Physics-based compact model of nanoscale MOSFETs – Part II: Effects of degeneracy on transport

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Physics-Based Compact Model of Nanoscale MOSFETs—Part II: Effects of Degeneracy on Transport

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***Abstract*—In this paper, we extend our derivation of an analytical model for nanoscale MOSFETs, focusing on the effects of Fermi–Dirac statistics on vertical electrostatics and on carrier transport. We derive a relation between mobility and mean-free path valid under degenerate statistics, and investigate the cases of rectangular and triangular quantum confinement under Fermi–Dirac statistics in the transition from DD to B transport. We derive a simple, physics-based and continuous analytical model that describes double-gate MOSFETs, fully depleted silicon-on-insulator MOSFETs, and bulk MOSFETs in the electric quantum limit in the whole range of transport regimes comprised between DD (device length much larger than mean-free path) and B (device length much maller than mean-free path).**

***Index Terms*—Ballistic (B) transport, compact modeling, degeneracy, MOSFETs, quantum confinement.**

I. Introduction

In Part I [1], we have pointed out that degeneracy is not taken into account in any compact model that is implemented in a circuit simulator. However, when nanoscale MOSFETs are considered, degeneracy effects must be included in more accurate descriptions of vertical electrostatics and carrier transport. Concerning vertical electrostatics, degeneracy should be included as a further contribution [2] to the inversion layer capacitance, therefore representing an additional cause of degradation of the gate capacitance, as it was discussed in [3] for a ballistic (B) MOSFET. Indeed, in [4] a degenerate charge-sheet model was discussed, where degeneracy is only included in the vertical electrostatics, while transport is described by the drift-diffusion (DD) equation with constant mobility and therefore it does not properly take in account the degenerate statistics. In [5] a model for double-gate (DG) MOSFETs was proposed, in which the Fermi–Dirac statistics is included only in the implicit version of the proposed model and not in the approximated explicit closed-form expressions. More recently, the UFDG model [6] was proposed, describing DGMOSFETs subject to quantum confinement, degenerate statistics and DD transport with velocity overshoot. Again, we want to remark that the above-mentioned models [4]–[6] describe the effect of Fermi–Dirac statistics only on the vertical electrostatics, while the effects of degeneracy on transport are not included. On the other hand, recent models describing B transport [7]–[9] generally include Fermi–Dirac statistics, because in that case it does not complicate the analytical treatment of transport.

We believe that a more realistic description of the transition from DD to B transport must account for the degeneracy in a more complete way. Indeed, degeneracy makes the ratio of diffusivity to mobility, or Einstein relation, a function of the spatial coordinate [10]. Such facts should suggest that mobility could be a local function also because of the effect of degeneracy.

In the present paper, starting from the description of the intermediate regime between quasi-equilibrium and B transport discussed in Part I, we propose a mobility model that includes the effect of Fermi–Dirac statistics in a fundamental way. Finally, we propose an EKV-like extended description of some device families, which includes the relevant physical effects characterizing nanoscale MOSFETs, i.e., triangular and rectangular quantum confinement, B and quasi-B transport and the effects of Fermi–Dirac statistics.

II. Effect of Fermi–Dirac Statistics on the Electrostatics

In the case of Fermi–Dirac statistics, equations can not be solved as easily as we have seen in Part I. In order to find simple analytical expressions, we make the assumption that only the lowest subband is populated (the "electric quantum limit"). Such approximation is typically very good for devices in which quantum confinement in the channel is triangular [11], such as bulk MOSFETs or DG and fully depleted silicon-on-insulator (FDSOI) MOSFETs with a thicker body, while in the case of rectangular confinement, it is reasonable only for ultrathin body devices, or at low temperature.

