Barrier Lowering and Backscattering Extraction in Short-Channel MOSFETs

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

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

Debabrata Maji
Taiwan Semiconductor Manufacturing Company (TSMC)

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

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Gino Giusi, Giuseppe Iannaccone, Senior Member, IEEE, Debabrata Maji, and Felice Crupi

Abstract—In this paper, we propose a fully experimental method to extract the barrier lowering in short-channel saturated MOSFETs using the Lundstrom backscattering transport model in one-subband approximation and carrier degeneracy. The knowledge of barrier lowering at the operative bias point in the inversion regime is of fundamental importance in device scaling. At the same time, we also obtain an estimate of the backscattering ratio and the saturation inversion charge. With respect to previously reported works on extraction of transport parameters based on the Lundstrom model, our extraction method is fully consistent with it, whereas other methods make a number of approximations in the calculation of the saturation inversion charge, which are inconsistent with the model. The proposed experimental extraction method has been validated and applied to results from device simulation and measurements on short-channel poly-Si/SiON gate nMOSFETs with gate lengths down to 70 nm. Moreover, we propose an extension of the backscattering model to the case of 2-D geometries (e.g., bulk MOSFETs). We found that, in this case, backscattering is governed by the carrier transport in a few nanometers close to the silicon/oxide interface and that the value of the backscattering ratio obtained with a 1-D approach can be significantly different from the real 2-D value.

Index Terms—Backscattering, barrier lowering, C–V measurements, device simulation.

I. INTRODUCTION

DUE TO THE continuous downsizing of MOSFET geometry, improved physical models are needed to accurately study the charge transport in the channel [1]–[8]. One of the simplest and most successful models was proposed by Lundstrom [2] on the basis of Natori’s theory for ballistic MOSFETs [1]. In his backscattering model, charge transport in the channel is regulated by the injection of the near-equilibrium thermal carriers at the top of the source–channel potential barrier (the virtual source). Only a fraction of the injected carriers reaches the drain side due to scattering in the channel. The ratio of the backscattered current to the total current injected by the virtual source is the backscattering coefficient.

The backscattering coefficient plays a pivotal role in understanding the scalability of a given technology (material and/or architecture). Since a wide range of technology options are currently under study to meet performance targets as scaling continues, the backscattering coefficient is gaining more and more popularity, and experimental procedures for its accurate estimation are strongly required [9]–[12].

Most of the measurements of the backscattering ratio have been done by using the method proposed by Chen et al. [9], where backscattering is extracted by measuring the saturation drain current at different temperatures [13]–[17]. However, as it has been discussed by Zilli et al. [18], the method accounts for a number of assumptions that strongly affect the value of the extracted backscattering. A more reliable method has been proposed by Lochtefeld et al. [10], [11], where the saturation inversion charge is obtained from the measurement of the gate-to-channel capacitance corrected for drain-induced barrier lowering (DIBL). However, because no experimental method exists to extract the DIBL at the specified bias point in the inversion regime, the charge is calculated by using a DIBL extracted in the subthreshold regime where it is easily calculated as a simple shift of the gate voltage for a constant drain current. Because the DIBL is generally a function of bias point, the extracted value of backscattering can be sensibly affected.

Differently, in this paper, we propose a fully experimental method that uses the correct DIBL, and it allows the extraction of barrier lowering directly in the inversion regime, which is of fundamental importance for device scaling, obtaining at the same time an estimation of the backscattering ratio and of the saturation inversion charge. Secondary transport parameters like injection velocity and mean free path can be evaluated as a direct consequence.

The remainder of this paper is divided as follows. In Section II, the Lundstrom backscattering model is discussed. In this section, we also extend the model to the case of a 2-D geometry. In Section III, the method proposed by Lochtefeld et al. for the backscattering ratio extraction is discussed. In Section IV, the proposed method is presented, and in Section V, it is exemplified through application to 2-D quantum-corrected device simulations and to measurements on short-channel poly-Si/SiON gate nMOSFETs.

