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<td>Author(s)</td>
<td>Chew, Kok Wai Johnny; Rofail, Samir S.; Yeo, Kiat Seng</td>
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A Temperature-Dependent DC Model for Quarter-Micron LDD pMOSFET’s Operating in a Bi-MOS Structure

Kok Wai Chew, Samir S. Rofail, Senior Member, IEEE, and Kiat Seng Yeo

Abstract—A temperature-dependent analytical model for deep submicrometer LDD p-channel devices operating in a Bi-MOS structure is reported for the first time. This model is based on experimental data obtained from 0.25-μm process wafers with a wide range of technologies (0.25–1.0 μm). The measurements have been performed within the temperature range 223–398 K (−50 °C to +125 °C). The model accounts for the effects of independently biasing the source, drain, gate and body potentials, scaling, and the influence of temperature on the threshold voltage and the device currents. The effect of temperature on the device transconductance and the output conductance have also been examined. The results revealed that close agreement between the analytical model and the experimental has been achieved. Comparisons between the principal MOS current and the lateral bipolar current have been made to demonstrate the improvement of the latter with temperature for the quarter-micron devices.

NOMENCLATURE

A LDD region fitting parameter.
A_{ipolar} Effective cross-sectional area for the bipolar current.
A_{space} Effective cross-sectional area for the space charge current.
C_{ox} Gate oxide capacitance per unit area.
\alpha_1 Coefficient 1 in the effective hole mobility model.
\alpha_2 Coefficient 2 in the effective hole mobility model.
\alpha_3 Coefficient 3 in the effective hole mobility model.
D_i Threshold adjust implant dosage per unit area.
D_p Hole diffusion constant.
\Delta E'_g Bandgap narrowing between source and body.
\epsilon_{ox} Permittivity of silicon dioxide.
\epsilon_{si} Permittivity of silicon.
\epsilon_{eff} Effective transverse electric-field.
E' Critical electric field.
E_g Bandgap energy.
E_F Fermi level of extrinsic semiconductor.
E_{Fi} Fermi level of intrinsic semiconductor.
\gamma Forward source-body effect factor.
\phi_s Surface potential of silicon.
\varphi Empirical parameter in defining \epsilon_{eff}.
g_{m1 Transconductance associated with the variation of the source-gate voltage.}
g_{m2 Transconductance associated with the variation of the source-body voltage.}
g_{nd Output conductance.}
h Planck constant.
\eta Drain-Induced Barrier Lowering parameter.
I_S Forward-bias saturation current of a pn junction.
I_{space} Space charge limiting current.
I_{mos} MOS current.
I_{ipolar} Lateral bipolar current.
I_{bbody} Body current.
\epsilon Bipolar current model parameter.
\epsilon_{s} (V_{SB}) Source-body bias dependent bipolar current parameter.
\epsilon_2(T) Temperature-dependent bipolar current parameter.
\lambda Source barrier height lowering fitting parameter.
k Boltzmann constant.
l_c Characteristic length.
L Device drawn channel length.
L_e Electrical channel length.
L_{eff} Device effective channel length.
L_{effav} Average effective channel length.
L_d Electrical channel length for the MOS current.
L_p Length of the LDD p-region.
\mu_1 Empirical parameter 1 in the effective hole mobility model.
\mu_2 Empirical parameter 2 in the effective hole mobility model.
\mu_3 Empirical parameter 3 in the effective hole mobility model.
\mu_{eff} Effective hole mobility.
\mu_{eff} Density-of-state effective mass for electrons.
\mu_{b Density-of-state effective mass for holes.
\mu_0 Electron mass at rest.
N_d Source/drain concentration.
N_{sub} LDD p-concentration.


I. INTRODUCTION

It is well known that bipolar transistors exhibit lower noise and higher speed performance as compared to MOSFET’s. However, MOS devices have lower power dissipation, higher packing density, and can operate at very low currents. Hybrid-mode devices, employing lateral pnp BJT in a pMOS structure, have been able to capitalize on the advantages of both type of devices. Hybrid-mode devices can also be referred to as devices in the Bi-MOS structure.

Hybrid-mode devices have received much attention in the past due to their high-performance and their availability without any additional processing steps [1]–[5]. In recent years, they have received renewed interest and have been frequently employed in CMOS/BiCMOS digital circuits for low-voltage applications [6]–[8], as well as in analog circuits [9]. An analytical model for deep submicrometer pMOSFET’s operating in a hybrid-mode environment has been reported [10]. However, the earlier model caters for quite a narrow range of technologies (0.4–0.7 μm) and did not address the effect of temperature on the hybrid-mode device performance. Its prediction for the ratio of the lateral bipolar current to the principal MOS current when the channel length scales to sub-half-micrometer (at room temperature and under high-level injection) has been verified in the present work. This work takes into consideration also the additional punchthrough implants in the well that accompanied scaling to suppress short-channel effects.

