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The Bipolar Field-Effect Transistor: IV. Short Channel Drift-Diffusion Current Theory (Two-MOS-Gates on Pure-Base)*

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Abstract: This paper gives the short channel analytical theory of the bipolar field-effect transistor (BiFET) with the drift and diffusion currents separately computed in the analytical theory. As in the last-month paper which represented the drift and diffusion current by the single electrochemical (potential-gradient) current, the two-dimensional transistor is partitioned into two sections, the source and drain sections, each can operate as the electron or hole emitter or collector under specific combinations of applied terminal voltages. Analytical solution is then obtained in the source and drain sections by separating the two-dimensional trap-free Shockley Equations into two one-dimensional equations parametrically coupled via the surface-electric-potential and by using electron current continuity and hole current continuity at the boundary between the emitter and collector sections. Total and the drift and diffusion components of the electron-channel and hole-channel currents and output and transfer conductances, and the electrical lengths of the two sections are computed and presented in graphs as a function of the D.C. terminal voltages for the model transistor with two identical and connected metal-oxide-silicon-gates (MOS-gates) on a thin pure-silicon base over practical ranges of thicknesses of the silicon base and gate oxide. Deviations of the two-section short-channel theory from the one-section long-channel theory are described.

Key words: bipolar field-effect transistor theory; MOS field-effect transistor; simultaneous electron and hole surface and volume channels; surface potential; two-section short-channel theory; double-gate pure-base
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1 Introduction

The silicon MOS field-effect transistor (FET) technology is advancing into the nanometer dimensions in the form of double-gate and thin pure-base, fin-like structure, known as the FinFETs[1]. Their experimental electrical current-voltage characteristics, recently reported by IMEC with Assignees from four companies[2], could not be accounted for[3] by the current MOSFET theory that was developed from the traditional 55-year-old unipolar field-effect theory of the p/n junction-gate field-effect transistor (JG-FET) invented and theorized by Shockley in 1952[4,5], and reduced to practice by Dacey and Ross[6]. This 1952-Shockley theory was followed by recent device theorists and engineers to compact model (i) the MOS-gate and Insulator-Gate FETs (MOS-FET and IGFET) with single-gate on semi-infinite-thick-base, "bulk" transistors[7,8] and (ii) also the FinFETs which was extensively and carefully reviewed by Ortiz-Conde, Garcia-Sanchez, Liou and students in January 2007[9]. It was soon theorized and demonstrated in March 2007[3] and later presented by us[3,10~14] that the observed experimental current-voltage characteristics reported by IMEC + Assignees[2] showed distinct bipolar behavior, namely the simultaneous presence of both electron and hole surface-inversion-channel currents, even a hint of volume-channel currents, giving six channels in their two-MOS-gates on thin-base FinFET structures. The bipolar nature of the FET and our theory were named the 100% Bipolar Field Effect Transistor (BiFET) Theory[3,10~14], since it includes all four currents, the drift and diffusion currents of both electrons and holes. In contrast, the now 55-year-old Shockley's 1952 Unipolar Field-Effect Transistor Theory (Uni-FET) is a 25% FET theory because its theory and analytical solution[4~6] considered only one current, the drift of one carrier species. This 25% UniFET theory was employed by 1964-Sah[15] in the constant threshold-voltage-based MOS transistor model with parabolic voltage dependence of the current, and it was used

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by the initial circuit simulator SPICE[7]. It was soon extended to account for the non-parabolic voltage dependence of the current by including the voltage-dependence of the threshold voltage from immobile impurity ions in the surface space-charge layer with voltage-dependent thickness by 1965-Sah-Pao[16], known as "bulk-charge". This was immediately used by the second generation SPICE[7]. These were further extended in the 1966 Sah-Pao theory[16, 17] for the 'bulk' or semi-infinite-thick MOSFET to include both the drift and the diffusion currents via the electrochemical potential gradient as the effective or total field that drives the current, but again for only one carrier species, the electron or the hole, but not both, thus, it is the 50% BiFET or the 100% UniFET theory. This was again extended in 1996-Sah and 2005-Jie-Sah[18~20] to provide rigorous 2-D analytical separation of the drift current due to electric field and the diffusion current due to charge-carriers' concentration gradient, in order to give the underlying physics of the multiple drift current terms, and to meet the preference of the more popular current transport theory via drift and diffusion currents, rather than electrochemical current. This paper completes the preceding three analytical expositions of the BiFET theory[12~14] by providing the analytical solutions and numerical results for the more popular analytically-separated drift and diffusion current long-channel theory[18~20], now for electrically short channels, so as to extend the results we just reported for the electrochemical current in electrically short channels[14]. Following the presentation format given for the analytically-separated drift-diffusion long channel[13], families of graphs are presented for the total and the drift-diffusion components of the drain current and also the output and transfer conductances, as well as the voltage dependences of the section length, y_0-V_{GS} and y_0-V_{DS}. Fractional or percent deviations of the long channel theory from the electrically short channel theory are also computed and presented in graphs.

