# An analytical model for the vertical electric field distribution and optimization of high voltage REBULF LDMOS*

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In this paper, an analytical model for the vertical electric field distribution and optimization of a high voltage-reduced bulk field (REBULF) lateral double-diffused metal–oxide-semiconductor (LDMOS) transistor is presented. The dependences of the breakdown voltage on the buried n-layer depth, thickness, and doping concentration are discussed in detail. The REBULF criterion and the optimal vertical electric field distribution condition are derived on the basis of the optimization of the electric field distribution. The breakdown voltage of the REBULF LDMOS transistor is always higher than that of a single reduced surface field (RESURF) LDMOS transistor, and both analytical and numerical results show that it is better to make a thick n-layer buried deep into the p-substrate.

**Keywords:** REBULF, LDMOS, vertical electric field, breakdown voltage

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## 1. Introduction

Lateral double-diffused metal–oxide–semiconductor (LDMOS) transistors have been widely used in power integrated circuits (PIC).[1–5] One of the main issues when designing power LDMOS field effect transistors is the blocking voltage capability. A novel concept of a reduced bulk field (REBULF) was put forward to improve the breakdown voltage of the power laterally diffused metal–oxide–semiconductor field-effect transistor (LDMOSFET) and a new device structure of REBULF LDMOS with an N+-floating layer embedded in the substrate was proposed.[6–8] Cheng *et al.*[9,10] and Zhang *et al.*[11] developed a new floating buried layer (FBL) LDMOSFET structure with a fully depleted n-layer buried in the p-substrate based on the REBULF concept.[9–11] The charges in the buried-layer modulate the bulk electric field, resulting in a nearly uniform electric field distribution and significantly improved the breakdown voltage. The FBL LDMOS structure was also used in super-junction LDMOS and longitudinal junction termination (LJT) LDMOS.[12,13] Since the REBULF technology was firstly presented in 2006, this technology has received widespread attention.[14,15] However, to date, no analytical model has been given for REBULF LDMOS. Especially for bulk silicon FBL LDMOS, the buried layer depth, thickness, and doping concentration all have great influences on the breakdown voltage and on-resistance of the device. An approximate REBULF condition has been given,[9] but the influence of the buried n-layer's depth on the breakdown voltage of the FBL LDMOS has not been taken into consideration and the optimal design method of the buried n-layer has not been given either.

The purpose of this paper is mainly to discuss the buried layer optimal design method for REBULF LDMOS (in this paper, REBULF LDMOS refers to FBL LDMOS). A two-dimensional (2D) analytical model mainly for the vertical electric field distribution and breakdown voltage of the REBULF LDMOS is given. The buried layer parameters such as the vertical position, thickness, and doping concentration greatly affect the blocking capability of the device, which have been discussed in detail with both analytical and numerical results. Moreover, the REBULF criterion and the optimal vertical electric field distribution condition are derived based on the optimization of the electric field distribution. Finally, the quantitative relationship of the breakdown voltage between the single reduced surface field (RESURF) transistor and the REBULF LDMOS transistor is obtained. It indicates that under REBULF criterion and the optimal vertical electric field distribution condition, it is better to make a thick n-layer buried deep into the p-substrate.

## 2. Analytical model

The cross section of the REBULF LDMOS is shown in Fig. 1.

The drift region is divided into two regions 1 and 2, and its length, thickness, and doping concentration are $L_d$, $t_S$, and $N_D$

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respectively while the length of region 1 is $L_1$. The buried n-layer is region 4 and its length, thickness, and doping concentration are $L_d - L_1$, $t_B$, and $N_B$ respectively. $t_P$ represents the depth of the upper boundary of the buried n-layer to the bottom of the drift region. Region 3 denotes part of the P substrate on the top of the buried n-layer. The doping concentration of the P-type substrate is $P_{sub}$. The P-substrate is assumed to be thick enough to deplete the substrate charge, and the widths of the substrate depletion layer are $t_{S1}$ and $t_{S2}$, respectively. When the device is in off-state and the drift region is fully depleted, the potential function $\varphi_i(x,y)$ of the REBULF LDMOS is satisfied by 2D Poisson's equations:

$$\frac{\partial^2\varphi_i(x,y)}{\partial x^2}+\frac{\partial^2\varphi_i(x,y)}{\partial y^2}=-\frac{qN_i}{\varepsilon_s},\quad i=1\sim 4, \tag{1}$$

where $N_1=N_2=N_D$, $N_3=-P_{sub}$, $N_4=N_B-P_{sub}$. There are several boundary conditions for Eq. (1):

$$\left.\frac{\partial\varphi_1(x,y)}{\partial y}\right|_{y=0}=0,\quad \left.\frac{\partial\varphi_2(x,y)}{\partial y}\right|_{y=0}=0, \tag{2}$$

$$\frac{\partial\varphi_1(x,t_S)}{\partial y}=-\frac{2}{t_{1S}}\varphi_1(x,t_S),$$

$$\frac{\partial\varphi_4(x,t_S+t_P+t_B)}{\partial y}=-\frac{2}{t_{2S}}\varphi_4(x,t_S+t_P+t_B), \tag{3}$$

$$\phi_1(L_1,0)=\phi_2(L_1,0),\quad \frac{\partial\phi_1(L_1,0)}{\partial x}=\frac{\partial\phi_2(L_1,0)}{\partial x}, \tag{4}$$

$$\frac{\partial\phi_2(x,t_S)}{\partial y}=\frac{\partial\phi_3(x,t_S)}{\partial y},$$

$$\frac{\partial\phi_3(x,t_S+t_P)}{\partial y}=\frac{\partial\phi_4(x,t_S+t_P)}{\partial y}, \tag{5}$$

$$\phi_2(x,t_S)=\phi_3(x,t_S),\quad \phi_3(x,t_S+t_P)=\phi_4(x,t_S+t_P), \tag{6}$$

$$\phi_1(0,0)=0,\quad \phi_2(L_d,0)=V_d. \tag{7}$$

In Eq. (2), it is assumed that the vertical electric field at the semiconductor surface may be minimized. Equation (3) is the continuity of electric flux density across the drift/substrate, and the buried-layer/substrate boundary. Equations (4)–(6) mean that the potential and the electric fields along the boundaries of 1–2, 2–3, 3–4 regions are continuous. The potential function $\varphi_i(x,y)$ can be approximated by two-order Taylor expanded formulas,[16,17] and the general differential equation for the surface potential distribution function can be described as

$$\frac{\partial^2\phi_i(x,0)}{\partial x^2}-\frac{\phi_i(x,0)}{t_i^2}=\frac{-qN_{i,\mathrm{eff}}}{\varepsilon_s},\quad i=1,2, \tag{8}$$

where

$$t_1=\sqrt{(t_S^2+t_{1S}t_S)/2}$$

and

$$t_2=\sqrt{[(t_S+t_P+t_B)^2+t_{2S}(t_S+t_P+t_B)]/2}.$$

Let

$$t_R=t_2=\sqrt{(t_D^2+t_{2S}t_D)/2},$$

which is the characteristic thickness of REBULF LDMOS, and $t_D=t_S+t_P+t_B$. So the equivalent concentration $N_{i,\mathrm{eff}}$ is expressed as

$$\begin{cases} N_{1,\mathrm{eff}}=N_D, \\ N_{2,\mathrm{eff}}=\dfrac{t_{2S}}{t_D^2+t_Dt_{2S}}[\alpha N_D-\beta P_{sub}+\gamma N_B], \end{cases} \tag{9}$$

where $\alpha$, $\beta$, and $\gamma$ denote the concentration coefficients of the drift region, substrate, and buried n-layer, respectively, and $\alpha=t_S+t_S(2t_D-t_S)/t_{2S}$, $\beta=(t_P+t_B)+(t_P+t_B)^2/t_{2S}$, and $\gamma=t_B+t_B^2/t_{2S}$. The widths of the substrate depletion layer $t_{S1}$ and $t_{S2}$ can be calculated by taking the first-order approximation.[18–20]

