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Emission-Diffusion Theory of the MOSFET

Mark Lundstrom, Supriyo Datta, and Xingshu Sun

Abstract—An emission-diffusion theory that describes MOSFETs from the ballistic to diffusive limits is developed. The approach extends the Crowell-Sze treatment of metal-semiconductor junctions to MOSFETs and is equivalent to the scattering/transmission model of the MOSFET. The paper demonstrates that the results of the transmission model can be obtained from a traditional, drift-diffusion analysis when the boundary conditions are properly specified, which suggests that traditional drift-diffusion MOSFET models can also be extended to comprehend ballistic limits.

Index Terms— ballistic transport, MOSFETs, nanoelectronics, semiconductor device modeling

I. INTRODUCTION

Short channel transistors operate in a quasi-ballistic regime in which the channel length (or the length of the critical part of the channel) is comparable to the mean-free-path for backscattering [1 - 3]. The still widely used traditional models for transistors are, however, based on the assumption that the channel (or the critical part of the channel) is many mean-free-paths long, so they do not scale gracefully from the diffusive to ballistic limits. The virtual source (VS) model [4, 5] is a semi-empirical model based on the physics of the scattering (or transmission) model [6-8]. The VS model includes, however, parameters that can only be determined by matching to experiments and does not provide a complete, analytical description for arbitrary gate and drain to source voltages and for short to long channel lengths. Recently, a Virtual Source Emission-Diffusion (VSED) model has been reported [9]. The VSED model removes the restriction of the VS model to short channels, it replaces the empirical drain current saturation function with a physics-based expression, and it predicts the high bias injection velocity rather than empirically fitting it to experimental data. The model provides a good description of short and long channel Si and III-V FETs [9]. One goal of this paper is to derive the model that was the starting point for [9].

The main goal of this paper is to show that results that have been previously derived by a number of different methods can all be derived using traditional drift-diffusion equations with appropriate attention to boundary conditions. The approach begins with the Crowell-Sze ballistic to diffusive treatment of the metal-semiconductor (MS) diode

[10] and extends it to MOSFETs. By employing for the most part, a traditional, well-known analysis approach, this paper demonstrates that when carefully used, drift-diffusion equations can describe quasi-ballistic and even ballistic transport.

This paper continues in Sec. II with a review of the derivation of the emission-diffusion model for the MS diode using the notation of this paper. In Sec. III, the I/V characteristics of a MOSFET are derived by extending the MS diode approach to include MOS electrostatics. The result is discussed in Sec. IV, and the contributions of the paper are summarized in Sec. V.

II. EMISSION-DIFFUSION THEORY OF THE MS DIODE

The diffusion theory of the MS diode assumes that the space charge region is many mean-free-paths long while the thermionic emission model assumes that carriers do not scatter (see Chapter 5 in [11]). Crowell and Sze developed an emission-diffusion theory that combines the two approaches and describes MS diodes from the ballistic to diffusive regimes [10]. Before developing an analogous emission-diffusion theory of the MOSFET, we review the emission-diffusion theory of the MS diode.

Figure 1 is a sketch of the energy band diagram of an MS diode under a reverse bias. The current and electron density in the semiconductor are related to the quasi-Fermi level, F_n , by

$$J_n = n\mu_n \frac{dF_n}{dx} = J_2 \quad (1)$$

$$n = N_C e^{(F_n - E_C)/k_B T}, \quad (2)$$

where Maxwell-Boltzmann statistics have been assumed, and N_C is the effective density-of-states. Using (1) and (2), we write the electron current in the semiconductor as

$$J_n = N_C \mu_n e^{(F_n - E_C)/k_B T} \frac{dF_n}{dx} = N_C k_B T \mu_n e^{-E_C/k_B T} \frac{d}{dx} \left(e^{F_n/k_B T} \right). \quad (3)$$

By assuming a constant current (no recombination-generation) and constant effective density-of-states and mobility, (3) can be integrated across the space-charge region to find

$$\frac{J_n}{q N_C D_n} \int_{0^+}^L e^{E_C(x)/k_B T} dx = \int_{F_n(0^+)}^{F_n(L)} d \left(e^{F_n/k_B T} \right) = e^{F_n(L)/k_B T} - e^{F_n(0^+)/k_B T} \quad (4)$$

where the Einstein relation, $D_n = (k_B T/q) \mu_n$, has been used.

