The Simulation Study of the SOI Trench LDMOS With Lateral Super Junction

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ABSTRACT A novel lateral double diffused metal oxide semiconductor (LDMOS) with trench oxide layer, featuring a lateral super junction structure based on the silicon-on-insulator technology is proposed. On the one hand, the lateral super junction combined with the TOL can enhance both the surface and the bulk electric field of the N-drift by the charge compensation. Thus, the breakdown voltage (BV) is improved. On the other hand, the N-Pillar of the lateral super junction provides another current channel for electrons at the forward conduction state, thus the Specific on resistance (Ron,sp) is decreased. As the simulation results show, the proposed LDMOS exhibits trapezoidal electric field distribution with BV of 422V, and double electron channels with Ron,sp of 30.7 mΩ·cm², thus the figure of merit (FOM) (FOM = BV²/Ron,sp), Baliga’s FOM) of 5.82 MW/cm² is achieved, breaking through the silicon limit.

INDEX TERMS Lateral double diffused metal oxide semiconductor (LDMOS), breakdown voltage (BV), specific on resistance (Ron,sp), Baliga’s figure of merit (FOM).

I. INTRODUCTION

The SOI-LDMOS (Silicon-On-Insulator Lateral Double-diffused Metal–Oxide–Semiconductor) is widely adopted in power ICs due to its voltage control and high switching frequency characteristics [1, 2]. Two key electrical parameters of LDMOS are the Breakdown Voltage (BV) and the Specific On Resistance (Ron,sp) [3]–[6]. However, the two parameters are contradicted from each other and the tradeoff can be expressed as Ron,sp ∝ BV². The Baliga’s Figure Of Merit (FOM) is used to evaluate the tradeoff relationship [7]–[12]. Many advanced structures are proposed to improve the FOM in recent years. Specifically, the LDMOS with Trench Oxide Layer in the N-drift region (TOL-LDMOS) is widely researched [13]–[17]. At reverse blocking state, the TOL can increase the BV significantly with the enhancement of the surface electric field and the expansion of depletion line in the N-drift region. However, at the forward conduction state, the electron current path of the device is distributed in U shape due to the TOL, which will increase the Ron,sp obviously.

Meanwhile, the Super Junction technology is also widely adopted to enhance the bulk electric field of the N-drift region by the charge compensation, which can break through the relationship between the BV and Ron,sp [9], [18]–[22]. In this paper, a TOL-LDMOS with Lateral Super Junction in the N-drift region is proposed to achieve better FOM for the BV and the Ron,sp.

II. THE DEVICE STRUCTURE AND MECHANISMS

The structure and mechanisms of the proposed TOL-LDMOS is shown in Fig. 1. Compared with a SOI LDMOS, a deep trench filled with oxide is inserted into the N-drift region, which is equivalent to the increase of the length of the N-drift region. The Lateral Super Junction is designed with charge balance, and it is composed by two float P-Pillars and an N-Pillar. The doping of the N-drift region is 5 × 10¹⁴ cm⁻³
the thickness $T_d$ and the width $W_d$ of the N-drift region are 25 $\mu$m and 17 $\mu$m, and the thickness $T_{BOX}$ of the SOI and the doping of the P-Substrate are 2 $\mu$m and $8 \times 10^{14}$ cm$^{-3}$, respectively. Additionally, the thickness $T_{ox}$ and the width $W_{ox}$ of the TOL are 11 $\mu$m and 10 $\mu$m, and the doping $N_N$ for the N-Pillar and the $N_p$ for the P-Pillar are optimized. The electrical characteristics of the device are investigated with TCAD MEDICI [23]. In the simulation the physical and electrical models, including the mobility, ionization and the recombination models, are adopted.