A. Rectangular Confinement

In the case of ultrathin film DGMOSFETs, in the electric quantum limit and in the presence of two different carrier populations at equilibrium with source and drain (i.e., the case of B transport), we can write the following equations for the B vertical electrostatic:

$$Q_m = \frac{qN_{1,l}}{2}[\Im_0(\eta_{Fs}) + \Im_0(\eta_{\rm Fd})] \tag{1}$$

$$Q_m = 2C_g\left[V_g - \phi_m + \chi - \frac{qN_A t_{\rm si}}{2}\left(\frac{1}{C_{\rm ox}} + \frac{t_{\rm si}}{4\epsilon_{\rm si}}\right) - \phi_c\right] \tag{2}$$

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where $\eta_{Fs} \equiv (\phi_c - V_s - \epsilon_{1,l})/\phi_t$, $\eta_{\rm Fd} \equiv (\phi_c - V_d - \epsilon_{1,l})/\phi_t$, Q_m, and ϕ_c are evaluated at the longitudinal coordinate corresponding to the peak of the subband, and the other variables are defined as in Part I, and $\Im_n(x)$ is the normalized Fermi–Dirac integral order of n. In the case of DD transport, a quasi-Fermi potential $V_{\rm Fn}$ is defined along the channel, so that we can put $V_s = V_d = V_{\rm Fn}$ in (2) in order to obtain for all values of the longitudinal coordinate

$$Q_m = qN_{1,l}\Im_0(\eta_{\rm Fn}) \tag{3}$$

where $\eta_{\rm Fn} \equiv (\phi_c - V_{\rm Fn} - \epsilon_{1,l})/\phi_t$. We want to stress the fact that the DD vertical electrostatic (3) must be considered locally valid along the whole channel in the gradual channel approximation, whereas the B vertical electrostatics (2) is valid only in a special point, that is the peak of the electrostatic potential in the channel. It can be interesting to rewrite the DD equation in the charge-based form; then, eliminating ϕ_c from equation set (2) and (3), we can easily write

$$V_g - \phi_m + \chi - \frac{Q_b}{2C_g} - V_{\rm Fn} = \frac{Q_m}{2C_g} + \phi_t \log\left[e^{\frac{Q_m}{qN_{1,l}}} - 1\right] + \epsilon_{1,l} \tag{4}$$

that can be seen as an extension of the electrostatics of EKV models capable to include degeneracy, through the quantum capacitance of the first subband $qN_{1,l}/\phi_t$ [2]. Remarkably, the inversion-layer charge model in [5] does not describe the degeneracy effects because of its particular structure and the absence of quantum capacitance in the explicit vertical electrostatics.

B. Triangular Confinement

In practical devices this is the most useful electrostatics because it applies to bulk MOSFETs and to SOI MOSFETs with film thicknesses of a few nanometers. Remarkably, bulk electrostatics shows two important differences with respect to the electrostatics of fully depleted silicon films with rectangular confinement. First, we have a field dependent depletion capacitance. Indeed, we write for the depletion charge the following approximate equation:

$$Q_b = \gamma C_{\rm ox}\sqrt{\phi_c - \phi_b} \tag{5}$$

where $\gamma = \sqrt{2qN_a\phi_t}/C_{\rm ox}$, and, in order to conserve the form of the analytical expressions, ϕ_c must be redefined as the surface potential, and $\phi_b = -E_{co}/q$, because in the description of bulk MOSFETs the charge sheet is considered placed at the interface with the oxide. In addition, there is a field-dependent quantum confinement, separating the first two-dimensional subband from the conduction band edge. Following the argumentation of [12] based on the work by Stern [13], we will consider the confinement in nanoscale bulk MOSFETs as triangular. A triangular quantum well provides a separation between the bottom of the conduction band and the first allowed energy level for a 100-oriented silicon substrate given by [12]

$$\epsilon_{1,l}^T = \left(\frac{\hbar^2}{2qm_l}\right)^{1/3}\left[\frac{\pi}{8\epsilon_{\rm si}}(Q_m + Q_b)\right]^{2/3}. \tag{6}$$

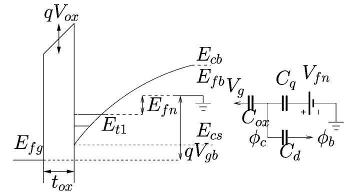

Fig. 1. Band diagram and related vertical electrostatics of a bulk MOSFET structure.

