

A New Equivalent MOSFET Representation of a HEMT to Analytically Model Non-Linear Charge Control for Simulation of HEMT Devices and Circuits

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Abstract—It is shown that, from the point of view of the behavior of the charge and position of the Two-Dimensional Electron Gas (2-DEG) as a function of gate-source and drain-source voltages, the complex High Electron Mobility Transistor (HEMT) can be regarded as a simple Buried-Channel (BC) MOSFET. Thus, the characteristics of a HEMT, namely channel charge and capacitance/transconductance as a function of gate voltage below and above threshold are akin those of a BC MOSFET. Hence, there are discrepancies in the conventional Surface Channel MOSFET-like approach to HEMT modeling. Existing simple BC MOSFET dc and ac models can be used for on-paper analysis and computer aided simulation of HEMT devices and circuits, if the HEMT is represented by an equivalent BC MOSFET as derived in this paper. The new representation can be useful for modeling of short-channel HEMT phenomena.

I. INTRODUCTION

THE DETAILS of the internal field distribution in a High Electron Mobility Transistor (HEMT) are more complex than those in a MOSFET. However the final relation between the Two-Dimensional Electron Gas (2-DEG) concentration n_s and the gate voltage V_G in the 2-DEG control regime is similar to that of a MOSFET [1], [2].

So far, the HEMT has been regarded as a Surface Channel (SC) MOSFET in which the insulator thickness is equal to the distance in HEMT between the gate and the 2-DEG position assuming the 2-DEG to be a charge sheet [1]–[5]. However, the 2-DEG position shifts significantly with gate to channel bias [6]–[8] amounting to variation of the insulator thickness along the channel length as a function of gate and drain voltages. This feature, apart from leading to an unrealistic SC MOSFET representation, complicates matters calling for either a numerical or at least an iterative analytical solution of model equations to derive any of the characteristics of interest [6], [8]. To enable evaluation of the characteristics through simple closed-form expressions associated with a realistic SC MOSFET representation, the 2-DEG position is assumed to be constant at a distance of 45–80 Å from the heterointerface [2], [3]–[6]. This MOSFET representation yields a linear $n_s - V_G$ relation and consequently constant

gate capacitance C or transconductance g_m due to 2-DEG at low drain-source voltages. These predictions are inaccurate, since actually the $n_s - V_G$ relation is nonlinear leading to a variation of the C or g_m with V_G [6]–[8]. Further, the threshold voltage predicted by this representation can be in error by as much as 25% [2], [9], [10]. Also, as shown later in this paper, similar discrepancies may result in other device parameters describing near-threshold and subthreshold current and capacitance conditions, as these parameters are closely tied to the 2-DEG location.

The objective of this paper is to present a more realistic equivalent MOSFET representation of the HEMT which depicts the internal charge conditions with greater fidelity, and predicts the various terminal HEMT characteristics more accurately, using only closed form equations avoiding numerical or iterative techniques. It is shown that the 2-DEG charge and position along the channel length in a general HEMT with given bias conditions, are simulated in a Buried-Channel (BC) MOSFET having appropriate physical parameters and same bias conditions. In this paper we have considered single-heterostructures only. Our approach can be extended to double-heterostructures [11] also.

II. THE EQUIVALENT BC-MOSFET REPRESENTATION OF A HEMT

For a given set of bias conditions, the similarity between the charge conditions within a BC MOSFET and a HEMT, assuming a fully depleted AlGaAs layer and charge sheet approximation of the 2-DEG in the HEMT, is illustrated in Fig. 1(a). The important feature of this similarity is the simulation of HEMT 2-DEG charge sheet location by the edge of the gate-controlled depletion layer in the BC MOSFET channel. This depletion layer expands on increase in the magnitude of gate to channel voltage. As a result, the reduction in the BC MOSFET conduction charge n_s is also accompanied by its shift away from the gate, much like the behavior of the 2-DEG in HEMT's.

