Temperature-Dependent Kink Effect Model for Partially-Depleted SOI NMOS Devices

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Abstract—This paper reports a closed-form analytical temperature-dependent kink effect model for the partially-depleted SOI NMOS devices. Based on the body-emitter voltage model, an analytical triggering V_{DS} formula for temperature-dependent kink effect has been obtained. According to the analytical model, at a higher operation temperature and with a lighter thin-film doping density, the onset of the kink effect occurs at a larger V_{DS} .

I. INTRODUCTION

Partially-depleted SOI NMOS devices have been intensively studied [1]–[3]. Due to the floating body structure, kink effect is an important phenomenon for partially-depleted SOI NMOS devices. The kink effect can be explained as follows. In partially-depleted SOI NMOS devices, owing to the existence of the neutral region in the body, the source-body potential barrier is large. Therefore, the generated holes due to impact ionization are easily trapped in the body. Consequently, the potential barrier between the source and the body decreases. The hole current generated by impact ionization flows from body to source. Due to the increase in the body potential, the threshold voltage changes depending on the drain bias—the kink effect [4], [5]. Recently, CMOS circuits such as dynamic logic gates, frequency dividers, and operational amplifier realized by SOI CMOS devices operating at an elevated ambient temperature have been reported [6]. Analysis of the SOI MOS devices operating at an elevated ambient temperature has also been reported [7]–[9]. At an elevated ambient temperature, kink effect is still important. Analysis of the kink effect for the partially-depleted SOI NMOS device has been reported [9]. However, it's not closed-form. In order to gain insights, a closed-form analytical temperature-dependent kink effect model is derived in this paper. In the following sections, the closed-form analytical model is derived first, followed by the model verification and discussion.

II. MODEL DERIVATION

For a partially-depleted SOI NMOS operating at high temperature, biased in the saturation region there are unsmooth transitions in the drain current due to impact ionization. This is the so-called kink effect [4], [5]. At any operating temperature, at the kink, the body-emitter voltage of the parasitic bipolar device (V_{BE}), which is the difference in the quasi-Fermi potential across the body-emitter junction [10] ($V_{BE} = \phi_p - \phi_n$, where ϕ_p and ϕ_n are the hole and the electron quasi-Fermi potential at the body-emitter junction, respectively), has an abrupt change. The sudden increase in the body-emitter voltage at the kink in the saturation region is due to the accumulated holes caused by the injection of the hole current generated by impact ionization. At an elevated operating temperature, the kink effect is reduced. In

this section, the temperature-dependent kink effect model is derived. In the following derivation, the temperature-dependent models for intrinsic concentration, electron mobility, generation/recombination lifetimes, and impact ionization are described subsequently, followed by the temperature-dependent current conduction mechanism.

A. Temperature-Dependent Parameters

For a partially-depleted SOI NMOS device, due to the neutral region in the thin film, it can be regarded as a combination of the MOS in top portion and the parasitic BJT in the bottom portion of the thin-film. When deriving the temperature-dependent model, both the top MOS and bottom parasitic bipolar effects should be included. There are four key temperature-dependent parameters used in the partially-depleted SOI NMOS device: intrinsic concentration, electron mobility, generation/recombination lifetimes, and impact ionization coefficients.

1) *Intrinsic Concentration*: When the operating temperature rises, the bandgap of the silicon narrows. As a result, the intrinsic concentration increases. The temperature-dependent intrinsic concentration can be expressed as [11]

$$E_g = 1.17 - \frac{4.73 \times 10^{-4} T^2}{T + 636} \quad (1)$$

$$n_i = 4.9 \times 10^{15} \left(\frac{m_n m_p}{m_o^2} \right)^{0.75} T^{1.5} \exp\left(\frac{-E_g}{2kT}\right) \quad (2)$$

where k is the Boltzmann's constant, T is the operating temperature in Kelvins, m_n and m_p are the effective mass of the electron and the hole, respectively ($m_n = m_o(1.034 + 5.826 \times 10^{-4} T - 2.826 \times 10^{-7} T^2)$, $m_p = m_o(0.552 + 1.1 \times 10^{-3} T - 7.769 \times 10^{-7} T^2)$) [12]. When the intrinsic concentration varies as the operating temperature rises, the related Fermi-potential and the depletion width in the device may change.

