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Temperature dependent analytical model for transfer characteristics of GaN HEMTs with $Al_xIn_yGa_zN$ barrier layer

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ABSTRACT

We present a temperature dependent analytical model for GaN HEMT with quaternary alloy $Al_xIn_yGa_zN$ barrier layer. HEMTs are also known as Heterojunction field effect transistors (HFETs). Change in the ambient temperature of device and the self-heating effects vary its threshold voltage and performance. We compare our calculated data with the available experimental data and find that the computed outcomes agree with the experimental observations existing in literature. Thereby, validating our claim that the proposed model might find use in the simulation of quaternary alloy based AlInGaN devices for various applications.

1. Introduction

Owing to the excellent show in high power and high frequency devices, a broad share of nanoelectronics industry is full of alloys based on nitride compound semiconductors. Nitride semiconductors have properties like wider band gap, greater breakdown voltage, high saturation velocity and an exclusive property of in-built spontaneous polarization. This unique property inclines to create two dimension electron gas (2DEG) in High Electron Mobility Transistors (HEMTs), resulting in venerable characteristics of these heterostructures [1]. However, the performance of AlGaN/GaN HEMTs degrade because of the lattice mismatched of AlGaN, and cause the strain in the AlGaN based spacer layer. Enhancement in Al mole fraction, causes possibility of crystal imperfection owing to lattice mismatch between AlGaN and GaN layers. It may lead to cracks and dislocation.

Lately, device with the AlInN/GaN material combination has been proposed by researchers. With higher Indium composition in barrier layer and with lower barrier thickness, same 2DEG density can be achieved with reduced interfacial stress. However, despite the higher $I_{d,max}$, low breakdown voltages have been reported on the AlInN/GaN-based devices [2]. To overcome this problem quaternary semiconductor is introduced. It resolves the problem of lattice mismatch in heterostructure. Designer can adjust lattice parameter by varying the composition of AlInGaN. Compromise between high breakdown voltage and high drain current density is managed using AlInGaN/GaN heterointerface. Such interfaces may replace the traditional ternary-N/GaN heterojunctions. Quaternary AlInGaN spacer layer contributes significantly in enhancing the 2DEG density and boost the drain current density and transconductance (g_m) because of its large spontaneous polarization and low sheet resistance [3-9].

Analytical models provide beforehand insight in the device characteristics like I_d-V_d, gain, transconductance, threshold voltage, device channel temperature etc. Ambient temperature and self-heating effect cause variation in energy bandgap, Schottky barrier height and the threshold voltage, thus, affecting overall performance of HEMTs. Therefore, the device temperature in crucial parameter to determine the overall performance of device.

We here investigate the effect of temperature variation on AlInGaN/GaN HEMT characteristics. We further work on our earlier basic model proposed in ref. 10 to incorporate here the temperature effects. Temperature dependent value of threshold voltage V_T and V- I characteristics are explored here.

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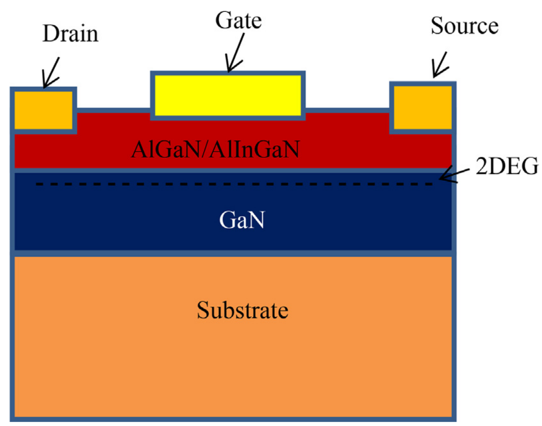

Fig. 1. AlInGaN/GaN HFET device structure.

2. Description of the device structure

Fig. 1 shows the cross sectional view of our HFET device. It consist of a barrier layer which can be of a ternary alloy AlGaN or quaternary AlInGaN on GaN buffer. Fig. 2 depicts the energy band diagram of the device. A polarization difference at the interface causes a net positive charge and formation of a conduction channel at GaN layer of HEMT [11].

