A novel high-voltage device structure with an N^+ ring in substrate and the breakdown voltage model*

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Abstract: A novel high-voltage device structure with a floating heavily doped N^+ ring embedded in the substrate is reported, which is called FR LDMOS. When the N^+ ring is introduced in the device substrate, the electric field peak of the main junction is reduced due to the transfer of the voltage from the main junction to the N^+ ring junction, and the vertical breakdown characteristic is improved significantly. Based on the Poisson equation of cylindrical coordinates, a breakdown voltage model is developed. The numerical results indicate that the breakdown voltage of the proposed device is increased by 56% in comparison to conventional LDMOS.

Key words: floating ring; model; breakdown voltage; modulation
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1. Introduction

With the development of the smart power integrated circuit, the lateral double diffused MOS transistor (LDMOS) is gaining worldwide attention[1, 2]. The surface electric field can be optimized by techniques such as reduced surface electric field (RESURF), double RESURF, variation of lateral doping, field plate, super junction, silicon on insulator (SOI) and others, its surface breakdown has been eliminated[3−8]. For conventional thin drift region RESURF devices, the maximum electric field is located at the horizontal junction under the drain and thus the breakdown voltage (BV) of a device is determined by the vertical BV. Zhang[9] has proposed a device with an n-type buried layer embedded in the substrate and the BV is increased by 75%, in which the charge balance condition must be satisfied and the key optimization parameters are the thickness, length and doping concentration of buried layer.

To further improve the vertical sustaining voltage and to simplify the process, the heavily doped N^+ rings in substrate are employed. The key optimization parameter of the N^+ ring is only the distance from the drift region. The electric field of the main junction is reduced due to the electric field modulation of the N^+ ring, thus the blocking ability is improved. Based on the Poisson equation of the cylindrical coordinates, an analytical model of BV to design the FR device is presented, from which the optimal spacing is also been obtained.

2. Analytical model

The schematic cross-section of the FR device is illustrated in Fig. 1, L_d, t_d and N_d are the length, thickness and doping concentration of the drift region, respectively. t_r is the distance of the N^+ ring from the main junction and r_1 is the curvature radius of the depletion region's outer boundary of the ring junction. P_b is the doping concentration of the buried layer underneath the channel. The substrate doping concentration is P_{sub}. Based on the conventional LDMOS, the FR LDMOS is realized by an extra two processes—n-type iron implantation and epitaxial processes.

For a thin drift region device, the bias voltage is sustained mainly by a depletion layer in the substrate. Assuming that a N^+ ring is absent at first, in terms of the theory of the abrupt pn junction, the potential $\varphi_m(y)$ and electric field $E_m(y)$ in the substrate depletion region of main junctions can be expressed as

$$E = E_m\left(1-\frac{y}{y_0}\right) = \frac{qP_{sub}y_0}{\varepsilon}\left(1-\frac{y}{y_0}\right), \tag{1}$$

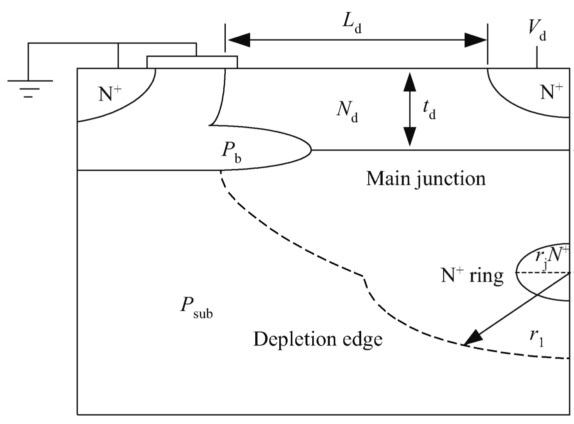

Fig. 1. Cross-section of FR LDMOS.

