Closed-Form Breakdown Voltage Model for PD SOI NMOS Devices Considering Impact Ionization of Both Parasitic BJT and Surface MOS Channel Simultaneously

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Abstract—This paper reports a compact breakdown voltage model for partially depleted (PD) silicon-on-insulator (SOI) n-metal-oxide-semiconductor (NMOS) devices considering BJT/MOS impact ionization. Via the improved current conduction model considering BJT/MOS impact ionization this compact model provides an accurate prediction of the breakdown behavior of the PD SOI NMOS devices as verified by the experimental data and the MEDICI results. Based on the analytical model, when the gate voltage is lowered, the breakdown voltage decreases due to a stronger function of the parasitic BJT. In the subthreshold region, the breakdown voltage increases at a decreased gate voltage due to a weaker function of the parasitic BJT.

Index Terms—Complementary metal-oxide-semiconductor (CMOS), compact model, partially depleted (PD), PD breakdown voltage, silicon-on-insulator (SOI), SPICE.

I. INTRODUCTION

FOR a silicon-on-insulator (SOI) metal-oxide-semiconductor (MOS) device with a small channel length, the breakdown behavior due to a high electric field is important [1], [2]. As for a bulk NMOS device, the breakdown behavior of a partially depleted (PD) SOI NMOS device is caused by impact ionization [3], [4]. Different from a bulk NMOS device, impact ionization of both the surface MOS channel and the parasitic BJT is important in determining the breakdown behavior of a PD SOI MOS device. Breakdown behavior of PD SOI complementary metal-oxide-semiconductor (CMOS) devices has been reported [5]–[8]. Analytical breakdown voltage models of PD SOI NMOS devices have been reported before [9], [10]. However, iterations are needed for a solution [9], [10] or floating-body-dependent base-emitter voltage model is not considered [9]. Until now, no closed-form analytical breakdown model could be found. A closed-form analytical breakdown voltage model is helpful in providing a better understanding of the relative importance of the various parameters while engineering a PD SOI CMOS device. In this paper, using the approach for modeling the kink effects [11], [12], a compact breakdown voltage model considering the BJT/MOS impact

Fig. 1. Two-dimensional contours of hole density of 10^{16} cm^{-3} in the PD SOI NMOS device with a gate oxide of 120 Å , a thin film of 1200 Å doped with a p-type density of 10^{17} cm^{-3} , and a channel length of 0.7 μm , biased at $V_{GS} = 3 \text{ V}$, 0.5 V , and various V'_{DS} s.

ionization for the PD SOI NMOS devices is described. In the following sections, the model derivation is presented first, followed by evaluation of the model, discussion, and conclusion.

II. BREAKDOWN VOLTAGE MODEL

Fig. 1 shows the two-dimensional (2-D) contours of hole density of 10^{16} cm^{-3} in a PD SOI NMOS device with a channel length of 0.7 μm , a gate oxide thickness of 120 Å , and a thin film of 1200 Å , with a p-type density of 10^{17} cm^{-3} , biased at $V_{GS} = 3 \text{ V}$, 0.5 V , and various V'_{DS} s. As shown in Fig. 1, for the device biased in the strong inversion region at $V_{GS} = 3 \text{ V}$ (solid lines), when V_{DS} increases from 2 V to 4 V , the contour of the hole density of 10^{16} cm^{-3} moves upward, indicating widening of the parasitic BJT. At the breakdown voltage of $V_{DS} = 5 \text{ V}$, from the 10^{16} cm^{-3} hole density contour, the parasitic BJT occupies most of the thin film. For the device biased in the subthreshold region at $V_{GS} = 0.5 \text{ V}$ (dashed lines), from the 10^{16} cm^{-3} hole density contours, the function of the parasitic BJT is even stronger as compared to the strong inversion counterpart. Therefore, for deriving the breakdown voltage model, impact ionization of both the surface MOS channel and the parasitic BJT should be included.

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Fig. 2. Current conduction mechanism in a PD SOI NMOS device for deriving the breakdown voltage model.

