Improvement on the breakdown voltage for silicon-on-insulator devices based on epitaxy-separation by implantation oxygen by a partial buried n^+-layer*

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A novel silicon-on-insulator (SOI) high-voltage device based on epitaxy-separation by implantation oxygen (SIMOX) with a partial buried n^+-layer silicon-on-insulator (PBN SOI) is proposed in this paper. Based on the proposed expressions of the vertical interface electric field, the high concentration interface charges which are accumulated on the interface between top silicon layer and buried oxide layer (BOX) effectively enhance the electric field of the BOX ($E_{\rm I}$), resulting in a high breakdown voltage (BV) for the device. For the same thicknesses of top silicon layer (10 μm) and BOX (0.375 μm), the $E_{\rm I}$ and BV of PBN SOI are improved by 186.5% and 45.4% in comparison with those of the conventional SOI, respectively.

Keywords: silicon-on-insulator, vertical breakdown voltage, separation by implantation oxygen, interface charges

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1. Introduction

Separation by implantation oxygen (SIMOX) is one of the most common and promising methods to prepare silicon-on-insulator (SOI) wafer.[1−3] However, the thin SOI layer of about 1800 Å (1 Å=0.1 nm) and the buried oxide layer (BOX) of about 3800 Å by SIMOX technology bring a very low breakdown voltage (BV) (less than 50 V) for the device fabricated on it. The thin top silicon layer can be grown to achieve a proper thickness by epitaxy-SIMOX (E-SIMOX),[4] whereas BV is still restricted by the thin BOX and Gauss theory without interface charge. Enhancing the electric field of the BOX ($E_{\rm I}$) is feasible to increase BV by enhancing dielectric layer field (ENDIF),[5−14] which is summarized as a general rule to improve the vertical BV of SOI device. In this paper, a novel SOI high voltage device based on E-SIMOX with a partial buried n^+-layer silicon-on-insulator (PBN SOI) is proposed, which provides a higher BV than the conventional E-SIMOX SOI device. The influences of structure parameters on BV are analysed by software MEDICI.[15]

2. Structure and mechanism

PBN SOI LDMOS is shown in Fig. 1 and a high concentration n^+-layer is inserted on the partial interface between the top silicon layer and the buried oxide layer on the source side. A p-top layer is used in PBN SOI LDMOS. $t_{\rm S}$, $t_{\rm I}$, $t_{\rm n^+}$, and $t_{\rm sub}$ represent the thicknesses of top silicon layer, BOX, PBN layers and substrate layer, $L_{\rm d}$, $L_{\rm n^+}$, and $L_{\rm S}$ are the lengths of drift region, PBN layer, and p-body region of the source respectively and $N_{\rm d}$ is the doping concentration of drift region.

When a high positive voltage $V_{\rm d}$ is applied to the drain while the source, gate and substrate are grounded, two-dimensional (2D) potential $\phi(x,y)$ in the drift region can be written as $\phi(x,y) = \omega(x,y) + \varphi(x,y)$, where $\omega(x,y)$ and $\varphi(x,y)$ are the contributions of $V_{\rm d}$ and depleted impurities in drift region, respectively,

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in which, $\varphi(x,y)$ satisfies 2D Poisson equation

$$\frac{\partial^2\varphi(x,y)}{\partial x^2}+\frac{\partial^2\varphi(x,y)}{\partial y^2}=-\frac{qN_{\rm d}}{\varepsilon_{\rm S}},$$
$$0\le x\le L_{\rm S}+L_{\rm d},\quad 0\le y\le t_{\rm S}, \tag{1}$$

where $\varepsilon_{\rm S}$ is the permittivity of silicon and q is electron charge. For fully-depleted drift region, the vertical electric field in the top silicon layer satisfies

$$E_y(x,y)=-\frac{\partial\varphi(x,y)}{\partial y}=\psi_1(x)+\psi_2(x)y,$$
$$0\le x\le L_{\rm S}+L_{\rm d},\quad 0\le y\le t_{\rm S}. \tag{2}$$