2 Short Channel Theory of the Two-Gate on Pure-Base Transistors

The voltage and current equations of the UniFET theory with single-gate on thick or semi-infinite impure-base from the Electrochemical Potential Theory given in 1966-Sah-Pao[16,17] and from the Drift-Diffusion Theory given in 1996-2005-Sah-Jie[18~20] were modified for the BiFET with two identical gates on a thin pure-base[3, 10~14]. They are immediately applicable to each of the two sections separated by the boundary $y = y_0(x)$. The complete analytical solution also requires the additional equations from matching the electric-potential and electric-current-density solutions in the two sections at their boundary.

From both the integration form and differential form of the electrochemical current theory[14], a match of the electron and hole currents at the boundary between the two sections of the BiFET gives the unipolar initial guess solution of the flatband line y_0[14]. From the drift and diffusion current theory, the electron and hole currents read:

$$I_{DN} = -(W/y_0)\iint[q\mu_n N E_Y + qD_n(\partial N/\partial y)]\,\partial x \partial y \quad (x = 0 \text{ to } x_B;\, y = 0 \text{ to } y_0) \tag{1}$$

$$I_{DP} = -[W/(L-y_0)]\iint[q\mu_p P E_Y + qD_p(\partial P/\partial y)]\,\partial x \partial y \quad (x = 0 \text{ to } x_B;\, y = y_0 \text{ to } L) \tag{2}$$

$$I_D = I_{DN} + I_{DP} = -I_S \tag{3}$$

where our notation and coordinate system in Ref.[14] are used. In the unipolar initial guess for the bipolar gate-voltage-equations, Equations (11), (13) and (14) of Ref.[14] are also used here. It is very important to note that when the flatband line is located inside the base region ($0 < y_0 < L$) away from its two physical boundaries $y = 0$ and $y = L$, the correct quasi-Fermi potential boundary values are $U_{NS} = U_{SB}$ and $U_{PD} = U_{DB}$ when $U_{SB} < U_{DB}$[14]. Following Ref.[13], the current equations (1) and (2) can be manipulated with the help of the bipolar Poisson equation. Thus, the three components (parabolic drift P_1, $(\partial/\partial y)(E_X)^2$ drift, and linear diffusion D_1)[13] of the drift-diffusion currents for electrically short channel BiFET are obtained as follows (for the range of $U_{DB} > U_{SB}$ or $U_{DS} > 0$ which is the case of initial electron surface inversion channel and later hole surface inversion channel when the electron current is saturated after $U_{DS} > U_{GS}$ or $U_{DG} > 0$ or $U_{GD} < 0$ to induce the surface-inversion hole channel in pure base, or surface accumulation hole channel in p-type base):

When $U_{GB} \leqslant U_{SB}$, $y_0 = 0$

$$I_{DN} = 0 \tag{4}$$

$$\begin{aligned} I_{DP} = {} & \mu_p(W/L) \times C_O(kT/q)^2 \times \{ [U_{GB} - U_S(L)]^2 - [U_{GB} - U_S(0)]^2 && \text{Parabolic drift } P_1 \\ & + 2[U_S(L) - U_S(0)] + (X_B/2)(C_O/C_D)[(U_{GB} - U_S(L))^2 - (U_{GB} - U_S(0))^2] && \\ & + (X_B/2)(C_D/C_O)[\exp(U_{SB} - U_S(0)) - \exp(U_{DB} - U_S(L))] \} && (\partial/\partial y)(E_X)^2 \text{ or drift } E_X^2 \\ & + D_p(W/L) \times 2C_O(kT/q) \times [U_S(L) - U_S(0)] && \text{Linear diffusion } D_1 \end{aligned} \tag{5}$$

