Non-depletion floating layer in SOI LDMOS for enhancing breakdown voltage and eliminating back-gate bias effect

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A non-depletion floating layer silicon-on-insulator (NFL SOI) lateral double-diffused metal–oxide–semiconductor (LDMOS) is proposed and the NFL-assisted modulated field (NFLAMF) principle is investigated in this paper. Based on this principle, the floating layer can pin the potential for modulating bulk field. In particular, the accumulated high concentration of holes at the bottom of the NFL can efficiently shield the electric field of the SOI layer and enhance the dielectric field in the buried oxide layer (BOX). At variation of back-gate bias, the shielding charges of NFL can also eliminate back-gate effects. The simulated results indicate that the breakdown voltage (BV) is increased from 315 V to 558 V compared to the conventional reduced surface field (RESURF) SOI (CSOI) LDMOS, yielding a 77% improvement. Furthermore, due to the field shielding effect of the NFL, the device can maintain the same breakdown voltage of 558 V with a thinner BOX to resolve the thermal problem in an SOI device.

Keywords: breakdown voltage, back-gate bias effect, self-heating effect, silicon-on-insulator

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1. Introduction

Silicon-on-insulator (SOI) is an attractive technology with the merits of reducing leakage current, fast switching, and noise immunity[1–7] as compared to bulk-Si counterparts. Recently, the buried N-island layer (BNIL)[8] induced charge-accumulated island layer has been reported to insert between the SOI layer and the buried oxide layer (BOX) to enhance the electric field in the BOX. A non-depletion compensation layer (NDCL) and N-buffer layer as charge-imbalance compensation layers have been introduced in super-junction devices for improving breakdown voltage (BV).[9,10] In other work, reduced bulk field (REBULF) technology is employed to modulate the electric field in high-voltage devices and higher BV is achieved.[11,12] However, SOI technology suffers from the back-gate bias effect, as has been widely reported.[13,14] A semi-insulating poly-silicon layer has been adopted to eliminate the negative bias of the back-gate effect.[15] SOI technology also suffers from the self-heating effect (SHE). To alleviate SHE, partial-SOI (PSOI) technology has been employed.[16,17] Though PSOI can efficiently resolve the SHE problem, it simultaneously harms the intrinsic reduction of leakage current.

In this paper, a non-depletion floating layer (NFL) SOI lateral double-diffused metal–oxide–semiconductor (LDMOS) is proposed. The introduction of NFL creates three main advantages in the proposed structure. First, the NFL takes advantage of the NFL-assisted modulated field (NFLAMF) principle to modulate the electric field more evenly in the SOI layer and hence BV is significantly improved. Second, due to a large number of holes accumulated on the bottom interface of the NFL, not only negative bias but also positive bias of the back-gate effect on BV (compared to the method in Ref. [15]) is simultaneously eliminated. Third, BV can maintain the same value with a thinner BOX, owing to the pinning effect of the NFL; hence the SHE problem is effectively alleviated.

2. Device structure and mechanism

The schematic cross section views of the proposed NFL SOI LDMOS and conventional reduced surface field (RESURF) SOI (CSOI) LDMOS are illustrated in Fig. 1. The NFL which is made up of a highly doped N^+-buried layer is located at the interface of SOI layer and the BOX. N_d and T_d represent the concentration and thickness of the N-drift region, respectively. N_p and T_p denote the concentration and thickness of the P-type Si region. N_{NFL} and T_{NFL} stand for the concentration and thickness of the NFL. T_I is the thickness of the BOX.