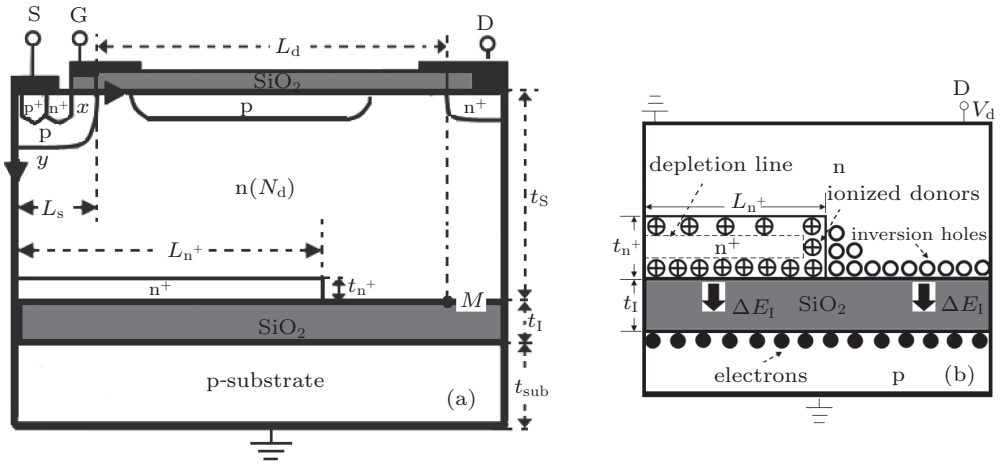


Fig. 1. Structure of PBN SOI LDMOS. Panel (a) shows the device structure and panel (b) the working mechanism.

The boundary conditions for Eq. (2) are given by

$$\left.\frac{\partial\varphi(x,y)}{\partial y}\right|_{y=0}=0, \tag{3a}$$
$$\varphi(0,0)=0,\quad \varphi(L_{\rm S}+L_{\rm d},0)=V_{\rm d}, \tag{3b}$$
$$\frac{\varepsilon_{\rm I}[\varphi(x,t_{\rm S})-\varphi(x,t_{\rm S}+t_{\rm I})]}{t_{\rm I}}=-\frac{\partial\varphi(x,y)}{\partial y}\varepsilon_{\rm S}\Big|_{y=t_{\rm S}}+q\sigma_{\rm in}(x), \tag{3c}$$

where $\varepsilon_{\rm I}$ is the permittivity of dielectric buried layer (SiO_2) and $\sigma_{\rm in}$ is the interface charge impurity. Equation (3c) is based on the continuity of electric displacement on the interface ($y=t_{\rm S}$). Solving Eq. (2) with the boundary conditions yields

$$\varphi(x,y)=-\frac{1}{2}\psi_2(x)y^2+\psi_2(x)t^2+\frac{q\sigma_{\rm in}(x)t_{\rm I}}{\varepsilon_{\rm I}}+\varphi(x,t_{\rm S}+t_{\rm I}), \tag{4}$$

where

$$t=\sqrt{\frac{1}{2}t_{\rm S}^2+\frac{\varepsilon_{\rm S}}{\varepsilon_{\rm I}}t_{\rm S}t_{\rm I}}$$

is the characteristic thickness of SOI device. From Eq. (4), surface potential distribution ($y=0$) is obtained as

$$\varphi(x,0)=-\psi_2(x)t^2+\frac{q\sigma_{\rm in}(x)t_{\rm I}}{\varepsilon_{\rm I}}+\varphi(x,t_{\rm S}+t_{\rm I}), \tag{5}$$

and so,

$$\psi_2(x)=\frac{\varepsilon_{\rm I}\varphi(x,0)-t_{\rm I}q\sigma_{\rm in}(x)-\varepsilon_{\rm I}\varphi(x,t_{\rm S}+t_{\rm I})}{\varepsilon_{\rm I}t^2}. \tag{6}$$

With Eq. (6), equation (4) yields

$$\varphi(x,y)=\frac{q\sigma_{\rm in}(x)t_{\rm I}+\varepsilon_{\rm I}\varphi(x,t_{\rm S}+t_{\rm I})-\varepsilon_{\rm I}\varphi(x,0)}{2\varepsilon_{\rm I}t^2}y^2+\varphi(x,0). \tag{7}$$

From Eq. (7), electric potential distribution under the drain ($x=L_{\rm S}+L_{\rm d}$) can be obtained as

$$\varphi(L_{\rm S}+L_{\rm d},y)=\frac{q\sigma_{\rm in}(L_{\rm S}+L_{\rm d})t_{\rm I}+\varepsilon_{\rm I}\varphi(L_{\rm S}+L_{\rm d},t_{\rm S}+t_{\rm I})-\varepsilon_{\rm I}\varphi(L_{\rm S}+L_{\rm d},0)}{2\varepsilon_{\rm I}t^2}y^2+\varphi(L_{\rm S}+L_{\rm d},0). \tag{8}$$