When $U_{SB} < U_{GB} < U_{DB}$, $0 < y_0 < L$

$$\begin{aligned}
I_{DN} = {} & \mu_n (W/y_0) \times C_O (kT/q)^2 \times \{[U_{GB} - U_S(0)]^2 && \text{Parabolic drift } P_1 \\
& + 2[U_{GB} - U_S(0)] + (X_B/2)(C_O/C_D)[U_{GB} - U_S(0)]^2 && \\
& + (X_B/2)(C_D/C_O)[1 - \exp(U_S(0) - U_{SB})]\} && (\partial/\partial y)(E_X)^2 \text{ or drift } E_X^2 \\
& + D_n (W/y_0) \times 2C_O (kT/q) \times [U_{GB} - U_S(0)] && \text{Linear diffusion } D_1 \qquad (6)
\end{aligned}$$

$$\begin{aligned}
I_{DP} = {} & \mu_p [W/(L - y_0)] \times C_O (kT/q)^2 \times \{[U_{GB} - U_S(L)]^2 && \text{Parabolic drift } P_1 \\
& + 2[U_S(L) - U_{GB}] + (X_B/2)(C_O/C_D)[U_{GB} - U_S(L)]^2 && \\
& + (X_B/2)(C_D/C_O)[1 - \exp(U_{DB} - U_S(L))]\} && (\partial/\partial y)(E_X)^2 \text{ or drift } E_X^2 \\
& + D_p [W/(L - y_0)] \times 2C_O (kT/q) \times [U_S(L) - U_{GB}] && \text{Linear diffusion } D_1 \qquad (7)
\end{aligned}$$

When $U_{GB} \geqslant U_{DB}$, $y_0 = L$

$$\begin{aligned}
I_{DN} = {} & \mu_n (W/L) \times C_O (kT/q)^2 \times \{[U_{GB} - U_S(0)]^2 - [U_{GB} - U_S(L)]^2 && \text{Parabolic drift } P_1 \\
& + 2[U_S(L) - U_S(0)] + (X_B/2)(C_O/C_D)[(U_{GB} - U_S(0))^2 - (U_{GB} - U_S(L))^2] && \\
& + (X_B/2)(C_D/C_O)[\exp(U_S(L) - U_{DB}) - \exp(U_S(0) - U_{SB})]\} && (\partial/\partial y)(E_X)^2 \text{ or drift } E_X^2 \\
& + D_n (W/L) \times 2C_O (kT/q) \times [U_S(L) - U_S(0)] && \text{Linear diffusion } D_1 \qquad (8)
\end{aligned}$$

$$I_{DP} = 0 \qquad (9)$$

3 Computed Variations of the Electrical Lengths with Electrical Potential

The numerical solutions of the analytical formulas given in the previous section are given in sixteen figures in this section. They are from the initial solution for the Bi-FET theory which is dominated by the majority carrier in each of the two sections, so the minority carriers are neglected in the initial solution. The higher order solutions including both carrier species and their approach to the bipolar solution is reported in a future paper to assess the deviations of the initial solutions and convergence speeds for optimization of deviation and computation time. To illustrate the voltage dependences of electrical length of the two sections, the normalized electrical lengths, y_0/L and $1-(y_0/L)$, and their voltage derivatives are graphed respectively in Figs. 1 and 2 as a function of the fractional current-saturation voltages, V_{GS}/V_{DS} from 0 to 1 and $1-(V_{GS}/V_{DS})$ from 0 to 1. These two figures show the continuous electrical lengths through the current saturation point, and the discontinuous voltage derivatives. These are indicative of the match of the analytical solutions from the two sections at the electrical boundary of the two sections, which was defined[14] as the flatband point (or line or plane), y_0.

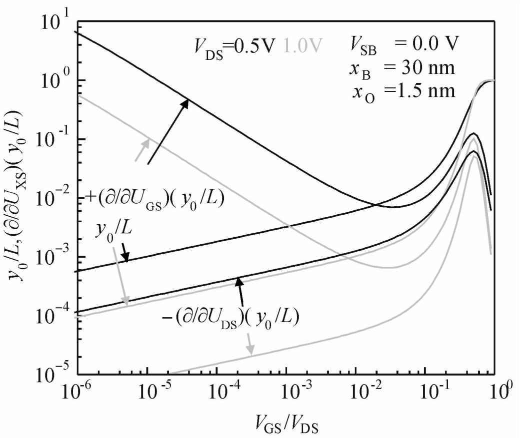

Fig. 1 Source section electrical length y_0/L is continuous at $V_{GS}=0$. Its derivative with respect to the drain voltage $(\partial/\partial U_{DS})(y_0/L)$ is continuous at $V_{GS}=0$. Its derivative with respect to the gate voltage $(\partial/\partial U_{GS})(y_0/L)$ diverges at $V_{GS}=0$ as shown in this log-log plot.