A. Current Conduction Mechanism

Fig. 2 shows the current conduction mechanism in a PD SOI NMOS device for deriving the breakdown voltage model. As shown in this figure, the drain current (I_D) is composed of the surface MOS portion (first term) and the parasitic BJT portion (second term) as indicated in the following:

$$I_D = M(I_{ch} + K_1 \alpha_f I_{ediff}) + M_B(I_{gen} + (1 - K_1) \alpha_f I_{ediff}). \quad (1)$$

For the surface MOS portion, it is the sum of the traditional surface channel current (I_{ch}) and a portion (K_1) of the electron diffusion current (I_{ediff}) in the neutral base of the parasitic BJT, flowing upward to merge with the channel current, amplified by the multiplication factor (M) due to impact ionization in the high electric field region near the drain— $M(I_{ch} + K_1 \alpha_f I_{ediff})$ [11], where K_1 is an empirical parameter [11]. For the parasitic BJT portion, it is the sum of the generation current in the base-collector region (I_{gen}) and the remaining portion of the electron diffusion current in the neutral base $(1 - K_1) \alpha_f I_{ediff}$, multiplied by the multiplication factor (M_B) accounting for impact ionization in the high electric field region of the parasitic BJT. In the following subsections, key components in the surface MOS and parasitic BJT portions are described.

B. Surface MOS Channel Current (I_{ch})

In the surface MOS channel, depending on the operation regime determined by the gate voltage, its conduction current (I_{ch}) varies. When the gate voltage is smaller than the threshold voltage, diffusion current dominates in the surface MOS channel. Therefore, I_{ch} is made of the diffusion current [13]

$$\begin{aligned} I_{diff} &= \frac{W}{L} I_x \exp\left(\frac{V_G - V_x}{n\left(\frac{kT}{q}\right)}\right) \left[1 - \exp\left(-\frac{V_{DS}}{\left(\frac{kT}{q}\right)}\right)\right] \\ I_x &= \mu_0 C_{ox} \left(\frac{kT}{q}\right)^2 \frac{\gamma}{2\sqrt{1.5\phi_f - V_{BE}}} \exp\left(-\frac{\phi_f}{2\left(\frac{kT}{q}\right)}\right) \\ V_x &= V_{FB} + 1.5\phi_f + \gamma\sqrt{1.5\phi_f - V_{BE}} \\ n &= 1 + \frac{\gamma}{2\sqrt{1.5\phi_f - V_{BE}}} \\ \gamma &= \frac{\sqrt{2q\epsilon_{si}N_A}}{C_{ox}} \end{aligned} \quad (2)$$

where

- W channel width;
- V_{FB} flat-band voltage;
- C_{ox} gate oxide capacitance ($C_{ox} = \epsilon_{ox}/t_{ox}$);
- ϕ_f Fermi potential— $\phi_f = (kT/q) \ln(N_A/n_i)$ for p-type silicon and $\phi_f = (kT/q) \ln(n_i/N_D)$ for n-type silicon;
- n_i intrinsic concentration.

When the gate voltage is larger than the threshold voltage, I_{ch} is dominated by the drift current [11]

$$\begin{aligned} I_{drift} &= \frac{W}{L} \frac{\mu_0 C_{ox}}{1 + \theta(V_G - V_T) - \theta_B V_{BE}} \\ &\quad \times \left[(V_G - V_T) V_{dm} - \frac{1}{2}(1 + \delta) V_{dm}^2 \right] \\ V_T &= V_{FB} + 2\phi_f + \gamma\sqrt{2\phi_f - V_{BE}} \\ V_{dm} &= V_{DS} + V_{DSAT} - (V_{DS}^m + V_{DSAT}^m)^{1/m} \\ V_{DSAT} &= \frac{E_c L (V_G - V_T)}{E_c L (1 + \delta) + (V_G - V_T)} \\ \delta &= \frac{\gamma}{2\sqrt{\phi_a + 2\phi_f - V_{BE}}} \end{aligned} \quad (3)$$

where V_{dm} is used to accommodate this general drift current formula for both triode ($V_{DS} < V_{DSAT}$) and saturation ($V_{DS} \geq V_{DSAT}$) regions with $m = 6$ commonly used. μ_0 , θ , and θ_B , which are used to describe the mobility behavior, are empirical parameters [13]. ϕ_a is used to compensate for the deviation caused by Taylor's approximation. E_c is the critical electric field.