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$$\varphi_{\mathrm{m}}(y)=\frac{qP_{\mathrm{sub}}y_o^2}{2\varepsilon}\left(1-\frac{y}{y_0}\right)^2, \tag{2}$$

where $y_0=\sqrt{\frac{2\varepsilon V_{\mathrm{D}}}{qP_{\mathrm{sub}}}}$ is the thickness of the depletion region in the main junction.

Now, assuming that the N^+ ring junction exists with t_{r1} ($t_{\mathrm{d}} \ll t_{\mathrm{r1}}$) from the surface of the device, solving the cylindrical coordinates of the Poisson equation of the N^+ ring junction for the boundary conditions where the electrostatic potential and electric field of the inner edge of depletion region in N^+ ring equal to zero gives

$$V_1=\frac{qP_{\mathrm{sub}}}{2\varepsilon}\left(\frac{r_1^2-r_{\mathrm{j}}^2}{2}-r_1^2\ln\frac{r_{\mathrm{j}}}{r_1}\right), \tag{3}$$

$$E_{\mathrm{r},1}=\frac{qP_{\mathrm{sub}}}{2\varepsilon}\left(\frac{r_1^2-r_{\mathrm{j}}^2}{r_{\mathrm{j}}}\right). \tag{4}$$

Assuming that the presence of the ring junction does not considerably perturb the depletion extension from the main junction, the first ring junction voltage V_1 at t_{r1} caused by the main junction is given by,

$$V_1=\frac{qP_{\mathrm{sub}}y_0^2}{2\varepsilon}\left(1-\frac{t_{\mathrm{r1}}}{y_0}\right)^2, \quad 0\leqslant t_{\mathrm{r1}}\leqslant y_0. \tag{5}$$

The outer boundary r_1 can be given by solving Eqs. (3) and (5). The edge peak electric field of the main junction is reduced due to the transfer of the voltage to the ring junction, so the final electric field of the main junction is determined by the electric field difference between those caused by the drain voltage and the ring junction voltage, therefore, the final peak field at the main junction is given as

$$E_{\mathrm{mf}}=\frac{qP_{\mathrm{sub}}y_0}{\varepsilon}-\frac{qP_{\mathrm{sub}}}{2\varepsilon}\frac{r_1^2-(r_{\mathrm{j}}+t_{\mathrm{r1}})^2}{r_{\mathrm{j}}+t_{\mathrm{r1}}}. \tag{6}$$

When Equation (4) or (6) reaches to critical intensity E_{c}[10],

$$E_{\mathrm{c}}=\left(\frac{6}{1.8\times10^{-35}}\right)^{1/7},$$

the breakdown phenomenon occurs. The breakdown voltage BV is given by

$$\mathrm{BV}=\frac{qP_{\mathrm{sub}}}{2\varepsilon}\left(\frac{r_1^2-r_{\mathrm{j}}^2}{2}-r_1^2\ln\frac{r_{\mathrm{j}}}{r_1}+2t_{\mathrm{r1}}y_0+t_{\mathrm{r1}}^2\right). \tag{7}$$

Optimal ring spacing is obtained when the edge field peaks of the main junction and the ring junction are simultaneously equal to the E_{c}.

More N^+ rings can be introduced in the substrate and according to an approximation of far-neighbor junction interaction[10], the voltage and edge peak field of the second and more ring junctions can be obtained. Taking into account the cost and complexity of fabrication of the device one ring is suggested.

