Accurate Modeling of Coulombic Scattering, and its Impact on Scaled MOSFETs

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Abstract

The importance of modeling Coulombic scattering in MOS inversion layers is established by demonstrating its impact on critical design parameters such as V_T and I_{off}. An accurate model for Coulombic scattering has been developed that, for the first time, properly accounts for 2D confinement and quantum mechanical effects in the inversion layer, thus disproving the viability of 3D classical models. In regimes where 3D models grossly over predict mobility, the new 2D model demonstrates its broad applicability by accurately reproducing experimental results over a wide range of channel dopings, substrate biases, and inversion charge densities.

Introduction

To address the issues of power dissipation in today's ULSI chips, especially those geared towards battery-powered portable applications, various technology options are being explored that would minimize both standby and active power dissipation without compromising the operating speeds. One such option is the design of low threshold devices with aggressively scaled V_{dd} [1]. Proper design and optimization of such devices would require accurate prediction of threshold voltage (V_T) and drain leakage current (I_{off}), particularly since small changes in V_T can significantly alter I_{off}. It is recognized that I-V characteristics of MOSFETs in the subthreshold region are severely affected by Coulombic scattering of inversion-layer electrons due to channel dopants. This is more so true in scaled devices, that tend to have high channel doping levels to prevent undesirable short channel effects. However, what is lacking is accurate characterization and modeling of Coulombic scattering in the inversion layer.

In light of the above concerns, based on a first-principles calculation, we present a new model for Coulombic scattering, whose form affords easy implementation in current device simulators. The validity of this model is established by comparing it with new and previously published experimental data. Finally, we demonstrate the impact of Coulombic scattering on accurately predicting critical device parameters such as V_T .

New Modeling Approach

Coulombic scattering consists of two parts: a screened part that varies with electron concentration, and an unscreened part that is independent of electron concentration. In the limit of low electron concentration, the screened part approaches the unscreened part. Unscreened Coulombic scattering is important in weak inversion, where it directly affects I_{off}. As carrier density in the channel increases, screened Coulombic scattering becomes important, whose affect is mostly to alter the curvature of I-V curves near threshold.

Previous attempt at modeling Coulombic scattering include the work of Brooks and Herring, who considered screening, and that of Conwell and Weisskopf, who neglected screening. Both the efforts concentrated on modeling Coulombic scattering in the bulk, i.e. where the electrons can be treated as a 3D gas. The new contribution by our analysis is that we treat the inversion-layer as a two-dimensional (2D) electron gas. In this regard, the principal difference between our new 2D model and previous 3D models is that: (1) we consider the 2D Coulombic potential, which has an ln(r) dependence in 2D, but 1/r in 3D, (2) we restrict scattering of electrons to within a plane, and (3) we correct for the fact that electrons in the inversion layer are scattered off repulsive Coulombic centers as opposed to attractive Coulombic centers in the bulk. The results of the new formulation are shown in Fig. 1. The principal difference between the expression for screened and unscreened mobility is the screening function $F(\alpha)$, which depends on the electron density, N_{inv} , in the inversion layer. It should be emphasized that based on the first-principles approach, the model appearing in Fig. 1 does not contain any calibrating or fitting parameters.

In order to verify the accuracy of this model, the predicted mobility was compared with experimental results, which were obtained using an improved version [2] of a well-established split C-V technique [3]. The difference in N_{inv} dependence between 2D and 3D is clearly demonstrated in Fig. 2. Compared to the Brooks-Herring model, a weaker screening dependence is observed in 2D, which is due to the fact that a confined electron-gas is unable to effectively screen (shield) a 3D Coulombic Potential. In Fig. 3, broad applicability of the new model is demonstrated by comparing it with experimental data over a wide range of channel doping levels and electron densities.

Substrate Bias Dependence

Although the effects of electron density and doping density on Coulombic scattering have been well documented, the effect of substrate bias has yet to be investigated. Experimental results shown in Fig. 4 indicate that Coulombic mobility is a very weak function of substrate bias, demonstrating that electron density and channel charge are the dominant parameters affecting Coulombic Scattering. These findings are also upheld by the new model. Results for Coulombic scattering are in sharp contrast to phonon and surface-roughness scattering, which are strong functions of substrate bias.