C. Parasitic BJT Currents

In addition to the currents from the surface MOS channel, the currents from the parasitic BJT are also important. As indicated in (1), in the parasitic BJT, the dominant currents are the generation current in the reverse biased base-collector junction (I_{gen}) and the electron diffusion current (I_{ediff}), which are amplified by the multiplication factor (M_B) of the impact ionization due to the high electric field region in the reverse-biased base-collector junction.

The generation current in the reverse-biased base-collector junction is expressed as

$$I_{gen} = \frac{qW_{BC}n_iA_J}{2\tau_g} \quad (4)$$

where A_J is the junction area, and τ_g is the generation lifetime in the base-collector junction. W_{BC} is the width of the depletion region between the floating-body and the drain ($W_{BC} = \sqrt{2\epsilon_{si}(V_{DS} + V_{bi} - V_{BE})/(qN_A)}$), where V_{bi} is the built-in voltage of the junction between the source and the thin film ($V_{bi} = (kT/q) \ln(N_A N_D/n_i^2)$), and V_{BE} is the floating-body potential.

The electron diffusion current in the base of the parasitic BJT is expressed as

$$\begin{aligned} I_{ediff} &= K_b \exp\left(\frac{V_{BE}}{\left(\frac{kT}{q}\right)}\right) \\ K_b &= \frac{qD_{eB}n_i^2 A_J}{N_A W_B} \end{aligned} \quad (5)$$

where

- D_{eB} electron diffusion constant ($D_{eB} = (kT/q)\mu_{eff}$);
- μ_{eff} electron mobility;
- W_B effective base width excluding the depletion region of the base-emitter and the base-collector junction ($W_B = L - W_{EB} - W_{BC}$);
- L channel length of the SOI device;
- W_{EB} depletion width of the base-emitter junction ($W_{EB} = \sqrt{2\epsilon_{si}(V_{bi} - V_{BE})/qN_A}$).

As indicated in (1), α_f is the forward common-base current gain ($\alpha_f = \alpha_t\gamma$) of the parasitic BJT considering the transport factor ($\alpha_t = 1/\cosh(W_B/L_{eB})$) and the injection efficiency [14]

$$\gamma = \frac{1}{\left(1 + \frac{(N_A D_{pE} W_B)}{(N_D D_{eB} W_E)} + \frac{1}{2} \sqrt{\frac{(q N_A W_B A_J)}{(D_{eB} I_{ediff})}} \frac{W_{EB}}{\tau_r}\right)}.$$

L_{eB} is the electron diffusion length in the base region, which is expressed as $L_{eB} = \sqrt{D_{eB}\tau_{eB}}$, where τ_{eB} is the electron lifetime in the base ($\tau_{eB} = \tau_0/(1 + N_A/5 \times 10^{16})$) and τ_0 is the hole lifetime in the base.

D. Impact Ionization

In the high electric field region after pinchoff in the surface MOS channel, due to impact ionization, the multiplication factor is expressed as

$$M = 1 + \frac{\alpha}{\beta}(V_{DS} - V_{DSAT}) \exp\left[-\frac{\beta l}{(V_{DS} - V_{DSAT})}\right] \quad (6)$$

where α , β , and l are impact-ionization-related parameters. Equation (6) is valid for the device in the strong inversion region ($V_G > V_T$). While in the weak inversion region ($V_G < V_T$), V_{DSAT} should be set to zero. Usually, in the triode region ($V_{DS} < V_{DSAT}$), impact ionization is negligible, thus $M = 1$.

In the high electric field region of the base-collector junction in the parasitic BJT, the multiplication factor due to impact ionization is

$$M_B = 1 + \frac{\alpha_b}{\beta_b}(V_{DS} - V_{BE}) \exp\left[-\frac{\beta_b l_b}{(V_{DS} - V_{BE})}\right] \quad (7)$$

where α_b , β_b , and l_b are the impact ionization coefficients.