2) *Electron Mobility*: Electron mobility is dependent on the doping density and the operating temperature. Considering the surface reduction factor (g_s) due to the surface scattering effect, the temperature-dependent electron mobility can be expressed as a function of the lattice mobility (μ_l) and the impurity mobility (μ_i) as [13]

$$\begin{aligned} \mu_{eff} &= g_s \left(\frac{1}{\mu_l} + \frac{1}{\mu_i} \right)^{-1} \\ \mu_l &= \mu_{l0} \left(\frac{T}{300} \right)^{-2.2} \\ \mu_i &= \frac{AT^{1.5}}{N_A} \left[\ln \left(1 + \frac{BT^2}{N_A} \right) - \frac{BT^2}{N_A + BT^2} \right]^{-1} \end{aligned} \quad (3)$$

where $A = 3.5 \times 10^{17} \text{ cm}^{-1} \text{ V}^{-1} \text{ s}^{-1} \text{ k}^{-\frac{3}{2}}$ and $B = 1.52 \times 10^{15} \text{ cm}^{-3} \text{ k}^{-2}$ are dependent on the doping density. From simulation results, the surface reduction factor due to the surface scattering effect is $g_s = 0.5$. At an elevated operating temperature, the lattice mobility (μ_l), which is the dominant factor, decreases.

3) *Generation/Recombination Lifetimes*: For a bipolar device, the generation/recombination lifetimes are important. In the bipolar device, the electron lifetime in the neutral region (τ_n), the generation lifetime (τ_g) and the recombination lifetime (τ_r) in the depletion region affect the leakage current of the device. The temperature-

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dependent electron lifetime, generation lifetime, and recombination lifetime can be expressed as [14]

$$\begin{aligned}\tau_n &= \tau_{n0} \left(\frac{T}{300} \right)^{2.2} \\ \tau_r &= 2\tau_{n0} \left(\frac{T}{300} \right)^{2.5} \\ \tau_g &= a_\tau T^{2.55} \cosh \left(\frac{b_\tau}{T} \right)\end{aligned}\quad (4)$$

where τ_{n0} is the electron lifetime at 300 K and $a_\tau = 3.5 \times 10^{-17}$ and $b_\tau = 20$ are process-dependent parameters. When the operating temperature rises, the lifetimes increase. Consequently, the diffusion length $L_{eB} = \sqrt{\frac{kT}{q} \mu_{eff} \tau_n}$ is affected.

4) *Impact Ionization Coefficient*: For a partially-depleted SOI NMOS device biased in the saturation region, impact ionization in the front channel and the back channel with a high electric field is important. Considering the temperature-dependent impact ionization effect, the multiplication factors of the front channel and the back channel are

$$\begin{aligned}M &= 1 + \frac{\alpha}{\beta} (V_{DS} - V_{DSAT}) \exp \left(\frac{-\beta l}{(V_{DS} - V_{DSAT})} \right) \\ M_B &= 1 + \frac{\alpha_b}{\beta_b} (V_{DS} + \phi_{bi}) \exp \left(\frac{-\beta_b l_b}{(V_{DS} + \phi_{bi})} \right)\end{aligned}\quad (5)$$

where $l = \sqrt{\frac{t_{ox1} x_c}{\epsilon_{ox}/\epsilon_{si}}}$, $x_c = \sqrt{\frac{2\epsilon_{si} 2\phi_f}{qN_A}}$, $l_b = F_c \sqrt{\frac{2\epsilon_{si} V_{DS}}{qN_A}}$, ϵ_{si} is the permittivity of the silicon, ϵ_{ox} is the permittivity of the oxide, t_{ox1} is the thickness of the front gate oxide, F_c is a fitting parameter [4], [5], and $\phi_{bi} = \frac{kT}{q} \ln \frac{N_A N_D}{n_i^2}$ is the built-in voltage. $\alpha = 1 \times 10^6$. $\beta = 2.8 \times 10^6 + 1.8 \times 10^3 T$. When the operating temperature is elevated from the room temperature, the travelling electron in the channel is subject to an increase in thermal scattering. As a result, the capability of producing electron-hole pairs owing to collision with lattice is reduced. Therefore, the multiplication factors (M , M_B) are lowered when the operating temperature is increased. Note that in the above equations, α , β , α_b , β_b are temperature-dependent empirical constants [15].

