A charge allocating model for the breakdown voltage calculation and optimization of the lateral RESURF devices

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Abstract: A new quite simple analytical model based on the charge allocating approach has been proposed to describe the breakdown property of the RESURF (reduced surface field) structure. It agrees well with the results of numerical simulation on predicting the breakdown voltage. Compared with the latest published analytical model, this model has a better accuracy according to the numerical simulation with simpler form. The optimal doping concentration (per unit area) of the epi-layer of the RESURF structures with different structure parameters has been calculated based on this model and the results show no significant discrepancy to the data gained by others. Additionally the physical mechanism of how the surface field is reduced is clearly illustrated by this model.

Key words: RESURF devices; analytical model; breakdown voltage; device optimization

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1. Introduction

Lateral DMOS (LDMOS) devices have been widely used in the high voltage integrated circuit (HVIC). The RESURF technique is one of the most applied methods for the design of high-voltage LDMOS with low on-resistance[1,2]. As shown in Fig. 1(a), the RESURF structure is constructed by a lateral P^+/N^- (P^+/N-epi) diode that defines the on-resistance characteristic of the device and a vertical P^-/N^- (P-sub/ N-epi) diode which supports a space-charge depletion region enabling high breakdown voltage. The basic properties of RESURF structures are determined by three parameters: the substrate doping concentration ($P_{\rm sub}$), the epitaxial layer doping concentration ($N_{\rm epi}$), and the epitaxial layer thickness ($T_{\rm epi}$). The surface electrical field of P^+/N-epi junction is reduced largely compared to the case without P-sub due to the interaction between the lateral P^+/N-epi junction and the vertical P-sub/N-epi junction.

Conventionally the properties of the RESURF devices are analyzed by computer aided numerical simulation. The analytical models generally reported in the literature focused on estimating the RESURF optimal epi-layer charge $Q_{\rm epi} = N_{\rm epi}T_{\rm epi}$ using a simple one-dimensional solution[1,3,4]. The solution in Refs. [1, 3, 4] focused only on providing a qualitative representation of the breakdown characteristics. In this paper, a simple one-dimensional analytical model based on the idea of charge allocating is proposed to describe the breakdown property of the RESURF structure. It shows a much better accuracy than the analytical model reported in Ref. [5]. The deductive process of those equations to build up this model is clear and simple. Finally the optimal epi-layer dose has been calculated based on this model.

2. Analysis

At any given applied reverse voltage $V_{\rm app}$, the basic RESURF structure shown in Fig. 1(a) can be considered as a composite of two 1-D planar diodes as shown in Figs. 1(b) and 1(c). The lateral P/N junction and vertical P/N junction in the RESURF structure are interactional because they share the positive depletion charges in the N-epi. Here we assume (1) electrical field lines generated from a positive charge must be directed to and end up at a negative charge; (2) electrical field lines generated from a positive charge incline to be directed to and end up at a nearest available negative charge to build the

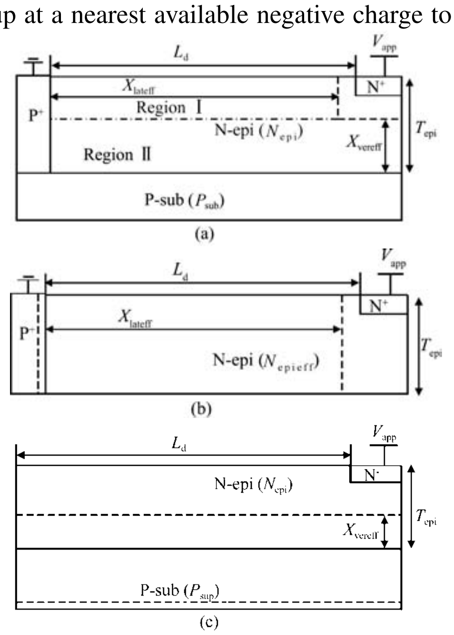

Fig. 1. (a) Basic RESURF structure demonstrating the charge allocating; (b) Lateral diode space-charge component; (c) Vertical diode space-charge component.