The appropriate equivalent BC MOSFET representation of a HEMT is one which satisfies the following three criteria:

- 1) the total areal doping concentration in the channel is equal to the maximum areal 2-DEG concentration n_{s0} ;

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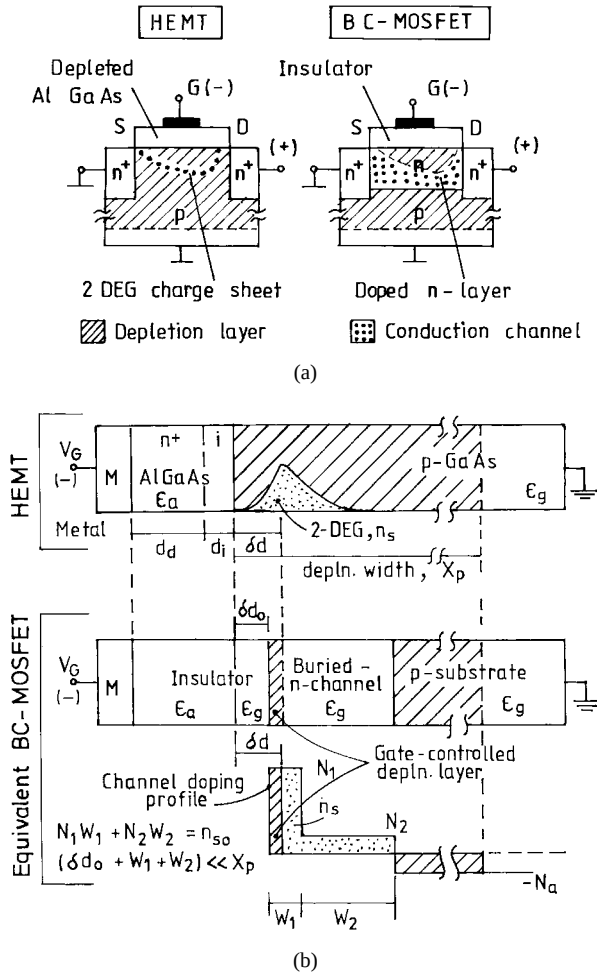


Fig. 1. The schematic cross section of a HEMT and its BC MOSFET equivalent. (a) Similarity between the charge conditions in the two devices under identical bias conditions. The 2-DEG in the HEMT is regarded as a charge sheet. The substrate controlled charge in the BC MOSFET is negligible. (b) Detailed correspondence between the geometrical and charge parameters of the two devices at a given position along the channel for a given bias condition.

- 2) the mathematical relation between V_G and the channel depletion charge controlled by it is invertible and integrable, so that closed-form expressions can be derived for $I-V$ and $C-V$ characteristics [12]; and
- 3) the depletion edge and conduction charge in the buried-channel follow, respectively, the 2-DEG position and the 2-DEG concentration in the HEMT, as a function of V_G .

The parameters of the equivalent BC MOSFET, namely channel width, channel length, and the substrate doping, are identical to those of the HEMT. Other parameters shown in Fig. 1(b) and expressed in Table I, namely the BC doping profile, the insulator thickness t_0 and the flat-band voltage V_{FB} are derived below from the above criteria.

The second criterion mentioned above has been shown to restrict the channel doping variation to either a single-step or a multi-step profile with uniform doping in each step [12]. Now consider the third criterion. A single-step or uniform doping implies a linear relationship between n_s and the depletion edge location. Therefore, a multi-step profile yields a piecewise-linear curve between n_s and the depletion edge location, with

TABLE I
THE PARAMETERS OF THE BC-MOSFET REPRESENTATION IN TERMS OF MAXIMUM 2-DEG CONCENTRATION AND OTHER HEMT PARAMETERS, AT TWO DIFFERENT TEMPERATURES FOR TWO DIFFERENT APPROACHES OF ESTIMATING ELECTRON CONFINEMENT EFFECTS

Parameter	Triangular well		Self-consistent	
	300 K	77 K	300 K	77 K
δd_0 (Å)	$173/\sqrt{n'_{s0}} - 55$ 1.39	$74/\sqrt{n'_{s0}} + 31$ 1.39	$56.2(n'_{s0})^{-2/3}$	$46.8(n'_{s0})^{-1/3}$
$W_1/\delta d_0$	2 $3.145 - \sqrt{n'_{s0}}$	1.52 $2.39 + \sqrt{n'_{s0}}$	0.91	0.39
N_1/N_2	15	14	$28 - 4n'_{s0}$	$47 - 14n'_{s0}$
ϕ_{f0} (mV)	$346\sqrt{n'_{s0}}$ $-55n'_{s0} - 152$	$148\sqrt{n'_{s0}}$ $+31n'_{s0} - 32$	$234.5(n'_{s0})^{1/3}$ -155	$97.6(n'_{s0})^{2/3}$
$N_1 = 0.73n_{s0}/W_1$ $W_2/W_1 = 0.37N_1/N_2$ $n'_{s0} = n_{s0} \times 10^{-12} \text{ cm}^2$				
$V_{FB} = \phi_B - \delta\phi_C - (q/2\epsilon_a) N_d d_d^2 + \phi_{f0} + q(n'_{s0} + N_a X_p)(d_d + d_i)/\epsilon_a$				
$t_0 = d_d + d_i + \delta d_0 (\epsilon_a/\epsilon_g)$				