The space charges distribution at reverse blocking state is illustrated in Fig. 1(a). The fixed charge is positive in the N-Pillar and Negative in the P-Pillar when the pillars are depleted, thus the vertical electric field is enhanced. Moreover, the Source region and Drain region are with fixed positive charge, and the electric field will stop at the P-Pillar 1. Meanwhile, the Bottom region is also with fixed positive charge, and the electric field will stop at the P-Pillar 2, thus the electric field in the whole N-drift region is enhanced and modulated. The double electron paths under conduction state are illustrated in Fig. 1(b), another conduction channel is introduced due to the N-Pillar of the lateral super junction. Furthermore, the doping $N_N$ of the N-Pillar is much higher than that of the N-drift, so the resistance is much lower. Thus, the Specific On Resistance $R_{on,sp}$ is reduced.

III. ELECTRICAL CHARACTERISTICS

A. THE REVERSE BREAKDOWN VOLTAGE BV

Fig. 2 shows the equi-potential contours and the depletion layers of the LDMOSs at breakdown state, the source, gate and the P-Substrate are shorted to the ground. For the conventional LDMOS (CON-LDMOS), the equi-potential contours are sparse and distributed at the surface of the N-drift when the device breaks down at the voltage of 160 V, as shown in Fig. 2(a). For the conventional TOL-LDMOS with $T_{ox}=22$ $\mu$m, the device will breakdown at the drain voltage of 401.4 V, the equi-potential contours get much denser both at the surface and in the bulk of the N-drift as shown in Fig. 2(b). For the proposed LDMOS (NEW-LDMOS), the thickness $T_p$ and $T_n$ of the P-Pillars and N-Pillar are both 3 $\mu$m, the doping concentrations $N_p$ and $N_n$ of the P-Pillar and N-Pillar are $8 \times 10^{14}$ cm$^{-3}$ and $1.5 \times 10^{15}$ cm$^{-3}$, respectively. Thus, $2T_pN_p \approx T_nN_n$ satisfies the charge balance according to the charge compensation theory of the super junction [4], [18], and the device will breakdown at the drain voltage of 422 V. The equi-potential contours are almost the same as the TOL-LDMOS, as shown in Fig. 2(c). From the point view of the depletion layers, the whole N-drift are completely depleted at the breakdown state, which indicates that the maximum BV will be achieved for all the devices.

Fig. 3 provides the surface and bulk electric field distributions along the lateral direction for the devices. At the cutline $y=0.5\mu$m as shown in Fig. 3(a), the interface of the surface is formed by SiO$_2$/Si for the CON-LDMOS and SiO$_2$/ SiO$_2$ for the TOL-LDMOS. Compared with CON-LDMOS, the maximum surface electric field is improved from $2.5 \times 10^5$ V/cm to $6.2 \times 10^5$ V/cm at the source region, and another peak electric field is improved from $4.7 \times 10^5$ V/cm to $6.5 \times 10^5$ V/cm at the drain region. The surface electric field for the NEW-LDMOS is almost the same as the TOL-LDMOS at the source region and it is further improved to $7.5 \times 10^5$ V/cm at the drain region, thus it exhibits trapezoidal electric field distribution. At the cutline $y=5$ $\mu$m as shown in Fig. 3(b), the N-drift region is formed by Si/Si for the CON-LDMOS and Si/ SiO$_2$ for the TOL-LDMOS and the NEW-LDMOS, the bulk electric field is improved from $0.7 \times 10^5$ V/cm (CON-LDMOS) to $2.8 \times 10^5$ V/cm (TOL-LDMOS and the NEW-LDMOS) at the N-drift region. At the cutline $y=11\mu$m as shown in Fig. 3(c), the N-drift region is formed by SiO$_2$/P-Pillar for the NEW-LDMOS, and the electric field is fluctuated at the interface. At the cutline $y=15\mu$m as shown in Fig. 3(d), the
FIGURE 3. The surface and bulk electric field distributions along the lateral direction for the CON-LDMOS, TOL-LDMOS and the NEW-LDMOS at the cutline (a) \(y=0.5\ \mu m\), (b) \(y=5\ \mu m\), (c) \(y=11\ \mu m\), (d) \(y=15\ \mu m\).

