Semi-Empirical Local NMOS Mobility Model for 2-D Device Simulation Incorporating Screened Minority Impurity Scattering

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Abstract

Ionized impurity scattering in the inversion layer of submicrometer MOSFETs has become increasingly important due to the presence of large number of dopant atoms in the channel. Ionized impurity scattering of inversion-layer electrons treated under the Born approximation, which assumes an attractive potential, gives inaccurate results since inversion-layer electrons experience a repulsive potential. We present a new phenomenological yet highly accurate local low-field mobility model that incorporates screened minority impurity scattering and reproduces the generalized mobility curve.

I Introduction

To be able to better predict the I-V characteristics of modern scaled MOSFETs, accurate mobility models are required to incorporate all of the basic scattering mechanisms operating in the inversion layer. Ionized impurity scattering is one such mechanism which becomes more important as the channel dopant concentration is increased to prevent punchthrough effects [1]. In this work, we define *Screened Minority Impurity Scattering* as the scattering of minority carriers (inversion-layer electrons) by ionized impurity atoms (acceptor atoms) that are screened by the net concentration of mobile carriers. For implementation in a 2-D device simulator, a local mobility model is preferable to a non-local one because in a local model: (i) complex, non-planar 2-D and 3-D geometries can be more easily simulated, (ii) a complete Jacobian can be set up for AC analysis, and (iii) parallelization of software can be made more efficient. A local model should follow the non-local *Generalized Mobility Curve* (GMC) which consists of a universal part (UMC) [2] and a non-universal part [1, 6]. MOS mobility model calibration can be done easily, efficiently, and accurately if it is performed using the GMC instead of I-V data alone [3]. In this work, we have developed a phenomenological yet highly accurate *local* low-field model for MOS mobility that incorporates *Screened Minority Impurity Scattering* and reproduces the *Generalized Mobility Curve*. Good agreement with several sets of experimental data is shown.

II Universal Mobility Curve

The fundamental scattering mechanisms operating in the inversion layer are surface acoustic-phonon, surface roughness, and screened minority impurity scattering. Phonon and surface roughness scattering contribute to the universal part of the GMC, whereas screened minority impurity scattering leads to its non-universal part. In order to capture the universal part of the GMC, an enhanced form of the low-field component of Lombardi's mobility model [4] has been used:

$$\mu_{\text{universal}}(x, y) = \boldsymbol{min}\left\{\left[\left(\frac{A}{E_{\perp}(x, y)} + \frac{B \cdot N_a^{\gamma}(x, y)}{T \cdot E_{\perp}^{1/3}(x, y)}\right)^{-1} + \left(\frac{C}{E_{\perp}^{2}(x, y)}\right)^{-1}\right]^{-1}, \mu_{\text{bulk}}(x, y)\right\} \quad \textbf{(1)}$$

Since parameters of Lombardi's model were not extracted to fit the UMC, the parameters in (1) have been re-calibrated for that purpose in this work. Table 1 shows the comparison between the old and the new parameter set. Effective-mobility versus effective-field curves obtained from (1) are shown in Fig. 1 and compared with several experimentally obtained UMCs. The most important property of the UMC is its invariance to changes in substrate doping, back-gate bias, and oxide thickness [2]. Figure 1 demonstrates that as the channel doping is varied, simulated UMCs remain unchanged. Similarly, Fig. 2 shows that simulated UMCs remain invariant to changes in oxide thickness and back-gate bias.

III Generalized Mobility Curve

One of the factors that leads to deviation from the universality of mobility is scattering by Coulombic centers in the inversion layer. This includes scattering of electrons from both the repulsive coulomb potential due to ionized acceptor atoms and the attractive coulomb potential due to positive interfacial charge. However, on account of progress in fabrication technology, and the trend towards miniaturization of MOSFETs, scattering due to channel dopants has become far more significant than scattering due to interfacial charge [1]. Coulombic scattering treated by the standard Brooks-Herring formulation applies only to scattering of majority carriers by ionized impurity atoms since the treatment assumes that an attractive screening potential would be experienced by the mobile carriers. This is clearly not the case in the inversion layer where negatively charged electrons experience a repulsive Coulomb potential due to negatively charged acceptor atoms. Accurate phase shift analysis shows that scattering cross-section due to a repulsive potential is typically lower than that due to an attractive potential. When coulombic mobility is extracted from GMCs, we find that it varies super-linearly with the average concentration of electrons in the inversion layer. On the other hand, the Brooks-Herring expression gives only a sub-linear dependence.

