher ON current but for the other hand it decreases mobility due to increased lattice scattering mechanisms. It also decreases the gate breakdown voltage to some extent as found in a lot of previously conducted experiments. Moreover, it was also tried to alter the donor AlGaN layer doping from uniform to delta, as an effort to combat problems like low breakdown voltage, trapping effects and extremely high Gate leakage [3]. However, the resistivity of an undoped AlGaN layer can’t achieve true MIS like gate characteristics. As, a result growing an insulator over the AlGaN layer under Schottky Gate attributes to MIS structure which led to further improvement of HEMT’s performance. The most challenging problem in GaN based High Electron Mobility Transistor (HEMT) has been the Gate leakage which has been resolved by the use of GaN metal–insulator–semiconductorHEMT (MISHEMT) having Schottky Gate and thin insulator film as Gate dielectric.

The Metal Insulator Semiconductor (MIS) gate structure with the introduction of high dielectric constant (high-k) materials as a gate dielectric represents one of the most promising ways to achieve viable power electronic devices. High microwave-noise performance can also be expected in MISHEMT’s due to the low gate-leakage current, thereby resulting in low gate-shot noise. Moreover, due to higher drain current because of increased Gate voltage swing their RF power output is also higher and are considered as the ideal replacements of HEMT’s as the next generation variable gain RF amplifier devices. Large conduction band discontinuity, thereby resulting in increased carrier confinement are the main reasons behind this higher value of sheet carrier concentration.GaN based devices are also suitable candidates for high temperature applications as they possess a high critical electric field, high current density and lower carrier generation rate by thermal activation.

The 2-DEG, formed closer to the heterointerface in AlGaN/GaN HEMTs is mainly determined by the piezoelectric and spontaneous polarizations, which in turn, is controlled by the alloy composition (Al content) of $Al_xGa_{1-x}N$ barrier [1, 2, 4-10]. An increase in Al mole fraction of $Al_xGa_{1-x}N$ donor layer leads to further improvement in charge carrier confinement and also cause larger 2-DEG density and higher breakdown fields.Al_2O_3 has been chosen as the Gate dielectric because compared to other dielectrics that had been tried as Gate insulator in MISHEMT’s such as SiO_2, Si_3N_4, Ga_2O_3 and HfO_2; SiO_2 has a high bandgap (9.0 eV),high breakdown field (600 MV/cm) and high relative dielectric constant (3.9). The larger band gap of 3.4 eV in GaN in comparison with 1.4 eV of GaAs causes GaN based devices to exhibit a high breakdown field (of 2×10^6 V/cm in comparison with 4×10^5 V/cm of GaAs), good thermal conductivity (of 1.3 W/cm in comparison with 0.5 W/cm of GaAs) and high peak and saturation carrier velocities (of 3×10^7 cm/s and 2×10^7 cm/s respectively in comparisonwith 2×10^7 cm/s and 1×10^7 cm/s in GaAs). Strong lattice polarization effects in GaN based materials due to spontaneous and piezoelectric polarizations, further leads to the formation of a high sheet carrier concentration (i.e. 10^{12}-10^{13} cm^{-3}) [5].

II. MOS-HEMT STRUCTURE

The proposed device consists of a 20nm unintentionally doped GaN layer over a 4H SiC substrate. An un-intentionally doped AlGaN donor layer of 2 Å vertical thickness is present over the GaN layer. We use the SiO_2 thin film as the gate dielectric of an AlGaN/GaN MISHEMT. The Gate length L_g is 20nm and Gate width W_g is 5nm. The Gate drain distance L_{gd} is 30nm.Si_3N_4 layer is deployed near the Gate electrode with 30nm length.Si_3N_4 acts as a surface passivation and also prevents underlying layers from getting oxidized unintentionally [6].

