Design and Parametric Analysis of GaN on Silicon High Electron Mobility Transistor for RF Performance Enhancement

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Abstract
The need of performance enhancement at the RF and millimeter wave is highly desirable to eliminate the heating effects and power dissipation. Silicon substrate found to be a suitable candidate which reduces about 70% channel temperature than sapphire. To achieve high performance, a GaN on the Silicon substrate high electron mobility transistor is designed and its various performance parameters are analyzed by varying the design specifications. Moreover, the problem of blocking voltage improvement is resolved by epitaxial design approach. Since, threshold voltage, doping-level, work-function of gate material and channel length are considered as some of the important parameters while device modeling. Therefore, the impact of these parameters is examined and analyzed to enhance the performance and reliability of the device for RF applications. The performance parameters like trans-conductance, drain current curves are plotted at different state of device physical and electrical parameters. Results exhibits maximum value of transconductance \( g_m = 13 \, \text{m-mho} \), minimum gate capacitance \( C_g = 0.5 \, \text{pF} \), whereas \( V_{th} \) is varied between \( -0.25 \, \text{V} \) to \( 0.25 \, \text{V} \).

Keywords GaN on silicon · High electron mobility transistor · Gate work-function · Doping effects · 2 dimensional electron gas

1 Introduction

With the continue down scaling of the transistor leads to switching speed and its efficiency losses in terms of short channel effects and hence renders large power dissipation. Form the past two decades, all the device are reliable on the silicon material for power device, however the silicon has some limits on handling high power devices [1–4]. In some domains, the power electronic devices are reaching to its fundamental limits, where the design and manufacturing unit facing the challenge in terms of operating voltage, temperature and frequency [5, 6]. As alternatives of sapphire substarte, researchers move to Silicon substrate for wide bandgap materials such as GaN or SiC. The related semiconductor like GaN/AlGaN/InGaN on Silicon substrate have been continuously recorded as a promising device for the next generation of high frequency, high electric field with wide temperature range [7, 8]. In particular, hetero-structure base on wide band gap materials like AlGaN/GaN are preferred in the channel interface to achieve the high mobility of the carriers [9, 10]. This happens due to its distinctive characteristics due to wide band gap, which yields high breakdown field with high drain current [11–15]. The high electron mobility transistor device commonly used for RF applications likewise in radar, cellular telecommunication, radio astronomy and the satellite broadcasting. These applications employ the low noise with high frequency and high critical electric field [16–18]. The high electron mobility transistor exhibits the three times higher power density than MOSFET which over all reduces the chip area in terms of their output performance. One of the special characteristics of the high electron mobility transistor is the formation of the two-dimensional electron gas molecule where the carrier mobility is extremely high [19, 20]. The important feature of AlGaInGaN based high electron mobility transistor structure is basically the formation of electrons confinement at the interface to from two dimensional electron gas (2DEG). The conventional AlGaInGaN hetero-structure suffers from high \( R_{ON} \) which owns the 2DEG density in gate-
source and gate-drain region, however low $R_{ON}$ can be achieved by polarization-induced high density and 2DEG mobility at the interface. Many other optimal approaches used for lowering the $R_{ON}$, like 2-DEG depletion can be attained by using a thin AlGaN barrier layer with low Aluminum concentration [21]. The 2DEG cannot be easily depleted at zero bias in schottky gate contact [22, 23] but due to the band-gap, the critical field strength is inversely proportion to the drift region thickness and hence, the ON-state resistance is lower [24].

In this paper, the response of the Gallium nitride (GaN) on Silicon substrate high electron mobility transistor is designed and being analyzed for the high voltage, high switching power for regulation of RF application at high temperature. The operation is associated with efficiently power switching in which the OFF-state voltage is highly blocked with minimum leakage current and ON state resistance. In order to operate at high voltage, these devices can be limited by the chain factor like subthreshold voltage and device scaling. However, the blocking voltage improvement is a complex problem which can be resolved by, epitaxial design, device structure and its scaling with favorable fabrication technology.

