An improved analytical model for the electric field distribution in an RF-LDMOST structure

Jiang Yibo(姜一波)†, Wang Shuai(王帅), Li Ke(李科), Chen Lei(陈蕾), and Du Huan(杜寰)

(Institute of Microelectronics, Chinese Academy of Sciences, Beijing 100029, China)

Abstract: This paper presents an improved analytical model for an RF-LDMOST structure based on the 2D Poisson equation. The derived model indicates the influence of high doped shallow drift and low doping concentration p epitaxial layer on the electric field distribution. In particular, the importance of the thickness of the p epitaxial layer for electric field distributions in RF-LDMOST are shown through MATLAB analytical results based on the model. Then ISE TCAD simulations and experiments are processed and their results are in agreement with the analytical model. This model contributes to the comprehension and optimization design of RF-LDMOST.

Key words: RF-LDMOST; analytical model; thickness of p epitaxial layer
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1. Introduction

The lateral double-diffused MOS transistor (LDMOST) is a type of high voltage device developed in the past few years. With the improvement of shallow drift region and low concentration p epitaxial layer, the RF-LDMOST emerges as a power amplifier due to its high voltage capability and excellent RF performance. As a result of the specific structure, both the $R_{\rm dson}$ (drain to source on-resistance) and $C_{\rm rss}$ (reverse capacitance) are reduced a lot and linearity is much improved. The RF-LDMOST is suitable for RF applications because of these advantages, like high power capability, impressive linearity and power gain.

For LDMOST, many factors affect the device performance, such as gate length, channel doping concentration and drift region length. To reveal the relationships between these parameters and device performance, various analytical models have been proposed. Based on the drift region charge, Wildi proposed a simplified model and Imam improved it[1, 2]. On the basis of the Poisson equation, He and Li modeled the bulk silicon and SOI LDMOST, respectively[3, 4]. Based on the physical origin, Kim processed the modeling work well[5]. However, all of these models are proposed for the conventional LDMOST. Compared with the conventional one, the structure of RF-LDMOST is specifically illustrated in Fig. 1. These models mentioned above are not fit for RF-LDMOST because they cannot explain the influence of the high doped shallow and p epitaxial layer, especially the thickness of the p epitaxial layer. An improved model is therefore required for RF-LDMOST. In this paper, an analytical model for RF-LDMOST is provided on the basis of a 2D Poisson equation, and the electric field distributions in RF-LDMOST are simulated with MATLAB. The influence of drift region doping concentration ($N_{\rm d}$), p epitaxial layer doping concentration ($N_{\rm e}$) and thickness ($T_{\rm e}$) will be discussed and validated through the device simulation through ISE TCAD simulations and experimental results.

2. Analytical model

For the analytical model, the cross section of RF-LDMOST is shown in Fig. 2. The horizontal x and vertical y constitute the coordinates. The most important region is NHV, which is named as drift or LDD region sometimes as well. LDMOST could suffer the high voltage applied at the $V_{\rm dd}$ due to the depleted NHV according to the RESURF principle[6]. Differing from the low doped and deep NHV of conventional LDMOST, RF-LDMOST has a high doped and shallow NHV. The length and thickness of NHV are defined as $L_{\rm d}$ and $T_{\rm d}$, respectively. Pepi is p epitaxial layer and its depletion thickness is t_1. The whole epitaxial layer under NHV is depleted because of its very low concentration, which is indicated by a dashed line. t_2 is depleted in thickness in Psub (p$^+$ substrate). In addition, NSD forms n$^+$ ohmic contact and PHV is the lateral diffusion region. Psinker shorts the terminals of the source and substrate directly.

The model is proposed based on the following assumptions:

(1) The doping concentrations of the Psub and the Psinker are ultra high. (2) The doping concentrations of all regions are uniform in both x and y directions. (3) The PN junctions are assumed to be abrupt junctions. (4) All of the depletion regions deplete completely.

