第29卷 第4期
2008年4月

半 导 体 学 报
JOURNAL OF SEMICONDUCTORS

Vol.29 No.4
Apr.,2008

An Ultra-Low Specific On-Resistance VDMOS with a Step Oxide-Bypassed Trench Structure

Duan Baoxing[1,†], Yang Yintang[1], Zhang Bo[2], and Li Zhaoji[2]

(1 *Key Laboratory of the Ministry of Education for Wide Band-Gap Semiconductor Materials and Devices,*
School of Microelectronics, Xidian University, Xi'an 710071, *China*)
(2 *State Key Laboratory of Electronic Thin Films and Integrated Devices, University of Electronic Science*
and Technology of China, Chengdu 610054, *China*)

Abstract: A novel Step Oxide-Bypassed (SOB) trench VDMOS structure is designed based on the Oxide-Bypassed concept proposed by Liang Y C. This structure is suitable for breakdown voltage below 300V to obtain ultra-low specific on-resistance. The main feature of this structure is the various thicknesses of sidewall oxide, which modulate electric field distribution in the drift region and the charge compensation effect. As a result, the breakdown voltage is increased no less than 20% due to the more uniform electric field of the drift region, while the specific on-resistance was reduced by 40%～60% for the step oxide bypassed compared with the oxide-bypassed structure.

Key words: step oxide-bypassed; VDMOS; breakdown voltage; specific on-resistance
EEACC: 1210; 2560
CLC number: TN386 **Document code:** A **Article ID:** 0253-4177(2008)04-0677-05

1 Introduction

In the field of power electric, the power MOSFET is widely used as a switch. In order for this to function properly, power MOSFET's should meet two requirements: very low on-resistance to minimize the conduction losses when the device is in the on-state and sustaining certain reverse voltage when the device is off. The former needs high doping levels, while the latter calls for lower doping concentrations. In conventional structures, the power law relation of the breakdown voltage (BV) and specific on-resistance (R_{on}) is fundamentally limited by $R_{\mathrm{on}} = 5.93 \times 10^{-9}(\mathrm{BV})^{2.5}$[1], which is satisfied resulting from only one dimension electric field modulating in the drift region. In order to break this limit, several structures have been proposed, such as COOLMOS[2～5], which was experimentally realized in a high voltage application, Trench VDMOS, which has been designed to apply in low voltage with Ultra-low R_{on}[6～10], and Novel LDMOS structures[11～13] based on the electric field modulation effect. The principle of these structures can be consolidated to a modulation effect by a new electric field that is introduced in the lateral dimension. The new electric field modulates the field distributions and doping concentrations in the drift region.

In this work, we propose a step oxide-bypassed (SOB) VDMOS based on the oxide-bypassed (OB structure) concept[8～10] to improve the electric field modulation effect by a step sidewall oxide. A more uniform electric field distribution in the drift region is obtained due to new electric field peaks produced by the step oxide-bypass. Meanwhile, a much higher concentration than that of the OB structure is depleted resulting from effective electric field modulation.

2 Device structure and simulation analysis

A schematic cross section of the proposed SOB VDMOS with one step oxide-bypass, including the most relevant parameters, is shown in Fig. 1. The prominent feature of this structure is that the uniform sidewall oxide in the OB structure is replaced with a

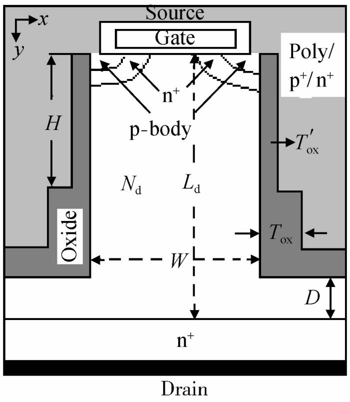

Fig.1 Cross-section of SOB with one step oxide-bypassed

---

† Corresponding author. Email: bxduan@163.com

Received 18 September 2007, revised manuscript received 6 November 2007

step oxide, by which new electric field peaks are created at the step to improve the breakdown voltage on account of a more uniform electric field distribution in drift region. This uniform field can be explained by the electric field modulation effect[14,15], and a much higher doping concentration in the drift region can be depleted compared with the OB structure, resulting from reducing the effective thickness of the sidewall oxide. Thus, the required breakdown voltage is obtained through the thick sidewall oxide at the bottom of the trench, while the low specific on-resistance is obtained due to the thin oxide at the top of the trench Oxide-Bypass. L_d and N_d are the length and doping concentration of the drift region. W and T_{ox} are the thicknesses of the drift region and sidewall oxide at the thickest location, respectively. H and D are the length of the thin sidewall oxide and the distance from the bottom of the OB to the drift region, respectively.

