

Compact model of Intersubband Coulomb scattering for FD-SOI transistors operating at cryogenic temperature

Miltiadis Alepidis
Univ. Grenoble Alpes,
CEA, Leti, F-38000
Grenoble, France
miltiadis.alepidis@cea.fr

Thomas Bédécarrats
Univ. Grenoble Alpes,
CEA, Leti, F-38000
Grenoble, France
thomas.bedecarrats@cea.fr

Aurélien Bajolet
Univ. Grenoble Alpes,
CEA, Leti, F-38000
Grenoble, France
aurelien.bajolet@cea.fr

Benjamin Dormieu
STMicroelectronics,
Crolles, France
benjamin.dormieu@st.com

Manohiaina Galal El Dine
STMicroelectronics,
Crolles, France
manohiaina.galaleldine@st.com

Patrick Scheer
STMicroelectronics,
Crolles, France
patrick.scheer@st.com

Issa Sidibe
Quobly, Grenoble, France
issa.sidibe@quobly.io

Bruna Cardoso Paz
Quobly, Grenoble, France
bruna.cardoso-paz@quobly.io

Sébastien Martinie
Univ. Grenoble Alpes,
CEA, Leti, F-38000
Grenoble, France
sebastien.martinie@cea.fr

Abstract— This paper introduces an InterSubband Coulomb scattering (ISCS) limited mobility model that captures the additional mobility degradation which appears in cryogenic measurements for strong forward back bias in FD-SOI nMOS transistors. To develop our phenomenological model, we first present a methodology that employs L-UTSOI compact model to isolate the additional mobility degradation due to ISCS from experimental data of FD-SOI 28 nm transistors. The ISCS mobility is traced with the fundamental L-UTSOI quantities, and its modeled tendencies are smoothly combined. Finally, our ICSC mobility correction is benchmarked with experimental cryogenic data from a 28 nm FD-SOI technology. The model shows a good fit for all tested bias conditions of an nMOS device.

Keywords— Intersubband scattering, compact modeling, L-UTSOI, FD-SOI, cryogenic SPICE simulation.

I. INTRODUCTION

The strong demand for cryogenic MOS circuits, mostly for quantum computing applications, requires accurate compact models for an efficient design. While cryogenic temperatures improve transistors performance thanks to mobility increase [1], they also introduce new cryogenic effects that could potentially limit these improvement such as the threshold voltage shift [2] or the subthreshold slope saturation [3]. Although, there are several modeling efforts to introduce cryogenic effects into compacts models [4], [5], [6], there are still significant challenges, such as the modeling of the InterSubband Coulomb Scattering effect (ISCS) observed in nMOS Fully-Depleted Silicon-On-Insulator (FD-SOI) devices [7]. ISCS is mostly governed by the interactions

between electrons that start to occupy the subbands as the device is driven into inversion at cryogenic temperatures [7]. Accurate physical modeling of the energy levels of the subbands would require a self-consistent solution of the Poisson-Schrodinger equations. However, such a solution is extremely challenging, especially for asymmetric double gate devices and if it has to conform with the requirements (robustness, continuity, compact equation formulation, etc.) of a standard compact model. To provide the designers with a pragmatic solution, here, we introduce a phenomenological model that is based on the fundamental quantities of the standard L-UTSOI compact model [8], [9], [10] for FD-SOI transistor. In this paper, we firstly present our methodology to isolate the ISCS-limited mobility component. Then, we present the key aspects of our phenomenological model. After, we demonstrate the model's ability to reproduce results from measurements taken on 28 nm FD-SOI technology. Finally, a step-by-step methodology for parameter extraction is detailed along with a discussion on model's limitations.

