

Determination of Threshold Voltage and Mobility of MOSFET by Proportional Difference Operator

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Abstract: Proportional Difference Operator (PDO) method is proposed for the first time to determine the key parameters of a MOSFET, including the threshold voltage and carrier mobility. This method is applied to the transfer characteristic of a MOSFET first, and then the effect of gate voltage on carrier mobility is considered. The dependence of carrier mobility on the gate voltage is obtained.

Key words: proportional difference operator; transfer characteristic; MOSFET

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1 Introduction

The determination of key parameters, such as threshold voltage and effective carrier mobility, is of the first magnitude for the characterization of MOS devices. Due to the disproportionate scaling-down of MOSFETs, the gate oxide layer experiences a higher electric field, which results in some serious variations in surface mobility with the gate voltage. Therefore, many methods reported^[1,2], in which the degradation of carrier mobility with the effective field has been neglected, will lead to an unreliable result in extracting the parameters of MOS devices. For example, as for the linear extrapolation and square root extrapolation method^[2], which is the one being used most frequently, the unsatisfactory threshold voltage values for an ultra-thin MOS device are presented due to the assumption that the gate voltage is independent of the carrier mobility.

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Currently, a spectral method, namely Proportional Difference Operator (PDO) method^[3], is proposed to determine the key parameters of a MOSFET. In this letter, it is used to extract the threshold voltage and the dependence of carrier mobility on the gate voltage.

2 PDO Method

For a simple asymptotic function $f(x)$, if $f(0) = A$, and $\lim_{x \rightarrow \infty} f(x) = B$, its proportional difference can be defined by:

$$\Delta_P f(x) = f(kx) - f(x), \quad (1)$$

where k is some given positive real number ($k > 1$) called proportional constant, and Δ_P is the proportional difference operator. Furthermore, according to the difference spectral function theorem developed by XU^[3], it is easy to prove that $\Delta_P f(x)$ has an extremum in $[0, \infty)$.

The basic drain current I_{DS} of an n-channel MOSFET is expressed as^[4]:

$$I_{DS} = \frac{W}{L} C_{OX} \frac{\mu_0}{1 + \theta(V_{GS} - V_{th})} (V_{GS} - V_{th}) V_{DS}, \quad (2)$$

where C_{OX} is the oxide capacitance; W, L are the width and length of the channel, respectively; V_{GS}, V_{DS} and V_{th} are the gate, drain and the threshold voltage, respectively; μ_0 and θ are the carrier mobility and its coefficient, respectively. This simplified equation is valid at a small drain voltage in comparison with $(V_{GS} - V_{th})$ and on the assumption that the diffusion current is negligible.

The PDO is applied to Eq. 2, then,

$$\begin{aligned} \Delta_P I_{DS}(V_{GS}) &= \frac{W}{L} C_{OX} \mu_0 V_{DS} \left[\frac{(kV_{GS} - V_{th})}{1 + \theta(kV_{GS} - V_{th})} - \frac{(V_{GS} - V_{th})}{1 + \theta(V_{GS} - V_{th})} \right] \\ &= \frac{W}{L} C_{OX} \mu_0 V_{DS} \frac{(k-1)V_{GS}}{[1 + \theta(kV_{GS} - V_{th})][1 + \theta(V_{GS} - V_{th})]} \end{aligned} \quad (3)$$

The peak is obtained by:

$$\left. \frac{\partial \Delta_P I_{DS}(V_{GS})}{\partial V_{GS}} \right|_{V_{GS} = V_{GP}} = 0 \quad (4)$$

i. e.

$$\theta = \frac{1}{\sqrt{k} V_{GP} + V_{th}} \quad (5)$$

where V_{GP} is the peak gate voltage of the proportional difference transfer characteristic.