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potential. Then if $L_d >> T_{epi}$, the positive depletion charges in the N-epi can be divided into two parts one of which in Region I (see Fig. 1(a)) corresponding to the negative depletion charges in the P^+ region is allocated to the lateral P^+/N-epi junction and the other part in Region Π (see Fig. 1(a)) corresponding to the negative depletion charges in the P-sub is allocated to the vertical P-sub/N-epi junction. After this allocation, the lateral junction and the vertical junction are decoupled and can be taken as stand alone abrupt junction, namely, a lateral P^+/N-epi junction shown in Fig. 1(b) and a vertical P-sub/N-epi junction shown in Fig. 1(c), both held at the same applied voltage V_{app}.

For the vertical P-sub/N-epi junction shown in Fig. 1(c), $X_{vereff}(V_{app})$ represents the spreading of the depletion region into the N-epi region and is given by

$$X_{vereff}(V_{app}) = \sqrt{\frac{2\varepsilon_s V_{app} P_{sub}}{qN_{epi}(P_{sub} + N_{epi})}}, \quad (1)$$

where q is the electronic charge and ε_s is the dielectric constant of silicon. The charge (per unit area) supported by $X_{vereff}(V_{app})$ is given by $Q_{ver}(V_{app}) = qN_{epi}X_{vereff}(V_{app})$. Considering vertical reach-through and nonreach-through conditions, a generalized single expression for the vertical breakdown voltage can be derived and is given by

$$\mathrm{BV}_{ver} = \frac{\mathrm{Min}[T_{epi}, X_{vereff}(\mathrm{BV}_{verj})]}{X_{vereff}(\mathrm{BV}_{verj})} \times \left\{2 - \frac{\mathrm{Min}[T_{epi}, X_{vereff}(\mathrm{BV}_{verj})]}{X_{vereff}(\mathrm{BV}_{verj})}\right\} \times \frac{\varepsilon_s E_{cver}^2}{2qN_{epi}} + \frac{\varepsilon_s E_{cver}^2}{2qP_{sub}}, \quad (2)$$

where BV_{verj} is the junction breakdown voltage ignoring vertical reach-through and is given by $\mathrm{BV}_{verj} = (\varepsilon_s E_{cver}^2/2q)(1/N_{epi} + 1/P_{sub})$. E_{cver} is the critical electrical field of the P-sub/N-epi junction which can be given by $E_{cver} = 3.5 \times 10^5/(1 - 0.33\lg\lambda)$[7] where $\lambda = N_{epi}P_{sub}/[10^{16}(N_{epi} + P_{sub})]$. $\mathrm{Min}[a, b]$ is a function that returns the minimum of the two variables a and b.

Referring to Fig. 1(a), the positive charge in Region I is given by $qN_{epi}(T_{epi} - X_{vereff}(V_{app}))X_{lateff}(V_{app})$ where $X_{lateff}(V_{app})$ represents the depletion region extension into the N-epi layer for the lateral junction at V_{app} (see Fig. 1(c)). Then the charge (per unit area) supported by X_{lateff} and the corresponding electric field at the P^+/N junction are given by

$$Q_{lat}(V_{app}) = qN_{epi}(T_{epi} - X_{vereff}(V_{app}))\frac{X_{lateff}(V_{app})}{T_{epi}} \quad (3)$$

$$E_{lat}(V_{app}) = \frac{Q_{lat}(V_{app})}{\varepsilon_s}. \quad (4)$$

As is known, for a planar P^+/N abrupt junction,

$$V_{app} = \frac{1}{2}E_{lat}(V_{app})X_{lateff}(V_{app}). \quad (5)$$

Combing Eqs.(3)–(5), E_{lat} can be derived by

$$E_{lat}(V_{app}) = \pm\sqrt{qN_{epi}\left|T_{epi} - X_{vereff}(V_{app})\right|\frac{2V_{app}}{T_{epi}E_s}}. \quad (6)$$