If we define

$$k_q \equiv \left(\frac{\hbar^2}{2qm_l}\right)^{1/3}\left(\frac{\pi C_{\rm ox}}{8\epsilon_{\rm si}}\right)^{2/3} \tag{7}$$

we can rewrite

$$\epsilon_{1,l}^T = k_q[V_g - (\phi_m - \chi) - \phi_c]^{2/3}. \tag{8}$$

From the band diagram of Fig. 1, we can write

$$V_g - \phi_c - (\phi_m - \chi) = \frac{Q_m + Q_b}{C_{\rm ox}} \tag{9}$$

that is valid in any transport regime. As we have seen in the previous subsection, Q_m is the surface mobile charge at the subband peak in the case of B transport while it is the local mobile charge in the case of DD transport $Q_m(V_{\rm Fn})$. We find for a B bulk structure

$$V_g - \phi_c - (\phi_m - \chi) = \frac{qN_{1,l}}{2C_{\rm ox}} \times[\Im_0(\eta_{Fs}) + \Im_0(\eta_{\rm Fd})] + \gamma\sqrt{\phi_c - \phi_b}. \tag{10}$$

In the case of local equilibrium we have

$$V_g - \phi_c - (\phi_m - \chi) = \frac{qN_{1,l}}{C_{\rm ox}}\Im_0(\eta_{\rm Fn}) + \gamma\sqrt{\phi_c - \phi_b}. \tag{11}$$

We want to remark that in the case of thick-film FDSOI and DG-MOSFETs we expect that quantum confinement is determined by triangular confinement (i.e., by the electric field) and not by rectangular confinement (geometry). The above equations can be used in fully depleted SOI devices if we substitute the depletion term $\gamma\sqrt{\phi_c - \phi_b}$ with a constant Q_b.

III. Effect of Fermi–Dirac Statistics on Transport Section Largely Rewritten

Now we discuss B transport in degenerate statistics. As we have seen in Part I, on the peak of the conduction band forward states are injected from the source, while reverse states come from the drain. From (2) and repeating the considerations in the Section IV of Part I, we find for $I_{\rm ds}$

$$I_{\rm ds} = \frac{qN_{1l}}{2}v_{\rm th}\left[\Im_{\frac{1}{2}}(\eta_{Fs}) - \Im_{\frac{1}{2}}(\eta_{\rm Fd})\right]. \tag{12}$$

Equation (2) allows us to obtain ϕ_c, and then $\eta_{{\rm Fd},s}$. As in Part I, we first intend to show that a DD transistor can be seen as a long enough chain of B transistors. Let us now consider a single B transistor of the chain, for which the source and the drain Fermi potentials are approximately equal to a quasi-continuous Fermi potential $V_{\rm Fn}$, similarly to the nondegenerate case discussed in Part I:

$$I_{\rm ds}^{\rm (DD)} = \frac{1}{L}\int_{V_s}^{V_d} \frac{\Im_{-\frac{1}{2}}(\eta_{\rm Fn})}{\Im_0(\eta_{\rm Fn})}\frac{v_{\rm th}\lambda}{2\phi_t} Q_m(V_{\rm Fn})\, dV_{\rm Fn}. \qquad (13)$$