In the blocking state, the drain is connected to the high voltage while the gate and source are grounded. The potential of NFL is floated up when the depletion region of P-type Si spreads into it and then pinned to a certain voltage determined by N_d, T_d, N_p, and T_p. The NFL introduces an additional diode D_2, as shown in Fig. 1(a). The voltage sustaining mechanism lies in the fact that the blocking voltage sustained by the BOX is equal to the blocking voltage sustained by D_2. The voltage drop sustained by the BOX is greatly increased due to the large number of holes accumulated on the bottom interface of

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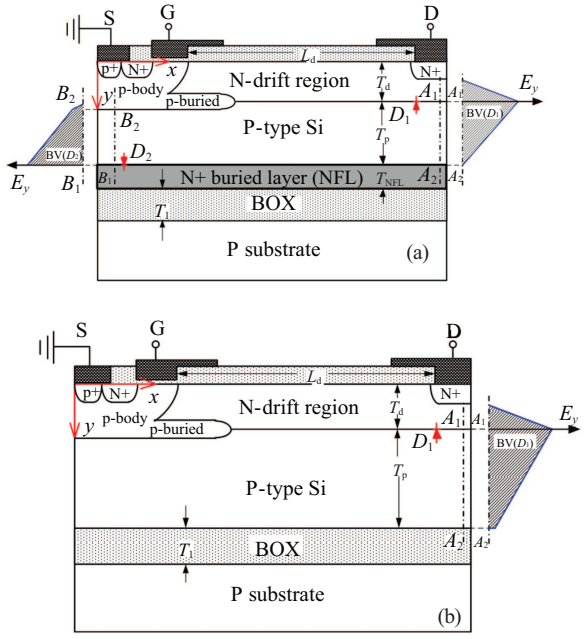


Fig. 1. Schematic cross section views of (a) NFL SOI LDMOS and (b) CSOI LDMOS.

the NFL because a metal–insulator–semiconductor (MIS)-like structure is formed by the NFL, the BOX and the P-type Si substrate. BV is hence described as

$$\begin{aligned} BV &= V(\mathrm{D}_1)+V(\mathrm{D}_2) \\ &\approx \frac{q(N_\mathrm{d}T_\mathrm{d}^2+N_\mathrm{p}T_\mathrm{p}^2)}{2\varepsilon_\mathrm{s}}+\frac{qN_\mathrm{p}T_\mathrm{p}^2}{2\varepsilon_\mathrm{s}}, \qquad (1) \\ V(\mathrm{D}_2) &= V(\mathrm{BOX}) = E_\mathrm{I}\times T_\mathrm{I} = \frac{Q_\mathrm{S}T_\mathrm{I}}{\varepsilon_\mathrm{I}}, \qquad (2) \end{aligned}$$

where ε_s and ε_I are the silicon dielectric constant and SiO_2 dielectric constant, respectively. $V(\mathrm{D}_1)$ and $V(\mathrm{D}_2)$ are the voltages sustained by the diodes D_1 and D_2, respectively. $V(\mathrm{BOX})$ means the voltage sustained by the BOX. Q_S denotes the charge of accumulated holes at the bottom interface of NFL. Due to the existence of D_2, the electric field is distributed more evenly in the device. While the CSOI has only one diode D_1, as shown in Fig. 1(b), the blocking voltage is mainly supported by D_1 and the BOX. Furthermore, in the proposed structure, a large number of holes are accumulated on the bottom interface of the NFL, which efficiently eliminates the back gate bias effect. At last, the thickness of the BOX can be reduced due to the pinning behavior of the NFL, which can significantly alleviate the thermal problem in the SOI devices. The proposed structure is fully compatible with the XFAB (silicon foundries with headquarters in Erfurt) XDH10 SOI high-voltage IC process (dielectric trench insulated smart power technology). The MEDICI TCAD tool[18] is employed to help analyze the device's electrical characteristics. The key physical dimensions and parameters of the device that were used in our simulation are listed in Table 1.

Table 1. Structure parameters of NFL SOI LDMOS.