slopes of different segments related to doping concentrations in the different steps. Calculations have shown that the 2-DEG location is a highly nonlinear function of n_s [6]–[8]. Hence at least two segments with different slopes are required to properly approximate this variation. This is shown in Fig. 2(a), where the 2-DEG offset δd which is the distance between the 2-DEG position and the heterointerface in the HEMT, has been plotted as a function of n_s . More details about this diagram appear later, but it is clear that the offset has a nonzero value δd_0 for $n_s = n_{s0}$. These considerations yield, as shown in Fig. 1(b), a double-step doping profile with total areal dopant concentration

$$N_1 W_1 + N_2 W_2 = n_{s0} \quad (1)$$

and an insulator thickness equal to the effective distance in HEMT between the gate and the 2-DEG position for $n_s = n_{s0}$. In the formula given in the table for t_0 , the widths of doped and spacer AlGaAs layers are d_d and d_i , respectively. As will be seen shortly, mathematical derivations using a double-step profile are as simple as those using a uniform profile. In fact such derivations are routinely carried out for a channel-implanted MOSFET [13].

The δd_0 expressions of the table are derived using [7]

$$\delta d = (\epsilon_g/q) d\phi_f/dn_s \quad (2)$$

where ϵ_g is the GaAs dielectric constant, q is the electron charge and ϕ_f is the fermi-level at the heterointerface with respect to the bottom of the GaAs conduction band edge. The relationship between ϕ_f and n_s including the quantum-mechanical confinement effects on electrons in 2-DEG can be evaluated using a triangular potential well approximation using the interface electric field [14] or from a self-consistent solution of Poisson's and Schrodinger's equations [7]. We have obtained the δd_0 expressions for both of the above confinement models using (2) and the $\phi_f - n_s$ expressions given in [7] and [14].

To derive expressions for N_1, W_1, N_2 , and W_2 , we have made extensive calculations and found that the third criterion

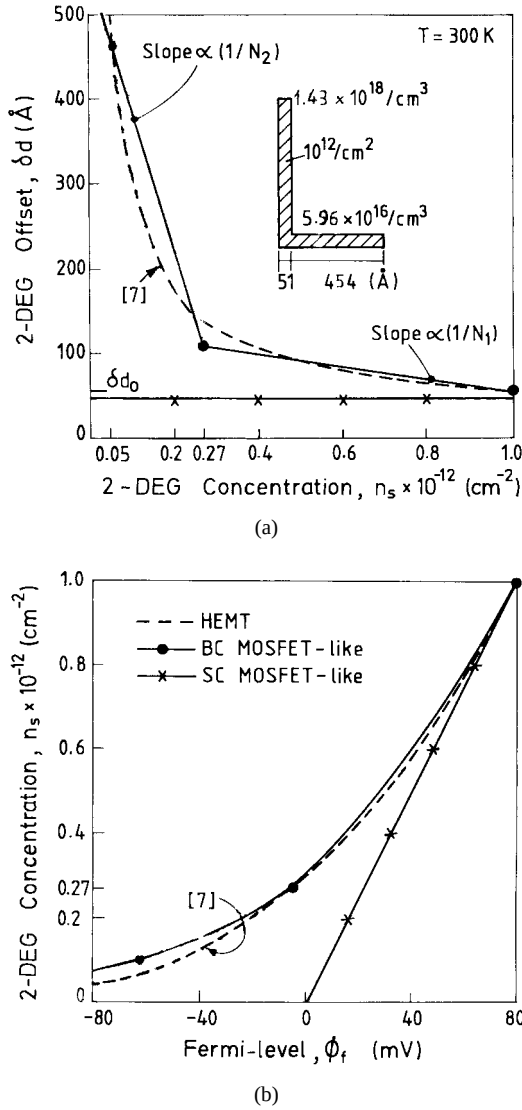


Fig. 2. HEMT characteristics as simulated by the BC doping profile shown. (a) A piecewise-linear two-segment approximation of the actual $\delta d - n_s$ relationship. (b) The $\phi_f - n_s$ relation.