In this work, the interdependencies between temperature, scaling, the different biases, the threshold voltage and the various current components that flow in the hybrid mode have been investigated and the findings incorporated into the analytical equations. The model caters for a wide range of technologies (0.25–1.0 μm) and biases, and it is based on experimental data obtained from 0.25-μm process wafers. The significance of this work arises from the fact that it accounts for the realistic operating conditions of hybrid-mode devices.

The paper is organized as follows. In Section II, we describe how the devices are fabricated. Sections III–VI outline the models of the threshold voltage, the space-charge current, the lateral bipolar current and the MOS current respectively. Section VII summarizes the effect of temperature on the device transconductance and the output conductance.

II. DEVICE FABRICATION

The transistors used in our study have been fabricated using the 0.25-μm process flow. To counter short-channel effects, the dual-doped polysilicon gate approach utilizing surface p-channel transistors has been adopted. The retrograde twin-well process has been used to improve the isolation and increase the packing density. Transistor sizes ranging from 20 μm down to 0.25 μm are available for characterization.

The transistor formation begins with the deposition of a thick resist to cater for high energy well implants. The retrograde n-well for the p-transistors is formed by the implantation of phosphorus (2e13 cm⁻², 490 keV) tilted at 7° to minimize channeling effects [11]. The n-well junction depth is about 1 μm with a sheet rho of approximately 675 Ω/□. Following that is the p-channel punchthrough implant (5e12 cm⁻², 140 keV) and the p-channel threshold adjust implant (3e12 cm⁻², 70 keV). A 50 Å nitrided (N₂O) gate oxide is next grown. The N₂O gate oxide prevents the diffusion of dopants from the p⁺ polysilicon gate into the silicon. After the polysilicon gate definition, boron difluoride (BF₂) p-LDD implant (2e14 cm⁻², 20 keV) is subsequently carried out. The p-LDD junction depth is approximately 0.075 μm.

Next, LDD spacers are formed by the deposition of a 1500 Å tetraethylorthosilane (TEOS) liner, followed by anisotropic etchback. The p⁺ source and drain regions are formed using BF₂ (3e15 cm⁻², 30 keV) for shallower junction formation and anneal using a short thermal cycle. The p⁺ junction depth is approximately 0.15 μm with a sheet rho of approximately 100 Ω/□. Note that for surface p-channel transistors, the

\[ N_c \] Effective density of states in conduction band.
\[ N_v \] Effective density of states in valence band.
\[ n_i \] Intrinsic doping concentration of silicon.
\[ n_f \] Ideality factor.
\[ \phi_c \] Hole concentration at the edge of the source(emitter)/n-well junction.
\[ Q_d \] Depletion carrier density.
\[ Q_i \] Inversion carrier density.
\[ q \] Electronic charge.
\[ R_{well} \] Average well resistance.
\[ \rho_j \] LDD p-implant junction depth.
\[ T_{ox} \] Gate oxide thickness.
\[ T \] Temperature at which measurements are carried out.
\[ T_{C1} \] Temperature compensation factor 1.
\[ T_{C2} \] Temperature compensation factor 2.
\[ T_{nom} \] Ambient room temperature.
\[ v_{sat} \] Saturation velocity of the carriers.
\[ V_{bi} \] Built-in potential of the LDD p-/n-well regions.
\[ V_{jd} \] Junction potential between the source and the body.
\[ V_{jd} \] Junction potential between the drain and the body.
\[ V_t \] Thermal voltage.
\[ V_{FB} \] Flatband voltage.
\[ V_{SB} \] Source-body voltage.
\[ V_{S,B} \] Effective source-body voltage.
\[ V_{SD} \] Source-drain voltage.
\[ V_{S,S} \] Effective source-drain voltage.
\[ V_{SG} \] Source-gate voltage.
\[ V_{Teff} \] Effective threshold voltage.
\[ \Delta V_T \] Threshold voltage shift.
\[ V_{TO} \] MOSFET threshold voltage at \( V_{SD} \) and \( V_{SB} = 0 \) V.
\[ W \] Device channel width.
\[ \theta \] Charge-sharing factor.
\[ X_{dep} \] Depletion layer thickness.
\[ X_{dm} \] Depletion width at the drain’s surface.
\[ X_j \] P⁺ implant junction depth.
\[ X_s \] Depletion width at the source.
\[ X_d \] Depletion width at the drain.
polysilicon gate is initially undoped but will be heavily p-doped during the p-LDD, source and drain implants. The wafers have been processed to metal layer 1, etched and sent for electrical characterization. The device currents were extracted using the HP4142 semiconductor parametric analyzer interfaced with ICCAP version 5.0 in a HP workstation. The wafers were placed inside the micro-chamber of a Cascade probing system and the chamber temperature controlled to within \( \pm 0.1 \) °C using the Temptronics temperature controller. Fig. 1 shows an annotated SEM photomicrograph of the cross section of one of the devices fabricated.

### III. The Threshold Voltage Model

The threshold voltage model is formulated by extending the classical long-channel threshold voltage to account for short-channel effects that occur with the scaling of technology. The effects included are 1) charge-sharing, 2) drain-induced barrier lowering (DIBL), and 3) forward source-body effects. The experimental threshold voltages have been obtained using the transconductance peak method [12].