B. Current Conduction Mechanism

When considering the current conduction in a partially-depleted SOI NMOS device, both the top MOS and the bottom parasitic BJT in the thin-film are important. When a partially-depleted SOI NMOS device is biased with $V_{GS} > V_T$ and $V_{DS} > 0$, the thin-film region above the buried oxide can be neutral—the parasitic npn bipolar device cannot be neglected. Due to the floating body effect, the parasitic bipolar device may be biased in the forward active region. For the parasitic npn bipolar device with the body-collector junction reverse biased, in the body-collector junction region, it has a reverse biased current (I_R), which is composed of the generation current (I_{gen}) in the space charge region and the electron diffusion current (I_{diff}) in the undepleted body region outside the space charge region [16]:

$$\begin{aligned}I_R &= I_{gen} + I_{diff} \\ I_{gen} &= \frac{qn_i A W_{bc}}{2\tau_g} \\ I_{diff} &= q \sqrt{\frac{D_n}{\tau_n}} \frac{n_i^2}{N_A} A\end{aligned}\quad (6)$$

where

- W_{bc} depletion width of the body-collector junction ($W_{bc} = \sqrt{\frac{2\epsilon_{si}(\phi_{bi} + V_{DS})}{qN_A}}$);
- D_n diffusion coefficient in the neutral region;
- A cross section of the current flow in the parasitic bipolar device ($A = W(t_{si} - \sqrt{\frac{2\epsilon_{si} 2\phi_f}{qN_A}})$);
- W width of the device;
- t_{si} thickness of the thin-film.

When the operating temperature is elevated, due to the influence from the intrinsic carrier concentration, the diffusion current (I_{diff}) becomes important in I_R . Across the forward biased body-emitter junction in the parasitic bipolar device, the conducting current (I_F) is made of the recombination current (I_{reco}) in the space charge region and the electron diffusion current (I_{ES}) [16]:

$$\begin{aligned}I_F &= I_{reco} \exp \left(\frac{V_{BE}}{2kT/q} \right) + I_{ES} \exp \left(\frac{V_{BE}}{kT/q} \right) \\ I_{reco} &= \frac{qn_i A W_{be}}{2\tau_r} \\ I_{ES} &= q \sqrt{\frac{D_n}{\tau_n}} \frac{n_i^2}{N_A} A\end{aligned}\quad (7)$$

where W_{be} is the depletion width of the body-emitter junction ($W_{be} = \sqrt{\frac{2\epsilon_{si} \phi_{bi}}{qN_A}}$). When V_{BE} is small, the first portion of the above equation dominates I_F . When V_{BE} is large, the second portion becomes dominant. In addition, when the operating temperature is raised, the diffusion current becomes important.

Considering the MOS portion of the partially-depleted SOI NMOS device, the threshold voltage is subject to the floating body effect. The accumulated holes near the body-emitter junction in the thin-film due to the parasitic bipolar device caused by the floating body increase the body-emitter voltage (V_{BE}). As a result, the threshold voltage is lowered. Considering this effect, the threshold voltage model (V_T) and the conducting current through the front channel (I_{CH}) under the front gate oxide have been reported in [5].

In this subsection, the current conduction mechanisms for the MOS portion and the parasitic bipolar portion of the partially-depleted SOI NMOS device have been explained. In the next subsection, the temperature-dependent kink effect model is derived for the device biased in the triode region ($V_{DS} \leq V_{DSAT}$) and the saturation region ($V_{DS} > V_{DSAT}$).

1) *Triode Region* $V_{DS} \leq V_{DSAT}$: Fig. 1(a) shows the current conduction mechanism of the partially-depleted SOI NMOS device biased in the triode region. In the front channel region near the drain, there is no impact ionization. Therefore, no holes are injected into the floating body. As a result, the body-emitter voltage (V_{BE}) is small. Consequently, the parasitic bipolar device does not turn on. Under this situation, the floating body can be regarded as two diodes connected back to back. At the body-emitter junction, which is forward biased, the conducting current is I_F . At the body-collector junction, which is reverse biased, the conducting current is I_R . Considering the impact ionization effect at the body-collector junction, the conducting current is magnified by a factor of M_B —the conducting current becomes $M_B I_R$. Considering the current conduction of the parasitic bipolar device ($I_F = M_B I_R$), from (5)–(7), the body-emitter voltage can be obtained:

$$V_{BE} = \frac{2kT}{q} \ln \left[\frac{-I_{reco} + \sqrt{I_{reco}^2 + 4I_{ES} M_B (I_{gen} + I_{diff})}}{2I_{ES}} \right]. \quad (8)$$