mentioned earlier is best met, and the overall C-V curve simulated by the BC MOSFET will track the actual curve of the HEMT due to 2-DEG, by imposing three restrictions on the doping profile. Firstly, 73% of the total channel charge is incorporated over the width W_1

$$N_1 W_1 = 0.73 n_{s0}. \quad (3)$$

Secondly, the simulated and actual values of ϕ_f match when this charge is just depleted, i.e., when $n_s = 0.27 n_{s0}$. Thirdly, the simulated and actual values of the offset δd match when only 5% of n_{s0} is left for conduction. Recall that a similar match between the two offset values already exists for $n_s = n_{s0}$, due to the choice of insulator thickness. The actual values of ϕ_f and δd are calculated from (2) and the $\phi_f - n_s$ expressions of [7], [14]. The simulated values of these two parameters are obtained from the $\phi_f - n_s$ and $\delta d - n_s$ relationships simulated by the BC MOSFET

$$\begin{aligned} \phi_f &= \phi_{f0} - (q/\epsilon_g)(n_{s0} - n_s)\delta d_0 - (q/2\epsilon_g)(n_{s0} - n_s)^2/N_1 \\ n_s &\geq N_2 W_2 = 0.27 n_{s0} \end{aligned} \quad (4)$$

$$\begin{aligned} \phi_f &= \phi_{f0} - (q/\epsilon_g)(n_{s0} - n_s)[\delta d_0 - W_1(N_1/N_2 - 1)] \\ &\quad - (q/2\epsilon_g)(n_{s0} - n_s)^2/N_2 \\ &\quad - (q/2\epsilon_g)N_1 W_1^2(N_1/N_2 - 1) \\ 0 &\leq n_s < N_2 W_2 = 0.27 n_{s0} \end{aligned} \quad (5)$$

$$\delta d = \delta d_0 + (n_{s0} - n_s)/N_1, \quad n_s \geq 0.27 n_{s0} \quad \text{and} \quad (6)$$

$$\begin{aligned} \delta d &= \delta d_0 + (n_{s0} - n_s)/N_2 - W_1(N_1/N_2 - 1) \\ 0 &\leq n_s < 0.27 n_{s0} \end{aligned} \quad (7)$$

where $\phi_f = \phi_{f0}$ when $n_s = n_{s0}$. The (4) and (5) are derived by matching the $V_G - n_s$ expressions of the HEMT [6]

$$\begin{aligned} V_G &= \phi_B - \delta\phi_c - (q/2\epsilon_a)N_d d_d^2 + \phi_f \\ &\quad + (q/\epsilon_a)(n_s + N_a X_p)(d_d + d_i) \end{aligned} \quad (8)$$

with that of the BC MOSFET [15]

$$\begin{aligned} V_G &= V_{FB} - (q/\epsilon_a)(n_{s0} - n_s)t_0 - (q/2\epsilon_g)(n_{s0} - n_s)^2/N_1 \\ n_s &\geq n_{s0} - N_1 W_1 \quad \text{and} \end{aligned} \quad (9)$$

$$\begin{aligned} V_G &= V_{FB} - (q/\epsilon_a)(n_{s0} - n_s) \\ &\quad \cdot [t_0 - (\epsilon_a/\epsilon_g)W_1(N_1/N_2 - 1)] \\ &\quad - (q/2\epsilon_g)(n_{s0} - n_s)^2/N_2 \\ &\quad - (q/2\epsilon_g)N_1 W_1^2(N_1/N_2 - 1) \\ 0 &< n_s \leq n_{s0} - N_1 W_1. \end{aligned} \quad (10)$$

Here, ϕ_B is the schottky barrier height, $\delta\phi_c$ is the conduction band discontinuity, ϵ_a and N_d are, respectively, dielectric constant and doping in AlGaAs. The term $N_a X_p$ denotes GaAs bulk depletion charge at threshold, N_a is doping and X_p is the depletion width (see Fig. 1). The flat-band voltage of the BC-MOSFET V_{FB} is equal to the gate voltage in the HEMT when the gate begins to deplete the 2-DEG, i.e., when $n_s = n_{s0}$, and is expressed in Table I. The values of $W_1/\delta d_0$ and N_1/N_2 so obtained have been listed in Table I along with the expressions for N_1 and W_2 obtained using (1) and (3), for both electron confinement models. It is important to note that these values are independent of bias conditions.

By way of example we demonstrate in Fig. 2(a) and (b), the $\delta d - n_s$ and $\phi_f - n_s$ characteristics predicted by the BC MOSFET representation for a HEMT with $n_{s0} = 10^{12}/\text{cm}^2$, assuming the self-consistent electron confinement model. It is mentioned here that for self consistent-calculations, we use the $\phi_f - n_s$ expressions of [7] when $n_s \geq 0.27 n_{s0}$; for smaller n_s values, the $\phi_f - n_s$ behavior approaches that of expressions given in [14], since confinement effects decrease.