In (13), $Q_m(V_{\rm Fn})$ is subject to local equilibrium (Drift-Diffusion) electrostatics (4) and V_s and V_d are the Fermi potentials of the outer source and drain of the chain. If we adopt the interpretation of transport described in Part I, we must identify the term

$$\mu_{\rm deg}(\eta_{\rm Fn}) \equiv \frac{v_{\rm th}\lambda}{2\phi_t}\frac{\Im_{-\frac{1}{2}}(\eta_{\rm Fn})}{\Im_0(\eta_{\rm Fn})} \equiv \mu_{no}\frac{\Im_{-\frac{1}{2}}(\eta_{\rm Fn})}{\Im_0(\eta_{\rm Fn})} \qquad (14)$$

in (13) as a "degenerate" mobility, while in the nondegenerate case is $\mu_{no} = v_{\rm th}\lambda/(2\phi_t)$. It is interesting the fact that in [14] a similar mobility was proposed in order to include the B limit in the linear operating region of HEMTs. The quantity the authors of [14] call "ballistic mobility" is calculated at source only and then is combined with the conventional mobility with the Mathiessen rule, as in [15], in order to recover phenomenologically the B limit. It is clear that the physical meaning of such "B mobility" is different from the mobility (14), because according to the interpretation of dissipative transport shown in Part I, (14) already includes all scattering mechanisms through λ and $N = L/\lambda$, so that the conventional macroscopic mobility is a direct consequence of (14). Such link between λ and $\mu_{\rm deg}$ has important consequences, since it is obvious that a uniformly spaced B chain does not imply a constant mobility in the channel. If we suppose a constant λ in the channel we find that $\mu_{\rm deg}$ depends on $\phi_c - V_{\rm Fn}$ and then on V_g when $\phi_c > V_{\rm Fn}$ approximately as $V_g^{-0.5}$. This fact can be interpreted as a mobility degradation at high vertical fields. In the following subsections, we will analyze the effect of degeneracy on thin FDSOI MOSFETs (rectangular quantum well) and then on bulk MOSFETs (triangular quantum well).

A. Degenerate DD Transport in Ultrathin Film (Was FDSOI) MOSFETs

From (13), we find

$$I_{\rm ds}^{\rm (DD)} = \frac{v_{\rm th}}{2\phi_t}\left(\frac{\lambda}{L}\right)\int_{V_s}^{V_d} \frac{\Im_{-\frac{1}{2}}(\eta_{\rm Fn})}{\Im_0(\eta_{\rm Fn})} Q_m(V_{\rm Fn})\, dV_{\rm Fn}. \qquad (15)$$

If we define

$$\rho \equiv \frac{qN_{1l}}{Q_n} \qquad (16)$$

we find

$$I_{\rm ds}^{(DD)} = \frac{\rho^2 Q_n\mu_{no}}{L}[\Im_{-1,-1/2}(\eta_{Fs}) - \Im_{-1,-1/2}(\eta_{\rm Fd})] + \frac{\rho Q_n \mu_{no}}{L}[\Im_{-1/2}(\eta_{Fs}) - \Im_{-1/2}(\eta_{\rm Fd}) \qquad (17)$$

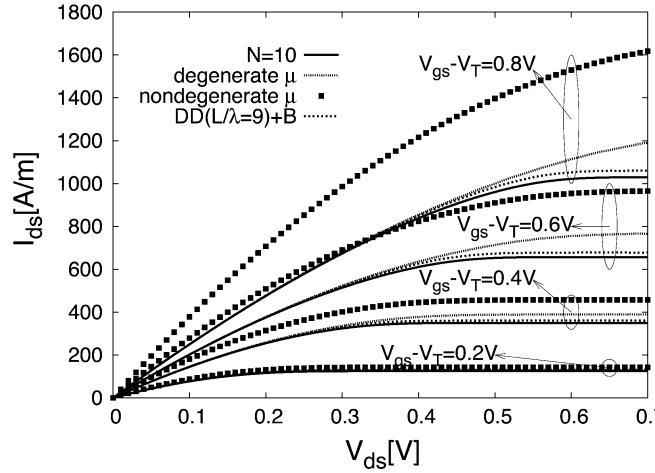

Fig. 2. Output characteristics for a B chain with $N = 10$ with degenerate statistics, and for models with degenerate mobility with $N = 10$ and the with nondegenerate mobility with $N = 10$. The output characteristics of the series of a DD MOSFET with $\lambda = L/9$ and a B transistor are also shown, indicated with DD+B. The considered structure is a DGMOSFET with a $t_{\rm ox} = 3$ nm, $t_{\rm si} = 5$ nm.