From Eq. (8), the vertical electric field under the drain ($x=L_{\rm S}+L_{\rm d}$) is derived as

$$E_y(L_{\rm S}+L_{\rm d},y)=\frac{\varepsilon_{\rm I}\varphi(L_{\rm S}+L_{\rm d},0)-q\sigma_{\rm in}(L_{\rm S}+L_{\rm d})t_{\rm I}-\varepsilon_{\rm I}\varphi(L_{\rm S}+L_{\rm d},t_{\rm S}+t_{\rm I})}{\varepsilon_{\rm I}t^2}y. \tag{9}$$

With Eq. (9) and Gauss-theory on the interface ($y = t_{\rm S}$), the electric fields in silicon and BOX (at M point) $E_{\rm S}$ and $E_{\rm I}$ are obtained respectively as

$$E_{\rm S} = \frac{V_{\rm d} - \varphi(L_{\rm S} + L_{\rm d}, t_{\rm S} + t_{\rm I})}{t^2} t_{\rm S} - \frac{t_{\rm I} t_{\rm S} q \sigma_{\rm in}(L_{\rm S} + L_{\rm d})}{\varepsilon_{\rm I} t^2}, \quad (10)$$

$$E_{\rm I} = \frac{\varepsilon_{\rm S} t_{\rm S}}{\varepsilon_{\rm I} t^2}[V_{\rm d} - \varphi(L_{\rm S} + L_{\rm d}, t_{\rm S} + t_{\rm I})] + \frac{t_{\rm S}^2 q \sigma_{\rm in}(L_{\rm S} + L_{\rm d})}{2\varepsilon_{\rm I} t^2}. \quad (11)$$

For the conventional SOI device, $\sigma_{\rm in}$ can be ignored ($\sigma_{\rm in} \approx 0$) because of the extraction of charges by the lateral electric field. As shown in Fig. 1(b), for the proposed PBN SOI device, the high concentration ionized donors in the undepleted PBN layer prevent the extracting effect of the lateral electric field in the drift region and an inversion hole layer is therefore formed on the interface without PBN layer (on the drain side). At the same time, there are plentiful electrons existing on the bottom interface of BOX. It follows from Eqs. (10) and (11) that interface charge $\sigma_{\rm in}$ of the PBN SOI can enhance $E_{\rm I}$ in comparison with the case of conventional SOI and shield the silicon layer electric field $E_{\rm S}$, thereby avoiding the premature breakdown of silicon layer. These all will contribute to the achievement of a higher BV.

3. Results and discussion

The charge concentration distributions on the top and the bottom interfaces of BOX for the PBN SOI and conventional SOI are shown in Fig. 2(a). It can been seen that $\sigma_{\rm in}$ of the conventional SOI is less than 5×10^{17} cm^{-3} whose effect on the interface electric field can be ignored as mentioned above. However, for the proposed PBN SOI, the interface inversion hole concentration under the drain is higher than 1.5×10^{18} cm^{-3} at the breakdown with an electron concentration of about 2×10^{18} cm^{-3} on the bottom interface of the BOX. Based on Eq. (11), the accumulated interface charges can effectively enhance $E_{\rm I}$ and $E_{\rm I}$ of the PBN SOI is improved to 490 V/μm from the conventional 171 V/μm when breakdown occurs as shown in Fig. 2(b).

As shown in Figs. 3(a)–3(c), because of the electric field modulated by the PBN layer, surface electric field and equipotential contours of the PBN SOI are more favourable than those of the conventional SOI and the interface electric field in silicon layer of PBN SOI is reduced compared with that in the conventional one. Moreover, the interface electric field in BOX of PBN SOI is effectively enhanced and uniform from source to drain due to the interface charges in Fig. 2(a).