FIGURE 4. The electric field distributions along the vertical direction for the CON-LDMOS, TOL-LDMOS and the NEW-LDMOS at the cutline (a) \(x=0.5\ \mu m\), (b) \(x=5\ \mu m\), (c) \(x=11\ \mu m\), (d) \(x=15\ \mu m\).

N-drift is formed by Super Junction for the NEW-LDMOS, and the electric field is decreased from \(6\times10^4\ \text{V/cm}\) at the source region to \(2.5\times10^4\ \text{V/cm}\) at the drain region.

Fig. 4 shows the electric field distributions along the vertical direction of the devices. At the cutline \(x=0.5\ \mu m\) as shown in Fig. 4(a), the junction is formed by P-body/N-drift for all the devices, and the maximum electric field is improved from \(1.2\times10^5\ \text{V/cm}\) for the conventional LDMOS to \(3\times10^5\ \text{V/cm}\) for the TOL-LDMOS and the NEW-LDMOS at the P-body/N-drift junction. Moreover, the electric field is stopped at the N-drift region for the conventional, and it is extended vertically to the SOI for the TOL-LDMOS and NEW-LDMOS. At the cutline \(x=5\ \mu m\) as shown in Fig. 4(b), the junction is formed by \(\text{SiO}_2/\text{Si}\) at the surface for the CON-LDMOS, \(\text{SiO}_2/\text{SiO}_2\) at the surface for the TOL-LDMOS, \(\text{SiO}_2/\text{SiO}_2\) at the surface and \(\text{SiO}_2/\text{P-Pillar}\) at the N-drift region for the NEW-LDMOS. The electric field is improved from \(2.2\times10^5\ \text{V/cm}\) for the conventional to \(5.1\times10^5\ \text{V/cm}\) for the TOL-LDMOS and the NEW-LDMOS at the surface. At the cutline \(x=11\ \mu m\) as shown in Fig. 4(c), the situation is almost the same as the Fig. 4(b) with \(x=5\ \mu m\). At the cutline \(x=15\ \mu m\) as shown in Fig. 4(d), the junction is formed by \(\text{N}+/\text{N-drift}\) for all the devices. The maximum electric field is \(1.8\times10^5\ \text{V/cm}\) for the conventional LDMOS and the TOL-LDMOS, and it is improved to \(2.5\times10^5\ \text{V/cm}\) for the NEW-LDMOS at the \(\text{N}+/\text{N-drift}\) junction, because the Super Junction helps to deplete the N-drift by charge compensation.

FIGURE 5. The Maximum impact ionization rate \(\text{IIR}_{\text{MAX}}\) at the breakdown state for (a) CON-LDMOS (b) TOL-LDMOS (c) NEW-LDMOS.

FIGURE 6. Forward conduction characteristics of the NEW-LDMOS with double current channels and the TOL-LDMOS with single current channel at the \(\text{N}_{\text{drift}}\) doping from \(7e14\) to \(1e15\) (the current distribution are given in the inset pictures).
B. THE SPECIFIC ON RESISTANCE $R_{\text{on,sp}}$

Fig. 6 shows the current voltage characteristics of the LDMOSs at forward conduction state. The source and the P-Substrate are shorted to the ground, the gate electrode $V_g$ is 15V. The currents are increased linearly with the drain voltage for both devices with the doping of the $N_{\text{drift}}$ from 7e14 to 1e15. Moreover, at the same doping of the $N_{\text{drift}}$, the current density of the NEW-LDMOS with double electron channels is much higher than the TOL-LDMOS with single channel as shown in the inset pictures.

C. THE LATERAL SUPER JUNCTION INFLUENCE ON THE BV AND $R_{\text{on,sp}}$

The BV and the $R_{\text{on,sp}}$ are functions of the N-Pillar of the Lateral Super Junction as shown in the Fig. 8. The $R_{\text{on,sp}}$ decreases with the increase of the thickness $T_n$ and the doping $N_n$ of the N-Pillar because the conduction capability of the current channel is improved as illustrated in the inset picture of Fig. 6. Meanwhile, the BV is decreased due to the charge imbalance between the N-Pillar and the P- Pillar.