Due to impact ionization, pairs of electrons and holes are generated in the high electric field region of the surface MOS channel and the parasitic BJT. Due to the positive drain voltage, the negatively charged electrons generated by impact ionization move toward drain to become the drain current I_D . The generated holes move in the negative direction toward the source terminal, accumulating in the floating-body to cause a floating-body potential. The generated hole current from the impact ionization in the surface MOS region is

$$I_{h1} = (M - 1)(I_{ch} + K_1\alpha_f I_{ediff}). \quad (8)$$

As shown by the dashed lines in Fig. 2, a portion of the hole current ($(1 - K_2)I_{h1}$), generated from the impact ionization in the surface MOS channel, is redirected toward the surface channel. The remaining portion of the generated hole current (K_2I_{h1}) still flows in the neutral thin film region identified as the floating-body, where K_2 is a fitting parameter [3]. At the bottom of the thin film, from the high electric field region of the parasitic BJT, impact ionization results in the magnification of the base-collector generation current (I_{gen}) and the base

electron diffusion current (I_{ediff}) amplified by the multiplication factor to become another hole current

$$I_{h2} = M_B I_{gen} + (M_B - 1)(1 - K_1)\alpha_f I_{ediff}. \quad (9)$$

The total hole current flowing toward the neutral region of the thin film is ($I_H = K_2I_{h1} + I_{h2}$)

$$I_H = K_2(M - 1)(I_{ch} + K_1\alpha_f I_{ediff}) + M_B I_{gen} + (M_B - 1)(1 - K_1)\alpha_f I_{ediff}. \quad (10)$$

E. Breakdown Condition

In the parasitic bipolar device, the emitter current is composed of the recombination current in the base-emitter junction (I_{erec}), the electron diffusion current (I_{ediff}), and the hole diffusion current (I_{hdiff}) over the base-emitter junction. The recombination current in the base-emitter junction (I_{erec}) is expressed as a function of the base-emitter voltage: $I_{erec} = K_a \exp(V_{BE}/2(kT/q))$, where $K_a = (qW_{EB}n_i A_J)/(2\tau_r)$, and τ_r is the recombination lifetime in the base-emitter junction. The hole diffusion current over the base-emitter junction (I_{hdiff}) is also a function of the base-emitter voltage: $I_{hdiff} = K_c \exp(V_{BE}/(kT/q))$, where $K_c = (qD_{pE}n_i^2 A_J)/(N_D W_E)$, D_{pE} is the hole diffusion constant ($D_{pE} = (kT/q)\mu_{peff}$, μ_{peff} is the hole mobility), N_D is the doping density of the source region, and W_E is the emitter width. Note from the above derivation the currents in the parasitic BJT are determined by the base-emitter voltage [11], [12], which is the floating-body potential. The base current is formed by the total hole current (I_H). The collector current is expressed as $\alpha_f I_{ediff}$. In the parasitic bipolar device, the emitter current is equal to the sum of the collector current and the base current ($I_E = I_C + I_B$). Therefore

$$I_{erec} + I_{ediff} + I_{hdiff} = I_H + \alpha_f I_{ediff}. \quad (11)$$

Since the emitter current is dominated by the electron diffusion current (I_{ediff}), (11) can be simplified as $I_H \cong (1 - \alpha_f)I_{ediff}$. Using (10), the electron diffusion current can be expressed as

$$I_{ediff} = \frac{K_2(M - 1)I_{ch} + M_B I_{gen}}{1 - \alpha_f - K_1 K_2(M - 1)\alpha_f - (M_B - 1)(1 - K_1)\alpha_f}. \quad (12)$$

From (1) and (12), the drain current becomes

$$I_D = \frac{f_1 I_{ch} + f_2 I_{gen}}{f_0} \quad (13)$$

$$f_0 = 1 - \alpha_f - K_1 K_2(M - 1)\alpha_f - (1 - K_1)(M_B - 1)\alpha_f$$

$$f_1 = M(1 - \alpha_f) + (1 - K_1)\alpha_f$$

$$\times [K_2 M_B(M - 1) - M(M_B - 1)]$$

$$f_2 = M_B[1 + (M - 1)K_1(1 - K_2)\alpha_f].$$

Taking a derivative of (13), one obtains

$$\frac{\partial I_D}{\partial V_{DS}} = \frac{1}{f_0^2} \left\{ \left(f_0 \frac{\partial f_1}{\partial V_{DS}} - f_1 \frac{\partial f_0}{\partial V_{DS}} \right) I_{ch} + \left(f_0 \frac{\partial f_2}{\partial V_{DS}} + f_2 \frac{\partial f_0}{\partial V_{DS}} \right) I_{gen} + f_0 \left(f_1 \frac{\partial I_{ch}}{\partial V_{DS}} + f_2 \frac{\partial I_{gen}}{\partial V_{DS}} \right) \right\}. \quad (14)$$