4 Computed Current-Voltage Characteristics and Channel Section Lengths

Selected results from computed terminal current-voltage and conductance-voltage characteristics and their voltage and oxide-base thicknesses dependences are illustrated in twelve figures from Figs. 3 to 14, in four groups of three figures each, versus V_{GS} or V_{DS}. These are similar to those in our second BiFET theory report[13] which were obtained, without taking into account of the electrically shortened channels, by letting $y_0 = L$ for the source electron emitter and $L - y_0 = L$ for the drain hole emitter. These 12 figures show increases of currents and conductances by the shortened channel, but not the general dependences on the terminal voltage, V_{GS} and V_{DS}. The

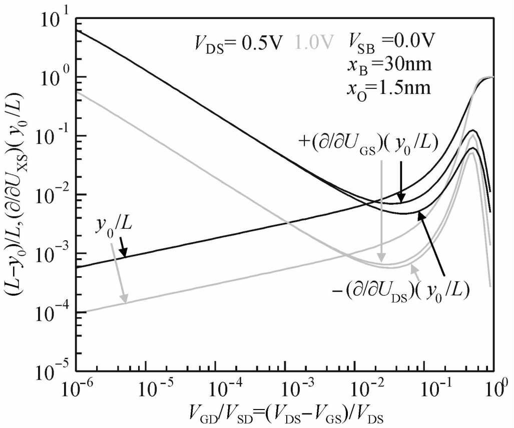

Fig. 2 Drain section electrical length $(L-y_0)/L$ is continuous at $V_{GS}=V_{DS}$. Its derivatives with respect to the gate voltage and drain voltage, $(\partial/\partial U_{GS})(y_0/L)$ and $(\partial/\partial U_{DS})(y_0/L)$ both diverge at $V_{GS}=V_{DS}$.

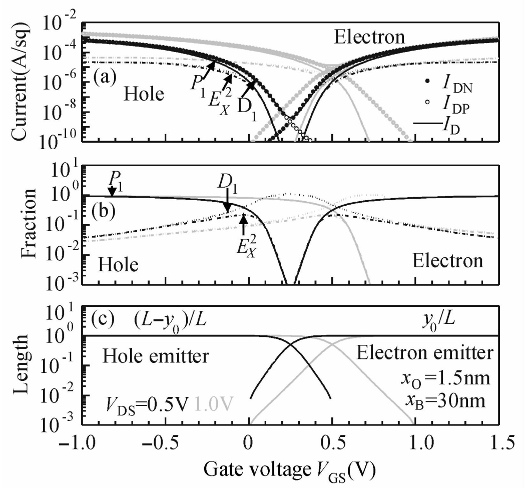

Fig. 3　The DC transfer characteristics at two Drain-Source voltages, V_{DS} = 0.50V and 1.0V. (a) The total drain current I_D and electron and hole drift and diffusion channel current components; (b) The fractional electron or hole parabolic drift current P_1, linear diffusion current D_1, and $(\partial/\partial y)(E_X^2)$ current normalized to the total electron or hole channel currents, I_{DN} or I_{DP}. (c) The normalized electron emitter electrical length y_0/L and hole emitter electrical length $(L-y_0)/L$.

quantitative details in percentage deviations are reported in Figs. 15 and 16.

4.1　Current-Voltage and Conductance-Voltage Characteristics

The V_{GS} and V_{DS} variations of the total drain current and the drift and diffusion components of the drain current, their transconductances and output conductances, and the electron and hole electrical channel lengths, are given in six figures, from Figs. 3 to 8.

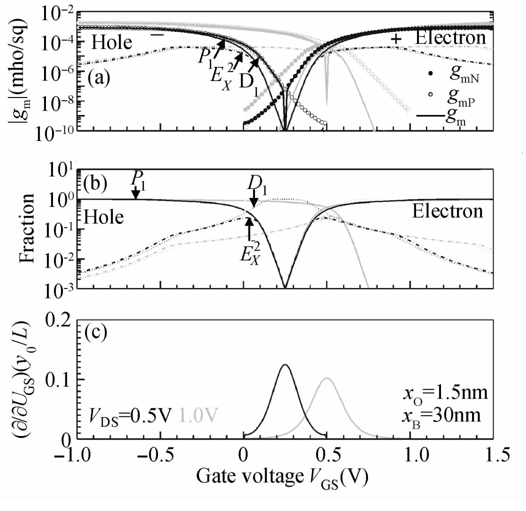

Fig. 4　The D. C. transconductance-gate-voltage characteristics at two V_{DS} = 0.5V and 1.0V. (a) The total transconductance g_m and electron and hole drift and diffusion components; (b) The fractional electron or hole transconductance from the parabolic drift current P_1, linear diffusion current D_1, and $(\partial/\partial y)(E_X^2)$ current normalized to the total electron or hole transconductances g_{mN} or g_{mP}. (c) The derivative of emitter length $(\partial/\partial U_{GS})(y_0/L)$. The discontinuity at V_{GS} = 0 and V_{DS} is not significant.