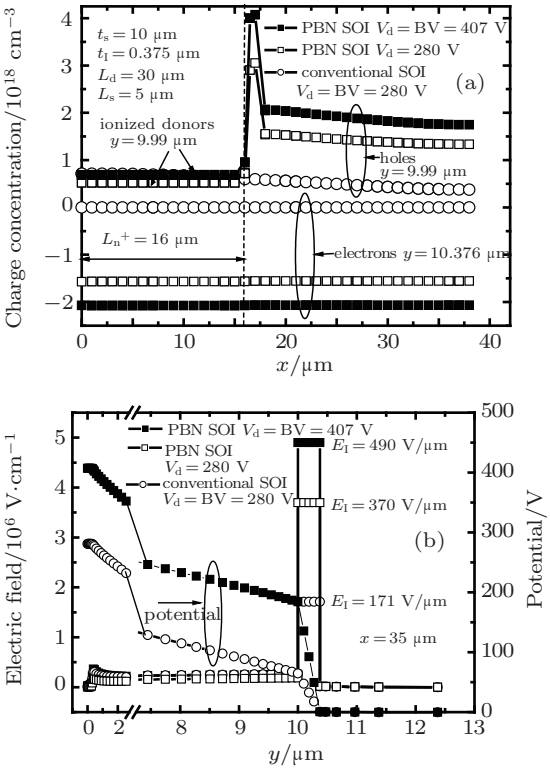


Fig. 2. Charge and electric field distributions ($L_{\rm d}$ = 30 μm, $t_{\rm S}$ = 10 μm, $t_{\rm I}$ = 0.375 μm, $L_{\rm S}$ = 5 μm, $N_{\rm n+} = 1\times10^{18}$ cm^{-3}, $L_{\rm n+}$ = 16 μm, $t_{\rm sub}$ = 2 μm). (a) Interface charge concentration distributions and (b) vertical electric fields and potentials under the drain (x = 35 μm).

The enhanced $E_{\rm I}$ (Fig. 2(b)) and the optimized lateral electric fields (Fig. 3(c)) lead to a high BV (407 V) for PBN SOI in comparison with that for the conventional SOI (280 V).

Figure 4 shows the BV against $L_{\rm d}$, $L_{\rm n+}$ and $N_{\rm n+}$ for PBN SOI. It can be seen from Fig. 4(a) that when $L_{\rm d}$ is less than 30 μm, the maximal values of BV ($\rm BV_{max}$) all increase with the increase of $L_{\rm d}$ and after that, they are equal because they are limited by the values of vertical BV. In addition, a smaller $L_{\rm n+}$ is needed for a shorter $L_{\rm d}$ to achieve the $\rm BV_{max}$. As shown in Fig. 4(b), $N_{\rm n+}$ has no influence on BV when $N_{\rm n+} \geq 1\times10^{17}$ cm^{-3} because the concentrations of interface ionized donors and inversion holes are saturated and irrespective with the depletion of PBN layer (C-region in Fig. 4(b)). BV tardily decreases when 2×10^{16} cm^{-3} $\leq N_{\rm n+} < 1\times10^{17}$ cm^{-3} because of partially-depleted PBN layer (B-region in Fig. 4(b))

and when $N_{n+} < 2 \times 10^{16}$ cm^{-3}, BV rapidly decreases with N_{n+} because PBN layer is fully depleted (A-region in Fig. 4(b)).

