第 31 卷 第 9 期 高 能 物 理 与 核 物 理 Vol. 31, No. 9
2007 年 9 月 HIGH ENERGY PHYSICS AND NUCLEAR PHYSICS Sep., 2007

Bias Dependence of Total Dose Effect of Partially Depleted SOI MOSFET

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Abstract Experiments show that total dose radiation effect in buried oxide of SOI (Silicon on Insulator) MOS is obviously dependent on bias condition. Trapped charge buildup during irradiation in buried oxide, which dominantly induces back channel leakage, is investigated. A numerical model, including process of carrier recombination and trapping, is developed to simulate the trapped charge buildup in buried oxide under different bias conditions. The simulation results, agreed with the experiment results, show the mechanism of bias dependence of total dose radiation effect.

Key words SOI, total dose radiation, back channel, buried oxide

1 Introduction

SOI (Silicon on Insulator) MOS is used more and more widely in space environment. The BOX (Buried Oxide) isolation and the small volume of silicon present many advantages for speed, density, and hardness to transient irradiation[1]. But the BOX introduces an additional path for total ionizing dose leakage currents[2]. Back channel in NMOS, as an extra leakage channel, has been found induced after irradiation by trapped holes in buried oxide. Different back channel responses are found under different bias conditions[3]. In this work, PD (Partially Depleted) SOI NMOS devices were fabricated and irradiated under different bias condition. The relations between back channel threshold voltage and radiation dose under three bias states (ON (on-state), OFF (off-state) and TG (transmission-gate)) are acquired and clearly show the bias dependence of back channel effect.

We focus on trapped charge buildup to acquire the mechanism of bias dependence. A numerical model based on one-dimensional continuity equation is developed to describe the process of charge trapping. Initial recombination, hole trapping and electron recombination are included. All these processes are influenced by Electric field in the BOX[4]. Through MEDICI 2-D device simulator, electric field distributions inside BOX under three bias states are obtained. At the given the electric field values, the model shows trapped charge distributions under three bias conditions, which helps to explain the experiment result.

In this work, we gain deeper understanding of total dose effect of SOI devices, which contributes to improving the radiation hardness of domestic SOI VLSI.

2 Experimental procedures and results

The tested SOI NMOS transistors were fabricated on SIMOX (Separation by Implanted Oxygen) wafers with top silicon thickness of 200nm and BOX thickness of 380nm. Enclosed gate (Fig. 1) structure was employed in the tested devices, which could effec-

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Received 25 November 2006

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tively survive such failure mechanisms as increase of drain-to-source leakage current due to turn-on of parasitic transistors[5]. The gate oxide thickness is 41nm, the gate length is 3μm and W/L is 60:3 (calculated by the method presented in Ref. [5]). External body contact is used to suppress floating-body effect and bipolar effect. The equivalent circuit of the SOI NMOS transistor is shown in Fig. 2.

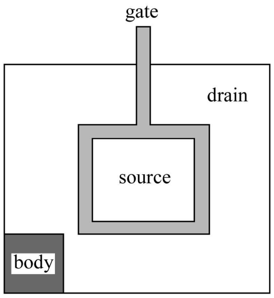

Fig. 1. Structure of enclosed-gate MOSFET.

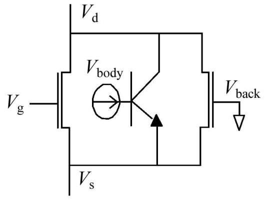

Fig. 2. Equivalent circuit of an SOI NMOS transistor.

The bias conditions under irradiation are consistent with usual bias of transistors in digital circuits (Table 1). They correspond to ON and OFF in inverters, and TG like access transistors in memory cells[6]. V_{dd} is 5V for this experiment.

Table 1. Bias conditions definition.

	source	drain	gate	body	substrate
ON	0	0	V_{dd}	0	0
OFF	0	V_{dd}	0	0	0
TG	V_{dd}	V_{dd}	0	0	0

The experimental results are shown in the following figures. Back gate I_d-V_g characteristic curve at pre-radiation, 90, 180, 540, 900krad and 1.8Mrad (SiO_2) under ON, OFF and TG bias are presented in Fig. 3. We extract the voltage corresponding to $I_d = 10^{-6}$A as the back channel threshold voltage and then the back channel response with total dose under three different biases are gained in Fig. 4. It is clear that the largest shift occurs under the TG bias condition.