The SOB can be fabricated by an additional process of etching the sidewall oxide compared with the OB process. There are five parts included in the SOB process to form a step shape. (1) The deep trench is formed beside the drift region by etching the silicon substrate. (2) The thick sidewall oxide is grown after the etching process. (3) The deep trench is filled partially by heavily-doped polysilicon. (4) The thick sidewall oxide is etched partially to form a thin sidewall oxide for the step oxide bypassed trench structure. (5) Finally, the trench is completely filled with heavily-doped polysilicon.

The 1-D electric field distributions along the vertical path in the middle of drift region and simulated potential contours by 2-D numerical simulations using MEDICI[16] at breakdown are shown in Fig. 2 for OB and SOB structures, respectively.

The main device parameters are as follows: $W = 1\mu m$; $L_d = 12\mu m$; $D = 0$; $T_{ox} = 1\mu m$; $T'_{ox} = 0.5\mu m$; $H = 4.5\mu m$. As seen in Fig. 2(a), there are two electric field peaks: one near the p-body/n^- junction at the top of the drift region and the other near the n^+/n^- junction, which is analogous to that in SOI power devices. In the proposed structure, there is a new electric field peak P_k near the middle of the drift region, and this peak is undoubtedly due to the newly generated peak at the edge of the step oxide-bypass, which results in the breakdown voltage increasing.

This peak can be explained by the following equation:

$$\frac{\partial^2 \varphi(y,0)}{\partial y^2} - \frac{\varphi(y,0)}{\lambda^2} = -\frac{\rho}{\varepsilon_{si}} \tag{1}$$

$$\lambda_i = \left(\frac{W^2}{2} + \frac{\varepsilon_{si}}{\varepsilon_{ox}} W T_{ox(i)}\right)^{\frac{1}{2}} \tag{2}$$

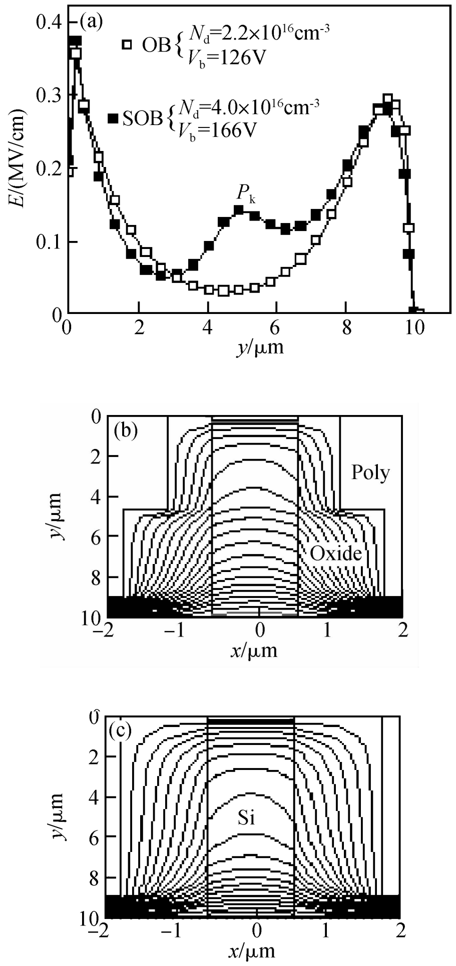

Fig. 2 Electric field distributions along the vertical path in the middle of drift region (a), simulated potential contours of SOB (b), and OB (c) at breakdown

where $\varphi(y,0)$ is the potential function in drift region along the vertical path and λ is a factor of Eq. (1) by which the electric field distributions of device can be obtained. Equation (1) can be obtained by Poisson's equation, which must be satisfied in the drift region and indicates the electric field can be modulated by parameters T_{ox}.