2 Device Structure and Simulation Framework

In high electron mobility transistor, the presence of a conduction band offset at the interface of two different bandgap materials produces two-dimensional electron gas (2DEG). The potential well is formed on the material side of the lower bandgap. Over the GaN side of the device, 2DEG is generated when higher bandgap material (AlGaN) develops on lower bandgap material (GaN). Due to ease of growth in the of GaN over silicon substrate with low cost and large size will make its choice better over the SiC and other material. Additionally, in heterostructure, GaN employed with polarization field in which two different layers of different bandgap are come together for single growth. However, this will create a difference in electric field and surface potential at heterojunction. Figure 1 show the schematic structure of AlGaN/GaN in which AlGaN is common in between source and drain electrodes. The doped high electron mobility transistor structure with AlGaN doped layer will help in improving the polarization across the layer. This enhances the transport characteristics by imprisonment of electron within the channel.

If the induced charge is positive, electrons will tend to compensate the induced charge resulting in the formation of the channel. The channel electrons in the high electron mobility transistor are referred to as a Two-Dimensional Electron Gas because they are trapped in a quantum well in a very restricted spatial region at the hetero-interface (2DEG) [25].

The equivalent device design parameters of high electron mobility transistor used during simulation work are shown in Table 1.

The simulation of the device is executed using Silvaco-ATLAS tool [26]. Drift-diffusion model which is based on the Boltzmann’s transport theory along with two advance transport models namely hydrodynamic transport model and energy balance transport model are considered while simulation to sustain the carrier temperature instead of the local electric field. Moreover, polarization model of GaN, fermi-dirac model, SRH model, low and high electric field models, and Selberherr’s impact ionization model are included during the simualtiing the device structure. A detailed analysis of the proposed device of AlGaN/GaN high electron mobility transistor is given with the structure dimensions. More attention towards thermal conduction and Schottky-gate reverse bias tunneling are carried out. The affecting parameters like doping concentration, channel length, gate work-function, transconductance and capacitance characteristics are observed by varying $V_{GS}$.

![Fig. 1 Schematic diagram of GaN on Silicon substrate high electron mobility transistor (high electron mobility transistor) TCAD tool structure](image)

| Parameter Used    | Length | Width  |
|-------------------|--------|--------|
| Device            | 6 μm   | 3 μm   |
| Channel           | 3 μm   | 0.03 μm|
| AlN 2DEG          | 6 μm   | 0.05 μm|
| Electrode Gate    | 1 μm   | 0.05 μm|
| Electrode Drain   | 1 μm   | 0.035 μm|
| Electrode Source  | 1 μm   | 0.035 μm|
| Silicon Substrate | 400 μm | 0.095 μm|
2.1 Polarization Effect

AlGaN/GaN have special characteristics which holds the two-dimensional electron gas without doping process. This happens due to piezoelectric properties and spontaneous polarization which is found in crystal structure of III-nitrides and can be represent by Fig. 2. The high tendency of atom to attract an electron bonding which is of tetrahedrally structure between III-nitrides elements, results in spontaneous polarization [27, 28]. In the crystal structure, the epitaxial GaN layer was grown at normal to (0001) position. Due to lack of inversion symmetry, it will result in spontaneous polarization in <0001> direction.

In comparison to GaN, the AlGaN is very thin in AlGaN/GaN in high electron mobility transistor structure, this is done due to lattice mismatch which need to be equal and constant. The piezoelectric polarization of the interface field can be expressed as:

\[ P_{PE} = 2\varepsilon_a \left( e_{31} - \frac{\varepsilon_{33} c_{13}}{\varepsilon_{33}} \right) \]  

The above equation is directly proportional to lattice constant(\( \varepsilon_a \)) and piezoelectric coefficient of AlGaN/GaN in high electron mobility transistor structure. The average polarization effect caused by AlGaN/GaN, where GaN consist negative polarization field and AlGaN consist of spontaneous and piezoelectric polarization effect \( (P_{SP}) \) [29, 30]. Since the spontaneous polarization \( (P_{PE}) \) is greater in comparison to the GaN, at the AlGaN/GaN interface charges.

\[ \sigma = (P_{SP,AlGaN} + P_{PE,AlGaN}) - P_{SP,GaN} \]  

Both the Eqs. 1 and 2, will conclude as a fixed permanent creation of a 2DEG polarization.

