A New Method to Determine Channel Mobility Model Parameters in Submicron MOSFET's using Measured S-Parameters

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Abstract - **A new method based on the slope extraction of the total gate charge versus mask gate length from measured S-parameters is developed to determine effective channel mobility model parameters directly from submicron MOSFET's. Since this method does not require a large test device, parasitic capacitance calibration, or the effective channel length measurement, it is simpler and more accurate than traditional methods.**

I. INTRODUCTION

Effective channel mobility (μ_{eff}) is an essential parameter for the characterization, modeling, and structure design of Si MOSFET's. The gate-voltage dependence of μ_{eff} due to the variation of the transverse electric field becomes crucial information to understand a carrier transport property in the inversion channel layer and to obtain a SPICE MOSFET model for the channel mobility [1]. The value of μ_{eff} is generally extracted at very small V_{DS} using the following relation [2]-[5]:

$$\mu_{eff} = \frac{L_{eff} I_{DS}}{W_{eff} V_{DS} Q_{in}} \tag{1}$$

where Q_{in} is the inversion channel charge (q_{in}) per unit area, W_{eff} is the effective channel width, and L_{eff} is the effective channel length.

In order to increase the accuracy of L_{eff}, and to neglect the series resistance (R_{sd}) and the parasitic capacitance associated with overlap and fringe components (C_p), a very long channel MOSFET is typically used to extract μ_{eff} [2]-[4]. However, the importance of the mobility extraction directly from submicron MOSFET's has been emphasized, and several direct μ_{eff} extraction methods have been reported [5], [6]. However, in the recent method of [5], Q_{in} was approximated by the linear equation: $Q_{in} = C_{OX}(V_{GS}-V_{TH})$, yielding inaccurate results due to the poor approximation around the threshold voltage (V_{TH}) and possible errors for extracting C_{OX}. As another approach to determine Q_{in}, a low-frequency split C-V method is widely used [2]-[5]. However, a very long-channel test device is still required and mobility extraction errors are generated by bias discrepancy between I-V and C-V measurements [4], [7].

Thus, an effective way to obtain the accurate Q_{in} directly from a short channel MOSFET without these errors may utilize S-parameters measured in the range of gigahertz, but the complicated extraction for L_{eff} and C_p is still needed. Therefore, in this paper, we propose a new mobility extraction method using the slope of the total gate charge (q_{gt}) vs. the mask gate length (L_{msk}).

II. MOBILITY EXTRACTION METHOD

The total dc resistance is expressed at very small V_{DS} as follows [5], [8]:

$$R_{tot} = \frac{V_{DS}}{I_{DS}} = A\, L_{msk} + B \tag{2}$$

$$A = \frac{1}{\mu_{eff} W_{eff} Q_{in}} \tag{3}$$

$$B = R_{sd} - A\Delta L \tag{4}$$

where ΔL ($= L_{msk} - L_{eff}$) is the channel length reduction. Here, A and B are the slope and y-intercept of the R_{tot} versus L_{msk} at a fixed $V_{GS} - V_{TH}$, respectively. As Lmsk varies, the threshold voltage is slightly shifted in short-channel MOSFETs. This short channel effect can be taken into account by fixing V_{GS}-V_{TH} instead of V_{GS} in (3) [8].

Rearranging (3) and using $q_{in} = Q_{in}W_{eff}L_{eff}$, we obtain the

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following equation [5]:

$$\mu_{eff} = \frac{1}{AW_{eff}Q_{in}} = \frac{L_{eff}}{A\,q_{in}} \qquad (5)$$

Equation (5) does not suffer serious extraction problem related to the gate voltage dependence of R_{sd}, because it is not function of B. Because of this advantage, a total resistance slope-based method using (5) has recently been proposed to determine μ_{eff} [5]. However, the determination of L_{eff} is still required and inaccurate extraction of Q_{in} may be induced in submicron MOSFET's.

The value of q_{in} in (5) is determined by integrating the gate-channel capacitance (C_{GC}):

$$q_{in} = \int_0^{V_{GS}-V_{TH}} C_{GC}(V')dV' \qquad (6)$$

The values of C_{GC} can be measured at zero V_{DS} using a C-V meter in the range of megahertz [2]-[5], but large errors associated with unavoidable pad capacitances [7], poor measurement sensitivity for low capacitance values, and difficult L_{eff} determination may occur in submicron devices. To eliminate these problems, measured S-parameters are used to obtain C_{GC} data in this work, because the de-embedding or calibration of parasitic pad parasitics is possible in GHz S-parameter measurements.