The BV and the $R_{\text{on,sp}}$ are functions of the P-Pillar of the Lateral Super Junction as shown in the Fig. 9. The $R_{\text{on,sp}}$ increases with the increase of the thickness $T_p$ and doping $N_p$ of the P-Pillar because the conduction capability is reduced, at the same time the BV is enhanced due to the charge balance between the N-Pillar and the P-Pillar.

D. THE THICKNESS OF TOL INFLUENCE ON THE BV AND $R_{\text{on,sp}}$

The BV and the $R_{\text{on,sp}}$ are functions of the thickness $T_{\text{ox}}$ of the Trench Oxide Layer as shown in the Fig. 10. The
FIGURE 10. The BV and the $R_{on,sp}$ are functions of the thickness $T_{ox}$ of the TOL for the LDMOSs (the $T_{ox}$ is reduced from 22 $\mu$m to 2 $\mu$m for the TOL-LDMOS, the $T_{ox}$ is reduced from 11 $\mu$m to 2 $\mu$m for the NEW-LDMOS).

FIGURE 11. Specific $R_{on,sp}$ versus BV relationship for the LDMOS device with the experimental and simulated data reported previously.

$T_{ox}$ is initially designed with 22 $\mu$m for the TOL-LDMOS and 11 $\mu$m for the NEW-LDMOS, when the $T_{ox}$ is reduced to 2 $\mu$m, the $R_{on,sp}$ is improved for both LDMOSs due to the reduction of the resistance at the Source region and Drain region as shown in Fig. 1(b). At the same time, the BV is also reduced for both LDMOSs, but the BV of the NEW-LDMOS is much higher than the TOL-LDMOS with the same $T_{ox}$ due to the lateral super junction as shown in Fig. 1 (a).

E. THE BALIGA’S FIGURE OF MERIT FOM
Fig. 11 shows the ideal silicon limit of the RESURF LDMOS given in [3], and the $R_{on,sp}$ versus the BV relationship of the devices with the experimental and simulated data reported previously [7], [13], [24]–[26]. It is apparent that the performance of the NEW-LDMOS breaks through the silicon limit. Moreover, the FOM (Baliga’s Figure Of Merit) is defined as $BV^2/R_{on,sp}$ to describe the tradeoff performance of the devices. It shows that the FOM is obtained 5.82 MW/cm$^2$ with the BV of 422 V and $R_{on,sp}$ of 30.7 m$\Omega$cm$^2$ for the NEW-LDMOS, compared the conventional LDMOS with 0.82 MW/cm$^2$ and the TOL-LDMOS with 3.67 MW/cm$^2$, the FOM is improved almost 702% and 158% respectively.

F. THE KEY PROCESS OF THE NEW-LDMOS
The key process of the NEW-LDMOS is compatible with the conventional TOL-DMOS as given in Fig. 12. However, extra three steps of epitaxies and ion implantation are needed to fabricate the P-Pillar and N-Pillar of the lateral super junction as illustrated in Fig. 12 (a-c). The process of Trench Oxide is given in Fig. 12 (d) for both NEW-LDMOS and TOL-LDMOS.

IV. CONCLUSION
A novel TOL-LDMOS with a Lateral Super Junction under the Trench Oxide is proposed, the multiple epitaxies and ion implantation are needed to prepare the P-Pillar and N-Pillar. The results show that the Lateral Super Junction combined with the TOL can improve the surface and bulk electric field in the N-drift, which significantly improves the BV. On the other hand, the N-Pillar of the Lateral Super Junction provides another electron current channel at the forward conduction state, which significantly decreases the Specific $R_{on,sp}$. Finally the tradeoff performance of the NEW-LDMOS breaks through the ideal silicon limit with superior FOM.

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