The Poisson equation in NHV is formulated by

$$\begin{aligned}\frac{\partial^2\phi(x,y)}{\partial x^2}+\frac{\partial^2\phi(x,y)}{\partial y^2}&=\frac{-\rho(x,y)}{\varepsilon_{\rm si}}\\&=-\frac{q}{\varepsilon_{\rm si}}\left[N_{\rm d}(x,y)-N_{\rm e}(x,y)+p-n\right].\qquad(1)\end{aligned}$$

Solving Eq. (1) above by integrating over the y direction, the Poisson equation in NHV is redescribed as:

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† Corresponding author. Email: jybjybjyb@gmail.com

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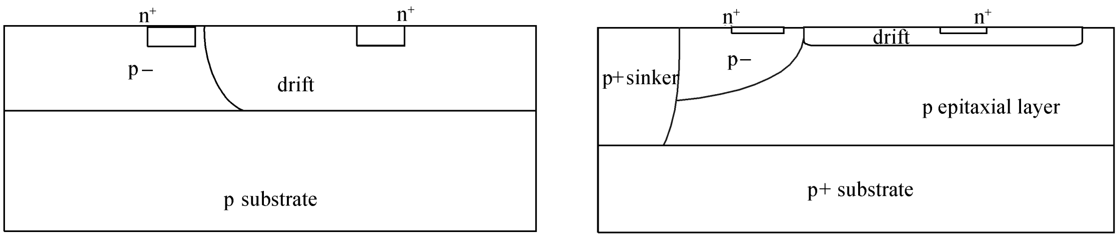

(a) (b)

Fig. 1. Structures of (a) conventional LDMOST and (b) RF-LDMOST.

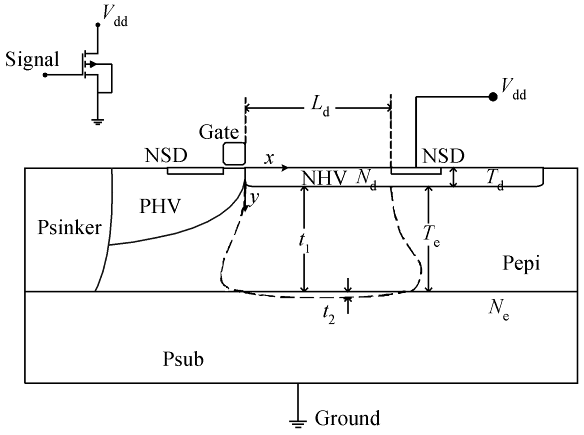

Fig. 2. Cross section of RF-LDMOST.

$$\int_0^{T_d} \frac{\partial^2\phi(x,y)}{\partial x^2}\mathrm{d}y + \left.\frac{\partial\phi(x,y)}{\partial y}\right|_{y=T_d} - \left.\frac{\partial\phi(x,y)}{\partial y}\right|_{y=0} = -\int_0^{T_d}\frac{q}{\varepsilon_{si}}\left[N_d(x,y)-N_e(x,y)+p-n\right]. \tag{2}$$

Considering that NHV of RF-LDMOS is very shallow and completely depleted in general, we can get the approximation

$$\int_0^{T_d} \frac{\partial^2\phi(x,y)}{\partial x^2}\mathrm{d}y = \int_0^{T_d} \frac{\partial^2\phi(x,0)}{\partial x^2}\mathrm{d}y. \tag{3}$$

Adding to the $N_d(x,y) - N_e(x,y) + p - n \approx N_d(x,y) \approx N_d$ in the depletion region, the simplified expression of Eq. (1) is

$$\int_0^{T_d} \frac{\partial^2\phi(x,0)}{\partial x^2}\mathrm{d}y + \left.\frac{\partial\phi(x,y)}{\partial y}\right|_{y=T_d} - \left.\frac{\partial\phi(x,y)}{\partial y}\right|_{y=0} = -\frac{qN_d}{\varepsilon_{si}}, \tag{4}$$

$$\left.\frac{\partial\phi(x,y)}{\partial y}\right|_{y=0} = 0, \tag{5}$$

$$\left.\frac{\partial\phi(x,y)}{\partial y}\right|_{y=T_d} = \xi(x,T_d) = -\frac{2\left[\phi(x,0)-\phi(x,T_d)\right]}{T_d}. \tag{6}$$