II. ISCS MODEL DEVELOPMENT AND BENCHMARK

To study the ISCS-limited mobility component, we extract it through the experimental data using the standard L-UTSOI model and $G_{mob} = \mu_0 / \mu_{eff}$ which is a normalized mobility degradation term of L-UTSOI with μ_0 and μ_{eff} respectively the low field and effective mobility. The model fit before correction is depicted in Fig. 1a. We observe the degradation of the drain current (I_D) for $V_B > 0$ V due to ISCS effect. The model is calibrated to accurately fit the $V_B = 0$ V curve where the ISCS has little to no effect. The initial model calibration is

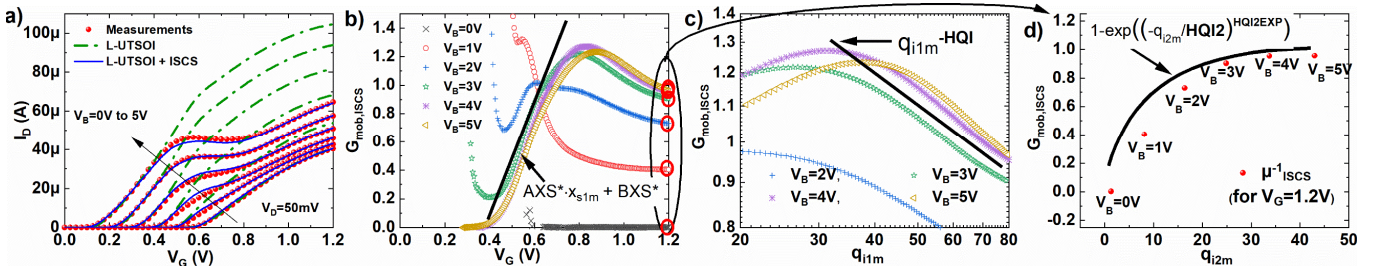


Figure 1: a) Drain current (I_D) versus front-gate voltage (V_G) for various back-gate voltages (V_B) of $W/L = 1 \mu m / 1 \mu m$ device (red dots) and simulated data with the standard L-UTSOI model without ISCS (green dash-dot line) and with ISCS (blue solid line) mobility correction. The extracted $G_{mob,ISCS}$ as a function of b) V_G and c) q_{i1m} (normalized inversion charge) for various V_B , in log-log scale. d) extracted $G_{mob,ISCS}$ as a function of q_{i2m} for $V_G = 1.2$ V and various V_B values. The temperature is set to $T = 4.2$ K.

equivalent to [11]. For the rest of the curves, the model fits until the onset of the ISCS effect (e.g., around $V_G = 0.4$ V for $V_B = 5$ V). To isolate the ISCS mobility degradation component, we first consider that the L-UTSOI model without ISCS correction would accurately predict the device charge [12] and all other mobility effects (such as Coulomb scattering and surface roughness). Our strategy is to find the additional mobility degradation term. This term is computed from the the mobility degradation terms of the device with and without ISCS that are extracted according to:

$$G_{mob,no-ISCS} = (W \cdot \mu_0 \cdot Q_{i,mod} \cdot V_D) / (L \cdot I_{D,mod}) \quad (1)$$

$$G_{mob,with-ISCS} = (W \cdot \mu_0 \cdot Q_{i,mod} \cdot V_D) / (L \cdot I_{D,exp}) \quad (2)$$

$$G_{mob,ISCS(extracted)} = G_{mob,no-ISCS} - G_{mob,with-ISCS} \quad (3)$$

where L and W are the device length and width, $I_{D,mod}$ and $I_{D,exp}$ are the model predicted and experimental drain currents respectively, $Q_{i,mod}$ is the inversion charge computed by the model and V_D the drain voltage. We note that the real relation between G_{mob} and I_D in linear regime is a bit more complex in L-UTSOI than the one presented in eq. (1) and (2), and this simplified version is reported here for reasons of clarity.

In Fig. 1b illustrates eq. (3), we first observe a linear increase of $G_{mob,ISCS(extracted)}$ with V_G from 0.4 V to 0.9 V. Note that, the initial decrease at low V_G for $V_B > 2$ V is an artifact due to the extraction procedure and it is not considered in the model. Then, and there is a power decrease with $q_{i1m} > 40$ (Fig. 1c) and a linear increase with q_{i2m} that slowly saturates (Fig. 1d), where q_{i1m} and q_{i2m} are the front-gate and back-gate inversion charge. The described behavior is empirically modeled as:

$$G_{lxs}^* = AXS^* \cdot x_{s1m} + BXS^* \quad (4a)$$

$$G_{lxs} = MAX(G_{lxs}^*, 0, \mathbf{SXS}) \quad (4b)$$

$$G_{hqi1} = q_{i1m}^{-HQI1} \quad (4c)$$

$$G_{hqi2} = \left(1 - \exp \left(\left(-\frac{q_{i2m}}{HQI2} \right)^{HQI2EXP} \right) \right) \quad (4d)$$

$$G_{hqi} = \mathbf{HQI} \cdot G_{hqi1} \cdot G_{hqi2} \quad (4e)$$

$$G_{mob,ISCS(modeled)} = MIN(G_{lxs}, G_{hqi}, \mathbf{SISCS}) \quad (4f)$$

where x_{s1m} is the front-gate surface potential, and all the parameter in bold are user extracted. AXS^* and BXS^* are explained later in the text. Eq. (4) is developed based on an analysis of $G_{mob,ISCS(extracted)}$ key tendencies on the fundamental L-UTSOI quantities used (x_{s1m} , q_{i1m} and q_{i2m}). Note that, for capturing the linear behavior of Fig. 1b we use x_{s1m} in eq. (4a), which is proportional to V_G but an internal L-UTSOI parameter. Also, the MIN and MAX functions definitions can be found in [13]. The ISCS mobility correction is added into the effective mobility of L-UTSOI such as:

$$G_{mob}^* = G_{mob} + G_{mob,ISCS} \quad (5)$$

where, G_{mob}^* is the mobility degradation including the ISCS correction. Now that our correction is integrated in L-UTSOI, it is benchmarked with experimental data in Fig. 1a and a good fit is observed for the $V_D = 50$ mV curves. To ensure that the model is accurate for all drain voltage conditions (Fig. 2a), we extract $G_{mob,ISCS}$ from the for I_D - V_G curves for various V_D values and at $V_B = 4$ V (see Fig. 2a) where ISCS is more prominent. The extracted $G_{mob,ISCS}$ is depicted in Fig. 2b. As V_D increases, the onset of the effect becomes weaker since the

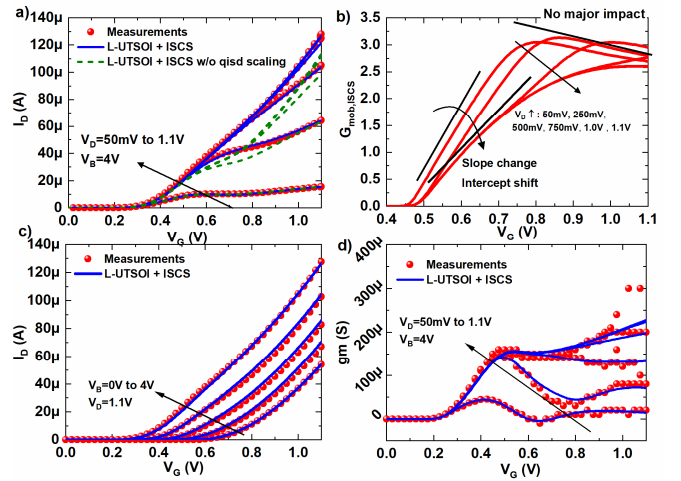


Figure 2: a) I_D - V_G curves for various V_D values and $V_B = 4$ V and simulated model with ISCS mobility with and without q_{isd} scaling (eq. (6a) and eq. (6b)). b) The extracted $G_{mob,ISCS}$ as a function of V_G for various V_D values and $V_B = 4$ V. c) I_D - V_G curves for various V_B values and $V_D = 1.1$ V and b) Transconductance (g_m) versus V_G curves for various V_D values and $V_B = 4$ V. The device geometry has a $W/L = 1 \mu m / 4 \mu m$ measured at 4.2 K.