The proposed threshold voltage model including short-channel effects and temperature variations is given by

\[
V_{\text{eff}}(T = T_{\text{nom}}) = V_{\text{eff}}(T = T_{\text{nom}}) + (TC_1 + TC_2 V_{SB\text{eff}}) \left( \frac{T}{T_{\text{nom}}} - 1 \right)
\]

where

\[
V_{\text{eff}}(T = T_{\text{nom}}) = V_{TO} - \eta V_{SD\text{eff}} - \gamma V_{SB\text{eff}}
\]

\[
V_{TO} = -V_{FB} + \frac{qD_i}{C_{\text{ox}}} + \phi_s + \frac{\theta}{C_{\text{ox}}} \sqrt{2\kappa_{\text{Si}} V_{SB\text{eff}}} \phi_s
\]

\[
V_{FB} = \frac{E_p}{2} + \frac{\phi_s}{2}
\]

\[
\theta = 1 - \kappa \gamma
\]

\[
\kappa = 2 \kappa e^{-22L^2} + 53 \kappa e^{-0.4L}
\]

\[
\eta = 0.8 e^{-70L^2} + 0.25 e^{-10L}
\]

\[
\gamma = 0.5 (1 - e^{-10L^2}) - V_{SB} e^{-50L}
\]

\( L \) is in micrometers. The experimentally extracted DIBL factor showed its insensitivity to temperature. A similar finding has been reported in [16]. The forward source-body effect factor has also been found to be a weak function of temperature (experimental data to justify this will be shown later).

The effect of scaling coupled with DIBL and forward source-body effects at two different temperatures is shown in Fig. 2. The threshold rolloff for \( L < 0.4 \) \( \mu m \) is due to the severe charge-sharing effect of very short-channel devices. The graph reaffirms that the DIBL effect and the forward source-body effect are rather insensitive to temperature. The plot of the threshold voltage against temperature depicted in Fig. 3 also supports the latter claim. It can also be seen that the threshold voltage changes linearly with temperature for the two different channel lengths. It decreases with temperature due to Fermi level shifts [17]. Figs. 4 and 5 illustrate the match of the analytical threshold voltage model with the experimental data for the range of source-drain and source-body biases considered in the experiment.

The threshold voltage shift at room temperature is shown in Fig. 6. This shift is defined as

\[
\Delta V_T(T = T_{\text{nom}}) = \eta V_{SD} + \gamma V_{SB}
\]

\( T_{\text{nom}} \) and \( T_{\text{nom}} \) are in kelvins, and \( r_i \) and \( L \) are in micrometers. \( V_{TO} \) is the threshold voltage at zero drain and body biases and it contains the charge-sharing factor \( \theta \) to account for the lowering of the threshold voltage due to termination of the built-in field by the overlapping depletion regions of the source and drain junctions. The effective source-drain and source-body voltages represent the reduction in the applied voltages due to the LDD regions.

The DIBL factor and the forward source-body effect factor have been modeled using the methodology outlined in [10] and they are given by

\[
\eta = 0.8 e^{-70L^2} + 0.25 e^{-10L} \quad (2)
\]

\[
\gamma = 0.5 (1 - e^{-10L^2}) - V_{SB} e^{-50L} \quad (3)
\]

Fig. 6 records the percentage contribution of \( \eta V_{SD} \) and \( \gamma V_{SB} \) to the room temperature threshold voltage shift for each technology. For \( L = 0.25 \) \( \mu m \), at large source-drain bias and forward source-body bias, the DIBL effect and the forward source-body effect have approximately equal contributions in the reduction of the threshold voltage. But for \( L = 1.0 \) \( \mu m \), the DIBL effect is nonexistent and the forward source-body effect is the sole cause for the lowering of the threshold voltage.

The temperature-dependent threshold voltage shift is depicted in Fig. 7. \( \Delta V_{T1} \) is obtained by finding the difference between the threshold voltages at \( V_{SB} = 0.6 \) V and \( V_{SB} = 0.0 \) V for each temperature, and \( \Delta V_{T2} \) is found by subtracting the threshold voltage for each temperature from that at \( T_{\text{nom}} \) for a particular \( V_{SB} \). The data for \( \Delta V_{T1} \) confirms...
Fig. 2. Effect of scaling the channel length on the threshold voltage for two different $V_{SD}$, $V_{SB}$, and temperature values.

Fig. 3. Effect of temperature variation on the threshold voltage for two different $V_{SD}$ and channel lengths.

that the forward source-body effect is a weak function of temperature. The data for $\Delta V_{T2}$ reveals that the threshold voltage shift due solely to temperature is linear over the range of temperatures concerned.

IV. THE SPACE-CHARGE CURRENT MODEL

Due to the close proximity of the source and drain regions of deep submicrometer devices, the depletion regions of the two reverse-biased p-n junction can spread and eventually touch each other giving rise to punchthrough condition. For very short-channel devices, carriers from the source can surmount the source-body barrier height by thermionic emission and then be swept across from the source to the drain by the strong longitudinal electric field, hence constituting to space-charge current flow.

