A Method for Extracting the Threshold Voltage of MOSFETs Based on Current Components

K. AOYAMA

NTT LSI Laboratories,
3-1, Morinosato Wakamiya, Atsugi-shi, Kanagawa Pref., 243-01 JAPAN

Abstract

A new method for extracting the threshold voltage of MOSFETs is presented. The threshold voltage is the gate voltage at which the second difference of the logarithm of the drain current takes a minimum value. The method is applied to a 0.6-μm NMOSFET. The threshold voltage characteristics are compared with ones measured with previous methods and it is shown that the proposed method overcomes previous problems. The threshold voltage is extracted based on a physical background verified with 2D device simulation and shows a transition voltage at which drift and diffusion components in the drain current are equal.

1. Introduction

A serious problem is that threshold voltage definitions in measurements differ from the one in compact MOSFET models. The threshold voltage in compact models is defined as the gate voltage at which the surface potential ψ_s of the channel reaches the double Fermi potential in the bulk $2\phi_f$. This definition is very popular but has the disadvantages that the position where $\psi_s = 2\phi_f$ in the channel is not clear and it is difficult to measure ψ_s in MOSFETs. On the other hand, threshold voltages in measurements are extracted by the constant current (CC), the linear extrapolation (LE) and the transconductance change (TC) methods [1], [2]. With CC, the difficulties are measuring the effective channel length and width and defining a constant value of the drain current. LE should be applied only in the low drain voltage region. In the high drain voltage region, however, the square root of current extrapolation (SRE) should be applied. With extrapolation methods such as LE and SRE, the continuity in all operation voltages is lost. The threshold voltage characteristics with TC are strange for drain voltage changes, as shown in Fig. 1. A threshold voltage definition that overcomes the above disadvantages is needed. This paper presents a new method for extracting the threshold voltage: the second difference of the logarithm of the drain current minimum (SDLM).

2. Method

The diffusion component and the drift component can be respectively approximated by an exponential function and a polynomial expression, as shown in Fig. 2. The first difference of the logarithm of the drain current almost stays constant when the diffusion component is dominant and gradually approaches zero when the drift component is dominant, as shown in Fig. 3 (a). Fig. 3 (b) shows the second difference takes a minimum value at the unique transition voltage in an NMOSFET. In this work, this voltage is defined as the threshold voltage. This threshold voltage is shown in Fig. 1 for various drain voltages compared to ones extracted with previous methods. The characteristics are reasonable even for drain voltage changes.

3. Verification

With a view to certify that the dominant component in the drain current changes from diffusion to drift at the threshold voltage extracted with the above method, the rate of each component was calculated by 2D device simulation. In the simulation, an NMOSFET with $L_g = 1.0\mu m$ was used with $V_{ds} = 3.0$V and $V_{sb} = 0$V. As a result, the minimum value is calculated with this method as shown in Fig. 4 like in measurements and the potential distributions at the interface of Si and SiO_2 obtained are those shown in Fig. 5. The drift component $[ids_{(drift)}]$ and diffusion component $[ids_{(diff)}]$ are

$$ids_{(drift)} = -q\mu n\frac{d\psi}{dx}, \qquad ids_{(diff)} = q\mu n\frac{d(\psi - \xi_n)}{dx}$$

where μ is the electron mobility, n is the electron density, ψ is the conduction band potential, $(\psi - \xi_n)$ is the relative potential and ξ_n is the electron quasi-Fermi potential. At each position at the interface, the rates of drift and diffusion compete with the rates of $(d\psi/dx)$ and $[-d(\psi - \xi_n)/dx]$. Fig. 6 shows the distribution of the rate of current components through the channel. The average rate of the drift component in the channel region $[RATE_{(drift)}]$ is

$$RATE_{(drift)} = \frac{1}{L}\int_{x_s}^{x_d} rate(x)dx$$

where x_s and x_d are the source edge and the drain edge and L is the channel length. Fig. 7 shows the rate of the drift component in the channel increases as the gate voltage increases. At $V_{gs} = 0.215$V, drift equals diffusion. Therefore, the threshold voltage defined with this method shows the unique gate voltage that is the transition voltage in the dominant component in the drain current.

4. Summary

A method for extracting the threshold voltage with the second difference of the logarithm of the drain current was proposed and verified from the physical point of view using 2D device simulation. The extracted threshold voltage has the following features: It is extracted from only the drain current without both the effective channel length and width and has a physical meaning. It shows the gate voltage at which drift and diffusion in the drain current are equal each other. These features may be useful for unifying the threshold voltage in compact models and in measurement.

References

[1] M. J. Deen and Z. X. Yan, "A new method for measuring the threshold voltage of small-geometry MOSFETs from subthreshold conduction", *Solid-State Electronics*, vol. 33, no. 5, pp. 503-511, 1990.

[2] H. -S. Wong, M. H. White, T. J. Krutsick and R. V. Booth, "Modeling of transconductance degradation and extraction of threshold voltage in thin oxide MOSFETs", *Solid-State Electronics*, vol. 30, no. 9, pp. 953-968, 1987.

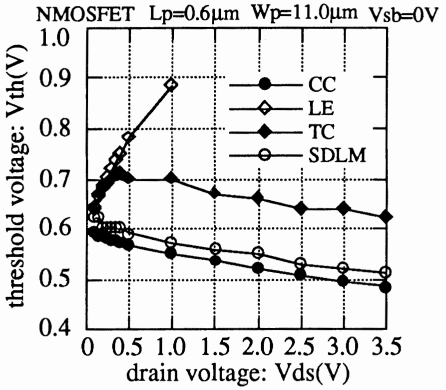


Fig. 1. Comparison of the threshold voltages extracted with previous methods and SDLM for various drain voltages using the measured drain current in the NMOSFET.