2.2 Parasitic Effects

The parasitic effects are also known as trapping effects, as the trap charges (electron and holes) are lie between the channel and the gate contact. The effect induces due to generation of available energy levels in energy bandgap of semiconductor, which are generally related to the lattice mismatched of different materials connected to each other [31]. In the ON condition of the device, it limits the active charges with respect to time and stress, which futher causes an effect to the static and dynamic performance of the device. In order to eliminates these trap charges, we need to apply operative electric field. This collision of trap and non-trap charge will make device performance degrading [32]. The two main parasitics effects are kink and current collapse effect. The kink effect are more effective at low drain voltage at degrade the ON drain current performance. However, this can be overcome by the increasing the voltage \( V_{ds} \) (drain-source voltage), resulting the pinch off voltage to be shifted towards more negative voltages and which impulsively raise the drain current. The disturbed DC current will effect on ON resistance \( (R_{on}) \) and transconductance \( (g_m) \). The upper trap charges of bandgap are acceptor and lower trap charges are donor. The position of the trap charges will play a vital role in the device performance. They are filled with the narrow AlGaN layer, in order to kept the trap charges level below the Fermi level. Due to narrow barrier, the charges will trap and pused hardly by the strong polarization effect of AlGaN. The emmision rate relation will the \( V_B \) can be exterated by using three given three Eqs. 3, 4, and 5. Initially consider the emission rate to be calculated by Arrhenius equation at random temperature [33].

\[ e = AT^2 \exp \left( \frac{E_F}{kT} \right) \]  

Where \( T, k \) and \( E_F \) are temperature, Boltzmann constant and Fermi energy level. The barrier (\( \beta \)) decreases due to high electric field with respect to square root of applied electric field given by Eq. (4).

\[ \Delta \eta_{PF} = \left( \frac{q^3}{\pi} \right)^{1/2} \sqrt{F} = \beta \sqrt{F} \]  

Here, \( q \) is a electron charges and \( \varepsilon \) represent the dielectric constant. The ionization energy of the field can be represented by:

\[ E_i(F) = E_i(0) - \beta \sqrt{F} \]  

The \( \Delta E_C \) is energy band gap difference between AlGaN and GaN, where at interface of AlGaN and GaN, \( E_i(F) \) is difference conduction band and fermi level. The current collapse near drain region occur near the surface of AlGaN layer resulting the channel depletion.

Figure 3 is given below to understand energy band diagram of the high electron mobility transistor, there is given three different regions of Metal, AlGaN and GaN. Quantum
tunneling valley happens in conduction band, basically the reason behind that being the tunneling of electrons present in two-dimensional electron gas layer.

According to energy band diagram observations there is almost same energy required in both the cases to move one electron from valance band to conduction band. So finally proposed device structure and ON state band diagram of the high electron mobility transistor has been drawn in above part and analysis has been done behind them. The conduction path was created by joining layer of AlGaN/GaN in high electron mobility transistor structure causes positive net charges, which pull the conduction band towards downwards. The positive change density is now attracted by electrons and trap at potential well at triangular shaped. Moreover, the polarization shifted net negative charges which now dragged the conduction band upwards. The confined electron will create 2-DEG at the GaN channel junction. The expression for 2DEG at the GaN channel can be described as:

\[
\begin{align*}
    n_x = & \left( \frac{\sigma_{\text{int}}}{q} \right) \left( \frac{E_{\text{F}}}{q^2 \Gamma_{\text{AlGaN}}} \right) \left( q \varphi_b + E_F + \Delta E_C \right) \\
    \text{where,} \quad & q \text{ is the electron change,} \quad \sigma \text{ is the AlGaN/GaN sheet charges at the interface,} \quad E_F \text{ is the fermi energy level,} \quad \varphi_b \text{ is the gate contact Schottky barrier height which can change the threshold voltage of the device.} \quad \Delta E_C \text{ represent the energy bandgap between AlGaN and GaN, where dielectric constant effects the breakdown field strength. Due to different value energy band gap of AlGaN and GaN, lattice mismatches occur which can be compensate by its thickness. Table 2 represent different properties of high electron mobility transistor structure which are arose by hetero structures, which generates a potential well for electron as a channel for easy movement of electron and forms 2DEG.}
\end{align*}
\]

3 Results and Discussion

In order to describe the parameter variation effects on the characteristics of an AlGaN–GaN high electron mobility transistor, the most important characteristics are discussed below, and with the help of these characteristics we analyze the fundamental concepts behind them.