Defining a critical length as

$$\ell \equiv \int_0^L e^{[E_C(x) - E_C(0^+)]/k_B T} dx \quad (5)$$

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Fig. 1. Energy band diagram of an n-type MS diode under reverse bias. The current, J_1 , is the thermionic current across the interface (i.e. the emission current), and J_2 , is the current across the space-charge region (i.e. the diffusion current). Since the two are in series, $J_1 = J_2 = J_n$.

and a diffusion velocity across this critical length,

$$v_D = D_n / \ell. \quad (6)$$

we can write (4) as

$$\frac{J_n e^{E_C(0+)/k_B T}}{N_C v_D} = e^{F_n(L)/k_B T} - e^{F_n(0+)/k_B T}. \quad (7)$$

Note that (7) follows simply from the diffusion equation (1). We could view it as the “diffusion component” of the emission-diffusion theory. Next, we need the “emission component” involving the metal-semiconductor interface in order to determine $F_n(0^+)$.

The boundary conditions on the quasi-Fermi level, F_n , are

$$F_n(x=0^-) = E_F \quad (8)$$

and

$$F_n(x=L) = E_F - qV_D. \quad (9)$$

Note that $x=0^-$ is in the metal; what we need in (7) is F_n at $x=0^+$, on the semiconductor side of the interface. For this we follow Crowell and Sze and write

$$J_n = q(n(0^+) - n_0(0^+))v_R = J_1, \quad (10)$$

where

$$v_R = \sqrt{\frac{k_B T}{2\pi m^*}} = \frac{v_T}{2} \quad (11)$$

is the so-called Richardson velocity and v_T is the unidirectional thermal velocity. Using (2) in (10), we find the “emission component” as

$$\frac{J_n e^{E_C(0+)/k_B T}}{qN_C v_R} = e^{F_n(0+)/k_B T} - e^{E_F/k_B T}. \quad (12)$$

Adding (7) to (12) we eliminate $F_n(0^+)$ to obtain the emission-diffusion result:

$$\frac{J_n e^{E_C(0+)/k_B T}}{N_C v_{eff}} = e^{F_n(L)/k_B T} - e^{E_F/k_B T} \quad (13a)$$

where

$$v_{eff} = \left[\frac{1}{D_n/\ell} + \frac{1}{v_R} \right]^{-1}. \quad (13b)$$

From (13) we have

$$J_n = qN_C v_{eff} e^{-\phi_{Bn}/k_B T} \left(e^{-qV_D/k_B T} - 1 \right), \quad (14)$$

noting that the Schottky barrier height (Fig. 1) is given by

$$q\phi_{Bn} = E_C(0^+) - E_F. \quad (15)$$

Equation (14) is the Crowell-Sze emission-diffusion theory of the MS diode [10]. The effective velocity in the current expression is the smaller of two velocities – the velocity at which electrons diffuse across the critical region, D_n/ℓ , and the thermal velocity, v_R , associated with the emission process. In the diffusive limit, $v_{eff} \rightarrow D_n/\ell$, and in the ballistic limit $v_{eff} \rightarrow v_R$. Note that the negative sign for the voltage in (14) comes from the fact that a positive voltage applied at $x=L$ reverse biases the Schottky barrier.

The emission-diffusion theory has proven to be a reliable description of the IV characteristics of MS diodes. We seek to develop an analogous theory for the IV characteristics of a MOSFET. To do so MOS electrostatics must be incorporated.

III. EMISSION-DIFFUSION THEORY OF THE MOSFET

Figure 2 is an energy band diagram for an n-channel MOSFET under high gate and drain bias. Electrons are thermionically emitted over the source to channel barrier and then flow down the potential drop to the drain. The quantity, $E_C(0) - E_F$, is analogous to the Schottky barrier height, $q\phi_{Bn}$, of the MS diode, and the drain current is analogous to the reverse bias current of a Schottky barrier diode. The difference is that the “Schottky barrier height” of the MOSFET is controlled by the gate voltage. It depends only weakly on the drain voltage when drain-induced barrier lowering (DIBL) is small. The MOSFET’s on-current is large because the barrier height is low, or even negative under high gate bias.