The step oxide-bypassed structure is equivalent to the Step Field Plate in conventional terminal technology, thus this peak can also be interpreted by Step Field Plate theory[17], which can be expressed simply by

$$E_y \propto e^{-0.6y/T_{ox}} \tag{3}$$

where E_y is the electric field in drift region along the vertical path and T_{ox} is the thickness of sidewall oxide there. Equation (3) shows that E_y will decrease exponentially when y increases. However this law can be broken by various T_{ox}. In fact, E_y can change abruptly at the location of the step sidewall oxide, which is shown in Fig. 2(a).

The contours of the SOB (shown in Fig. 2(b)) are uniform. Thus, the avalanche breakdown voltage

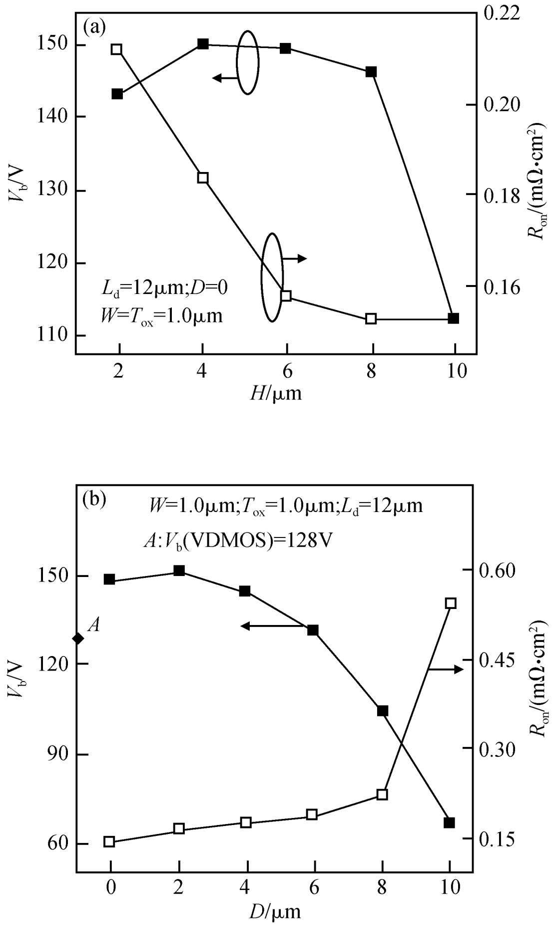

Fig. 3　V_b and R_{on} as a function of H (a) and D (b) for SOB with one step oxide-bypassed

reaches 166V with a drift region doping concentration of 4.0×10^{16} cm^{-3}. Meanwhile, in Fig. 2(c), the OB structure shows field crowding at the p-body/n$^-$ and n$^+$/n$^-$ junctions and the breakdown voltage is limited to 126V with a doping concentration of 2.2×10^{16} cm^{-3}, which is nearly 50% less than that of SOB.

Figure 3 shows the breakdown voltage and specific on-resistance as a function of H and D for SOB with one step sidewall oxide, respectively. Fig. 3(a) demonstrates that R_{on} is decreased gradually when H increases, which results from the drift region concentration increasing gradually due to the reduction in the effective thickness of sidewall oxide as H increases. In this case, the breakdown voltage does not change until H is close to the length of the sidewall oxide. The drift region electric field distribution in Fig. 2(a) shows that the breakdown voltage can not be influenced when the P_k moves in the drift region by a shift in H. However, the breakdown voltage decreases abruptly when the electric field peak P_k and the peak produced by the n$^-$/n$^+$ junction overlap. In Fig. 3(b), R_{on} is increases gradually as D increases, which results from the reduced modulation effect of the step sidewall oxide in this process. The drift region can not be depleted completely, which results in breakdown voltage decreasing gradually.