There are two unknown parameters θ and V_{th} in Equation 4, so it is necessary to introduce a new equation. Substitute Eq. 2 in Eq. 3,

$$\Delta_P I_{DS}(V_{GS}) = \frac{I_{DS}}{V_{GS} - V_{th}} (k-1) \frac{V_{GS}}{[1 + \theta(kV_{GS} - V_{th})]} \quad (6)$$

Comparing Eq. 5 with Eq. 6 to eliminate θ , then we obtain,

$$V_{th} = \frac{k + \sqrt{k} - \sqrt{k} F(V_{GP})}{F(V_{GP}) + k + \sqrt{k}} V_{GP} \quad (7)$$

where $F(V_{GP}) = \frac{I_{DS}(V_{GP})(k-1)}{\Delta I_{DS}(V_{GP})}$. Subsequently, μ_0 is obtained by substituting Eqs. 7 and 5 into Eq. 2. Thus, both the peak height $\Delta I_{DS}(V_{GP})$ and the peak gate voltage of proportional difference transfer characteristic V_{GP} are used to extract the results.

3 Experiment and Discussion

The n-channel MOSFET used in this study was fabricated by a conventional CMOS process on a p-type, (100)-oriented silicon wafer with the resistivity about $6-8\Omega\cdot\text{cm}$. The drawn channel width/length are $50\mu\text{m}/5\mu\text{m}$ in the devices. The gate oxide thickness is 10nm with LOCOS isolation. The transfer characteristics of a MOSFET were automatically obtained when $V_{DS} = 0.05\text{V}$ by an HP 4145B semiconductor parameter analyser. Then, the proportional difference values were obtained by a simple computer program.

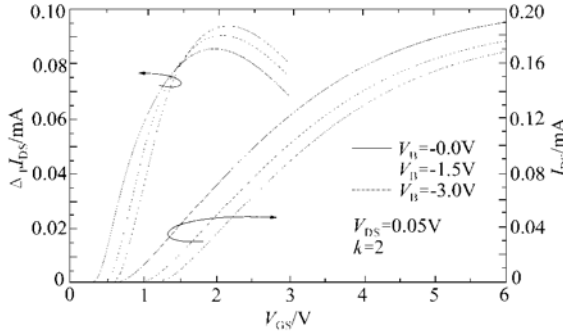


FIG. 1 Transfer Characteristic and Its Proportional Difference Characteristic ($k=2$) at Different Substrate Voltage, V_B

—, Solid Line $V_B = 0\text{V}$; — —, Dash Line $V_B = -1.5\text{V}$;
- · -, Dash-Dot Line $V_B = -3\text{V}$

Figure 1 shows the transfer characteristic and its proportional difference. In this figure, the peak gate voltage of the proportional difference transfer characteristic curves are sensitive to the substrate voltage V_B . Moreover, it is noticed that the gate voltage, from which the peak of proportional difference curve is obtained, falls into the voltage range when the drain current model in this method is valid, as succeeds in avoiding any influence of other factors, such as the diffusion current. The threshold volt-

ages obtained from Eq. 7 are shown in Fig. 2. The voltage shift with the substrate voltage from 0 to V_B is estimated using the following expression on condition that the surface potential varies linearly in the channel region from $2\phi_b$ to $2\phi_b + V_B$ and is independent of the drain biases ($V_{DS} = 0.05\text{V}$).

$$\Delta V_{th} = \gamma(\sqrt{2\phi_b + V_B} - \sqrt{2\phi_b}) \quad (8)$$

where ϕ_b is the Fermi potential, $\gamma = \sqrt{2qN_A\epsilon_s/C_{ox}}$, V_B refers to the absolute value of substrate voltage. Assuming that the intrinsic carrier concentration $n_i = 1.45 \times 10^{10}\text{cm}^{-3}$, substrate concentration $N_A = 3.6 \times 10^{16}\text{cm}^{-3}$ and the oxide thickness $T_{ox} = 10.1\text{nm}$, the voltage shift 0.456V calculated by Eq. 8 is consistent with the experimental results of 0.476V, as verifies the correctness of this method.