II. BACKSCATTERING MODEL

Saturation backscattering coefficient ($r_{sat}$) is defined as the ratio of the negative-directed current ($I^−$) at the virtual
source \((x_0)\) to the positive-directed current \((I^+)\) at the virtual source (Fig. 1)

\[
r_{\text{sat}} = \frac{I^-}{I^+} \tag{1}
\]

\[
I_{D,\text{sat}} = I^+ - I^-(2)
\]

where \(I_{D,\text{sat}}\) is the drain current in saturation. The Lundstrom backscattering model in saturation is governed by the following equations [3]:

\[
I_{D,\text{sat}} = qW N_{2D} v_{th} \delta_{1/2}(\eta_{\text{sat}}) \frac{1 - r_{\text{sat}}}{2} \tag{3}
\]

\[
Q_{\text{sat}} = q N_{2D} \frac{1 + r_{\text{sat}}}{2} \delta_0(\eta_{\text{sat}}) \tag{4}
\]

where \(q\) is the electron charge; \(W\) is the device width; \(N_{2D} = kT (\pi m_{\text{DOS}}/\hbar^2)\) is the 2-D effective density of states, with \(k\) being the Boltzmann constant, \(T\) being the absolute temperature, \(g\) being the subband degeneracy, \(\hbar\) being the reduced Planck constant, and \(m_{\text{DOS}}\) being the effective electron mass for the density of states of the considered subband; \(v_{th} = \sqrt{2kT m_C}/(\pi m^2_{\text{DOS}})\) is the average 1-D thermal velocity, with \(m_C\) being the conduction effective electron mass for the considered subband; \(Q_{\text{sat}}\) is the inversion charge per unit area at the virtual source; \(\delta_{1/2}(\cdot)\) is the Fermi–Dirac integral on the order of one-half (zero); and \(\eta_{\text{sat}} = (E_{\text{FS}} - E_1)/kT\) is the energy distance (in units of \(kT\)) of the populated subband \((E_1)\) with respect to the source quasi Fermi level \((E_{\text{FS}})\). The model is intrinsically 1-D (along the channel direction), and for this reason, the theory has been developed mainly for thin double-gate (DG) devices. Moreover, the Lundstrom model assumes that only one subband \((E_1)\) is populated. This approximation is good, specifically for high transverse fields. An empirical approach to take into account multiband occupation has been proposed by Barral et al. [12] in the case of DG/SOI devices. In this paper, to validate the proposed method, also in the case of bulk devices, we use a 2-D approach for calculating the backscattering ratio.

**A. Extension to a 2-D Geometry**

As stated earlier, the backscattering model is 1-D and based on a subband description while we need to calculate \(r_{\text{sat}}\) in a 2-D geometry and a quantum-corrected semiclassical simulation. To serve this purpose, we propose a straightforward extension of the Lundstrom backscattering model for a 2-D semiclassical device. Indeed, in a 2-D semiclassical device, the position of the virtual source along the longitudinal direction \((x)\) depends on the position of the plane along the vertical \((y)\) axis. We divide the channel, along the \(y\)-direction, into thin slices of length \(L\) (the channel length) and thickness \(\Delta y\) (see Fig. 1). For each slice, we find the position of the virtual source \(x_0(y)\), and we calculate the local charge density and the local current as

\[
Q(y) = q \int_y^{y+\Delta y} n(x_0, y') \, dy' \tag{5}
\]

\[
I_D(y)/W = \int_y^{y+\Delta y} J_D(x_0, y') \, dy' \tag{6}
\]

where \(n\) is the electron concentration and \(J_D\) is the current density. Now, the 1-D model [(3) and (4)] can be used within the slice, getting the local values for \(Q(y)\), \(I_D(y)\), and \(r(y)\). By solving (1) and (2) within the slice, we can also calculate the local values for \(I^+(y)\) and \(I^-(y)\). Now, the 2-D backscattering ratio can be calculated as

\[
r_{\text{sat}}^2 = \frac{\sum_{y'} I^-(y')}{\sum_{y'} I^+(y')} \tag{7}
\]