Symbols	Quantity	Value
L_d/μm	N-drift region length	40
T_d/μm	N-drift region thickness	2
T_p/μm	P-type Si thickness	17.5
$N_\mathrm{NFL}/\mathrm{cm}^{-3}$	NFL concentration	1×10^{17}
T_NFL/μm	NFL thickness	0.5

3. Results and discussion

Use of the RESURF principle[19] to design high voltage LDMOS is very common. The basic RESURF dose requirement of the drift region is 1×10^{12} cm^{-2}. According to the charge neutrality principle, the dose requirement of the depletion region of P-type Si needs to be equal to that of the drift region. However, the introduced NFL with enhancing substrate-assisted depletion can deplete the P-type Si. Thus, based on the NFLAMF principle, the basic dose requirement of P-type Si is shifted to 1.4×10^{12} cm^{-2} ($N_\mathrm{p}\times T_\mathrm{p}=1.4\times10^{12}$ cm^{-2}) in this proposed structure.

To analyze the electric field distribution, the longitudinal electric fields of NFL SOI LDMOS and CSOI LDMOS along A_1A_2 and B_1B_2 lines (shown in Fig. 1) are illustrated in Fig. 2. $N_\mathrm{p}=8\times10^{14}$ cm^{-3} is the optimized value which satisfies the NFLAMF principle for NFL SOI LDMOS to achieve the maximum BV. In the proposed structure, when the potential of NFL is floated up under the reverse bias, the electric field peak around D_1 is 2.9×10^5 V/cm and the peak around D_2 is 2.6×10^5 V/cm. The voltage drop is simultaneously supported by D_1 and D_2, as expressed in Eq. (1). Therefore, the electric field distribution is much more uniform in the SOI layer. As a comparison, the CSOI LDMOS with the same structure parameters is also drawn in Fig. 2. The electric field peak around D_1 is 2.8×10^5 V/cm while there is no electric field peak around D_2. Furthermore, due to an MIS-like structure being formed by the NFL, the BOX, and the P-type Si substrate in the proposed structure, a large number of holes are accumulated on the bottom interface of the NFL. As a result, the electric field in the BOX is greatly enhanced to 3.1×10^6 V/cm, which significantly improves BV to 558 V, while there is no high concentration of holes located at the same location, and the BV is only 315 V for the CSOI LDMOS.

The equipotential contours of NFL SOI LDMOS with $N_\mathrm{p}=8\times10^{14}$ cm^{-3} is shown in Fig. 3(a). The voltage drop is sustained by D_1 ($q(N_\mathrm{d}T_\mathrm{d}^2+N_\mathrm{p}T_\mathrm{p}^2)/2\varepsilon_\mathrm{s}$) and D_2 ($qN_\mathrm{p}T_\mathrm{p}^2/2\varepsilon_\mathrm{s}$) as shown in Eq. (1) and the equipotential contours are distributed evenly in the SOI layer. As a comparison, the equipotential contours of CSOI LDMOS with the same structure parameters are illustrated in Fig. 3(b). Due to the absence of NFL, the voltage drop is mainly sustained by D_1 ($q(N_\mathrm{d}T_\mathrm{d}^2+N_\mathrm{p}T_\mathrm{p}^2)/2\varepsilon_\mathrm{s}$), the equipotential contours concentrate around the drain side, and BV is much lower with only 315 V. The reason

is the same as mentioned before.

