第26卷 第5期 半 导 体 学 报 Vol.26 No.5
2005年5月 CHINESE JOURNAL OF SEMICONDUCTORS May,2005

# Sensitivity of Total-Dose Radiation Hardness of SIMOX Buried Oxides to Doses of Nitrogen Implantation into Buried Oxides

Zheng Zhongshan[1,3], Liu Zhongli[1], Zhang Guoqiang[1], Li Ning[1], Li Guohua[1], Ma Hongzhi[1], Zhang Enxia[2], Zhang Zhengxuan[2], and Wang Xi[2]

(1 Microelectronics R&D Center, Institute of Semiconductors, Chinese Academy of Sciences, Beijing 100083, China)
(2 Shanghai Institute of Microsystem and Information Technology, Chinese Academy of Sciences, Shanghai 200050, China)
(3 Department of Physics, Jinan University, Jinan 250022, China)

**Abstract:** In order to improve the total-dose radiation hardness of the buried oxides (BOX) in the structure of separation-by-implanted-oxygen (SIMOX) silicon-on-insulator (SOI), nitrogen ions are implanted into the buried oxides with two different doses, $2\times10^{15}$ and $3\times10^{15}cm^{-2}$, respectively. The experimental results show that the radiation hardness of the buried oxides is very sensitive to the doses of nitrogen implantation for a lower dose of irradiation with a Co-60 source. Despite the small difference between the doses of nitrogen implantation, the nitrogen-implanted $2\times10^{15}cm^{-2}$ BOX has a much higher hardness than the control sample (i.e. the buried oxide without receiving nitrogen implantation) for a total-dose irradiation of $5\times10^4$rad(Si), whereas the nitrogen-implanted $3\times10^{15}cm^{-2}$ BOX has a lower hardness than the control sample. However, this sensitivity of radiation hardness to the doses of nitrogen implantation reduces with the increasing total-dose of irradiation (from $5\times10^4$ to $5\times10^5$rad(Si)). The radiation hardness of BOX is characterized by MOS high-frequency (HF) capacitance-voltage ($C$-$V$) technique after the top silicon layers are removed. In addition, the abnormal HF $C$-$V$ curve of the metal-silicon-BOX-silicon (MSOS) structure is observed and explained.

**Key words:** SIMOX; buried oxide; radiation-hardness; nitrogen implantation
**EEACC:** 2550R; 2810
**CLC number:** TN305.3 **Document code:** A **Article ID:** 0253-4177(2005)05-0862-05

## 1 Introduction

The circuits based on the silicon-on-insulator (SOI) technology have a faster speed, lower power, and higher device density[1]. Also, SOI CMOS integrated circuits (ICs) are immune to latch-up effect as compared to bulk-silicon CMOS ICs. In particular, SOI ICs show a lower single event upset (SEU) sensitivity and reveal a stronger tolerance to high dose rate transient radiation upset effects. All these SOI benefits are due to buried dielectric isolation in SOI devices[2]. However, the presence of buried dielectric layers also makes it complex to harden SOI devices to total-dose irradiation. This is because the radiation-induced trapped holes in buried dielectric layer can cause a parasitic back-channel conduction for SOI nMOSFETs[3] and a front-channel threshold voltage shift for fully depleted SOI MOSFETs[4]. Thus, the hardening of the buried dielectric layers in SOI devices becomes very important for those SOI ICs operating in radiation environment. Considering nitrided oxides have a higher radiation hardness than thermal pure oxides in MOS devices[5,6], the nitrided buried oxides in SOI devices are expected to have an improved radiation hardness to total-dose irradiation. A buried $SiO_2$-$Si_3N_4$-$SiO_2$ multilayer dielectric has been fabricated as a hardened buried layer in SOI structure by the zone-melting recrystallization (ZMR) tech-

Received 24 November 2004, revised manuscript received 25 January 2005 

nique[7]. In addition, the hardened SOI buried layers formed by oxygen and nitrogen implantation have also been reported[8]. Undoubtedly, for hardening SOI buried layers, the doses of nitrogen implantation should play a very important role. However, the effect of the doses of nitrogen implantation on the radiation hardness of buried layers has not yet been studied well. In this paper, a preliminary investigation on this effect has been performed by implanting nitrogen into the buried oxides (BOX) of the separation-by-implanted-oxygen (SIMOX) SOI wafers with different doses. The sensitivity of the radiation hardness of SIMOX BOX to the doses of nitrogen implantation has been exhibited.