At breakdown, the slope of the drain current approaches infinity: $(dI_D/dV_{DS}) \rightarrow \infty$. In addition, at breakdown, the drain current also approaches infinity: $I_D \rightarrow \infty$. From these two conditions and (13) and (14), one obtains $f_0 = 0$, and hence the following equation as the condition for breakdown:

$$K_1 K_2 (M - 1) \beta_f + (1 - K_1) (M_B - 1) \beta_f = 1. \quad (15)$$

From this equation, with the multiplication factors of impact ionization in the surface MOS channel and the parasitic BJT, the breakdown voltage could be found.

1) *Strong Inversion Regime:* When the device is biased in the strong inversion region ($V_G > V_T$), since multiplication factors (M, M_B) of impact ionization in the surface MOS channel and the parasitic BJT are transcendent functions of the drain voltage (V_{DS}), a solution of (15) in terms of V_{DS} is difficult to get. When the surface MOS channel dominates, the second term is negligible. Then (15) is simplified as

$$\beta_f K_1 K_2 \frac{\alpha}{\beta} (BV_{DSm} - V_{DSAT}) \exp \left[-\frac{\beta l}{(BV_{DSm} - V_{DSAT})} \right] = 1. \quad (16)$$

The exponential term in (16) can be approximated using Taylor's expansion as

$$\exp \left[-\frac{\beta l}{(BV_{DSm} - V_{DSAT})} \right] \cong \exp \left[-\frac{\beta l}{BV_{DSm}} \right] \times \exp \left[-\frac{\beta l V_{DSAT}}{BV_{DSm}^2} \right]. \quad (17)$$

Applying log function to both sides of (16), and using the approximation: $\ln(x) = 2((x-1)/(x+1))$ and $\ln(1-x) = -x - (x^2/2)$, (16) becomes

$$(G - 2)BV_{DSm}^3 + (G + 2 + V_{DSAT} + \beta l)BV_{DSm}^2 + \left(V_{DSAT} + \frac{1}{2}V_{DSAT}^2 + \beta l + \beta l V_{DSAT} \right) BV_{DSm} + \left(\frac{1}{2}V_{DSAT}^2 + \beta l V_{DSAT} \right) = 0 \quad (18)$$

where $G = \ln(1/(K_1 K_2) \beta / \alpha ((1/\alpha_f) - 1))$. From (18), the breakdown voltage for the surface MOS channel-dominated regime is

$$\begin{aligned} BV_{DSm} &= \left(-\frac{m}{2} + \sqrt{D} \right)^{1/3} + \left(-\frac{m}{2} - \sqrt{D} \right)^{1/3} \\ D &= \left(\frac{n}{3} \right)^3 + \left(\frac{m}{2} \right)^2 \\ n &= \frac{1}{3} \left[3 \left(\frac{S_3}{S_1} \right) - \left(\frac{S_2}{S_1} \right)^2 \right] \\ m &= \frac{1}{27} \left[2 \left(\frac{S_2}{S_1} \right)^3 - 9 \left(\frac{S_2}{S_1} \right) \left(\frac{S_3}{S_1} \right) + 27 \left(\frac{S_4}{S_1} \right) \right] \\ S_1 &= G - 2 \\ S_2 &= G + 2 + V_{DSAT} + \beta l \\ S_3 &= V_{DSAT} + \frac{1}{2}V_{DSAT}^2 + \beta l + \beta l V_{DSAT} \\ S_4 &= \frac{1}{2}V_{DSAT}^2 + \beta l V_{DSAT}. \end{aligned} \quad (19)$$

When the parasitic BJT dominates, (15) becomes

$$\frac{1}{\alpha_f} - 1 = (1 - K_1) \frac{\alpha_b}{\beta_b} (BV_{DSmb} - V_{BE}) \times \exp \left[-\frac{\beta_b l_b}{(BV_{DSmb} - V_{BE})} \right]. \quad (20)$$