Because series resistance components in a small-signal MOSFET model [9] are omitted in the very low range of gigahertz, the gate capacitance as a function of V_{GS}-V_{TH} can be measured using the following imaginary term of Y_{11}-parameter converted from S-parameters:

$$C_G(V_{GS}-V_{TH}) = C_{GS}+C_{GD} = \frac{1}{\omega}\,\mathrm{Imag}\,(Y_{11}) \qquad (7)$$

The measured gate capacitance for all devices with different Lmsk consists of the following components:

$$C_G(V_{GS}-V_{TH}) = C_P + C_{GC} \qquad (8)$$

In order to obtain q_{in} accurately, C_P should be subtracted from C_G. However, the accurate determination of C_P is very difficult in submicron CMOS technology. In addition, for obtaining μ_{eff} using (5), the extra knowledge for L_{eff} that strongly depends on extraction methods [10] and gate voltage [11] is still required.

Therefore, in this paper, the following new equation is proposed to avoid this difficult C_P and L_{eff} extraction. The From (5), we obtain the following equation for the measured total gate charge:

$$q_{gt} = \int_0^{V_{GS}-V_{TH}} C_G(V')dV' = C_p(V_{GS}-V_{TH}) + q_{in}$$

$$= C_p(V_{GS}-V_{TH}) + \frac{L_{msk} - \Delta L}{A\mu_{eff}} = C\,L_{msk} + D \qquad (9)$$

where C and D are the slope and y-intercept of the extracted q_{gt} versus L_{msk} at a fixed V_{GS}-V_{TH}, respectively. Here, the slope C is independent of L_{msk}, because the effect of the threshold voltage shift disappears by fixing V_{GS}-V_{TH} for different Lmsk.

From (9), we easily extract μ_{eff} in the following simple expression :

$$\mu_{eff} = \frac{1}{AC} \qquad (10)$$

This inverse-slope-product equation is not affected by errors of D generated in the extraction of C_p and L_{eff}, thus making the new method more reliable than the previously reported method [5] using (5).

III. RESULTS

Under common source-bulk configuration, S-parameters were measured in the gigahertz range on n-MOSFET's of 4 x 10 µm gate width with L_{msk} of 0.8, 1.0, and 1.2 µm [12], and pad and interconnection de-embedding was carried out using "open" and "short" test patterns [13]. In this case, the same bias of V_{DS} = 50mV as I-V measurements is applied to eliminate bias discrepancy errors [4].

The measured data and their best fit lines of R_{tot} vs. L_{msk} are plotted with varying V_{GS}-V_{TH} in Fig. 1, and these data are straight lines at fixed V_{GS}-V_{TH}. This indicates the independence of A on L_{msk}. Using (9), the measured values of q_{gt} are determined by integrating C_{GC} values obtained from (7) with respect to V_{GS}-V_{TH}. These q_{gt} data are plotted as a function of L_{msk} at several fixed bias points of V_{GS} - V_{TH}, and the good linearity is observed in Fig. 2. The plot of q_{gt} versus V_{GS} - V_{TH} is also shown in Fig. 3 for various L_{msk}. As expected by the theory, the q_{gt} data are linearly proportional to V_{GS}–V_{TH}. Fig. 4 shows slopes A and C extracted from best fit lines in Figs. 1 and 2, respectively. By substituting the slopes into (10), the gate-voltage dependence of μ_{eff} is accurately extracted from this new method in Fig. 5.

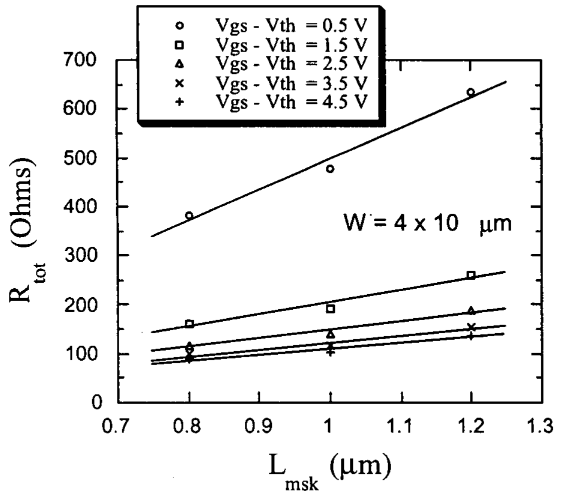

Fig. 1. The measured data and their best fit lines of R_{tot} for different V_{GS} - V_{TH} as a function of L_{msk} at V_{DS} = 50mV.