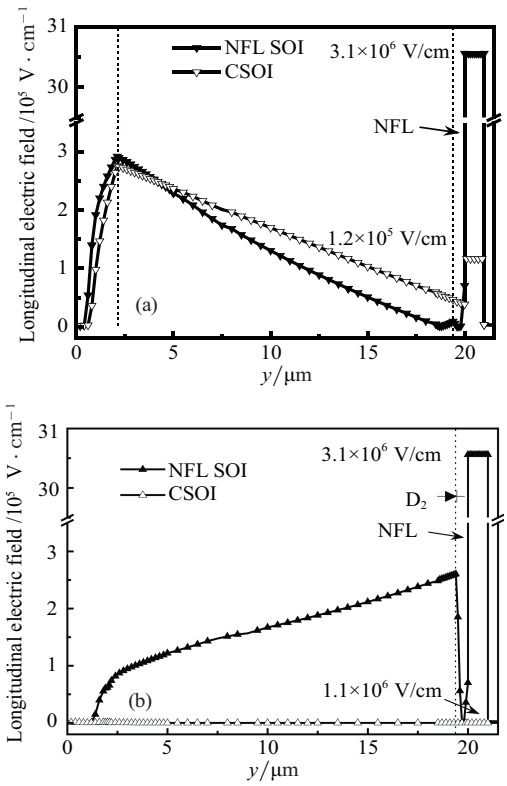


Fig. 2. Longitudinal electric field for NFL SOI LDMOS and CSOI LDMOS of (a) along A_1A_2 line and (b) along B_1B_2 line ($T_I = 1.0$ μm).

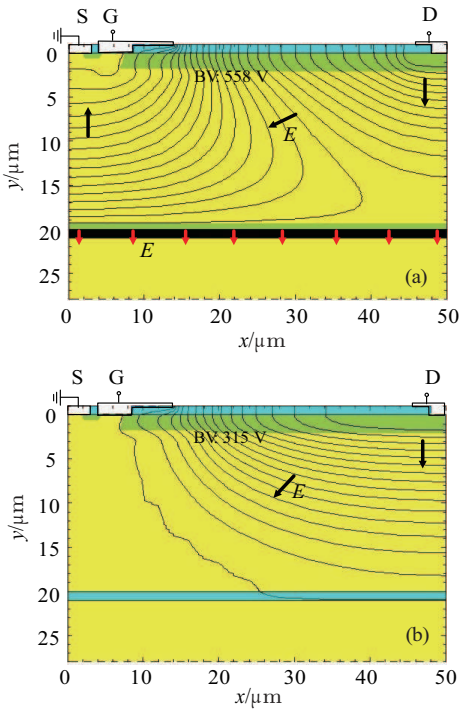


Fig. 3. Equipotential contours at breakdown of (a) NFL SOI LDMOS and (b) CSOI LDMOS ($T_I = 1.0$ μm).

The NFL needs to be highly doped to become an equipotential component to modulate the electric field distribution. The basic requirement of N_{NFL} for NFLAMF is investigated in Fig. 4. When N_{NFL} is low, the N^+-buried layer (shown in Fig. 1(a)) becomes a Depletion Floating Layer (DFL) and partly modulates the electric field in the SOI layer. BV is hence low. When N_{NFL} is high enough, the N^+-buried layer becomes NFL and becomes an equipotential component and can effectively modulate the electric field in the SOI layer, as shown in Fig. 3(a). As a result, the concentration of NFL must be high enough to ensure the NFL can modulate the electric field in the proposed structure and achieve high BV.

To analyze the effect of V_{bg} on BV, the potentials along A_1A_2 line (shown in Fig. 1) at different V_{bg} for NFL SOI LDMOS and CSOI LDMOS are plotted. The potential of NFL is pinned to 306 V when the proposed structure is under reverse bias and only the voltage drop in BOX changes with the variation of V_{bg}. As a result, the potential distributions in the SOI layer of NFL SOI LDMOS are immune to the variation of V_{bg}. BV maintains a constant of 558 V when $V_{bg} = -100$ V, $V_{bg} = 0$ V, $V_{bg} = 100$ V. However, due to the absence of an NFL in the CSOI LDMOS, the BV is sustained by the SOI layer and the BOX. When the V_{bg} varies, the potential distribution is easily affected. The RESURF principle is hence affected and BV declines. BV is 305 V, 315 V, 278 V when $V_{bg} = -100$ V, $V_{bg} = 0$ V, $V_{bg} = 100$ V in the CSOI LDMOS.

