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Confined Energy State Based Hypothetical Observations about Device Parameters of AlGaN / GaN HEMT

Palash Das*, Dhrubes Biswas

Indian Institute of Technology Kharagpur, Kharagpur, India

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In this paper, the gate threshold voltage of AlGaN / GaN HEMT devices has been analytically predicted based on the calculated energy levels inside triangular quantum well at the hetero-interface and found to be comparable with experimental data. The conceptual explanation of device linearity in large signal applications has been presented in terms of quantized energy levels in the quantum well. The dependence of threshold voltage and linear operable gate voltage range on a newly introduced parameter named "Surface Factor" is analyzed as well.

Keywords: AlGaN / GaN, Modeling, Threshold voltage, Linearity.

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1. INTRODUCTION

Theoretical determination of Threshold voltage and transconductance for High Electron Mobility Transistor (HEMT) devices is important for device performance predictions. The general approach for calculating the transconductance is involved with differentiation [1] of drain current with respect to gate voltage. However, those two parameters as explained here with a different approach involving the quantized energy levels in AlGaN / GaN hetero-interface.

2. THEORETICAL MODELING

This discussion is started in conjunction with our previously reported 2DEG carrier concentration vs. Fermi energy level relation in composite AlGaN/GaN heterostructures for HEMT application. The general expression for carrier concentration and Fermi level of composite AlGaN / GaN heterostructure was given as [2]

$$n_S = \frac{V_{GS} - V_{th} - 0.1429}{4.096\times10^{-18} + \dfrac{q}{C_{||}}} \quad \text{(At 300 K)} \qquad (2.1)$$

$$E_F = 0.1429 + 4.096\times10^{-18} n_S \quad \text{(At 300 K)} \qquad (2.2)$$

Here V_{GS}, V_{th}, q and E_F are the gate to source voltage, threshold voltage, electron charge and Fermi energy level respectively.

The 2DEG has been found to be growth dependent and its value may vary [3] with the growth conditions and even with different epitaxial growth equipments [4] for the similar Al molar fraction and the AlGaN barrier thickness. The grown surface is one of the main dependable factors of different growth environments. Hence, it is hereby considered that the surface energy level pinning happens differently for different growth environments. A new parameter named Surface Factor (SF) been introduced in this work and considered to be linearly modifying the surface pinning. Then the modified expression for threshold voltage can be written as

$$V_{th} = \varphi_b + SF - \Delta E_C - \frac{qN_D d_d}{2C_{||}|_d} - \frac{q\sigma_{tot}}{C_{||}} \qquad (2.3)$$

Here φ_b, ΔE_C, q, N_D, d_d, σ_{tot} and ε are the conduction band discontinuity, electron charge, doping density, doped layer thickness, total polarization charge and dielectric constant respectively. The series capacitance effect of all the AlGaN layers in composite barrier with different dielectric constants and layer widths have been considered here such that

$$\frac{1}{C_{||}} = \sum_i \frac{d_i}{\varepsilon_i}$$

for $i = 1, 2, 3 \ldots$ all barrier layers and suffix d stands for the doped layers

The calculations give the predicted values of E_F, ground state energy level (E_0) and first excited state energy level (E_1). E_F and E_0 provide us the information about the carrier confinement, which has been discussed in the next parts.

The dependence of carrier confinement, pinch off voltage and linearity of the devices on the energy levels inside the triangular potential well at AlGaN / GaN heterojunction are hypothetically discussed in this part. The main interpretation has been considered for the difference between Fermi and ground state energy levels.

2.1 Carrier Confinement and Energy Levels

If the position of the ground state energy level (E_0) inside the potential well is below the position of the Fermi energy level (E_F) it can be well understood that there are two dimensional carriers present in the quantum well. It can be identified as well that more the depth of ground energy state with respect to Fermi level, more energy will be required to pull up the ground state electrons towards Fermi level. Here gate voltage may be considered as the source of this pulling energy upon the ground state electrons. This directly means that more the depth of ground state energy level with

* d.palash@gmail.com

respect to Fermi level ($E_F - E_0$), the electrons have more possibilities to be well confined in the quantum well and more gate voltage (in negative value for depletion mode device) is required to "pull out" the electrons above Fermi level. Hence it can be said that $E_F - E_0$ can provide the information about the degree of carrier confinement inside the quantum well. The positions of the energy levels are considered at 300 K temperature. It can be found that the decrease in gate voltage for HEMT heterostructures causes decrease in the energy level difference between E_F and E_0. At some particular gate voltage, the value of $E_F - E_0$ becomes close to zero and at that point practically there will be no confined carrier inside the potential well. Hence the situation can be interpreted as the gate voltage pinch off condition. The energy level diagram is also described pictorially in Fig. 1.

