A Microscopically Accurate Model of Partially Ballistic NanoMOSFETs in Saturation Based on Channel Backscattering

Giuseppe Iannaccone
Dipartimento di Ingegneria dell'Informazione: Elettronica, Informatica, Telecomunicazioni, Università di Pisa

Gino Giusi
Dipartimento di Elettronica, Informatica e Sistemistica, Università della Calabria

Felice Crupi
Dipartimento di Elettronica, Informatica e Sistemistica, Università della Calabria

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A Microscopically Accurate Model of Partially Ballistic NanoMOSFETs in Saturation Based on Channel Backscattering

Gino Giusi, Giuseppe Iannaccone, *Senior Member, IEEE*, and Felice Crupi

***Abstract*—We propose a model for partially ballistic metal–oxide–semiconductor field-effect transistors (MOSFETs) and for channel backscattering that is an alternative to the well-known Lundstrom model (LM) and is more accurate from the point of view of the actual energy distribution of carriers. The key point is that we do not use the concept of "virtual source." Our model differs from the LM in two assumptions: 1) the reflection coefficients from the top of the energy barrier to the drain and from top of the barrier to the source are approximately equal (whereas, in the Lundstrom model, the latter is zero); and 2) inelastic scattering is assumed through a ratio of the average velocity of forward-going carriers to that of backward-going carriers at the top of barrier $k_v > 1$ ($k_v = 1$ in the Lundstrom model). We support our assumptions with 2-D full-band Monte Carlo simulations, including quantum corrections in n-channel MOSFETs. We show that our model allows to extract from the electrical characteristics a backscattering coefficient very close to that obtained from the solution of the Boltzmann transport equation, whereas the LM overestimates the backscattering by up to 40%.**

***Index Terms*—Backscattering, ballistic transport, Monte Carlo (MC) simulation, nanoscale metal–oxide–semiconductor field-effect transistors (nanoMOSFETs).**

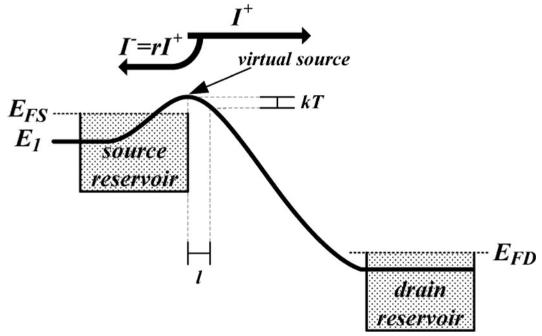

Fig. 1. LM picture. The model is 1-D, and only one subband E_1 is considered populated. The top of the source to channel energy barrier is called the VS because carriers are considered to be injected by the source reservoir, which extends from the source contact to the VS. Carriers inside the source reservoir (Fermi Level E_{FS}) are injected from the VS to the channel and constitute I^+. In saturation, a fraction of them (r) backscatters due to the scattering inside the critical layer l and constitutes I^-. The scattering is assumed elastic $(v^+ \approx v^-)$, and the positive-directed moments (I^+, n^+) are assumed to be equal to the ballistic case [see (1)–(4)].

I. INTRODUCTION

CHARGE transport in nanoscale metal–oxide–semiconductor field-effect transistors (nanoMOSFETs) requires a physical description that does not use the concept of mobility. One would really need analytical device models directly usable for extracting transport parameters from experimental characteristics [1]–[10]. Among these, the simplest and the most successful is the Lundstrom model (LM) [2], based on the Natori theory for ballistic transport [1], which relies on the concept of *backscattering*. In the Lundstrom model, the transport in the channel is regulated by the elastic injection and reflection of thermally distributed carriers at the *virtual source* (VS; see Fig. 1). In saturation, the backscattering coefficient is defined as the ratio I^-/I^+ between the source-injected current I^+ and the backscattered current I^-. The strength of the model is that it provides just a number, i.e., the backscattering coefficient r, which includes all scattering mechanisms in the channel and that it is easily extracted from I–V and C–V characteristics [11]–[19]. Quasi-ballistic transistors have r close to zero so that all the injected carriers reach the drain side, providing a maximum current drive. Technology developers and transistor designers must aim at devices with low r in order to enhance the performance. In this sense, the backscattering coefficient is a parameter that provides information about the scalability of a given technology (material and/or architecture). The picture of the Lundstrom Model has been revolutionary because it moved attention from the drain side to the source side. However, the assumption of an elastic transport has attracted criticisms [19], [20], as well as the specific expression for the backscattering coefficient [5]. In this paper, we propose a charge-transport model that is an alternative to the LM and is more accurate from the point of view of the actual energy distribution of carriers.