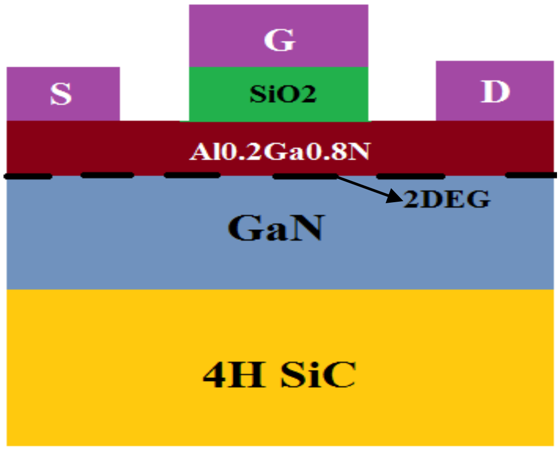

Fig.1: Cross section of proposed AlGaN/GaN MISHEMT

Table 1
Structural parameters of the device

Gate length (L_g)	20 nm
Drain Gate distance (L_{gd})	30 nm
Si_3N_4 Passivation	30 nm
SiO_2	1 Å
AlGaN donor layer	2 Å
GaN buffer layer	20 nm

III. RESULTS AND DISCUSSIONS

III. 1 Output Characteristics

$$I_{ds} = W\mu q n(x)\frac{dV(x)}{dx} \qquad (1)$$

where, W is the channel width, n(x) is the electron density and μ is the mobility. If we take the entire channel length as L and we apply the boundary conditions as, V(x = 0) = $R_s \times I_{ds}$ and V(x = L) = $V_{ds}-(R_s+R_d)\times I_{ds}$, Where $R_s$and $R_d$are the source and drain contact resistances and V_{ds} is the bias voltage applied to the drain with respect to the source. Therefore

$$I_{ds} = \int_{x=0}^{x=L} W\mu q n(x)\frac{dV(x)}{dx}. \qquad (2)$$

If we want to re write the equation in saturation regime, then we can write

$$I_{ds} = \frac{\mu_n C_s}{2L} W (V_{gs} - V_{off})^2 \qquad (3)$$

where $V_{off} = V_{bi} - V_{po} - \frac{\Delta E_c}{q}$ and $V_{po} = \frac{9 N_d a^2}{2\varepsilon_r \varepsilon_o}$.

We calculated the variation in I_{ds} at V_{gs}=4V, 4.4V, 4.5V, 4.9V, 5V. The current is seen to be increasing with increasing V_{ds} and the saturation current is 315 mA for a V_{gs} of 5V.

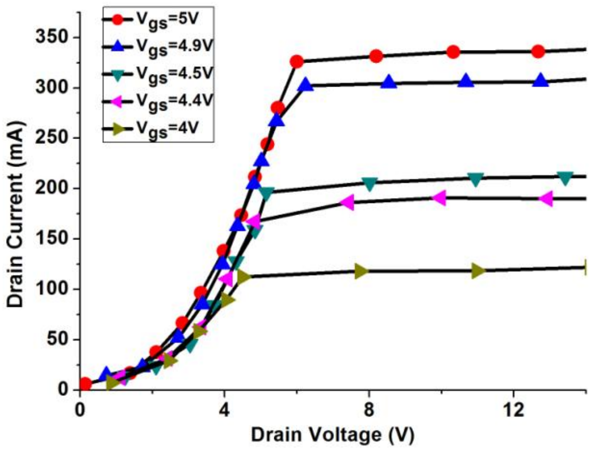

Fig.2: Calculated variations of I_{ds} with respect to V_{ds} at different values of gate to source voltage (V_{gs})

The threshold voltage is an important parameter because it is a measure of when the HEMT device will begin to conduct. V_{th} can be expressed as,

$$V_{th} = \phi_B - \Delta E_c - \frac{q N_D d^2}{2\varepsilon_i} \qquad (4)$$

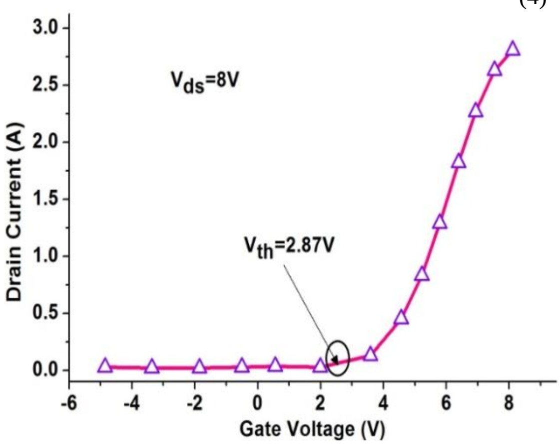

Fig.3: Calculated variation of drain current and gate

leakage current with respect to V_{gs}.