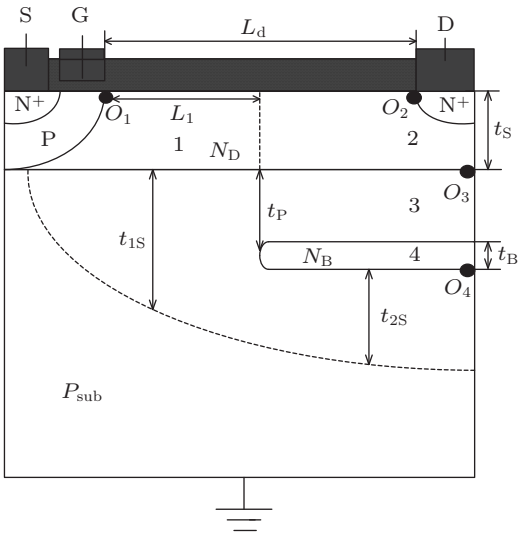



**Fig. 1.** Schematic cross section of the REBULF LDMOS.

In order to discuss the influences of the n-buried layer on the vertical electric field and the vertical breakdown voltage, the vertical electric field distribution is derived by substituting the two-order Taylor expanded formula into Eq. (8)[21] (where $L_1<x<L_d$) as follows:

$$E_{2y}(x,y)=\delta y,\quad 0\le y\le t_s, \tag{10}$$

$$E_{3y}(x,y)=\delta y-\frac{q(P_{sub}+N_D)}{\varepsilon_s}(y-t_S),$$

$$t_S\le y\le t_S+t_P, \tag{11}$$

$$E_{4y}(x,y)=\delta y-\frac{q(P_{sub}+N_D)}{\varepsilon_s}(y-t_S)+\frac{qN_B}{\varepsilon_s}(y-t_S-t_P),$$

$$t_S+t_P\le y\le t_D, \tag{12}$$

where

$$\delta=\frac{\varphi_2(x,0)}{t_R^2}-\frac{q}{\varepsilon_s}(N_{2,\mathrm{eff}}-N_D),\quad (L_1\le x\le L_d).$$

The vertical electric field distribution at $L_0<x<L_1$ can be easily obtained by using a similar approach.[22,23]

When the drift region is fully depleted, $|E_{3y}(L_d, t_S + t_P)| < \max[E_{2y}(L_d, t_S), E_{4y}(L_d, t_D)]$. So the vertical breakdown can only occur at $O_3$ or $O_4$, as seen in Fig. 1. When breakdown occurs at $O_3$, $E_{2y}(L_d, t_S) > E_{4y}(L_d, t_D)$. The vertical breakdown voltage $BV_{R1}$ can be obtained from $E_{2y}(L_d, t_S) = E_C$ as follows:

$$BV_{R1} = E_C \frac{t_R^2}{t_S} + \frac{q t_R^2}{\varepsilon_s}(N_{2,\text{eff}} - N_D). \tag{13}$$

When breakdown occurs at $O_4$, $E_{4y}(L_d, t_D) > E_{2y}(L_d, t_S)$. The vertical breakdown voltage $BV_{R2}$ can be obtained from $E_{4y}(L_d, t_D) = E_C$ as follows:

$$BV_{R2} = E_C \frac{t_R^2}{t_D} + \frac{q t_R^2}{\varepsilon_s}\left[(N_{2,\text{eff}} - N_D) + \frac{(P_{sub} + N_D)(t_P + t_B) - N_B t_B}{t_D}\right]. \tag{14}$$

The optimal vertical electric field distribution is obtained when $E_{2y}(L_d, t_S) = E_{4y}(L_d, t_D) = E_C$ and $P_{sub}(t_P + t_B) = N_B t_B$, hence the vertical breakdown voltage for REBULF LDMOS is:

$$BV_R = \frac{q t_R^2}{\varepsilon_s} N_{2,\text{eff}}. \tag{15}$$

## 3. Numerical results and optimization

In order to verify the modulation effect of the n-layer on the vertical electric field, the analytical and simulation results of the vertical electric field distribution at the right boundary of the device are discussed. The analytical results are based on Eqs. (10)–(15).