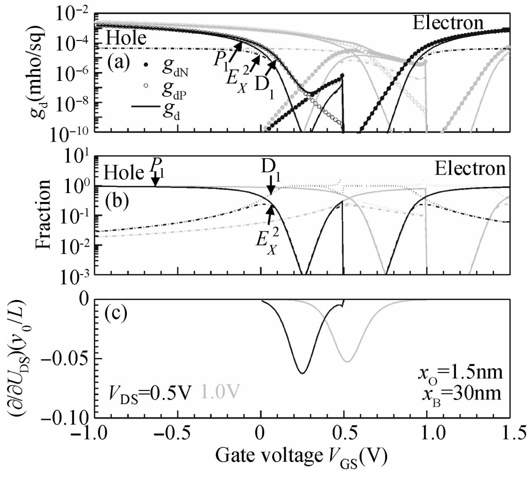

Fig. 5　The D. C. output-conductance-gate-voltage characteristics at two V_{DS} = 0.5V and 1.0V. (a) The total output conductance g_d and electron and hole drift and diffusion components; (b) The fractional output conductance from the parabolic drift current P_1, linear diffusion current D_1, and $(\partial/\partial y)(E_X^2)$ current normalized to the total output conductances g_{dN} or g_{dP}. (c) The derivative of emitter section electrical length $(\partial/\partial U_{DS})\times(y_0/L)$. The discontinuity at V_{GS} = V_{DS} is apparent.

Figures 3, 4, and 5 are the currents and two conductances and their drift and diffusion components, as well as the length of the two electrical sections versus V_{GS}.

Figures 6, 7, and 8 are the currents and two conductances and their drift and diffusion components, as well as the length of the two electrical sections versus V_{DS}.

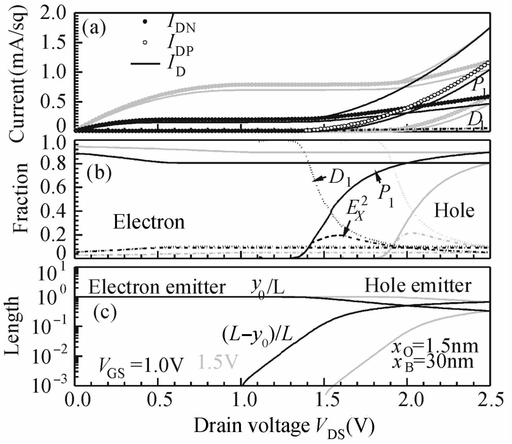

Fig. 6　The DC output current-voltage characteristics at two gate-source voltages V_{GS} = 1.0V and 1.5V. (a) The total drain current I_D and the electron and hole drift and diffusion channel current components; (b) The fractional electron or hole parabolic drift current P_1, linear diffusion current D_1, and the $(\partial/\partial y)(E_X^2)$ drift current normalized to the total electron or hole current, I_{DN} or I_{DP}. (c) The electron emitter length y_0 and the hole emitter length $(L-y_0)$.

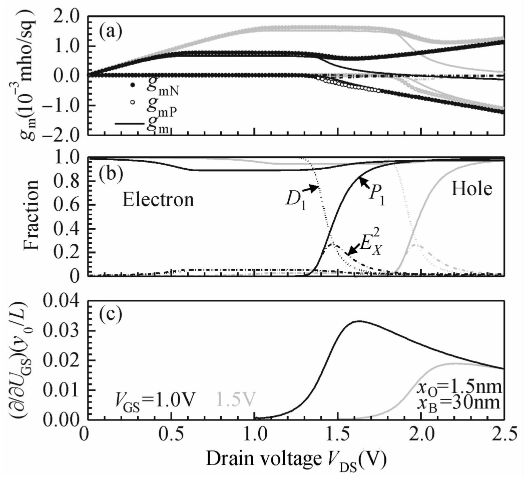

Fig. 7　The transconductance-drain-voltage characteristics at two $V_{GS} = 1.0V$, $1.5V$. (a) The total transconductance g_m and electron and hole drift and diffusion components; (b) The fractional electron or hole transconductance from the parabolic drift current P_1, linear diffusion current D_1, and $(\partial/\partial y)(E_X^2)$ current normalized to the total electron or hole transconductances g_{mN} or g_{mP}. (c) The derivative of emitter length $(\partial/\partial U_{GS})(y_0/L)$. The discontinuity at $V_{GS} = V_{DS}$ is not significant.

4.2　Gate-Oxide and Base Thickness Dependences

The V_{GS} and V_{DS} variations of the variables just shown in the six figures, Figs. 3～8, at $x_0 = 1.5$nm and $x_B = 30$nm, are given in six more figures in Figs. 9～14, for two base thicknesses, $x_B = 3$nm and 300nm and two oxide thickness, $x_O = 2$nm and 1nm.