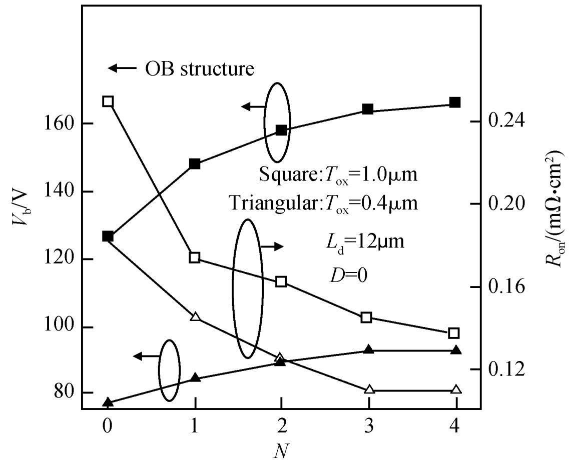

Fig. 4　V_b and R_{on} as a function of number of step oxide-bypassed (N) for SOB

Figure 4 shows the V_b and R_{on} versus the number of step oxide-bypassed (N) for SOB at different T_{ox}. The dots in the broken line denote the V_b and R_{on} of the OB structure. The V_b increases gradually as N is added because the drift region's electric field is more uniform after the electric field peaks are added, which are produced at the step of the sidewall oxide. The R_{on} are decreased gradually by increasing N, which results from the drift region concentration increasing gradually. The V_b and R_{on} achieve saturation when the number of step sidewall oxides is three. This indicates that the electric field modulation effect will achieve saturation at a certain step shape, which is helpful to design SOB for the necessary V_b and R_{on}. In terms of this analysis, the number of step oxide-bypasses will be three for the following discussion.

In the trench MOS structure, the breakdown voltage will increase with the width of the trench for optimal drift region concentration. This law can be seen from Fig. 5, and the breakdown voltage in the SOB structure is higher than that of the OB structure due to a more uniform electric field. In conventional VDMOS, the breakdown voltage is not dependent on W because the lateral electric field is absent, and it is lower than that of the trench structure in the same length of the drift region for optimal doping concentration, which is less than that of SOB and OB. The specific on-resistance for the SOB and OB structure also increase gradually with W, resulting from the weakened lateral electric field modulation effect of the doping concentration of the drift region in this process. Figure 5 indicated that the R_{on} of SOB is less than that of OB due to the comparatively thin sidewall oxide, and the R_{on} of conventional VDMOS is more than that of the other two structures.

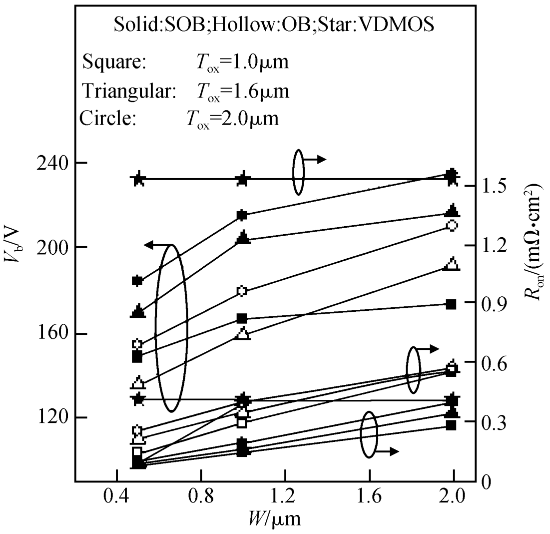

Fig.5 V_b and R_{on} as a function of W for SOB $L_d = 12\mu m$; $N = 3$

The breakdown voltage and specific on-resistance as a function of T_{ox} is shown in Fig. 6. The breakdown voltage increases with T_{ox} for SOB and OB structures due to the part of the breakdown voltage that is born by the sidewall oxide. When the sidewall oxide near the n^-/n^+ junction and the length of the drift region are the same thicknesses (12μm in Fig. 6(a)), the breakdown voltage of the SOB is higher than that of the OB because the electric field is more uniform for the step oxide-bypassed modulation. The breakdown voltage of conventional VDMOS, which is not dependent on T_{ox}, is less than that of the SOB or OB at the same length of drift region for large T_{ox}, which can be seen from Fig. 6(a).

The specific on-resistance is dependent on the doping concentration of the drift region, which can be explained by the following equation:

$$R_{on} = \frac{L_d}{q\mu_n N_d} \tag{4}$$

where L_d and N_d are the length and doping concentration of the drift region, respectively, and μ_n is the electron mobility.

The doping concentration of the drift region in the OB structure can be expressed[9] by

$$N_d = 2.90 \times 10^{11}(T_{ox}W)^{-4/7} \tag{5}$$

where W is the mesa width of the drift region.

