Temperature dependent DC characterization of InAlN/(AlN)/GaN HEMT for improved reliability

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Abstract. In$_x$Al$_{1-x}$N/AlN/GaN HEMT device performance is analysed at various temperatures with the help of physics based 2-D simulation using commercially available BLAZE and GIGA modules from SILVACO. Various material parameters viz. band-gap, low field mobility, density of states, velocity saturation, and substrate thermal conductivity are considered as critical parameters for predicting temperature effect in In$_x$Al$_{1-x}$N/AlN/GaN HEMT. Reduction in drain current and transconductance has been observed due to the decrease of 2-DEG mobility and effective electron velocity with the increase in temperature. Degradation in cut-off frequency follows the transconductance profile as variation in gate-source/gate-drain capacitances observed very small.

1. Introduction
Limitation of mature silicon technology for high power and high temperature operation paves the way for wide-band gap semiconductors like GaN, SiC etc. These semiconductors are extremely attractive for commercial and military applications because of their high power handling capabilities. Low carrier generation by thermal activation and high breakdown field in wide band semiconductor makes them excellent candidate for high temperature applications. Various heterostructures like AlGaN/GaN, InAlN/GaN, AlN/GaN, etc., are prominent for utilizing the optical and electrical properties of nitride materials. One of the key issues for high power/high temperature applications is the junction and channel temperature which affects the key device parameters like mobility, saturation velocity etc. thus affecting the device characteristics and reliability. Therefore, an in-depth study of device operation at high temperature is required for efficient thermal management and to improve the device reliability. As compared to conventional Al$_x$Ga$_{1-x}$N/GaN HEMT, In$_x$Al$_{1-x}$N, $x$~0.19 barrier layer on GaN eliminates the strain induced reliability issues and exhibits a high two dimensional electron gas (2DEG) density of the order of \( \sim 2.5 \times 10^{13} \text{cm}^{-2} \), almost double than normally obtained in Al$_x$Ga$_{1-x}$N /GaN heterostructure, therefore allows the realization of device with higher power density. The device performance is further improved by inserting thin layer of AlN between the In$_x$Al$_{1-x}$N barrier layer and GaN active layer to reduce the alloy disorder scattering thus improving the transport properties in the channel. High sheet carrier concentration (order of \( 2.8 \times 10^{13} \text{cm}^{-2} \)) is also developed at AlN/GaN interface due to large polarization difference and band gap discontinuity without intentionally doping the barrier layer. Moreover, AlN also possesses highest spontaneous polarization in materials matrix and a Curie temperature well above 1000°C [1]. Further, lattice matched In$_x$Al$_{1-x}$N /GaN HEMT is
thermally, chemically and electrically stable at high temperature then AlxGa1-xN /GaN counterpart, potentially allowing operation at higher temperature and improving robustness. In the present work, TCAD analysis of InxAl1-xN /AlN/GaN HEMT in the temperature ranges from 300 K to 800 K is carried out to study the impact of temperature on device characteristics like drain current, transconductance, gate-source/gate-drain capacitance and cut-off frequency.

2. Device structure and Material Model Specification

Figure 1 shows the schematic of the device considered in the analysis. It consist of 13 nm InAlN followed by 1 nm AlN inter-layer separating the active 2 μm thick GaN layer on sapphire substrate. The schottky gate length (Lg) of 0.25 μm with a source-gate distance (Lsg) of 1 μm and gate-drain distance (Lsd) of 1.35 μm are considered.

![Figure 1. Schematic of InAlN/AlN/GaN HEMT](image)

Great deal of efforts is seen in literature to idealize the value of polarization charges for InAlN/AlN/GaN HEMTs (Table 1). Although, polarization in III-Nitrides is very high, a very small change in this polarization is observed with temperature [2-4]. However, significant changes on various material parameter such as band gap, saturation velocity, thermal conductivity and density of states have been observed with temperature [2-4] and their effect have been incorporated in the device simulation using suitable models. Low thermal conductivity of III-V semiconductors creates the necessity of lattice heating models for high power devices. The GIGA module has been used consistently with BLAZE in order to encounter the effects of lattice temperature on material and transport parameters.

| Material       | a0 (Å) | Psp (C/m²) | ε31 x (C/m²)/ε33 | α   | β   | γ   | κ   | Ref. |
|----------------|--------|------------|-------------------|-----|-----|-----|-----|------|
| GaN            | 3.189  | -0.029     | -0.68             | -1.08 | 745  | -0.28 | 130 | [5]  |
| AlN            | 3.112  | -0.081     | -0.86             | -1.799 | 1462 | -1.64 | 285 | [5]  |
| InxAl1-xN, x=0.19 | 3.200  | -0.071     | -                  | -    | -    | -    | -   |      |

\[
C \frac{\partial T_L}{\partial t} = \nabla(\kappa \nabla T_L + H)
\]

(1)

Where \( C \) is heat capacitance per unit volume, \( \kappa \) is thermal conductivity (Table 1), \( H \) is heat generation, and \( T_L \) is local lattice temperature.