Figure 2 shows the analytical and numerical results of the vertical electric field distributions for REBULF LDMOS at different breakdown points. It can be seen that when $E_C = E_{2y}(L_d, t_S) > E_{4y}(L_d, t_D)$, breakdown occurs at point $O_3$ and $BV = 811$ V while when $E_{2y}(L_d, t_S) < E_{4y}(L_d, t_D) = E_C$, breakdown occurs at point $O_4$ and $BV = 893$ V. The highest breakdown voltage is obtained when $E_{2y}(L_d, t_S) = E_{4y}(L_d, t_D) = E_C$ and breakdown occurs simultaneously at points $O_3$ and $O_4$. The breakdown voltage is $BV = 1032$ V, of which the increments are $\Delta BV_1 = 221$ V and $\Delta BV_2 = 139$ V respectively. The analytical results of the vertical electric field distribution when $E_{2y}(L_d, t_S) = E_{4y}(L_d, t_D) = E_C$ are also plotted in Fig. 2(a) for comparison. Both the analytical and numerical results show that the optimal vertical electric distributions and the maximum breakdown voltage are obtained when $E_{2y}(L_d, t_S) = E_{4y}(L_d, t_D) = E_C$ under condition $P_{sub}(t_P + t_B) = N_B t_B$.

When designing REBULF LDMOS, the key parameters are $t_P$ and $t_B$. Figure 3 firstly gives the influence of $t_P$ on the breakdown voltage of REBULF LDMOS. Figure 3(a) shows that the breakdown voltage increases from 920 V at $t_P = 8$ μm to 1090 V at $t_P = 32$ μm, which implies that the REBULF effect is more significant with a larger depth of the buried n-layer. The analytical result of the vertical electric field distributions when $t_P = 16$ μm is also plotted in Fig. 3(a) for comparison. It can also be seen from Fig. 3 that as $t_P$ increases, the electric field peak $E_{3y}(L_d, t_S + t_P)$ at the lower boundary of the buried n-layer decreases until $t_P = N_D t_s / P_{sub}$ and $E_{3y}(L_d, t_S + t_P) = 0$. If $t_P$ continues to increase, then $E_{3y}(L_d, t_S + t_P) < 0$ and neither the p-substrate nor the buried n-layer can be fully-depleted, resulting in the breakdown voltage decreasing.[21] The optimal vertical electric field distributions and the maximum breakdown voltage are obtained when $E_{2y}(L_d, t_S) = E_{4y}(L_d, t_D) = E_C$ and $E_{3y}(L_d, t_S + t_P) = 0$, from which the optimal depth of the buried n-layer is obtained: $t_{P,op} = N_D t_s / P_{sub}$.