Using a similar approach as for the case dominated by the surface MOS channel, one obtains a polynomial equation in terms of the breakdown voltage as

$$\begin{aligned} (G_b - 2)BV_{DSmb}^3 &+ (G_b + 2 + V_{BE} + \beta_b l_b)BV_{DSmb}^2 \\ &+ \left(V_{BE} + \frac{1}{2}V_{BE}^2 + \beta_b l_b + \beta_b l_b V_{BE} \right) BV_{DSmb} \\ &+ \left(\frac{1}{2}V_{BE}^2 + \beta_b l_b V_{BE} \right) = 0 \end{aligned} \quad (21)$$

where $G_b = \ln(1/(1 - K_1)(\beta_b/\alpha_b)((1/\alpha_f) - 1))$. From (21), the breakdown voltage for the parasitic-BJT-dominated regime is

$$\begin{aligned} BV_{DSmb} &= \left(-\frac{m_b}{2} + \sqrt{D_b} \right)^{1/3} + \left(-\frac{m_b}{2} - \sqrt{D_b} \right)^{1/3} \\ D_b &= \left(\frac{n_b}{3} \right)^3 + \left(\frac{m_b}{2} \right)^2 \\ n_b &= \frac{1}{3} \left[3 \left(\frac{S_{3b}}{S_{1b}} \right) - \left(\frac{S_{2b}}{S_{1b}} \right)^2 \right] \\ m_b &= \frac{1}{27} \left[2 \left(\frac{S_{2b}}{S_{1b}} \right)^3 - 9 \left(\frac{S_{2b}}{S_{1b}} \right) \left(\frac{S_{3b}}{S_{1b}} \right) + 27 \left(\frac{S_{4b}}{S_{1b}} \right) \right] \\ S_{1b} &= G_b - 2 \\ S_{2b} &= G_b + 2 + V_{BE} + \beta_b l_b \\ S_{3b} &= V_{BE} + \frac{1}{2}V_{BE}^2 + \beta_b l_b + \beta_b l_b V_{BE} \\ S_{4b} &= \frac{1}{2}V_{BE}^2 + \beta_b l_b V_{BE}. \end{aligned} \quad (22)$$

From the surface MOS channel-dominated and the parasitic BJT-dominated breakdown voltages (19) and (22), the universal breakdown voltage formula is

$$BV_{DS} = BV_{DSm} + BV_{DSmb} - (BV_{DSm}^6 + BV_{DSmb}^6)^{1/6}. \quad (23)$$

2) *Subthreshold Regime:* The breakdown formula derived above is for the device biased in the strong inversion regime. When the device is biased in the weak inversion regime, (19) and (22) are not applicable. At weak inversion (V_{DSAT} negligible), if the surface MOS channel dominates, using a similar approach as for the strong inversion regime, (16) is simplified and the breakdown voltage of the surface MOS channel-dominated regime is

$$BV_{DSm} = \frac{-(G + 2 + \beta l) + \sqrt{(G + 2 + \beta l)^2 - 4(G - 2)\beta l}}{2(G - 2)}. \quad (24)$$

TABLE I
PARAMETERS USED IN THE BREAKDOWN
MODEL OF THE PD SOI NMOS DEVICE

Symbol	Value	Unit
K_1	0.2	
K_2	0.8	
μ_0	300	$\text{cm}^2/\text{V}\cdot\text{sec}$
θ	0.1	$1/\text{V}$
θ_B	0.1	$1/\text{V}$
ϕ_a	0.2	
τ_0	1	μsec
τ_g	10	nsec
τ_r	100	nsec
α	2.5×10^6	cm^{-1}
β	3.5×10^6	V/cm
l	1×10^{-6}	cm
α_b	3×10^5	cm^{-1}
β_b	5×10^5	V/cm
l_b	5×10^{-6}	cm
E_C	1×10^6	V/cm

At weak inversion, if the parasitic BJT dominates, V_{BE} is negligible, thus (20) is simplified and the breakdown voltage for the parasitic BJT-dominated regime is

$$BV_{DSmb} = \frac{-(G_b + 2 + \beta_b l_b) + \sqrt{(G_b + 2 + \beta_b l_b)^2 - 4(G_b - 2)\beta_b l_b}}{2(G_b - 2)}. \quad (25)$$

Thus, (23)–(25) are the breakdown voltage formulas for the device biased in the weak inversion regime.