The space-charge current has been extracted using the methodology outlined in [10] and modeled as a function of temperature by [17]–[20]

\[
I_{\text{space}} = \frac{\alpha_{\text{space}} f_{\text{sat}} \mu_p V_{SD}^2}{I_{\text{eff}}^3} < V_{\text{sat}} \quad (5a)
\]
\[
I_{\text{space}} = \frac{\alpha_{\text{space}} f_{\text{sat}} V_{SD}^2}{I_{\text{eff}}^3} \geq V_{\text{sat}} \quad (5b)
\]
where [see (5c), shown at the bottom of the page]

\[
\alpha = 5.0 \times 10^{-14} \left( \frac{T}{49} \right) \quad \text{(5d)}
\]

\[
N_{\text{sub}} = 0.9121 \ n_{\text{c}} e^{E_F - E_F/kT} \quad \text{(5e)}
\]

\[
n_{\text{i}} = \sqrt{(N_{\text{c}} N_{\text{d}})} e^{-(E_g/2kT)} \quad \text{(5f)}
\]

\[
N_c = 2 \left( \frac{2 \pi m^* k^4}{h^2} \right)^{3/2} \times 10^{-6} \quad \text{(5g)}
\]

\[
N_v = 2 \left( \frac{2 \pi m^*_0 k^4}{h^2} \right)^{3/2} \times 10^{-6} \quad \text{(5h)}
\]

\[
\eta^* = (1.036 + 4.263 \times 10^{-4}T) \times \eta_0 \quad \text{(5i)}
\]

\[
\eta^*_0 = (0.58 + 7.72 \times 10^{-4}T) \times \eta_0 \quad \text{(5j)}
\]

\[
E_g = 1.170 \left( \frac{4.73 \times 10^{-4}T^2}{T + 288} \right) \quad \text{(5k)}
\]

\[
\eta_{\text{sat}} = \frac{6}{1 + 0.86e^{T/1000}} \quad \text{(5l)}
\]

\[
\mu_p = 54.3 \left( \frac{T}{T_{\text{nom}}} \right)^{-0.57} + \frac{1.36 \times 10^8 T^{-2.23}}{1 + \left( \frac{N_{\text{sub}}}{2.35 \times 10^{17} \left( \frac{T}{T_{\text{nom}}} \right)^{-2A}} \right)^{0.88} \times \left( \frac{T}{T_{\text{nom}}} \right)^{-0.46}} \quad \text{(5c)}
\]
Fig. 8. Effect of varying $V_{SD}$ and temperature on the space-charge current of the quarter-micron device.

Fig. 9. Effect of temperature variation on the space-charge current of the quarter-micron device for different $V_{SD}$. However, a slight decrease in the analytical value of the space-charge current can be observed at room temperature. This is due to the two competing exponential terms in the $N_{stab}$ equation [see (5e) and (5f)]. The intrinsic carrier concentration, increases with temperature, whereas the term $e^{E_F-E_F/kT}$ decreases with temperature. As a result, there is an unexpected peak in $N_{stab}$ at room temperature. This phenomenon will affect all other current components, as well as the conductances.

V. THE LATERAL BIPOLAR CURRENT MODEL

Under forward source-body bias, high source-drain bias and for very short-channel lengths, lateral bipolar action occurs beneath the channel region [9]. Rofail and Yeo [10] have explained the need to model this secondary current component and have modeled the lateral bipolar current using a modified transport equation. This model has been extended in the present work to quarter-micron devices and the effect of temperature variations taken into consideration as follows:

$$I_{bipolar} = \frac{q\mu_d V_l P_{A_{bipolar}}}{L_e(1 - \xi)} \left(1 - e^{-\xi L_e V_{ext}/D_p}\right)$$

(6a)

where

$$\xi = \xi_1(V_{SB}) \xi_2(T) \frac{V_{SBeff}}{V_{SBeff} + 1.6 \times 10^{-9} e^{-400L}}$$

(6b)

$$\xi_1(V_{SB}) = 1 - e^{-12.1(14(\Delta P/L_3)V_{SB})}$$

(6c)

$$\xi_2(T) = 0.755 + 0.245\left(1 - e^{-0.418(6.21 - (T/100))^{1.25}}\right)$$

(6d)

$T$ is in kelvins, and $L_e$ is in micrometers. $\xi$ is a semi-empirical factor encompassing the effects of source-drain and source-body biases, device technology, and temperature. At room temperature, it approaches unity at high source-drain and source-body biases and for shorter channel lengths. When the temperature increases from 223 to 398 K, $\xi$ decreases gradually from the unity asymptote.

