Vol 15 No 3, March 2006
1009-1963/2006/15(03)/0636-05

Chinese Physics

© 2006 Chin. Phys. Soc.
and IOP Publishing Ltd

Numerical simulation of transconductance of AlGaN/GaN heterojunction field effect transistors at high temperatures*

Chang Yuan-Cheng(常远程)†, Zhang Yi-Men(张义门), and Zhang Yu-Ming(张玉明)

Key Lab of Ministry of Education for Wide Band-Gap Semiconductor Materials and Devices
Microelectronics Institute, Xidian University, Xi'an 710071, China

(Received 2 June 2005; revised manuscript received 3 November 2005)

Based on the investigation of the influence of temperatures on parameters, including polarization, electron mobility, thermal conductivity, and conduction band discontinuity at the interface between AlGaN and GaN, the temperature dependence of transconductance for AlGaN/GaN heterojunction field effect transistors (HFETs) has been obtained by using a quasi-two-dimensional approach, and the calculated results are in good agreement with the experimental data. The reduction in transconductance at high temperatures is primarily due to the decrease in electron mobility in the channel. Calculations also demonstrate that the self-heating effect becomes serious as environment temperature increases.

Keywords: AlGaN/GaN HFETs, transconductance, high temperature
PACC: 7280E, 0650M, 6120J

1. Introduction

Due to superior material properties, many prototype AlGaN/GaN heterojunction field effect transistors (HFETs) have been successfully fabricated for applications in high-power and high-frequency application.[1−3] These devices are excellent candidates for the next generation of high-power microwave system. However, under large static drain bias, the high-power operation of AlGaN/GaN HFETs may result in high junction temperature. This effect has been reported to be of great influence on the static characteristics and is commonly referred to as "self-heating". It causes a reduction in electron mobility and drift velocity, thus degrading the device performance, or even damaging the device itself.[4,5] Particularly, when the device works in a high-temperature environment, its self-heating becomes more serious. To reduce the self-heating effect, a reasonably accurate estimation of the channel temperature is often desired. In this paper, a quasi-two-dimensional approach is adopted to calculate the transconductance at different temperatures by analysing the influence of self-heating on some important factors. The proposed model is valuable for predicting and evaluating the performance of devices with different structures and packages.

2. Model description

2.1. The electron density distribution

In order to investigate the operational mechanisms of AlGaN/GaN HFETs, Schrödinger's equation is used in a self-consistent approach coupled with Poisson's equation.[6] The potential V is obtained from Poisson's equation with an initial guess of the mobile charge density, and then inserted into Schrödinger's equation to obtain the energy levels and wave function of the quantum well. The new electron density is then calculated according to Fermi statistics. The calculated electron density is then inserted into Poisson's equation again, and such an iteration is repeated until the convergence is achieved. In the iteration the dependence of some important parameters on Al compo-

*Project supported by the National Basic Research Program of China (Grant No 2002CB311904).
†E-mail: ychchang@mail.xidian.edu.cn

sition and temperature should be taken into account.

a) Band gap The temperature dependence of the band gap $E_{\rm g}(T)$ refers to[7]

$$E_{\rm g}(T) = E_{\rm g}(0) - \frac{\alpha T^2}{T+\beta}, \tag{1}$$

where $E_{\rm g}(0)$ is the energy gap at 0K and α is an empirical constant, β is also a constant, but related with the Debye temperature in some case. For GaN α and β are –1.08meV/K, 745K[7] and for AlN –1.80meV/K, 1462K[8] respectively. Van Schilfgaarde found that the band gap of $Al_xGa_{1-x}N$ was

$$\begin{aligned} &E_{\rm g}^{\rm AlGaN}(T,x) \\ =&xE_{\rm g}^{\rm AlN}(T) + (1-x)E_{\rm g}^{\rm GaN}(T) - bx(1-x), \end{aligned} \tag{2}$$

where b is a bowing parameter and its value is 0.6,[9] x is mole fraction of Al. The conduction band discontinuity $\Delta E_{\rm c}$ at the heterointerface is a principal parameter to determine the density of two-dimensional electron gas. It can be defined as[10]

$$\Delta E_{\rm c} = 0.70\left(E_{\rm g}^{\rm AlGaN}(T,x) - E_{\rm g}^{\rm GaN}(T)\right). \tag{3}$$