## 2 Experiment

The SIMOX SOI wafers were prepared by implanting oxygen into p-type, ~20Ω·cm, ⟨100⟩ silicon wafers with a dose of around $2\times10^{18}cm^{-2}$ and post-implantation 1300 ℃ annealing in $O_2$ + $Ar_2$ ambient. The prepared SIMOX SOI wafers have a 200nm top silicon layer and a 375nm BOX. For the improvement of the radiation hardness of the BOX, with 160keV, nitrogen ions were subsequently implanted into the BOX with the doses of $2\times10^{15}$ and $3\times10^{15}cm^{-2}$, respectively. The nitrogen-implanted SOI wafers were annealed at 1200 ℃ in $N_2$ ambient. So, SOI wafers 1#, 2# were obtained, respectively corresponding to the two nitrogen doses. In addition, for comparison, SOI wafer 0# as a control wafer dose not receive nitrogen implantation.

The metal-BOX-semiconductor (MOS) capacitors, MOS 0# ~2 #, were respectively fabricated on the SOI wafers 0# ~2# after the top silicon layers were removed by reactive-ion etching. All the MOS capacitors have a $1.96\times10^{-3}cm^{-2}$ Al-gate by electron beam evaporation. Additionally, a metal-silicon-BOX-silicon (MSOS) capacitor, MSOS 0#, was prepared on SOI wafer 0#.

The high-frequency (HF) *C-V* characteristics of all the capacitors were measured by a computer-controlled HP4275 LCR meter at 1MHz before and after irradiation. The capacitors were irradiated with a Co-60 source at a dose rate of $1.38\times10^4$ rad(Si)/min. MOS 0# ~2# received respectively the total-dose irradiations of $5\times10^4$ and $1\times10^5$ rad(Si) with a +6.5V gate bias during irradiation. In addition, with a zero gate bias during irradiation, MOS 0# ~2# received a total-dose irradiation of $5\times10^5$ rad(Si).

## 3 Results and discussion

Figures 1, 2, and 3 show the HF *C-V* curves of MOS 0# ~2 # capacitors before and after the irradiations of $5\times10^4$, $1\times10^5$, and $5\times10^5$ rad(Si), respectively. In the figures, symbols $C$, $C_{BOX}$, and $V_G$ denote the total capacitance, the BOX capacitance, and the gate sweep voltage, respectively. It is well known that the bulk-trapped holes due to irradiation in BOX similar to fixed oxide charges can only result in the negative parallel shift of a HF *C-V* curve along voltage axis[9]. From Fig. 1, it is obvious that the HF *C-V* curve of MOS 1# shows a

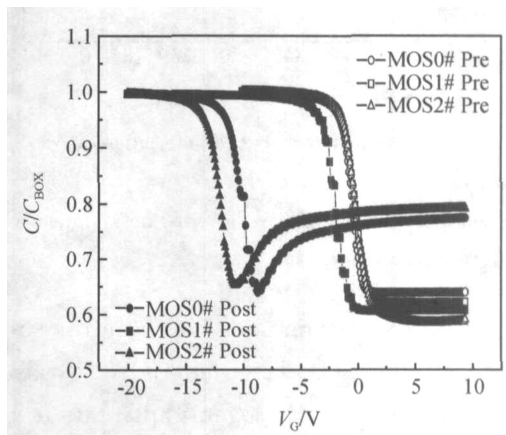


Fig. 1 High frequency *C-V* characteristics of MOS 0# ~2# capacitors measured at a frequency of 1MHz before and after $5\times10^4$ rad(Si) irradiation Gate bias is 6.5V during irradiation.