Increasing the source-drain bias has a modulating effect on the lateral bipolar current as illustrated in Fig. 10. Fig. 11 shows that the bipolar current increases exponentially with temperature such that at higher temperatures and larger source-body biases, the lateral bipolar current is comparable to the principal MOS current. For $V_{SB} = 0.8$ V and $T = 398$ K, the ratio of the experimental lateral bipolar current to the experimental MOS current is approximately 1/16. This phenomenon can be explained by the fact that an increase in the operating temperature will cause 1) the intrinsic carrier densities to increase, 2) the bandgap energies to decrease, and 3) the carrier mobility to decrease. The first two effects overwhelm the last thus resulting in an overall increase in the lateral bipolar current with temperature. Furthermore, it has been reported in [1] that the injection barrier for holes in a hybrid-mode lateral BJT is given by

$$\psi_{Bh} = \left(V_{BE} - \frac{\Delta E_F}{q}\right) - V_{SB}.$$  

(7)

Equation (7) suggests that the hole injection barrier in hybrid-mode devices decreases with temperature.

Fig. 12 depicts the effect of temperature coupled with scaling on the lateral bipolar gain, which is defined by

$$\text{Lateral Bipolar Gain} = \frac{I_{bipolar}}{I_{body}}.$$  

(8)

$I_{bipolar}$ is the collector current of the lateral pnp transistor, whereas $I_{body}$ is the base current. The gain is fractional because of the addition of the p-channel punchthrough implant during the transistor formation. This implant will impede the flow of carriers in the vicinity of the active region by increasing the rate of recombination. However, the implant is necessary to suppress short-channel effects in 0.25-μm CMOS process.
Fig. 10. Effect of variation of $V_{SD}$ on the lateral bipolar current for two different channel lengths and temperature values.

Fig. 11. Comparison of the effects of temperature variation on the MOS and lateral bipolar currents of the quarter-micron device for different $V_{SD}$.

VI. THE MOS CURRENT MODEL

Much work has already been done to model the effect of temperature on the carrier mobility of MOSFET’s [21]–[23]. The piecewise MOS current model employed in [10] has been extended to quarter-micron devices with the temperature effects taken into consideration. The recent work on a temperature-dependent MOSFET inversion layer carrier mobility model for device and circuit simulation [24] has been adopted to account for the major scattering mechanisms in the MOSFET inversion layer. This is given by

$$\frac{1}{\mu_{\text{eff}}} = \frac{1}{\mu_1} \left( \frac{10^6}{E_{\text{eff}}} \right)^{\alpha_1} + \frac{1}{\mu_2} \left( \frac{10^6}{E_{\text{eff}}} \right)^{\alpha_2}$$

$$+ \frac{1}{\mu_3} \left( \frac{10^{16}}{N_{\text{sub}}} \right)^{-\varphi} \left( \frac{10^{-12}}{Q_{\text{inv}}} \right)^{\alpha_3} \quad (9a)$$

$$E_{\text{eff}} = \frac{1}{C_{\text{dl}}} (Q_{\text{dep}} + \varphi Q_{\text{inv}}) \quad (9b)$$

$$Q_{\text{dep}} = \sqrt{2q\Phi_{\text{SN}}N_{\text{sub}}(\Phi_{\text{S}} - V_{\text{SB}})} \quad (9c)$$

$$Q_{\text{inv}} = C_{\text{ox}}(V_{\text{SG}} - V_{\text{TB}}) \quad (9d)$$

$$\varphi = 0.42 - 2.9 \times 10^{-4}T. \quad (9e)$$

$T$ is in kelvins. Fig. 13 demonstrates that a reasonably good agreement between the experimental data and the analytical model of the MOS current has been achieved for a wide range of technology in the triode and saturation regions for temperatures of 223 and 398 K. Fig. 14 illustrates that the MOS current decreases with temperature. In the triode region, devices with channel lengths of 0.25 and 1.0 $\mu$m show approximately equal enhancement (2–4 $\mu$A/K) of the drain current when the temperature reduces from 398 K to 223 K. This is due to the common sensitivity of the carrier mobility to temperature. In the saturation region, although the saturation velocity is relatively insensitive to temperature and has been reported to increase by only 30% [17], the effect of a greater reduction in the electrical channel length of the MOS current $L_d$ for $L = 0.25 \mu$m results in approximately 6 $\mu$A/K increase in the MOS current with lower temperature. In retrospect, the gradual decline in the MOS current with temperature can be compensated for by the exponential increase in the lateral bipolar current shown earlier in Fig. 11. At higher temperatures and larger source-body bias, the bipolar current will have approximately the same order of magnitude as the MOS current, thereby complimenting the MOS current in enhancing the overall device performance.

VII. THE DEVICE PARAMETERS

A. The Device Transconductance

For a MOSFET operating in a hybrid-mode environment, its device transconductance can be written as

$$\Delta I_{SD} = g_{m1}\Delta V_{SG} + g_{m2}\Delta V_{SB} \quad (10a)$$
where

\[ g_{m1} = \frac{\delta I_{SD}}{\delta V_{SG}} \] at constant \( V_{SB} \) and \( V_{SD} \) \hspace{1cm} (10b)

\[ g_{m2} = \frac{\delta I_{SD}}{\delta V_{SB}} \] at constant \( V_{SB} \) and \( V_{SD} \) \hspace{1cm} (10c)

\[ \frac{\delta I_{SD}}{\delta V_{SG}} = \frac{\delta I_{moe}}{\delta V_{SG}} + \frac{\delta I_{space}}{\delta V_{SG}} \] \hspace{1cm} (10d)

\[ \frac{\delta I_{SD}}{\delta V_{SB}} = \frac{\delta I_{moe}}{\delta V_{SB}} + \frac{\delta I_{spoke}}{\delta V_{SB}} + \frac{\delta I_{space}}{\delta V_{SB}} \] \hspace{1cm} (10e)

The expressions for the derivatives are shown in Appendix A.