The remainder of this paper is divided as stated in the following. In Section II, we briefly recall the Lundstrom backscattering model. In Section III, the proposed model is presented. In Section IV, the backscattering calculated with our model is compared with the backscattering calculated with the LM and with the true value extracted by 2-D Monte Carlo (MC) device simulations. Finally, conclusions are drawn in Section V.

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G. Giusi and F. Crupi are with the Department of Electronics, Computer and System Sciences (DEIS), University of Calabria, 87036 Arcavacata di Rende (CS), Italy (e-mail: ggiusi@deis.unical.it).

G. Iannaccone is with the Department of Information Engineering: Electronics, Informatics, and Telecommunications, and the Smart Energy-Efficient Design Center, University of Pisa, 56122 Pisa, Italy.

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II. LUNDSTROM MODEL

The LM picture is illustrated in Fig. 1. The model is 1-D along the channel direction, and only one subband E_1 is considered populated. The top of the source to the channel energy barrier is called the VS because carriers are considered to be injected by the source reservoir, which extends from the source contact to the VS. Carriers inside the source reservoir (Fermi Level $E_{\rm FS}$) are injected from the VS into the channel and constitute I^+. The positive-directed moments (I^+, n^+) at the VS are assumed equal to the ballistic case $(I^+_{S,\rm BL}, n^+_{S,\rm BL})$, i.e.,

$$I^+ \approx I^+_{S,\rm BL} \tag{1}$$

$$n^+ \approx n^+_{S,\rm BL}. \tag{2}$$

The ballistic-directed moments $(I^+_{S,\rm BL}, n^+_{S,\rm BL})$ at the VS are calculated using the Natori model for ballistic transport [1], i.e.,

$$I^+_{S,\rm BL} = qW\frac{N_{\rm 2D}}{2}v_{\rm th}\Im_{1/2}(\eta) \tag{3}$$

$$n^+_{S,\rm BL} = \frac{N_{\rm 2D}}{2}\Im_0(\eta) \tag{4}$$

with

$$\eta = \frac{E_{\rm FS}-E_1}{kT} \qquad N_{\rm 2D} = kT\frac{m_{\rm DOS}}{\pi\hbar^2} \qquad v_{\rm th} = \sqrt{\frac{2kT}{\pi m_C}}$$

where q is the electronic charge, W is the device width, $N_{\rm 2D}$ is the effective 2-D density of states, $v_{\rm th}$ is the unidirectional thermal velocity, k is the Boltzmann constant, $\hbar$ is the reduced Planck constant, T is the absolute temperature, $m_{\rm DOS}$ is the density-of-states' effective mass, m_C is the conduction effective mass, $\Im_j$ is the Fermi–Dirac integral of order j, and E_1 is the energy of the populated subband. The average velocity of the positive source-injected component v^+ is equal to the ballistic case, i.e.,

$$v^+ = \frac{I^+}{qWn^+} \approx \frac{I^+_{S,\rm BL}}{qWn^+_{S,\rm BL}} = v^+_{S,\rm BL} = v_{\rm th}\frac{\Im_{1/2}(\eta)}{\Im_0(\eta)}. \tag{5}$$

In saturation, the drain injection is suppressed, and current I^- at the VS is only due to fraction r of the source-injected current I^+. The backscattering occurs in a *critical layer l*, and it is assumed elastic, that is, the average velocity of transmitted carriers is equal to the average velocity of backscattered carriers $(v^+ \approx v^-)$. From the knowledge of current I_D and of the charge density Q at the VS, backscattering r can be calculated by solving the following coupled equations:

$$\begin{aligned} I_D &= I^+ - I^- = (1-r)I^+ \approx (1-r)I^+_{S,\rm BL} \\ &= (1-r)qW\frac{N_{\rm 2D}}{2}v_{\rm th}\Im_{1/2}(\eta) \end{aligned} \tag{6}$$

$$\begin{aligned} Q &= qn = q(n^+ + n^-) = n^+\left(1 + r\frac{v^+}{v^-}\right) \approx n^+_{S,\rm BL}(1+r) \\ &= \frac{N_{\rm 2D}}{2}\Im_0(\eta)(1+r) \end{aligned} \tag{7}$$

where the assumption of elastic scattering $(v^+ \approx v^-)$ has been used in (7). Equations (6) and (7) can be compacted in the following form:

$$I_D = \frac{1-r}{1+r}WQv^+_{S,\rm BL} \tag{8}$$

where term $B = (1-r)/(1+r)$ is referred as the *ballistic ratio.*

III. PROPOSED MODEL

In our picture (illustrated in Fig. 2), we do not use the VS concept, and we treat in a symmetric way the backscattering of forward- and backward-going electrons. Exploiting current continuity, the source- and drain-injected ballistic components can be traced back to the physical injection contact, i.e., $I^+_{S,\rm BL}$ $(I^-_{D,\rm BL})$ at the source (drain) are due to carriers injected at $x_{S,\rm inj}$ $(x_{D,\rm inj})$ and with an energy higher than $E_{\rm TOP}$. In the absence of scattering between $x_{S,\rm inj}$ $(x_{D,\rm inj})$ and $x_{\rm max}$, I^+ (I^-) at $x_{\rm max}$ would be equal to $I^+_{S,\rm BL}$ $(I^-_{D,\rm BL})$. However, in the presence of scattering, current I^+ (I^-) is the sum of the transmitted fraction $1 - r_{SD}$ $(1 - r_{DS})$ of $I^+_{S,\rm BL}$ $(I^-_{D,\rm BL})$ and of the backscattered component r_{SD} (r_{DS}) of I^- (I^+), i.e.,

$$I^+ = (1-r_{SD})I^+_{S,\rm BL} + r_{SD}I^- \tag{9}$$

$$I^- = (1-r_{DS})I^-_{D,\rm BL} + r_{DS}I^+ \tag{10}$$

where r_{SD} (r_{DS}) is the backscattering coefficient between $x_{S,\rm inj}$ $(x_{D,\rm inj})$ and $x_{\rm max}$. In saturation $(V_{DS} \gg kT/q)$, the injection from the drain contact is suppressed, and neglecting the scattering at the drain, we get $I^-_{D,\rm BL} \approx 0$. Moreover, if $r_{SD} \approx r_{DS} = r$, we obtain the following from (9) and (10):

$$I^+ + I^- \approx I^+_{S,\rm BL} + I^-_{D,\rm BL} \approx I^+_{S,\rm BL}. \tag{11}$$

The model is completed by the same approximation used in the LM for the charge density [see (2)], i.e., n^+ is assumed to be equal to concentration $n^+_{S,\rm BL}$ of forward-going carriers that we would have at $x_{\rm max}$ in the case of the ballistic transport [see (2)]. We can provide a rough justification for such approximation, which will be confirmed ex post in Section IV by detailed MC simulations. If we divide (11) by qWv^+, we get

$$n^+ \approx n^+_{S,\rm BL}\frac{v^+_{S,\rm BL}/v^+}{1+r}. \tag{12}$$

Obviously, in the case of the ballistic transport, the fraction is equal to 1. If the scattering increases, carriers injected from $x_{S,\rm inj}$ lose energy due to the inelastic scattering that is reducing their average velocity so that $v^+ < v^+_{S,\rm BL}$ and the numerator in the fraction of (16) increases. At the same time, the denominator $(1+r)$ increases, too. To simplify the model, we assume that these two effects compensate one another so that $n^+ \approx n^+_{S,\rm BL}$.

Equation (11) is different from (1), which is used in the LM, since we include in the model the scattering between $x_{S,\rm inj}$ and $x_{\rm max}$. As a matter of fact, (9) reduces to the Lundstrom assumption [see (1)] when $r_{SD} \approx 0$. Based on (2) and (11) and

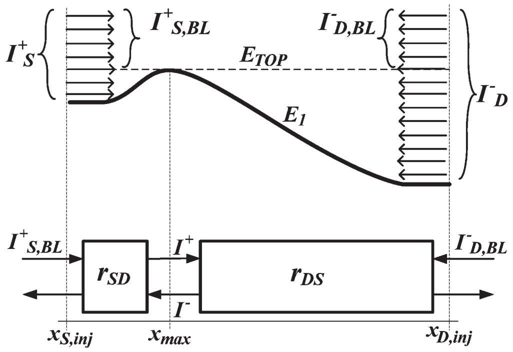

Fig. 2. Proposed-model picture. Carriers are injected from two injection points $x_{S,\mathrm{inj}}$ and $x_{D,\mathrm{inj}}$ by source I_S^+ and drain I_D^- reservoirs into the channel. Their ballistic components $I^+_{S,\mathrm{BL}}$ and $I^-_{D,\mathrm{BL}}$, respectively, will experience scattering going toward $x_{\max}$. I^+ (I^-) is the positive-directed (negative-directed) current at $x_{\max}$. Only a fraction $1 - r_{SD}$ $(1 - r_{DS})$ of $I^+_{S,\mathrm{BL}}$ $(I^-_{D,\mathrm{BL}})$ will be a part of I^+ (I^-), and the rest will be backscattered toward the source (drain). Current I^+ (I^-) is completed by the backscattered component of I^- (I^+) through coefficient r_{SD} (r_{DS}) [see (9) and (10)].

