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An Increase in TDDB Lifetime of Partially Depleted SOI Devices Induced by Proton Irradiation *

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The effects of proton irradiation on the subsequent time-dependent dielectric breakdown (TDDB) of partially depleted SOI devices are experimentally investigated. It is demonstrated that heavy-ion irradiation will induce the decrease of TDDB lifetime for many device types, but we are amazed to find a measurable increase in the TDDB lifetime and a slight decrease in the radiation-induced leakage current after proton irradiation at the nominal operating irradiation bias. We interpret these results and mechanisms in terms of the effects of radiation-induced traps on the stressing current during the reliability testing, which may be significant to expand the understanding of the radiation effects of the devices used in the proton radiation environment.

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The total ionizing dose (TID) damage caused by proton irradiation induced oxide trap charge and interface state, and with time elapsed after irradiation, the oxide-trapped charge disappears partly by thermal emission of electrons from the oxide valence band or by tunneling from the oxide and at the same time, an increase of the interface charge $\Delta Q_{\rm it}$ takes places. On the other hand, the gate dielectric reliability is seriously affected by the increase of the electric field inside devices as the oxide thickness becomes thinner and thinner, due to the slower decrease of the operating voltage as compared with the feature size.[1−3]

Extensive studies of the gate dielectric reliability about the interplay between heavy-ion irradiation and electrical stress have been carried out, especially in the framework of single event gate rupture (SEGR). It has been demonstrated that a remarkable decrease of time-dependent dielectric breakdown (TDDB) lifetime was detected after heavy-ion irradiation for various device types and exposure conditions.[4−6] A few works about proton, electron, γ or x-ray influence on gate oxide reliability were also reported. The effects of proton irradiation on the characteristics of partially depleted (PD)-SOI MOSFET were investigated in Ref. [7], showing that the radiation-induced leakage current (RILC) can be increased and the electric performance can be degraded after irradiation. Hayama *et al.* then reported similar behavior in partially depleted (PD) SOI devices after electron irradiation at different dose rates.[8] However, both works used the same devices of PDSOI MOSFETs and did not measure the influence of irradiation on TDDB lifetime. In addition, Paccagnella *et al.* found that the TDDB was either unaffected by γ-ray irradiation, or larger than that obtained by stressing unirradiated samples.[9] There is just one result here that an increase in TDDB lifetime was found after x-ray exposure performed under bias up to 1 Mrad (SiO_2) on 130 nm MOSFETs, by Silvestri *et al.*[1] Compared with heavy ions, there have been fewer works reported on the proton impact on the gate oxide lifetime data and no uniform mechanism to explain. Furthermore, protons occupy more than eighty percent of the particles in the space radiation environment. Thus it is quite necessary to study the effects of proton irradiation on the gate dielectric.

In this study, we analyze these issues utilizing 130 nm PD-SOI MOS capacitors irradiated with protons of different energies (3, 10 and 23 MeV) and fluence under a nominal operating voltage and subsequently stressed in inversion mode under the Fowler–Nordheim (FN) injection. The effects of proton irradiation on the subsequent TDDB and the mechanisms responsible for the observed phenomena are discussed.

The test samples consisted of several n- and p-substrate 130 nm PD-SOI MOS capacitors with a gate oxide thickness of 6.8 nm, which have the nominal operating voltage of $V_{\rm dd} = 3.3$ V. The gate electrodes of these devices are in polysilicon with an area of 40 μm×100 μm and the active area is isolated by shallow trench isolation (STI). Capacitors with common gate and source and separate drain pads were mounted

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in 24 pins dual-in-line packages for the biased irradiations. Device characterization was performed as soon as the proton-induced activation of some metallic parts was below the critical level (three days after the exposure). A Keithley 4200 semiconductor device analyzer was used to measure the RILC before and after proton irradiation.

Table 1. Irradiation matrix for the PD-SOI MOS capacitors.