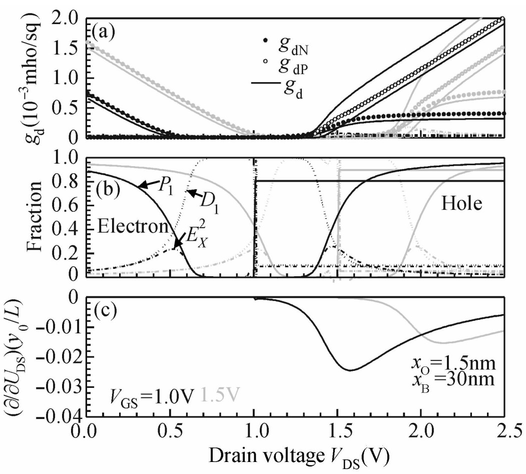

Fig. 8　The output-conductance-drain-voltage characteristics at two $V_{GS} = 1.0V$ and $1.5V$. (a) The total output conductance g_d and the electron or hole drift and diffusion components; (b) The fractional electron or hole output conductance from the parabolic drift current P_1, linear diffusion current D_1, and the $(\partial/\partial y)(E_X^2)$ current normalized to the total electron or hole output conductance g_{dN} or g_{dP}. (c) The derivative of emitter electrical length $(\partial/\partial U_{DS})(y_0/L)$. The discontinuity at $V_{GS} = V_{DS}$ is apparent.

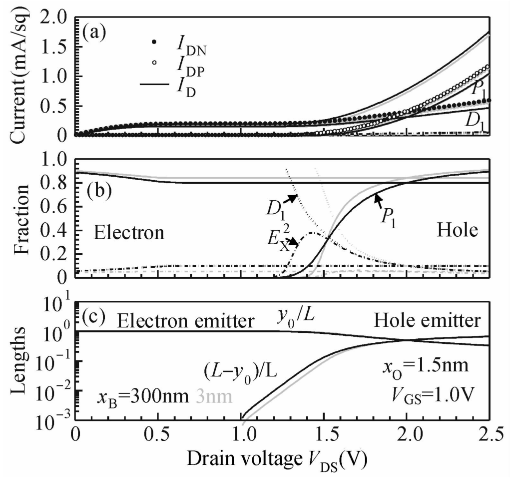

Fig. 9　The DC output current-voltage characteristics at two base thicknesses, $x_B = 300$nm and 3nm. (a) The total drain current I_D and electron or hole drift and diffusion channel current components; (b) The fractional parabolic electron or hole parabolic drift current P_1, linear diffusion current D_1, and the $(\partial/\partial y)(E_X^2)$ current, normalized to the total electron or hole channel currents, I_{DN} or I_{DP}. (c) The electron emitter electrical length y_0 and the hole emitter electrical length $(L - y_0)$.

4.3　Deviations of the Long Channel Solution from the Short Channel Solution

The deviations of the three components of drain current, transconductance and output conductance of the one-section long-channel BiFET theory[13] from the two-section short-channel BiFET theory are given in Figs. 15 and 16. In the one-section long-channel BiFET theory,

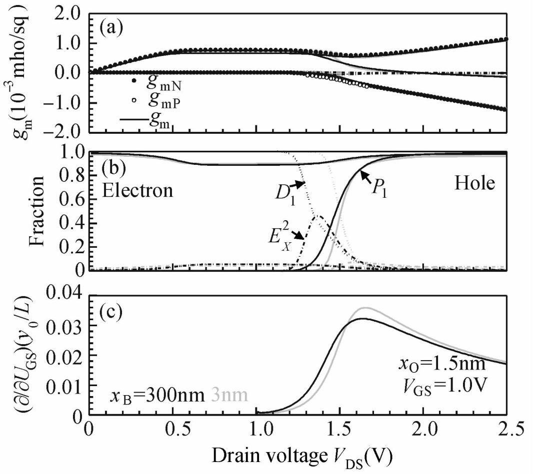

Fig. 10　Base thickness x_B dependence of the transconductance-drain-voltage characteristics. (a) The total transconductance g_m and electron and hole drift and diffusion components; (b) The fractional transconductance from the parabolic drift current P_1, linear diffusion current D_1, and the $(\partial/\partial y)(E_X^2)$ current, normalized to the total electron or hole transconductances g_{mN} or g_{mP}. (c) The derivative of emitter electrical length $(\partial/\partial U_{GS})(y_0/L)$. The discontinuity at $V_{GS} = V_{DS}$ is not significant.