Fig. 15 shows the effect of temperature on \( g_{m1} \) in the triode and saturation regions for \( L = 0.25 \mu m \) and \( L = 1.0 \mu m \). The plot shows that \( g_{m1} \) of the quarter-micron device increases by approximately 2.2 and 1.5 \( \mu A/K \) in the saturation and triode regions respectively, when the temperature reduces from 398 K to 223 K. For \( L = 1.0 \mu m \), the respective rates are 1.5 \( \mu A/K \) and 0.67 \( \mu A/K \). This is in agreement with the explanation stated in the previous section for the variation of the MOS current with temperature.

Fig. 16 illustrates the variation of \( g_{m2} \) with temperature. As evident from the graph, \( g_{m2} \) in general increases with temperature. Furthermore \( g_{m2} \) in the triode region is larger than \( g_{m2} \) in the saturation region. This is because in the triode region the output resistance is relatively smaller, hence the drain current has a strong dependence on both the drain and the body potentials. In the saturation region, when the velocity
of the carriers start to saturate, this dependence begins to diminish.

B. The Device Output Conductance

The output conductance of a MOSFET operating in a hybrid-mode environment is given by

\[
\begin{align}
g_{\text{os}} &= \frac{\delta I_{SD}}{\delta V_{SD}} \quad \text{at constant } V_{SG} \text{ and } V_{SB} \quad (11a) \\
\frac{\delta I_{SD}}{\delta V_{SD}} &= \frac{\delta I_{\text{pace}}}{\delta V_{SD}} + \frac{\delta I_{\text{bipolar}}}{\delta V_{SD}} + \frac{\delta I_{\text{space}}}{\delta V_{SD}}. \quad (11b)
\end{align}
\]

The expressions for the derivative are shown in Appendix B.

The effect of temperature on $g_{\text{os}}$ in the triode and saturation regions for $L = 0.25 \ \mu m$ and $L = 1.0 \ \mu m$ is shown in Fig. 17. The results reveal that scaling the channel length to $0.25 \ \mu m$ increases the saturation output conductance by approximately 1 order of magnitude. This is due to the nonsaturation of the drain current for the quarter-micron devices and is desirable in digital applications for faster switching. On the other hand, the lowering of temperature brings about very minimal increase in the saturation output conductance for $L = 0.25 \ \mu m$.

VIII. CONCLUSIONS

A model has been presented to account for the various short-channel effects and the influence of temperature on pMOSFET’s in a Bi-MOS structure fabricated using the 0.25-$\mu m$ CMOS process. It caters for a wide range of technologies and biases.

The threshold voltage has been modeled as two components: one which includes short-channel effects and another being the temperature compensation term. The threshold voltage decreases with temperature due to Fermi level shifts. DIBL and forward source-body effects have been found to be weak functions of temperature. The forward source-body effect dominates for $L = 1.0 \ \mu m$, whereas both the DIBL effect and the forward source-body effect are comparable for $L = 0.25 \ \mu m$. The threshold voltage shifts linearly with temperature. Both the space-charge and the lateral bipolar currents have been found to be direct exponential functions of temperature. On the contrary, the MOS current decreases linearly with temperature. Hence, operating the transistor at higher temperature would mean degrading the MOS current and greater leakage at zero gate bias. On the other hand, elevated temperatures are able to increase the lateral bipolar current to approximately the same order of magnitude as the principal MOS current. For $V_{SB} = 0.8 \ \text{V}$ and $T = 308 \ \text{K}$, the ratio of the experimental lateral
bipolar current to the experimental MOS current of the quarter-micron device is approximately 1/16. This secondary current component can be utilized to enhance the switching speed of the transistor. In general, the transconductance associated with the variation of the source-gate voltage, and the output conductance, decrease with higher temperature. On the other hand, the transconductance associated with the variation of the source-body voltage, exhibits the opposite trend due to the exponential increase of the lateral bipolar and space-charge currents.