on the Natori equations (3) and (4), the drain current I_D and the total charge density Q at $x_{\max}$ (which we prefer not to call VS anymore since we abandon the VS concept) can be calculated as

$$I_D = I^+ - I^- = \frac{1-r}{1+r}(I^+ + I^-) \approx \frac{1-r}{1+r} I^+_{S,\mathrm{BL}} = \frac{1-r}{1+r} qW \frac{N_{2\mathrm{D}}}{2} v_{\mathrm{th}} \Im_{1/2}(\eta) \tag{13}$$

$$Q = qn = q(n^+ + n^-) = n^+\left(1 + r\frac{v^+}{v^-}\right) \approx n^+_{S,\mathrm{BL}}(1 + rk_v) = \frac{N_{2\mathrm{D}}}{2}\Im_0(\eta)(1 + rk_v). \tag{14}$$

Ratio $k_v = v^+/v^-$ is not assumed 1 as in the LM but is directly extracted from MC simulations so that we do not assume the elastic scattering at around $x_{\max}$. As stated in Section IV, it is approximately equal to 1.35 according to [20]. The average velocity of source-injected carriers is found to be equal to

$$v^+ = \frac{I^+}{qWn^+} \approx \frac{I^+_{S,\mathrm{BL}}}{qW(1+r)n^+_{S,\mathrm{BL}}} = \frac{v^+_{S,\mathrm{BL}}}{1+r}. \tag{15}$$

Finally, (13) and (14) can be compacted as

$$I_D = \frac{1-r}{(1+r)(1+rk_v)} WQv^+_{S,\mathrm{BL}} \tag{16}$$

where the term in fraction is the ballistic ratio, which differs for term $1 + rk_v$ at the denominator with respect to the LM [see (8)], thus implying that backscattering r calculated with our model is expected to be lower with respect to the backscattering calculated by the Lundstrom model.

IV. VALIDATION BY MC SIMULATIONS

In order to develop a comparative analysis between the LM and the proposed model, 2-D semiclassical quantum-corrected simulations were performed with the full-band MC simulator "MoCa," which includes all relevant scattering mechanisms [21], [22]. The simulated device (see Fig. 3) is a double-gate n-channel MOSFET (DG nMOSFET) with a very thin undoped silicon body ($t_{\mathrm{Si}} = 1.5$ nm) [4]. Such a thin body is chosen in order to match the 1-D transport and the one-subband hypothesis of the Natori model. We make the common assumption that only the first band of the unprimed ladder is occupied so that $m_{\mathrm{DOS}} = 2m_t$ and $m_C = m_t$, where $m_t = 0.19m_0$ is the transverse mass and m_0 is the electron-free mass, as confirmed by Schrodinger–Poisson simulations. In Fig. 4, (9) and (10) are solved, with respect to r_{SD} and r_{DS}, for each point x inside the channel for a device with channel length $L = 20$ nm. $I^-_{D,\mathrm{BL}}$ is assumed 0 (saturation) so that $r_{DS} \approx I^-/I^+$ and the source injection point $x_{S,\mathrm{inj}}$ is taken at the source/channel junction $(x = -L/2)$. $I^+_{S,\mathrm{BL}}$ is calculated by taking the energy distribution of the positive-directed current at $x_{S,\mathrm{inj}}$ (I^+_S), which is integrated for energies higher than the barrier height between $x_{S,\mathrm{inj}}$ and $x_{\max}$. Hypothesis $r_{SD} \approx r_{DS}$ is verified in a point very close to $x_{\max}$ so that the approximation of (11) holds. To verify the hypothesis of the proposed model [see (2)–(11)] with respect to the hypothesis of the LM [see (1) and (2)], (2)–(11) and (1) and (2) have been inverted with respect to η from the knowledge of I^+, I^-, and n^+. The result is plotted in Fig. 5 for different values of L. As can be

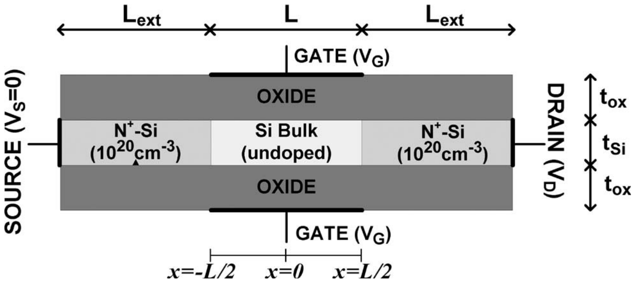

Fig. 3. Simulated structure is a DG nMOSFET with ultrathin undoped silicon body ($t_{\mathrm{Si}} = 1.5$ nm), oxide thickness $t_{\mathrm{ox}} = 1.5$ nm, and long source/drain extensions ($L_{\mathrm{ext}} = 35$ nm). The threshold voltage is 0.4 V.