III. MODEL EVALUATION

In order to evaluate the effectiveness of the analytical breakdown model developed here, the model results have been compared with the 2-D simulation results and experimentally measured data. The test device under study is a PD SOI NMOS device with a front gate oxide of 120 Å, a thin film of 1200 Å doped with a p-type density of 10^{17} cm^{-3} , and a channel length of 0.7 μm. The parameters used in the analytical model are listed in Table I, where fitting parameters are determined from [13] and 2-D simulation results. Fig. 3 shows (a) the drain current and (b) the related V_{BE} of the parasitic BJT characteristics of this test device based on the compact model and the MEDICI 2-D results. As shown in this figure, the breakdown of the device is strongly correlated to V_{BE} of the parasitic BJT, which is also related to the kink effect [11], [12]. At the larger V_{GS} of 3 V, the related V_{BE} is smaller, which indicates a weak function of the parasitic BJT while the surface MOS channel is dominant. At the smaller V_{GS} of 0.5 V, the parasitic BJT turns on earlier and the contribution of impact ionization from the parasitic BJT becomes more important. As shown in the figure, at a high drain voltage, the deviation in the base-emitter voltage between the

Fig. 3. (a) Drain current and (b) related body-emitter voltage versus drain voltage of the PD SOI NMOS device with a front gate oxide of 120 Å, a thin film of 1200 Å doped with a p-type density of 10^{17} cm^{-3} , and a channel length of 0.7 μm based on the analytical model and 2-D simulation results.

model and the simulation results becomes noticeable, which results in a substantial deviation in the threshold voltage. The deviation is due to the over-simplified parasitic bipolar device modeled used for describing the complicated floating-body effect mechanism. In addition, drain-induced barrier lowering (DIBL) is not considered. Nevertheless, the analytical model still could predict the breakdown voltage with a reasonable accuracy.

Fig. 4 shows the breakdown voltage versus the gate voltage of the PD SOI NMOS device as described for Fig. 3 with channel lengths of 0.7 μm and 2.7 μm, based on the compact model, the 2-D simulation results, and the experimentally measured data [9]. As shown in Fig. 4, in the strong inversion, when the gate voltage decreases, the breakdown voltage decreases due to a larger influence from the parasitic BJT. In the subthreshold region, when the gate voltage becomes smaller, the breakdown voltage increases due to a weaker function of the parasitic BJT. As shown in this figure, the analytical model predicts well the breakdown voltage as verified by the 2-D simulation results and the experimentally measured data.

IV. DISCUSSION

Fig. 5 shows the breakdown voltage versus the channel length of the PD SOI NMOS devices (a) with various thin film doping

Fig. 4. Breakdown voltage versus gate voltage of the PD SOI NMOS device with a gate oxide of 120 Å, a thin film of 1200 Å doped with a p-type density of 10^{17} cm^{-3} , and channel lengths of 0.7 μm and 2.7 μm , based on the analytical model, the MEDICI 2-D simulation results, and the experimentally measured data.

Fig. 5. Breakdown voltage versus channel length of the PD SOI NMOS device: (a) with various thin film doping densities and thin film thicknesses, biased at $V_{GS} = 2 \text{ V}$ and (b) with various V'_{GS} s, based on the compact model and the experimentally measured data.

densities and thin film thicknesses biased at $V_{GS} = 2 \text{ V}$ and (b) with various V'_{GS} s, based on the compact model and the experimentally measured data [3], [9]. As shown in Fig. 5(a), when the channel length is larger, the breakdown voltage increases.

Fig. 6. Breakdown voltage by considering both the surface MOS channel and the parasitic BJT (BVDS), by considering only the surface MOS channel ($M - 1$), and by considering only the parasitic BJT ($M_B - 1$) versus channel length of the PD SOI NMOS device with a gate oxide of 150 Å, a thin film of 1500 Å doped with a p-type density of $8 \times 10^{16} \text{ cm}^{-3}$, based on the analytical model and the experimental data.

With a thicker thin film, the breakdown voltage is smaller due to a stronger parasitic BJT. As shown in Fig. 5(b), at a smaller V_{GS} , the breakdown voltage becomes smaller since the function of the parasitic BJT becomes stronger.

