On the effective mobility for electrons in MOS inversion channels

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Abstract--The results of this paper are twofold. First, the relation between the local mobility model $\mu_l(\vec{E})$ and the long channel measured effective mobility $\mu_{eff}(V_{gs})$ is investigated. This allows to find a mathematical condition [1] which any μ_l model in a 2D numerical device simulator should fulfill. Here, we extend the work of [1] by using this condition to find the model parameters of a MEDICI μ_l model. We reach very good quantitative agreement with experiment for a complete L-array, even for poly lengths down to 0.08 µm [2]. Secondly, it is advocated that the long channel effective mobility cannot be used to model short channel devices. We show experimentally and theoretically that the short channel effective mobility depends on the channel length due to the high internal drain-channel built-in field.

I. INTRODUCTION

As MOSFET devices continue to shrink, the ability to simulate the device characteristics correctly becomes more difficult. The mobility is a key quantity for the purpose of modeling. The experimental material provides an effective mobility μ_{eff} which is related to the terminal current I_d and the inversion charge Q_{inv} for small drain voltages V_d

$$\mu_{eff} = \lim_{Vd \to 0} \frac{I_d}{\frac{W}{L} Q_{inv} V_d} \qquad (1)$$

The microscopic details of the mobility in an inversion layer are not exactly known. However, very useful models for the local mobility μ_l have been proposed by parameterising the model by an effective field Eeff or a local vertical field $E_\perp$ (e.g. $\mu_l=\mu_o/(1+(E_\perp/E_C)^n)$). In a typical 2D device simulator, the current at each node in the MOS inversion layer is calculated using this local mobility μ_l depending on the local transverse field E_{eff} or $E_\perp$ of that particular node. However, each model for μ_l has a number of unknown parameters (e.g. n, E_C) which have to be found by comparison with experimental data.

II. LONG CHANNEL EFFECTIVE MOBILITY

Many authors have used the hypothesis that $\mu_l=\mu_{eff}$. However, it was noted by Shin in [3] that there should exist a relation between the experimentally measured μ_{eff} and the local mobility model μ_l used within the device itself during simulation. The µeff is not necessarily equal to the μ_l. The derivation in [3], however, is based on a simplified long channel analysis and neglects the variation of the vertical field along the Si/SiO_2 interface. This variation results in a nonuniform carrier distribution and has to be taken into account if one wants to compare μ_l and μ_{eff}, as correctly observed by Li in [4].

Using the technique of the integral representations [5], it is possible to find a more accurate expression for the terminal current I_{ds} [1] depending on the internal local quantities E, T_e and μ_l.

$$I_d = q\, W N_{sd}\, V_{th} \int_0^{\delta_n} \frac{(\exp(-\gamma(L,y))-1)}{\int_0^L \mu_l^{-1}(x)\exp(-\gamma(x,y))\,dx}\,dy \qquad (2)$$

$$with \quad \gamma(x,y) = \int_0^x \frac{-q}{kT_e(u,y)} E(u,y)\,du$$

To find the relation between the measured μ_{eff} and the local model μ_l for long channel devices, this new expression for I_{ds} (2) can be plugged into (1), resulting in

$$\mu_{eff}(E_{eff}) = \frac{C_{ox}}{\varepsilon_{si}} \exp\left(\frac{\psi_o-\psi_{gs}}{V_{th}}\right) \frac{V_{th}(1-\exp(-\frac{V_{ds}}{V_{th}}))}{\int_{E_{\perp 0}}^{E_{\perp L}} \mu_l^{-1}(E_\perp)\exp(-\frac{\varepsilon_{ox}}{\varepsilon_{si}}\frac{t_{ox}E_\perp}{V_{th}})\,dE_\perp}$$
$$= \frac{\mu_o}{1+\frac{\Gamma(n+2)}{(n+1)\Gamma(n+1)}\frac{\left(\frac{E_{\perp o}}{E_c}\right)^n-\left(\frac{E_{\perp L}}{E_c}\right)^n\exp(-\frac{V_{ds}}{V_{th}})}{1-\exp(-\frac{V_{ds}}{V_{th}})}} \qquad (3)$$

with $E_{\perp 0}$ and $E_{\perp L}$ the vertical fields at source and drain side which can be written as a function of E_{eff} or V_{gs}. It can be seen that μ_{eff} is not equal to μ_l as many authors assume ! The μ_{eff} is an average of μ_l, modulated by an exponential function, as can be seen from the integral. The last equality in (3) is for a chosen model of µl [6] suggested above. If μ_l is taken independent of the field, (3) reduces to $\mu_{eff}=\mu_o$ as expected. Fig.1 shows experimental data of μ_{eff} and the RHS of (3) with different fitting parameters of 'E_C' and 'n'. Several values for 'n' and 'E_C' can be found in literature [6,7] (see table 1).

