Design optimization of field-plate assisted RESURF devices

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Abstract— A mathematical model for optimizing the 2-D potential distribution in the drift region of field-plate (FP)-assisted RESURF devices (Fig. 1) is presented. The proposed model extends earlier work [1-2] by including top-bottom dielectric asymmetry (typical in SOI devices [3]), non-zero field plate potentials V_{FP} and grading of design parameters other than drift region doping. This generally-applicable, TCAD-verified [4], model provides a guideline for optimizing the drain extension in a wide range of FP-assisted RESURF devices.

I. INTRODUCTION

The RESURF (Reduced SURface Field [5]) effect is commonly used to improve the specific on-resistance vs. breakdown voltage ($R_{on}A$ - BV) trade-off in high-voltage (HV) transistors [6]. RESURF optimization aims to achieve a constant horizontal field at breakdown using various methods: pn -junctions [5], super-junctions [7], field-plates [8] or a combination [9]. FP-assisted RESURF can be realized in both SOI [8] and trench-MOS [10] technology by tailoring one of the following design parameters: (Fig. 1a) drift region doping N_D [2, 11], (Fig. 1b) dielectric layer permittivity ϵ_d [12], (Fig. 1c) dielectric layer thickness t_d [13], (Fig. 1d) semiconductor layer thickness t_s [14] and (Fig. 1e) FP-potential V_{FP} [15, 16]. In this work, a complete mathematical model is presented that allows $R_{on}A$ - BV optimization for all above mentioned FP-RESURF devices.

The paper is outlined as follows: Section II presents a modular look at the mathematical model and its TCAD verification; Section III focuses on its application and attainable $R_{on}A$ - BV trade-off, while in Section IV conclusions are drawn.

II. FP-ASSISTED RESURF MODEL

The model proposed in this paper extends the work by S. Merchant [2] to a broader application range, while achieving deeper physical insight into the trade-offs related to $R_{on}A$ - BV optimization of FP-assisted RESURF devices. For this purpose, a more general model is presented describing the optimal RESURF electric fields and potential distributions in drain extensions using any substrate/dielectric combination or (2-D) symmetry (Fig. 1).

A. Constant Lateral Field Condition

The general description of the field distribution in the depleted drain extension is given by the 2-D Poisson equation (assuming only a lateral variation in drift doping $N_D(x)$ and semiconductor permittivity ϵ_s):

$$\frac{dE_x(x, y)}{dx} + \frac{dE_y(x, y)}{dy} = \frac{qN_D(x)}{\epsilon_s} \quad (1)$$

Fig. 1: Breakdown voltage (BV) optimization methods for FP-assisted RESURF devices. Optimal structures shown for: **a)** graded N_D ; **b)** graded ϵ_d ; **c)** graded t_d ; **d)** graded t_s ; **e)** graded V_{FP} . The methods shown are also applicable to vertical devices.

Since optimal RESURF design requires a constant horizontal field $E_x = -BV/L$ at breakdown [2], Eq. 1 can be solved for the 2-D potential distribution giving $\psi(x, y) = \frac{BV}{L}x + V(x, y)$ with $V(x, y)$ obtained by integrating Eq. 1 and using $dE_x/dx = 0$. This yields the general expression:

$$\psi(x, y) = \frac{BV}{L}x - \frac{qN_D(x)}{2\epsilon_s}y^2 \quad (2)$$

It can be shown (Fig. 2) that various drain extensions (single-sided (SS), double-sided asymmetrical (ASYM) and symmetrical (SYM)) can be modeled as a symmetrical field-plate/semiconductor structure with equivalent MOS depletion thickness $t_{eq}(x)$. For a SS device, $t_{eq} = \sqrt{2t_s(\frac{t_s}{2} + \frac{\epsilon_s}{\epsilon_d}t_d)}$ and is related to the λ -parameter introduced in [2] (see Eq. 6a) using the relation $t_{eq} = \sqrt{2}\lambda$. Imposing the boundary condition $\psi(x, t_{eq}(x)) = V_{FP}(x)$ to Eq. 2 and rearranging the terms yields the general constant lateral field condition:

$$\frac{\epsilon_s \left[\frac{BV}{L}x - V_{FP}(x) \right]}{qN_D(x) \frac{t_{eq}^2(x)}{2}} = 1 \quad (3)$$

Fig. 2: **a)** Cut along the y -direction of cross sections shown in Fig. 1 for SS, ASYM and SYM devices and the equivalent structure. Dark gray: dielectric, white/light gray: semiconductor **b)** Potential distribution $\psi(y)$ for ASYM devices including representation of t_{eq} .