III. NON-LINEAR CHARGE CONTROL AND CAPACITANCE EXPRESSIONS

We first consider the above threshold and subthreshold conditions of the 2-DEG control regime separately and then unify the expressions in the two regions.

A. Above Threshold Conditions

Inverting (9) and (10) we obtain

$$\begin{aligned} n_s &= n_{s0} - (\epsilon_g N_1 / C_0) \\ &\quad \cdot [\sqrt{1 - (V_G - V_{FB}) / (q N_1 \epsilon_g / 2 C_0^2)} - 1] \\ V_1 &\leq V_G \leq V_{FB} \quad \text{and} \end{aligned} \quad (11)$$

$$n_s = N_2 W_2 - (\epsilon_g N_2 / C_1) \cdot \left[\sqrt{1 - (V_G - V_1) / (q N_2 \epsilon_g / 2 C_1^2)} - 1 \right] \quad (12)$$

$$V_T \leq V_G < V_1.$$

Here

$$C_0 = \epsilon_a / t_0 \quad (13)$$

denotes the insulator capacitance

$$C_1 = \epsilon_g / (W_1 + t_0 \epsilon_g / \epsilon_a) \quad \text{and} \quad (14)$$

$$V_1 = V_{FB} - q N_1 W_1 / C_0 - (q / 2 \epsilon_g) N_1 W_1^2 \quad (15)$$

respectively, denote the capacitance and gate voltage when the channel depletion width is W_1 , and

$$V_T = V_1 - q N_2 W_2 / C_1 - (q / 2 \epsilon_g) N_2 W_2^2 \quad (16)$$

represents the pinch-off/threshold voltage, i.e., the gate voltage when $n_s = 0$. Note that (11) and (12) can be readily integrated from source to drain to obtain closed form relations directly in terms of bias voltages, for both small-signal gate to source/drain/bulk capacitances as per the Meyer model and dc current.

In the 2-DEG control regime, as the gate is made more negative, the three distinct phases of the C-V behavior common to HEMT and BC MOSFET are: capacitance decrease with reduction in channel charge, rapid capacitance fall near channel pinch-off to a value decided by the substrate depletion width, and the slow capacitance rise thereafter due to gradual collapse of this depletion width [6], [16]. Using (11), (12), and

$$C = q \, dn_s / dV_G \quad (17)$$

we obtain

$$C = C_0 / \sqrt{1 - [(V_G - V_{FB}) / (q N_1 \epsilon_g / 2 C_0^2)]} \quad (18)$$

$$V_1 \leq V_G \leq V_{FB}$$

$$C = C_1 / \sqrt{1 - [(V_G - V_1) / (q N_2 \epsilon_g / 2 C_1^2)]} \quad (19)$$

$$V_T \leq V_G < V_1.$$

Note that the $n_s - V_G$ relations (11) and (12) and $C - V_G$ relations (18) and (19) are as simple as those of a MOS capacitor with a uniformly doped substrate.

B. Subthreshold Conditions

Applying available BC MOSFET results [17] to our representation

$$n_s = n_0 \exp[(V_G - V_T) / \eta V_t] \quad \text{for } V_G < V_T \quad (20)$$

and using (17)

$$C = (q n_0 / \eta V_t) \exp[(V_G - V_T) / \eta V_t] \quad \text{for } V_G < V_T. \quad (21)$$

Here, V_t is the thermal voltage and

$$\eta = 1 + (C_p / C_T) = 1 + [(W_1 + W_2 + t_0 \epsilon_g / \epsilon_a) / X_p] \quad (22)$$

is the ideality factor signifying capacitive coupling from gate to substrate [17]

$$C_p = \epsilon_g / X_p \quad (23)$$

is the channel-substrate capacitance, and

$$C_T = \epsilon_g / (W_1 + W_2 + t_0 \epsilon_g / \epsilon_a) \quad (24)$$

is the gate-channel capacitance at threshold which is given by (19) at $V_G = V_T$. The value of n_0 is derived below.