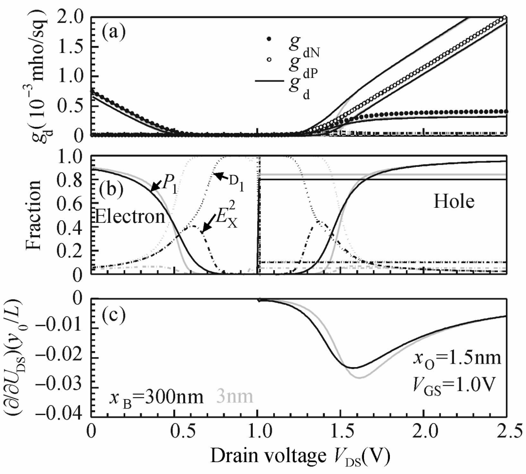

Fig. 11 Base thickness x_B dependence of the output-conductance-drain-voltage characteristics. (a) The total output conductance gd and electron and hole drift and diffusion components; (b) The fractional output conductance from the electron or hole parabolic drift current P_1, linear diffusion current D_1, and the $(\partial/\partial y)(E_X^2)$ current, normalized to the total electron or hole output conductances g_{dN} or g_{dP}. (c) The derivative of emitter length $(\partial/\partial U_{DS})(y_0/L)$. The discontinuity at $V_{GS} = V_{DS}$ is apparent.

the channel section lengths are taken as the physical base length L, not taking account of the shorten electrical lengths of both electron and hole emitters.

5 Summary

The electrically short channel is a universal intrinsic property of all field-effect transistors. Our previous-month paper[14] reported its effects using the electrochemical potential representation in which the drift and diffusion currents are combined into oneterm which is proportional to the electrochemical potential gradient. This paper reports the electrically short channel effects using the more popular and traditional representation in which the drift and the currents are each represented by its own term, the drift is proportional to the electric field and the diffusion is proportional to the concentration gradient. The electrically short channel increases the currents

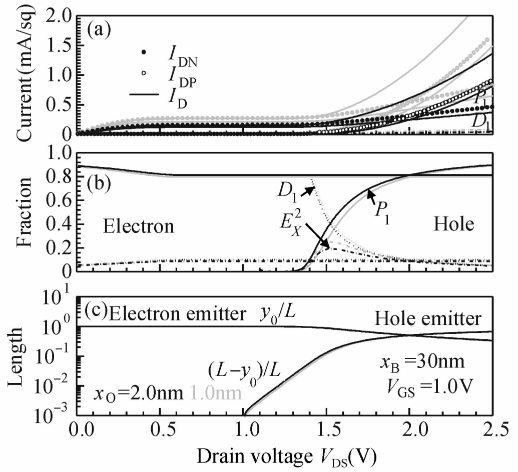

Fig. 12 Oxide thickness x_O dependence of the DC output current-voltage characteristics. (a) The total drain current I_D and the electron or hole drift and diffusion channel current components; (b) The fractional electron or hole parabolic drift current P_1, linear diffusion current D_1, and the $(\partial/\partial y)(E_X^2)$ current, normalized to the total electron or hole current, I_{DN} or I_{DP}. (c) The electron emitter length y_0 and the hole emitter length $(L - y_0)$.

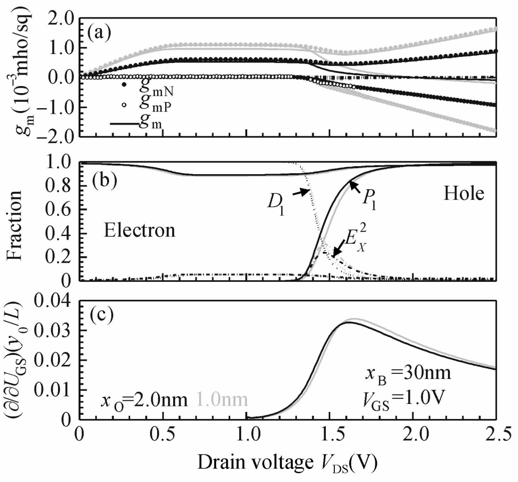

Fig. 13 Oxide thickness x_O dependence of the transconductance-drain-voltage characteristics. (a) The total transconductance g_m and electron and hole drift and diffusion components; (b) The fractional electron and hole transconductance from the parabolic drift current P_1, linear diffusion current D_1, and the $(\partial/\partial y)(E_X^2)$ current normalized to the electron or hole total transconductances g_{mN} or g_{mP}. (c) The derivative of emitter length $(\partial/\partial U_{GS})(y_0/L)$. The discontinuity at $V_{GS} = V_{DS}$ is not significant.