Energy (MeV)	Fluence rate (p/cm^{2}s)	Fluence (p/cm^2)	TID (krad) (SiO_2)	DDD (MeV/g)
3	2.8×10^8	3.68×10^{11}	500	7.57×10^9
10	2.8×10^8	8.97×10^{11}	500	7.07×10^9
23	2.8×10^8	1.6×10^{12}	500	8.86×10^9

Irradiations were performed with the gate electrode biased with a nominal operating voltage and other pins grounded. Proton beams were supplied by the State Key Laboratory of Nuclear Physics and Technology of Peking University and China Institute of Atomic Energy. A variety of energy and fluence proton irradiations have been applied, as listed in Table 1.

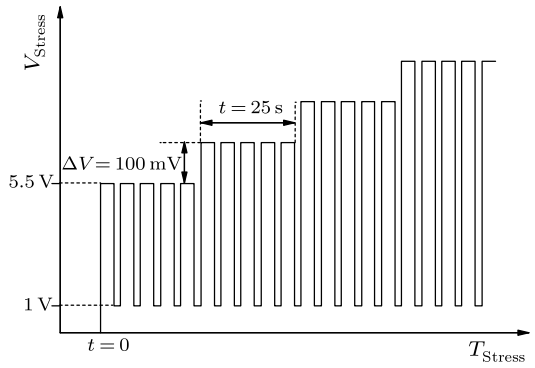


Fig. 1. Simplified representation of the ramped voltage stress (RVS) used in our experiments. It starts from 5.5 V and is updated by 100 mV every 25 s until breakdown occurs. Periodically we sample the current at 1 V to detect soft breakdown events.

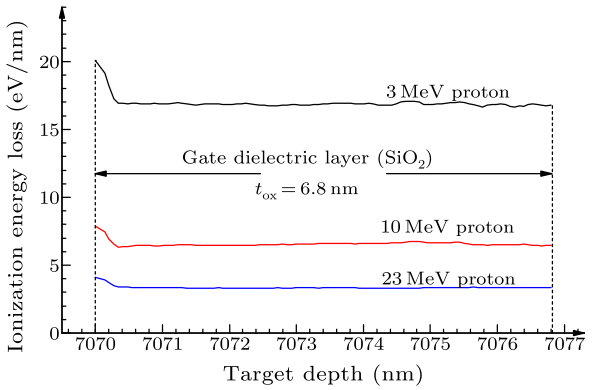


Fig. 2. Ionization energy loss distribution (3, 10 and 23 MeV proton irradiation, respectively) of the gate dielectric layer (SiO_2) for the PD-SOI MOS devices studied in this work.

After irradiation, we subjected the p-substrate capacitors with a gate oxide thickness of 6.8 nm to accelerate ramped voltage stress (RVS) with a ramp rate of 4 mV/s starting from 5.5 V, as shown schematically in Fig. 1. The electrical stress has been performed on irradiated and unirradiated devices with a step voltage of 100 mV steps and 25 s duration for each step. After each 25 s stressing interval, we measured the I_g–V_g curve, then the gate voltage was automatically increased by 100 mV until breakdown occurred. During stress the gate current was monitored at the stress voltage and a low voltage (1 V, sampled periodically) to detect soft-breakdown events. The same procedures, with negative voltage, were performed for n-substrate capacitors. The breakdown voltage is defined as the voltage at which the gate current suddenly increases by at least one order of magnitude or drops down due to failure in the interconnection caused by the breakdown current.[10]

Ionization energy loss distribution in the device was calculated by SRIM simulations.[11] As shown in Fig. 2, the distribution of ionization energy loss in the gate dielectric layer (SiO_2) is almost uniform, due to the fact that the thickness of the gate dielectric layer is sufficiently thin (6.8 nm) relative to the device (the gate dielectric layer locates at 7070 nm depth of the PD-SOI MOS device).