slope of $G_{mob,ISCS}$ reduces and the maximum value appears for higher V_G values. In the high inversion regime, the behavior seems relatively unaffected. Thus, an adaptation of only the onset part (eq. 1a) of our model seems to be sufficient to correctly capture the effect of V_D . Here, we propose empirical equation:

$$AXS^* = \mathbf{AXSD} \cdot q_{isd}^{AXSDEXP} + \mathbf{AXS} \quad (6a)$$

$$\mathbf{BXS}^* = \mathbf{BXSD} \cdot q_{isd} + \mathbf{BXS} \quad (6b)$$

where q_{isd} is an inversion charge term [14] that depends on the effective quasi-fermi potential at the drain side [9], [10]. When eq. (6a) and eq. (6b) are replaced in eq. (4a), the model accurately fits the experimental data for all the tested drain voltages applied as illustrated in Fig. 2a and Fig 2c. Additionally, the transconductance (g_m) is also well modeled for $V_B = 4$ V and various drain voltages in Fig. 2d. Although the model can accurately fit the experimental data, it requires a large number of user-extracted parameters. In the next section, we present a parameter extraction methodology.

III. PARAMETER EXTRACTION AND MODEL FIT

The ISCS parameter extraction requires firstly an accurate capacitance fit and calibration of the I_D - V_G for $V_B = 0$ V for V_D values corresponding to linear and saturation regimes including calibration of the linear-to-saturation transition, visible on the I_D - V_D curves, as detailed in [14]. Then, using the classic L-UTSOI parameters (**BETNB**, **CSBI**, etc.), the user should calibrate the model to fit the $V_B > 0$ V until the onset of the ISCS effect, exactly as shown in the green dotted lines in Fig. 1a.

Then, the ISCS parameters that are summarized in Table I can be extracted, starting from the parameters of eq. (4). Having the I_D - V_G curves for $V_D = 50$ mV, that corresponds to the linear operation regime, as a reference there is a four-step parameter extraction process:

Step 1) The onset of ISCS mobility degradation has to be initialized through the parameters **AXS** and **BXS** on the I_D -

TABLE I: ISCS PARAMETER DESCRIPTION

Name	Description ^a	Range
AXS	ISCS first degradation factor for weak electric field	$[0, \infty)$
AXSD	AXS linear factor of drain voltage dependence	$(-\infty, \infty)$
AXSDEXP	AXS exponent factor of drain voltage dependence	$(-\infty, \infty)$
BXS	ISCS second degradation factor for weak electric field	$(-\infty, \infty)$
BXSD	BXS linear factor of drain voltage dependence	$(-\infty, \infty)$
HQI	High electric field factor of ISCS	$[0, \infty)$
HQI1	Front channel high electric field dependency of ISCS	$[0, \infty)$
HQI2	Back channel high electric field dependency of ISCS	$(0, \infty)$
HQI2EXP	HQI2 exponent factor	$[0, \infty)$
SXS	Smooth parameter of the ISCS onset	$[0, \infty)$
SISCS	Smooth parameter of ISCS mobility from weak to strong inversion	$[0, \infty)$

V_G curves for $V_G = 50$ mV with $V_B = 3, 4$ and 5 V while keeping **AXSD** and **BXSD** fixed at zero to ensure no V_D dependence at this parameter extraction stage. This corresponds to the calibration of the linear tendency of Fig. 1b.

Step 2) A positive value is set for the pre-factor **HQI** and along with the front-gate dependence parameter **HQI1** a second parameter optimization step is applied for $V_B = 3$ V, 4 V and 5 V of Fig. 1a. Now the power dependence described in Fig. 1c is fitted. Currently, the eq. (4d) is not initiated but since the extraction was focused on the high V_B values, the model is calibrated roughly at the plateau of Fig. 1d.

Step 3) To extract the back-gate dependence parameters we activate **HQI2** and **HQI2EXP** along with **AXS**, **BXS**, **HQI** and **HQI1** and we optimize the parameters at the I_D - V_G curves for $V_D = 50$ mV. In this step, not only the back-gate dependence (Fig. 1d) will be optimized but also the co-optimization of all ISCS model parameters will allow for a good fit of the I_D - V_G curves at the linear regime.