C. Unification of Above Threshold and Subthreshold Expressions

To ensure continuity in charge equations as well as their first derivatives, the pairs (12), (20) for the charge and (19), (21) for the capacitance, can be pieced together at a gate voltage slightly above V_T given by

$$V_T' \approx V_T + \eta V_t [1 - (\eta V_t C_T / q) / (2 N_2 \epsilon_g / C_T)] \quad (25)$$

using

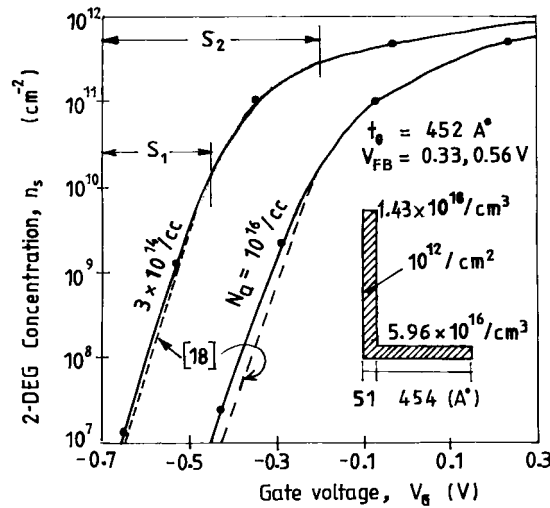
$$n_0 \approx (0.368 \eta V_t C_T / q) [1 + (3 \eta V_t C_T / q) / (2 N_2 \epsilon_g / C_T)]. \quad (26)$$

Thus, (12) and (19) are used for $V_G > V_T'$ rather than $V_G > V_T$, and similarly (20) and (21) are used for $V_G \leq V_T'$ rather than $V_G \leq V_T$.

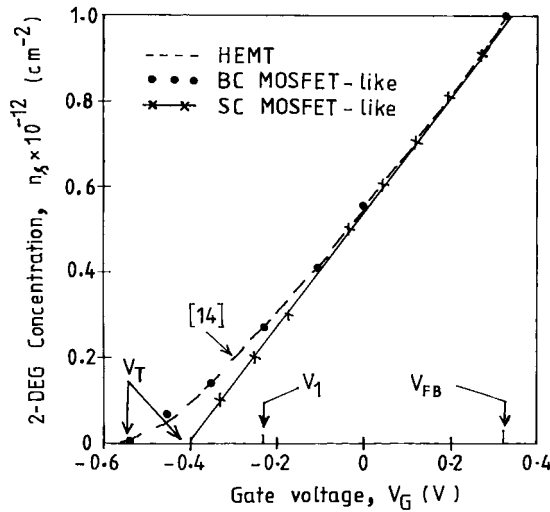
IV. COMPARISONS AND DISCUSSIONS

The $n_s - V_G$ and $C - V_G$ calculations of a HEMT using (8) and (17) and rigorous $\phi_f - n_s$ relations are compared with those of its BC MOSFET representation in Fig. 3. The HEMT parameters are $n_{s0} = 10^{12} / \text{cm}^2$, $d_d + d_i = 400 \text{ \AA}$, $[\phi_B - \delta \phi_c - (q / 2 \epsilon_a) N_d d_d^2] = -0.4 \text{ V}$. The equivalent BC MOSFET parameters calculated using Table I appear in figure inserts, the parameters for Fig. 3(b) and (c) being identical. The entire range of charge conditions from subthreshold to saturation, for values of $N_a X_p = 8 \times 10^{10}$ and $4.6 \times 10^{11} / \text{cm}^2$ associated with $N_a = 3 \times 10^{14}$ and $10^{16} / \text{cm}^3$, respectively, is covered in Fig. 3(a), where the HEMT calculations are based on self-consistent unified charge control model of [18]. The behavior above threshold is emphasized in Fig. 3(b) using triangular potential well model based on interface electric field assuming negligible N_a [14], and Fig. 3(c) shows the capacitance behavior for this case. It is mentioned here that our analysis incorporates effects of $N_a X_p$ on AlGaAs potential drop. But $N_a X_p$ effects on ϕ_f for $n_s > 0.05 n_{s0}$ or $n_s > 5 \times 10^{10} / \text{cm}^2$ are ignored, making the BC doping shape independent of N_a . This does not cause significant errors for $N_a < 10^{16} / \text{cm}^3$, which are the values in practice, as is evident from Fig. 3(a).

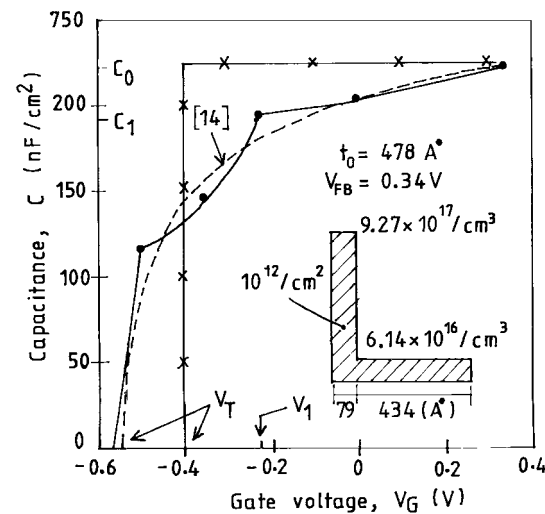
The good agreement between the compared results establishes the ability of our approach to predict subthreshold and above threshold dc and ac characteristics. Further, our expressions are invertible, integrable and continuous with continuous first derivatives, i.e., have properties adequate for circuit simulation [19], [20]. They are physics based, use no empirical fitting parameters, and can be written down using elementary FET theory. The parameters, namely t_0 , N_1 , W_1 , N_2 , W_2 , V_{FB} and η used in the expressions permit simulation directly in terms of process conditions, or if necessary, can be readily extracted from simple charge/current and capacitance measurements as is clear from Fig. 3. In contrast, existing models are lacking in one or more of the above aspects. The models such