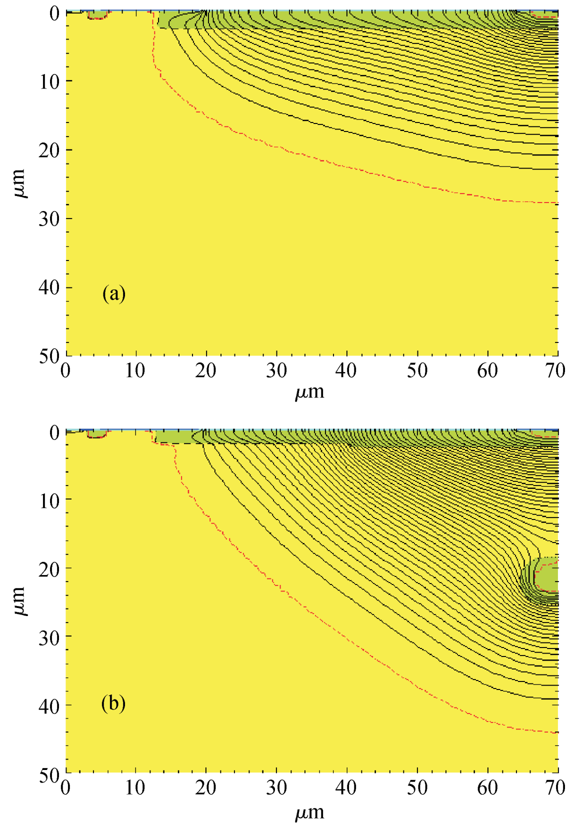

Fig. 2. Equipotential contours of (a) conventional LDMOS and (b) FR LDMOS.

3. Results and discussion

Figure 2 shows potential contour distributions at breakdown. The depletion area of the FR LDMOS is further extended into the substrate thanks to the transfer of voltage from the main junction to the ring junctions and the equipotential contours are evenly spaced, as compared with that of its conventional counterpart. The effect of the floating N^+ ring is similar to that of the field limiting ring of a device with field limiting rings in the drift region.

The vertical electric field and potential distributions underneath the drain are shown in Figs. 3(a) and 3(b) for the FR and optimal conventional LDMOS. There is only one electric field peak and the reverse bias voltage is sustained completely by the main junction $N_{\mathrm{d}}/P_{\mathrm{sub}}$ for conventional LDMOS. There is a new triangle-shaped field peak at the N^+ ring edge of the FR LDMOS besides the electric field peak at the main junction. The drain voltage is shared by the main junction and rings junction. The reverse bias sustained by the ring junction increases with the decrease of t_{r}. This is why the breakdown voltage of the FR LDMOS is higher than in a conventional device. When a conventional device breaks down at 340 V, the edge electric field in the FR device is still small and its breakdown voltage can reach 530 V. Figure 3(c) shows the electric field distributions at the surface of the FR and the conventional LDMOS, respectively. There are only two electric field peaks at the drain and source for conventional LDMOS. An extra electric field peak is brought in FR LDMOS in comparison to conventional LDMOS due to the electric field modulation effect by the P_{b}