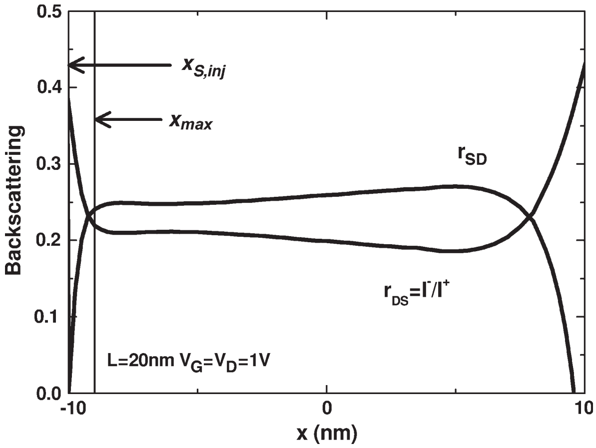

Fig. 4. Backscattering along the channel. Equations (9) and (10) are solved with respect to r_{SD} and r_{DS}, for each point x inside the channel. $I^-_{D,\mathrm{BL}}$ is assumed 0 (saturation) so that $r_{DS} = I^-/I^+$ and the source injection point $x_{S,\mathrm{inj}}$ is taken at the source/channel junction ($x = -10$ nm). Hypothesis $r_{SD} \approx r_{DS}$ is verified very close to $x_{\max}$ so that (11) holds.

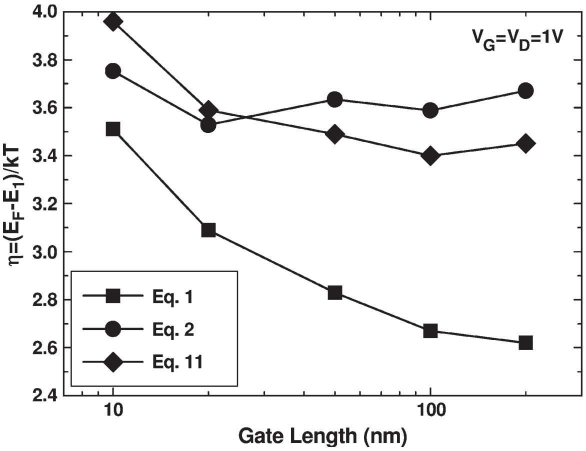

Fig. 5. Verification of the LM and of the proposed model. Equations (1) and (2), and (2)–(11) have been inverted in order to calculate η. Equations (2)–(11) (proposed model) give very similar values of η, while (1) and (2) (Lundstrom model) give different values.

noticed, (2)–(11) (proposed model) yield very similar values of η, while (1) and (2) (LM) do not. A further proof of our assumptions is shown in Fig. 6, where ballistic and nonballistic simulations are compared (in the ballistic case, the scattering is turned off only in the channel). Fig. 6 (top) shows that the sum of $I^+ + I^-$ at $x_{\max}$ is close to that of the nonballistic case (error of 1.2%), confirming the hypothesis of (11), while I^+ significantly differs (9.3%) from the ballistic case [see (1)]. Moreover, Fig. 6 (bottom) shows that the hypothesis for n^+ [see (2)] is well verified (4.2%). From Fig. 6 (top), one can also note that $I^+ + I^-$ significantly differs from I^+ for the ballistic case. The explanation can be found in Fig. 7, where the potential-energy profile E_P and the average total energy E_T in the ballistic case are shown. Ballistic carriers lose energy close to the drain where they have a sufficient energy to be backscattered and surmount the channel energy barrier giving a contribution to I^-. However, when the scattering is turned on in the channel, carriers arrive at the drain side with a lower energy, and backscattered carriers at the drain have lower chances to surmount the channel energy barrier [20]. In Fig. 8, r (top) and v^+ (bottom), calculated with the proposed model and with the Lundstrom model, are compared with the results extracted directly from MC simulations for different values of L, V_G, and V_D. Moreover, the backscattering obtained with the LM using the true $k_v = v^+/v^-$ extracted directly from MC simulation is shown. It can be observed that the backscattering coefficient extracted with the LM differs significantly from I^-/I^+ calculated by MC simulation (40%–50%) and that using the true k_v value is not sufficient to compensate the gap (20%–30%). As can be noticed, the proposed model reproduces very well the MC results for both r and v^+. We find that $k_v = v^+/v^-$ is a weak function of the device geometry and bias, and it is approximately equal to 1.35 (according to [20]). This number can be used for experimental extraction.

