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A compact drain current model for heterostructure HEMTs including 2DEG density solution with two subbands

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ABSTRACT

An explicit and precise model for two dimensional electron gas (2DEG) charge density and Fermi level (E_f) in heterostructure high electron mobility transistors (HEMTs) is developed. This model is from a consistent solution of Schrödinger's and Poisson's equations in the quantum well with two important energy levels. With these closed-form solutions, a unified surface potential calculation valid for all the operation regions is derived. With the help of surface potential, a single-piece drain current model is developed which is also capable of describing the current collapse effect by using a semi-empirical expression of source/drain access region resistances. Comparisons with numerical and measured data show that the proposed model gives an accurate description of E_f and drain current in all regions of operation.

1. Introduction

In recent years, heterostructure high electron mobility transistors (HEMTs) have attracted much attention in high-speed and high-power applications. One of the most interesting properties of these devices is the formation of the two dimensional electron gas (2DEG) with a very high electron mobility at the heterointerface. From the computer-aided design perspective, there is still an urgent demand for an accurate and computationally efficient compact DC model for HEMTs.

The formation of 2DEG in the quantum well near the heterointerface is the main principle of the HEMT device operation, and the modeling of 2DEG sheet carrier density (n_s) is a basic requirement in the development of a compact model for these devices. The calculation of n_s has to be obtained from the well-known charge control equations [1] as a self-consistent solution of Poisson's and Schrödinger's equations in the quantum well. This quantum well can be approximated as a triangular well and has two lowest subbands (E_0 and E_1). The major challenge in calculating n_s is due to the complicated transcendental equation of n_s which varies with the gate biases (V_{gs}). Obviously, the transcendental equation is not suitable for compact modeling. Recently, the physical-based approximations [2–4] for explicit solution of n_s were developed and the surface-potential-based drain current models were also presented. However, their calculations were derived by only considering one subband (E_0) in the quantum well and ignoring the other one (E_1). In our previous work [5], we also used this assumption and presented an explicit solution to efficiently compute n_s and the quasi-fermi potential E_f. Compared with the models in [2–4], our scheme [5] is more straightforward and accurate. Nevertheless, as indicated in [6,7], the assumption of neglecting the contribution of the second subband (E_1) is only valid for certain types of devices, and E_1 has a significant impact on device characteristics when device parameters are varied. In [6], an initial result without considering E_1 was obtained first. To enhance the accuracy of the initial, refinements including the contribution from E_1 were carried out by Householder's method for solving implicit functions. In addition, [6] does not take the case of $E_f > E_1$ into account which is important for GaAs-based HEMTs. Therefore, Zhang et al. [7] improved the model in [6], and analytical expressions for n_s and E_f as explicit functions of the terminal biases were proposed. However, this model is very complex. Thus, it is very important to achieve a simply but accurate solution for compact models.

In this paper, accounting for the two lowest subbands in the quantum well, we present an improved analytical calculation for n_s and E_f based on our previous work [5]. After that, the surface potential (ψ_s) calculation can be obtained using E_f. Therefore, a surface-potential-based compact model for HEMTs is developed to predict the current–voltage (I–V) characteristics. Furthermore, the current collapse in I–V characteristics is also captured by using a semi-empirical model for source/drain access region resistances.

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2. The calculation of the Fermi level

As shown in Fig. 1, a self-consistent solution of Schrödinger's and Poisson's equations in the triangular well including two subbands, is given by [7]

$$n_s = \frac{\varepsilon}{qd}(V_{gs} - V_{off} - \phi_n - E_f) \quad (1)$$

$$n_s = D\phi_{th}\left\{\ln\left[1+\exp\left(\frac{E_f - E_0}{\phi_{th}}\right)\right] + \ln\left[1+\exp\left(\frac{E_f - E_1}{\phi_{th}}\right)\right]\right\} \quad (2)$$

$$E_0 = \gamma_0 n_s^{2/3} \quad (3)$$

$$E_1 = \gamma_1 n_s^{2/3} \quad (4)$$

where ε and d are the permittivity and thickness of the material between the gate and 2DEG, respectively, V_{off} is the cutoff voltage, E_f is the Fermi potential with respect to the bottom of conduction band, ϕ_n is the channel potential, D is Density of States, γ_0 and γ_1 are determined by Robin boundary condition [8], and ϕ_{th} is the thermal voltage. Note that, Eqs. (1)–(4) are based on the one-dimensional (1D) Poisson's and Schrödinger's equations, but for high voltage and high field modes, the two-dimensional system has to be solved. For simplification, we only apply the 1D Poisson's and Schrödinger's equations in this paper.

As indicated by Zhang et al. [7], different sets of parameters $\{\gamma_0, \gamma_1, D\}$ lead to different contributions of E_0 and E_1. Therefore, this variation results in a more complicated solution of E_f and n_s. Obviously, as shown in Eqs. (1)–(4), the exact solutions of E_f and n_s are transcendental in nature. To obtain a computationally efficient solution, which is suitable for circuit simulators, the regional approach [3] is employed here. As a result, three operation regions are divided, i.e., the strong 2DEG region, the moderate 2DEG region, and the subthreshold region.