b) Electron mobility A simple analytical approximation, which is recently employed successfully for silicon carbide, is used to analyse the low-field mobility in GaN

$$\mu_i(N,T) = \mu_{{\rm max},i}(T_0)\frac{B_i(N)\left(\dfrac{T}{T_0}\right)^{\xi}}{1+B_i(N)\left(\dfrac{T}{T_0}\right)^{\delta+\xi}}, \tag{4}$$

where

$$B_i(N) = \left[\frac{\mu_{{\rm min},i} + \mu_{{\rm max},i}\left(\dfrac{N_{{\rm g},i}}{N}\right)^{\gamma}}{\mu_{{\rm max},i} - \mu_{{\rm min},i}}\right]\Bigg|_{T=T_0},$$

i=n or p denotes electron or hole respectively, N is the doping concentration, and T_0=300K. The values of model parameters $\mu_{{\rm max},i}, \mu_{{\rm min},i}, N_{{\rm g},i}, \gamma, \delta$ and ξ are cited from Ref.[11] and listed in Table 1.

Table 1. The values of the parameters.

$\mu_{{\rm max},i}/({\rm cm^2/V\cdot s})$	$\mu_{{\rm min},i}$ $/({\rm cm^2/V\cdot s})$	$N_{{\rm g},i}/{\rm cm^{-3}}$	γ	δ	ξ
1000	55	2×10^{17}	1.0	2.0	0.7

c) Spontaneous and piezoelectric polarization The good agreement between the theoretical values and experimental measurements of the sheet carrier concentration versus Al composition is obtained when the nonlinear formulation of the polarization is applied.[12] The spontaneous polarization of $Al_xGa_{1-x}N$ is given to second order of x by[13]

$$\begin{aligned} P_{\rm AlGaN}^{\rm sp}(x) =&(-0.090x - 0.034(1-x) \\ &+ 0.021x(1-x)){\rm C/m^2}. \end{aligned} \tag{5}$$

Although the spontaneous polarization is very strong in group III nitrides, the pyroelectric coefficients to describe the change of the spontaneous polarization with temperature are measured to be surprisingly small. We take the recent data and obtain $\dfrac{{\rm d}P}{{\rm d}T} = 7.5\mu{\rm C}/({\rm K\cdot m^2})$ [12] for AlN and $\dfrac{{\rm d}P}{\varepsilon {\rm d}T} \sim 10^4{\rm V/mK}$[14] for GaN, here ε is the static dielectric permittivity. The nonlinear form of piezoelectric polarization is used and its magnitude can be determined by[13]

$$\begin{aligned} &P_{\rm AlGaN/GaN}^{\rm pz}(x) \\ =&(-0.0525x + 0.0282x(1-x)){\rm C/m^2}. \end{aligned} \tag{6}$$

As we know, there have been no reports on the temperature dependence of piezoelectric polarization. The temperature dependence of piezoelectric polarization is neglected in our simulation since it is expected to be very small as indicated in spontaneous polarization. The total polarization is the sum of the spontaneous polarization and the piezoelectric polarization. For GaN, a value of $-0.029{\rm C/m^2}$ is used as its spontaneous polarization at room temperature.[15]

2.2. Current model including self-heating

A quasi-two-dimensional model is utilized for calculating $I-V$ characteristics of AlGaN/GaN HFETs, using an exact value of sheet charge density of the channel, which is obtained from the solution of Schrödinger's and Poisson's equations presented above. The device structure is shown in Fig.1 where the x-axis is the direction along the channel, V_x is the voltage in x direction, and the z-axis is perpendicular to the channel. When a drain bias is applied, the sheet electron charge density is determined by

$$n_{\rm s}(V_x) = \int n(V_x, z)\,{\rm d}z. \tag{7}$$

Neglecting the diffusion component, the drain line current density $I_{\rm ds}$ is

$$I_{\rm ds} = -qWv(E)\,n_{\rm s}(x). \tag{8}$$

Here W is the width of the gate, $v(E)$ is the mean electron velocity that can be expressed by

$$v(E) = \frac{\mu_0 E}{1 + \dfrac{E}{E_{\rm c}}}, \tag{9}$$

where μ_0 is the low field mobility, $E_{\rm c}$ is the critical electric field and $E_{\rm c} = \dfrac{v_{\rm sat}}{\mu_0}$, and $v_{\rm sat}$ is the saturation velocity.[16]