where we have defined in order to have a more compact notation

$$\Im_{[-1,-1/2]}(x) \equiv \int_{-\infty}^{x} \Im_{-1/2}(u)\Im_{-1}(u)\, du \qquad (18)$$

and now $\eta_{Fs} \equiv (\phi_{cs} - V_s - \epsilon_{1,l})/\phi_t, \eta_{\rm Fd} \equiv (\phi_{cd} - V_d - \epsilon_{1,l})/\phi_t$ are evaluated at source and drain, respectively. We can interpret $I_{\rm ds}^{\rm (DD)}$ as the sum of drift and diffusion contributions

$$\begin{cases} I_{\rm ds}^{\rm (Drift)} = \frac{\rho^2 Q_n \mu_{no}}{L}[\Im_{[-1,-1/2]}(\eta_s) - \Im_{[-1,-1/2]}(\eta_d)] \\ I_{\rm ds}^{\rm (Diffusion)} = \frac{\rho Q_n \mu_{no}}{L}[\Im_{-1/2}(\eta_s) - \Im_{-1/2}(\eta_d)]. \end{cases} \qquad (19)$$

It is worth noticing that in the limit $qN_{1l} \gg Q_n$, i.e., $\rho \to \infty$ we recover the EKV model

$$\begin{cases} I_{\rm ds}^{\rm (Drift)} = \frac{\mu_{no}}{2LQ_n}\left(Q_{ms}^2 - Q_{md}^2\right) \\ I_{\rm ds}^{\rm (Diffusion)} = \frac{\mu_{no}}{L}(Q_{ms} - Q_{md}) \end{cases}. \qquad (20)$$

Concerning the transition, similarly to the case of nondegenerate B chain, it is clear that the degenerate B chain with constant λ can be modeled as a series of a DD transistor (taking into account the first $N-1$ B transistors) and one B transistor, as can be verified in Fig. 2.

It is extremely important to include the effects of degeneracy not only on the local charge, but also on the mobility, even it is not typically done in the other compact models. In our case, by approximating the ratio $\Im_{-1/2}/\Im_0$ with unity in (13) corresponds to discard the effects of degeneracy on mobility. In such case, we would obtain the following expression:

$$I_{\rm ds} = \frac{\lambda}{L}\left(\frac{kT}{q}\right)^2 \left[\frac{Q_{ms}^2 - Q_{md}^2}{2C_g} + kTN_{1l} \times \left(\mathcal{M}\left(\frac{Q_{ms}}{qN_{1l}}\right) - \mathcal{M}\left(\frac{Q_{md}}{qN_{1l}}\right)\right)\right] \qquad (21)$$

where we have placed

$$\mathcal{M}(x) \equiv \int_0^x \frac{ue^u}{e^u - 1} du \tag{22}$$

$$= \frac{x^2}{2} + x\log(1-\exp(x)) + \mathrm{Li}_2(\exp(x)) \tag{23}$$

where $\mathrm{Li}_2(.)$is the polylogarithm of order 2. As we can see in Fig. 2, neglecting the effects of degeneracy on mobility, as in [4] and [5], would lead to a significant bias-dependent overestimation of the total current.