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	n_1	E_{c1}	n_2	E_{c2}
best fit	2.35	0.205	-	-
after [6]	0.657	0.0305	-	-
after [7]	0.33	0.0775	1	1.5625

Table 1 The model parameters used in Fig.1

We believe our values which are found by fitting (3) with the experimental data are more accurate. This is checked by comparing experimental I-V curves and 2D simulation using MEDICI with our new values for 'n' and 'E_c'. The cross-section of the device is shown in Fig.2 showing the increased gate oxide thickness at the edges due to the poly-reoxidation (consistent with our TEM pictures). The metallurgical junction was measured using the modified shift & ratio method [8]. Fig.3 shows the results of the comparison. For the first time good agreement is obtained between simulation and experiment *for a complete L-array ranging from Lpoly=10 μm to Lpoly=0.08 μm*. This indicates that our new mobility parameter values are well chosen on the basis of condition (3).

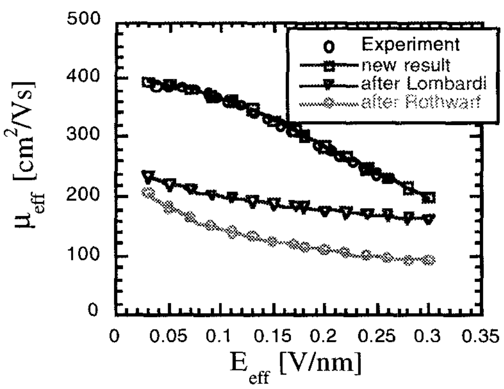

Fig.1 Comparison between the experimentally measured effective mobility and the evaluation of (3) for three sets of model coefficients (see table 1).

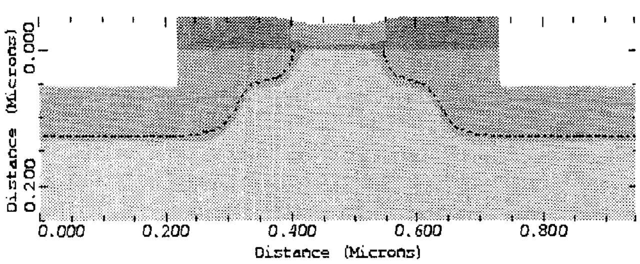

Fig.2 Cross-section of the simulated device. Oxide thickness is 5.3 nm, silicide depth is 50 nm. Due to a poly-reoxidation, the gate oxide is thicker at the ends.

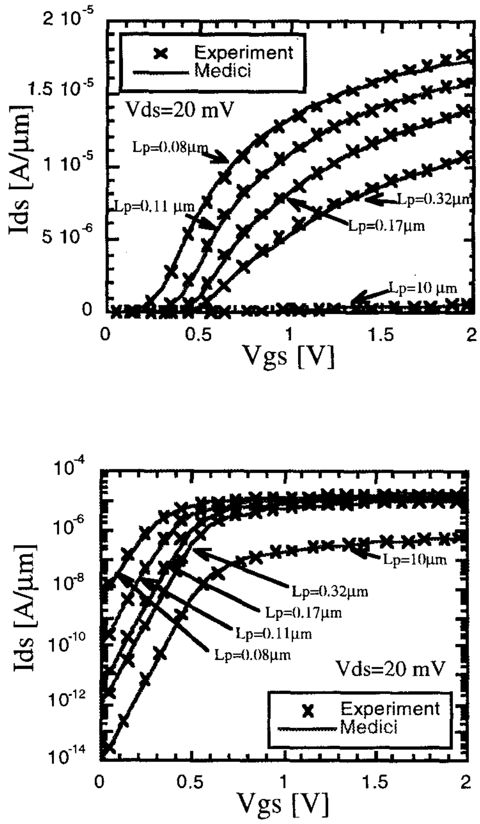

Fig.3 Comparison of the experimental IV curves with the simulated data using MEDICI. The coefficients for the mobility model were found using (3). The metallurgical channel length (L_{met}) was found using the modified shift & ratio method. Top : linear scale, bottom : Log-scale.

III. SHORT CHANNEL EFFECTIVE MOBILITY

For circuit simulation, an effective mobility [9] independent of channel length is usually used. This is correct for long channel devices (3). However, for channel lengths below 0.25 μm, it can be shown that the effective mobility μ_{eff} defined in (1) actually depends on L_{eff}. This was already experimentally found by other authors [10]. Note that only μ_{eff} can depend on L, not μ_l ! Using the same analysis to obtain (3) but with an appropriate model for the potential [11], one can theoretically verify this and calculate the L-dependence of $\mu_{eff}(L_{eff})$. The difference with (3), which is valid for long channel devices where we assumed a constant field in the channel, is that the potential is not necessarily linear due to the importance of the source-drain built-in fields shown in Fig.4. This will limit the channel mobility (e.g. $\mu_l=\mu_o/(1+E_{||}/E_d)$). A new expression for $\mu_{eff}(L_{eff},E_{eff})$ is found to be (λ can be found in [11])