Fig. 2 shows the results of device simulation performed on short-channel silicon devices \((L = 70 \text{ nm}, t_{\text{ox}} = 1.2 \text{ nm})\) biased in saturation. As expected, the currents \(I^+\) and \(I^-\) have
a maximum close to the interface (~1 nm), where the charge also has a maximum, and decrease rapidly going far from it. \( r_{2D} \) is the cumulative 2-D backscattering coefficient evaluated through (7) as a function of integration depth along the vertical direction \( y \). As expected, it can be observed from Fig. 2 that \( r_{2D} \) is significantly affected by the charge transport in a region of few nanometers close to the interface, while it becomes constant far from it. It is difficult to do a fair comparison between \( r_{2D} \) with the value of the backscattering calculated using a 1-D assumption \( (r_{1D}) \) because a question arises about the correct definition of \( Q_{sat} \) in a 2-D geometry. However, if we evaluate \( Q_{sat} \) as the sum of the charges at \( x_0(y) \) in each slice [5], we can calculate \( r_{1D} \) through (3) and (4). Fig. 2 shows that the value of the backscattering ratio obtained with a 1-D method \( (r_{1D}) \) can be significantly different from the real 2-D value \( (r_{2D}) \).

### III. Lochtefeld Method for Backscattering Extraction

In the Lochtefeld method [10], [11], to extract the backscattering coefficient in a short-channel device, the saturation inversion charge is estimated by integration of the gate-to-channel capacitance \( (C_{GC}) \)

\[
Q_{sat} = \int_{-\infty}^{\infty} C_{GC}(V) \, dV
\]

where \( V_G \) is the gate voltage of the specified bias point and \( \Delta V_G \) is a correction term. Because it is difficult to measure \( C_{GC} \) in a short-channel device due to parasitic capacitances (overlap and instrumentation), \( C_{GC} \) is measured in a longer reference device so that \( \Delta V_G \) includes corrections for the threshold-voltage \( (V_T) \) roll-off and for the DIBL. As stated in the Introduction, the DIBL is evaluated in the subthreshold regime where it is easily calculated as a simple shift of the gate voltage for a constant drain current. Fig. 3 shows the barrier lowering simulated (expected DIBL) as a function of gate bias point. This number has been calculated by taking the difference of the potentials at the virtual source and at the maximum of the charge (~1 nm far from the interface) for cases \( V_D = 1 \) \( \text{V} \) and \( V_D = 50 \) \( \text{mV} \), where \( V_D \) is the drain-to-source voltage. It is apparent that the DIBL is a strong function of bias point, and in particular, it is totally different in subthreshold with respect to the inversion regime affecting the calculated inversion charge. This is due to the bias dependence of the capacitive channel–drain coupling, which is a component of the bulk capacitance. In fact, the shape of the DIBL as a function of gate voltage resembles the shape of the gate capacitance as a function of gate voltage. However, some authors have reported that a DIBL in the subthreshold regime is sometimes sufficient to reproduce device characteristics [21]. Once that \( Q_{sat} \) is estimated, \( \eta_{sat} \) is calculated from

\[
Q_{sat} = qN_{2D}3_0(\eta_{sat}). \tag{9}
\]

From the knowledge of \( \eta_{sat} \) and measuring the saturation drain current, backscattering is extracted by (3). Let us note that

![Fig. 3. Barrier lowering simulated as a function of gate bias with the proposed method, the Lochtefeld method, and the one expected, calculated by taking the difference of the potentials at the virtual source and at the maximum of the charge (~1 nm far from the interface) for cases \( V_D = 1 \) \( \text{V} \) and \( V_D = 50 \) \( \text{mV} \). The simulated devices are silicon n-MOSFETs with poly-Si gate, bulk doping of \( 10^{18} \) \( \text{cm}^{-3} \), oxide thickness \( t_{ox} = 1.2 \) nm, and gate length \( L = 70 \) nm. The expected DIBL is a strong function of bias point. The DIBL calculated with our method matches very well with the expected DIBL, while the value calculated with the Lochtefeld procedure underestimates strongly the expected value showing a strong inconsistency with the subthreshold expected DIBL used to calculate the inversion charge.](image)