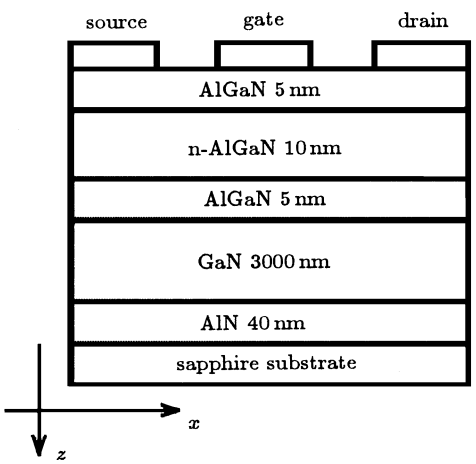


Fig.1. Structure of the HFET with Al mole fraction of 0.3.

The numerical solution is based on the discretization of Eq.(8) by dividing the channel length into N sections, each with a length of h, so that $Nh = L_{\rm g}$. Let V_i and V_{i-1} denote the potentials across the ith section. Therefore $V_i = V_{i-1} + E_i h$, where E_i is the horizontal electric field in the ith section. By performing iterative calculation for all the N sections, we can obtain the value of the voltage $V_{\rm d}$ across the channel that corresponds to an assumed current $I_{\rm ds}$. Parasitic components are included explicitly in terms of the values of the drain and source resistivity ($R_{\rm d}$ and $R_{\rm s}$), so the voltage $V_{\rm ds}$ between the source and the drain is given by

$$V_{\rm ds} = V_{\rm d} + (R_{\rm d} + R_{\rm s})\,I_{\rm ds}. \tag{10}$$

In the calculation the self-heating effect is taken into account as follows. The temperature difference between the channel and the bottom of the substrate ($\Delta T = T_{\rm channel} - T_{\rm sub}$) is given by[17]

$$\frac{\Delta T}{T_{\rm sub}} = \frac{1 - \left(1 - \dfrac{P_{\rm diss}}{4P_0}\right)^4}{\left(1 - \dfrac{P_{\rm diss}}{4P_0}\right)^4}, \tag{11}$$

where $T_{\rm channel}$ is the channel temperature and $T_{\rm sub}$ is the temperature of the substrate bottom. P_0 is referred to as a characterization quantity with the dimension of power

$$P_0 = \frac{\pi K(T_{\rm sub})\,WT_{\rm sub}}{\ln\left(\dfrac{8t_{\rm sub}}{\pi L_{\rm g}}\right)}, \tag{12}$$

where $P_{\rm diss} = I_{\rm ds}V_{\rm ds}$ is the power dissipation, $K(T_{\rm sub})$ is the thermal conductivity, $t_{\rm sub}$ is the thickness of substrate, and $L_{\rm g}$ is the length of the gate.

An initial value of $V_{\rm ds}$ is evaluated for a given $I_{\rm ds}$, then ΔT and other parameters at this temperature are calculated from Eqs.(1)–(6). Repeating similar steps for a certain range of $I_{\rm ds}$, the corresponding values of $V_{\rm ds}$ and the $I-V$ characteristics of the device are achieved.

In addition, the following two assumptions are applied:

(a) The device structure includes two parts: the epitaxial layers and the substrate. In each part, the temperature changes smoothly.

(b) The bottom temperature of the substrate $T_{\rm sub}$ changes linearly with the dissipated power:

$$T_{\rm sub} = T_{\rm en} + \lambda P_{\rm diss}, \tag{13}$$

where λ is an empirical parameter corresponding to the thermal resistance of the package, and $T_{\rm en}$ is the environment temperature.