Constant E_x condition

$$\frac{\varepsilon_s \left(\frac{BV}{L}x - V_{FP} \right)}{qN_D \lambda^2} = 1 \Rightarrow \begin{cases} N_D(x) = \frac{\varepsilon_s}{q\lambda^2} \left(\frac{BV}{L}x - V_{FP} \right) & (a) \\ \lambda^2(x) = \frac{\varepsilon_s}{qN_D} \left(\frac{BV}{L}x - V_{FP} \right) & (b) \\ V_{FP}(x) = \frac{BV}{L}x - \frac{qN_D}{\varepsilon_s} \lambda^2 & (c) \end{cases} \Rightarrow \begin{cases} \varepsilon_d(x) = \frac{2q\varepsilon_s N_D t_d t_s}{2\varepsilon_s \left(\frac{BV}{L}x - V_{FP} \right) - qN_D t_s^2} & (i) \\ t_d(x) = -\frac{t_s \varepsilon_d}{2\varepsilon_s} + \frac{\varepsilon_d \left(\frac{BV}{L}x - V_{FP} \right)}{qN_D t_s} & (ii) \\ t_s(x) = \frac{\varepsilon_s t_d}{\varepsilon_d} + \sqrt{\left(\frac{\varepsilon_s t_d}{\varepsilon_d} \right)^2 + \frac{2\varepsilon_s}{qN_D} \left(\frac{BV}{L}x - V_{FP} \right)} & (iii) \end{cases}$$

Rewriting Eq. 3 in terms of λ leads to Eq. 4, which describes how the different design parameters can be tailored (Fig. 1) in order to achieve optimal RESURF by means of: (a) graded doping (Eq. 4a and Fig. 1a), (b) “ λ -RESURF” achieved through graded dielectric constant (Eq. 4i and Fig. 1b) or graded layer (t_d or t_s) thicknesses (Figs. 1c-d and Eqs. 4ii-iii), and (c) FP-potential RESURF (Eq. 4c and Fig. 1e). Optimal RESURF can also be obtained using a combination of graded profiles as long as Eq. 4 is fulfilled. Although the graded profiles from Eq. 4 are not always exact solutions of the Poisson equation, good agreement between the model and TCAD simulations is achieved.

From each of the boundary conditions corresponding to the different vertical device symmetries (SS, ASYM and SYM), a relation for t_{eq} and therefore λ can be derived:

$$\lambda = \begin{cases} \sqrt{t_s \left(\frac{t_s}{2} + \frac{\varepsilon_s}{\varepsilon_d} t_d \right)} \Rightarrow \text{SS} & (a) \\ \sqrt{t_{s1,2} \left(\frac{t_{s1,2}}{2} + \frac{\varepsilon_s}{\varepsilon_{d1,2}} t_{d1,2} \right)} \Rightarrow \text{ASYM} & (b) \\ \sqrt{\frac{t_s}{2} \left(\frac{t_s}{4} + \frac{\varepsilon_s}{\varepsilon_d} t_d \right)} \Rightarrow \text{SYM} & (c) \end{cases} \quad (5)$$

$$t_{s1,2} = \frac{\frac{t_s}{2} \left(t_s + 2 \frac{\varepsilon_s}{\varepsilon_{d2,1}} t_{d2,1} \right)}{t_s + \frac{\varepsilon_s}{\varepsilon_{d1}} t_{d1} + \frac{\varepsilon_s}{\varepsilon_{d2}} t_{d2}} \quad (6)$$

Equations 4-6 thus provide a guideline for RESURF optimization across a wide range of drain extensions types. However, they will only lead to optimal RESURF if the device breakdown voltage is limited by the lateral field E_x , as discussed in following section.