However, T_{ox} is thinner in the SOB than that in the OB due to the step shape, thus yielding

$$\begin{gathered} T_{ox(SOB)} < T_{ox(OB)} \\ N_{d(SOB)} > N_{d(OB)} \end{gathered} \tag{6}$$

Based on Eq. (1), the specific on-resistance of the SOB is less than that of the OB. This law is shown in Fig. 6(b) for various W.

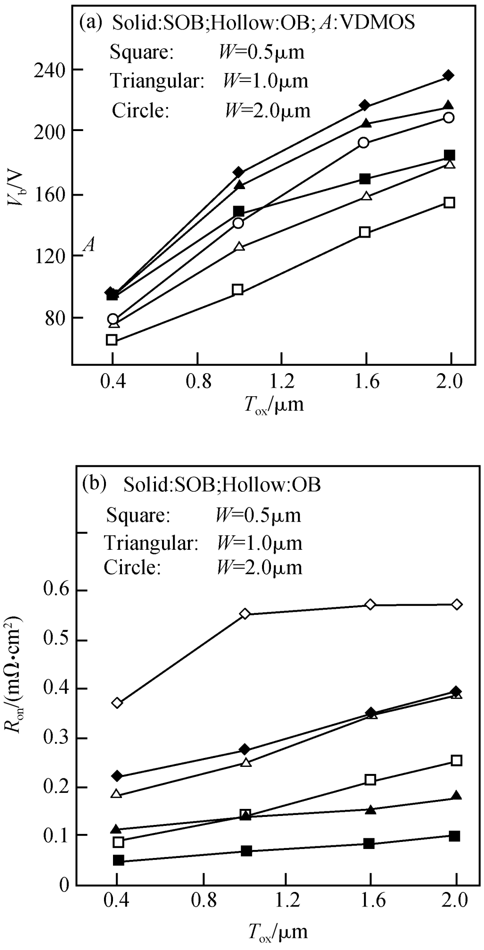

Fig.6 V_b(a) and R_{on}(b) as a function of T_{ox} for SOB with three step oxide-bypassed at different thicknesses of drift region

In general, the longer the drift region length is, the higher the breakdown voltage will be. But, the device breakdown voltage will saturate due to the saturation of the lateral breakdown voltage. This phenomenon is shown in Fig. 7. In the SOB structure, the saturated breakdown voltage is higher than that of the OB structure since the vertical breakdown voltage of the SOB is higher than that of the OB thanks to the electric field modulation effect by a step sidewall oxide.

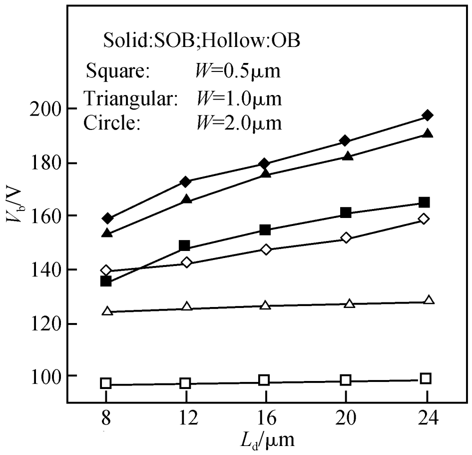

Fig.7 V_b as a function of L_d for SOB and OB

3 Conclusion

This paper reports a SOB trench VDMOS based on the OB concept. The trade-off relation between the breakdown voltage and the specific on-resistance in the OB structure is improved by a step sidewall oxide that enhances the electric field modulation effect produced along the lateral dimension. The parameters that affect the breakdown voltage and specific on-resistance were analyzed by 2D numerical simulations. The results show that the specific on-resistance is reduced by 40%～60%, while the breakdown voltage is increased no less than 20% resulting from the enhancement of the electric field modulation effect by the step sidewall oxide.