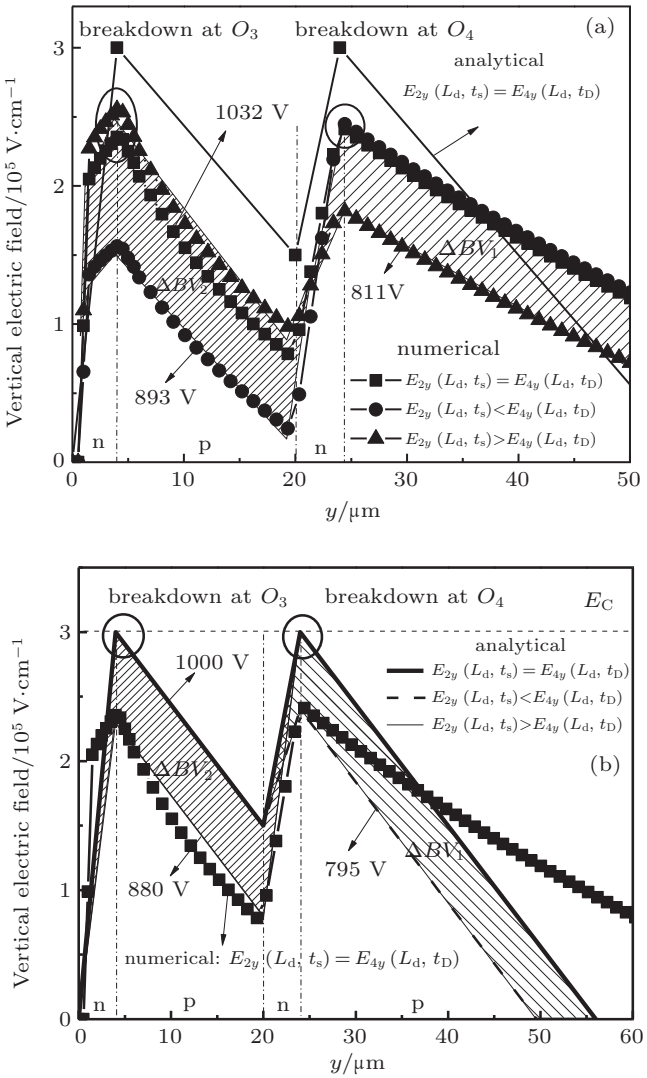



**Fig. 2.** Numerical (a) and analytical (b) results of the vertical electric field distributions for REBULF LDMOS at different breakdown points with $t_S = 4$ μm, $t_P = 16$ μm, $t_B = 4$ μm, $L_d = 100$ μm, $L_1 = 50$ μm, $P_{sub} = 2 \times 10^{14}$ cm$^{-3}$, $E_C = 3 \times 10^5$ V/cm.

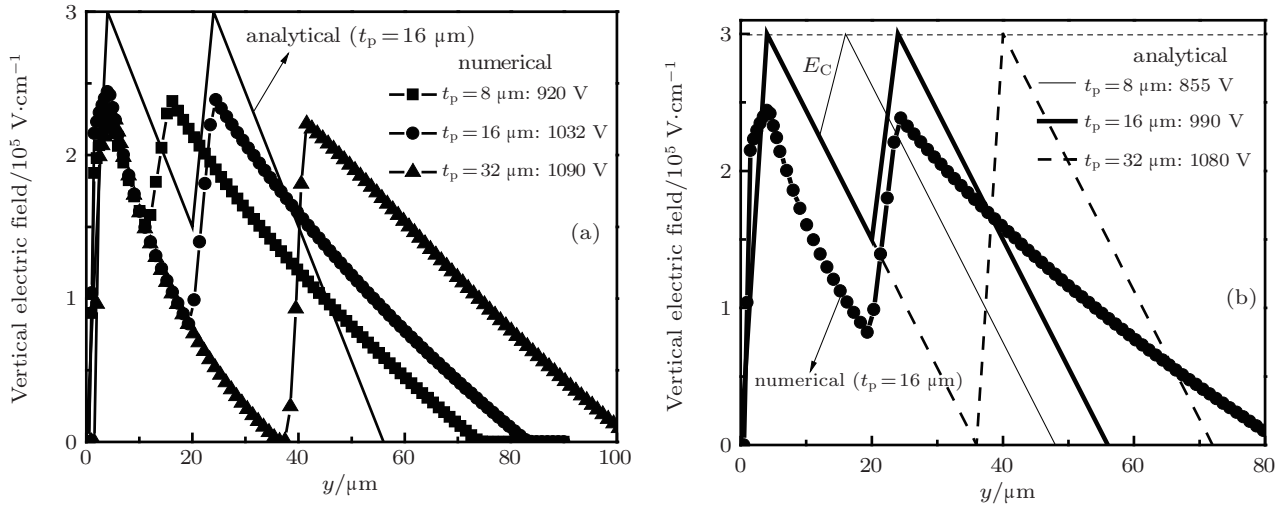



**Fig. 3.** Influences of $t_P$ on the breakdown voltage of REBULF LDMOS, obtained numerically (a) and analytically (b) with $t_S = 4$ μm, $t_B = 4$ μm, $L_d = 100$ μm, $L_1 = 50$ μm, $N_D = 1.7 \times 10^{15}$ cm$^{-3}$, $P_{sub} = 2 \times 10^{14}$ cm$^{-3}$, $E_C = 3 \times 10^5$ V/cm.