(a)



(b)



(c)

Fig. 3. A comparison of the approximations simulated by the BC-MOSFET representation with rigorous calculations for a HEMT. (a) Subthreshold and above threshold $n_s - V_G$ for two different bulk dopings. S_1 and S_2 indicate, respectively, BC-MOSFET-like and conventional subthreshold regions for a given doping. (b) Above threshold $n_s - V_G$. (c) $C - V_G$.

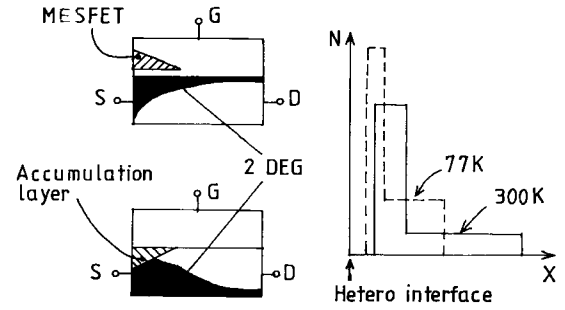


Fig. 4. Pictorial depiction of 2-DEG in HEMT. (a) Prevailing SC MOSFET-like (e.g., [3]–[5]). (b) Improved BC MOSFET-like (simulation of parasitic MESFET by BC accumulation layer is also shown). (c) Increase in charge confinement with lowering of temperature as revealed by BC doping.

as [20]–[22] suitable for circuit simulation employ nonphysical approximations in the form of empirical fits to the actual $n_s - V_G$ variation, require experimental parameter extraction, are valid above threshold only, and [21], [22] treat dc characteristics only. The unified charge control models [18], [23] describe subthreshold and above threshold regions by a single $n_s - V_G$ expression whose all derivatives are continuous, unlike in our method. However, the expression in [23] requires fitting parameters (m and γ) to define the shape of the dc $I - V$ curve, and cannot be analytically integrated to obtain small-signal gate to drain/source/bulk Meyer capacitances needed in ac simulation. Similarly, the expression in [18] cannot be inverted or integrated to yield capacitance or $I - V$ characteristics explicitly in terms of bias voltages. Thus it is useful for simulating a single device and not circuits, and this applies also to the physical model in [8], which moreover is limited to above threshold conditions. In addition, as pointed out in the remaining part of this section, our approach has important modeling features which have not been exposed by the earlier models.

Our model is not merely an analytically manageable continuous piecewise multisection fit to actual $n_s - V_G$ characteristics. As shown in Fig. 4, the BC MOSFET representation improves upon the prevailing SC MOSFET-like pictorial depiction of the spatial 2-DEG distribution (e.g., [3]–[5]). Pictorial depiction provides an intuitive feel for conditions within the device based on which device analysis is carried out, and hence should be as accurate as possible. The BC doping profile makes transparent, the rate and extent of 2-DEG movement away from the AlGaAs/GaAs interface as the charge condition varies from saturation to threshold, and changes in these with temperature. It is immediately clear from the representation that, a BC MOSFET or MESFET-like approach to HEMT modeling is more appropriate than a SC MOSFET-like approach. Note that a MESFET is equivalent to a BC MOSFET of zero insulator thickness. Derivation of parameters, particularly those capturing near threshold current phenomena, in a SC MOSFET-like manner can lead to discrepancies, since these parameters are closely tied to the 2-DEG location. This is demonstrated below.