Fig. 6 shows the breakdown voltage by considering both the surface MOS channel and the parasitic BJT (BVDS), by considering only the surface MOS channel ($M - 1$), and by considering only the parasitic BJT ($M_B - 1$) versus the channel length of the PD SOI NMOS device with a gate oxide of 150 Å, and a thin film of 1500 Å doped with a p-type density of $8 \times 10^{16} \text{ cm}^{-3}$ based on the analytical model and the experimental data [3]. As shown in Fig. 6, when the channel length is small, the breakdown voltage of the device is predominantly determined by the surface MOS channel since the impact ionization at the surface is more important due to a large lateral electric field. When the channel length becomes large, dominance of impact ionization by the surface MOS channel is replaced by that of the parasitic BJT.

The analytical breakdown model is not just for a long channel case. It is applicable for a short channel case as well. Fig. 7 shows the drain current versus the drain voltage of a 0.25- μm PD SOI NMOS device with a front gate oxide of 50 Å, and a thin film of 800 Å, doped with a p-type density of $5 \times 10^{17} \text{ cm}^{-3}$, based on the analytical model and the 2-D simulation results. As shown in Fig. 7, for a channel length of 0.25 μm , the analytical model still could predict the breakdown behavior well.

Fig. 8 shows the ratio of the breakdown voltage determined by only the surface MOS channel to that by only the parasitic BJT (BV_{DSm}/BV_{DSmb}) versus the channel length of the PD SOI NMOS device with various thin film structures based on the compact model. As shown in this figure, when the channel length is small, (BV_{DSm}/BV_{DSmb}) is less than one, which implies dominance of the surface MOS channel. The solid lines show the cases with the multiplication factor coefficient of the surface MOS channel equal to 1.5 times that of the parasitic BJT ($(\alpha/\beta)_M/(\alpha/\beta)_{MB} = 1.5$). Under this situation, when the thickness of the thin film is increased from 1500 Å to 3000 Å, the BV_{DSm}/BV_{DSmb} curve moves upward from SOI1

Fig. 7. Drain current versus drain voltage of the PD SOI NMOS device with a front gate oxide of 50 Å, a thin film of 800 Å, doped with a p-type density of $5 \times 10^{17} \text{ cm}^{-3}$, and channel length of 0.25 μm based on the analytical model and 2-D simulation results.

Fig. 8. Ratio of the breakdown voltage determined by only the surface MOS channel to that by only the parasitic BJT versus the channel length of the PD SOI NMOS device with various thin film structures based on the analytical model.

to SOI2, which implies the relative weight of parasitic BJT tends to become more important. When the thin film doping density is increased from $8 \times 10^{16} \text{ cm}^{-3}$ to 10^{17} cm^{-3} , the BV_{DSm} / BV_{DSmb} curve also moves upward from SOI1 to SOI3, which can be reasoned as follows. With a higher thin film doping density, although the function of the parasitic BJT is reduced, the extent of the increase in the threshold voltage of the surface MOS device is even more. As a result, with an increase in the thin film doping density, the relative weight of the parasitic BJT in terms of impact ionization increases when the thin film doping density is raised. When the multiplication factor coefficient of the surface MOS channel is reduced to 0.5 times that of the parasitic BJT ($(\alpha/\beta)_M / (\alpha/\beta)_{MB} = 0.5$), the BV_{DSm} / BV_{DSmb} curve (dashed line) is higher than the original one—SOI1 (solid line) with $(\alpha/\beta)_M / (\alpha/\beta)_{MB} = 1.5 \text{ V}$.

V. CONCLUSION

In this paper, a compact breakdown voltage model for PD SOI NMOS devices considering BJT/MOS impact ionization

has been presented. Via the improved current conduction model considering BJT/MOS impact ionization, this compact model provides an accurate prediction of the breakdown behavior of the PD SOI NMOS devices as verified by the experimental data and the MEDICI results. Based on the analytical model, in the strong inversion region, when the gate voltage is lowered, the breakdown voltage decreases. In the subthreshold region, a smaller gate voltage leads to a larger breakdown voltage due to a weaker function of the parasitic BJT.

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