For realistic TCAD simulation, critical temperature dependent parameters have also been modeled in the present study. The temperature dependence of the energy gap is approximated by Varshini formula which is expressed by the following equation [4],

\[
E_g = E_g(0) \left( \frac{\alpha T^2}{T + \beta} \right)
\]

(2)

Where \( E_g(0) \) is energy band gap at 0 K, \( \alpha \) and \( \beta \) are empirical constants. The values used for GaN, AlN and ternary InAlN compounds are obtained through extensive bibliographic review and linear interpolation using Vegard’s rule. These values are summarized in table 1 for reference. The temperature dependence on the electron mobility has been taken into account using the Albrecht mobility model. Along with temperature dependence, this model also takes care of the effects caused
by ionized impurities and compensation ratio dependency of drift mobility. The expression for this model is given as [7]

\[
\frac{1}{\mu} = a \left( \frac{N_I}{10^3 \text{cm}^{-3}} \right) \ln \left[ 1 + \beta \left( \frac{T}{300} \right)^2 + b \left( \frac{T}{300} \right)^3 + c \left( \frac{1}{T} \left( \frac{\Theta}{T} \right)^{-1} \right) \right]
\]

(3)

Where \( T \) is temperature in K; \( N_I \) is ionized donor concentration (cm\(^{-3}\))

\[ a, \ b \ \text{and} \ c \ \text{are the fitting parameters whose values are} \ 2.0 \times 10^{-4}, \ 2.5 \times 10^{-4} \ \text{and} \ 1.7 \times 10^{-2} \ \text{respectively.} \]

Temperature dependent mobility of minority carriers are modeled using more generic models expressed as:

\[
\mu_n = \mu_n(300) \left( \frac{T}{300} \right)^{-1.5}
\]

(4)

\[
\mu_s = \mu_s(300) \left( \frac{T}{300} \right)^{-1.5}
\]

(5)

3. Results & Discussion

In order to validate the TCAD simulation, the device under study has been calibrated with the experimentally demonstrated device structure both at room and high temperature [8]. Various aspects of the DC characteristics like \( I_D-V_D \), transfer characteristics, threshold voltage have been analyzed in the temperature range of 300 K to 800 K. figure 2(a) plots the \( I_D-V_D \) for temperature variation from 300 K to 800 K. The value of maximum drain current decreases as the operating temperature is increased from room temperature to 800 K. At 300K, the device exhibited a saturated drain current (\( I_D \)) of 1.6 A/mm, which decreases to 0.83 A/mm as the temperature was raised to 800ºC. This significant reduction in maximum drain current can be explained from the degradation in 2-DEG mobility and effective electron velocity with increasing temperature. The inefficient thermal management due to low thermal conductivity of 42 WK\(^{-1}\)m\(^{-1}\) (148 WK\(^{-1}\)m\(^{-1}\) for Si) of sapphire adds further degradation at high temperatures. Lower value of thermal conductivity results in more lattice heating due to inefficient dissipation of the heat generated in the device. This lattice heating results in additional phonon scattering, further degrading the carrier mobility hence lower drain current.

In order to further explore the thermal heating effects on the device performance, the \( I_d \) Vs \( V_{gs} \) and transconductance behavior of the device have been plotted in figure 2(b) at various temperatures at 10 V of drain bias. It is observed from the figure that the peak transconductance value also follows downward trend as temperature is scaled up. In contrast to the current and \( g_m \) degradation at high temperature, \( g_m \) profile becomes flatter (an average \( g_m \sim 140 \text{ mS/mm at 800 K over } V_{GS}=-4.4 \text{ to } 0.3 \text{ V} \)) which indicates an improvement in the overall linearity of the device.

A slight positive shift in threshold voltage can also be observed with the increase in temperature, which is depicted clearly in figure 2c. This positive shift with increase in temperature can be explained by the phenomena of trapping effect at the gate-source and gate-drain recess interface. Similar increase in threshold voltage with temperature has also been studied by S. Arulkumaran et al. [9] and can be explained by the following expression

\[
V_{th} = V_{th} - q(N_d - N_T) \frac{a^2}{2\epsilon}
\]

Where \( V_{th} \) build in potential, \( \epsilon \) dielectric constant of barrier layer, \( N_d \) is carrier density and \( N_T \) is carrier trap density.

Variation in cut-off frequency and total gate capacitance with temperature variation has been plotted in figure 2(d). It can be seen from the figure that there is little variation in capacitance profile while the
cut-off frequency shows almost linearly degradation with the increase in temperature. Degradation in $g_m$ and increase in the value of capacitance supports the sharp decay in $f_T$, but the variation in $g_m$ is almost 3 times greater than that of $C_{gs}+C_{gd}$, so $g_m$ degradation plays a dominant role.

Figure 2. (a-d) Temperature dependent (a) $I_D-V_D$ characteristics at $V_{GS}=0$ V (b) Transfer characteristics and transconductance variation (c) $I_D-V_D$ characteristics at $V_{GS}=0$ V and at $V_{GS} = -8$ V (Pinch off) (d) Variation in cut-off frequency, gate capacitance ($C_{gs}+C_{gd}$) with temperature from 300 K to 800 K.

4. Conclusion
The degradation in the device performance with the adverse thermal condition is observed through the DC and RF characteristics of the device. This degradation is attributed to the phonon scattering which deteriorates the 2DEG mobility and effective electron velocity. The phenomena of trapping effects may explain the positive $V_{th}$ shift observed with the increase in temperature. The reduction in channel thickness may arrest the degradation observed in the present study by confining the 2DEG channel thus reducing the carrier scattering and dispersion of the carriers. The cut-off frequency follows $g_m$ variation as capacitance maintains a constant profile, which will be studied further using engineered epitaxial design or channel engineering so that degradation in $g_m$ and hence $f_T$ could be avoided. This work is currently under study and presents one of the possible solutions for better device performance even at higher temperatures.

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