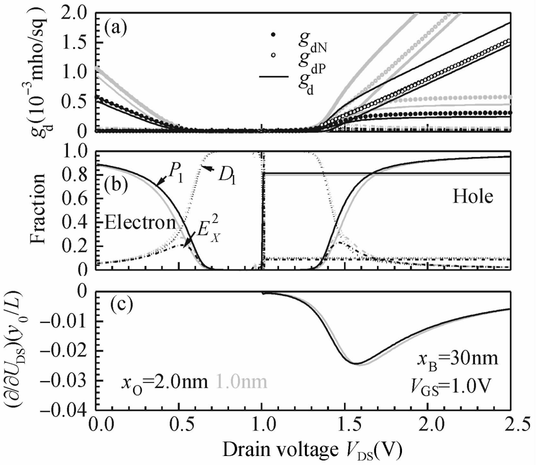

Fig. 14 Oxide thickness x_O dependence of the output-conductance-drain-voltage characteristics. (a) The total output conductance g_d and electron or hole drift and diffusion components; (b) The fractional electron or hole output conductance from the parabolic drift current P_1, linear diffusion current D_1, and the $(\partial/\partial y)(E_X^2)$ current, normalized to the total electron or hole output conductances g_{dN} or g_{dP}. (c) The derivative of emitter length $(\partial/\partial U_{DS})(y_0/L)$. The discontinuity at $V_{GS} = V_{DS}$ is apparent.

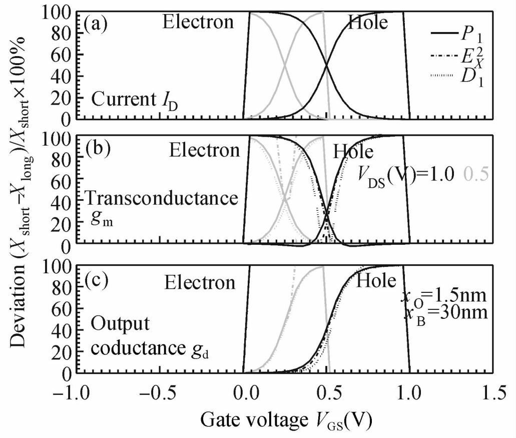

Fig. 15　Deviations of the BiFET long channel solution (X_{long}) from the BiFET short channel solution (X_{short}) versus the gate voltage. (a) The three components (parabolic drift current P_1, linear diffusion current D_1, and the drift $(\partial/\partial y)E_X^2$ current) of the electron channel current I_{DN} and the hole channel current I_{DP}; (b) The three components of the electron and hole transconductances g_{mN} and g_{mP}. (c) The three components of the electron and hole output conductances g_{dN} and g_{dP}.

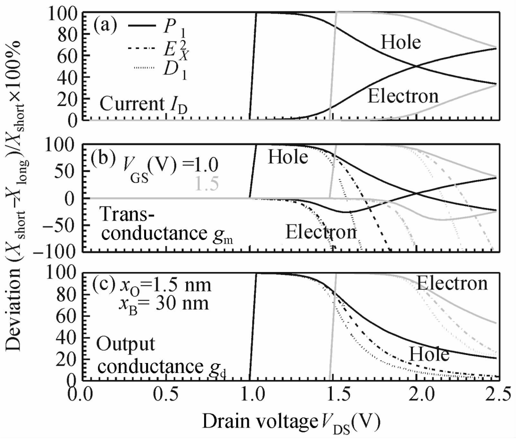

Fig. 16　Similar to Fig. 15, except versus the drain voltage.

and the conductances as anticipated and the general dependences on the voltages are maintained.

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双极场引晶体管:IV. 短沟道飘移扩散理论(双 MOS 栅纯基)*,**

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摘要：本文描述双极场引晶体管(BiFET)短沟道解析理论，用解析理论分别计算飘移扩散电流.上月文章用单项电化电流描述飘移扩散电流.正如那篇文章里，两维晶体管分成两个区域，源区和漏区.每区在特定外加端电压下既可为电子或空穴发射区又可为电子或空穴收集区.把两维无缺陷 Shockley 方程分离为两个以表面势为参变量的一维方程，并运用源区和漏区界面处电子电流和空穴电流连续性，得到在源区和漏区内解析方程.典型 BiFET 包括薄纯基上两个等同金属氧化物硅(MOS)栅.用图形提供实用硅基和氧化层厚度范围内，随直流电压变化，输出和转移电流和电导总量，电子沟道与空穴沟道飘移扩散分量，和两区电学长度.描述两区短沟道理论相对一区长沟道理论偏差.

关键词：双极场引晶体管理论；MOS 场引晶体管；同时并存空穴电子表面沟道 和体积沟道；表面势；两区短沟道理论；双栅纯基.
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