Theory of Bipolar MOSFET (BiFET) with Electrically Short Channels

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ABSTRACT

Bipolar MOSFETs with a pure base and two MOS gates usually have electrically short channels compared with its intrinsic Debye length of about 25μm at room temperatures. This short channel effect was missed by all previous authors because they neglected the gradient of the longitudinal electrical field in their computations of the long-channel characteristics of the transistors. This paper evaluates the short channel contributions to the drain current, drain conductance and transconductance. The results show that long-channel electrical characteristics are still good approximations when the physical channel length is several hundred times shorter than the intrinsic Debye length (25μm/100=250nm) but the long channel electrical characteristics are substantially modified at 25nm.

Keywords: BiFET, pure base, intrinsic Debye length, long-channel characteristics, short-channel correction.

1 INTRODUCTION

The theory of the semiconductor transistors started from the two inventions by Shockley: the p-n junction transistor in 1949 [1] and the unipolar field-effect transistor in 1952 [2]. Shockley included only minority carrier diffusion current in his p-n junction transistor theory, and only majority carrier drift current in his unipolar field-effect transistor theory. In 1966, Sah included both diffusion current and drift current of the majority carriers in a surface channel using the gradient of the electrochemical potential, and the electric potential at the surface or the SiO_2/Si interface as the coupling parameter between the transverse-direction gate-voltage equation and the longitudinal-direction drain-current equation [3, 4]. This approach is later referred by the compact modeling community as the surface potential modeling [5]. In 1996, Sah derived the two-dimensional exact analytical drain current equation with drift current components and diffusion current components of the majority carriers in a surface channel [6, 7]. In the last three years, we have developed the theory of the bipolar field-effect transistors (BiFETs), which contains all eight current components simultaneously: drift and diffusion currents of the two charge carriers in both surface and volume channels [8, 9, 10]. The concept of the complete semiconductor transistor was introduced and a complete form of the complete semiconductor transistor was described [11, 12].

As an example, a bipolar field-effect transistor with a pure base and two MOS gates is configured to realize the circuit function provided by the CMOS voltage inverter. We have reported the voltage-voltage and current-voltage characteristics of this transistor, denoted as CMOS-BiFET [13]. A BiFET with a pure base was also configured to operate in the unipolar (electron) current mode, called nMOS-BiFET. The long-channel characteristics of nMOS-BiFET were computed by neglecting the gradient of the longitudinal electrical field in the Poisson Equation [14]. When the gate voltage is near zero, the electron current is very near zero, and thus the two-section model proposed by us, consisting of the electron-emitter and electron-collector sections, must be used. However, it is shown that when the gate voltage is larger than 0.1 volt, a tenth of the operation voltage, the electron collector section has a length less than 10^{-4} of the base length, which can be neglected. In the practical range, only one section, the electron-emitter section needs to be considered, which means the electron surface channel covers the whole base length.

In transistors with pure base, the transistors are almost always electrically short, because there are so few electrons and holes to screen the charges, so the linear carrier-screening distance or the Debye Length, $L_{Di} \simeq 25$ μm, is so much larger than the make-ups and dimensions of the transistors [15]. It is practically very important to know whether the long-channel characteristics of the nMOS-BiFET can adequately describe the nanometer BiFET. This paper will shed light on this question.

2 EQUATIONS

The schematic diagram of a nMOS-BiFET was given in Figure 1 of Reference 14. The boundary conditions of this transistor were listed as Equations (1) and (2) of Reference 14. By neglecting the gradient of the longitudinal electrical field in the Poisson Equation, the transverse-direction or X equations are the Voltage Equation (3) and Thickness Equation (4) of Reference 14. One additional assumption is employed to derive these two X equations: the x-independence of the electron and hole electrochemical potentials.

The electron current can be computed in two equivalent representations: electrochemical potential representation [9] and drift-diffusion representation [10]. With the neglect of the gradient of the longitudinal electric field, and with the constancy and near-thermal-equilibrium of the electron mobility and diffusivity, the electron current in the electrochemical potential representation reads:

$$\begin{aligned}
I_N = {} & 2qD_n n_i L_{Di}\,(W/L) \times \int \partial U_N \exp(-U_N) \times && U_N = U_{SB} \text{ to } U_{DB} \\
& \int \text{sign}(U-U_0)\exp(+U)\partial_x U \times && U = U_0 \text{ to } U_S \\
& [\exp(U-U_N)-\exp(U_0-U_N)+\exp(U_P-U)-\exp(U_P-U_0)]^{-1/2} &&
\end{aligned} \qquad (1)$$

where the notations are defined in References 9 and 14. The electron electrochemical potential, U_{N1}, at any position $Y_1 = y_1/L$ along the longitudinal or y direction can be numerically solved by the Newton-Raphson method from the following implicit integration equation:

$$\begin{aligned}
Y_1 = {} & 2qD_n n_i L_{Di}\,(W/L) \div I_N \times \int \partial U_N \exp(-U_N) \times && U_N = U_{SB} \text{ to } U_{N1} \\
& \int \text{sign}(U-U_0)\exp(+U)\partial_x U \times && U = U_0 \text{ to } U_S \\
& [\exp(U-U_N)-\exp(U_0-U_N)+\exp(U_P-U)-\exp(U_P-U_0)]^{-1/2} &&
\end{aligned} \qquad (2)$$