The proposed device displays a V_{th} of 2.87V at a V_{ds} of 8V as can be seen in Figure 3.

$$g_m = \frac{\Delta I_d}{\Delta V_{gs}} = \left(\frac{\Delta n}{\Delta V_{gs}}\right) ev + \left(\frac{\Delta v}{\Delta V_{gs}}\right) ne \quad (5)$$

Here Δn describes the contribution of carrier concentration change and the second term gives the change in velocity of electrons net contribution to the total transconductance of the device.

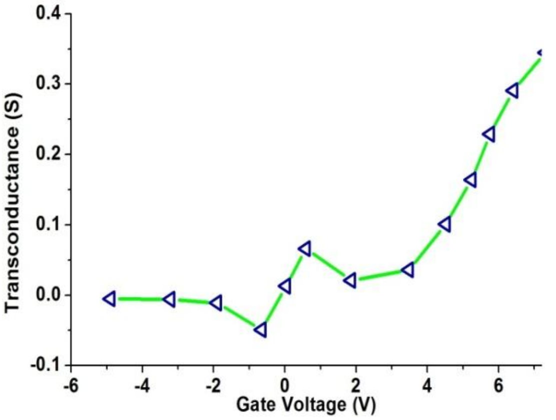

Fig.4: Calculated variation of transconductance w.r.t V_{gs} at a drain bias of 8V.

From figure 4 it can be seen that the ultra scaled device shows a $g_{m.max}$ (Maximum transconductance) of 0.31S at a V_{ds} of 8V.

III. 2. 2DEG Transport

Two dimensional electron gas or 2DEG is an one dimensional quantum well formed at the hetero interface when a wide band gap semiconductor is grown over a narrow band gap material. The growth of AlGaN material over GaN provides a unique polarization field such as spontaneous and piezoelectric polarization apart from the 2DEG formation, which results in a higher potential barrier at the backside of the 2DEG.

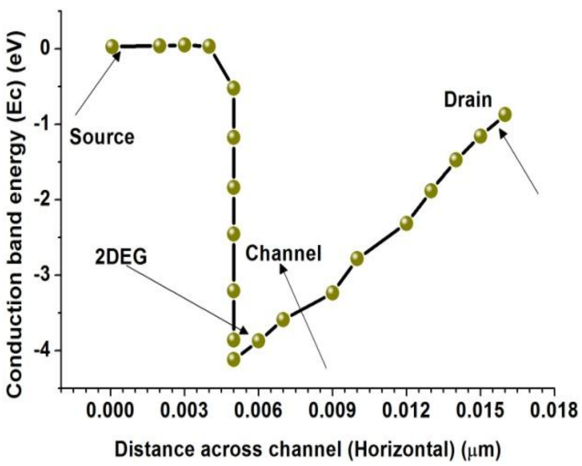

Fig.5: Calculated variation of conduction band energy with distance for the proposed device.

It can be seen from Fig. 3 that the formation of 2DEG is observed at a distance of 50Å from the surface of the device. The carrier confinement, is further improved due to a deeper notch or quantum well which causes a significant decrease in gate leakage.

In figure 6 the simulated electric field distribution along MISHEMT surface is shown:

$$E = -\frac{dV}{dx} \quad (6)$$

The peak electric field at the drain side is seen to be as high as $1.35\text{x}10^7$ V/cm where the breakdown occurs.