3. Model description

3.1. Threshold voltage calculation for AlInGaN/GaN heterostructure

Temperature dependent threshold voltage for AlInGaN/GaN HEMTs can be expressed as.

$$V_T(T) = \varnothing_b(T) - \Delta E(T) - \frac{qn_d d_{AlInGaN}^2}{2\varepsilon} - \frac{\sigma_{int}}{\varepsilon} d_{AlInGaN} \quad (1)$$

Where $\varnothing_b(T)$ and $\Delta E(T)$ are the temperature dependent height of Schottky barrier and the conduction band discontinuity respectively. n_d is the doping concentration, ε is the permittivity of AlInGaN, $d_{AlInGaN}$ is the thickness of AlInGaN layer and $\sigma_{int} = P_{GaN} - P_{AlInGaN}$.

$$P_{AlInGaN} = P_{sp}(Al_xIn_yGa_zN) + P_{pz}(Al_xIn_yGa_zN) \quad (2)$$

where $P_{sp}(Al_xIn_yGa_zN)$ is spontaneous polarization and $P_{pz}(Al_xIn_yGa_zN)$ is piezoelectric polarization due to AlInGaN barrier layer. Spontaneous polarization $P_{sp}(Al_xIn_yGa_zN)$ can be reproduced with the help of interpolation model and can be expressed as.

$$P_{sp}(Al_xIn_yGa_zN) = x.P_{sp}(AlN) + y.P_{sp}(InN) + z.P_{sp}(GaN) + b_{AlGaN}.z.x + b_{InGaN}.y.z + b_{AlInN}.x.y + b_{AlInGaN}.x.y.z \quad (3)$$

where $b_{AlGaN}, b_{InGaN}, b_{AlInN}$ are bowing parameters of ternary alloy.

$$P_{pz}(Al_xIn_yGa_zN) = x.P_{pz}(AlN,\eta) + y.P_{pz}(InN,\eta) + z.P_{pz}(GaN,\eta). \quad (4)$$

where η is basal strain.

Temperature dependent conduction band discontinuity can be defined as.

$$\Delta E(T) = 0.7(E_g(AlINGaN,T) - E_g(GaN,T)) \quad (5)$$

Temperature dependent energy band gap for quaternary AlInGaN is expressed as.

$$E_g(AlINGaN,T) = x.y.E_g^s(AlInN,T) + y.z.E_g^t(InGaN,T) + x.z.E_g^u(AlGaN,T)$$

$$E_g^s(AlInN,T) = s.E_g(InN,T) + (1-s)E_g(AlN,T) - s(1-s)b_{AlInN}$$

$$E_g^t(InGaN,T) = t.E_g(GaN,T) + (1-t)E_g(InN,T) - t(1-t)b_{InGaN}$$

$$E_g^u(AlGaN,T) = u.E_g(AlN,T) + (1-u)E_g(AlN,T) - u(1-u)b_{AlGaN}$$

$$s = \frac{(1-x+y)}{2}, t = \frac{(1-y+z)}{2}, u = \frac{(1-x+z)}{2}$$

$$E_g(AlN,T) = -\frac{0.001799T^2}{1462+T} + 6.312$$

$$E_g(GaN,T) = -\frac{0.000909T^2}{830+T} + 3.51$$

$$E_g(InN,T) = -\frac{0.000245T^2}{624+T} + 1.994$$

Threshold voltage shifts with the temperature due to change in Schottky barrier height with temperature. On the basis of thermionic emission model, Schottky barrier height can be written as.

$$\varnothing_b(T) = \frac{KT}{q} ln\left(\frac{SA^*T^2}{I_0}\right) \quad (6)$$

where A^* is effective Richardson constant as can be expressed as.

$$A^* = \frac{q\pi m^* k^2}{h^3}$$

where m^* is effective mass of AlInGaN, k is boltzman constant and h is plank's constant.

3.2. Sheet charge density model

The 2DEG sheet charge density n_s at the position k in the channel, can be achieved by resolving the one dimensional Poisson's equation and is represent as.

$$n_s(T) = \varepsilon(V_g - V_T(T) - V_k - E_F/q)/qd_i \quad (7)$$

where d_i, V_k, and E_F is total length of AlInGaN and GaN layer, channel potential at distance k and Fermi level respectively.

Sheet charge density $n_{s,}$ as a function of V_g, can be expressed as.

$$n_s = [AV_{go}/(1+B)]\left[\left(1 - A^{2/3}\gamma_0\right)/(1+B)^{2/3}V_{go}^{1/3}\right] \quad (8)$$

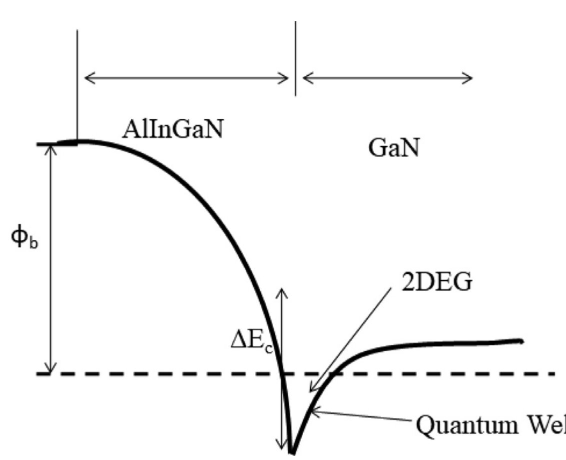

Fig. 2. Energy band diagram of heterointerface in AlInGaN/GaN HFET.

where $V_{go} = V_g - V_T(T)$, $A = \varepsilon/qd_{AlInGaN}$ and $B = A/qD$.