The V_T estimated in our approach coincides with the transition in the mode of channel conduction from subthreshold diffusion to above threshold drift. It can be measured as the gate

voltage at which the drain-conductance or transconductance approaches zero (e.g., [24]), or as the gate voltage when drain current of $(W/L)q\mu n_0[\eta V_T + qn_0 t_0/\epsilon_a]$ i.e., $\sim (W/L) \times 1 \mu A$ is flowing (e.g., [3]), the conductance and current measurements being carried out at low drain to source voltage of ~ 0.1 V. In fact, comparing various threshold voltage definitions of HEMT's and their measurement procedures, it has been shown [3] that the V_T defined and determined as mentioned above is more appropriate than the V_T obtained from the X -intercept of the drain current vs V_G (or n_s vs V_G) plot which has some inadequacies [3]. The difference between our and X -intercept V_T estimates is seen from Fig. 3(b), where we have shown the linear SC MOSFET-like $n_s - V_G$ plot for the HEMT, taking insulator thickness $d_d + d_i + 80 \text{ \AA} = 480 \text{ \AA}$ [2]. The $V_T = -0.4$ V predicted by the SC MOSFET representation is about 25% more positive as compared to $V_T = -0.53$ V predicted by the BC MOSFET. It is pertinent to note that authors in [10] report significant measured drain-source conductance even at voltages which are 0.2 V less than the X -intercept V_T . Further, as per the present SC MOSFET-like HEMT convention, the nonlinear portion of the $n_s - V_G$ curve for $V_T < V_G < V_1$ in Fig. 3(a) and (b), which forms a significant part of the overall $n_s - V_G$ curve, would be classified as subthreshold although the drain current in this region would be calculated based on drift transport (e.g., [21], [22]). All such discrepancies are eliminated if the V_T is defined in terms of the BC MOSFET representation proposed in this paper.

It is interesting to note that (12) expressing η is different from that derived in the unified charge control model of [18] from SC MOSFET considerations. For the limiting case of AlGaAs layer thickness approaching zero, the value of $(\eta - 1)$ approaches zero in [18] but a nonzero value in our case. Consequently, for small AlGaAs layer thickness, the experimentally extracted value of substrate doping from η expression of [18] tends to be higher than that obtained using our expression. Further the subthreshold parameter n_0 in our model as per (26) turns out to be about seven times smaller than the corresponding value of $5 \times 10^{10}/\text{cm}^2$ derived empirically in [18], and the threshold voltage values in the two models differ by about 80 mV.

Now we take up short-channel effects like drain induced barrier lowering and V_T reduction in submicron channel length devices. It has been shown that these effects in HEMT's are MESFET-like and originate from 2-D potential distribution under the gate, and that movement of the 2-DEG has to be taken into account to avoid considerable loss of accuracy in their analysis [25]. A simultaneous solution of Poisson's and Schrodinger's equations in two dimensions is necessary for this analysis [25]. The charge-voltage values obtainable from such a solution for the HEMT, involving enormous computation, can be readily simulated in the simple equivalent BC MOSFET geometry by solving the Poisson's equation alone, and such an approach opens up the possibility of an analytical solution along lines existing for MESFET's or MOSFET's [26]. That such a simulation is accurate in one-dimension has been established in this paper. The confidence that it can be fairly accurate even in two dimensions stems from encouraging results obtained in analogous context involving simulation

of short-channel effects in nonuniformly doped MOSFET's [13]. A simplified 'Box' doping, used to simulate the one-dimensional charge-voltage relation in nonuniformly doped channel, proved quite useful in simulation of 2-D charge-voltage conditions governing the short-channel effects [13].

Finally, it may be mentioned that we have not addressed the parasitic MESFET conduction in HEMT's [5], since it occurs mostly outside the 2-DEG control regime which is the subject of this paper. Nevertheless, it is interesting to note that, for gate voltage conditions identical to those in a HEMT when the MESFET appears in the AlGaAs layer, an accumulation layer appears in the BC MOSFET. Except for the distance between the MESFET channel and the gate, other details of the charge distributions along the channel length in the MESFET for various gate and drain biases, are simulated by the accumulation layer conditions in the BC MOSFET [27] as shown Fig. 4. Further, the approach presented in this paper neglects capacitance contribution from AlGaAs donor naturalization effects. This component of the capacitance simply adds on to the 2-DEG capacitance modeled in this paper [5].

V. CONCLUSION

We have established that the nonlinear 2-DEG charge-voltage phenomena of the complex HEMT can be replicated in the much simpler BC MOSFET, provided the parameters of the BC MOSFET are chosen appropriately as derived in this paper. This fact may be exploited to model a HEMT directly in terms of its process parameters, using simple closed-form expressions of the BC MOSFET with suitable changes in the mobility parameters. The new approach yields a HEMT model useful to the circuit engineer for computer aided simulation of static and dynamic performance of circuits, without sacrificing the appeal to the physical intuition of a device physicist carrying out design, analysis and simulation of devices.

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