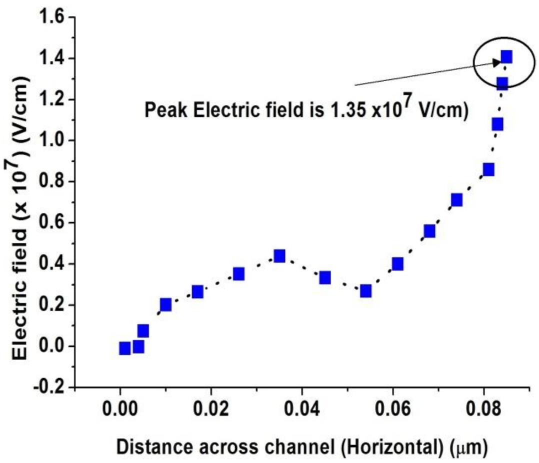

Fig.6: Calculated variation of electric field with distance for proposed device

In figure 7 the variation in surface potential with distance is shown. The drain bias is found to be high as expected with the source terminal connected to round.

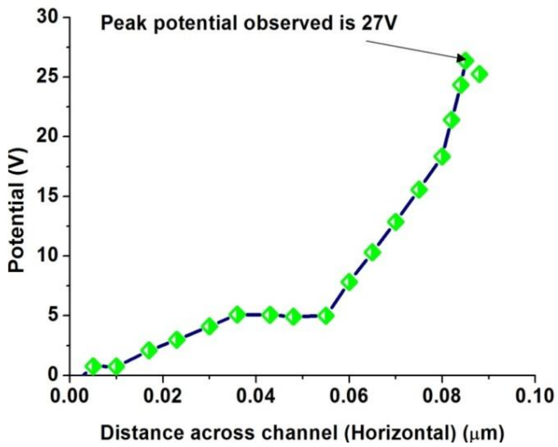

Fig.7: Calculated variation of surface potential with distance for proposed MISHEMT

The effective drift velocity of electrons in the channel

$$v_d = \mu E \quad (7)$$

was also found out. As observed from figure 5 due to higher bias at drain side the peak electric field at which the device breakdown occurs is found to be very high.

The higher electric field results in a higher electron drift velocity which is clear from Eq. 7. The peak velocity as observed from figure 8 is 7.1×10^{9}cm/sec and velocity at the 2DEG is about 2.4 $x10^{9}$cm/sec. The higher drift velocity resulted from higher carrier mobility indicates higher switching speed of the device which is very much essential in various high speed applications like 4G,mobile base stations, wi-fi etc [8].

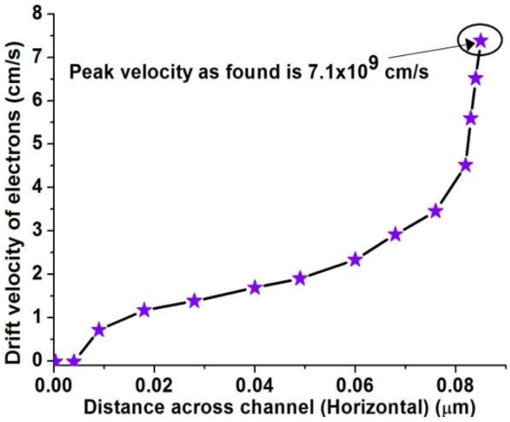

Fig.8: Calculated variation of electron drift velocity with horizontal distance across the channel for the proposed MISHEMT.

The variation of electron concentration with distance across channel is also found for the proposed device. From Figure 9 it can be observed that the electron concentration in the 2DEG is of the order of $1.5x10^{17}$ cm^{-3}. It gradually decreases from source to drain side and the peak concentration is of the order of $1.1x10^{19}$. The increased carrier concentration in the 2DEG indicates a higher density of total current in the proposed device [7].

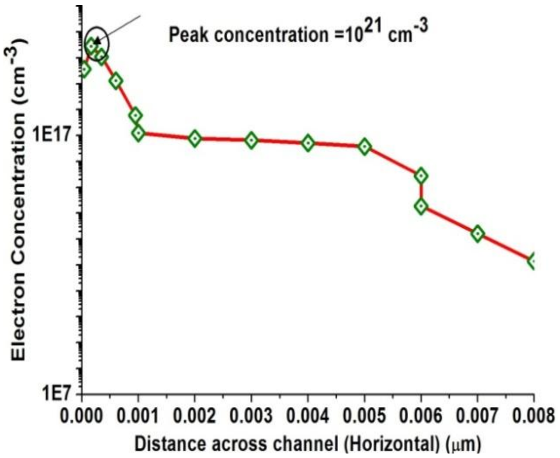

Fig.9: Calculated variation in electron concentration with horizontal distance along the channel in log scale