B. Breakdown

Breakdown in 2-D structures can occur in three possible ways: lateral (E_x) breakdown, vertical (E_y) breakdown and P-body/ N^+ -drain junction breakdown. The breakdown voltage BV of the device is determined by the lowest of each of the three contributions. In this section, the breakdown mechanisms are analyzed by: 1) solving Eq. 7 (obtained using [2]) for $u(x)$, representing the potential along the symmetry line $y=0$ ($u(x) = \psi(x, 0)$); 2) deriving the field distributions from Eq. 8; and 3) calculating the impact ionization (II) integrals using Eqs. 9-10. The results are then compared with TCAD simulations.

$$\frac{d^2 u(x)}{dx^2} - \frac{u(x) - V_{FP}(x)}{\lambda^2(x)} = -\frac{qN_D(x)}{\varepsilon_s} \quad (7)$$

$$\begin{aligned} E_x(x, 0) &= -u'(x) \\ E_y(x, y) &= \frac{u(x) - V_{FP}(x)}{\lambda^2(x)} y \end{aligned} \quad (8)$$

E_x breakdown: (Fig. 3) occurs when the II-integral (α_x (in Si), Eq. 9a) along the symmetry line in the drift region ($y=0$, [path 1](#)

Fig. 4a) reaches 1. Since for $V_{DS}=BV$ the longitudinal field $E_x=BV/L$ at $y=0$, the integration of α_x simply returns the optimal BV vs. drift length (L) relation (Eq. 9b).

$$\alpha_x = \int_{\text{Path1}} a_n \cdot \exp\left(\frac{-b_n}{E_x(x, 0)}\right) dx \quad (9a), \quad BV_{ideal} = \frac{b_n L}{\ln(a_n L)} \quad (9b)$$

Using the silicon coefficients $a_n=7.03 \cdot 10^5 \text{ cm}^{-1}$, $b_n=1.47 \cdot 10^6 \text{ Vcm}^{-1}$ [8] and the lateral field description (Eq. 8), the results obtained from the model and TCAD are in good agreement for the whole V_{DS} range and across multiple (optimal and non-optimal) gradient values (Fig. 3).

Fig.3: a) TCAD simulated and modeled E_x -ionization integrals (E_x -II) for SYM graded- N_D and graded- V_{FP} RESURF in three different cases: optimal (opt) graded-RESURF slope (for max. E_x -BV, Eq. 4), reduced grading (0.8-opt) and increased grading (1.2-opt). b) As in a) but for graded- t_d . For all simulations a Si/SiO₂ structure is assumed with a fixed $\varepsilon_s/\varepsilon_d$ ratio of ~3.

E_y breakdown: (Figs. 4-5) The E_y II-integral (Eq. 10) is calculated along the longest path (amongst t_{s1} and t_{s2}) at the edge of the depletion region ($x=W(V_{DS})$, [path 2](#) in Fig. 4a), where E_y is maximum. It is worth mentioning that the solution of Eq. 10 is not analytical. In addition, a transcendental equation [2, 17] needs to be solved for determining $W(V_{DS})$.

$$\alpha_y = \int_{\text{Path2}} a_n \cdot \exp\left(\frac{-b_n}{E_y(W(V_{DS}), y)}\right) dy \quad (10)$$

Fig.4: a) Highest electron impact ionization (highest e^- -II) paths [17] for BV modeling in SS, ASYM and SYM structures. b) E_y -II integrals calculated for SYM, ASYM and SS devices showing premature vertical breakdown as the y -path length (Path 2) increases. Inset: matching simulated off-state I - V in the three cases.

Fig.5: BV vs. drift length L for graded- N_D RESURF, showing the limitations on the choice of t_d imposed by E_y -breakdown. Inset shows a comparison between simulated and modeled BV for $L=40 \mu\text{m}$.

Modeled and TCAD verified E_y breakdown limited cases are compared in Fig. 4b (for increasing vertical path 2 length) and Fig. 5 (for increasing E_y field peak). Breakdown occurs when $\max(\alpha_x, \alpha_y) = 1$, as verified by TCAD (inset of Fig. 5).

Junction breakdown: (Fig. 6) A high initial doping N_0 ($N_D(x=0)$) can lead to an increased E_x field peak (at $x=0$, Fig. 6a) causing premature junction breakdown. Its occurrence was first described by Appels and Vaes in [5] resulting in the general max. junction dose rule $t_s \cdot N_D(0) = 2 \cdot 10^{12}$. The TCAD results in Fig. 6 show how junction breakdown can limit the ideal device performance of t_d -graded RESURF extensions.