3.3. Drain current model

The drain current of HEMT can be formulated using.

$$I_d = q\mu_0 W n_s \upsilon_s$$

where W, υ_s, μ_0 is width of the device, drift velocity and low vertical field mobility respectively. By incorporating the current I_d under the area of source to drain, a simplified expression for the drain current can be realized as.

$$I_d = \left(q\mu_{eff}W/L\right)\left\{\left[(A+D)\left(n_s^2 - n_D^2\right)/2AD\right] + \left(2\gamma_0\left(n_s^{5/3} - n_D^{5/3}\right)/5\right) + kT(n_s - n_D)/q\right\} \quad (9)$$

where n_s and n_d is the charge carrier concentrations at the source and drain respectively. L is the gate length. Therefore, n_s is calculated as equation (8). The n_D can be calculated by considering the saturation voltage and effective mobility which can be explained in the section 3.4.

3.4. Model for saturation voltage

The modeling for saturation voltage are given in the literature [12], which can be represented as.

$$V_{Sat} = \upsilon_s V_{go}/\left[\upsilon_s + \left(\mu_{eff}V_{go}/2L\right)\right] \quad (10)$$

where μ_{eff} is the effective mobility and υ_s is the saturation velocity.

$$\mu_{eff} = \mu_0/\left(1 + t_1V_{go} + t_2V_{go}^2\right)(1 + t_3V_{ds})$$

where t_1, t_2 and t_3 are the fitting parameters.

Saturation voltage creates the variation in drain voltage of devices, which can be calculated as V_{ds} for $V_{ds} < V_{sat}$ and approaches V_{sat} for.$V_{ds} = V_{sat}$

$$V_{effD} = V_{sat}\left[1 - \ln\left[1 + \exp(1 - \alpha V'_{ds}/V_{sat})\right]/\ln(1 + e)\right] \quad (11)$$

where α, V_{ds} is the transition width parameter and effective drain-source voltage[10]. The charge carrier concentration at the drain, n_D, is deliberate using equation (8) by changing V_{go} with $V_{go} = V_{go} - V_{effD}$.

3.5. Self-heating effect (SHE)

In HEMTs, the self-heating effect happens when channel is excited due to dissipated power. It affects the working of the HEMT unfavorably. Therefore, it is required to incorporate the self-heating effects by calculating the change in channel temperature. An expression for channel temperature is given by [13] as.

$$T_{channel}(T) = \frac{1 - (1 - (P_{diss}(T)/4P_0)^4}{(1 - (P_{diss}(T)/4P_0)^4}T_{sub} + T_{sub} \quad (12)$$

where $P_o = \frac{\pi K(T_{sub})ZT_{sub}}{\ln(\frac{8t_{sub}}{\pi l_g})}$, $P_{diss}(T) = I_dV_d$ is power dissipation, $K(T_{sub})$ is thermal conductivity and t_{sub} is thickness of substrate. Temperature of subtract is also varies linearly with the dissipated power $T_{sub} = 300 + \lambda P_{diss}(T)$. First I_d is calculated at room temperature using equation (9). Power dissipation is calculated with product of I_d and corresponding V_d, which gives the channel temperature. At this channel temperature and ambient temperature, various parameters are calculated. These are substituted in model to calculate the final I_d-V_d and I_d-V_g characteristics.

4. Result and discussion

To authenticate our model, we applied it on the experimental devices with ternary alloy AlGaN and quaternary alloy AlInGaN at barrier layer. The model was applied on experimental data proposed in ref [14] with ternary $Al_{0.24}Ga_{0.76}N$ barrier layer of thickness 25 nm. In proposed model, the mole fraction of *In* is considered as 0% to validate the data with ternary alloy. Experimental device is unpassivated and has gate width W = 15 µm and gate length L = 1.5 µm, other parameters of device are mentioned in Table 1. Fig. 3 shows the drain current characteristics with respect to drain voltage of ternary AlGaN HEMT at V_g = 1.5 V and different temperature. It is observed that with the increase in temperature the drain current of device decreases. At the room temperature T = 300 K, our model shows good agreement with the experimental results reported in [14]. Also with decrease in gate voltage V_g to − 0.5 V, the drain current also decreases, as depicted in Fig. 4. It can also be inferred from Figs. 3 and 4 that because of self-heating effect, the drain current decreases in saturation region with increase in drain voltage.