III. 3. Small signal characteristics

For a healthy operating range the Schottky junction in AlGaN/GaN HEMT system, (metal-AlGaN) is reverse biased and the AlGaN layer is fully depleted. This makes the system a non-linear capacitor as only displacement current is present. The displacement current is due to the variation in the 2-DEG and the GaN layer charge with V_{gs}. The expression for channel capacitance, C_{ch} is

$$C_{ch} = 2v_{th}C_{gs}\left\{\frac{\frac{V_j'}{V_j}(G(V_{off})+\beta V_{th}(V_h-1))}{(G(V_{off})+\beta V_{th}(V_{-h}-1))^2}\right\} - 2V_{th}C_{gs}\left\{\frac{\ln(V_j)(G'(V_{off})+\beta V_{th}V_{-j}'}{(G(V_{off})+\beta V_{th}(V_{-h}-1))^2}\right\} \quad (8)$$

and,

$$G(V_{off}) = \frac{1}{f(V_{off})}$$

where,

$$f(V_{off}) = \frac{V_{off} + V_{th}(1-\ln(\beta V_{gon})) - \frac{\kappa_0}{3}\left(\frac{C_{gs}V_{off}}{q}\right)^{2/3}}{V_{off}\left(1+\frac{V_{th}}{V_{gon}}\right) + \frac{2\kappa_0}{3}\left(\frac{C_{gs}V_{off}}{q}\right)^{2/3}}$$

$$V_{gon} = \frac{V_{off}\phi_n}{\sqrt{V_{off}^2 + \phi_n^2}}$$

$$\beta = \frac{C_{gs}}{qDV_{th}} \qquad \phi_n = \frac{e}{\beta}$$

$$V_h = 1 + e^{\frac{V_{off}}{2V_{th}}}$$

and

$$V_{-h} = 1 + e^{\frac{V_{-off}}{2V_{th}}}$$

$$V_h' = \frac{dV_h}{dV_{gs}}$$

and

$$V_{-h}' = \frac{dV_{-h}}{dV_{gs}} .$$

When the 2-DEG is quite strong the GaN layer charge and C_{gs} in such a case is equal to the gate-channel capacitance C_{ch}, which is $qdns/dV_{gs}$.

So, from (8) we can write

$$C_{ch} = C_{gs} = q\frac{dn_s}{dV_{gs}} . \quad (9)$$

The variation in gate source capacitance with gate voltage is shown in figure 10.

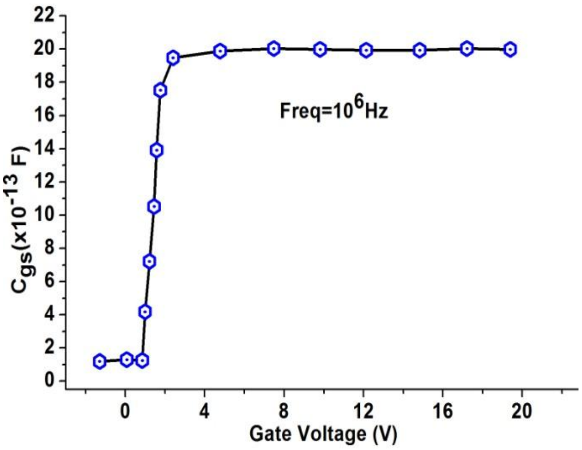

Fig. 10: Calculated variation of gate source capacitance with gate voltage.