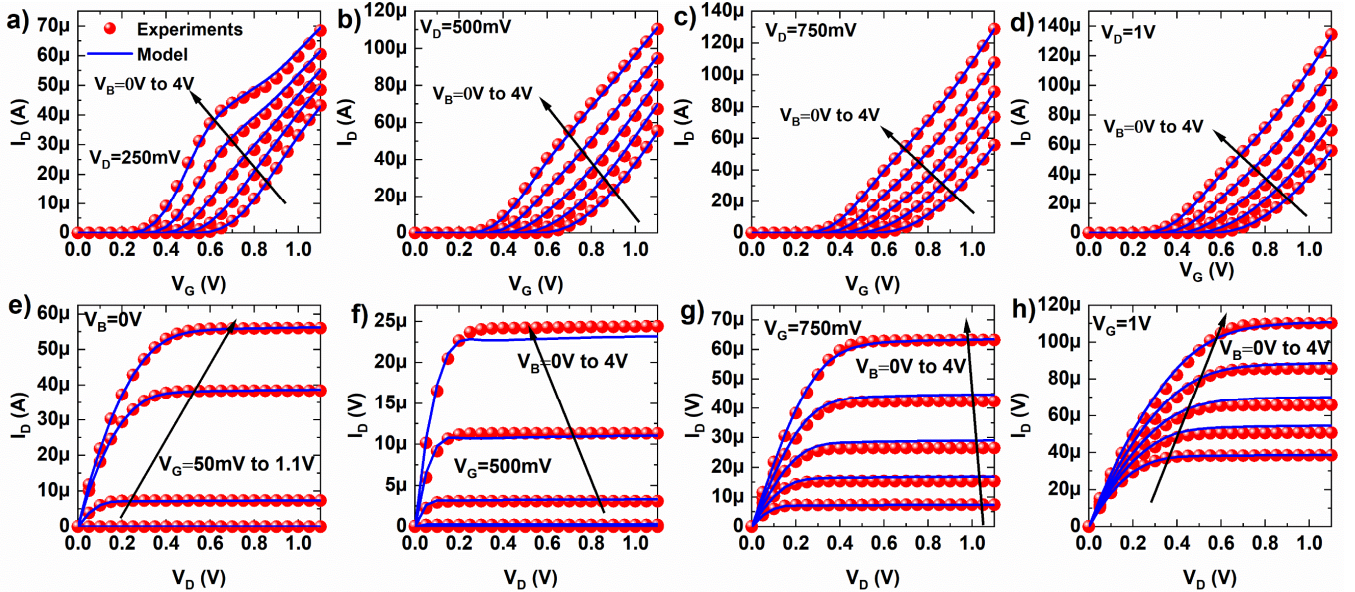


Figure 3: I_D - V_G curves for various V_B values and a) $V_D = 250$ mV, b) $V_D = 500$ mV, c) $V_D = 750$ mV, d) $V_D = 1$ V. e) I_D - V_D curves for various V_G and $V_B = 0$ V. I_D - V_D curves for various V_B and f) $V_G = 500$ mV, g) $V_G = 750$ mV and h) $V_G = 1$ V. The device geometry has a $W/L = 1 \mu\text{m}/4 \mu\text{m}$ measured at 4.2 K.

Step 4) The user might choose to re-optimize all the ISCS parameters for the linear regime, including the smoothing parameters **SXS** and **SISCS**, with the classic L-UTSOI mobility parameters (**BETN**, **BETNB**, **CS**, **CSBI**, etc.) to find the best compromise. This will result to the blue lines of Fig. 1a. then the drain voltage dependence needs to be extracted.

The ISCS effect is more prominent for high V_B values, thus we chose to extract the parameters related to V_D from the I_D - V_G curves at $V_B = 4$ V and various V_D values depicted in Fig. 2a. After an optimization of **AXS**, **AXSD**, **AXSDEXP**, **BXS** and **BXSD** the model rapidly converges from the green line to the blue line of Fig. 2a.