2.1. Strong 2DEG region

Here, we assume that $E_1 > E_0$. In the strong 2DEG region, we have $E_f > E_0$. Thus, there exist two possible conditions: (A) $E_f > E_1$ and (B) $E_0 < E_f < E_1$. For case (A), Eq. (2) can be approximated as

$$n_s = D(E_f - E_0) + D(E_f - E_1) = 2DE_f - D(\gamma_0 + \gamma_1)n_s^{2/3}. \quad (5)$$

Using Eq. (1), E_f as a function of V_{gs} can be expressed as

$$A(V_{go} - E_f) = 2DE_f - D(\gamma_0 + \gamma_1)A^{2/3}(V_{go} - E_f)^{2/3} \quad (6)$$

where $A = \varepsilon/qd$ and $V_{go} = V_{gs} - V_{off} - \phi_n$. Except for some coefficients, Eq. (6) is very similar to the relation of E_f vs. V_{gs} in our previous work [5], but [5] neglected the contribution of E_1. Furthermore, Eq. (6) can be rewritten as a cubic equation

$$aE_f^3 + bE_f^2 + cE_f + e = 0 \quad (7)$$

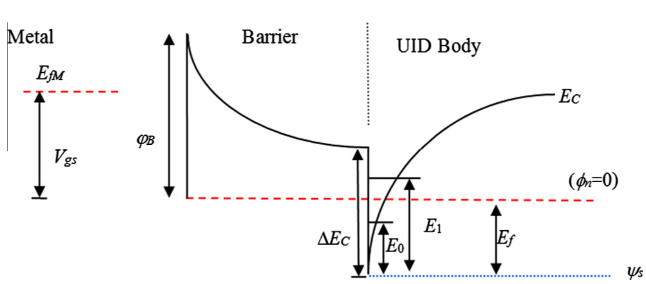

Fig. 1. Energy-band diagram of a HEMT.

where $a = (2 + A/D)^3$, $b = 3(-A/D)V_{go}(2 + A/D)^2 - (\gamma_0 + \gamma_1)^3 A^2$, $c = 3(A/D)^2 V_{go}^2(2 + A/D) + 2(\gamma_0 + \gamma_1)^3 A^2 V_{go}$, and $e = (-A/D)^3 V_{go}^3 - (\gamma_0 + \gamma_1)^3 A^2 V_{go}^2$.

The explicit solution of E_f can be calculated by the S. Fan formulas [9]

$$E_{f,1} = \frac{-b - Y_1^{1/3} - Y_2^{1/3}}{3a} \quad (8)$$

$$Y_{1,2} = A_0 b + 1.5a(-B_0 \pm \sqrt{\Delta}) \quad (9)$$

where $E_{f,1}$ denotes the Fermi potential in the case (A), $\Delta = B_0^2 - 4A_0C_0$, $A_0 = b^2 - 3ac$, $B_0 = bc - 9ae$, and $C_0 = c^2 - 3be$.

For case (B), Eq. (2) is reduced to

$$n_s = D(E_f - E_0) = D(E_f - \gamma_0 n_s^{2/3}). \quad (10)$$

Eq. (10) is the same as the case where E_1 is negligible, which can be solved in the same way as given before [5]. As a consequence, the solution for case (B) is marked as $E_{f,0}$.

2.2. Moderate 2DEG region

In the moderate 2DEG region, we have $0 < E_f < E_0$. Therefore, Eq. (2) can be simplified as [7]

$$n_s = D\phi_{th}\exp\left(\frac{E_f - \gamma_0 n_s^{2/3}}{\phi_{th}}\right). \quad (11)$$

It should be noted that, from [1], Eq. (2) can be re-expressed as

$$E_f = \phi_{th}\ln(Y) \quad (12)$$

$$Y = -\frac{R+S}{2} + \sqrt{\left(\frac{R+S}{2}\right)^2 - RS(1 - e^{n_s/D\phi_{th}})} \quad (13)$$

where $R = e^{1/\phi_{th}E_0}$, $S = e^{1/\phi_{th}E_1}$, and $Y = e^{1/\phi_{th}E_f}$. We plot the relation between E_f and $n_s^{2/3}$ using Eqs. (12) and (13) in Fig. 2, which shows a linear approximation between E_f and $n_s^{2/3}$. Consequently, Eq. (11) can be approximated as

$$n_s = D\phi_{th}\exp\left[\frac{E_f - \gamma_0(k_3E_f + k_1)}{\phi_{th}}\right] = D\phi_{th}\exp\left(\frac{-\gamma_0 k_1}{\phi_{th}}\right) \times \exp\left[\frac{(1 - \gamma_0 k_3)E_f}{\phi_{th}}\right], \quad (14)$$

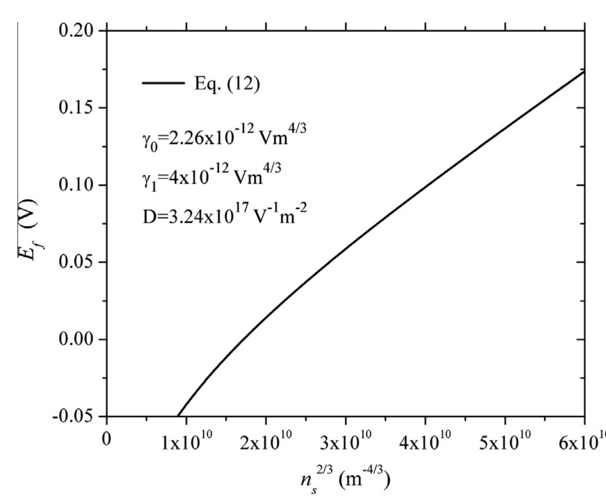

Fig. 2. E_f as a function of $n_s^{2/3}$.