A gate-volatage dependent curve of μ_{eff} is modeled by the SPICE expression:

$$\mu_{eff} = \frac{U_O}{1+U_A\left[\frac{V_{GS}-V_{TH}}{T_{OX}}\right]+U_B\left[\frac{V_{GS}-V_{TH}}{T_{OX}}\right]^2} \tag{11}$$

By performing the best curve-fit of (11) to extracted μ_{eff}, it is extracted that U_O = 463cm^2/Vs, U_A/T_{OX} = 0.055 V^{-1}, and U_B/T_{OX}^2 = 0.032 V^{-2}. This modeled curve of μ_{eff} agrees well with extracted data as shown in Fig. 5.

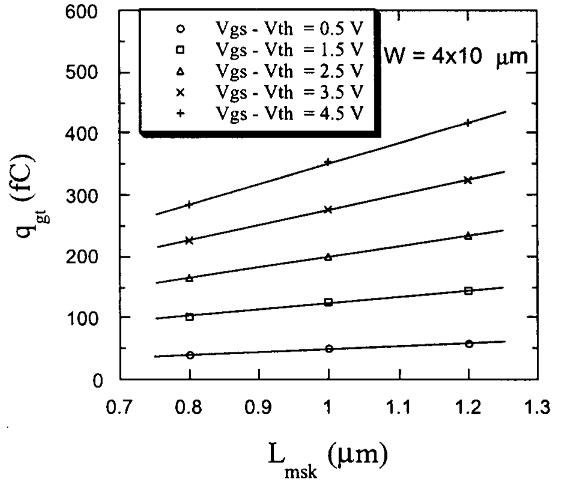

Fig. 2. The extracted data and their best fit lines of the total gate charge q_{gt} for various V_{GS} - V_{TH} as a function of L_{msk} at V_{DS} = 50mV.

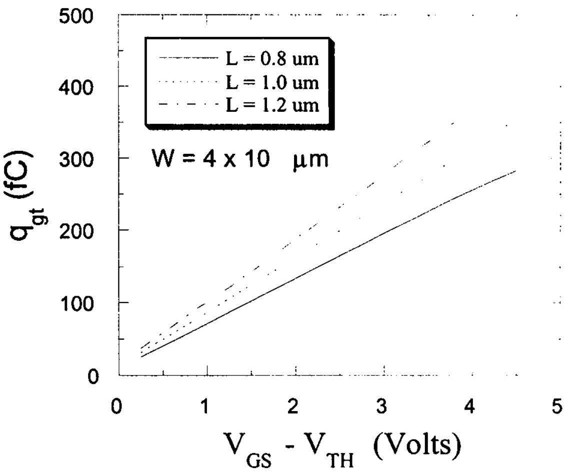

Fig. 3. The extracted data of q_{gt} as a function of V_{GS} - V_{TH} for various L_{msk} at V_{DS} = 50mV.

IV. CONCLUSIONS

We propose a new method for determining μ_{eff} directly from submicron MOSFET's, using the slope information of q_{gt} versus L_{msk} plot obtained from the measured S-parameters. Unlike conventional approaches, a very long-channel test device or the extra determination of C_P and L_{eff} is not required to extract the μ_{eff}, thus making the new method simpler and more accurate. The SPICE mobility model curve extracted from a simple curve-fit process agrees well with measured data.

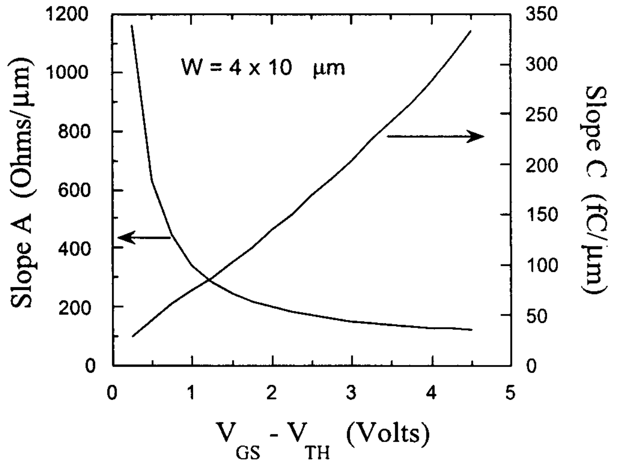

Fig. 4. The extracted slopes A and C as a function of V_{GS} - V_{TH}.