In order to model Coulombic scattering phenomenologically, we decompose it into a screened part and an unscreened part. The screened part takes into account the scattering seen by mobile carriers when the Coulomb potential is being screened by mobile carriers. The unscreened part considers the scattering due to a bare Coulomb potential. The necessity for decomposition is because of the fact that the screened mobility tends to zero as the carrier concentration goes to zero. However, physically, we know that a residual mobility remains, which is treated by the unscreened part. Thus, we get the following model:

$$\mu_{\text{impurity}}(x, y) = \boldsymbol{max}\{\mu_{\text{screened}}(x, y), \mu_{\text{un screened}}(x, y)\} \quad \textbf{(2)}$$

$$\mu_{\text{screened}} = D_1 \cdot \frac{n^{\alpha}(x, y)}{N_a^{\beta_1}(x, y)} \qquad \mu_{\text{un screened}} = \frac{D_2}{N_a^{\beta_2}(x, y)} \quad \textbf{(3)}$$

Table 2 gives the parameter values appearing in (3) for room temperature operation. In formulating a local model, the local electron concentration has been used in equation (3). The total mobility, $\mu_{\text{generalized}}(x, y)$, is obtained by combining (1) and (2) in a Matthiessen-rule like expression [5]:

$$\frac{1}{\mu_{generalized}} = \frac{1}{\mu_{universal}} + \frac{1}{\mu_{impurity}} \quad \textbf{(4)}$$

GMCs obtained from integrating $\mu_{generalized}$ along the depth of the inversion layer are shown in Fig. 3 and are compared with Nishinohara's [6] data which are a corrected version of Takagi's [1] data. The generalized mobility model captures the sharp roll-off of effective mobility quite well.

For a given doping profile, varying back-gate bias has qualitatively the same affect as varying channel doping for a fixed back-gate bias. BSIMjr2 [7] provides a quick and efficient means of extracting GMCs from I-V data without requiring the need to perform C_{gs}-V_{gs} measurements. Figure 4 compares BSIMjr2's methodology with that of PISCES for obtaining GMCs. Figure 5 shows that as back-gate bias is increased, GMCs bend further down at low effective-field, and converge to a narrow band at high effective-field. This trend is clearly reflected by both PISCES and BSIMjr2 results.

IV Acknowledgments

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V References

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Table 1

Parameter	*Equation (1)*	*Lombardi Model*
A	8.95×10^5	4.75×10^7
B	3.23×10^6	1.74×10^5
γ	0.0284	0.125
C	8.29×10^{14}	5.82×10^{14}

Table 2

Parameter	*Equation (2)*
D_1	1.35×10^{11}
α	1.5
β_1	2.0
D_2	2.89×10^8
β_2	0.35

Units: mobility (cm^2/V-s), Doping (cm^{-3}), Electric Field (V/cm)

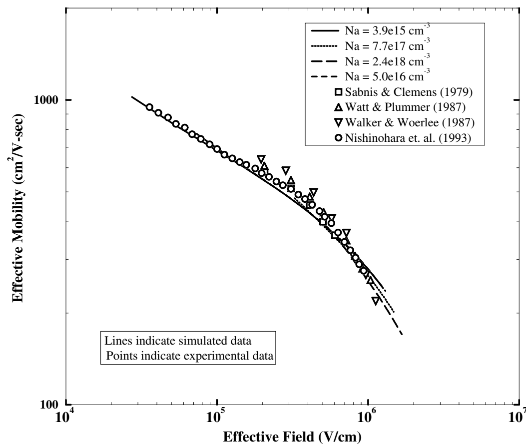

Figure 1: Comparison between UMCs obtained from equation (1) and from experimental I-V and C-V data. UMCs obtained from equation (1) remain invariant to changes in doping.

