Role of shape factor in forming surface electric field basin in RESURF Lateral Power Devices and its optimization design

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Abstract—The drift region shape factor \(L_d/t\) plays a sophisticated role in affecting RESURF effect and breakdown characteristics. In this paper, based on the Effective Doping Concentration (EDC) theory, an Improved EDC concept is proposed to explore the impact of shape factor on 2-D coupling effect in RESURF lateral power devices. The Improved EDC concept indicates that the sophisticated 2-D coupling in N-well resulting an effective N-I-P type drift region. Thus, the surface electric field basin may exist because of the expansion of Vertical Depletion Region (VDR). The proposed model presents a more adaptive trait in describing 2-D coupling effect under various device structure parameters when compared to the conventional EDC model. Furthermore, a corresponding structure optimization criterion is provided to further improve the trade-off between Breakdown Voltage \(B(V)\), On-resistance \(R_{on}\) and costs. The results obtained by the proposed model are found to be accurate comparing with TCAD simulation results.

Index Terms—1-D model; Shape factor; Effective doping; RESURF effect; Breakdown voltage

I. INTRODUCTION

The introduction of Reduced Surface Field (RESURF) technique enables lateral power devices to operate one-step closer to the ideal switch that features infinite electrical conductivity or resistivity when turned ON or OFF\cite{1-8}. It has been widely accepted in lateral power design that a good tradeoff between BV and Ron can be achieved when doping dose \((Q=Na \times t)\) fulfills RESURF principle. However, except the epilayer thickness \((t_f)\), the breakdown characteristic is also a strong function of drift region length \((L_d)\)\cite{9-11}. Also, the drift region length has a great impact on the Ron. More importantly, the device area is closely related to the costs while the lateral approach is more area-consumable than vertical solutions\cite{12-14}. In order to be commercially competitive, it is vital for a lateral power device to achieve a good device area utilization rate. In practical, a long drift region may result in a surface electric field basin\cite{5-8}. The existence of this electric field basin indicates that there is one part of drift region contributes to neither lateral nor vertical breakdown voltage. Whereas, the electric field basin doesn’t exist when the drift region is short enough. Apparently, the variation of the drift region shape factor alters the 2-D coupling effect between the vertical and lateral structure\cite{12-14}. Hence, a reasonable inference can be drawn that the drift region shape factor \((L_d/t)\) ought to be considered in designing to achieve a good performance and low costs.

In order to take the benefits of both the simplicity of 1-D models and the veracity of 2-D models, the EDC model has been proposed to provide reasonable physical insight for the 2-D coupling effect\cite{7}. Though EDC models are proven to be sufficiently simple and accurate in describing surface electric field profile and breakdown mechanism at short drift region cases, with the increase of \(L_d\), abnormal deteriorations in accuracy are observed\cite{15}. It has been clear that the rectangle Sharing Charge Region (SCR) assumption is too simple to enable conventional EDC model depicts the complexity of Vertical Depletion Region (VDR) expansion when \(L_d/t \gg 2\).
Even the 2-D models consider the breakdown structure as a rectangle region for modeling to reduce its complexity.

In this paper, in order to enrich the EDC theory and provide a universal optimization criterion, we propose an improved EDC concept to explore the impact of shape factor-induced 2-D coupling effect on BV characteristics. The improved EDC concept indicates that the excessively long drift region enhances the vertical depletion and thus creating a surface electric field basin which provides no benefits to device’s BV characteristic. To our knowledge, the improved EDC theory and corresponding 1-D model is the first methodology that can qualitatively and quantitatively explore the influence of shape factor on RESURF effect. The analytical model is validated by the good agreement between the modeling results and simulation results by MEDITI, a commercial TCAD tool. The simulation models used in MEDITI are CONSRH, AUGER, BGN, FLDMOB, IMPACT.I and CCSMOB.