smallest shift after $5\times10^4$ rad(Si) irradiation. In particular, this *C-V* curve shift of MOS 1# (about 2V) is much smaller than those of MOS 0# (about 10V) and MOS 2# (about 12V). Namely, the BOX of MOS 1# has a much higher radiation hardness

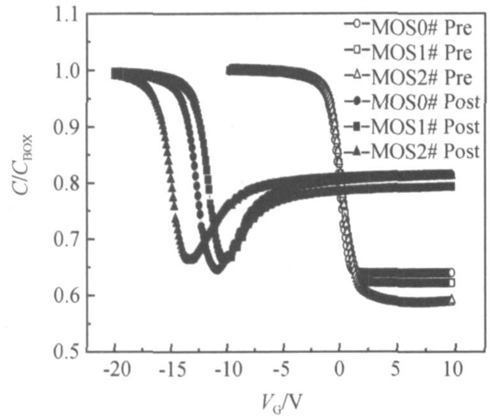


Fig. 2 High frequency *C-V* characteristics of MOS 0# , 2# capacitors measured at a frequency of 1MHz before and after 1 $\times 10^5$ rad (Si) irradiation Gate bias is 6.5V during irradiation.

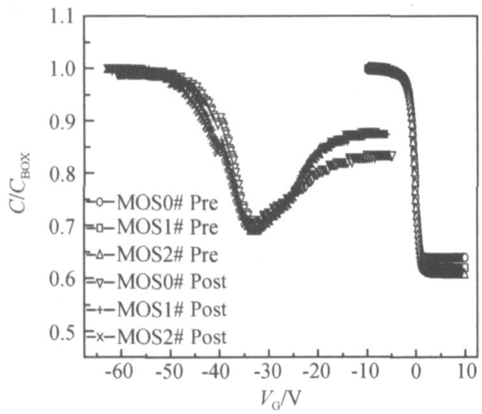


Fig. 3 High frequency *C-V* characteristics of MOS 0# ～2 # capacitors measured at a frequency of 1MHz before and after 5 $\times 10^5$ rad (Si) irradiation Gate bias is 0V during irradiation.

to 5 $\times 10^4$ rad (Si) irradiation. This result is surprising, because the BOX layer in MOS 2# also received a 3 $\times 10^{15}$ cm$^{-2}$ nitrogen implantation. However, the tolerance of MOS 2# to 5 $\times 10^4$ rad(Si) irradiation is even poorer than that of MOS 0# as a control sample. Considering the small difference between the nitrogen doses of 2 $\times 10^{15}$ and 3 $\times 10^{15}$ cm$^{-2}$ as compared to the oxygen dose of around 2 $\times 10^{18}$ cm$^{-2}$ in BOX, this means the radiation hardness of the BOX to 5 $\times 10^4$ rad (Si) irradiation is very sensitive to nitrogen doses. However, this sensitivity decreases with the increasing total doses of irradiation, as seen in Fig. 2. After $10^5$ rad(Si) irradiation, the *C-V* curve of MOS 1# becomes close to that of MOS 0#, while the difference of the *C-V* curve shifts between MOS 0# and MOS 2# is slightly larger than 5 $\times 10^4$ rad (Si) irradiation in Fig. 1. This is probably due to the difference between the densities of the BOX electron and BOX hole traps induced by nitrogen implantation[10,11]. Namely, for 2 $\times 10^{15}$ cm$^{-2}$ nitrogen implantation, the more electron traps are created because of this implantation in BOX, as compared to the hole traps created by the same implantation. Thus, the electron trapping in MOS 1# BOX suppresses the negative *C-V* shift of MOS 1# related to the hole trapping after 5 $\times 10^4$ rad(Si) irradiation. However, after 5 $\times 10^4$ rad(Si) irradiation, the most of the electron traps in MOS 1 # BOX are occupied. As a result, the hole trapping in MOS 1# BOX is dominant during $10^5$ rad(Si) irradiation. Thus, the large *C-V* shift of MOS 1# occurs after $10^5$ rad(Si) irradiation. On the other hand, for 3 $\times 10^{15}$ cm$^{-2}$ nitrogen implantation, a contrary case probably appears in BOX due to this implantation. That is, in MOS 2 # BOX there are the more hole traps induced by this nitrogen implantation than the number of electron traps induced by the same implantation. This leads to a larger *C-V* shift of MOS 2# than that of MOS 0# after irradiation. Therefore, the concentrations of the electron and hole trap in BOX are probably sensitive to the different doses of nitrogen implantation. In Fig. 3, after 5 $\times 10^5$ rad(Si) irradiation, the *C-V* curves of MOS 1# ～2# almost overlap completely and display a worse distortion than that of MOS 0# due to the interface-trapped charges[9]. The 1200 ℃ annealing after the implantation of nitrogen into BOX may be responsible for a poorer BOX/Si interface[12], which is helpful for the generation of the interface traps during irradiation. Even so, the influence of interface traps on *C-V* curves is negligible in the case of a lower dose irradiation.