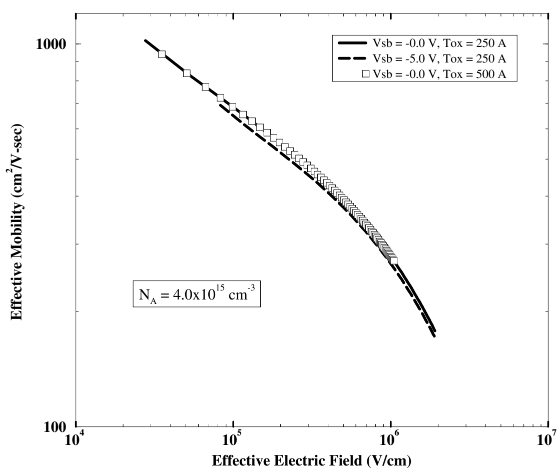

Figure 2: UMCs obtained from equation (1) remain invariant to changes in oxide thickness or back-gate bias.

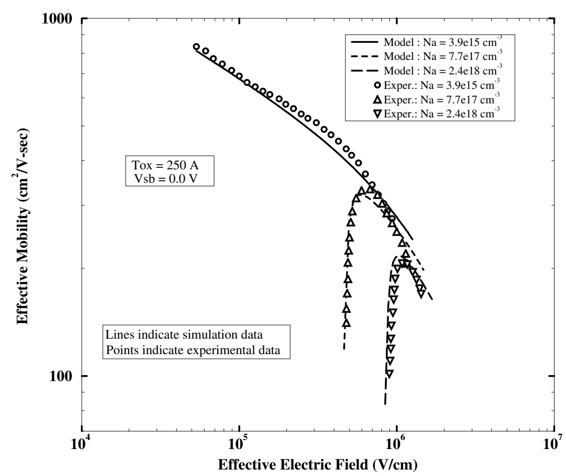

Figure 3: Comparison between Nishinohara's experimental GMCs and GMCs obtained from equation (4). The sharp roll-off of universal mobility with channel doping is the main feature of non-universality.

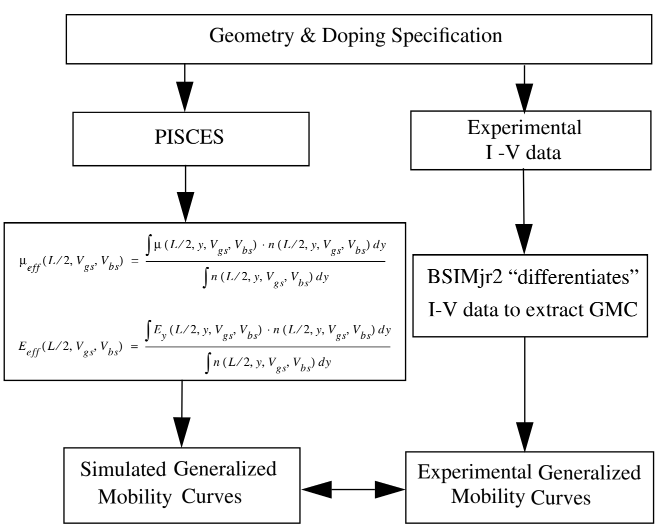

Figure 4: Comparison of methodology of extraction of GMCs between PISCES and BSIMjr2.

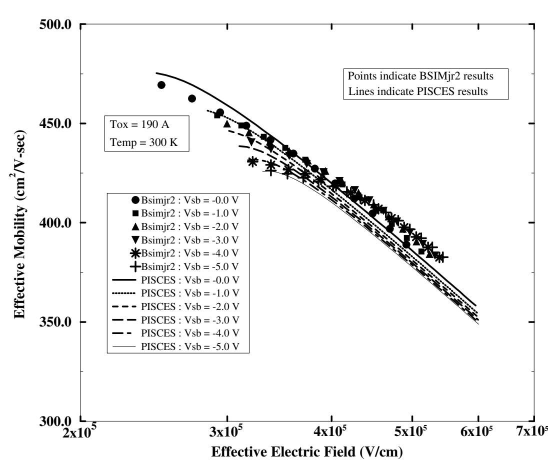

Figure 5: Comparison between the GMCs obtained from PISCES and BSIMjr2 as back-gate bias is varied from 0 to 5 V for a given doping profile and oxide thickness.