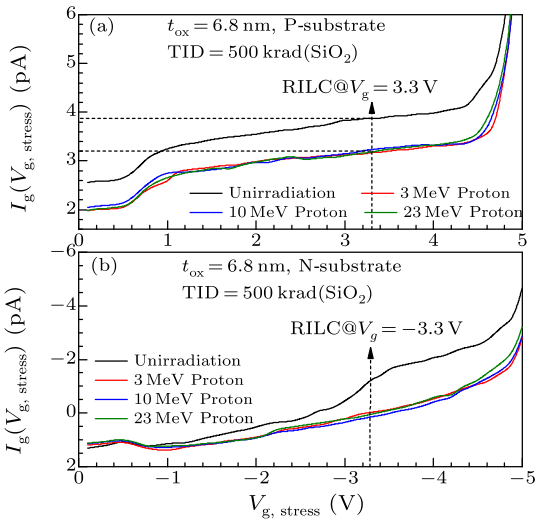


Fig. 3. Gate leakage current during stress for unirradiated (as processed) and irradiated up to 500 krad (SiO_2) (3, 10 and 23 MeV proton irradiation, respectively) MOS capacitors: (a) 6.8 nm p-substrate capacitors, and (b) 6.8 nm n-substrate capacitors.

Figure 3 shows the gate current versus gate voltage

(I_g–V_g) measured before and after proton irradiation of SOI MOS capacitors with three kinds of energies (3, 10 and 23 MeV) and fluence, which all correspond to a TID in equivalence of 500 krad (SiO_2). Obviously, the similar result to the p- and n-substrate SOI MOS capacitors, the gate leakage current reduced after proton irradiation and the RILC characteristics were similar under the same TID (500 krad (SiO_2)) damage conditions caused by proton irradiation. As shown in Fig. 2(a), the monitored leakage currents of the p-substrate devices irradiated up to 500 krad (SiO_2) are about 3.2 pA, as compared with 3.9 pA exhibited unirradiated devices.

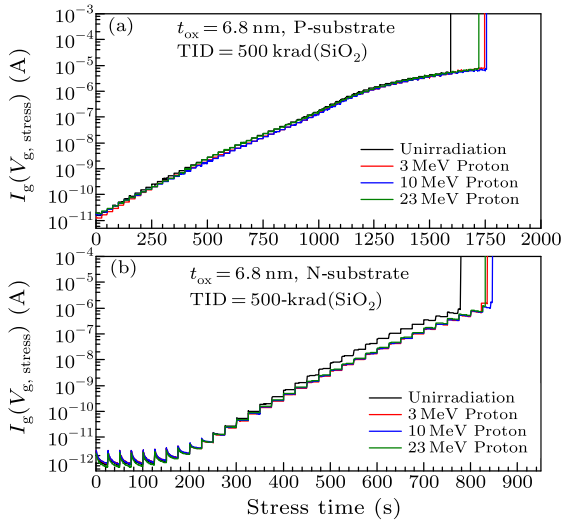


Fig. 4. A test procedure of I_g–stress time (V_g) and gate breakdown. During a voltage applied by 0.1 V steps for 25 s, a gate current is monitored and integrated until hard breakdown occurs. The stress was performed on fresh and proton irradiated devices with three different energies (3, 10 and 23 MeV) and fluence, which all correspond to a TID in equivalence of 500 krad (SiO_2): (a) 6.8 nm p-substrate capacitors, and (b) 6.8 nm n-substrate capacitors.

Figure 4 shows the gate current versus stress time. We can find clearly that there are uniform characters for the p- and n-substrate SOI MOS capacitors that a small but measurable increase in TDDB lifetime appears after proton irradiation with three different energies (3, 10 and 23 MeV) and fluence, which all correspond to a TID in equivalence of 500 krad (SiO_2). More interestingly, the TDDB lifetimes are also similar under the same TID (500 krad (SiO_2)) damage conditions caused by proton irradiation. The TDDB lifetimes of the p-substrate devices irradiated up to 500 krad (SiO_2) by protons are about 1750 s, as compared with 1580 s exhibited unirradiated devices after stress, as shown in Fig. 4(a). Moreover, by comparing results shown in Figs. 4(a) and 4(b), we can find clearly that the unirradiated p-substrate capacitors have longer lifetimes than the unirradiated n-substrate devices.