**APPENDIX A**

**DEVICE TRANSCONDUCTANCE**

\[
\frac{\delta I_{\text{space}}}{\delta V_{SG}} = 0
\]

\[
\frac{\delta I_{\text{bbeff}}(\text{tri})}{\delta V_{SB}} = \frac{I_{\text{bbeff}}(\text{tri})}{\left(1 + \frac{\Lambda L_p}{L_c}\right)\left(1 + \frac{V_{SD} - V_{TN}}{E_c L_c}\right)}
\]

\[
\left\{ X_1 \rho_{eff} - \frac{2V_{Sat}X_2 V_{SD} L_{eff}}{1 + \frac{V_{SD} - V_{TN}}{E_c L_c}} \frac{(E_c L_c)^2}{(X_2 V_{SD} L_{eff})^2}
\right. \\
\left. + \frac{1}{V_{SG} - V_{TN} - \frac{1}{2} V_{SD}} \right\}
\]

[and see (A2), shown at the top of the next page]

\[
X_1 = \frac{\alpha_1}{\mu_1} \left( \frac{10^6}{E_{eff}} \right) \left( \frac{E_{eff}}{E_{eff}} \right) \left( \frac{10^{12}}{Q_{inv}} \right)
\]

\[
X_2 = \frac{\alpha_1}{\mu_1} \left( \frac{10^6}{E_{eff}} \right) \left( \frac{E_{eff}}{E_{eff}} \right) \left( \frac{10^{12}}{Q_{inv}} \right)
\]

\[
X_3 = TC \left( \frac{T}{T_{nom}} - 1 \right) - \gamma
\]

\[
X_4 = \frac{V_{SB} - V_{TN}}{Q_{dep}}
\]
\[
\frac{\delta I_{\text{mos(sat)}}}{\delta V_{SG}} = I_{\text{mos(sat)}} \left\{ \frac{(V_{SG} - V_{Teff}) \left[ 1 + \frac{E_c L_d}{V_{SG} - V_{Teff}} + 2 \lambda \eta_{\text{sat}} X_1 L_d \right] + E_c L_d}{(V_{SG} - V_{Teff})^2 \left[ 1 + \frac{E_c L_d}{V_{SG} - V_{Teff}} \right]} \right\}
\]

\[
\frac{\delta I_{\text{mos(sat)}}}{\delta V_{SB}} = I_{\text{mos(sat)}} \left\{ \frac{1 + \frac{E_c L_d}{V_{SG} - V_{Teff}}}{(1 + \frac{\Delta L_p}{L_c})(1 + \frac{E_c L_d}{V_{SG} - V_{Teff}})} \right\} \left\{ \frac{1 + \frac{E_c L_d}{V_{SG} - V_{Teff}}}{1 + \lambda V_{SBeff} - \frac{X_3}{V_{SG} - V_{Teff}}} \right\}
\]

\[
X_5 = C_{\text{ox}} \left\{ \gamma - V_{SBeff} e^{-\frac{\Delta L_p}{L_c}} \left( 1 + \frac{\Delta L_p}{L_c} \right) \right\} - TC_2 \left( \frac{T}{T_{\text{nom}}} - 1 \right)
\]

\[
X_d^* = X_d \left[ 1 + \frac{I_s R_{\text{well}}}{n_j V_t} e^{\frac{\varphi V_{T}}{n_j V_t}} \right]
\]

\[
\frac{\delta I_{\text{space}}}{\delta V_{SB}} = 0.
\]

**Appendix B**

**Device Output Conductance**

\[
\frac{\delta I_{\text{mos(tri)}}}{\delta V_S} = \frac{I_{\text{mos(tri)}}}{(1 + \frac{\Delta L_p}{L_c})(1 + \frac{V_{SDeff}}{E_c L_d})}
\]

\[
\left\{ \left( 1 + \frac{V_{SDeff}}{E_c L_d} \right)(\eta C_{\text{ox}} h_{\text{eff}} X_8 + \frac{1}{V_{SG} - V_{Teff} - \frac{1}{2} V_{SDeff}} + \frac{1}{V_{SDeff} - 2 \lambda \lambda \eta C_{\text{ox}} X_8 V_{SDeff} L_{\text{eff}} + E_c L_d}) \right\}
\]

\[
X_8 = \frac{\alpha_1}{\mu_1} \left( \frac{10^6}{E_{\text{eff}}} \right)^{\alpha_1-1} \left( \frac{\varphi 10^6}{E_{\text{eff}}} \right) + \frac{\alpha_2}{\mu_2} \left( \frac{10^6}{E_{\text{eff}}} \right)^{\alpha_2-1}
\]

\[
\left\{ \frac{\varphi 10^6}{E_{\text{eff}}} + \frac{\alpha_2}{\mu_3} \left( \frac{10^6}{N_{\text{sub}}} \right)^{\alpha_2-1} \left( \frac{10^6}{Q_{inv}} \right) \right\}
\]

\[
\frac{\delta I_{\text{mos(sat)}}}{\delta V_{SD}} = \frac{I_{\text{mos(sat)}}}{(1 + \frac{\Delta L_p}{L_c})(1 + \frac{E_c L_d}{V_{SG} - V_{Teff}})} \left\{ \left( 1 + \frac{E_c L_d}{V_{SG} - V_{Teff}} \right)(\frac{V_{SG} - V_{Teff}}{V_{SG} - V_{Teff}}) \right\}
\]