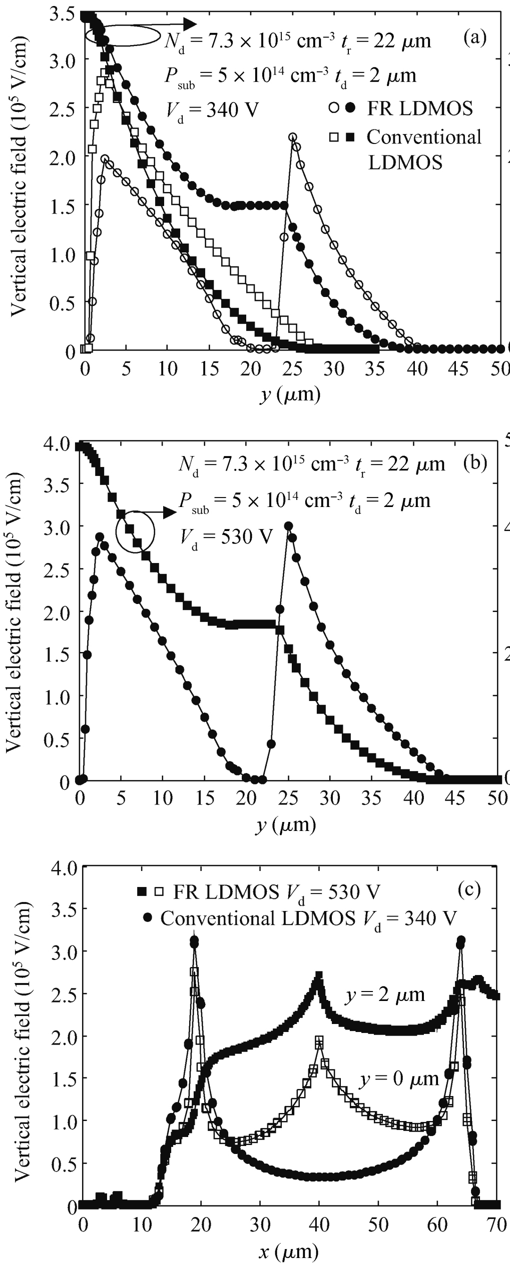

Fig. 3. Electric field and potential distributions. (a) $V_\mathrm{d} = 340$ V for both FR and conventional LDMOS at $x = 70$ μm. (b) $V_\mathrm{d} = 530$ V for FR LDMOS at $x = 70$ μm. (c) $V_\mathrm{d} = 530$ V for both FR and conventional LDMOS at $x = 70$ μm at $y = 0$.

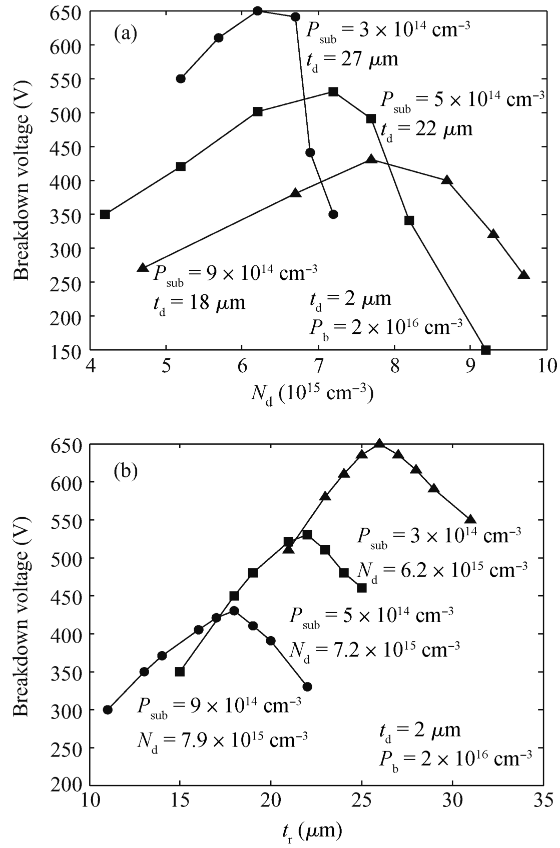

Fig. 4. Breakdown voltage as a function of (a) N_d and (b) t_r.

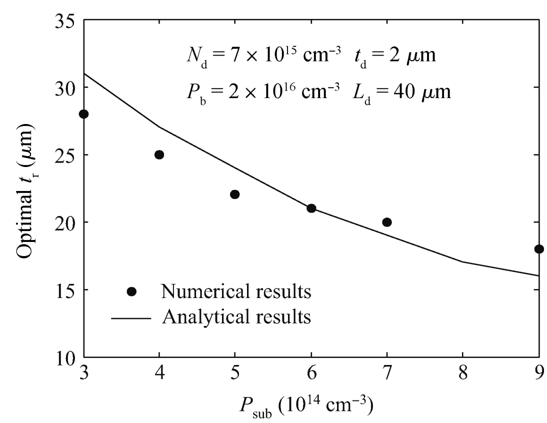

Fig. 5. Influence P_sub of on optimal ring distance t_r.

buried layer, which results in a more uniform electric field distribution by dramatically decreasing the height of the electric field peaks near the drain and source.