II. EFFECTIVE DOPING CONCENTRATION

For the 2-D cross-section shown in Fig.1(a), when a reverse-biased voltage is applied, the potential function in the silicon film satisfies the 2-D Poisson’s equation, which yields:

$$\frac{\partial^2 \phi(x,y)}{\partial x^2} + \frac{\partial^2 \phi(x,y)}{\partial y^2} = -\frac{qN_d}{\varepsilon_e} \tag{1}$$

By using the second-order Taylor series expansion along the y dimension, a general differential equation for the surface potential distribution function can be given by:

$$\frac{\partial^2 \phi(x,0)}{\partial x^2} - \frac{\phi(x,0)}{t^2} = -\frac{qN_d}{\varepsilon_e} \tag{2}$$

The EDC theory assumes that the impact of 2-D/3-D effect on BV characteristic can be equivalent to the variation of EDC profile of drift region. When the device operates in off state, a Sharing Charge Region (SCR) is formed to sustain applied reverse voltage. The SCR is limited by the lateral and vertical depletion length $x_{drl}$ and $x_{dv}(x)$, respectively. In conventional EDC model, as shown in Fig.1(a), such an SCR is considered as a rectangle region. Thus, in [3], the EDC profile that contributes to the lateral depletion can be presented with a linear function, which yields:

$$N_d(x) = N_d \left[ 1 - \frac{\eta}{\eta_{\text{Min}}(x_{drl}, x)} \right] \tag{3}$$

where $\eta=x_{dv}(L_d+t_d)/t$, is the ratio of the spreading of the VDR into the epitaxial layer under drain region and SOI layer thickness. $\eta$ also indicates the 2-D coupling effect between lateral structure and Region II. By applying the EDC theory reported in [7], Eq.(2) can be further simplified as:

$$\frac{\partial^2 \phi(x,0)}{\partial x^2} = -\frac{dE_v(x,0)}{dx} = -\frac{qN_d(x)}{\varepsilon_e} \tag{4}$$

So far, by using Eq.(3) and (4), the conventional EDC model can be obtained accordingly. Although the conventional EDC model can accurately depict the 2-D coupling effect at short $L_d$ case, its accuracy drops significantly with the increase of drift region shape factor. In fact, as Fig.1(a) shows, for a practical lateral power device, the Region I and II together compose the drift region. Apparently, both Region I and II contribute to the 2-D coupling effect. Among them, the vertical depletion region

![Graph](image_url)

Fig. 2. Drift region Effective Doping Concentration of the drift region for various (a) drift region length($V_{app}=200V, N_d=1.5 \times 10^{15} \text{cm}^{-2}, t_r=7\mu m$), (b) applied voltage ($N_d=1.5 \times 10^{15} \text{cm}^{-2}, t_r=7\mu m, L_d=100\mu m$) with $L_s=2\mu m$.

![Graph](image_url)

Fig. 3. Effective NIP-type lateral structure and the electric field distribution of the RESURF lateral power device.

in Region I is limited by the surface electric potential $q(x,0)$. Therefore, the 2-D coupling between Region I and lateral structure highly depends on drift region shape factor. To quantitatively depict the influence of such a 2-D coupling on lateral surface electric potential and field profiles, we propose that only a part of the drift region is involved in lateral depletion and the corresponding EDC can be given as:

$$N_f(x) = N_f \left[ \frac{1}{L_f} + \frac{1-x}{L_s} \right] \tag{5}$$

where $\sigma=L_d t$ being the drift region shape factor, $t=(0.5t_r^2+K(d_{ox}))^{0.5}$ is the characteristic thickness[34], $K_{\text{oxid}}/t_{\text{ox}}=3$ is the dielectric constant ratio of silicon and silicon dioxide material, $t_r$ being the epitaxial layer thickness and $d_{ox}$ represents the thickness of the buried oxide layer. As shown in Fig.1(b), Eq.(5) indicates that the parts of drift region away from PN junctions and N’ junctions tend to have less contribution to the 2-D coupling effect. Accordingly, by considering the 2-D coupling effect in Region I, Eq.(3) is replaced by:
It is worthy to be noted that the EDC profile obtained by Eq.(6) can also be applied to explore the 2-D coupling effect in bulk silicon case. To do so, the characteristic thickness ought to be amended to  \( t = (0.5t_s^2 + t_{sox})^{0.5} \).