B. DD Current in Degenerate Bulk MOSFETs

The previous calculations are valid if the energy separation from the first subband to the bottom of conduction band $\epsilon_{1,l}^T$ and depletion charge are strictly constant, as it is in the case of FDSOI and DGMOSFETs with thin film. In the case of bulk electrostatics, a complete analytical treatment of the integral (15) is very arduous and we will reduce it to simpler expressions by making the following observations. As it was discussed in [16] and [17], it is reasonable to linearize the effects of depletion charge and quantum confinement near a suitable potential ϕ_{cm}, which we will discuss later. It is useful to define

$$n_b \equiv 1 + \frac{\gamma}{2\sqrt{\phi_{cm} - \phi_b}} \tag{24}$$

and

$$n_q \equiv 1 - \frac{\epsilon_{1,l}^T}{\phi_c} = 1 + \frac{\frac{2}{3}k_q}{(V_g - \phi_{cm} - (\phi_m - \chi))^{\frac{1}{3}}} \tag{25}$$

where n_b is the conventional depletion capacitance slope factor, while n_q can be interpreted as a slope factor caused by quantum confinement. Using the function $\Im_{-1/2,-1}$, previously introduced in Section III-A, the current is

$$I_{\mathrm{ds}} = \frac{Q_n \rho \mu_{no}}{L} \left\{ \Im_{\frac{1}{2}}(\eta_{Fs}) - \Im_{\frac{1}{2}}(\eta_{\mathrm{Fd}}) + \frac{n_q}{n_b}\rho \right. \\ \left. \times \left[\Im_{[-\frac{1}{2},-1]}(\eta_{Fs}) - \Im_{[-\frac{1}{2},-1]}(\eta_{\mathrm{Fd}}) \right] \right\}. \tag{26}$$

Evidently if $n_q = 1$ and $n_b = 1$, (26) reduces to the current for DGMOSFET.

C. Remark on ϕ_{cm}

It was observed in the literature [16] that an appropriate choice for the linearization is

$$\phi_{cm} = \frac{\phi_{cs} + \phi_{cd}}{2} \tag{27}$$

because the surface potential shows a quasi-linear behavior with mobile charge surface density Q_m. This choice leads to a symmetrical model near $V_{ds} = 0$. Several compact models are based on similar approximations and some of them are discussed in [16], [18] and [19]. Symmetrical linearization can be verified in Fig. 3. We can note that the current expression can be simplified, if we apply the symmetrical linearization also to the current integral

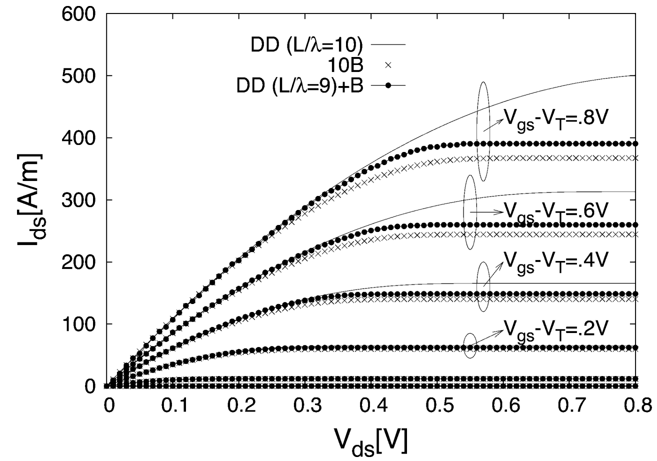

Fig. 3. (Solid line) Output characteristics obtained with the exact calculation of the current integral (15), with the B chain ($N = 10$), and with the decomposition DD + B, where the DD section is calculated with expression (26). In the DD section, (29) was used, obtained through the symmetrical linearization [16]. The considered structure is a bulk MOSFET with $t_{\mathrm{ox}} = 5$ nm, $t_{\mathrm{si}} = 5$ nm, $N_A = 10^{23}\ \mathrm{m}^{-3}$.

