# Experimental Extraction of Barrier Lowering and Backscattering in Saturated Short-Channel MOSFETs

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**Abstract**

In this work we propose a fully experimental method to extract the barrier lowering, at the operative bias point above threshold, in short-channel saturated MOSFETs using the Lundstrom backscattering transport model. At the same time we obtain also an estimate of the backscattering ratio. Respect to previously reported works, our extraction method is fully consistent with the Lundstrom model, 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 2D quantum corrected device simulation and to measurements on short-channel poly-Si/SiON gate nMOSFETs with gate length down to 70 nm.

## 1. Introduction

Due to the continuous downscaling 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 M. Lundstrom [1] on the basis of the Natori theory for ballistic MOSFETs [2]. The strength of the model is that it provides just a number, the backscattering coefficient, which includes all the information about the scattering in the channel. 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 measurements of the backscattering ratio have been done by using the method proposed by Chen *et al.* [9], where the 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 which strongly affect the value of the extracted backscattering. A more reliable method has been proposed by Lochtefeld [10], where the saturation inversion charge is obtained from the measurement of the gate-to-channel capacitance corrected for the 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 sub-threshold 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 the bias point, the extracted value of the backscattering can be sensibly affected. Differently, in this paper, we propose a fully experimental method which uses the correct DIBL and it allows the extraction of the 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. Secondary transport parameters like injection velocity and mean free path can be evaluated as a direct consequence.

## 2. The Backscattering Model

The 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)

$$r_{sat} = \frac{I^-}{I^+} \quad (1)$$

$$I_{D,sat} = I^+ - I^- \quad (2)$$

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

$$I_{D,sat} = qWN_{2D}v_{th}\Im_{1/2}(\eta_{sat})\frac{1-r_{sat}}{2} \quad (3)$$

$$Q_{sat} = qN_{2D}\frac{1+r_{sat}}{2}\Im_0(\eta_{sat}) \quad (4)$$

where $q$ is the electron charge, $W$ is the device width,

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$N_{2D} = kT \frac{g m_{DOS}}{\pi \hbar^2}$ is the two-dimensional effective density of states with $k$ the Boltzmann constant, $T$ the absolute temperature, $g$ the sub-band degeneracy, $\hbar$ the reduced Planck constant, $m_{DOS}$ the effective electron mass for the density of states of the considered sub-band, $v_{th} = \sqrt{2kTm_C/(\pi m_{DOS}^2)}$ is the average one-dimensional (1D) thermal velocity with $m_C$ the conduction effective electron mass for the considered sub-band, $Q_{sat}$ is the inversion charge per unit of area at the virtual source, $\Im_{1/2}$ ($\Im_0$) is the Fermi-Dirac integral of order one half (zero) and $\eta_{sat} = (E_{FS} - E_1)/kT$ is the energy distance, in units of $kT$, of the populated sub-band ($E_1$) with respect to the source quasi Fermi level ($E_{FS}$). The model is intrinsically one-dimensional (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 sub-band ($E_1$) is populated. An empirical approach to take into account multi-band occupation has been proposed by Barral *et al.* [11] in the case of DG/SOI devices. In this work, to validate the proposed method also in the case of bulk devices, we use a 2D approach for calculating the backscattering ratio.

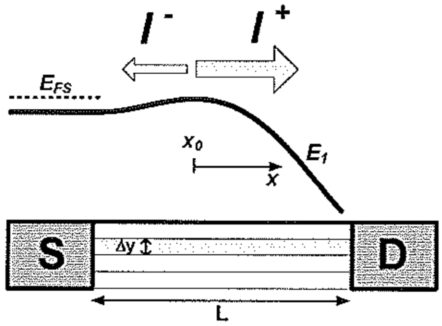


Figure 1. (Top) Sub-band ($E_1$) energy profile in saturation along the channel direction $x$. (Bottom) The backscattering in a 2D geometry is evaluated by dividing the channel along the vertical $y$ direction into thin slices with thickness $\Delta y$.

### 2.1 Extension to a 2D geometry

As stated, the backscattering model is 1D and based on a sub-band description, while we need to calculate $r_{sat}$ in a 2D geometry and a quantum corrected semi-classical simulation. To serve this purpose, we propose a straightforward extension of the Lundstrom backscattering model for a 2D semiclassical device. Indeed, in a 2D 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

$$Q(y) = q \int_{y}^{y+\Delta y} n(x_0, y')dy' \quad (5)$$

$$I_D(y)/W = \int_{y}^{y+\Delta y} J_D(x_0, y')dy' \quad (6)$$

where $n$ is the electron concentration and $J_D$ is the current density. Now the 1D model (Eqs. 3-4) 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 calculate also the local values for $I^+(y)$ and $I^-(y)$. Now the 2D backscattering ratio can be calculated as

$$r_{2D} = \frac{\sum_{y'} I^-(y')}{\sum_{y'} I^+(y')} \quad (7)$$

### 3. Lochtefeld Method for Backscattering Extraction

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

$$Q_{sat} = \int_{-\infty}^{V_G+\Delta V_G} C_{GC}(V)dV \quad (8)$$

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 sub-threshold regime where it is easily calculated as a simple shift of the gate voltage for a constant drain current. Figure 2 shows the barrier lowering simulated (expected DIBL) as a function of the 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 (~1nm far from the interface) for the cases $V_D$=1V and $V_D$=50mV where $V_D$ is the drain to source voltage. It is apparent that the DIBL is a strong function of the bias point, and in particular, it is totally different in sub-threshold 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 function of the gate voltage resembles the shape of the gate capacitance as function of the gate voltage. However some authors have reported that a DIBL in the sub-threshold regime is sometimes sufficient to reproduce device characteristics [19]. Once that $Q_{sat}$ is estimated, $\eta_{sat}$ is calculated from

$$Q_{sat} = qN_{2D}\Im_0(\eta_{sat}) \tag{9}$$

From the knowledge of $\eta_{sat}$ and measuring the saturation drain current, the backscattering is extracted by Eq. 3. Let us note that Eq. 9 contains the relationship between charge and potential when $V_D$=0, while the correct equation that should be used is Eq. 4, in fact Eq. 4 reduces to Eq. 9 when $r_{sat}$=1.