To develop a model for the IV characteristics of MOSFETs, we assume two-dimensional electrons in the MOSFET channel and follow a procedure like that for the MS diode to find an expression for the current analogous to (14),

$$J_n = qN_{2D} v_{eff} e^{-(E_C(0) - E_F)/k_B T} \left(e^{-qV_{DS}/k_B T} - 1 \right), \quad (16)$$

where V_{DS} is drain-source voltage, v_{eff} is given by (13b), and

$$N_{2D} = g_V \frac{m^* k_B T}{\pi \hbar^2} \text{ m}^{-2}. \quad (17)$$

Fig. 2. Energy band diagram for an n-channel MOSFET under high gate and drain bias. The current, J_1 , is the thermionic current injected from the source to the top of the barrier, and J_2 is the current that flows in the channel. Since the two are in series, $J_1 = J_2 = J_n$.

To proceed, we need to determine the gate voltage dependent effective Schottky barrier height of the MOSFET, $(E_C(0) - E_F)$, which brings in MOS electrostatics.

The charge at the top of the barrier (virtual source), can be written as

$$Q_n(x=0) = q \left(\frac{F^+(0) + F^-(0)}{v_T} \right) \text{C/m}^2, \quad (18)$$

where F^+ and F^- are the $+x$ and $-x$ -directed fluxes, which are assumed to move at the thermal velocity, v_T . Similarly, the net current can be written as

$$J_n = -q(F^+(0^+) - F^-(0^+)) \quad (19)$$

which can be combined with (18) to write

$$Q_n(x=0) = \frac{q}{v_T} (2F^+ + J_n/q). \quad (20)$$

Treating the source as a thermal equilibrium reservoir, we recognize that $F^+(0)$ is a thermal equilibrium flux injected from the source and given by

$$F^+(x=0^+) = \frac{N_{2D}}{2} e^{(E_F - E_C(0^+))/k_B T} v_T \quad (21)$$

Using (21) in (20), we find

$$e^{-(E_C(0) - E_F)/k_B T} = \frac{Q_n(0)}{qN_{2D}} - \frac{J_n}{qN_{2D}v_T}, \quad (22)$$

which can be used in (16) to find

$$J_n = \frac{Q_n(0)v_{eff}}{1 + \frac{v_{eff}}{v_R} (e^{-qV_{DS}/k_B T} - 1)} (e^{-qV_{DS}/k_B T} - 1). \quad (23)$$

Equation (23) is the desired result, but it is convenient to express it in terms of the transmission, $\mathcal{T}$, so that it can be compared with the corresponding results obtained from the

flux method [12-15] or the Landauer approach. Beginning with (13b) and using the relation between diffusion coefficient and mean-free-path for backscattering, $D_n = v_T \lambda / 2$, [16] we find

$$\frac{v_{eff}}{v_R} = \frac{1}{2} \left[\frac{\lambda}{\lambda + \ell} \right] = \frac{1}{2} \mathcal{T}, \quad (24)$$

where

$$\mathcal{T} = \left[\frac{\lambda}{\lambda + \ell} \right] \quad (25)$$

is the transmission, the probability that an electron injected into the channel from the source exits at the drain [16, 17]. Using (24) in (23) and defining a positive drain current as current flowing into the drain terminal, we find

$$I_D = -WJ_n = WQ_n(0) \left(\frac{\mathcal{T}}{2 - \mathcal{T}} \right) v_T \left(\frac{1 - e^{-qV_{DS}/k_B T}}{1 + \left(\frac{\mathcal{T}}{2 - \mathcal{T}} \right) e^{-qV_{DS}/k_B T}} \right). \quad (26)$$

Equation (26) agrees with (4.12) in the non-degenerate limit as derived in [14, 15]. The difference is that we now have an expression for $\mathcal{T}(V_{GS}, V_{DS})$ in terms of the channel potential, $V(x)$ as given by (5) and (25), and we have derived the results using traditional semiconductor theory. It may seem surprising that the results of a drift-diffusion analysis are identical to those obtained with the flux method [8] or Landauer approach [16]. There is, however, a deep connection between the approaches [13, 16, 17].