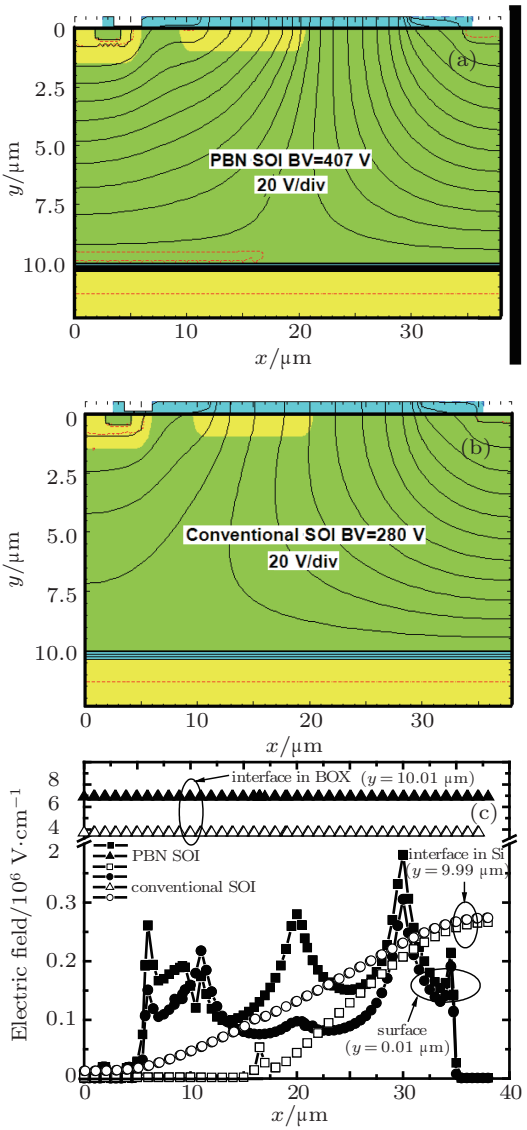


Fig. 3. (colour online) Equipotential contours and electric field distributions at breakdown for PBN SOI and the conventional SOI with $L_d = 30$ μm, $t_S = 10$ μm, $t_I = 0.375$ μm, $L_S = 5$ μm. (a) Equipotential distribution for PBN SOI ($N_d = 9\times10^{14}$ cm^{-3}), (b) equipotential distribution for the conventional SOI ($N_d = 1\times10^{15}$ cm^{-3}), and (c) surface ($y = 10.01$ μm) and interface electric field distributions for the two structures.

Figure 5 shows the BV against N_d for different values of t_{n+}. It can be seen that with t_{n+} increasing from 0.3 μm to 0.8 μm, the BV_{max} is almost a constant of about 407 V for each t_{n+} and the N_d for each BV_{max} decreases with the value of t_{n+} decreasing because of the reduced surface field (RESURF) condition.[16,17] This shows that t_{n+} has a feeble effect on BV if only N_d is optimized.

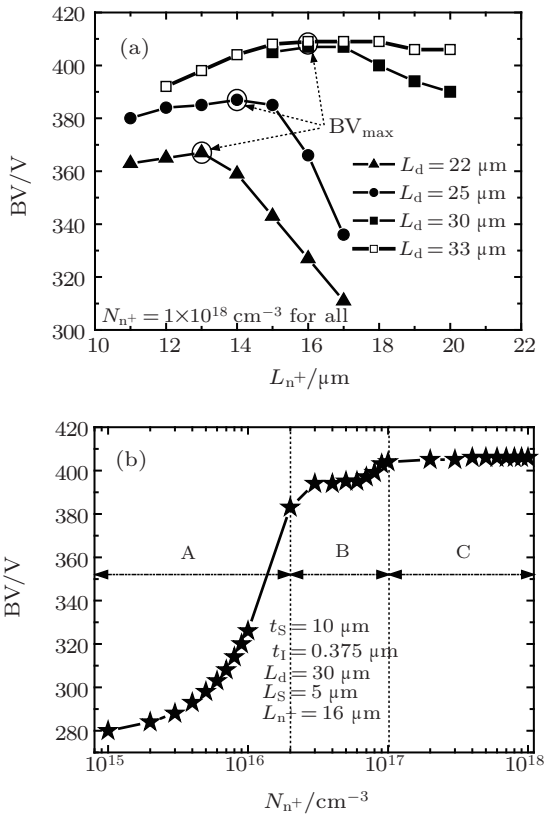


Fig. 4. BV against L_{n+}, L_d, and N_{n+} with $t_S = 10$ μm, $t_I = 0.375$ μm, and $L_S = 5$ μm, (a) BV against L_{n+} and L_d ($N_{n+} = 1 \times 10^{18}$ cm^{-3}); (b) BV against N_{n+} ($L_{n+} = 16$ μm).

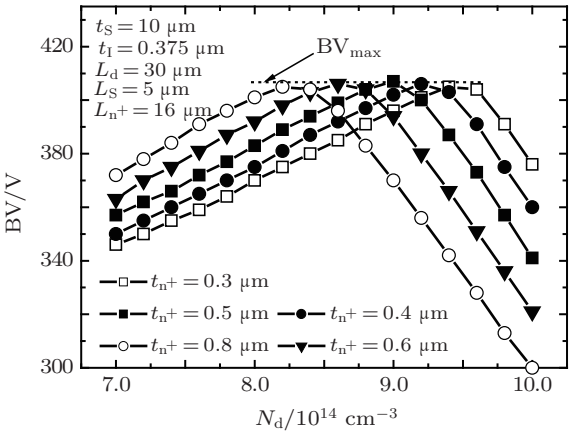


Fig. 5. BV against t_{n+} for PBN SOI, with $L_d = 30$ μm, $t_S = 10$ μm, $t_I = 0.375$ μm, and $L_S = 5$ μm.

Only one additional process of phosphor implantation is needed to form PBN SOI and its process tolerance is good.

4. Conclusion

A novel SOI high-voltage device of PBN SOI is proposed in this paper. With the same thicknesses of

top silicon layer and BOX, $E_{\rm I}$ and BV of PBN SOI are improved to 490 V/ μm and 407 V from 171 V/ μm and 280 V of the conventional SOI, respectively.

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