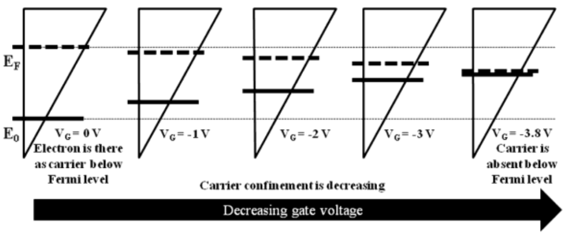

Fig. 1 – Relative positions of Fermi and ground state energy level with decreasing gate voltages for depletion mode transistor

2.2 Device Linearity and Energy Levels

The discussion can be started from fundamental conceptions of the transistor biasing conditions. The device linearity is defined here as macro level of linearity and micro level of linearity. If the drain to source current is an exact replica (with amplitude magnification) to the gate to source voltage then the HEMT device is said to be completely linear. The non-linearity takes place when operating point of the transistor has not been chosen correctly. If the operable gate voltage span is large enough *i.e.* the confined carrier is present inside the quantum well for a large negative gate bias, then the transistor operating point can also be chosen more widely. The previous section already described that the confinement of carrier depends on the energy level difference $E_F - E_0$. Hence it can be understood that more the value of $E_F - E_0$, more will be the linearly operable gate voltage range. This linearity is considered as macro level of linearity for the HEMT.

In another situation, if there is distorted drain current with respect to the gate to source voltage, the situation is considered as micro level non-linearity. This may arise when the same change in gate voltage will result different change in drain to source current for different gate voltage regions. For a tiny change in gate voltage from V_{G1} to V_{G2}, the drain to source current changes from I_{D1} to I_{D2}. In the same application, for gate voltage change from V_{G3} to V_{G4}, the drain to source current changes from I_{D3} to I_{D4}. If $V_{G1} = \sim V_{G2} = V_{G3} \sim V_{G4}$, then the device will be completely linear if $I_{D1} \sim I_{D2} = I_{D3} \sim I_{D4}$. Fig. 2 shows the pictorial representation of the same. One of the most vital factors for drain current is the amount of confined carriers inside the quantum well. It can be physically said that the change in the confinement may cause the change in the output drain current. Hence the measurement of small changes in confinement (that is $E_F - E_0$) with respect to the small changes in gate voltage that is $d(E_F - E_0) / dV_G$ can be considered for gate voltage linearity range measurement of the HEMT device.

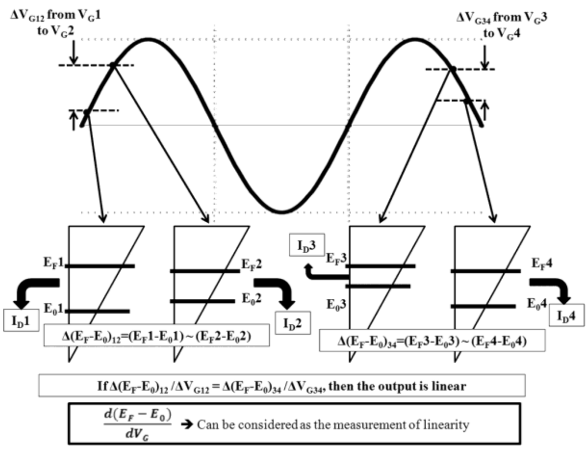

Fig. 2 – Change in carrier confinement caused by the difference between Fermi energy level and ground state energy level with respect to the gate voltage change defines linearity