3.1 Impacts on \( I_d-V_{GS} \) Characteristics

Figure 4 shows the DC I-V characteristics of an AlGaN/GaN high electron mobility transistor on Al2O3 substrate at various doping levels. The drain current is plotted with the gate gate voltages at the drain source voltage of 2 V. It is seen that at low level doping i.e. from \( 10^{10} / \text{cm}^3 \) to \( 10^{12} / \text{cm}^3 \) the drain current remain constant and it start increasing when doping level rises from \( 10^{13} / \text{cm}^3 \). At the doping level of \( 10^{15} / \text{cm}^3 \) maximum drain current \( I_d = 22 \text{ mA} \) is achieved.

The impact of gate work fuction (wf) on the drain current is plotted on the Fig.5. This graph is plotted keeping the constant doping level of \( 10^{15} / \text{cm}^3 \) and at the \( V_{ds} = 2 \text{ V} \). It can be noticed that on increasing the gate work function from 4 eV to 4.5 eV initially the drain current increses by 2 orders but on futher increasing the work function the drain current starts decreasing. So, the maximum drain current is observed at gate work function of 4.5 eV.

According to the above characteristics, the threshold voltage is directly proportional to the doping of the device. Threshold voltage expression is given below.

\[
\begin{align*}
    V_{TH} = & V_{FB} + 2 \varphi_F + \gamma \sqrt{\varphi_F} \\
    \gamma = & \frac{2 q \varepsilon N}{C_{ox}}
\end{align*}
\]

Now third observation has been taken that is impacts of work-function on I-V characteristics. Threshold voltage is again directly proportional to work-function of metal so the characteristics show slightly high threshold voltage compared to previous results.

\[
\begin{align*}
    V_{th} = & \text{Ideal threshold volt.} + V_{FB} \\
    \text{Where,} \quad & V_{FB} \text{ is the flat band voltage.}
\end{align*}
\]

\[
\begin{align*}
    V_{FB} = & \varphi_{\text{ms}} \frac{Q_{\text{b}}}{C_{ox}}
\end{align*}
\]

The variation of the drain current with different channel length are plotted in Figs. 6 and 7 at high bulk doping and low bulk doping respectively. The simulation is carried out at the gate work function of 4. eV and \( V_{ds} = 2 \text{ V} \). It is noticed
that at the high doping level the drain current decreases on increasing the channel length while at the low doping level the variation is less as compared to the high doping level. Threshold voltage is very small compared to the previous one because the charge in the oxide increases, that is mentioned in above Eqs. 9 and 10. It is also observed that the drain current at the low level doping is 78% lower than the drain current at high doping level.

3.2 Impacts on \( g_m - V_{GS} \) Characteristics

The trans-conductance is defined as change in drain current with respect to gate to source voltage at constant \( V_{ds} \).

\[
g_m = \frac{\partial I_D}{\partial V_{GS}}
\]  

(11)

Figure 8 shows the characteristics of \( g_m \) vs. \( V_{gs} \) at the different doping concentration of the bulk. Transconductance shows maximum at value \( V_{gs} = 1.5 \) V and at the doping level of \( 1 \times 10^{18} \) cm\(^{-3}\). Initially the the transconductance increases with increase in the doping but eventually it start decreasing when the doing level reaches to \( 1 \times 10^{18} \) cm\(^{-3}\).

For RF applications \( g_m \) should be maximum because the cutoff frequency of the device should be large and \( g_m \) is directly proportional to \( f_T \). Now the trans-conductance depends upon various parameters so the mathematical equation of the trans-conductance is given below-

\[
g_m = \mu_n C_{ox} \frac{W}{L} (V_{gs} - V_{th})
\]  

(12)

\[
g_m = \sqrt{2\mu_n C_{ox} \frac{W}{L} I_D}
\]  

(13)

Comparison between two \( g_m \) characteristics clearly shows the effect of doping concentration on the trans-conductance and it is observed that trans-conductance is inversely proportional to the doping concentration. We have observed that impact ionization increases with the decrease in the doping concentration and vice versa.