$$I = \frac{Q_n \rho \mu_{no}}{L} \int_{V_s}^{V_d} \Im_{-\frac{1}{2}}(\eta_{\mathrm{Fn}})\, dV_{\mathrm{Fn}} \tag{28}$$

$$\simeq \frac{Q_n \rho \mu_{no}}{L} \left[\Im_{-\frac{1}{2}}(\eta_F) \frac{dV_{\mathrm{Fn}}}{d\phi_c} \right]_{\phi_{cm}} (\phi_{cd} - \phi_{cs}) \tag{29}$$

that is equivalent to an evaluation of the integral with the rectangle formula after the substitution of integration variable $V_{\mathrm{Fn}} \rightarrow \phi_c$. For EKV-like compact models such relation would be exact. When compared with the exact calculation and with (26) such approximation results slightly worst, but has the advantage of eliminating the need of the transcendental function $\Im_{[-(1)/(2),-1]}(x)$.

IV. Compact Model for MOSFETs With Degenerate Statistics

In summary, the discussed model describes the effect of degeneracy capacitance on electrostatics, the mobility reduction caused by degenerate statistics, the triangular confinement in bulk MOSFETs, the variable depletion charge in bulk MOSFETs and the transition from B to DD transport. The macromodel can be extended including series resistances, and in order to describe the two-dimensional effects, we introduce two geometrical capacitances that model the electrostatics coupling of source and drain on the peak of B transistor (the so-called drain-induced barrier lowering), C_s and C_d. Moreover such geometric capacitances are introduced in the DD section in order to model the short-channel effects in the subthreshold region. Therefore, the following parameters are needed for the complete model of low frequency: (L/λ), t_{ox}, N_A, N_p, $\Phi_m - \chi$, C_s, C_d, R_s, R_d. In Fig. 4, we fit the compact model with experimental curves from a bulk MOSFET with $L = 30$ nm appeared in the literature [20].

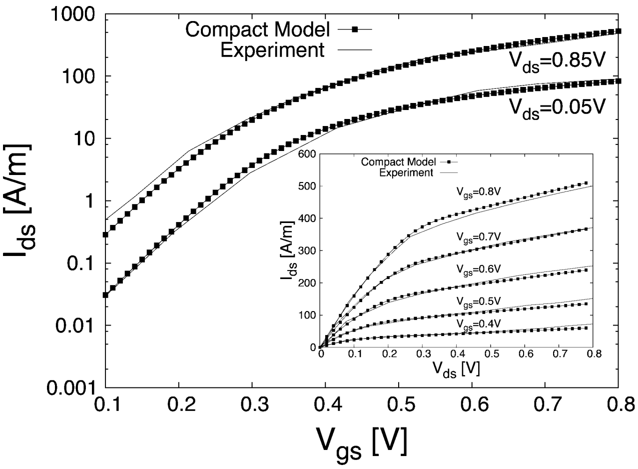

Fig. 4. Comparison between the experimental transfer characteristics and those obtained with the compact model for a bulk MOSFET with $L = 30$ nm reported in [20]. In the inset, the output characteristics are reported.

V. Conclusion

We have studied an extension of the model proposed in Part I in order to describe the effects of Fermi–Dirac statistics in the so-called electric quantum limit. Starting from the interpretation of transition from DD to B transport that was used in Part I, an extended relation between the degenerate mobility μ and the mean-free path λ is found. The model is studied in the case of rectangular and triangular quantum confinement, and it shows that degeneracy significantly degrades the low-field mobility, whereas the unidirectional thermal velocity is enhanced by the Fermi–Dirac statistics. The model based on the segmentation in a DD and a B transistor is verified to be adequate also under Fermi–Dirac statistics, so describing the transition from DD to B transport in degenerate devices. Finally, a comparison of the model with experimental curves of a bulk transistor [20], has been shown. We believe that our approach can be the basis for the development of a fully unified model that describes bulk, DGMOSFETs and FDSOI MOSFETs in any transport regime and under quantum confinement.

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