Fig. 1. The current conduction mechanism in the partially-depleted SOI NMOS device biased at (a) $V_{DS} \leq V_{DSAT}$ and (b) $V_{DS} > V_{DSAT}$.

In the above equation, the α_b and the β_b used in M_B are $\alpha_b = 7.5 \times 10^5$ and $\beta_b = 3.41 \times 10^6 + 1.3 \times 10^3 T$ [15].

2) *Saturation Region* $V_{DS} > V_{DSAT}$: For the partially-depleted SOI NMOS device biased in the saturation region, the current conduction mechanism is shown in Fig. 1(b). In this region, due to $V_{DS} > V_{DSAT}$, the impact ionization in the front channel region near the drain is important. As a result, a large amount of holes due to

the front channel impact ionization are injected into the floating body. Consequently, the accumulated holes near the body-emitter junction turn on the bottom parasitic bipolar device since the body-emitter voltage V_{BE} becomes large. From [5], in the saturation region, V_{BE} can be expressed as

$$V_{BE} = V_{BE1} + V_{BE2} - (V_{BE1}^m + V_{BE2}^m)^{1/m} \quad (9)$$

TABLE I
IMPORTANT PARAMETERS OF THE PARTIALLY-DEPLETED
SOI NMOS DEVICE UNDER STUDY

Symbol	Value	Unit
W	50	μm
L	25	μm
N_A	1×10^{17}	cm^{-3}
t_{ox1}	250	$\text{\AA}$
t_{ox2}	4500	$\text{\AA}$
t_{si}	2500	$\text{\AA}$
μ_{l0}	1500	cm^2/Vs
τ_{n0}	0.9	ns
F_c	0.6	
m	6	

where V_{BE1} is the V_{BE} when recombination current dominates the parasitic bipolar device; V_{BE2} is the V_{BE} when diffusion current dominates the parasitic bipolar device. Based on the above analysis as shown in Fig. 1(a) and (b), the drain current of the partially-depleted SOI NMOS device is composed of the front channel current in the front MOS portion and the collector current in the bottom parasitic bipolar device (see (10), shown at the bottom of the page). The above formulas are the closed-form analytical temperature-dependent kink effect model for the partially-depleted SOI NMOS device.

III. MODEL EVALUATION

In order to verify the effectiveness of the analytical temperature-dependent kink effect model for the partially-depleted SOI NMOS device, the model results have been compared with the experimental data [9] and two-dimensional (2-D) simulation results. As shown in the table, the test device under study has a channel length of 25 μm and a channel width of 50 μm . The gate oxide is 250 $\text{\AA}$. A thin-film of 2500 $\text{\AA}$ is atop a buried oxide of 4500 $\text{\AA}$. The doping density of the thin-film is 10^{17} cm^{-3} . Fig. 2 shows (a) V_{BE} and (b) I_D versus V_{DS} of the partially-depleted SOI NMOS device biased at $V_{GS} = 3.5 \text{ V}$, based on the analytical model, the experimental data [9] [Fig. 2(b)] and the 2-D simulation results. As shown in Fig. 2(a), at all three operating temperatures, at the kink the body-emitter voltage of the parasitic bipolar device has an abrupt change. As described in the previous section, the sudden increase in the body-emitter voltage at the kink in the saturation region is due to the accumulated holes caused by the injection of the hole current generated by impact ionization. As shown in the figures, at an elevated operating temperature, the kink effect is reduced. As verified by the experimental data [Fig. 2(b)] and the 2-D simulation results, the analytical model provides a good prediction of the temperature-dependent kink effect behavior of the partially-depleted SOI NMOS device. As shown in the figure, at a small V_{DS} , the model result on V_{BE} is deviated from the simulation results due to the omission of the V_{BE} term from $W_{bc} = \sqrt{\frac{2\epsilon_{si}(\phi_{bi} + V_{DS} - V_{BE})}{qN_A}}$ as indicated in the sentence below.