Actually the charges allocated to the lateral junction are a little more than that defined by Region I (or by Eq.(3)), so X_{vereff} in Eq.(6) should be multiplied by a factor of 0.75 and Equation (6) is renewed as

$$E_{lat}(V_{app}) = \pm\sqrt{qN_{epi}\left|T_{epi} - 0.75X_{vereff}(V_{app})\right|\frac{2V_{app}}{T_{epi}E_s}}. \quad (7)$$

The method to calculate the breakdown voltage can be described as following. Firstly the value of BV_{ver} can be derived by solving Eqs. (1) and (2). Secondly calculating $E_{lat}(V_{app})$ repeatedly with increasing V_{app} by solving Eqs. (1) and (7) until $|E_{lat}(V_{app})| > E_{clat}$. E_{clat} represents the critical field of the P^+/N-epi junction and is given by $E_{clat} = 3.4 \times 10^5/[1\text{–}0.38\times \lg(N_{epi}/10^{16})]$[7]. Once this E_{lat} calculation is finished, BV_{lat} defined as the maximum value of V_{app} is gained as the breakdown voltage of the lateral junction. The breakdown voltage of the RESURF structure is determined by the minimum value of BV_{lat} and BV_{ver}. In other words,

$$\mathrm{BV}_{resurf} = \mathrm{Min}[\mathrm{BV}_{lat}, \mathrm{BV}_{ver}]. \quad (8)$$

If $\mathrm{BV}_{lat} > \mathrm{BV}_{ver}$, the breakdown occurs at the vertical junction, otherwise occurs at the lateral junction.

3. Discussion

Referring to Fig. 1(b), the effective charge (per unit area) in the epi-layer for the lateral junction is defined as N_{epieff} and given by $N_{epieff} = N_{epi}(T_{epi} - X_{vereff}(V_{app}))\ X_{lateff}(V_{app})/T_{epi} = N_{epi}(1\text{-}\eta(V_{app}))$. If $\eta(V_{app}) > 1$, N_{epieff} becomes negative and the negative value of Eq. (7) should be selected for E_{lat}. That means the already fully depleted "N-type" epi-layer now appears to behave as "P-type" equivalent so the breakdown point has been shifted from the P^+/N-epi junction to the N^+/N-epi junction. The calculated E_{lat} and N_{epieff} variations with V_{app} are shown in Fig. 2. It can be seen that E_{lat} increases with V_{app} firstly and then decreases. After the N_{epieff} becomes negative, E_{lat} increases again but in the reverse direction until the breakdown happens.

Once the voltage V_{app} is applied, the depletion region in epi-layer will be extended with increased V_{app}. If the doping concentration of epi-layer is high enough, T_{epi} is made thick or P_{sub} is very low, the breakdown will happen at the lateral P^+/N-epi junction (in such situation $E_{lat}(\mathrm{BV}_{lat}) > 0$, $\mathrm{BV}_{lat} < \mathrm{BV}_{ver}$) before the epi-layer is entirely depleted.If the doping concentration (per unit area) of the epi-layer is low, the epi-layer will be depleted completely before breakdown happens. When $E_{lat}(\mathrm{BV}_{lat}) < 0$, $\mathrm{BV}_{lat} < \mathrm{BV}_{ver}$, the breakdown

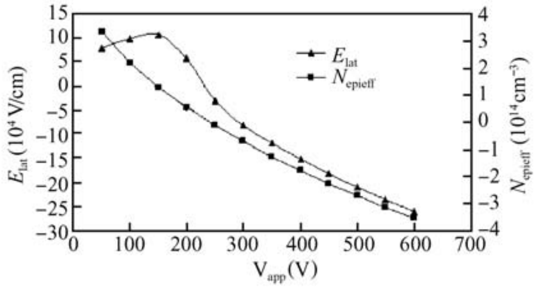

Fig. 2. Calculated E_{lat} and N_{epieff} variations with V_{app}. $N_{epi} = 6.15 \times 10^{14}$ cm^{-3}, $T_{epi} = 10\,\mu$m, $N_{sub} = 1.48 \times 10^{14}$ cm^{-3} and $L_d = 100\,\mu$m.