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

The proposed method is based on directly using equations (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 $Q_0=qN_{2D}F_0(\eta_0)$.

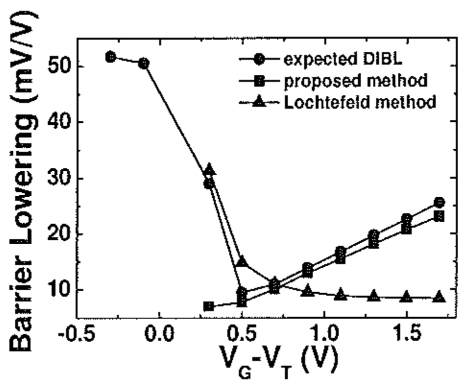


Figure 2. The barrier lowering simulated as a function of the gate bias overdrive, with the proposed method, with the Lochtefeld method and the one extracted directly from device simulation (expected).

$Q_0$ is the equilibrium charge extracted from CV measurement corrected for the $V_T$ roll-off. Substituting Eq. 10 into Eq. 4, one obtains an equation in the two unknowns $\Delta\eta$ and $r_{sat}$:

$$Q_0 + \int_{V_G}^{V_G+\frac{kT}{q}\Delta\eta} C_{GC}(V)dV = qN_{2D}\frac{1+r_{sat}}{2}\Im_0(\eta_0+\Delta\eta) \tag{11}$$

By solving the non linear 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 Eqs. 3-4 are used. Two main differences can be found with respect to the Lochtefeld method: *i)* the DIBL correction in the charge calculation is done directly using the correct barrier lowering at the specified bias point in inversion regime and not in sub-threshold , *ii)* scattering is included in the charge calculation ( the term $(1+r_{sat})/2$ in Eq. 11 ).

## 5. Validation by numerical simulation and measurements

A comparison of the accuracy of the Lochtefeld method and of the proposed method is made through 2D density gradient device simulation using MEDICI device simulator [20]. To this purpose, in Fig. 3 (left side) we compare, for different gate lengths, the expected values of the barrier lowering (calculated as discussed in Section III) and of the backscattering (calculated by Eq. 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.

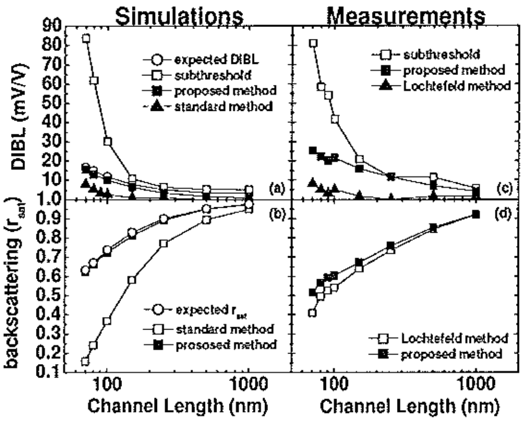


Figure 3. Simulated (left) and measured (right) barrier lowering (top) and backscattering (bottom) in 2D short-channel poly-Si gate nMOSFETs with $t_{ox}$=1.2 nm at the bias $V_G$-$V_{T,LONG}$=1V and $V_D$=1V, where $V_G$ is fixed and $V_{T,LONG}$ is the $V_T$ of the long reference device.

Moreover the DIBL calculated in the sub-threshold regime is plotted. The simulated devices are silicon n-MOSFETs with poly-Si gate, bulk doping of $10^{18}$ $cm^{-3}$ and oxide thickness $t_{ox}$=1.2nm. Equilibrium Schrodinger-Poisson simulations show that 80% of the charge is confined in the first sub-band of the unprimed ladder thus justifying, in part, the one sub-band approximation. $N_{2D}$ and $v_{th}$ (Eqs. 3-4) are calculated, for the considered sub-band, with $m_{DOS}=m_C=m_t=0.19m_0$ and $g=2$, where $m_t$ is the transversal effective mass and $m_0$ is the free electron 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 the barrier lowering extraction is maintained also by changing the gate voltage (Fig. 2). 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. 2) 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 1D while the expected backscattering is 2D. 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 (3-4). Experimental measurements have been performed on short-channel nMOSFETs with electrical parameters similar to those used in device simulation. The behavior of the DIBL and of the backscattering ratio extracted from experiments in Fig. 3 (right side) is in good agreement with that of the same parameters obtained from simulations reported in the same figure (left side), so that we do not spend any further comment here. The gate lengths reported in Fig. 3 are the mask lengths. The $V_T$ roll-off used to calculate $Q_0$ is evaluated by using the maximum trans-conductance method for the threshold voltage extraction [21]. Moreover, the term $\Delta V_G$ in Eq. 10 includes an additional correction term $(-R_S I_{D,sat})$ due to the series resistance $R_S$ [10] which is extracted by a common linear extrapolation technique [21].

## 6. Conclusions

In this work we have proposed a fully experimental method to extract the barrier lowering and hence the backscattering in short channel saturated MOSFETs that is completely consistent with the Lundstrom backscattering model, as it must be. The proposed experimental extraction method has been validated and applied to results from 2D quantum corrected device simulations and to measurements on short-channel poly-Si/SiON gate nMOSFETs with gate length down to 70 nm.

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