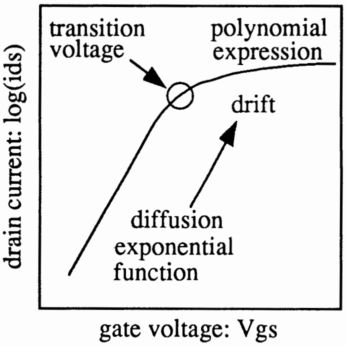
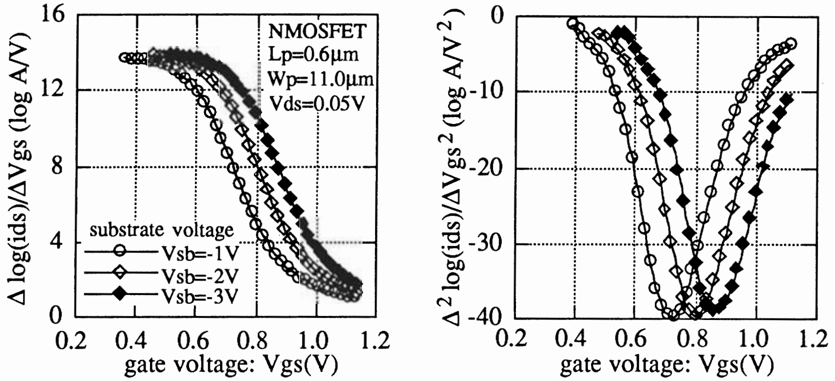
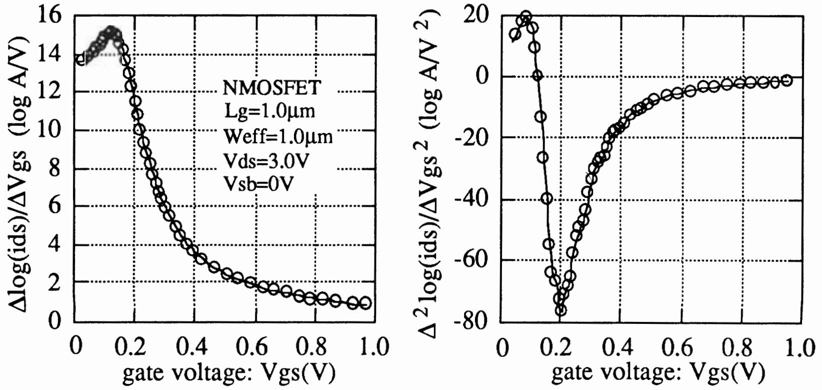


Fig. 2. The idea of extracting the threshold voltage in this work.



(a) (b)

Fig. 3. Results for this method when applied to a submicron NMOSFET for the various substrate voltages. (a) The first difference of the drain current. (b) The second difference of the drain current.



(a) (b)

Fig. 4. The derivatives of the drain current calculated from 2D device simulation.
(a) The first difference of the drain current. (b) The second difference of the drain current.

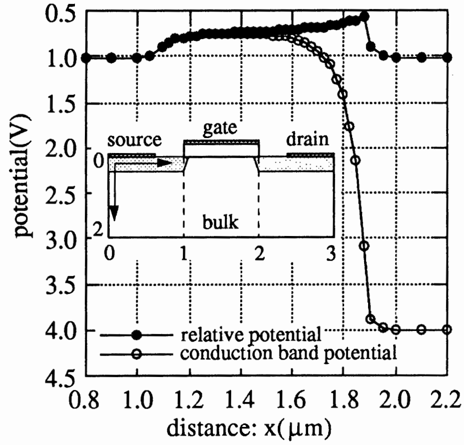


Fig. 5. The conduction band potential and the relative potential distribution at the interface at Vds=3.0V and Vgs=0.2V using 2D device simulation results. The device structure used in the simulation is also shown.

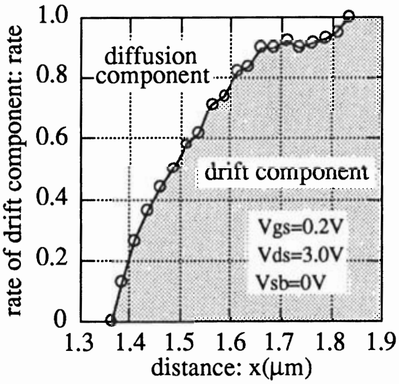


Fig. 6. The rate of the two drain current components in the channel calculated using the conduction band potential and the relative potential at the interface of Si and SiO_2.

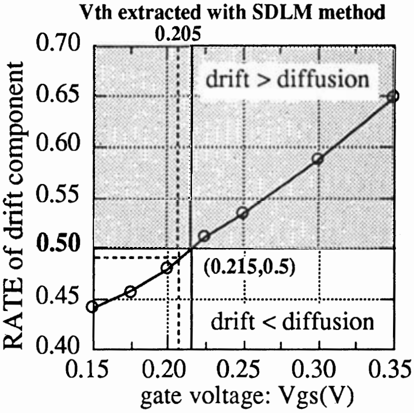


Fig. 7. The RATE of the drift current component at the interface for various gate voltages. At Vgs=0.215V, the drift component is equal to the diffusion component.