With the combination of Eqs. (4)–(6), a differential equation is expressed finally as

$$\frac{\partial^2\phi(x,0)}{\partial x^2} - \lambda\phi(x,0) = C, \tag{7}$$

where λ and C are not relevant with x. And focusing on the specific structure of RF-LDMOST, we can get the relationship between the field and the potential over vertical y as

$$\begin{aligned}&\phi(x,T_d) - \phi(x,T_d+T_e)\\ &= \frac{T_e(-\xi(x,T_d)+\xi(x,T_d+T_e))}{2} - T_e\xi(x,T_d+T_e),\end{aligned} \tag{8}$$

$$\phi(x,T_d+T_e) = -\frac{t_2\xi(x,T_d+T_e)}{2}, \tag{9}$$

$$\frac{\xi(x,T_d)-\xi(x,T_d+T_e)}{T_e} = -\frac{qN_e}{\varepsilon_{si}}, \tag{10}$$

where N_d and N_e mean a doping concentration of NHV and Pepi, respectively. Owing to the ultra high concentration of Psub, $t_2 \to 0$ can be approximated. From Eqs. (8)–(10), we get

$$C = -\frac{qN_d}{\varepsilon_{si}} + \frac{qN_e}{2\varepsilon_{si}}\frac{T_e^2}{(T_d+2T_e)T_d}, \tag{11}$$

$$\lambda = \frac{2}{(T_d+2T_e)T_d}. \tag{12}$$

Considering the boundary condition $\phi(0,0) = 0$ and $\phi(L_d,0) = V_d$, the differential equation is solved to be

$$\phi(x,0) = \frac{C}{\lambda} + \frac{\left(V_d - \dfrac{C}{\lambda}\right)\sinh\dfrac{x}{\sqrt{\lambda}} - \dfrac{C}{\lambda}\sinh\dfrac{L_d-x}{\sqrt{\lambda}}}{\sinh\dfrac{L_d}{\sqrt{\lambda}}}. \tag{13}$$

According to $\xi_m = -\Delta\phi$, the surface electric field expresses as

$$\xi(x,0) = -\frac{\left(V_d - \dfrac{C}{\lambda}\right)\cosh\dfrac{x}{\sqrt{\lambda}} + \dfrac{C}{\lambda}\cosh\dfrac{L_d-x}{\sqrt{\lambda}}}{\sqrt{\lambda}\sinh\dfrac{L_d}{\sqrt{\lambda}}}. \tag{14}$$

In the result of analytical model, λ and C depend on T_e, T_d, N_e and N_d apparently referring to Eqs. (11) and (12). Although its final expression from Eqs. (13) and (14) is similar