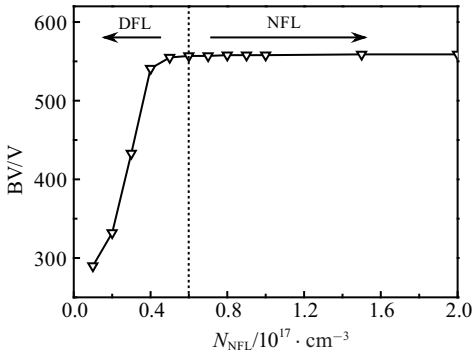


Fig. 4. The basic requirement of N_{NFL} for NFLAMF principle ($T_I = 1.0$ μm).

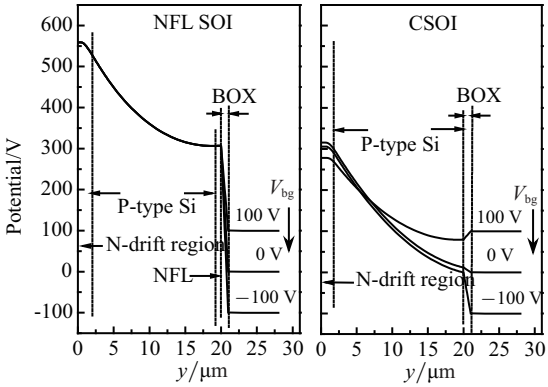


Fig. 5. Longitudinal potentials along A_1A_2 line at different V_{bg} for NFL SOI LDMOS and CSOI LDMOS ($T_I = 1.0$ μm).

To further analyze the effect of V_{bg} on BV, the hole concentration at the bottom interface of the NFL is plotted in

Fig. 6 to investigate the shielding effect. As mentioned before, the potential of the NFL is pinned to 306 V in the proposed structure and only the voltage drop in the BOX changes with the variation of V_{bg}. This phenomenon can be explained by that the variation in the high concentration of holes leads to a change of the voltage drop in the BOX, as shown in Eq. (2). When V_{bg} is grounded, the high concentration of holes with 1.1×10^{18} cm^{-3} already exists in NFL SOI LDMOS. When $V_{bg} = 100$ V, the hole concentration is 6.9×10^{17} cm^{-3}. When $V_{bg} = -100$ V, the hole concentration is 1.5×10^{18} cm^{-3}. The high concentration of holes varies with the variation of V_{bg} and can effectively shield the SOI layer from the effect of V_{bg}. However, when V_{bg} is grounded in the CSOI LDMOS, the hole concentration at the same location is very low. So when V_{bg} varies, it affects the RESURF condition in the CSOI LDMOS and degrades the BV.

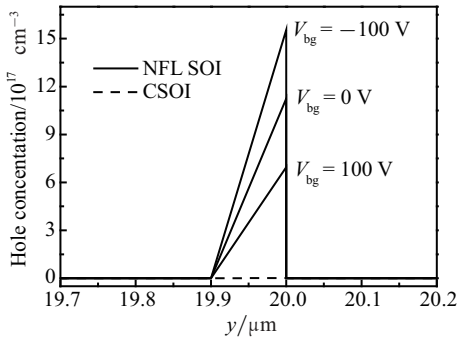


Fig. 6. Hole concentration at different V_{bg} for NFL SOI LDMOS and CSOI LDMOS ($T_I = 1.0$ μm).

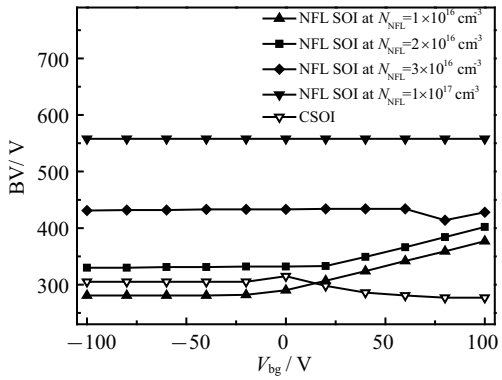


Fig. 7. Effects of V_{bg} on BV at different N_{NFL} for NFL SOI LDMOS and CSOI LDMOS ($T_I = 1.0$ μm).