Table 1 – Comparison of experimental and analytical values of threshold voltage

Al molar fraction(s) (%)	AlGaN Thicknesses (nm) / doping (cm^{-3})	Threshold voltage reported	Threshold voltage calculated	Reference
30	25 / UID	– 2.50 V	– 1.90 V	Ref. [6]
30, 30, 30	5 / UID, 15 / 2 × 1018,5 / UID	– 3.50 V	– 2.49 V	Ref. [6]
30, 30, 30	5 / UID, 15 / 5 × 1018, 5 / UID	– 4.50 V	– 4.44 V	Ref. [6]
0, 30, 30, 30	5 / UID, 6 / UID, 10 / 1 × 1019, 3 / UID	– 3.50 V	– 3.09 V	Ref. [6]
25	20 / UID	– 2.00 V	– 1.20 V	Ref. [7]
30	25 / UID	– 5.50 V	– 5.85 V	Ref. [8]
0, 29, 100	3 / UID, 21 / UID, 1 / UID	– 5.00 V	– 4.73 V	Ref. [9]
30, 30, 30, 5	2 / UID, 21 / 2 × 1018, 3 / UID, 6 / UID	– 6.00 V	– 6.20 V	Ref. [5]
35	25 / UID	– 4.50 V	– 4.58 V	Ref. [10]
34, 34, 34	3 / UID, 15 / 4 × 1018, 7 / UID	– 3.00 V	– 3.82 V	Ref. [11]

3. VALIDATION OF MODEL AND DISCUSSIONS

The prediction of threshold voltage has been done in energy level approach which has been already discussed hypothetically in the previous sections. If differential energy level ($E_F - E_0$) reaches zero value or close to that, it means there is absolutely no 2DEG carrier present in the channel and has been described here as the threshold. The comparisons of reported and calculated values of threshold voltages of different AlGaN / GaN HEMT structures are presented in Table 1 and are found in good agreement. The deviations are assumed to be resulted from the post processing effects on the surface factors. Liu et al. [5] reported good linearity of their HEMT device with the composite structure, and the mathematical model presented here can also show that the operable linear range of the device is comparably greater than other reported devices.

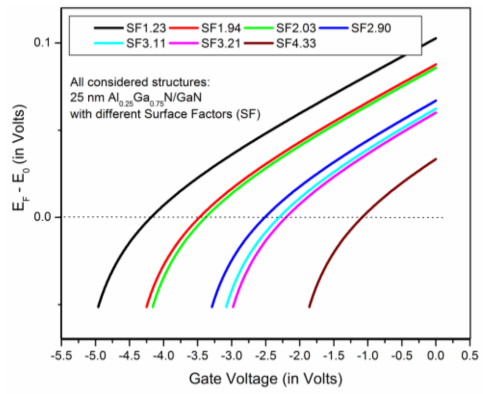

Fig. 3 – Calculated dependence of energy level difference between Fermi energy and ground state energy on SF for 25 nm $Al_{0.25}Ga_{0.75}N$ / GaN HEMT structures

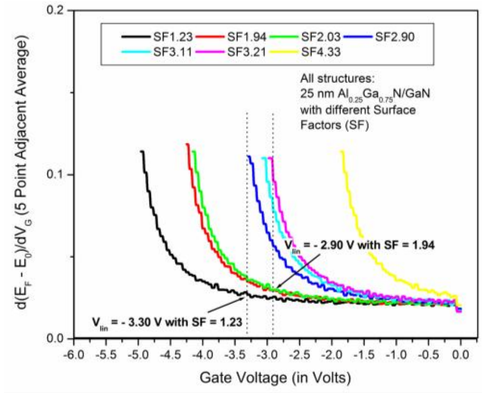

Fig. 4 – Calculated dependence of linearity on SF for 25 nm $Al_{0.25}Ga_{0.75}N$ / GaN HEMT structures

Previously reported single barrier HEMT structures with AlGaN composition in the range of 25 % to 27 % are taken into consideration and those are normalized to 25 nm of $Al_{0.25}Ga_{0.75}N$, with different calculated SF. The plot of $E_F - E_0$ vs. gate voltage (V_G) shown in Fig. 3, states the prediction that there may be negative influence of SF on the threshold voltage. The relation between $d(E_F - E_0) / dV_G$ and V_G as shown in Fig. 4 concludes that gate voltage linearity range is inversely influenced by SF as well.

4. CONCLUSION AND FUTURE SCOPE

It has been hypothetically presented that the difference between ground state and Fermi energy level may be informative about the carrier confinement and may be used to determine the threshold gate voltage and linear operable gate voltage range of the HEMT device. The growth and process dependent surface factor has been shown to be inversely related with the device parameters. The explanation of good linearity in compositionally graded AlGaN / GaN devices can be done using this energy level approach.

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