Fig.2 intuitively illustrate the variation of EDC profile under various structure parameters and bias. As shown in Fig.2(a), when shape factor is relatively small, the proposed EDC profile tends to coincide with the conventional EDC profile defined by Eq.(3). For a fixed vertical structure, the increase of drift region length results in a deviation of EDC from linear estimation. As shown in Eq.(3). For a fixed vertical structure, the increase of drift region tends to coincide with the conventional EDC profile defined by Eq.(3). As shown in Eq.(3), although the \( N_{eq}(0) \) and \( N_{eq}(L_d) \) that obtained by Eq.(3) and (6) are same, the difference of EDC within the drift region indicates the SCR is overestimated by the conventional EDC model. As illustrated in Fig.2(b), an equivalent intrinsic region appears in the drift region which means no charges in this region contributes to the lateral depletion. Such an equivalent intrinsic region forms an equivalent N-I-P drift region. Therefore, as shown in Fig.3, a surface electric field basin may be expected under long drift region cases. In its essence, an excessively long drift region weaken the grip of lateral PN and N’N junctions on drift region. The charges that far away from the source and drain region is more easily being affected by vertical structure and thus forming a hump-shaped VDR shown in Fig.1(b).

III. VERIFICATION AND DISCUSSION

A. Surface Electric Field Profile

As the 2-D coupling effect on the lateral structure is reflected by EDC that Eq.(6) defines, the surface electric field (EF) profile \( E(x,0) \) can be obtained by submitting Eq.(6) to 1-D Poisson’s function [Eq.(4)], which yields:

\[
E(x,0) = E_s - \frac{q N_{eq} L_s}{\varepsilon_s \varepsilon_0} \left[ \left( 1 - \eta \right) \left( \frac{x}{L_s} \right)^{\alpha - 1} - \left( 1 - \frac{x}{L_s} \right)^{\alpha - 1} \right]
\]  
(7)

The Eq.(7) can be further simplified without causing the observable error when \( \alpha > 5 \), which yields:

\[
E(x,0) = E_s - \frac{q N_{eq} L_s}{\varepsilon_s \varepsilon_0} \left[ \left( 1 - \eta \right) \left( \frac{x}{L_s} \right)^{\alpha - 1} \right]
\]  
(8)

According to Eq.(8), when drift region shape factor satisfies \( \alpha = 1 \), the proposed model is consistent with conventional EDC model. To further validate the correctness of proposed methodology, we have compared the modeled surface electric field with results obtained by TCAD and conventional EDC model in Fig.4. As shown in Fig.4(a) and (b), when shape factor is relatively small(\( L_d/t = 2 \), the conventional EDC model is capable maintain a good consistency between simulation results. Whereas, as the shape factor increases with the lengthening of drift region, the rectangle SCR assumption resulting in a large mismatch in EF profile with simulations can be observed. Meanwhile, as the improved EDC model simultaneously considers both the 2-D coupling effect of Region I and II, such mismatch is no longer exist. Furthermore, as shown in Fig.4(b)-(d), since the bump-shaped VDR in Region I only determined by drift region shape factor, the variation of applied voltage has no effect on the equivalent intrinsic region. In other words, the surface electric field basin is inevitable for an excessively long drift region.

Notably, same as that in conventional EDC model, the surface EF peaks at PN\(_d\) and N’N\(_d\) junctions reach the same
height when \( \eta=2 \). In which case, the maximum lateral breakdown voltage is achieved as lateral EF peaks reach critical electric field (\( E_c \)) simultaneously\(^{[7]} \).