3. Simulation results and discussion

An $Al_xGa_{1-x}N$ /GaN HFET with $L_{\rm g} = 1.3\mu$m and $W = 100\mu$m is used to verify our model. The device is composed of $Al_xGa_{1-x}N$ (5nm) /n- $Al_xGa_{1-x}N$ (10nm) / $Al_xGa_{1-x}N$ (5nm) / GaN (3000nm) / AlN (40nm) and sapphire substrate, as shown in Fig.1.[18]

A Schottky barrier height of $\varphi_B = 1.3x + 0.85$eV[19] is used for the Ni/Au–$Al_xGa_{1-x}N$ interface, and the effective mass is 0.19 for electron in both GaN and $Al_xGa_{1-x}N$ layers and static dielectric constant $\varepsilon_r = 9.7 - 1.2x$.[20] The saturation rate is derived by fitting the results of Monte Carlo simulation and its value is 2.87×10^7cm/s.[21]

The temperature difference ΔT between the channel and the bottom of the substrate is obtained from Eqs.(11) and (12). The values of ΔT are 93K, 119K

and 127K when the environment temperatures T_{en} are 296K, 376K and 460K respectively after drain current becomes saturated at a gate voltage of 0V. It can be seen that ΔT becomes great as T_{en} increases.

The electron mobility in the channel changes drastically from 485cm^2/V·s to 243cm^2/V·s, i.e. it decreases by about 50%, when environment temperature increases from 296K to 460K. Band offset and the saturation rate are weakly dependent on temperature. Their values are almost constant while the temperature increases. Although the spontaneous polarization is very strong in group III nitrides, the change of the spontaneous polarization with temperature is only 0.62% and 1.23% for GaN and $Al_xGa_{1-x}N$ respectively due to the pyroelectric coefficients being measured to be very small. The drain and source resistances should be the same as ohmic contact resistance. An ohmic contact resistivity of about 2Ω·mm is adopted in order to accord with the measured value of the device.[22]

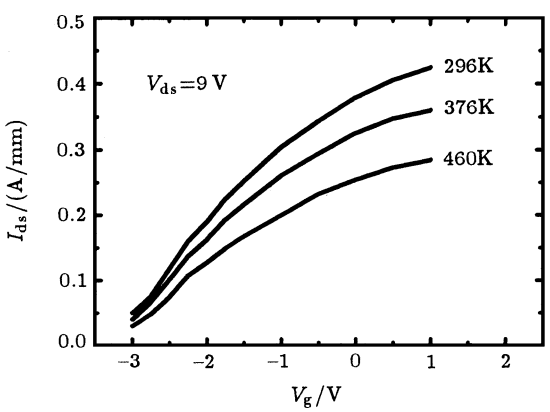


Fig.2. Drain current I_{ds} as a function of gate voltage V_g at different temperatures.

Drain current as a function of gate voltage at different temperatures is shown in Fig.2. Figure 3 presents a comparison of transconductance between calculations and measurements. Their good agreement is achieved. This implies that the present model is reasonable. The value of λ is about 5K/W. From Fig.3 we can immediately notice that the transconductance of the device depends strongly on temperature. The increase in temperature reduces the electron mobility and the electron density in the channel; consequently less transconductance is caused. So temperature is a main external factor to dominate transconductance when the dimension of device is fixed. The maximum transconductance of the device deceases drastically from 110 mS/mm to 72 mS/mm i.e. by about 34.5% while temperature increases from 296K to 460K. This demonstrates that degradation of device performance happens at higher temperatures.

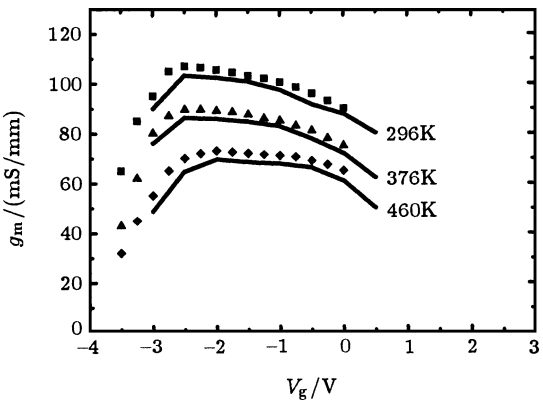


Fig.3. Comparison of transconductance g_m between experimental data (symbols) and simulation results (line) at different temperatures. The measurements are cited from Ref.[18].

In the simulation, the influence of temperature on the bulk resistance in the active area and the piezoelectric polarization at the heterointerface between AlGaN and GaN is neglected. In fact increasing temperature may increase the bulk resistance and reinforce the piezoelectric effects and then make the value of sheet charge density n_s increase. Thus there appears a deviation between measurements and calculations.