The concentration of the NFL is also a key parameter to investigate the shielding effect. The effects of V_{bg} on BV at different N_{NFL} for NFL SOI LDMOS and CSOI LDMOS are plotted in Fig. 7. As mentioned before, the N_{NFL} must be high enough to make the NFL become an equipotential component, and then the MIS-like structure is formed by the NFL, the BOX, and the P-type Si substrate. A high concentration of holes is thus accumulated at the bottom interface of the NFL to shield the SOI layer from the effects of V_{bg}. BV can maintain the high value of 558 V while V_{bg} varies, and the reason for this was already interpreted before. However, when N_{NFL} is low, the N^+-buried layer is depleted and there is no high concentration of holes at the bottom interface of the NFL. So when V_{bg} varies, it affects the electric field distribution in the SOI layer and deteriorates the BV as shown in Fig. 7. As a comparison, the effect of V_{bg} on BV for CSOI LDMOS is also plotted in Fig. 7. Due to the same reason of the absence of high concentration holes, BV is easily degraded when V_{bg} varies.

When the N_{NFL} is high enough, NFL becomes an equipotential component and is pinned to 306 V. Therefore, when T_I is decreased, BV can maintain the same high value in the proposed structure. The potentials and longitudinal electric fields for NFL SOI LDMOS along the A_1A_2 line at different T_I are plotted in Fig. 8. When T_I is decreased from 1.0 μm to 0.5 μm, the electric field is enhanced from 3.1×10^6 V/cm to 6.1×10^6 V/cm, and the potential of the NFL is pinned to 306 V, as shown in Fig. 8. Therefore, BV maintains the high value of 558 V with an unlimited decrease of T_I. The minimum T_I only needs to take the critical electric field of SiO_2[20] into account to avoid the pre-breakdown happening in the BOX. The characteristic can effectively resolve the thermal problem in SOI device. The maximum temperature (T_{max}) at the power of 1 mW/μm is investigated at different T_I to study the SHE effect. The substrate temperature is set to 300 K, and the gate voltage (V_g) is 15 V during the thermal analysis. T_{max} decreases from 319 K to 312 K when T_I decreases from 1.0 μm to 0.5 μm with the same BV of 558 V.

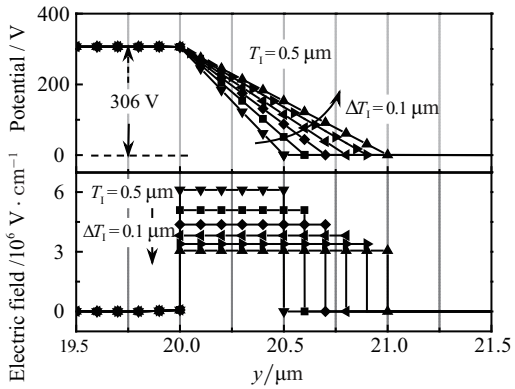


Fig. 8. Potential and longitudinal electric field for NFL SOI LDMOS along A_1A_2 line.

4. Conclusion

The NFL SOI LDMOS is proposed and investigated in this paper. Due to a more evenly distributed electric field in the SOI layer, BV is increased from 315 V for CSOI LDMOS to 558 V, yielding a 77% improvement. Also, the back-gate bias effect on BV is eliminated owing to the layer of highly concentrated holes shielding the SOI layer. Furthermore, SHE is effectively alleviated because the thickness of the BOX can be reduced to a very thin 0.5 μm in the proposed structure while still maintaining the same BV of 558 V. The proposed device

is fully compatible with the XFAB XDH10 SOI high-voltage IC process. As a result, NFL SOI LDMOS is a promising candidate for future applications in power ICs.

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