\[
\frac{E_c \xi_{\text{si}}}{q \eta_{\text{sat}} X_d n_{dm} X_5} + 2 \lambda \lambda \eta_{\text{sat}} \xi_{\text{f}} X_8 L_d \right) + E_c \lambda \eta \right\}
\]

\[
\frac{\delta I_{\text{mos(sat)}}}{\delta V_{SD}} = \frac{I_{\text{mos(sat)}}}{(1 + \frac{\Delta L_p}{L_c})(1 + \frac{E_c L_d}{V_{SG} - V_{Teff}})} \left\{ \left( 1 + \frac{E_c L_d}{V_{SG} - V_{Teff}} \right)(\frac{V_{SG} - V_{Teff}}{V_{SG} - V_{Teff}}) \right\}
\]
\[
\frac{\delta I_{\text{space}}}{\delta V_{SD}} = \frac{2I_{\text{space}}}{V_{\text{SDoff}} \left( 1 + \frac{\Lambda P}{L_c} \right)} \quad \text{for} \quad \mu_{\text{F}} \frac{V_{\text{Ssat}}}{L_{\text{eff}} v_{\text{sat}}} < \frac{1}{V_{\text{Ssat}}}.
\]

\[
\frac{\delta I_{\text{space}}}{\delta V_{SD}} = \frac{I_{\text{space}}}{V_{\text{SDoff}} \left( 1 + \frac{\Lambda P}{L_c} \right)} \quad \text{for} \quad \mu_{\text{F}} \frac{V_{\text{Ssat}}}{L_{\text{eff}} v_{\text{sat}}} \geq \frac{1}{V_{\text{Ssat}}}. \quad \text{(B7b)}
\]

Acknowledgment

The authors would like to sincerely thank C. H. Gan and L. Chan of Chartered Semiconductor Manufacturing (CSM) of Singapore for their advice and support in the fabrication of the test wafers.

References


Kok Wai Chew received the B.Eng. degree in electrical engineering (honors) and the M.Eng. degree (by research) from the Nanyang Technological University, Singapore, in 1996, and 1999, respectively. He is currently with Chartered Semiconductor Manufacturing Ltd, Singapore, working on CMOS technologies for high-frequency applications. His research interests include the characterization and modeling of deep submicrometer devices for low-voltage, low-power applications and both active and passive components for high-frequency applications.
Samir S. Rofail (S’74–M’78–SM’83) received the B.Sc. degree in electrical engineering from Cairo University, Cairo, Egypt, and the B.Sc. degree in mathematics from Ain Shams University, Benha, Egypt, in 1971 and 1973, respectively. He received the M.A.Sc. and the Ph.D. degrees, both in electrical engineering, from the University of Waterloo, Waterloo, Ont., Canada, in 1975 and 1978, respectively.

He has been involved in teaching, research, and consultancy in the areas of semiconductor devices and integrated circuits for the last 20 years. He worked for Cairo University from 1971 to 1973 and for the University of Waterloo as a Teaching and Research Assistant from 1973 to 1978. He held faculty positions in the United States, Canada, Saudi Arabia, and Singapore. From 1990 to 1992, he was with the VLSI Group of the University of Waterloo working on the modeling and design of BiCMOS digital circuits. He has been with Nanyang Technological University (NTU), Singapore since 1992, where he is currently the coordinator of the IC-Design Group. At NTU, he led an intensive research activity with a primary focus on low-voltage, low-power BiCMOS/CMOS circuits. His research interests also include the modeling of deep submicrometer MOSFET’s, and high-performance VLSI circuits. He serves as a technical reviewer for several international journals and has published more than 40 journal papers, several of which are on IC-design for low-power applications. He is the principal author of the book Low-Voltage, Low-Power BiCMOS Digital Circuits, Circuit Design, Comparative Study, and Sensitivity Analysis (Englewood Cliffs, NJ: Prentice-Hall, 1999)

Prof. Rofail is listed in Who’s Who in the World.

Kiat Seng Yeo received the B.Eng. degree (honors) and the Ph.D. degree in electrical engineering from Nanyang Technological University, Singapore.

Since 1993, he has been with Nanyang Technological University, where he is currently a member of the faculty at the School of Electrical and Electronic Engineering. Previously, he was with Toshiba and STMicroelectronics. He has many years of teaching and research experience in integrated circuit design. He gives consultancy to statutory boards and multinational corporations in the areas of semiconductor devices and electronic circuit design. He has been extensively involved in the modeling and fabrication of small MOS/Bipolar integrated technologies for the last six years. His research interests also include the design of new circuits and systems (based on scaled technologies) for low-voltage, low-power applications, integrated circuit design of CMOS/BiCMOS multiple-valued logic circuit, domino logic, and memories, and device characterization of deep submicrometer MOSFET’s. He authored the book Low-Voltage Low-Power Digital BiCMOS Circuits (Englewood Cliffs, NJ: Prentice-Hall, 1999), holds one patent, and published numerous articles on CMOS/BiCMOS technology and integrated circuit design in leading technical journals worldwide. He is a Technical Reviewer for several international journals.

Dr. Yeo was awarded a book prize in 1992 for excellent academic achievements.