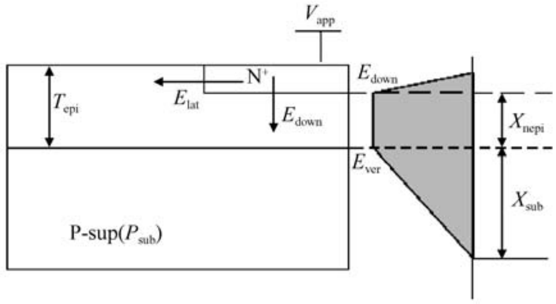

Fig. 3. Illustration of the components of the electrical field at the breakdown point of the N$^+$/N-epi junction.

Table 1. Comparison of the junction field.

V_{app}	E_{lat} (10^4V/cm)	E_{alone} (10^4V/cm)
50	7.84	9.66
100	9.82	13.7
150	10.7	16.7
200	5.75	19.3
250	3.18	21.6

happens at the lateral N$^+$/N-epi junction. If the design is carefully optimized to achieve high breakdown voltage, the breakdown will happen at the vertical P-sub/N-epi junction in which case $E_{lat}(BV_{lat}) < 0$ and $BV_{lat} > BV_{ver}$.

If the breakdown happens at the N$^+$/N-epi junction, the electrical field at the breakdown point defined as $E_{tot}(V_{app})$ actually includes two components the lateral one of which is given by Eq. (7). As shown in Fig. 3,

$$E_{tot}(V_{app}) = \sqrt{E_{lat}{}^2(V_{app}) + E^2_{down}(V_{app})}, \qquad (9)$$

where $E_{down}(V_{app}) = (X_{vereff}(V_{app}) - X_{nepi})/X_{vereff}(V_{app}) \times 2V_{app}/(X_{sub}(V_{app}) + X_{vereff}(V_{app}))$, and $X_{sub}(V_{app}) = N_{epi} \times X_{vereff}(V_{app})/P_{sub}$.

This model gives a clear insight on the mechanism of the RESURF technique. The electrical field at the P$^+$/N-epi junction is reduced compared to the case of the standalone junction because only a part of the positive depletion charges in the epi-layer are corresponding to the negative charges in P$^+$ region and the electrical field lines generated from most of them are led to the negative depletion charges

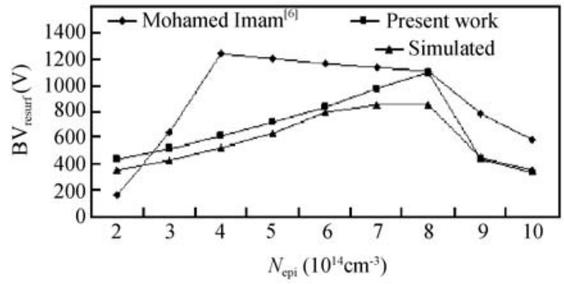

Fig. 4. The calculated breakdown voltage according to present work, the model reported in Ref. [5] and the simulated results.