It is worth noting that the above discussion about vertical electric field optimization is all under the REBULF condition. The optimal surface electric field distribution is obtained when $E_1(0,0) = E_2(L_d,0) \le E_C$ where $E_i(x,0)$ is described as

$$E_1(x,0) = (V_1 - \frac{qN_Dt_1^2}{\varepsilon_s})\frac{\cosh(x/t_1)}{t_1\sinh(L_1/t_1)} + \frac{qN_Dt_1^2}{\varepsilon_s}\frac{\cosh[(L_1-x)/t_1]}{t_1\sinh(L_1/t_1)}, \quad 0 \le x \le L_1, \tag{16}$$

$$E_2(x,0) = (V_d - \frac{qN_{2,eff}t_R^2}{\varepsilon_s})\frac{\cosh[(x-L_1)/t_R]}{t_R\sinh[(L_d-L_1)/t_R]} - \left(V_1 - \frac{qN_{2,eff}t_R^2}{\varepsilon_s}\right)\frac{\cosh[(L_d-x)/t_R]}{t_R\sinh[(L_d-L_1)/t_R]}, \quad L_1 \le x \le L_d, \tag{17}$$

where $V_1$ is the surface potential of boundary 1–2 and can be calculated from potential continuity equations.[24] The REBULF criterion is then obtained ($2L_1 = L_d$) as follows:

$$\frac{N_Dt_1^2[2\sinh(L_d/2t_R)-1][\sinh(L_d/2t_1)-1]+N_{2,eff}t_R^2[\sinh(L_d/2t_R)-1]}{2t_1\sinh(L_d/2t_1)\sinh(L_d/2t_R)-t_R\sinh(L_d/2t_R)-t_1\sinh(L_d/2t_1)} \le \frac{E_C\varepsilon_S}{q}. \tag{18}$$

From the optimization of the vertical electric field distribution, it can be concluded that the optimal vertical electric field distribution of REBULF LDMOS is obtained when $E_{2y}(L_d,t_S) = E_{4y}(L_d,t_D) = E_C$ and $E_{3y}(L_d,t_S+t_P) = 0$ under the conditions of $P_{sub}(t_P+t_B) = N_Bt_B$ and $t_PP_{sub} = N_Dt_s$. Substituting the two expressions into Eq. (9), the equivalent concentration $N_{2,eff}$ can be rewritten as $N_{2,eff} = N_Dt_s/t_D$. So the REBULF criterion can be rewritten as

$$N_D\left\{\frac{t_1^2[2\sinh(L_d/2t_R)-1][\sinh(L_d/2t_1)-1]+0.5t_S(t_D+t_{2S})[\sinh(L_d/2t_R)-1]}{2t_1\sinh(L_d/2t_1)\sinh(L_d/2t_R)-t_R\sinh(L_d/2t_R)-t_1\sinh(L_d/2t_1)}\right\} \le \frac{E_C\varepsilon_S}{q}. \tag{19}$$

Figure 4 shows the REBULF LDMOS doping optimal region under optimal vertical electric field distribution condition. Both the analytical and numerical results are in the REUBLF design area according to Ref. [9]. It can also be seen that for small values of $t_P$ and $t_B$, since $\sinh(L_d/2t_1) \gg 1$ and $\sinh(L_d/2t_R) \gg 1$, equation (19) reduces to an equation under the single RESURF condition $N_Dt_1 \le E_C\varepsilon_S/q$. This indicates that the REBULF effect becomes weak with small values of $t_P$ and $t_B$.