Systematic Extraction Technique

Although methods such as [2] exist to experimentally characterize screened Coulombic mobility, such techniques become invalid in subthreshold regime, and as yet a systematic approach to extract *unscreened* Coulombic scattering is lacking. Our method proposes to extract unscreened Coulombic scattering by comparing simulated I_{ds} with measured I_{ds} in the subthreshold region. Systematic corrections need to be made to simulation data before unscreened Coulombic scattering can be extracted. These corrections, shown in Fig. 5, are due to interfacial charge, fixed-oxide charge, band-gap narrowing, and quantum effects. The first three effects are determined by comparing theoretical and measured high-frequency C-V curves, whereas quantum correction is determined by comparing N_{inv}-Vgs curves of a self-consistent Schrodinger-Poisson solution with a classical Poisson solution. After incorporating all these corrections, any discrepancy that finally remains between measurement and simulation is attributed to unscreened Coulombic scattering.

The results of such an extraction scheme are shown in Fig. 6, where unscreened Coulombic mobility is seen to decrease with channel doping. Good agreement between the new model and extracted data validates the extraction procedure. Clearly, the 3D model grossly over predicts mobility.

Impact of Coulombic Scattering on V_T

Threshold voltage is a very important design parameter for digital MOS applications since it represents the trade-off between I_{off} and current drivability (I_{on}). Aggressive device design and optimization demands an accurate prediction of V_T. Fig. 7 demonstrates the importance of unscreened Coulombic scattering in determining V_T. Conventional model is one that corrects for interface and oxide charge. More sophisticated simulators would correct for quantum effects. Even after these corrections, significant error remains between experimental and simulated value for V_T, more so at higher channel dopings. Therefore, accurate prediction of V_T requires that precise mobility models for Coulombic scattering be implemented in current device simulators.

1995 Symposium on VLSI Technology Digest of Technical Papers, pp. 99-100, Kyoto, Japan.

Conclusion

The importance of modeling Coulombic scattering in MOS inversion layers has been established by demonstrating its impact on critical design parameters such as V_T and I_{off}. An accurate model for Coulombic scattering has been developed that, for the first time, properly accounts for 2D confinement and quantum mechanical effects in the inversion layer, thus disproving the viability of 3D classical models. In regimes where 3D models grossly over predict mobility, the new 2D model demonstrates its broad applicability by accurately reproducing experimental results over a wide range of channel dopings, substrate biases, and inversion charge densities.

Acknowledgments

Authors gratefully acknowledge Junji Koga for new experimental data. This work was supported by Semiconductor Research Corporation (SRC).

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$$\mu_{screened} = \frac{\pi\mu_{unscreened}}{F(\alpha)} \cdot \frac{Z_{sub}}{Z_{inv}}, \quad \mu_{unscreened} = \frac{640\pi^3 h \varepsilon_{si}^2 \varepsilon_o^2 k_b T_L}{G(P)\, m^* e^3 N_A Z_{sub}}$$

$$F(\alpha) = \frac{1}{\alpha\left(1-\alpha^2\right)} - \frac{\alpha}{\left(1-\alpha^2\right)^{1.5}} \log\left[\frac{\alpha^2 + \alpha\left(1+\sqrt{1-\alpha^2}\right)}{\alpha^2 + \alpha\left(1-\sqrt{1-\alpha^2}\right)}\right], \quad \alpha = \frac{\left(k_b T_L\right)^{-1.5} h e^2 N_{inv}}{8\pi\varepsilon_{si}\varepsilon_o\sqrt{2m^*}}$$

Figure 1. Primary difference between screened and unscreened mobility is the screening function $F(\alpha)$, which is a function of electron density in the inversion layer. G(P) term corrects for the fact that electrons in the inversion layer experience a repulsive Coulombic potential [5]. Z_{sub} and Z_{inv} are inversion-layer thicknesses in subthreshold and strong inversion respectively.

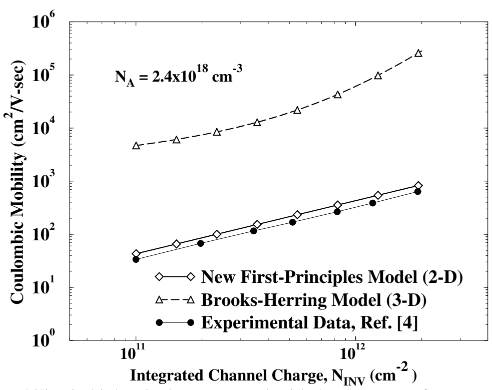

Figure 2. Mobility is higher in 3D compared with 2D because of stronger screening, which results from the fact that field lines in 3D can never be completely screened in 2D.