### B. Breakdown Voltage

For a lateral power device, the lateral and vertical structures simultaneously sustain reversed-biased voltage. The BV of the device is limited by the minimum of lateral and vertical \( \text{BV} \). In full-depletion condition, the RB voltage that lateral structure sustains can be given by using Eq. (4) and (7):

\[
V_{lat} = E_c L_d - (a + 2 - \eta) V_0 \left( \frac{a^2}{(a + 1)(a + 2)} \right) \tag{9}
\]

where \( V_0 = qN_d \varepsilon_s \), \( E_c \) is the surface electric field at \( x=0 \). Same as the EDC model, the proposed EDC methodology can also be applied to elaborate the partially depleted. Nevertheless, the partially depleted breakdown is a lack of meaning in the application of lateral power devices, we will not elaborate it in this paper. As shown in Fig.3 and 4, the lateral structure has two electric field peaks at the two ends of the drift region, respectively. Therefore, for the full-depletion lateral breakdown, there are two cases. For PN\(_d\) junction breakdown case (\( \eta=2 \)), \( E_c=E_0 \). Whereas, for the N\(_N\)\(_d\) breakdown case (\( \eta\geq2 \)), \( E_c=E(L_d) \). Hence the lateral \( \text{BV} \) can be obtained as:

\[
\text{BV}_{lat} = \begin{cases} 
E_c L_d - \left[ (a + 2 - \eta) \right] V_0, & \eta < 2 \\
E_c L_d - \left[ (a + 1) \eta - a - 2 \right] V_0, & \eta \geq 2 
\end{cases} \tag{10}
\]

where \( E_c=3.0 \times 10^7/[1-0.33 \log_0(N_d/10^16)] [\text{V/cm}] \) is the critical electric field, \( V_0=q[a^2/(a^2+3a+2)] \). Apparently, as discussed above, the lateral breakdown voltage reaches its maximum (\( \text{BV}_{lat, \text{Max}} \)) when \( \eta=2 \). For a high shape factor case (\( a>5 \)), the Eq.(10) can be further simplified while maintaining its accuracy, which yields:

\[
\text{BV}_{lat} = \begin{cases} 
E_c L_d - \left[ (a + 2 - \eta) \right] V_0, & \eta < 2 \\
E_c L_d - \left[ (a + 1) \eta - a - 2 \right] V_0, & \eta \geq 2 
\end{cases} \tag{11}
\]

As for the vertical breakdown voltage, its mathematical expression can be given by:

\[
\text{BV}_{ver} = \frac{qN_d L_d}{E_c} \left( K_{\text{pt}} + \frac{2\eta - 1}{2} \right) \tag{12}
\]

The device breakdown voltage is determined by the lowest breakdown voltage among lateral and vertical structures, which yields:

\[
\text{BV} = \text{Min} [\text{BV}_{lat}, \text{BV}_{ver}] \tag{13}
\]

Fig. 5(a) and (b) show the \( \text{BV}_{N_d} \) and \( \text{BV}_{L_d} \) characteristics. As shown Fig.5(a), with the increase of drift region doping concentration, the breakdown of lateral power device successively undermines four stages: N\(_N\)\(_d\) junction full depletion(\( \text{BV}_{lat, \text{FNN}} \)), vertical breakdown(\( \text{BV}_{ver} \)), PN\(_d\) junction full depletion(\( \text{BV}_{lat, \text{PPN}} \)) and PN\(_d\) junction partial depletion(\( \text{BV}_{lat, \text{PP}} \)). In order to achieve a high breakdown voltage while maintaining an acceptable process tolerance, in practical, lateral power devices are designed to have the vertical breakdown when the critical electric field is reached. As Fig.5(a) intuitively shows, a longer drift region length means a bigger process tolerance. However, a longer \( L_d \) also results in bigger \( \text{Ron} \) and lower area utilization rate. Considering the fact that the \( N_d \) is normally varying between 0.9-1.1\( N_d \) in fabrication, an excessively long drift region is not only unnecessary but also uneconomic. For example, when the designed optimized \( N_d=1.65 \times 10^{15} \text{cm}^{-3} \), the variation of \( N_d \) is within 1.5-1.8\( \times 10^{15} \text{cm}^{-3} \). Therefore, as Fig.5(a) indicates, when \( L_d=20 \mu m \), the process tolerance constraint has already been met. Meanwhile, a longer drift region would inevitably result in a higher \( \text{Ron} \) and larger device area. As shown in Fig.5(b), with the increase of \( L_d \), the breakdown of lateral power device successively undermines three stages: N\(_N\)\(_d\) junction full depletion(\( \text{BV}_{lat, \text{FNN}} \)), PN\(_d\) junction full depletion(\( \text{BV}_{lat, \text{PPN}} \)) and vertical breakdown(\( \text{BV}_{ver} \)). The vertical breakdown occurs when \( \text{BV}_{lat, \text{Max}} \geq \text{BV}_{ver} \). After reaching the vertical breakdown, the increase of drift region length will no longer increase the \( \text{BV} \). In such case, the \( \text{BV} \) is limited by Eq.(12). By using Eq.(12) and (10), to achieve the vertical breakdown voltage, the drift region length requirement yields as follows:

\[
L_d > \left( 8t_r^2 - 3t_r \right)/(8t_r - 4r) \tag{14}
\]

As shown in Fig.4(a), an electric field basin exists in long drift region cases which means the drift region is only partially contributing to lateral depletion resulting in a low area utilization. In this paper, an Area Utilization Rate (AUR) is defined as \( \text{AUR}=\text{BV}_{lat, \text{Max}}/(E_cL_d) \) to evaluate the surface area utilization in drift region designing. For an ideal case, the surface electric field reaches even, thus the \( \text{AUR}=1 \). For a RESURF lateral power device, the maximum AUR can be obtained by using \( \eta=2 \) and Eq.(10), which yields:

\[
\text{AUR} = 1 - \frac{V_0}{E_c a} \left( \frac{a^2}{a^2+3a+2} \right) \tag{15}
\]

As Eq.(15) indicates, the AUR is not a linear function of \( L_d \). For the devices shown in Fig.4(a), since \( L_d=20 \mu m \) already satisfies Eq.(14), the \( \text{AUR} \) can be improved more than 11% when drift
region length shrunk from 100 to 20μm while maintaining the same device BV.

So far, by using the improved EDC model, the surface electric field profile and breakdown voltage have been qualitatively and quantitatively discussed. As shown in Fig.4 and 5, the consistency between the analytical solution and the simulation has demonstrated the proposed EDC to be valid. It worthy to be noted that, by submitting Eq. (6), (8) and (11), it can be found that the proposed model also consistent with 2-D Poisson function, thus further verifying the efficiency of the proposed methodology.

IV. STRUCTURE OPTIMIZATION

For a lateral power device, the goal of structure optimization is to achieve a good tradeoff between the BV, Ron, and area utilization. Due to a complicated role that shape factor plays in affecting On/Off characteristics and area utilization, it is essential to optimize the geometric structure of drift region during the design phase. Considering the shape factor-induced 2-D coupling, such a complicated 2-D effect also leads to a higher degree of optimization complexity. Clearly, the conventional RESURF criterions are too simple to provide effective designing guidance.

As discussed above, in order to maintain a high BV while achieving a big process tolerance, it is desirable to make device happens vertical breakdown. Accordingly, the theoretical window for optimizing the drift region doping dose is Q=Q_\text{up}(x,t) can be obtained by using Eq.(10) and (12). The upper (Q_{up}) and lower (Q_{down}) limits of the optimized doping dose (ODD) can be given as:

\[ Q_{\text{up}} = \frac{e_C}{q} \left( \frac{2 + b^2 - 2ab - 2a^2 \sqrt{a^2 + 3a + 2}}{1 - 2a^2 / (a+1)} \right) \]

\[ Q_{\text{down}} = \frac{e_C}{q} \left( \frac{2 + b^2 - 2ab + 2a^2 \sqrt{a+2}}{1 + 2a^2 / (a+1)} \right) \]

where \( b=t_t/L \) is the vertical structure factor. For the simplicity, the \( E_C \) used in Eq.(16) and (17) is \( E_C = 3.0 \times 10^5 \text{V/cm} \)\([7,14]\]. Hereby, the structure optimization criterion can be given as:

\[ Q_{\text{down}} \leq Q \leq Q_{\text{up}} \]

