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Analysis of bias effects on the total ionizing dose response in a 180 nm technology

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ABSTRACT

The effects of gamma ray irradiation on the shallow trench isolation (STI) leakage current in a 180 nm technology are investigated. The radiation response is strongly influenced by the bias modes, gate bias during irradiation, substrate bias during irradiation and operating substrate bias after irradiation. We found that the worst case occurs under the ON bias condition for the ON, OFF and PASS bias mode. A positive gate bias during irradiation significantly enhances the STI leakage current, indicating the electric field influence on the charge buildup process during radiation. Also, a negative substrate bias during irradiation enhances the STI leakage current. However a negative operating substrate bias effectively suppresses the STI leakage current, and can be used to eliminate the leakage current produced by the charge trapped in the deep STI oxide. Appropriate substrate bias should be introduced to alleviate the total ionizing dose (TID) response, and lead to acceptable threshold voltage shift and subthreshold hump effect. Depending on the simulation results, we believe that the electric field distribution in the STI oxide is the key parameter influencing bias effects on the radiation response of transistor.

1. Introduction

In modern submicron bulk CMOS technologies, the radiation induced gate threshold voltage shift is not the major factor limiting total dose hardness since charge trapping in the ultra-thin gate oxide is very small [1,2]. For sub-0.25 μm technologies, shallow trench isolation (STI) is the only viable scheme for achieving the required packing density and speed performance by tight active area pitches and improved planarity [3]. Typical STI dimensions for CMOS technologies smaller than 180 nm range from 300 to 450 nm in depth, and width is on the order of 280 nm [4]. Although the gate oxide becomes thinner, the STI oxide doses not scale down correspondingly. As a consequence radiation induced charge trapping in the STI oxide still leads to macroscopic effects such as drain-to-source leakage currents, ultimately limiting the radiation tolerance of CMOS circuits [5–7].

It is well known that the radiation generated electrons are swept out of the oxide very rapidly, in a time on the order of picoseconds, but in that time some fraction of them recombines with the holes [8]. The fraction of holes escaping recombination is determined mainly by two factors: the magnitude of the electric field, which acts to separate the e–h pairs, and the initial density of charge pairs created by the incident radiation. The electric field extends into the trench region and plays an important role in both the initial separation of e–h pairs and charge migration. Three process are involved at this juncture [9]: a) charge yield, which is the fraction of electron–hole pairs that do not immediately recombine, b) charge transport by drift and diffusion and c) hole trapping at the interface between the trench oxide and the adjacent silicon. Electric field is one of the most important parameters influencing the radiation response of transistor. Radiation effects dependences on bias mode and gate bias during irradiation are comprehensively studied by some publications [10–12]. A few papers focused on the impact of negative substrate bias on the total ionizing dose (TID) effect, especially for the substrate bias applied during irradiation. In Ref. [13], the impact of substrate bias on proton damage in 130 nm CMOS was studied. The authors found that the negative substrate bias during radiation produces different dominant damage mechanisms. In Ref. [14], the work had shown how the substrate bias condition during irradiation plays a dramatic role in the resulting radiation damage. However, the simulation result of radiation response is

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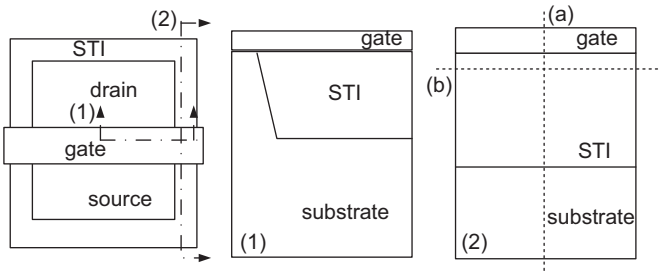

Fig. 1. Illustration of electric field corresponding to the cutline used in this work. Top view of the device: (1) cut-plane views along the width direction across the channel and STI region and (2) cut-plane views along the length direction in the STI region tilted 87° along the STI sidewall.

not shown there. Also, TID response under the same substrate bias during and after irradiation needs to be discussed in more detail.

The purpose of this work is to investigate the bias dependence of TID effect on deep submicron transistor, including bias mode, gate bias during irradiation, substrate bias during irradiation and operating substrate bias after irradiation. 3D simulation is introduced to explain the experimental result. The simulation uses the process and device simulation tool from Silvaco. The STI corner structures were defined from the TEM picture. The doping level of the p-well was obtained by process simulation. The process parameters were obtained from the foundry. The models used include the conventional drift diffusion model for transport and the Shockley Read Hall (SRH) model for generation–recombination. Parallel Electric Field Dependence (FLDMOB) is required to model the velocity saturation effect. Electric field distribution in the STI is used to analyze the mechanism of bias dependence. As shown in Fig. 1(a) the electric field corresponds to the vertical cutline at the center of channel on the STI sidewall surface and (b) the electric field corresponds to the horizontal cutline under the gate 50 nm along the device's length direction on the STI oxide sidewall surface.