To summarize, the drain current of a MOSFET is given by

$$I_D = WQ_n(0) \left(\frac{\mathcal{T}}{2 - \mathcal{T}} \right) v_T \left(\frac{1 - e^{-qV_{DS}/k_B T}}{1 + \left(\frac{\mathcal{T}}{2 - \mathcal{T}} \right) e^{-qV_{DS}/k_B T}} \right) \quad (27)$$

$$\mathcal{T} = \frac{\lambda}{\lambda + \ell} = \frac{1}{1 + v_T / (2D_n / \ell)}$$

$$\ell = \int_0^L e^{-q(V(x) - V(0))/k_B T} dx$$

IV. DISCUSSION

Equations (27) provide a complete description of the IV characteristic of a MOSFET above and below threshold and from low to high drain bias and from the ballistic to diffusive limits. The model requires an accurate expression for $Q_n(x=0, V_{GS}, V_{DS})$, such as the one used in the VS model [4].

It also requires an accurate channel potential profile, $V(x)$, which could come from a numerical simulation that provides a sufficiently accurate channel potential profile that could be post-processed to predict realistic currents in the presence of scattering. Simplified analytical profiles can also be used, but,

as discussed in [9], some care in the selection of an appropriate channel profile for long or short channel devices is required.. The implementation of (27) in a complete model and its application to short and long channel Si MOSFETs and to short channel III-V HEMTs is discussed in [9].

Each of the equations in (27) has been derived before. What is new here is the derivation of all three using a drift-diffusion approach. A number of questions about the validity of (27) can be raised, and the simplifying assumptions have been the subject of many studies (e.g. [19-25]). It is not our intent to re-visit these issues here, but the successful application of the simple model to 30 nm channel length Si MOSFET [1, 9] and 30 nm III-V HEMTs [9] suggests that it captures the important essentials.

Equations (27) assume non-degenerate carrier statistics. Rakheja et al. [9] successfully applied this model to III-V HEMTs, but a generalization to non-degenerate carrier statistics would be useful. The non-degenerate expression for the drain current in (27) has been reported [14, 15], but general expressions for the critical length do not, to our knowledge, exist. The challenge in extending the derivation to non-degenerate statistics is the exponential integrating factor used in (3), which does not generalize to Fermi-Dirac integrals. This is an issue that future work should consider.

The expressions for transmission and critical length in (27) are similar to expressions in [10] for MS diode and have been previously derived and discussed for MOSFETs [26, 27] Gildenbalt derived these expressions from the Shockley-McKelvey equations assuming thermal (near-equilibrium) fluxes [26] The Shockley-McKelvey equations can be shown to be equivalent to the drift-diffusion equation [13], so it is not surprising that we obtain the same answer, but the drift-diffusion derivation of the unusual drain current expression might not have been expected. Clerc et al. [27] used a “relaxation length” approximation to consider the effect of hot carriers on the transmission. In the near-equilibrium limit, their results also reduce to the transmission and critical length in (27). In practice, one might want to use the more accurate expressions for transmission in [27], but to date, analysis of experimental data has shown no clear need at this time to go beyond the near-equilibrium expressions in (27) [1, 9].

Finally, we note that a model that treats transistors from the ballistic to diffusive regimes has been reported by Mugnain and Iannaccone [28, 29]. The difference here is our use of traditional drift-diffusion equations.

V. SUMMARY

Extending an emission-diffusion approach previously developed for MS diodes, we have derived an analytical model that describes MOSFETs from the ballistic to diffusive limits. An implementation of this model and applications to Si MOSFETs and III-V HEMTs has been discussed by Rakheja, et al. [9]. The new contribution of this work is the demonstration that it is possible to develop a ballistic to diffusive analytical model of the MOSFET using traditional semiconductor analysis methods, which suggests that it may be possible to extend widely-used compact modeling

approaches for MOSFETs to comprehend ballistic and quasi-ballistic transport. The paper also presents an interesting new view of a MOSFET as a reverse biased Schottky barrier with a gate voltage dependent Schottky barrier height.

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Xingshu Sun (S'13) received the B.S. degree from Purdue University, West Lafayette, IN, in 2012, where he is currently working toward the Ph.D. degree in electrical and computer engineering. His current research interests include device simulation and compact modeling for photovoltaics and nanoscale transistors.