Now,

$$C_{gg} = \frac{dQ_g}{dV_g} \quad (10)$$

and

$$G_{gg} = \frac{dQ_g}{dV_g} \quad (11)$$

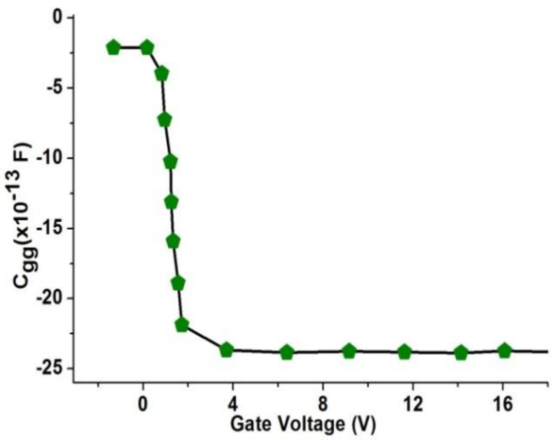

Fig. 10: Calculated variation of C_{gg} with gate voltage V_{gs} at 1 MHz frequency.

We calculated the values of small signal capacitances and conductance's for our proposed device. The value of C_{gg} was found to be $23.47\text{x}10^{-13}$ F at a V_{gs} of 2.3 V and the variation of C_{gg} with gate voltage is shown in figure 11.

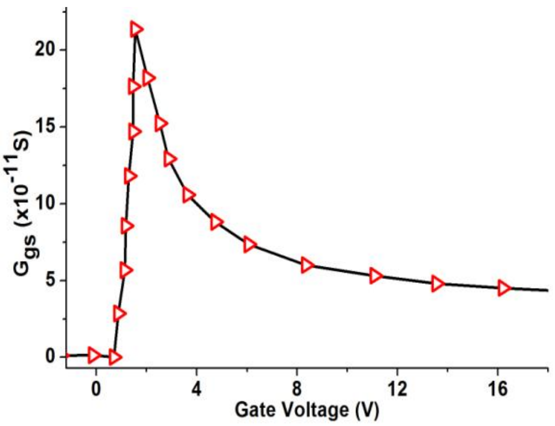

Fig. 11: Calculated variation of G_{gs} with gate voltage V_{gs} at 1 MHz frequency.

The variations in small signal parasitic components in the form of small signal conductance's are portrayed in Figures 11 and 12 respectively. The device also possess very low conductance's which is subsequently evaluated as 23×10^{-11} S at a Gate bias of 2.7 V for G_{gs} and $0.7\text{x}10^{-10}$ S for G_{gg} at V_{gs} of 2 V respectively.

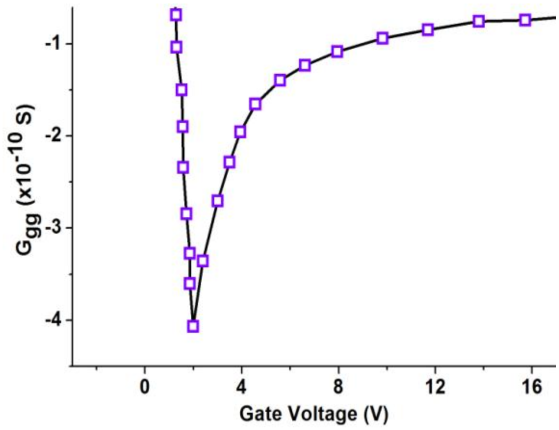

Fig. 12: Calculated variation of G_{gg} with gate voltage V_{gs} at 1 MHz frequency.

Table 2
Device parameters

V_{th}	2.87 V
C_{gs}	$19.2\text{x}10^{-13}$ F
C_{gg}	-2.71×10^{-13} F
G_{gg}	$-0.7\text{x}10^{-10}$ S
G_{gs}	$23\text{x}10^{-11}$ S
I_{dsat}	320 mA
g_{max}	0.33 S

IV. CONCLUSION

Novel characteristics of a ultra scaled 20nm AlGaN/GaN MOSHEMT has been studied. The proposed device is found to have high velocity of carriers in the channel and also high value of peak electric field in the order of 10^7V/cm apart from extremely low parasitic capacitance and conductance of the order of a few hundreds of Femto

Farads. The DC characteristics as well as C-V characteristics using small signal analysis are also presented in this paper. The results are quite satisfactory owing to all the short channel effects which are induced due to short channel length and short source to gate distance of 30 nm.The device can be utilized as a high speed component in vital speed based applications like 4G and mobile base stations etc. [8, 9].

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