The breakdown voltage as a function of the drift concentration N_d for different substrate concentrations P_sub are shown in Fig. 4(a). Maximal BV increases with a decrease of the substrate doping concentration, but the range and magnitude of the optimal N_d values decreases. The BV has a clear optimum. For higher drift concentration, the drift region cannot be depleted fully, so the BV is smaller. When the drift region concentration is low, the BV increases with the increase of the drift region concentration. In general, the lower the substrate concentration is, the higher the BV. Figure 4(b) shows that ring distance t_r has an optimum that depends on the substrate doping. With the increase of t_r, the electric field peak of the ring junction decreases and the electric field peak at main junction increases. When an optimal value of t_r is obtained, the electric field peaks at t_r and main junction are equal and the maximum BV appears. For a decreasing substrate concentration, the optimal t_r and the maximum BV increase.

Figure 5 shows the dependence of t_r on the P_sub. With the increase of P_sub, the optimal t_r decreases. A fair accordance between the analytical and numerical results may generally be found, showing the validity of the model presented. If the ring spacing is small or large, a higher field peak occurs at the main or ring junction edge, leading to a lower BV.

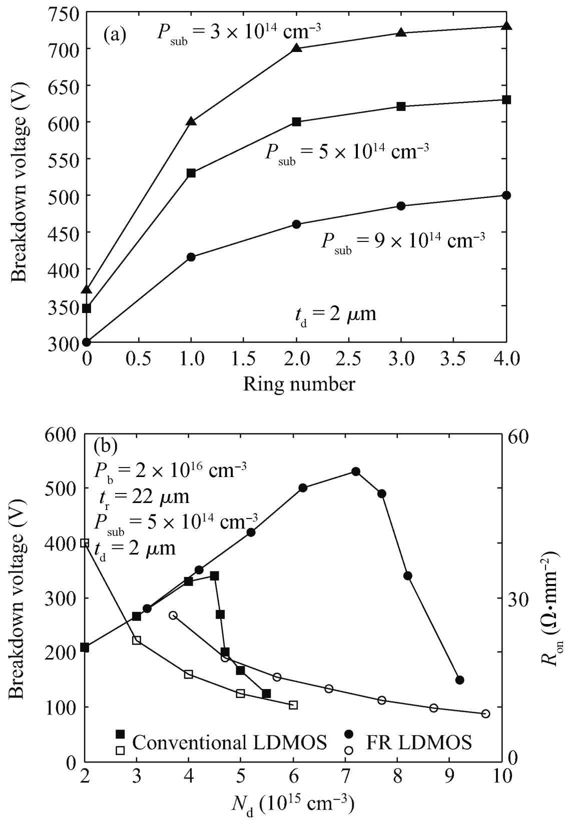

Fig. 6. (a) Influence of ring number on the breakdown voltage. (b) Influence of N_d on breakdown voltage and on-resistance.

In FR LDMOS, more rings can be introduced underneath the drain in the substrate. It is apparent from Fig. 6(a) that the curve is characterized by both the linear and saturation regions. In the linear region, because rings can broaden the thickness of the depletion region in substrate, so the more N^+ rings in substrate, the higher BV will be. The BV reached an almost saturated value when the number of N^+ rings is increased to two. The saturated BV increases with a decrease of substrate doping concentration. The N^+ ring in substrate will help deplete substrate, which makes it possible to have a higher drift region doping concentration. To illustrate this fact, Figure 6(b) shows the dependences of the BV and on-resistance on the drift region concentrations. The N_d has an optimum value for each structure. The optimum N_d of FR is higher about 80% than that of conventional device thanks to the auxiliary depletion effect by the N^+ ring, which causes the on-resistance of FR to be reduced in comparison to conventional LDMOS and the BV is improved by 56%. The drop ratio of the on-resistance in FR LDMOS compared to conventional LDMOS with the same structure parameters exceeds that in Refs. [9, 11].

4. Conclusion

A new high-voltage device structure with a N^+ ring in substrate has been proposed. The electric field peak at the main junction is reduced because the drain voltage is shared by the main junction and N^+ ring, which results in the significant improvement of trade-off between the BV and on-resistance. A 2-D electric field model based on the Poisson equation of the cylindrical coordinates and the optimization condition has been obtained. The analytical model will be helpful in FR LDMOS design.

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