### IV. Proposed Method for Barrier Lowering and Backscattering Extraction

The proposed method is based on directly using (3) and (4), which define the backscattering model. In addition, the term \( Q_{sat} \) is estimated as

\[
Q_{sat} = Q_0 + \int_{V_G}^{V_G+\frac{kT}{q} \Delta \eta} C_{GC}(V) \, dV \tag{10}
\]

where \( \Delta \eta = \eta_{sat} - \eta_0 \), \( \eta_0 \) is the value of \( \eta \) at equilibrium \( (V_D = 0) \) extracted from \( Q_0 = qN_{2D}F_0(\eta_0) \). \( Q_0 \) is the equilibrium charge extracted from \( CV \) measurement corrected for the \( V_T \) roll-off. Substituting (10) into (4), one obtains an equation in the two unknowns \( \Delta \eta \) and \( r_{sat} \)

\[
Q_0 + \int_{V_G}^{V_G+\frac{kT}{q} \Delta \eta} C_{GC}(V) \, dV = qN_{2D} \frac{1+r_{sat}}{2} \Delta \eta_0 (\eta_0 + \Delta \eta). \tag{11}
\]

By solving the nonlinear system [(3) and (11)], one obtains both \( r_{sat} \) and \( \Delta \eta \). The DIBL is simply represented by \( kT/q \cdot \Delta \eta \). Let us note that the proposed method is fully consistent with the backscattering model because (3) and (4) are used. Two main differences can be found with respect to the Lochtefeld method: 1) the DIBL correction in the charge calculation is done directly using the correct barrier lowering at the specified bias point in the inversion regime and not in the subthreshold regime, and 2) scattering is included in the charge calculation [the term \( (1+r_{sat})/2 \) in (11)].
Fig. 4. (a) Simulated barrier lowering and (b) backscattering in 2-D short-channel poly-Si gate nMOSFETs with $t_{ox} = 1.2$ nm at biases $V_G - V_{T,\text{LONG}} = 1$ V and $V_D = 1$ V, where $V_G$ is fixed and $V_{T,\text{LONG}}$ is the $V_T$ of the long reference device. It is apparent that the values extracted with the proposed method match very well with the expected values directly obtained from the simulation using the procedure discussed in Section II-A, whereas the Lochtefeld method overestimates the barrier lowering. Moreover, the DIBL extracted with the Lochtefeld method is inconsistent with the subthreshold expected DIBL used to calculate the inversion charge.

V. VALIDATION BY NUMERICAL SIMULATION AND MEASUREMENTS

A comparison of the accuracy of the Lochtefeld method and of the proposed method is made through 2-D density gradient device simulation using Medici device simulator [19]. To serve this purpose, in Fig. 4(a) and (b), we compare, for different gate lengths, the expected values of barrier lowering (calculated as discussed in Section III) and of backscattering [calculated by (7)] obtained directly from simulation with the ones extracted by applying the Lochtefeld method and the proposed method on the simulated $I-V$ and $C-V$ characteristics. Moreover, the DIBL calculated in the subthreshold regime is plotted. The simulated devices are silicon n-MOSFETs with poly-Si gate, bulk doping of $10^{18}$ cm$^{-3}$, and oxide thickness $t_{ox} = 1.2$ nm. Equilibrium Schrodinger–Poisson simulations show that 80% of the charge is confined in the first subband of the unprimed ladder $\Delta^2(1)$ (see the inset in Fig. 6), thus justifying in part the one-subband approximation. $N_{2D}$ and $v_{th}$ [(3) and (4)] are calculated, for the considered subband, with $m_{DOS} = m_e = m_t = 0.19m_0$ and $g = 2$, where $m_t$ is the transversal effective mass and $m_0$ is the electron free mass. Let us note the excellent agreement between the values of the expected DIBL and the DIBL extracted with our proposed method. The excellent agreement in barrier lowering extraction is maintained also by changing the gate voltage (Fig. 3). The inconsistency of the Lochtefeld method is apparent when one compares the DIBL used to calculate the charge (expected DIBL in the subthreshold range) and the DIBL calculated as $kT/q \cdot \Delta \eta$ (Lochtefeld method in Fig. 3), which is, in any case, much smaller with respect to the expected value. A comparison between the backscattering extracted with the proposed method and the one extracted with the Lochtefeld method is difficult to do because both methods are intrinsically 1-D while the expected backscattering is 2-D as discussed in Section II-A (see the difference between 2-D and 1-D backscattering as function of the gate voltage in Fig. 5). We repeat that the comparison is not totally fair, but we are confident that the value extracted with our method is more consistent because it has been extracted by directly using the Lundstrom backscattering equations (3) and (4).
in (10) includes an additional correction term \((-R_SI_{D,sat}\)) due to the series resistance \(R_S\) [10], which is extracted by a common linear extrapolation technique [20].