Therefore, the function $U_N(Y)$ is numerically available, with the neglect of the gradient of the longitudinal electric field. From the Voltage Equation and Thickness Equation, the surface potential U_S and the mid-plane potential U_0 as a function of U_N are obtained numerically. As a result, the first derivative and second derivative of the potentials U_S and U_0 with respect to the Y position can be computed numerically.

Following Equation (65) of Reference 10, considering the pure base of the nMOS-BiFET, the electron current in the drift-diffusion representation reads:

$$\begin{aligned}
I_N = {} & +2kT\,\mu_n\,n_i\,L_{Di}\,(W/L) \times \{ \\
& \quad +\partial/\partial Y[(C_O/C_D)\times(2U_{GS}\times U_S - U_S^2)] + \partial/\partial Y \int (\partial U/\partial X)^2 \partial X \\
& \quad - (L_{Di}/L)^2\,\partial/\partial Y \int (\partial U/\partial Y)^2 \partial X \} \qquad X = 0 \text{ to } X_B \\
& + 2q\,D_n\,n_i\,L_{Di}\,(W/L) \times \{ \\
& \quad + \partial/\partial Y[(C_O/C_D) \times 2U_S] \\
& \quad + 2(L_{Di}/L)^2\,\partial/\partial Y \int (\partial^2 U/\partial Y^2) \partial X \} \qquad X = 0 \text{ to } X_B
\end{aligned} \qquad (3)$$

Due to the zero hole current in the nMOS-BiFET, the drain current I_D is the electron current I_N. Compared with the long-channel electron current described by the electron current equation (10) of Reference 14, the drain current then consists of two parts, the long-channel current I_{DL} and the short-channel correction I_{DS}. It should be clear that the long-channel current is those terms without the longitudinal electric field and the pre-factor (L_{Di}/L), and the short-channel correction is those terms with the longitudinal electric field and the pre-factor (L_{Di}/L).

It is important to note that the two integrations $\int(\partial U/\partial Y)^2 \partial X$ and $\int(\partial^2 U/\partial Y^2)\partial X$ are generally difficult to evaluate, since the first and second derivatives of the potential with respect to the Y position, or longitudinal electric field and its gradient, at any spatial (x, y) position cannot be computed from the Voltage Equation, Thickness Equation and Electron Current Equation. However, the two boundary values of these two derivatives, which are the derivatives of the surface potential and mid-plane potential, are easy to obtain, as described in the above. Therefore, the two integrations are estimated by their boundary values as follows:

$$\int(\partial U/\partial Y)^2 \partial X \approx [(\partial U_S/\partial Y)^2 + (\partial U_0/\partial Y)^2]/2 \times X_B \qquad (4)$$

$$\int(\partial^2 U/\partial Y^2)\partial X \approx [\partial^2 U_S/\partial Y^2 + \partial^2 U_0/\partial Y^2]/2 \times X_B \qquad (5)$$

Electron current in Eq. (3) is a differential form evaluated at any Y position. It is necessary to convert the differential form into an analytical form to obtain both the long-channel current I_{DL} and the short-channel correction I_{Ds}. It must be noted that the constancy of long-channel current along the Y direction, expressed in Eq. (1), has been assumed to compute the derivatives of the surface potential and mid-plane potential. By assuming that the short-channel correction does not alter the constancy of the drain current I_D, integrating from the source end Y=0 to any position $Y=Y_1$, the following relations are obtained:

$$\begin{aligned}
Y_1 \times I_{DL} = {} & +2kT\,\mu_n\,n_i\,L_{Di}\,(W/L) \times \{ \\
& (C_O/C_D)\times[(2U_{GS}\times U_S - U_S^2)|(Y=Y_1) - (2U_{GS}\times U_S - U_S^2)|(Y=0)] + \\
& (-1)\int[\exp(U-U_N)-\exp(U_0-U_N)+\exp(U_P-U)-\exp(U_P-U_0)]^{1/2}\partial U \\
& \qquad |(Y=Y_1) - \\
& (-1)\int[\exp(U-U_N)-\exp(U_0-U_N)+\exp(U_P-U)-\exp(U_P-U_0)]^{1/2}\partial U \\
& \qquad |(Y=0)\} \\
& + q\,D_n\,n_i\,L_{Di}\,(W/L) \times \{ \\
& (C_O/C_D) \times [2U_S\,|(Y=Y_1) - 2U_S\,|(Y=0)]\,\}
\end{aligned} \qquad (6)$$