Table 1
Model and Device Parameters.

Parameter name (units)	Parameters	
	Device-A (AlGaN barrier layer) *AlGaN/GaN*	Device-B (AlInGaN Barrier layer) *AlInGaN/GaN*
Depicted in	Figs. 3, 4	Fig. 5,6,7
Al mole fraction in Barrier Layer × (Unitless)	0.26	0.66
In mole fraction in Barrier Layer *y* (Unitless)	–	0.14
Barrier Layer Thickness (nm)	25	10.3
Gate Length *L* (µm)	1.5	1
Gate Width *W* (µm)	15	100
Low Field Mobility μ_0 (cm^2/V-s)	950	1790
t_1 (1/Volt)	−0.875	−0.0805
t_2 (1/$Volt^2$)	0.28	0.0805
t_3 (1/Volt)	0.65	0.08
Source-Gate region resistance R_s (Ohm)	0.6	0.6
Drain-Gate region resistance R_d (Ohm)	0.6	0.6
Transition width parameter α (unitless)	0.1	0.9

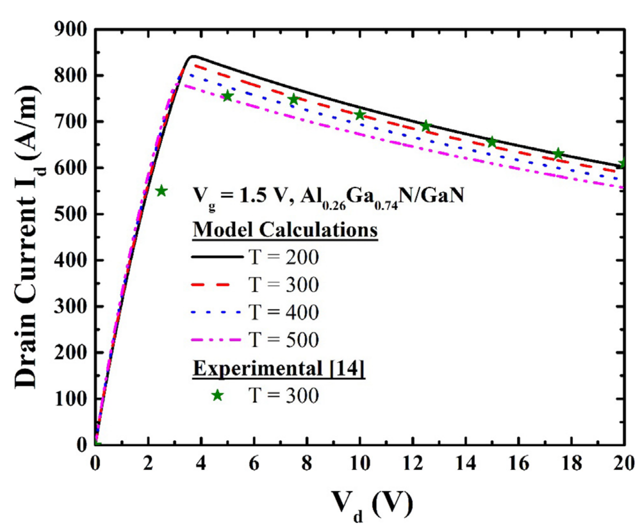

Fig. 3. Drain current - Voltage characteristics of HEMT at V_g = *1.5 V*, $Al_{0.24}Ga_{0.76}N$ at different temperature.

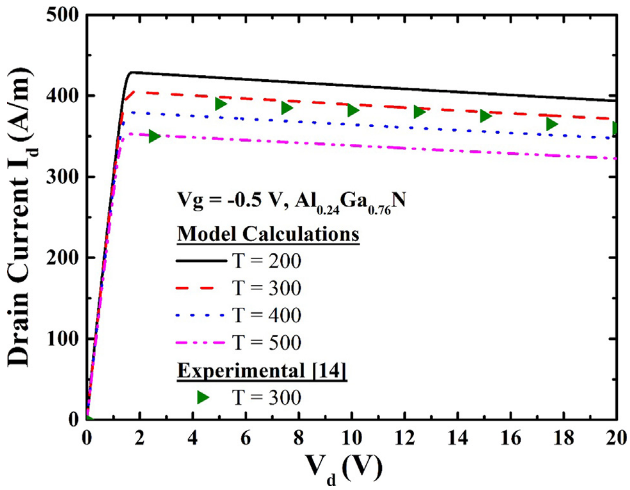

Fig. 4. I_d-V_d Characteristics of HEMT at V_g = *-0.5 V*, $Al_{0.24}Ga_{0.76}N$ at different temperature.

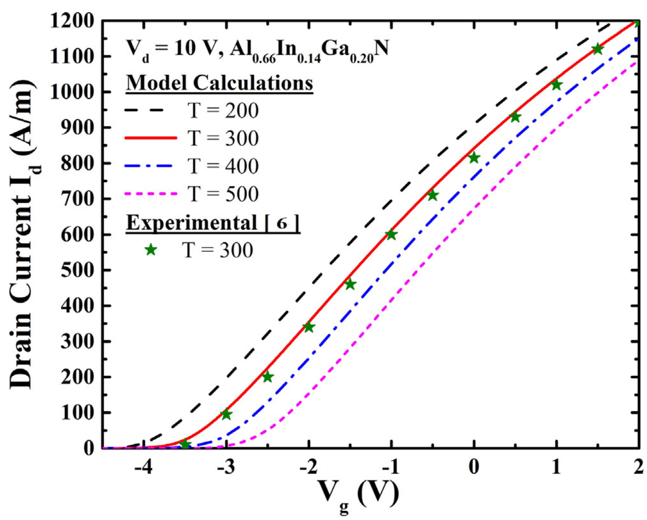

Fig. 5. I_d-V_g characteristics of $Al_{0.66}In_{0.14}Ga_{0.20}N$ HEMT at V_d = 10 V and different temperatures.