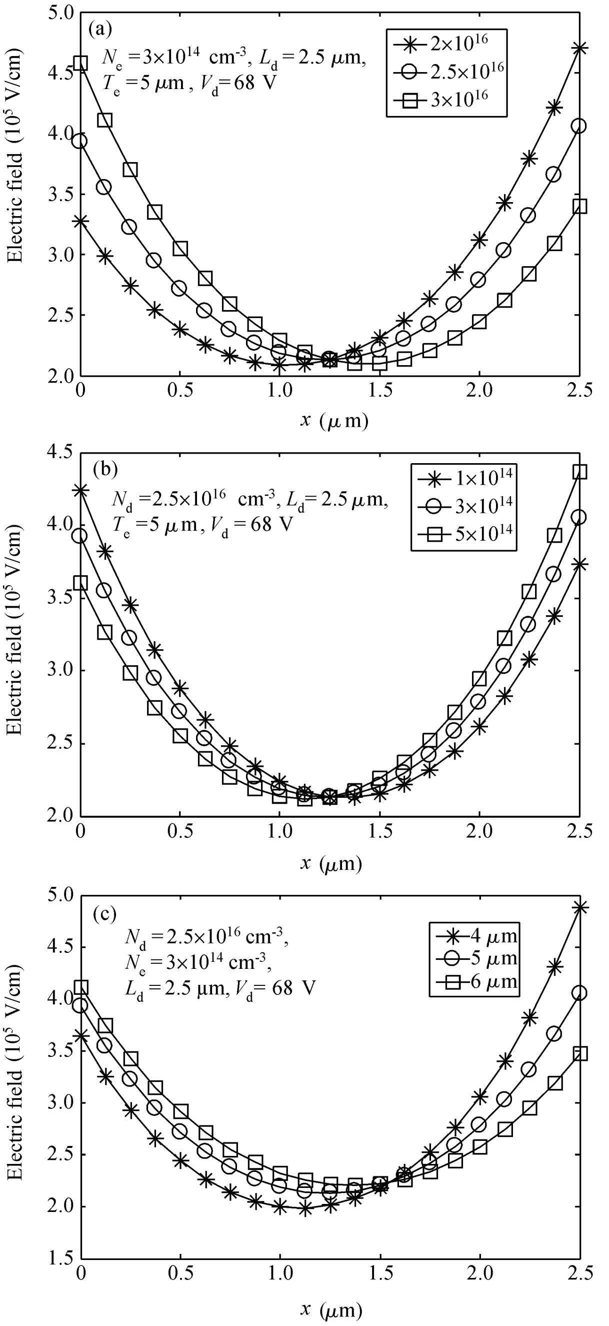

Fig. 3. Influence of (a) the drift doping concentration N_d, (b) the doping concentration of the p epitaxial layer N_e and (c) the thickness of the p epitaxial layer T_e on electric field distributions simulated through MATLAB based on the analytical model.

to conventional LDMOST, the improved analytical model explains the influence of a specific RF-LDMOST structure, especially p epitaxial layer, which does not exist in conventional LDMOST. The detailed analytical results will be discussed in the next section.

3. Discussion

Based on the analytical model above, the surface electric field $\xi(x, 0)$ is simulated by MATLAB. The following analytical results reveal the influence on electric field distributions of the drift region doping concentration N_d, the doping concentration of the p epitaxial layer N_e and the thickness T_e of the p epitaxial layer.

Figure 3(a) shows the significant effect of N_d on the electric field distribution. The distribution of the electric field is similar to conventional LDMOST. The value of the field becomes higher at $x = 0$ and decreases at $x = L_d$ when the N_d increases from 2×10^{16} to 3×10^{16} cm^{-3}. Meanwhile, the peak of the electric field transfers from $x = L_d$ to $x = 0$. Figure 3(b) reveals the opposite effect of N_e compared with N_d in the RF-LDMOST structure. When the N_e rises from 1×10^{14} to 5×10^{14} cm^{-3}, the electric field peak transfers from $x = 0$ to $x = L_d$. Figure 3(c) illustrates that the T_e play an important role in field distribution also. The curves from 4 to 6 μm reflect the decrease in the electric field at $x = L_d$ and the increase at $x = 0$. From the MATLAB results, it is apparent that varying N_d, N_e and T_e causes the different field distribution.

According to the avalanche breakdown mechanism, the breakdown takes place when

$$\int_{x_1}^{x_2} \alpha(x)\mathrm{d}x = 1, \tag{15}$$

where x_1, x_2 are the starting and terminal point of avalanche multiplication path respectively. The ionization rate $\alpha(x) = C\xi(x)^7$ and is the majority function of $\xi(x)$. Because of the strong dependence of the ionization rate on the field, integration around the critical electric field ξ_m (defined as the maximum electric field when breakdown occurs) determines the integral value over the whole avalanche multiplication path. Additionally, ξ_m varies slowly with either doping concentration or ionization rate. In silicon, the ξ_m approximates to a fixed value of the order of 10^5 V/cm[7]. It is suggested that the device will break down once the electric field in the device increases over the ξ_m and the field distribution determines the breakdown voltage. According to the influence on field distribution of the shallow drift region and the p epitaxial layer that the analytical model indicates, RF-LDMOST with high voltage capability and low R_{dson} (which relies on the N_d mostly[8]) can be designed through optimized high N_d, low N_e and appropriate T_e.