Figure 5 shows the influences of $t_B$ on the breakdown voltage of REBULF LDMOS. It can be seen from Fig. 5(a) that the breakdown voltage increases from 1032 V at $t_B = 4$ μm to 1197 V at $t_B = 16$ μm, and from Fig. 5(b) it follows that the breakdown voltage increases from 1080 V at $t_B = 4$ μm to 1260 V at $t_B = 16$ μm because the REBULF effect is more remarkable with a larger thickness of the buried n-layer. However, as seen in Fig. 5(a), when $t_B = 32$ μm, the numerical result is much smaller than analytical result ($BV = 1162$ V$<1500$ V) because $E_{3y}(L_d,t_S+t_P) < 0$, neither the p-substrate nor the buried n-layer can be fully-depleted. According to REBULF condition Eq. (19), even if the vertical electric field is optimized, the drift doping decreases with the

value of $t_B$ increasing, as seen in Fig. 6. On the one hand, when $t_P = 4$ μm, $N_D$ approximately decreases by $\Delta N_{Dl}$ as $t_B$ increases from 5 μm to 30 μm and when $t_B = 5$ μm $N_D$ also decreases by $\Delta N_{Dl}$ as $t_P$ increases from 4 μm to 32 μm. On the other hand, when $t_P = 32$ μm, $N_D$ approximately decreases by $\Delta N_{Dh}$ as $t_B$ increases from 5 μm to 30 μm and when $t_B = 30$ μm, $N_D$ decreases by $\Delta N_{Dh}$ as $t_P$ increases from 4 μm to 32 μm. Considering $\Delta N_{Dh} \approx 2\Delta N_{Dl}$, it can be concluded that to satisfy both the optimal vertical electric field distribution condition and the REBULF criterion, the optimal design is a thin n-layer buried deep into the p-substrate or a thick n-layer buried shallowly into the p-substrate. Otherwise, the breakdown voltage will be reduced as a result of a non-depleted effect or the on-resistance will be increased due to the decrease of drift doping.

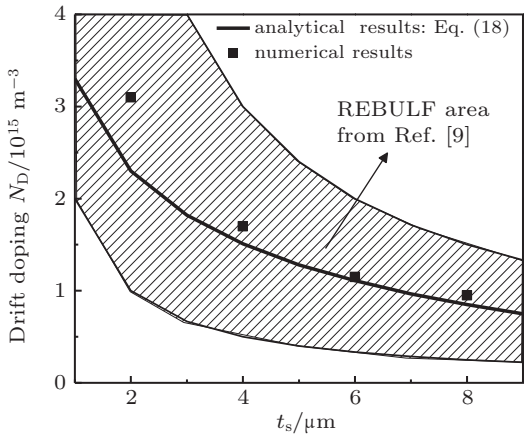



**Fig. 4.** REBULF LDMOS doping optimal region with $L_1 = 50$ μm, $L_d = 100$ μm, $t_P = 32$ μm, $t_B = 16$ μm, $E_C = 3 \times 10^5$ V/cm. The shaded area represents the REBULF region from Ref. [9].