(a)

(b)

Fig. 2. (a) V_{BE} (b) I_D versus V_{DS} of the partially-depleted SOI NMOS device based on the analytical model, the experimental data [9] (b) and the two-dimensional (2-D) simulation results.

IV. DISCUSSION

The triggering V_{DS} at the onset of the kink effect is dependent on the operating temperature. Define V_{kink} as the triggering V_{DS} when the kink effect is about to occur. At the onset of the kink effect, the body-emitter voltage is

$$V_{BE} = V_{BES} + 10\text{mV} \quad (11)$$

where V_{BES} is V_{BE} at $V_{DS} = V_{DSAT}$. From [5], V_{kink} is found (see (12), shown at the top of the next page). Based on (12), Fig. 3 shows the triggering V_{DS} (V_{kink}) at the onset of the kink effect versus the operating temperature of the partially-depleted SOI NMOS device for various thin-film doping densities, based on the analytical model. At an elevated operating temperature, V_{kink} is increased—the kink effect is suppressed. With a higher doping density in the thin-film, V_{kink} is lowered—the kink effect is more easily to occur since at a

$$I_D = \begin{cases} I_{CH} + M_B(I_{gen} + I_{diff}), & \text{for } V_{DS} \leq V_{DSAT} \\ (I_{CH} + k_1 \alpha_F I_{ES} \exp(\frac{V_{BE}}{kT/q}))M + M_B(I_{gen} + I_{diff} + (1 - k_1) \alpha_F I_{ES} \exp(\frac{V_{BE}}{kT/q})), & \text{for } V_{DS} > V_{DSAT}. \end{cases} \quad (10)$$

$$\begin{aligned}
V_{\text{kink}} &= V_{D \text{ SAT}} + \frac{-D_2 + \sqrt{D_2^2 - 4D_1D_3}}{2D_1} \\
D_1 &= \ln\left(\frac{I_{\text{reco}}}{I_{\text{CH1}}} \frac{\beta}{\alpha} \exp\left(\frac{V_{\text{BES}}}{2kT/q}\right) \left(e^{\frac{0.01}{2kT/q}} - 1\right)\right) - 2 \\
D_2 &= \ln\left(\frac{I_{\text{reco}}}{I_{\text{CH1}}} \frac{\beta}{\alpha} \exp\left(\frac{V_{\text{BES}}}{2kT/q}\right) \left(e^{\frac{0.01}{2kT/q}} - 1\right)\right) + 2 + \beta l \\
D_3 &= \beta l \\
I_{\text{CH1}} &= \frac{W}{L} \mu_{\text{eff}} C_{\text{ox}} V_{D \text{ SAT}} \\
&\quad \times \frac{(V_G - V_{fb} - 2\phi_f - \gamma\sqrt{2\phi_f - V_{\text{BES}} - 0.01} - \frac{1}{2}(1 + \frac{\gamma}{2\sqrt{\phi_a + 2\phi_f - V_{\text{BES}} - 0.01}})V_{D \text{ SAT}})}{1 + \theta(V_G - V_{fb} - 2\phi_f - \gamma\sqrt{2\phi_f - V_{\text{BES}} - 0.01}) - \theta_B(V_{\text{BES}} + 0.01)}. \tag{12}
\end{aligned}$$

Fig. 3. The triggering V_{DS} (V_{kink}) at the onset of the kink effect versus the operating temperature of the partially-depleted SOI NMOS device based on the analytical model for various thin-film doping densities.

higher doping density in the thin-film, the parasitic bipolar device is weaker. As a result, the impact ionization generated holes are less likely to be recombined in the base of the parasitic bipolar device. Instead, they are more likely to be accumulated at the body-emitter junction. As a result, the kink effect is more easily to occur.

V. CONCLUSION

In this paper, a closed-form analytical temperature-dependent kink effect model for the partially-depleted SOI NMOS devices has been described. Based on the body-emitter voltage model, an analytical triggering V_{DS} formula for temperature-dependent kink effect has been obtained. According to the analytical model, at a higher operation temperature and with a lighter thin-film doping density, the onset of the kink effect occurs at a larger V_{DS} .

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