Figure 3 shows the relationship between the effective carrier mobility μ_{eff} and V_{GS} . μ_{eff} is calculated by $\mu_{eff} = \frac{\mu_0}{1 + \theta(V_{GS} - V_{th})}$, where the parameters, μ_0 and θ , are extracted by the

PDO method. The results obtained in our previous work^[5] on the same sample are also shown, which is in a good agreement with the current ones when $V_{GS} > 3V$. The mobility is obtained by the method^[5] when taking the drain voltage effect into consideration, while the results are obtained when neglecting the effect. So, under a high gate voltage ($V_{GS} > 3V$), the effect of the drain voltage on mobility is negligible compared with that of the gate volt-

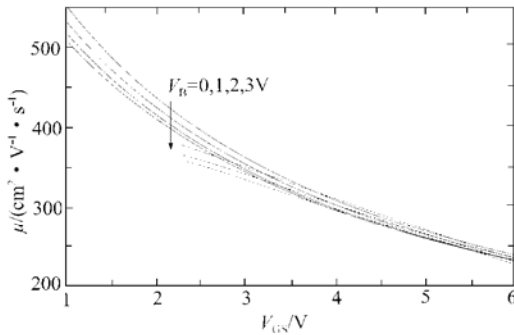


FIG. 3 Comparison Between Effective Carrier Mobility (Solid Line) as a Function of Gate Voltage at Different Substrate Voltage and Previous Results (Dash Line)

($\psi_s = 2\psi_B$), and V_L as that when $\psi_s = \psi_B$ ^[4]. $V_M = V_{th0} + nkT/q$, $V_H = V_{th0} + \Delta V$, $n = 12$ and $\Delta V = 0.5 - 0.7V$. In addition, the deep inversion threshold voltage V_A is defined to explain the experimental result. In Fig. 4, a good agreement can be seen between the calculated result and the experimental one in the gate voltage range from V_H to V_A . Beyond this voltage range, the deviation between them is caused by the effect of diffusion current or by the inapplicability of the current mobility

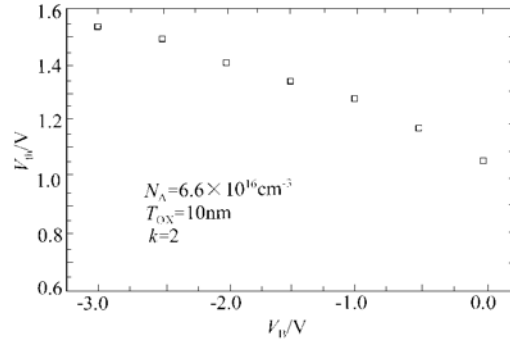


FIG. 2 Threshold Voltage V_{th} Versus Substrate Voltage V_B

age. In the gate voltage range ($V_{GS} > 3V$), the results obtained by these two methods are consistent with each other very well.

Figure 4 shows the result of the calculated and experimental drain current versus the gate voltage. The theoretical surface potential versus the gate voltage is also shown. The theoretical drain current is calculated by Eq. 2, where μ_0 and θ are extracted by PDO method. Some threshold voltages are designated in Fig. 4, where V_{th0} is the classical threshold voltage, which has been defined as required gate voltage for the surface band-bending of

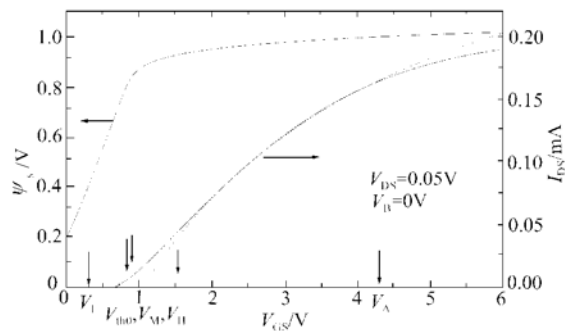


FIG. 4 Calculated (Dash Line) and Experimental (Solid Line) Drain Current Versus Gate Voltage. The theoretical surface potential is plotted.

model. In this experiment, V_A is set $V_{th0} + 3.5V$. It is noted that the peak voltage of proportional difference characteristic is located within the voltage range from V_H to V_A . It proves that the results extracted from PDO method will not be affected by the diffusion current or by the high order effect of the mobility at high gate voltage. A more complicated mobility model should be used to consider the effect of high gate voltage and will be given in our future work.

4 Conclusion

A new application of PDO method to determine the threshold voltage, carrier mobility has been presented. Due to the consideration of the effect of gate voltage on carrier mobility, the dependence of effective mobility on the gate voltage has been obtained by PDO method. In addition, the peak of proportional difference characteristic used to determine the results has also been obtained in the moderate gate voltage range, where the drain current model is valid, as ensures the validity of this method. Furthermore, the PDO method is of the advantage of easy-to-use in practice.

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