References

[1] Baliga B J. Power semiconductor devices. Boston, MA: PWS, 1996: 373

[2] Deboy G, März M, Stengl J P, et al. A new generation of high voltage MOSFETs breaks the limit line of silicon. IEDM Tech Dig, 1998: 683

[3] Chen X B, Sin J K O. Optimization of the specific on-resistance of the COOLMOS™. IEEE Trans Electron Devices, 2001, 48(2): 344

[4] Nassif-Khalil S G, Andre C, Salama T. Super-junction LDMOST on a silicon-on-sapphire substrate. IEEE Trans Electron Devices, 2003, 50(5): 1385

[5] Saito W, Omura I, Aida S, et al. Over 1000V semi-superjunction MOSFET with ultra-low on- resistance below the SI-limit. Power Semiconductor Devices and ICs (ISPSD), 2005: 306

[6] Baliga B J, Syau T, Venkatraman P. The accumlation-mode field-effect transistor: a new ultra-low on-resistance MOSFET. IEEE Electron Device Lett, 1992, 13(8): 427

[7] Mehrotra M, Baliga B J. Trench mos barrier Schottky (TMBS) rectifier: a Schottky rectifier with higher than parallel plane breakdown voltage. Solid-State Electron, 1995, 38(4): 801

[8] Liang Y C, Gan K P, Samudra G S. Oxide-bypassed VDMOS (OBVDMOS): an alternative to superjunction high voltage MOS power devices. IEEE Electron Device Lett, 2001, 22(8): 407

[9] Liang Y C, Yang X, Samudra G S, et al. Tunable oxide-bypassed VDMOS (OBVDMOS): breaking the silicon limit for the second generation. Power Semiconductor Devices and ICs (ISPSD), 2002: 201

[10] Yang X, Liang Y C, Samudra G S, et al. Tunable oxide-bypassed trench gate MOSFET: breaking the ideal superjunction MOSFET performance line at equal column width. IEEE Electron Device Lett, 2003, 24(11): 704

[11] Duan Baoxing, Zhang Bo, Li Zhaoji. Breakdown voltage analysis for step buried oxide SOI structure. Chinese Journal of Semiconductors, 2005, 26(7): 1396 (in Chinese) [段宝兴，张波，李肇基. 阶梯埋氧型 SOI 结构的耐压分析. 半导体学报，2005，26(7)：1396]

[12] Duan Baoxing, Zhang Bo, Li Zhaoji. Breakdown voltage analysis for double step buried oxide SOI structure. Chinese Journal of Semiconductors, 2006, 27(5): 886 (in Chinese) [段宝兴，张波，李肇基. 双面阶梯埋氧型 SOI 结构的耐压分析. 半导体学报，2006，27(5)：886]

[13] Duan Baoxing, Zhang Bo, Li Zhaoji. New power lateral double diffused metal-oxide-semiconductor transistor with a folded accumulation layer. Chin Phys Lett, 2007, 24(5): 1342

[14] Duan Baoxing, Zhang Bo, Li Zhaoji. A new thin-film power MOSFET's with a buried oxide double step structure. IEEE Electron Device Lett, 2006, 27(5): 377

[15] Duan Baoxing, Zhang Bo, Li Zhaoji. A new partial SOI power device structure with p-type buried layer. Solid-State Electron, 2005, 49(12): 1965

[16] 'TMA MEDICI 4.2' Technology Modeling Associates Inc. Palo Alto, US.

[17] Chen X B. A simple expression for the surface field profile of a p-n^+ junction with field plate. Acta Electronica Sinica, 1986, 14(1): 36

具有超低导通电阻阶梯槽型氧化边 VDMOS 新结构

段宝兴[1,†]　杨银堂[1]　张　波[2]　李肇基[2]

(1 西安电子科技大学微电子学院 宽禁带半导体材料与器件教育部重点实验室，西安　710071)
(2 电子科技大学微电子与固体电子学院 电子薄膜与集成器件国家重点实验室，成都　610054)

摘要： 基于国际上 Liang Y C 提出的侧氧调制思想，提出了一种具有阶梯槽型氧化边 VDMOS 新结构. 新结构通过阶梯侧氧调制了 VDMOS 高阻漂移区的电场分布，并增强了电荷补偿效应. 在低于 300V 击穿电压条件下这种结构使 VDMOS 具有超低的比导通电阻. 分析结果表明：较 Liang Y C 提出的一般槽型氧化边结构，器件击穿电压提高不小于 20% 的同时，比导通电阻降低 40%～60%.

关键词： 阶梯氧化边；VDMOS；击穿电压；导通电阻
EEACC： 1210；2560
中图分类号： TN386　**文献标识码：** A　**文章编号：** 0253-4177(2008)04-0677-05

---

† 通信作者. Email: bxduan@163.com

2007-09-18 收到，2007-11-06 定稿