From Figs. 1～3, after irradiation, all the *C-V* curves begin to rise rapidly in near inversion, and then reach their respective constants in strong inversion. An explanation can be given through the mechanism of the lateral spreading of inversion layer beyond the gate[13]. Namely, the trapped holes in BOX and the positive interface-trapped charges due to radiation give rise to the formation of inversion layer for p-type silicon substrate. The inversion layer beyond the gate provides minority carriers (i.e. electrons) and increases the effective area of the gate, causing the increase of semiconductor capacitance in inversion region. The higher the irradiation doses, the more the trapped holes in BOX, the larger the *C-V* curve shifts, the more the minority carriers in inversion layer, and the greater the semiconductor capacitance in inversion (as seen in Figs. 1～3).

The HF *C-V* curves of MSOS 0# in Fig. 4 are abnormal. They look like quasi-static *C-V* curves rather than HF *C-V* curves[7] to a great extent. The reason for this should be that the existence of the permanent inversion layers beyond the gate (similar to MOS structures, as mentioned above[13]). Before irradiation, the key factor of forming the inversion layers in the MSOS structure should be the positive impurity ions (such as $Na^+$) existing on the sidewall of the silicon island and the BOX surface (see Fig. 5). After irradiation, the bulk-trapped holes due to irradiation in BOX not only attract more electrons into the permanent inversion layers but also cause a spread of the permanent inversion layers. As a result, the bigger semiconductor capacitances occur in inversion, bringing the *C-V* curves of MSOS 0# to a higher level (as seen in Fig. 4). Additionally, the bulk-trapped holes in BOX due to irradiation lead to a change of the surface potential of semiconductor. Thus, the stretch-out of MSOS 0 # *C-V* curves happens in Fig. 4.

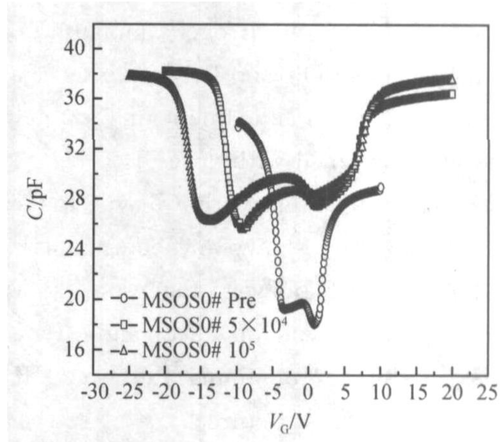


Fig. 4 High frequency *C-V* characteristics of MSOS 0# capacitor measured at 1MHz before and after $5 \times 10^4$ and $10^5$ rad(Si) irradiation Gate bias is 6.5V during irradiation.