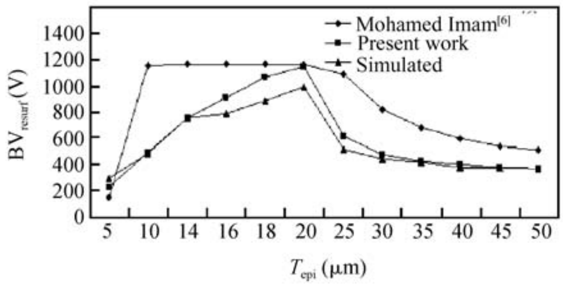

Fig. 5. The calculated breakdown voltage according to present work, the model reported in Ref. [5] and the simulated results.

in the P-sub region. The quantitative comparison between them has been given in Table 1. When $X_{vereff} = T_{epi}$, most of the positive charges in epi-layer are corresponding to the negative charges in the P-sub region. If V_{app} continues to increase, a part of N$^+$ region (the drain region) will be depleted because no more positive charges can be generated in N-epi layer to correspond to the extra negative charges generated in the P-sub region after N-epi layer has been entirely depleted. The electrical field lines generated from the depletion charges in the N$^+$ region will be led to the negative depletion charges in the P-sub region to build higher potential and it increases the electrical field at the N$^+$/N-epi junction. Thus it seems that the depletion charges in the epi-layer become negative from the viewpoint of the N$^+$/N-epi junction.

4. Results

According to the equations and description mentioned above, a program to calculate the breakdown voltage can be made. The calculated breakdown voltages as a function of epi-layer concentration are shown in Fig. 4 for $T_{epi} = 15\,\mu$m, $L_d = 100\,\mu$m and $P_{sub} = 1.7 \times 10^{14}$ cm^{-3}. For comparison, the calculated results according to the model reported in Ref. [5] and the simulated results also have been plotted. The simulated data are provided by the software of Silvaco Atlas and the simulated structures are directly created in the software of Silvaco Devedit with the same shape as that shown in Fig. 1(a). Figure 5 shows the calculated breakdown voltage variations with the epi-layer thickness for $N_{epi} = 6 \times 10^{14}$ cm^{-3}, $N_{sub} = 1.7 \times 10^{14}$ cm^{-3} and $L_d = 100\,\mu$m. A better agreement with the simulated results can be seen compared with the data given by the model reported in Ref. [5].

Table 2. Calculated optimal epi-layer concentration per unit area (cm^{-2}).

Case	P_{sub}	N_{epi}	Ref. [6]	This paper
1	5×10^{13}	0.8×10^{15}	0.4×10^{12}	0.7×10^{12}
2	1×10^{14}	1.2×10^{15}	0.6×10^{12}	0.8×10^{12}
3	2×10^{14}	1.8×10^{15}	0.9×10^{12}	1.0×10^{12}
4	3×10^{14}	2.4×10^{15}	1.2×10^{12}	1.2×10^{12}
5	4×10^{14}	2.9×10^{15}	1.5×10^{12}	1.3×10^{12}

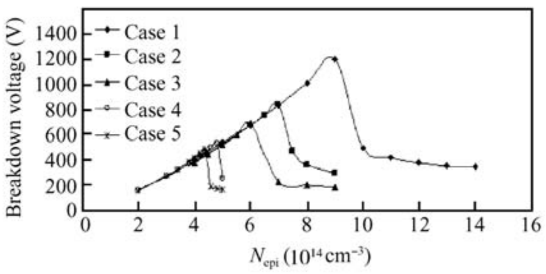

Fig. 6. Calculated breakdown voltage BV_{resurf} versus T_{epi} for different P_{sub} and N_{epi}.

For RESURF devices, the epi-layer concentration (per unit area) $N_{epi}T_{epi}$ should be carefully decided to achieve high breakdown voltage. For different P_{sub} and N_{epi}, the optimal values of $N_{epi}T_{epi}$ are calculated and listed in Table 2 along with the data reported in Ref. [6]. The calculated breakdown voltage variations versus T_{epi} for the 5 cases described in Table 2 are plotted in Fig. 6. For each case, when the breakdown voltage reaches maximum the optimal epi-layer dose has been derived.

The model in this paper gives a clear insight on the physical mechanism of the RESURF technique and a quite simple way to estimate the breakdown voltage of RESURF devices. It will be helpful to the designers by providing accurate first-order design schemes on the optimization of RESURF devices.

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