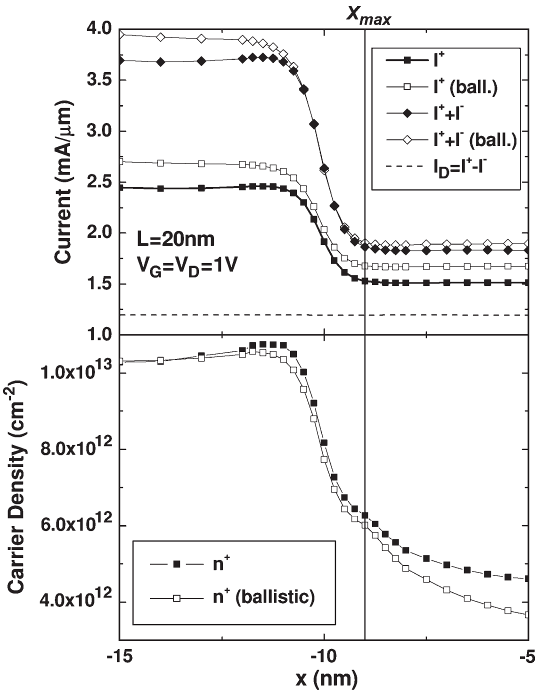

Fig. 6. (Top) Directed currents and (bottom) carrier density along the device in the ballistic and nonballistic cases. It is evident that the assumption of (11) (proposed model) is better verified than assumption of (1) (Lundstrom model; 1.2% versus 9.3%). Moreover, the assumption of (2) (Lundstrom and proposed models) is well verified (4.3%).

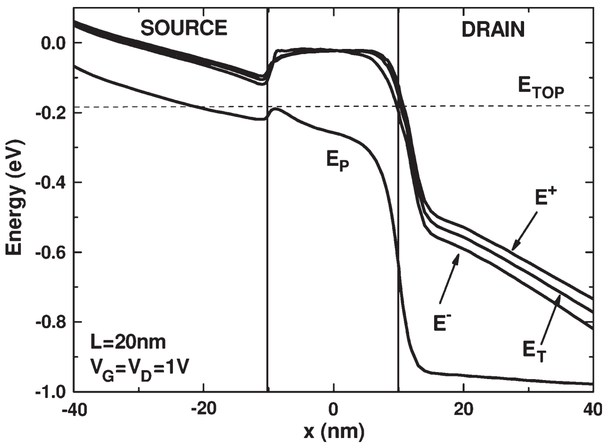

Fig. 7. Ballistic simulation of the potential-energy profile E_P, average total energy E_T, and average total energy of positive- and negative-directed fluxes E^+ and E^-, respectively. E_T is at the level of E_{TOP} at the drain junction so that the backscattering of the ballistic source-injected carriers contributes to the negative flux in $x_{\max}$.

Finally, let us discuss the two main limitations of the proposed method. The first limitation is that the proposed model assumes that the point where $r_{SD} \approx r_{DS}$ (let's call it x_{cross}) is very close to $x_{\max}$. As a matter of fact, (11) holds only at x_{cross}, whereas the Natori model [see (3) and (4)] is valid only at $x_{\max}$. Indeed the carrier distribution can be approximated by a Fermi–Dirac expression also for $x_{S,\mathrm{inj}} \leq x \leq x_{\max}$ so that, neglecting the small potential variation, (3) and (4) can be applied in this region. This means that our model is approximately valid until $x_{\mathrm{cross}} \leq x_{\max}$. Fig. 9 shows $x_{\max}$ and x_{cross} for different bias and gate lengths. It shows that, for low gate voltages, $x_{\mathrm{cross}} \leq x_{\max}$ and our model works. As the gate voltage increases, x_{cross} moves toward the drain. For higher gate voltages, x_{cross} is significantly different from $x_{\max}$, the carrier distribution is very different from a Fermi–Dirac distribution, and the voltage drop with respect to $x_{\max}$ is high