Fig.6: a) Junction breakdown for t_d -graded RESURF. As the uniform doping concentration N_D is increased, the higher E_x -field peak at the pn -junction interface leads to premature 1-D breakdown preventing full E_x -expansion in the drift region. b) BV vs. N_D for different thicknesses t_s showing how the onset of junction breakdown is shifted towards higher N_D when reducing t_s (see also inset).

C. Field-plate potential

Obtaining a constant E_x is in principle not always possible with grounded field-plates ($V_{FP}=0$ V), because Eq. 4 predicts unrealistic (e.g. negative) values for device parameters at $x=0$. Equation 12 shows how to tailor the V_{FP} -value to achieve a constant E_x for different types of FP-RESURF. Vertical and junction breakdown are avoided by tuning the non-graded parameters (Fig. 7a-c).

$$V_{FP}^{comp} = \begin{cases} -\frac{qN_D(0)t_s}{\epsilon_s} \left[\frac{t_s}{2} + \frac{\epsilon_s}{\epsilon_d} t_d \right] & N_D(x) \\ -\frac{qN_D t_s}{\epsilon_d} \left[t_d(0) + \frac{t_s \epsilon_d}{2\epsilon_s} \right] & t_d(x) \\ -\frac{qN_D t_s}{\epsilon_s} \left[\frac{t_s}{2} + \frac{\epsilon_s}{\epsilon_d(0)} t_d \right] & \epsilon_d(x) \\ -\frac{2\epsilon_s t_s(0)}{qN_D} \left[t_s(0) - 2\frac{\epsilon_s}{\epsilon_d} t_d \right] & t_s(x) \end{cases} \quad (12)$$

III. APPLICATION GUIDELINE AND RESULTS

Using the proposed model, the following guideline for optimizing FP-assisted RESURF design can be derived: 1) first determine the drift-region length (L) for the desired ideal BV from Eq. 9b; then 2) optimize the lateral (x) BV (Fig. 3) by grading one of the design parameters according to Eq. 4; finally 3) tailor the other device parameters such that: a) the device is not subjected to vertical breakdown (Figs. 4-5) or

Fig. 7: a) Simulated E_x -fields at breakdown for graded- N_D RESURF with and without V_{FP} -compensation showing optimal E_x -breakdown (Eq. 7) when the right $V_{FP\text{comp}}$ value (Eq. 10) is applied. b) Simulated and modeled E_x -BV vs. V_{FP} for different values of the initial doping $N_D(0)$. c) Simulated and modeled BV vs. $N_D(0)$ with and without V_{FP} -compensation for different values of t_s . d) Comparison of theoretical $R_{on}A$ -BV trade-off for graded- N_D RESURF with and without V_{FP} -compensation for both horizontal and vertical devices. For $t_s = 1\mu\text{m}$ (SYM device) and optimal $N_D(x)$ profile (Eq. 4a), the other design parameters (t_d and $N_D(0)$) are selected to achieve minimum $R_{on}A$ for ideal BV.

junction breakdown (Fig. 6); and b) the specific on-resistance $R_{on}A$ is minimized (Fig. 7d).

Specific on-resistance ($R_{on}A$) optimization

A negatively-biased V_{FP} in off-state can be used to reduce the specific $R_{on}A$ of the device without affecting the BV (Fig. 7a-c). This is possible because a negative FP-potential acts on the depleted charge distribution as an equivalent doping of opposite polarity. Therefore, an arbitrarily-high drift doping can in principle be used if properly compensated by a $V_{FP} < 0$, as suggested by Eq. 12 for $N_D(x)$. In practice, extreme values of $N_D(x)$ might lead to premature vertical breakdown (Fig. 7c), thus limiting the minimum achievable resistivity in the drift region. Using a numerical optimization routine, the limit value of the drift doping $N_D(x)$ for achieving minimum $R_{on}A$ while preventing vertical breakdown can be determined. Performing such optimization on a graded- N_D device (Fig. 7d) shows that a theoretical $R_{on}A$ -BV improvement (by a factor ~ 5 for lateral and ~ 2 for vertical devices) can be achieved when using negatively-biased V_{FP} compared to its grounded V_{FP} counterpart.

IV. CONCLUSION

A mathematical model describing field and potential distributions in different configurations of FP-assisted

RESURF devices has been presented and verified by TCAD simulations. Using the proposed model, an optimal $R_{on}A$ -BV trade-off can be achieved for both horizontal and vertical devices.

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