4. Simulated and experimental results

In this section, the results of ISE TCAD simulations are discussed and the experiments are introduced. ISE TCAD is a TCAD (technology computer aided design) tool. The process simulation runs the real process flow that we designed. It must point that all of the parameters listed below are technological parameters, not the final parameters of the device like the list in the analytical model. For instance, 1.3×10^{12} cm^{-2} is the implanted dose in Fig. 4(a). 1.1×10^{15} is the initial doping concentration of the epitaxial layer in Fig. 4(b). 9.5 μm is the initial epitaxial thickness in Fig. 4(c). After process flow completion, implanted doses transform into bulk concentrations, which equal the N_d in Fig. 3(a). For the epitaxial layer, the initial doping concentration is not changeless and its actual thickness reduces a lot due to longtime anneal. They are finally close to N_e and T_e in Figs. 3(b) and 3(c).

Figure 4 shows the ISE TCAD simulated results. Some key parameters, like gate length, PHV doping concentration, PHV and NHV annealing time, are 0.6 μm, 2.6×10^{13}cm^{-2},

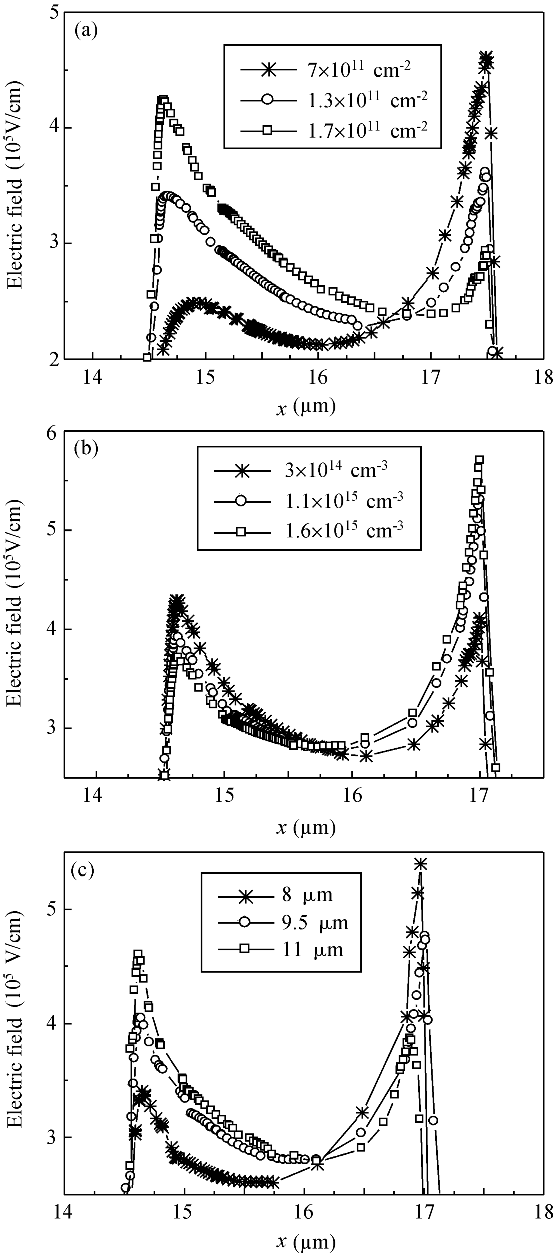

Fig. 4. Electric field distribution simulated through ISE TCAD. (a) Influence of drift doping concentration N_d. (b) Influence of p epitaxial layer doping concentration N_e. (c) Influence of p epitaxial layer thickness T_e.