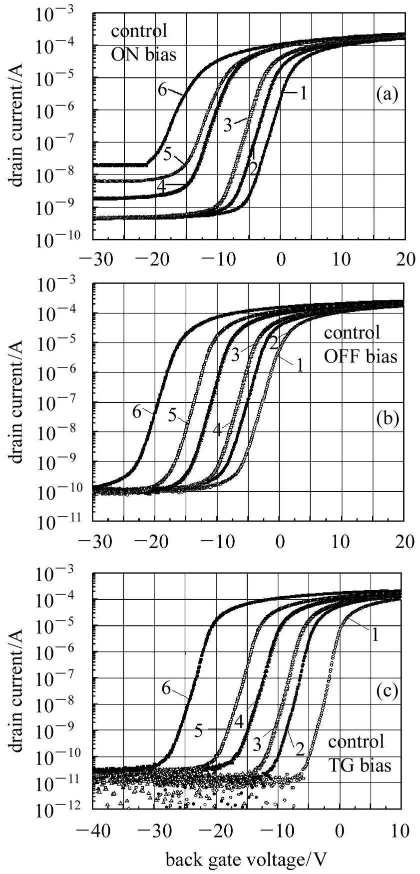

Fig. 3. Pre-radiation and radiation induced back channel sub-threshold voltage characteristic shifts under ON, OFF and TG bias condition.
1. Pre-radiation; 2. 90krad (SiO_2); 3. 180krad (SiO_2); 4. 540krad (SiO_2); 5. 900krad (SiO_2); 6. 1.8Mrad (SiO_2).

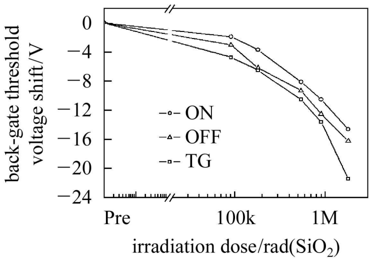

Fig. 4. Back channel threshold voltage as a function of total dose for three bias conditions.

3 Trapped charge model

To gain an understanding of the experimental results, we developed a model to calculate trapped charge buildup in BOX. The method for thermal oxide trapped charge model[7] is quoted. The one-dimension model is built in vertical direction. X=0 is defined at top-Si/BOX interface and $X = t_{ox}$ at

BOX/Sub-Si, where t_{ox} is the thickness of BOX. We mainly consider three factors, carriers yield from radiation after initial recombination, holes trapped by neutral traps and electrons captured by positively charged traps. So we have continuity equations as follow:

$$\frac{\partial n}{\partial t}=n_0D'Y+\frac{1}{q}\left(\frac{\partial j_{\mathrm{n}}}{\partial x}-\sigma_{\mathrm{nr}}j_{\mathrm{n}}P_{\mathrm{T}}\right)\ , \tag{1}$$

$$\frac{\partial p}{\partial t}=n_0D'Y+\frac{1}{q}\left[-\frac{\partial j_{\mathrm{p}}}{\partial x}-\sigma_{\mathrm{pt}}j_{\mathrm{p}}(N_{\mathrm{TP}}-P_{\mathrm{T}})\right]\ , \tag{2}$$

$$\frac{\partial P_{\mathrm{T}}}{\partial t}=\frac{1}{q}\left[\sigma_{\mathrm{pt}}j_{\mathrm{p}}(N_{\mathrm{TP}}-P_{\mathrm{T}})-\sigma_{\mathrm{nr}}j_{\mathrm{n}}P_{\mathrm{T}}\right]\ , \tag{3}$$

where n, p is concentration of electrons, holes, j_{n}, j_{p} is flux of electron, hole, n_0 is electron-hole pair concentration generated per unit dose in SiO_2 which is equal to $7.6\times10^{12}\mathrm{cm}^{-3}\cdot\mathrm{rad}^{-1}$[8], D' is dose-rate, Y is electron-hole escape recombination probability, P_{T} is trapped hole concentration, N_{TP} is the trap density in SiO_2, σ_{nr} is electron capture cross section by charged traps and σ_{pt} is hole capture cross section by neutral traps. In a low dose rate and high total dose case, we assume that electrons and holes reach steady state in a time shorter than the time for irradiation. The equations can be solved to get an expression of P_{T} as following:

$$P_{\mathrm{T}}=N_{\mathrm{T}}f(x)(1-\mathrm{e}^{-\tau(x)^{-1}t})\ , \tag{4}$$

where,

$$f(x)=\frac{\sigma_{\mathrm{pt}}x}{\sigma_{\mathrm{pt}}x+\sigma_{\mathrm{nr}}(t_{\mathrm{ox}}-x)}\ , \tag{5}$$

$$\tau(x)^{-1}=n_0D'Y[\sigma_{\mathrm{pt}}x+\sigma_{\mathrm{nr}}(t_{\mathrm{ox}}-x)]\ . \tag{6}$$

To get distribution of P_{T}, we now should concentrate on parameters Y, σ_{n} and σ_{pt}. All the three parameters depend on electric field.