By comparing the RILC results shown in Fig. 3 and the TDDB results in Fig. 4, we can find that the gate leakage currents and the TDDB lifetimes of the irradiated devices by protons are dependent on TID damage but independent of the energy of protons.

The gate oxide degradation typically is driven by uniformly generated defects, or localized at the drain edge in the case of channel hot carrier (CHC) stress.[12] Both kinds of accelerated aging mechanisms are based on the injection of carriers through the gate oxide, which adds new defects to the intrinsic ones. Electron conduction band tunneling (ECBT) is the main injection process during the stress of inverted p-substrate MOS capacitors. When the bias is high enough, another tunneling process from the bulk valence band (EVBT) starts to take place, enhancing the total electron injection. In contrast, in inverted n-substrate MOS capacitors, the injection of holes from the valence band (HVBT) is the main process, but it is coupled with the electron injection from the gate and valence band.[13] As a consequence, the injection of both holes and electrons in n-substrate capacitors could explain the shorter lifetime we find in n-substrate devices (compared Figs. 4(a) and 4(b)).

As described in Figs. 3 and 4, it is clear that proton irradiation can influence significantly the results of subsequent electrical FN stress. The increase of the lifetime after proton irradiation is clear for all of the testing devices under a nominal operating voltage, both p- and n-substrate SOI MOS capacitors. More interestingly, by comparing Figs. 3 and 4, we can find that the displacement damage of the gate dielectric caused by proton irradiation has no effect on the RILC and TDDB characteristics. It is most likely because the corresponding linear energy transfer (LET) is too small to influence these characteristics.[7] The damage induced by proton irradiation, before electrical stress, influences the dynamics of carrier trapping and consequently the charge that flows across the gate oxide during FN experiments. Consequently, the gate current during stress is a good monitor to observe this behavior and there is a strong correlation between the decrease of the gate current and the prolongation of the TDDB lifetime.

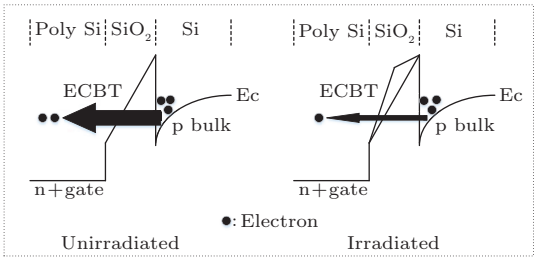


Fig. 5. Schematic representation of radiation-induced traps as a function of the irradiation in p-substrate MOS devices. The traps change the net barrier height, reducing the gate current during subsequent stress.

In Fig. 5 we show schematically the influence of traps on the barrier height for the p-substrate MOS devices. As we all know, the more TID damage can induce more negatively charged traps near the interfaces. The larger the density of negatively charged traps near the interfaces, the greater the barrier experienced by electrons, and consequently the lower the gate current.[1,14] As a consequence, the gate leakage currents of the devices are reduced and the TDDB lifetimes of the devices become longer after proton irradiation. This is in agreement with Ref. [15], and electrically pre-damaged oxides have been found to be more robust to subsequent electrical FN stress, as compared with virgin ones.[16,17]

In summary, we have found that proton irradiation affects the TDDB of the 130 nm SOI MOS capacitors examined here. For devices and irradiation conditions employed here, an interplay exists between proton irradiation and FN stress, producing a longer TDDB lifetime and a smaller gate leakage current after irradiation. We attribute this behavior to the effect of radiation-induced traps that reduce the injected charge during subsequent stress. Moreover, there is a large dependence on the TID damage but independent of the energy of protons, and the displacement damage of the gate dielectric caused by proton irradiation has no effect on the RILC and TDDB characteristics, possibly because the corresponding LET is too small to create the necessary neutral electron traps in the oxide. As for the correlation between TID damage and the RILC and TDDB characteristics, we will carry out further research in the next step.

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