As discussed above, to realize vertical breakdown, for a fixed vertical structure, the drift region length has to exceed the length requirement limited by Eq.(14). However, a longer drift region also means a smaller area utilization rate. Thus, as shown in Fig.6(a), when the drift region length satisfies \( L_d > 5t \), the shape factor has a small impact on the drift region ODD. In such case, Eq.(16) and (17) can be further simplified as:

\[ Q_{\text{up}} = \frac{e_C}{q} \left( \frac{2 + b^2 - 2ab - 2}{1 - 2a} \right) \]

\[ Q_{\text{down}} = \frac{e_C}{q} \left( \frac{2 + b^2 - 2ab + 2a}{1 + 2a} \right) \]

In order to verify the proposed EDC model and optimization method, we simulate the BV and EF profile under two drift region length. As shown in Fig.7, when the vertical structure of the lateral power device is fixed as \( t_{ox}=2\mu \text{m}, t_{r}=7\mu \text{m} \), the characteristic thickness \( t \) is about 8.2μm. For the long drift region case, as shown in Fig.7(a), the shape factor \( a=L_d/t \) is about 7.32 (\( L_d=60\mu \text{m} \)). According to Eq.(16) and (17), \( Q=11.0 \times 10^{11} \text{cm}^{-2} \) (\( N_{d,up}=1.6 \times 10^{15} \text{cm}^{-2} \)) satisfies the ODD. Meanwhile, for a short drift region case, as shown in Fig.7(b)-(c), the drift region length is 20μm, thus the shape factor is about 2.44. Considering the maximum process tolerance (\( \pm 10\% N_{d,up} \)), the \( N_d \) used in the devices shown in Fig. (b) and (c) are 1.45 and 1.85\times10^{15} \text{cm}^{-2}, respectively. As shown in Fig.7(a)-(c), for a fully depleted drift region, three electric occur at: 1) the PN junction (A-Point); 2) N’N junction (B-Point) and 3) Si–SiO\(_2\) interface under the drain region (C-Point). As shown in Fig.7(d), the simulation results indicate that both long and short drift region cases reach the vertical breakdown at BV=325V simultaneously. Therefore, even the drift region length shrinks by 67\%, the same BV characteristic can be still achieved. Moreover, when the drift region length decreases from 60 to 20μm, the BFM improves 8 times. In light of that, the proposed optimization method can be considered as an effective tool in optimizing RESURF lateral power device on SOI substrate. As shown in Figs. 6 and 7, the predictions of the proposed EDC model agree very well with the TCAD simulation.

V. CONCLUSION

In order to enrich the conventional EDC model and elaborate the physical meaning of the shape factor-induced 2-D coupling effect, we proposed the improved EDC concept. The proposed EDC concept indicates that for a long drift region case the drift region can be equivalent as a 1-D N–I–P structure. Therefore, as a result of the expansion of the VDR, a surface electric field basin may occur when the drift region is long enough. Using the improved EDC concept, a novel 1-D analytical model is
proposed to qualitatively and quantitatively explore the impact of shape factor-induced 2-D coupling on surface electric field and breakdown characteristics for the first time. Based on the proposed EDC concept, an effective optimization criterion is proposed to provide designing guidance. The analytical solutions are found out to be consistent with TCAD simulations.

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Fig. 7 Distribution of potential contours at BV = 325 V of (a). long drift region case (Ld=60μm), (b). short drift region case with Nd=0.9N_{opt}, (c). short drift region case with Nd=1.1N_{opt} and comparison of (d) surface electric field profile under an unified coordinate.

Microelectronics devices reliability and RF and power integrated circuits and systems.

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