For Y, some experimental expressions were derived. Here we quote following expression[9], where E is in MV/cm.

$$Y(E)=\left(\frac{E+0.1}{E+1.35}\right)^{0.9}\ . \tag{7}$$

For σ_{n}, cascade capture model of a charged trap and Frenkel-Poole barrier lowering are involved[7]. The following expressions characterize σ_{n},

$$\sigma_{\mathrm{nr}}=\pi r^2\ , \tag{8}$$

$$r=\left(r_{\mathrm{e}}+\frac{r_{\mathrm{e}}^2}{2r_0}\right)-\left[\left(r_{\mathrm{e}}+\frac{r_{\mathrm{e}}^2}{2r_0}\right)^2-r_{\mathrm{e}}^2\right]^{\frac{1}{2}}\ , \tag{9}$$

$$r_0=\frac{q}{8\pi\varepsilon(kT/q)}\ , \tag{10}$$

$$r_{\mathrm{e}}=(q/4\pi\varepsilon E)^{\frac{1}{2}}\ , \tag{11}$$

where r_0 is the zero field electron capture radius and r_{e} is characteristic length in Frenkel-Poole barrier lowering effect.

For σ_{pt}, calculation is almost in the same way, except that the hole trap is neutral and polarization effect is induced. σ_{pt} is modified by E as following expression[7]:

$$\sigma_{\mathrm{pt}}=\sigma_{\mathrm{pt0}}(1+1.9\times10^{-4}E^{0.55})^{-1}\ , \tag{12}$$

where σ_{pt0}, the cross section at room temperature, is equal to $1.4\times10^{-14}\mathrm{cm}^2$ and E has unit of V/cm.

With equation (4)—(12), P_{T} can be expressed by total dose D't, position X and electric field E. It describes field and total dose dependence of trapped charge buildup.

4 Simulation and discussion

To get trapped charge distribution under three bias conditions, MEDICI1), 2-D device simulator, is utilized to gain the vertical electric field of our NMOSFET at 100nm under top-Si/BOX interface. Introducing electric field distribution and total dose of 1Mrad(SiO_2) into P_{T} expression, P_{T} distribution normalized by N_{TP} is acquired for the three bias conditions in Fig. 5.

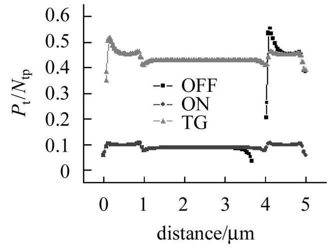

Fig. 5. Trapped charge distribution at 100nm below top-Si/BOX interface for the three bias conditions after 1Mrad(SiO_2) irradiation.

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1) Taurus Medici TM user guide, version W-2004.09, Sept.2004.

Notice that there is a break in the OFF condition. That is attributed to invalidity of the model to deal with electric field of negative value. Distance from 1μm to 4μm is the area just blew channel, which deserves extra concern. It is obviously shown that TG condition induced most trapped charge in BOX. The OFF and ON conditions have nearly the same quantity of trapped charge blow channel, but the OFF condition has much higher density blow drain-body junction than the ON condition.

This simulation result agrees with experiment result quite well and explains the result shown in Fig. 4. Because of preponderant quantity of trapped charge, TG condition gains the largest back channel threshold voltage shift. Although OFF condition induces no more trapped charge blow channel area than ON condition, distinct high density exists blow drain-body junction for OFF condition. That high density is concluded to influence the potential of back channel and make OFF condition suffer more back channel leakage.

5 Conclusions

In this paper, we analyzed the bias dependence of total dose effect on PD SOI MOSFET. A numerical model is developed and proved to be valid to estimate trapped charge distribution in BOX of SOI devices. The experiment result and simulation result show that back channel threshold voltage shift depends on bias condition during irradiation. Bias condition inducing higher density of trapped charge suffers large back channel threshold voltage shift. TG bias condition is the worst case for this experiment.

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部分耗尽SOI MOSFET总剂量效应与偏置状态的关系

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摘要 实验表明SOI MOSFET掩埋氧化层中的总剂量辐射效应与辐射过程中的偏置状态有关. 对诱发背沟道泄漏电流的陷阱电荷进行了研究. 建立一个数值模型来模拟不同偏置下陷进电荷的建立, 它包括辐射产生的载流子复合和俘获的过程. 模拟结果与实验结果相符, 解释了总剂量辐射效应受偏置状态影响的机理.

关键词 绝缘体上的硅 总剂量辐射 背沟道 掩埋氧化层

2006 – 11 – 25 收稿

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