VI. CONCLUSION

Standard methods to extract backscattering need the inversion charge at the virtual source, which is difficult to estimate in saturated short-channel devices. This charge is usually measured in a longer reference device by a \(CV\) roll-off and DIBL. DIBL correction is usually done in the subthreshold regime with the well-known method of gate voltage shift for a constant drain current. Because backscattering is calculated in inversion, the DIBL should be calculated in inversion and not in subthreshold as is usually done. In this paper, we have shown that using the DIBL in subthreshold may lead to severe errors in barrier lowering extraction and, hence, in backscattering and saturation inversion charge extraction. Moreover, standard methods neglect the influence of scattering in the calculation of the saturation inversion charge. We have proposed a fully experimental method to extract the DIBL and, hence, the backscattering and saturation inversion charge in short-channel MOSFETs, which is completely consistent with the backscattering model, as it must be. The proposed experimental extraction method has been validated and applied to results from device simulation and measurements on short-channel poly-Si/SiON gate nMOSFETs with gate lengths down to 70 nm. Moreover, we have proposed an extension of the backscattering model to the case of 2-D geometries. We found that backscattering is governed by the carrier transport in a few nanometers at the silicon/oxide interface and that the value of the real 2-D backscattering ratio can be sensibly affected by a 1-D method when bulk MOSFETs are investigated.

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Giuseppe Iannaccone (M’98–SM’10) received the M.S. and Ph.D. degrees in electrical engineering from the Università 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 with the Department of Electrical Engineering, Università di Pisa, as an Assistant Professor, where he has been an Associate Professor of electronics with the Department of Information Engineering (DIIIEI) since January 2001. He 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 for leading journals in the fields of condensed-matter physics, device electronics, and circuit design. 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 interests include transport and noise in nanoelectronic and mesoscopic devices, the development of device modeling and TCAD tools, and the design of extremely low-power circuits and systems for RFID and ambient intelligence scenarios.

Debabrita Maji received the B.Tech. and M.Tech. degrees in radiophysics and electronics from the Institute of Radio Physics, University of Calcutta, Kolkata, India, in 2001 and 2003, respectively, and the Ph.D. degree in microelectronics from the Indian Institute of Technology, Bombay, India, in 2009.

In 2006, he was a postdoctoral research fellow with Taiwan Semiconductor Manufacturing Company (TSMC), Ltd., Hsinchu, Taiwan. In 2008, he was a Visiting Indian Researcher with the University of Calabria, Rende, Italy, where he worked on the reliability and study of low-frequency noise in advanced MOSFETs. In 2010, he joined TSMC as a Principal Engineer with the Advanced Reliability Development Program Group. His research interests include device characterization, reliability, and noise measurement in advanced MOS devices.

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 (IMEC), 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 Sistemiatica, Università della Calabria, Rende, Italy, as an Associate Professor of electronics. In 2006, he was a Visiting Scientist with the Universitat Autonoma de Barcelona, Barcelona, Spain. He serves as a Reviewer for leading journals and conferences in the field of electronic devices. He has been a Coordinator of research projects at the national and international levels. 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 the reliability of VLSI 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.