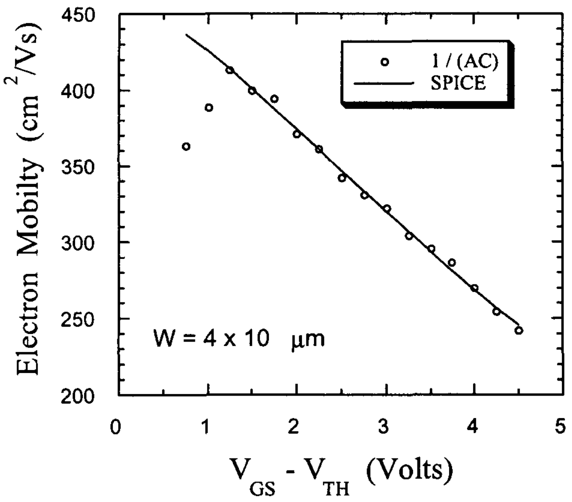

Fig. 5. The extracted μ_{eff} data from the new method using (10) and their fitted SPICE curve using (11).

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REFERENCES

[1] P. Antognetti and G. Massobro, *Semiconductor device modeling with SPICE*, New York: McGraw-Hill, 1991.

[2] C. G. Sodini, T. W. Ekstedt, and J. L. Moll, "Charge accumulation and mobility in thin dielectric MOS transistors," *Solid-State Electron.*, vol. 25, pp. 833-841, Sept. 1982.

[3] C.-L. Huang and G. Sh. Gildenblat, "Measurements and Modeling of the n-channel MOSFET inversion layer mobility and device characteristics in the temperature range 60-300 K," *IEEE Trans. Electron Device*, vol. 37, pp. 1289-1300, May 1990.

[4] C.-L. Huang, J. V. Faricelli, and N. D. Arora, "A new technique for measuring MOSFET inversion layer mobility," *IEEE Trans. Electron Device*, vol. 40, pp. 1134-1139, June 1993.

[5] G. Niu, J. D. Cressler, S. J. Mathew, and S. Subbanna, "A total resistance slope-based effective channel mobility extraction method for deep submicrometer CMOS technology," *IEEE Trans. Electron Device*, vol. 46, pp. 1912-1914, Sept. 1999.

[6] H. J. Wildau, H. Bernt, D. Friedrich, W. Seifert, P. Staudt-Fischbach, H. G. Wagemann, and W. Windbracke, "The inversion layer of subhalf-micrometer n-channel and p-channel MOSFET's in the temperature range 208-403 K," *IEEE Trans. Electron Device*, vol. 40, pp. 2318-2325, Dec. 1993.

[7] J. Banqueri, J. A. Lopez-Villanueva, F. Gamiz, J. E. Carceller, E. Lora-Tamayo, and M. Lozano, "A procedure for the determination of the effective mobility in an N-MOSFET in the moderate inversion region," *Solid-State Electron.*, vol. 39, pp. 875-883, June 1996.

[8] S. E. Laux., "Accuracy of an effective channel length/external resistance extraction algorithm for MOSFET's," *IEEE Trans. Electron Devices.*, vol. ED-31, pp. 1245-1251, Sept. 1984.

[9] S. Lee, H. K. Yu, C. S. Kim, J. G. Koo, and K. S. Nam, "A novel approach to extracting small-signal model parameters of silicon MOSFET's," *IEEE Microwave and Guided Wave Lett.*, vol. 7, pp. 75-77, March 1997.

[10] J. Latif, A. Ortiz-Conde, J. J. Liou, and F. J. Garcia Sanchez, "A study of the validity of capacitance-based method for extracting the effective channel length of MOSFET's," *IEEE Trans. Electron Devices.*, vol. 44, pp. 340-343, Feb. 1997.

[11] G. J. Hu, C. Chang, and Y.-T. Chia, "Gate-voltage-dependent effective channel length and series resistance of LDD MOSFET's," *IEEE Trans. Electron Devices.*, vol. 34, pp. 2469-2475, 1987.

[12] C. S. Kim, H. K. Yu, H. Cho, S. Lee, and K. S. Nam, "CMOS layout and bias optimization for RF IC design applications in *IEEE MTT-S Int. Microwave Symp. Dig.*, pp. 945-948, 1997.

[13] S. Lee, "Effects of pad and interconnection parasitics on forward transit time in HBTs," *IEEE Trans. Electron Devices*, vol. 46, pp. 275-280, Feb. 1999.