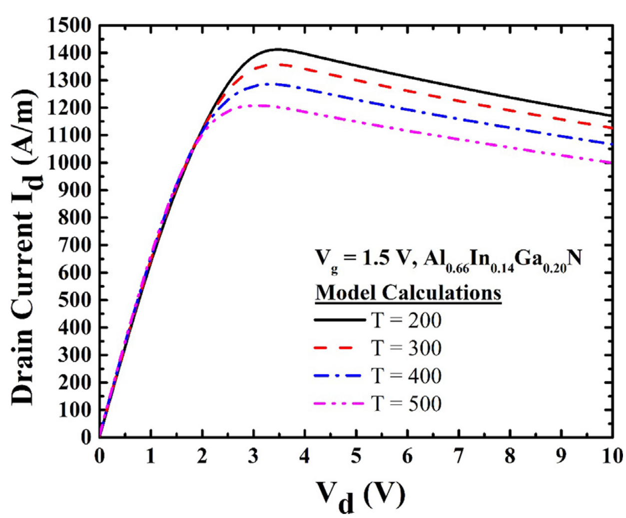

Fig. 6. I_d-V_d Characteristics of $Al_{0.66}In_{0.14}Ga_{0.20}N$ HEMT at V_g = 1.5 V and at different temperatures.

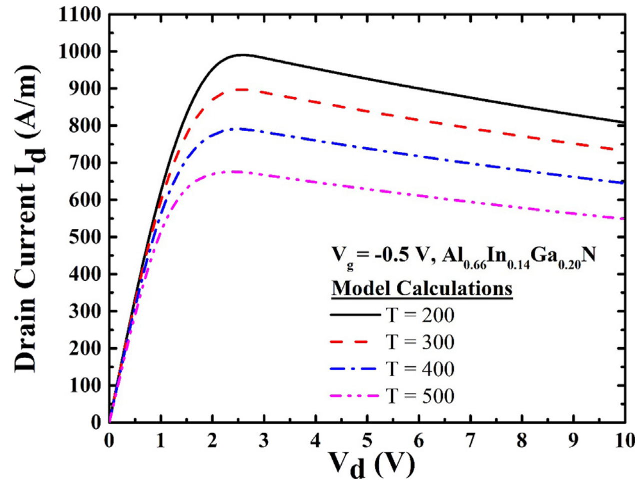

Fig. 7. I_d-V_d Characteristics of $Al_{0.66}In_{0.14}Ga_{0.20}N$ HEMT at V_g = − 0.5 V and at different temperatures.

For validation of model on quaternary barrier layer, we have applied proposed model on experimental device reported in ref.15, with quaternary alloy $Al_{0.66}In_{0.14}Ga_{0.20}N$ barrier layer of thickness 10.3 nm. Gate length of HEMT L = 1 μm and width of device W = 100 μm, other parameters are defined in Table 1. Fig. 5 shows the I_d-V_g characteristics of devices at V_d = *10 V* at different temperatures. It can be observed from Fig. 5 that the threshold voltage of device varies with the variation in ambient temperature. Variation in temperature caused the change in Schottky barrier height and polarization of semiconductor which affects the V-I characteristics of device.

On increase in temperature, threshold voltage shifted towards positive value and drain current decreased. Model calculations show good agreement with the experimental result at T = 300 K reported in [6]. Figs. 6 and 7 show the I_d-V_d characteristics of quaternary HEMTs with V_g = 1.5 V and − 0.5 V respectively.

5. Conclusion

We suggested a temperature reliant analytical model for quaternary AlInGaN/GaN HFET. Threshold voltage, an important device parameter, of the HFET changes with the change in the ambient temperature. Along with the ambient temperature, self-heating effect vary the channel temperature which cause the variation in threshold voltage and performance of device as well. Our computational results agree well with the available experimental findings. Thus, demonstrating the effectiveness of our model. It can be utilized to simulate the quaternary alloy AlInGaN based devices before fabrication.

CRediT authorship contribution statement

Kavita Thorat Upadhyay: Validation, Formal analysis, Investigation. **Neha Pande:** Writing – original draft, Visualization. **K. Manju Chattopadhyay:** Conceptualization, Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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