2. Experiment detail

All devices were fabricated in a 180 nm technology process. STI was introduced for field isolation filled by high density plasma (HDP) oxide. The STI with very steep sidewalls ($\sim 87^\circ$) had a thick oxide layer of about 400 nm thickness. The transistor's gate oxide layer was 3 nm thick. Devices with channel width (W) 10 μm and channel length (L) 0.18 μm were used. All the samples were ceramic packaged. The operating voltage was 1.8 V.

Irradiation experiments were carried out at the Xinjiang Technical Institute of Physics and Chemistry, Chinese Academy of Sciences using ^{60}Co γ source, typically at a dose rate of 200 rad(Si)/s. Three bias conditions were used in the experiment. Firstly, during radiation exposure, the bias modes are consistent with usual bias of transistors in digital circuits (Table 1). They correspond to on-state (ON) and off-state (OFF) in inverters, and transmission-gate (PASS) like access transistors in memory cells. Secondly, some devices were irradiated at $V_g=0$, 0.9 and 1.8 V, and other terminals grounded. Thirdly, other samples were irradiated at substrate bias $V_{sub,B}=0$, -0.9 and -1.8 V, with $V_g=1.8$ V and other terminals grounded. The temperature was monitored and kept at room temperature. Electrical measurements were obtained prior to irradiation and after different irradiations up to 100, 200, 300, 400 and 500 krad(Si). Transfer (I_{ds}–V_{gs}) characteristics were measured in the ohmic region ($V_{ds}=0.05$ V) for all devices with different substrate bias $V_{sub,T}$ at 0, -0.9 and -1.8 V. These I–V curves were taken within half an hour following exposure.

Table 1
Bias mode definition.

Type	Gate (V)	Source (V)	Drain (V)	Substrate (V)
ON	1.8	0	0	0
OFF	0	0	1.8	0
PASS	0	1.8	1.8	0

3. Experiment result and discussion

3.1. Effects of bias mode

As shown in Fig. 2(a), after total dose radiation level of 200 krad(Si) for transistor with $W/L=10$ μm/0.18 μm, significant increase of off-state leakage current is observed. When the total ionizing dose accumulated to 400 krad(Si) , the off-state leakage current (I_{ds} at $V_{gs}=0$ V) is 2×10^{-8} A. As shown in Fig. 2(b) the curve obtained after a total dose of 200 krad(Si) for ON bias exhibits significant off-state leakage current, which is approximately 3 orders of magnitude higher than the corresponding pre-irradiation value. The increase of off-state leakage current is associated with radiation induced charge in the isolation oxides [15]. However, negligible increase of leakage current was observed for PASS and OFF biases. Up to 400 krad(Si), radiation induced positive charge in the STI oxide is not large enough to generate sidewall leakage paths between drain and source in this later condition.

The threshold voltage shifts are barely detectable (about 3 mV) in irradiated 180 nm transistors, confirming the large degree of radiation hardness associated with very thin gate oxides [16]. The threshold voltage is extracted by the constant current method, which is not shown here for the sake of simplicity. A leakage current criterion of 1 nA was introduced to analyze subthreshold region response of TID for PASS and OFF biases. The voltage is defined as the gate voltage corresponding to the current of 1 nA. Voltage shift is obtained by subtracting the pre-irradiation value. The voltage shift at dose level of 400 krad(Si) is 46 mV for PASS bias and 30 mV for OFF bias. That is to say, the subthreshold hump effect is worse for PASS bias than OFF bias. In order to explain the difference of response for different bias modes, 3D simulation is used to analyze this phenomenon.

Fig. 3 shows the simulation results of an NMOSFET device with trench isolation. The electric field extending into the trench region is important for the separation of e–h pairs and charge migration. The first interesting region is the high electric field region at the top 150 nm of STI oxide. For ON bias, electric field is 1 order higher than the other two bias conditions. Electric field of PASS bias is larger than that of OFF bias. On the other hand, electric field under 50 nm of the STI along the device's length direction for three bias conditions is shown in Fig. 3(b). The minimum and the maximum electric field in the channel region of OFF bias are lower than those of the PASS bias, and both of them are lower than those of the ON bias.

Fig. 4 shows the simulation result of TID response for device under ON bias condition. Non-uniform charge distribution along the STI sidewall is applied in the model [1]. By introducing constant charge along the STI sidewall between the drain and source, good agreement between experiment result and simulation result is demonstrated. The pre-irradiation I–V curve is shown in the picture for comparison. Large increase of off-state leakage and insignificant hump effect were observed.