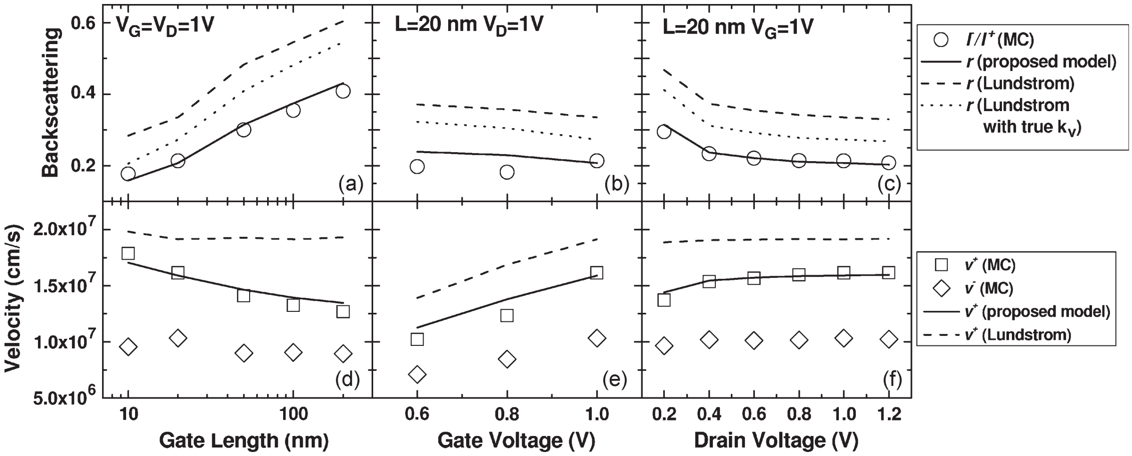

Fig. 8. (a–c) Backscattering and (d–f) positive-directed velocity calculated with the proposed model and with the LM compared with the true results directly extracted from the MC simulation for different (left) gate lengths, (middle) gate voltages, and (right) drain voltages. The proposed model reproduces very well the MC results, while the LM overestimates them (40%–50%). Moreover, the backscattering obtained with the LM using the true $k_v = v^+/v^-$ directly extracted from the MC simulation is shown. It is found that it significantly differs from I^-/I^+ so that the approximation on k_v is not sufficient to justify this gap. The negative-directed velocity is also shown. It is found that $k_v = v^+/v^-$ is approximately equal to 1.35 according to [20].

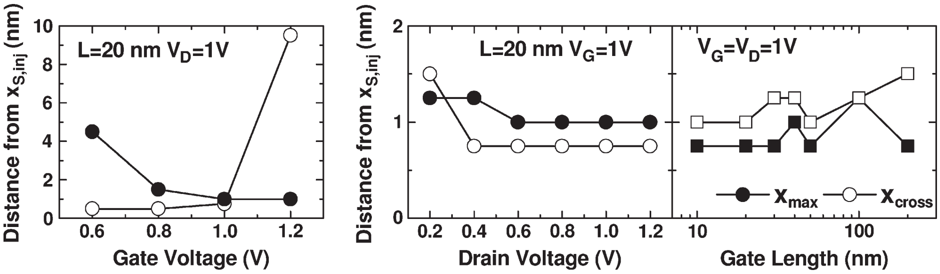

Fig. 9. Distance (in nanometers) between the source edge $x_{S,\mathrm{inj}}$ and (filled symbols) $x_{\max}$ and (empty symbols) x_{cross} for different bias and gate lengths. For low gate voltages, we have $x_{\mathrm{cross}} \leq x_{\max}$, and the carrier distribution is close to the Fermi–Dirac; the Natori equations (3) and (4) are approximately valid, and the proposed model can be used. For higher gate voltages, x_{cross} moves toward the drain, where the carrier distribution cannot be approximated by the Fermi–Dirac so that (3) and (4), and the proposed model are no more valid. Moreover, for a gate voltage in the operating range ($V_G = 1$ V), drain-voltage and channel-length variations do not significantly influence the relative position of $x_{\max}$ and x_{cross}.

so that (3) and (4), and the proposed model cannot be applied. In the simulation conditions, the model continues to work with a gate overdrive of 0.6 V (threshold voltage is 0.4 V). Moreover, for a gate voltage in the working range ($V_G = 1$ V), drain-voltage and channel-length variations do not significantly influence the relative position of $x_{\max}$ and x_{cross}.

Another limitation of the model is due to the single-subband approximation. Schrodinger–Poisson simulations, performed with ATLAS device simulator, have been used to evaluate the percentage of the occupation of the first subband E_1 as a function of the silicon thickness. Fig. 10 shows that, when the silicon thickness is increased above 2 nm, the occupation of higher energy bands starts to become important. We argue that this is not a problem of our assumption [$r_{SD} \approx r_{DS}$ or (11)] but it is related to the underlying Natori model so that a similar problem is shared with the Lundstrom model. A multiband version of our equations, using, for example, the approach proposed in [15], could be used to overcome this limitation.

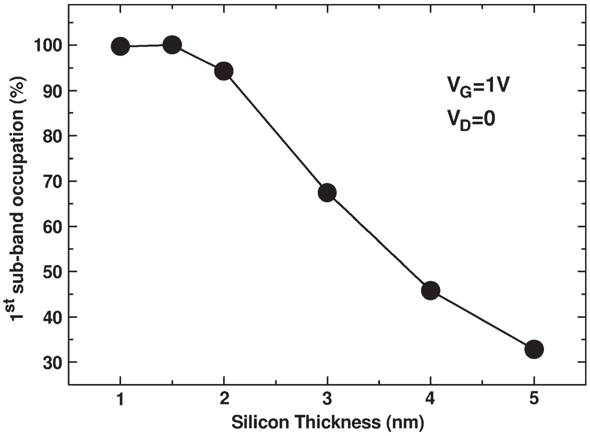

Fig. 10. First-subband occupation as a function of silicon thickness, evaluated by Schrodinger–Poisson simulations performed with ATLAS. When the silicon thickness is increased above 2 nm, the occupation of higher energy bands starts to become important. This is not a problem of our assumption [$r_{SD} \approx r_{DS}$ or (11)], but it is related to the underlying Natori model so that a similar problem is shared with the Lundstrom model. A multiband version of our equations, using, for example, the approach proposed in [15], could be used to overcome this limitation.