50 min and 60 min respectively. Owing to the non-uniform doping concentration in the diffusion device, the difference between the analytical results and the device simulations inevitably exist. Compared with Fig. 3(a), Figure 4(a) indicates the same influence of drift region concentration on the electric field distribution. The value of the electric field decreases below the gate and field peak transfers with the increasing implanted dose, which means that the drift region concentration increases. Figure 4(b) also shows an opposite effect compared to Fig. 4(a). This is accordant to the analytical model. Figure 4(c) suggests that the thickness of the p epitaxial layer plays an important role for RF-LDMOST like the analytical model reveals. Different thicknesses cause apparently different field distributions. Great attention should be paid to this when we design a RF-LDMOST.

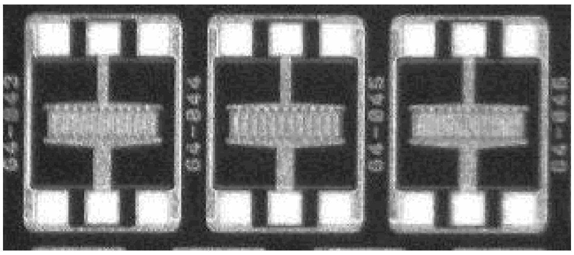

Fig. 5. Fabricated RF-LDMOST with the test structure.

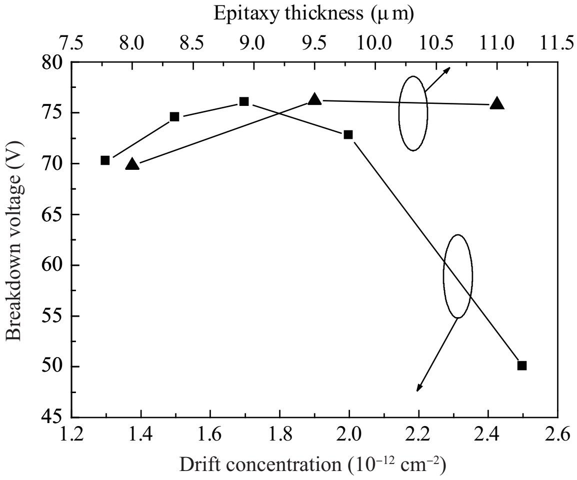

Fig. 6. Dependence of breakdown voltage on the drift concentration and the p epitaxial layer thickness (data from experimental results).

For further validation, the results of the experiments are introduced. Figure 5 shows the fabricated RF-LDMOST with the test structure. Because it is difficult to present the electric distribution in the fabricated device, the analytical model is validated through BV (breakdown voltage) indirectly. From the relationship between ξ_m and the breakdown mentioned above, it can be assumed that the device breakdown takes place if the electric field in the device increases over ξ_m, which approximates to a fixed value.

Figure 6 shows the dependence of the BV on the drift concentration and thickness of the epitaxial layer. In the analytical model, the value of the field increases at $x = 0$ and decreases at $x = L_d$ when the drift region doping concentration becomes higher. The value of the field peak which spots at $x = L_d$ moves further from ξ_m. This means that the higher voltage can be applied while the field in device does not exceed the ξ_m. In other words, the BV increases with increasing drift region doping concentration. When the values of the field at $x = 0$ and $x = L_d$ are equal, the BV reaches the maximum value. With further incensement of the drift concentration, the peak of electric field spots from $x = L_d$ to $x = 0$ and BV should fall off. This is accordant to what Figure 6 shows. Similarly, the different epitaxy thickness induces the varying BV and the fabricated devices indicate that also. For too thin p epitaxial layer, the field peak at $x = L_d$ is easy to exceed ξ_m and the BV is low. So we must not ignore the influence of the thickness of the p epitaxial layer when a RF-LDMOST is designed.

5. Conclusion

Focusing on the shallow drift region and the low concentration epitaxial layer, an analytic model for the RF-LDMOST is proposed and simulated by MATLAB. This indicates well the relationship between the electric field distribution and some parameters, like $N_{\rm e}$, $T_{\rm e}$ and $N_{\rm d}$. Most impressive is how the model explains how the thickness of the p epitaxial layer affects the electric field distribution in the RF-LDMOST structure through an analytical way. With these discussions, it can be revealed that the appropriate drift region and the p epitaxial layer are important for the satisfying performance of RF-LDMOST.

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