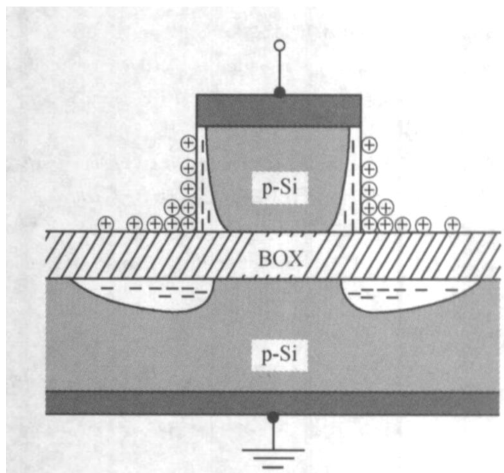


Fig. 5 Schematic illustration of permanent inversion layers caused by positive impurity ions for a MSOS structure before irradiation

## 4 Conclusions

For $5 \times 10^4$ rad(Si) irradiation, the total dose radiation hardness of the nitrogen-implanted BOX shows a strong sensitivity to the doses of nitrogen implantation. For $2 \times 10^{15} cm^{-2}$ nitrogen implantation, the BOX exhibits a much greater tolerance to radiation than for $3 \times 10^{15} cm^{-2}$ and zero nitrogen implantation. This sensitivity may be related to the electron and hole traps induced by nitrogen implantation in BOX. However, as the total dose of irradiation is up to $10^5$ rad(Si), this sensitivity has a significant reduction. Particularly, for a high dose irradiation of $5 \times 10^5$ rad(Si), there is no longer this sensitivity. The high temperature annealing after nitrogen implantation probably leads to a degradation of BOX/Si interface. The decrease of annealing temperature and time after nitrogen implantation may be useful to avoid a poorer BOX/Si interface.

A proper condition of nitrogen implantation for hardening SIMOX BOX and BOX/ Si interface may be found through the adjustment of the implantation energies combined with doses.

The MSOS structure with a p-type top silicon and p-type substrate shows an abnormal HF C-V curve. The detailed analysis suggests the MSOS structure with an n-type top silicon and n-type substrate is suitable for obtaining the true HF C-V curves of the MSOS structures.

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# SIMOX 埋氧层的总剂量辐射硬度对埋氧层中注氮剂量的敏感性


郑中山[1,3] 刘忠立[1] 张国强[1] 李 宁[1] 李国花[1] 马红芝[1] 张恩霞[2] 张正选[2] 王 曦[2]

(1 中国科学院半导体研究所 微电子研究与发展中心, 北京 100083)

(2 中国科学院上海微系统与信息技术研究所, 上海 200050)

(3 济南大学物理系, 济南 250022)



**摘要**: 为了提高 SIMOX(separation-by-implanted-oxygen) SOI(silicon-on-insulator) 结构中埋氧层(BOX)的总剂量辐射硬度, 埋氧层中分别注入了 $2\times10^{15}cm^{-2}$ 和 $3\times10^{15}cm^{-2}$ 剂量的氮. 实验结果表明, 在使用 Co-60 源对埋氧层进行较低总剂量的辐照时, 埋氧层的总剂量辐射硬度对注氮剂量是非常敏感的. 尽管埋氧层中注氮剂量的差别很小, 但经 $5\times10^4$ rad(Si) 剂量的辐照后, 注入 $2\times10^{15}cm^{-2}$ 剂量氮的埋氧层表现出了比未注氮埋氧层高得多的辐射硬度, 而注入 $3\times10^{15}cm^{-2}$ 剂量氮的埋氧层的辐射硬度却比未注氮埋氧层的辐射硬度还低. 然而, 随辐照剂量的增加(从 $5\times10^4$ 到 $5\times10^5$ rad(Si)), 这种埋氧层的总剂量辐射硬度对注氮剂量的敏感性降低了. 采用去掉 SOI 顶硅层的 MOS 高频 C-V 技术来表征埋氧层的总剂量辐射硬度. 另外, 观察到了 MSOS(metal-silicon-BOX-silicon) 结构的异常高频 C-V 曲线, 并对其进行了解释.



**关键词**: SIMOX; 埋氧; 辐射硬度; 注氮

**EEACC**: 2550R; 2810

**中图分类号**: TN305.3 **文献标识码**: A **文章编号**: 0253-4177(2005)05-0862-05

2004-11-24 收到, 2005-01-25 定稿