$$\mu_{eff}(L_{eff}, E_{eff})$$

$$= \mu_o \Big(1 + \frac{\Gamma(n+2)}{(n+1)\Gamma(n+1)} \frac{\left(\frac{E_{\perp o}}{E_c}\right)^n - \left(\frac{E_{\perp L}}{E_c}\right)^n \exp(-\frac{V_{ds}}{V_{th}})}{1-\exp(-\frac{V_{ds}}{V_{th}})} + \backslash \qquad (4)$$

$$\frac{(V_{bi}-\psi_o)V_{ds}^2}{E_d(\lambda^2 V_{ds}^2 - L^2 V_{th}^2)} \left(\frac{\lambda(1+\cosh(L/\lambda))}{\sinh(L/\lambda)} - \frac{L V_{th}}{V_{ds}} \frac{1+\exp(-V_{ds}/V_{th})}{1-\exp(-V_{ds}/V_{th})}\right)\Big)^{-1}$$

Fig.5 plots μ_{eff} (4) as a function of V_{gs} for different channel lengths while Fig.6 compares experimental I_{ds}-V_{gs} curves with the model playback for the L-independent μ_{eff} and a $\mu_{eff}(L_{eff})$ dependent on L_{eff}. Expression (4) is physics based and contains most of the device geometric properties. For use in circuit simulation, one can parameterise it in a more simple expression. Its importance is clear if one wants to simulate circuits which have small devices with different channel lengths. If one uses a constant μ_{eff}, large errors can be made. Many authors compensate for this by adjusting the series resistance R_S which we feel is less physical.

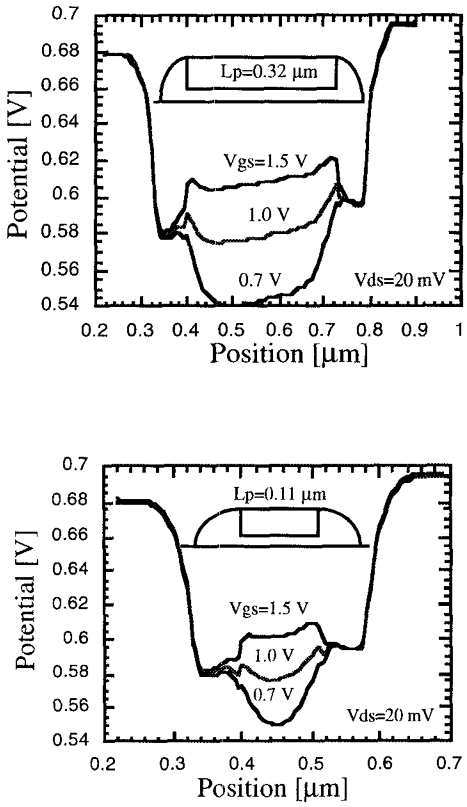

Fig.4 Surface cut along the Si/SiO$_2$ interface of the electrical potential for L_{poly}=0.32 μm and 0.11 μm. For the larger device, a linear potential is observed for V_{gs}> V_T(=0.5V). However, as we progress towards smaller poly lengths, the lateral built-in source-drain field has to be taken into account.

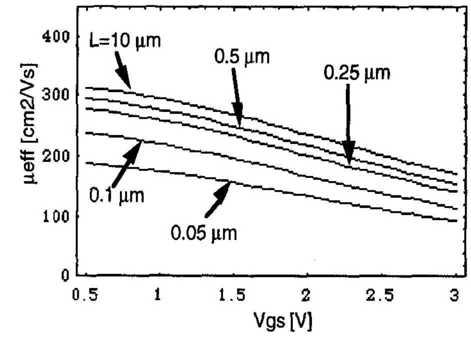

Fig.5 The effective mobility as a function of gate bias for different channel lengths on the basis of (4).

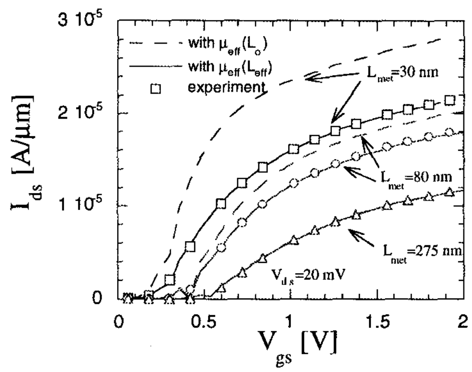

Fig.6 Comparison between experimental I_{ds}-V_{gs} curves with model playback showing that if the long channel μ_{eff} (1, dashed line) is used, the current is overestimated.

IV. REMARK

The extraction of the μ_l model parameters resembles much the difficulties found in finding the specific contact resistance ρ_C of a silicide-Si contact often found in deep submicron devices. Due to the 2D nature of the problem, a transmission line model has to be solved in order to find a relation between the measured resistance and the local quantity ρ_C. Similarly, we derived on the basis of the drift-diffusion model a relation between the measured μ_{eff} and the model of μ_l.

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