The effect of metal gate work function on the transconductance is plotted in Fig. 9. Which shows \( g_m \) is maximum at \( V_{gs} = 1 \) V for the work function of 4.5 eV, the maximum value of the \( g_m \) is obtained as 11 m mho. Eq. 12 already mentions that \( g_m \) is linear and inversely dependent on threshold voltage so it is ultimately inversely dependent on gate work-function.

The variation of the transconductance with the channel length is plotted in Fig. 10. It is seen that on increasing the
channel length the transconductance decreases because the drain current reduces with the increase in the channel length. If the channel length increases the drain current decreases because the number of electrons or electron density decreases so if the drain current gives approximate linear characteristic then the trans-conductance will be constant or saturate according to Eq. 11.

3.3 Impacts on Gate Capacitance

For RF applications, the gate capacitances; gate to source capacitance \( C_{gs} \) and gate to drain capacitance \( C_{gd} \) plays a major role while determining the device performance. Gate voltage versus gate capacitance \( C_{gs} \) and \( C_{gd} \) characteristics are shown in Fig. 11a and b respectively at different doping variations. It is seen that initially there is little variation on the \( C_{gs} \) and \( C_{gd} \) with the doping but on further increasing the doping level in th bulk both source and drain capacitance increases since the number of charge carrier increases. At the higher gate voltage its value varies in the range of 1.5 pF to 2 pF.

Figure 12 shows the variation of gate capacitance with the applied gate bias for different channel lengths. Figure 12a is drawn for gate to source capacitance while Fig. 12b is drawn for gate to drain capacitance. It is noticed that on increasing the channel length both capacitances \( C_{gs} \) and \( C_{gd} \) increase with the gate voltage. The obtained values of the gate capacitance lies in the range of 0.2 pF to 0.8 pF.

The impact of work function on the variation of the gate to source capacitance \( C_{gs} \) and gate to drain capacitance \( C_{gd} \) is plotted in the Fig. 13a and b respectively. It is observed that the both capacitances increase when the metal work function rises and their values lie in the range of 0.2 pF to 1 pF.

The cut-off frequency expression is given as-

\[
f_T = \frac{g_m}{2\pi C_g}
\]

(14)
The gain falls at high frequency and low frequency so there is a frequency range where the gain of the device is maximum. According to Eq. 14 the cut-off frequency depends on two parameters so \( g_m \) is directly proportional and overall gate capacitance is inversely proportional to cut-off frequency. Therefore, \( C_g \) should be less and \( g_m \) should be high to acquire high cut-off frequency range. If we observe the characteristic, then doping plays a major role in capacitance so in one hand, the doping of device should be less but for good conduction and for high gain the doping is required.

### 4 Conclusion

This paper presents design and comparative performance analysis of the high electron mobility transistor on silicon substrate for RF applications. The variation in the performance parameters drain current, transconductance, and total gate capacitance is analyzed by varying the various design parameters like doping level, channel length and work-function of gate material. In the proposed device a good performance with maximum \( g_m = 13 \) m-mho, minimum gate capacitance \( C_g = 0.5 \) pf is achieved. \( V_{th} \) is varied between

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**Fig. 10** \( g_m \)-\( V_{gs} \) characteristics for various channel length

**Fig. 11** (a) \( C_{gs} \)-\( V_{gs} \), and (b) \( C_{gd} \)-\( V_{gs} \) Characteristics for various doping levels

**Fig. 12** Variation of (a) gate to source capacitance \( C_{gs} \) and (b) gate to drain capacitance \( C_{gd} \) for different channel length
One characteristic is basic device parameter and other two RF characteristics are investigated.

Author Contributions All authors have equally participated in the preparing of the manuscript during implementation of ideas, findings result, and writing of the manuscript.

Data Availability Current submission does not contain the pool data of the manuscript but the data used in the manuscript will be provided on request.

Declarations

Ethical Standard The Authors accepted principles of ethical standard and they have no conflict of interest.

Informed Consent Not Applicable.

Consent to Participate Informed consent.

Consent for Publication Consent is granted.

Research Involving Human Participants and/or Animals No human and/or animal are involved to carry this work.

Conflict of Interest The authors declare that they have no conflict of interest.

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Fig. 13 Variation of (a) gate to source capacitance Cgs and (b) gate to drain capacitance Cgd for different metal gate work function

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