V. CONCLUSION

In this paper, we have proposed a charge-transport model for partially ballistic nanoMOSFETs in saturation based on channel backscattering, which is an alternative to the well-known Lundstrom model. In our picture, we have removed the concept of VS, and we have assumed that equilibrium-distributed carriers are injected in the channel from a source and a drain injection point so that forward- and backward-going fluxes are treated in a symmetrical way. The main difference with respect to the LM is that we have included in the model the scattering between the source injection point and the VS, leading to the result that the sum of the forward- and backward-going fluxes at the VS is approximately equal to the sum of the source- and drain-injected ballistic components. Moreover, our model takes into account for the inelastic scattering at the VS by an approximately constant ratio between the average velocities of forward- and backward-going fluxes. We have shown that, through 2-D full-band MC simulations with quantum corrections, our model represents a significant improvement in terms of accuracy with respect to the model proposed by Lundstrom (up to 40%) and succeeds in connecting the backscattering coefficient with its true value, which can be extracted through particle-based MC simulations.

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Gino Giusi received the M.S. and Ph.D. degrees in electronic engineering from the University of Messina, Italy, in 2002 and 2005, respectively.

In 2005, he was a Visiting Scientist with the Interuniversity Micro-Electronics Center, Leuven, Belgium. In 2006, he was with the Institute for Microelectronics and Microsystems, National Council of Research, Catania, Italy, as a Contract Researcher. In 2009, he was a Visiting Scientist with the Purdue University, West Lafayette, Indiana. He is currently a Contract Researcher and a Contract Professor with the University of Calabria, Rende, Italy. He has authored or coauthored more than 40 publications in peer-reviewed journals and in international conference proceedings. His main research interests include the study of electrical characterization techniques and reliability for solid-state electronic devices, the modeling and simulation of nanoscale complementary metal–oxide–semiconductor transistors and memories, and the design of ultralow noise electronic instrumentation and techniques for low-frequency noise measurements.

Dr. Giusi serves as a reviewer of leading journals in the field of electronic devices.

Giuseppe Iannaccone (M'98–SM'10) received the M.S. and Ph.D. degrees in electrical engineering from the Universitá di Pisa, Pisa, Italy, in 1992 and 1996, respectively.

In 1996, he took a permanent position as a Researcher with the Italian National Research Council, and in the same year, he obtained a faculty position of an Assistant Professor with the Department of Electrical Engineering, Universitá di Pisa, where he has been an Associate Professor in electronics since January 2001. He has authored or coauthored more than 120 papers published in peer-reviewed journals and more than 80 papers in proceedings of international conferences. His research interests include transport and noise in nanoelectronic and mesoscopic devices, development of device modeling and technology computer-aided design tools, and the design of extremely low-power circuits and systems for radio-frequency identification and ambient intelligence scenarios.

Dr. Iannaccone has coordinated a few European and national projects involving multiple partners and has acted as the Principal Investigator in several research projects funded by public agencies at the European and national levels and by private organizations. He is in the technical committee of few international conferences and serves as a Referee of leading journals in the fields of condensed-matter physics, device electronics, and circuit design.

Felice Crupi received the M.S. degree in electronic engineering from the University of Messina, Messina, Italy, in 1997 and the Ph.D. degree from the University of Firenze, Firenze, Italy, in 2001.

Since 1998, he has been a repeat Visiting Scientist with the Interuniversity Micro-Electronics Center, Leuven, Belgium. In 2000, he was a Visiting Scientist with the IBM Thomas J. Watson Research Center, Yorktown Heights, NY. Since 2002, he has been with the Dipartimento di Elettronica, Informatica e Sistemistica, Università della Calabria, Rende, Italy, as an Associate Professor in electronics. In 2006, he was a Visiting Scientist with the Universitat Autonoma de Barcelona, Barcelona, Spain. He has authored or coauthored more than 60 publications in peer-reviewed journals and more than 40 publications in international conference proceedings. His journals have been cited more than 500 times, and his h-index is equal to 12. His main research interests include reliability of very large scale integration (VLSI) complementary metal–oxide–semicondutor (CMOS) devices, modeling and simulation of VLSI CMOS devices, electrical characterization techniques for solid-state electronic devices, and the design of ultralow-noise electronic instrumentation.

Dr. Crupi serves as a reviewer of leading journals and conferences in the field of electronic devices. He has been the Coordinator of research projects at national and international levels.