4. Conclusions

AlGaN/GaN HFETs have been investigated by self-consistent schemes. The profound influence of temperature on polarization, electron mobility, thermal conductivity, conduction band discontinuity at the interface between AlGaN and GaN has been shown. The drain current characteristics and transconductance at different temperatures have been obtained by using a quasi-two-dimensional approach and compared with the experimental data. Desirable agreement is achieved. In spite of the good thermal conductivity of the sapphire material, the large power dissipation in AlGaN/GaN HFETs leads to a considerable difference in temperature between the channel and the bottom of the substrate. Calculation demonstrates that the temperature difference becomes great when environment temperature is relatively high. This phenomenon leads to the substantial lowering of transconductance of device. Also we can see from the presented study that this degradation of device performance is primarily due to the decreasing of electron mobility in channel when temperature increases.

References

[1] Kuliev A, Kumar V, Schwindt R, Selvanathan D, Dabiran A M, Chow P and Adesida I 2003 *Solid-State Electron.* **47** 117

[2] Mishra U K, Parikh P and Wu Y F 2002 *Proc. IEEE* **90** 1022

[3] Javorka P, Alam A, Wolter M, Fox A, Marso M, Heuken M, Luth H and Kordos P 2002 *IEEE Electron Device Lett.* **23** 4

[4] Jeong P, Moo W S and Lee C C 2004 *IEEE Trans. Electron Device* **51** 1753

[5] Nuttinck S, Wangner B K, Banerjee B, Venkataraman S, Gebara E, Laskar J and Harris H M 2003 *IEEE Trans. Microwave Theory and Techniques* **51** 2445

[6] Zhang J F, Zhang J C and Hao Y 2004 *Chin. Phys.* **13** 1334

[7] Teisseyre H, Perlin P, Suski T, Pietraszko A and Moustakas T D 1994 *J. Appl. Phys.* **76** 2429

[8] Guo Q X and Yoshida A 1994 *Jpn. J. Appl. Phys.* **33** 2453

[9] Sher A, Van Schilfgaarde M, Berding M A, Krishnamurthy S and Chen A B 1999 *MRS Internet J. Nitride Semicond. Res.* **4S1** G 5.1

[10] Martin G, Botchkarev A, Rockett A and Morkoc H 1996 *Appl. Phys. Lett.* **68** 2541

[11] Mnatsakanov T T, Levinshtein M E, Pomortseva L I, Yurkov S N, Simin G S and Khan M A 2003 *Solid State Electron.* **47** 111

[12] Kong Y C, Zheng Y D and Zhu R M 2003 *Chin. Phys.* **52** 1756

[13] Ambacher O, Majewski J, Miskys C, Link A, Hermann M, Eickhoff M, Stutzmann M, Bernardini F, Fiorentini V, Tilak V, Schaff B and Eastman L F 2002 *J. Phys. Condens. Matter* **14** 3399

[14] Shur M S, Bykhovski A D and Gaska R 1999 *MRS Internet J. Nitride Semicond. Res.* **4S1** G1.6

[15] Kong Y C, Zheng Y D, Zhou C H, Deng Y Z, Gu S L, Shen B, Zhang R, Han P, Jiang R L and Shi Y 2004 *Acta Phys. Sin.* **53** 2320

[16] Sacconi F, Carlo A D, Lugli P and Morkoc H 2001 *IEEE Trans. Electron Device* **48** 450

[17] Canfield P C, Lam S C F and Allstot D J 1990 *IEEE J. Solid-State Circuits* **25** 299

[18] Akita M, Kishimoto K and Mizutani T 2001 *Phys. Stat. Sol.* (a) **188** 207

[19] Ambacher O, Foutz B, Smart J, Shealy J R, Weimann N G, Chu K, Murphy M, Sierakowski A J, Schaff W J, Eastman L F, Dimitrov R, Mitchell A and Stutzmann M 2000 *J. Appl. Phys.* **87** 334

[20] Freeman J C 2004 Microwave Symposium Digest *IEEE MTT-S International* **3** 2031

[21] Gabriela E B, Dunham S T and Moustakas T D 1999 *MRS Internet J. Nitride Semicond. Res.* **4S1** G6.41

[22] Akita M, Kishimoto S and Mizutani T 2001 *IEEE Electron Device Lett.* **22** 376