$$\begin{aligned}
Y_1 \times I_{Ds} = {} & +2kT\,\mu_n\,n_i\,L_{Di}\,(W/L) \times \{ \\
& (L_{Di}/L)^2\,[\int(\partial U/\partial Y)^2\partial X|(Y=Y_1) - \int(\partial U/\partial Y)^2\partial X|(Y=0)]\,\} \\
& + 2q\,D_n\,n_i\,L_{Di}\,(W/L) \times \{ \\
& 2(L_{Di}/L)^2 \times [\int(\partial^2 U/\partial Y^2)\partial X|(Y=Y_1) - \int(\partial^2 U/\partial Y^2)\partial X|(Y=0)]\}
\end{aligned} \qquad (7)$$

After computing the long-channel current and the short-channel correction from Eqs. (6) and (7), one can obtain the drain current I_D as the sum of the two. Then, drain conductance and transconductance are evaluated by numerical derivatives or analytical derivative of the least-squares-fit formula.

3 RESULTS AND DISCUSSION

Figures 1 and 2 show the long-channel current and short-channel correction of a nMOS-BiFET versus the gate voltage. This BiFET has a channel length of 10μm, which is comparable to the intrinsic Debye length 25μm. Its oxide thickness is 1.5nm and its pure-base thickness is 30nm. The source voltage and hole electrochemical potential are zero. These two current components are evaluated at three positions Y_1 = 0.50, 0.90 and 0.99. Consistent with current continuity and the description in Section 2, the long-channel currents are indeed independent of the Y_1 position.

However, the short-channel corrections increase when the Y_1 positions move to the drain end. When the position Y_1 is closer to the drain end, the electron electrochemical potential increases exponentially, which leads to the rapidly increasing longitudinal electric field and then larger short-channel correction. Another feature in Figures 1 and 2 is the presence of a threshold gate voltage of the short-channel correction current, at which the correction current increase rapidly with increasing gate voltage. With reference to the long-channel currents in Figs. 1 and 2, this threshold, about 0.3 V in this case, is in the deep-sub-threshold range of the nMOS-BiFET, where the electrons flow not in the surface channel but throughout the volume channel of the pure base. One expects little short-channel effect on the volume channel current.

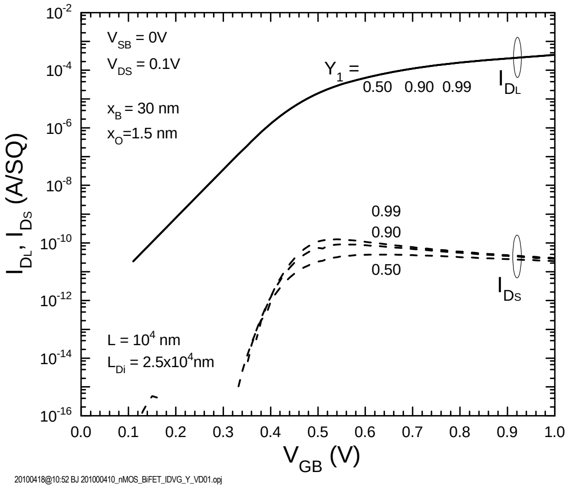

Figure 1: Long-channel current I_{DL} and short-channel correction I_{DS} with three positions Y_1 = 0.50, 0.90 and 0.99 are plotted versus the gate voltage V_{GB} with the drain voltage V_{DB} = 0.1V. The channel length L=10μm is comparable to the intrinsic Debye length 25μm.

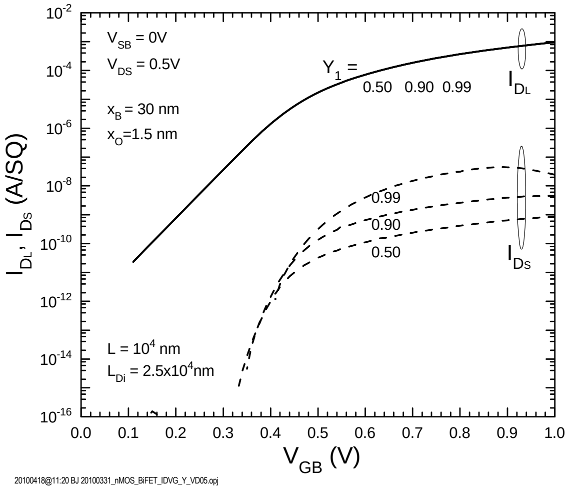

Figure 2: the same as Figure 1 except V_{DB} = 0.5V.