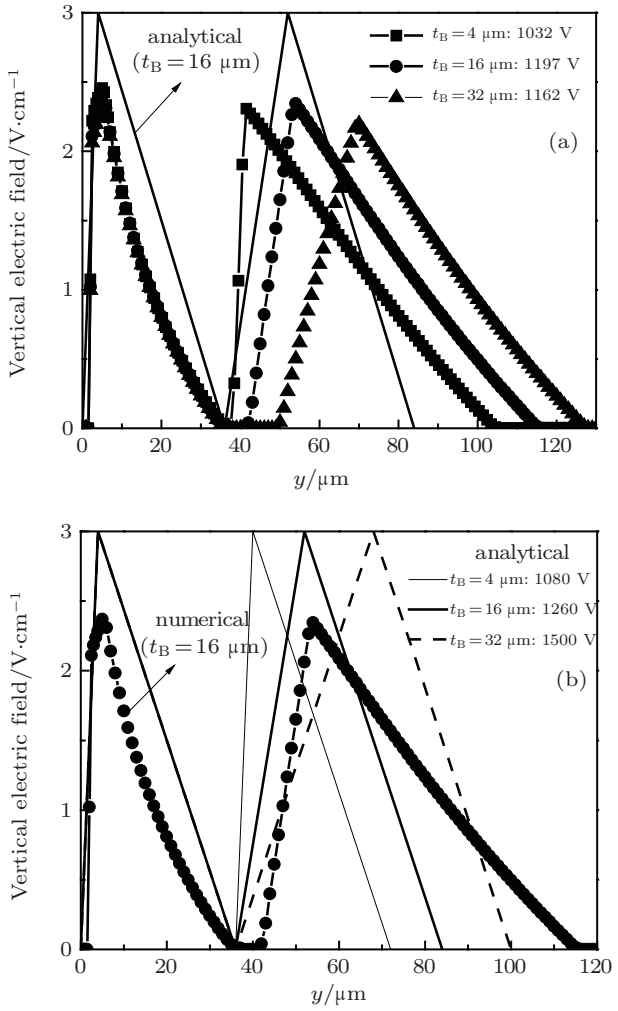



**Fig. 5.** Influences of $t_B$ on the breakdown voltage of REBULF LDMOS, obtained numerically (a) and analytically (b) with $t_S = 4$ μm, $t_P = 32$ μm, $L_d = 100$ μm, $L_1 = 50$ μm, $N_D = 1.7 \times 10^{15}$ cm$^{-3}$, $E_C = 3 \times 10^5$ V/cm.

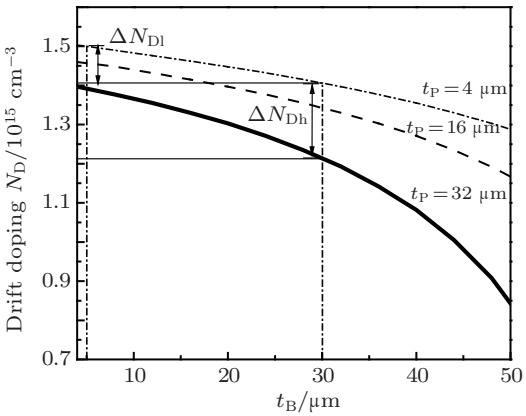



**Fig. 6.** Relationships between $N_D$ and $t_B$ at different $t_P$ values under the REBULF criterion and optimal vertical electric field distribution condition with $t_S = 4$ μm, $L_d = 100$ μm, $L_1 = 50$ μm, $E_C = 3 \times 10^5$ V/cm.

To design REBULF LDMOS, both the REBULF criterion and optimal vertical electric field condition must be satisfied. The vertical breakdown voltage of REBULF LDMOS Eq. (15) can be rewritten as follows:

$$\begin{aligned} BV_R &= \frac{qN_D t_s(t_S + t_P + t_B + t_{2S})}{2\varepsilon_s} \\ &= BV_S\left(1 + \frac{t_B + t_P + t_{2S} - t_{sub}}{t_S + t_{sub}}\right), \end{aligned} \tag{20}$$

where $BV_S$ and $t_{sub}$ are the breakdown voltage and the width of the substrate depletion layer of single RESURF LDMOS. It can be seen from Eq. (20) that the breakdown voltage of the REBULF LDMOS is always higher than that of single RESURF LDMOS. Moreover, the breakdown voltage increases with $t_B$ and $t_P$ values increasing, which is consistent with the previous analysis. In a word, on the premise of a certain on-resistance, the maximum n-layer depth and thickness are determined according to the REBULF criterion and the blocking capability of the REBULF LDMOS is obtained. So, it is better to make a thick n-layer buried deep into the substrate under the REBULF criterion and the optimal vertical electric field distribution condition.

## 4. Conclusions

The buried layer optimal design method for REBULF LDMOS is discussed in this paper. A 2D analytical model

mainly for the vertical electric field distribution and optimization of high voltage REBULF LDMOS is presented. The REBULF criterion and the optimal vertical electric field distribution condition are derived on the basis of the optimization of the electric field distributions. The influences of the buried n-layer parameters such as its depth, thickness, and doping concentration on breakdown voltage are discussed in detail with both analytical and numerical results. Finally, the quantitative relationship of the breakdown voltage between single RESURF and REBULF LDMOS is obtained. It indicates that under the REBULF criterion and the optimal vertical electric field distribution condition, it is better to make a thick n-layer buried deep into the p-substrate.

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