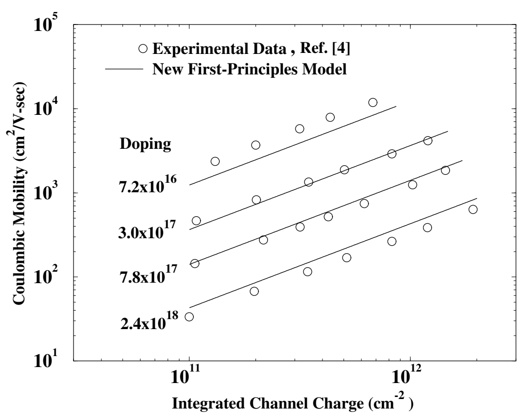

Figure 3. Broad applicability of the new model is demonstrated by comparing it with experimental data over a wide range of channel doping levels and electron densities.

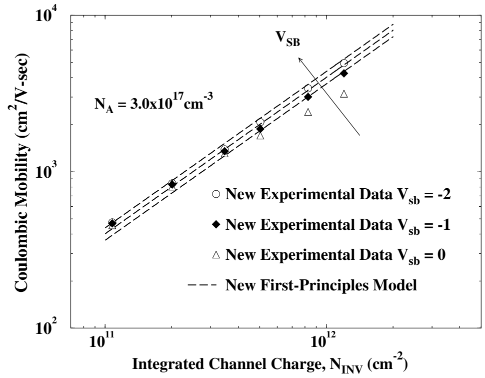

Figure 4. Coulombic mobility is shown to be a weak function of substrate bias, demonstrating that electron density and channel charge are the dominant parameters affecting Coulombic Scattering.

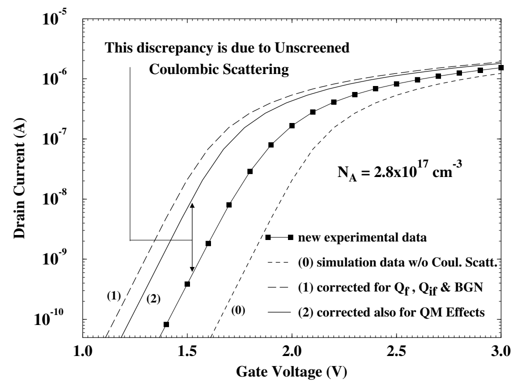

Figure 5. Systematic corrections need to be made to simulation data in order to extract unscreened Coulombic mobility from subthreshold I_{DS}. These corrections consist of interfacial charge, fixed-oxide charge, band-gap narrowing, and quantum effects.

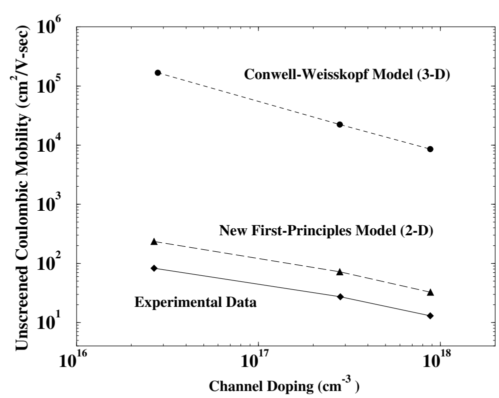

Figure 6. Unscreened Coulombic mobility extracted using the methodology shown in Fig. 5. Good agreement between the new model and extracted data validates the extraction procedure. 3D model is shown to grossly over-predicts mobility.

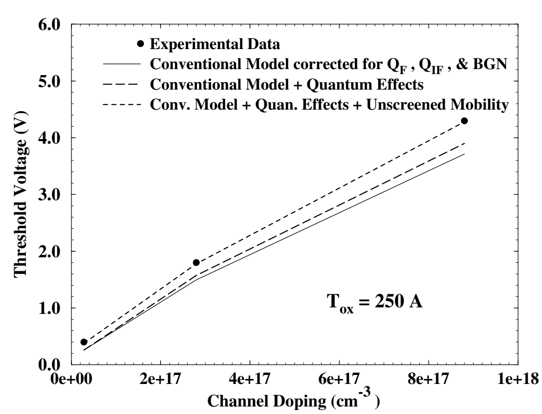

Figure 7. Comparison between simulated threshold voltage and experimental threshold voltage considering various physical effects. Accurate prediction of V_T requires precise mobility models for Coulombic scattering.