A reduction of the short channel correction current with the increasing gate voltage is observed in Figs. 1 and 2. The reason is that when the gate voltage is significantly larger than the drain voltage, the surface channel thickness is decreased from the source end all the way to the drain end, thus the thickness to length ratio of the surface channel is reduced. This is equivalent to an increasing channel length at a constant channel thickness, thus, a reduction of the short-channel correction current.

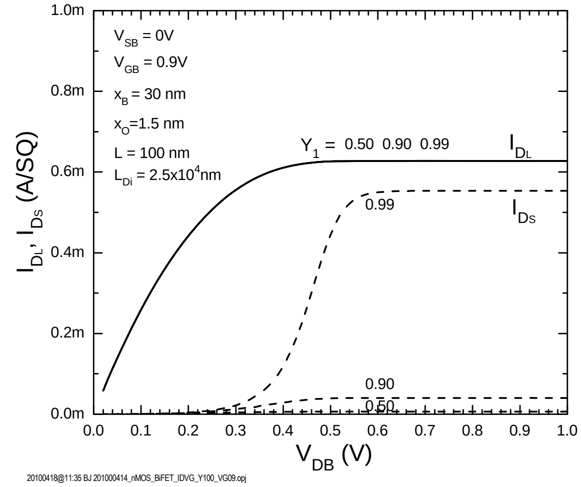

Figure 3: Long-channel current I_{DL} and short-channel correction I_{DS} with three positions Y_1 = 0.50, 0.90 and 0.99 are plotted versus the drain voltage V_{DB} with the drain voltage V_{GB} = 0.9V. The channel length L=100nm.

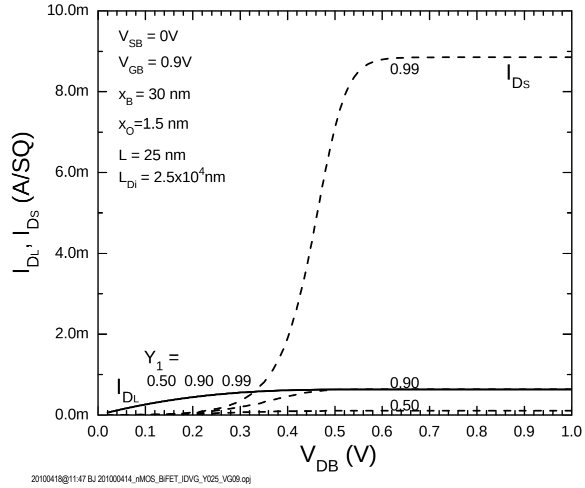

Figure 4: the same as Figure 3 except L = 25nm.

The long-channel currents are at least four orders of magnitude larger than the short-channel corrections in Figs. 1 and 2, because the channel length is comparable to the intrinsic Debye length, and thus the gradient of longitudinal electric field can be neglected along the whole surface channel except at the drain end point. Figures 3 and 4 show drain voltage dependence of the long-channel currents and short-channel corrections at three Y_1 positions 0.50, 0.90 and 0.99 at a constant gate voltage of $V_{GB} = 0.9V$. In Fig. 3, at the channel length $L = 100nm = L_{Di}/250$, the three short-channel corrections are still less than the long-channel currents. In Fig. 4, at the channel length $L = 25nm = L_{Di}/10^3$, the short-channel correction using $Y_1 = 0.5$ is less than the long-channel current, while the short-channel correction using $Y_1 = 0.99$ is significantly larger than the long-channel current.

Due to the page limitation of this paper, other computation results, including drain conductance and transconductance, will be presented in the invited paper to be published in Journal of Semiconductors in the July, 2010 issue (www.jos.ac.cn).

4 SUMMARY

We have presented in this paper the long-channel currents and short-channel corrections of the nMOS-BiFETs with a pure base and two MOS gates. The long-channel currents are current components in the drift-diffusion representation without the longitudinal electric field and the pre-factor (L_{Di}/L), and the short-channel corrections are those with the longitudinal electric field and the pre-factor (L_{Di}/L). When the physical channel length L is comparable to L_{Di}, the short-channel corrections are indeed negligibly smaller than the long-channel currents. This proves the self-consistency of the assumptions made to derive the long-channel current formulae. When L drops to $L_{Di}/10^2 = 250$ nm, the short-channel corrections are still smaller than the long-channel currents, thus, the long-channel characteristics of the nMOS-BiFETs are still good approximations for the transistors. When L is about $L_{Di}/10^3 = 25$ nm, the long-channel characteristics are no longer good approximations, and the surface electron channel must be divided into two parts: one part in which the gradient of the transverse electric field is much larger than the gradient of the longitudinal electric field, and the other part in which the two-dimensional effects must be taken into account. This investigation has been supported by CTSAH Associates.

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