Now, the model calibration is benchmarked with experimental data for various measurements conditions in Fig. 3. Fig. 3a to Fig. 3d depict I_D - V_G curves for increasing $V_D = 250$ V to 1 V. The model shows an excellent agreement with the experimental data for all bias conditions presented. Fig. 3e shows the I_D - V_D curve for various V_G values which was optimized during the prerequisite step in [14]. As a result, the model fits accurately the $V_B = 0$ V. In Fig. 3f to Fig. 3h we observe the influence of V_B on the output characteristics and the good model fit for all back-gate bias conditions. Note that, this fit quality arrived naturally from the parameter optimization of the model in Fig. 1a and Fig. 2a without calibrating any additional saturation L-UTSOI parameters for $V_B > 0$ V. Now that the model is calibrated and ready for circuit design, we discuss its symmetry in the next section.

IV. GUMMEL SYMMETRY

While the mobility equations proposed for ISCS are simple without major numerical issues, they depend indirectly on V_D through the parameter on $q_{isd} = 0.5(q_{is} - q_{id})$ where q_{is} is the inversion charge on the source side and q_{id} the inversion charge at the drain side. We developed our ISCS model based on q_{isd} instead directly on V_D to mitigate the asymmetries or singularities around zero since a smooth is

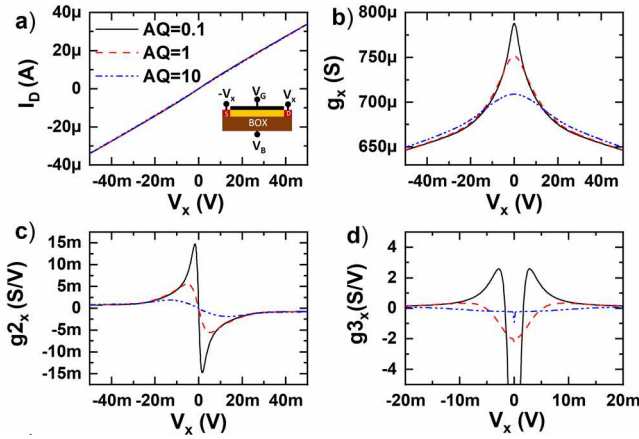


Figure 4: The inset of (a) shows the simulation conditions for an FD-SOI under Gummel symmetry test. I_D as a function of V_x . a) I_D as a function of V_x b) g_x and $g3_x$ as a function for V_x for various AQ values.

applied on q_{isd} at the vicinity of zero (with AQ as smooth parameter) as explained in [13].

We perform the Gummel symmetry test [15] on our model. Practically, the device is simulated with the source and drain terminals connected to $-V_x$ and V_x voltage sources that are swept around $V_x = 0$ V with a fine step and the gate voltage drives the transistor into saturation regime, $V_D = 1$ V in our case. A schematic of the bias conditions is presented as an inset of Fig. 4a. Then, the current along with the first three derivatives ($g_x = dI_x/dV_x$, $g2_x = d^2I_x/dV_x^2$, ...) with respect to V_x are analyzed for continuity and singularities around 0 V. The I_D and its five three derivatives are illustrated in Fig.4 and the simulated data are traced for various AQ values. While how increasing AQ values resolve the singularities for g_x and $g2_x$ $g3_x$ experiences a singularity at $V_x = 0$ V. The issue probably stems from the exponential dependence of AXS^* that depending on the extracted values, might generate strong q_{isd} dependencies around zero. Note that, the intensity of this singularity seems to depend on AQ . This parameter could potentially mitigate the issue up to the third derivative and provides with a tuning parameter to the parameter extraction engineer to calibrate the model for specific applications.

V. CONCLUSION

We demonstrate for the first time a mobility model that accurately captures the InterSubband Coulomb scattering effect. The proposed solution uses only the fundamental quantities of the standard L-UTSOI model, which are based on a methodology that isolates and studies the ISCS effect. Our phenomenological model well describes the device behavior in all tested bias conditions and correctly fits the transconductance. The proposed solution could be implemented in the standard model for FD-SOI devices, L-UTSOI, allowing an accurate SPICE simulation of cryogenic device with strong forward back-bias. A step-by-step parameter extraction flow is provided for the model engineer. The model symmetry is tested with the Gummel test and to pass the test up the third derivative and a smooth parameter, already present from our last work, also improves symmetry providing the user with an additional flexibility.

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