Hot-Carrier Effects on Total Dose Irradiated 65 nm n-Type Metal-Oxide-Semiconductor Field-Effect Transistors *

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The influence of total dose irradiation on hot-carrier reliability of 65 nm n-type metal-oxide-semiconductor field-effect transistors (nMOSFETs) is investigated. Experimental results show that hot-carrier degradations on irradiated narrow channel nMOSFETs are greater than those without irradiation. The reason is attributed to radiation-induced charge trapping in shallow trench isolation (STI). The electric field in the pinch-off region of the nMOSFET is enhanced by radiation-induced charge trapping in STI, resulting in a more severe hot-carrier effect.

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Due to the heavier well doping, the 65 nm complementary metal-oxide-semiconductor (CMOS) technology has higher total ionizing dose (TID) tolerance than older generations, which is very suitable for high dose emission up to Mrads (Si) such as middle earth orbit (MEO) and high energy physics (HEP).[1] TID experiments on 65 nm CMOS technology to a total dose of Mrads (Si) showed relatively small changes in transistor parameters for core transistors except that transistors have width less than 360 nm.[2] However, at the same time, the 65 nm CMOS technology has more obvious reliability problems than larger devices before, such as hot-carrier degradation resulting from increasing electrical fields in devices.[3] The average integrated circuit lifetime of 65 nm CMOS is even less than 15 y, which is a challenge for applying 65 nm devices on long-life satellites.[4]

Moreover, the device used in a radiation environment will suffer TID irradiation and reliability damage simultaneously. The principles of damage formation for irradiation and reliability are similar, while both of them degrade the device parameters by inducing trapped charges in the oxide or at the oxide/bulk interface.[5,6] Thus we wonder whether there is interaction between reliability degradation and irradiation damage, and lifetime of 65 nm technology may be further decreased by this interaction. In fact, possible combined effects or correlations between hot-carrier effect and irradiation have been investigated in deep submicron bulk-silicon nMOSFETs by Marco *et al.* and Cui *et al.*[7,8] Experimental results showed that previous irradiation worsens the behavior of nMOSFETs during hot-carrier stresses in small width core transistors. However, to the best of our knowledge, there is no study on combined effects between hot-carrier effect and TID irradiation of the 65 nm CMOS technology. Compared with the deep submicron technology, the 65 nm CMOS technology has higher TID tolerance but more obvious reliability problems, thus combined effects between hot-carrier effect and TID irradiation of 65 nm technology may be different from the deep submicron technology.

In this Letter, hot-carrier effect on irradiated 65 nm nMOSFETs is investigated, focusing on the influence of total dose irradiation on hot-carrier degradation of devices with different geometries. The enhanced hot-carrier degradation is found in irradiated narrow channel 65 nm nMOSFETs. The mechanism of radiation-induced enhanced hot-carrier degradation in narrow channel devices is discussed.

The nMOSFETs used in this work were fabricated in a 65 nm CMOS process, by using the shallow trench isolation (STI) for isolation scheme. Wide (W/L = 10000 nm/65 nm) and narrow (W/L = 310 nm/65 nm) channel devices were selected as the samples. All the devices were mounted in 48-pin dual-in-line packages and the normal operating voltage is 1.2 V.

The irradiation experiments were carried out on ^{60}Co γ ray in the Xinjiang Technical Institute of Physics and Chemistry, Chinese Academy Sciences, with dose rate of 100 rad(Si)/s. The bias condition during irradiation is the ON state, i.e., gate voltage equal to the supply voltage and other terminals grounded. All devices were irradiated to the total dose level of 1 Mrad (Si). Before and after irradiation, the I–V characteristics of the devices were measured by

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a Keithley 4200 parameter analyzer at room temperature. Irradiated devices and reference un-irradiated devices were carried on channel hot-carrier stresses. Hot-carrier stress voltage was chosen to maximize the substrate current, with drain voltage 2 V, gate voltage 1 V, and source grounded. We periodically interrupted the electrical stresses according to logarithmic time to measure the characteristics curves.

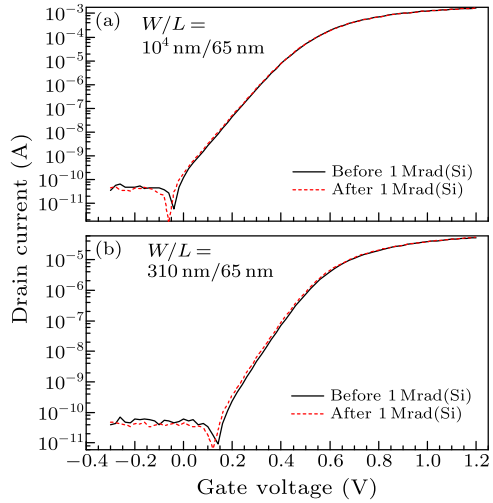

Fig. 1. Drain current versus gate voltage (I_{ds}–V_g) curves of 65 nm nMOSFETs before and after 1 Mrad(Si) (rad: radiation absorbed dose, 1 rad=0.01 J/kg) of irradiation (a) for the wide channel device and (b) for the narrow channel device.

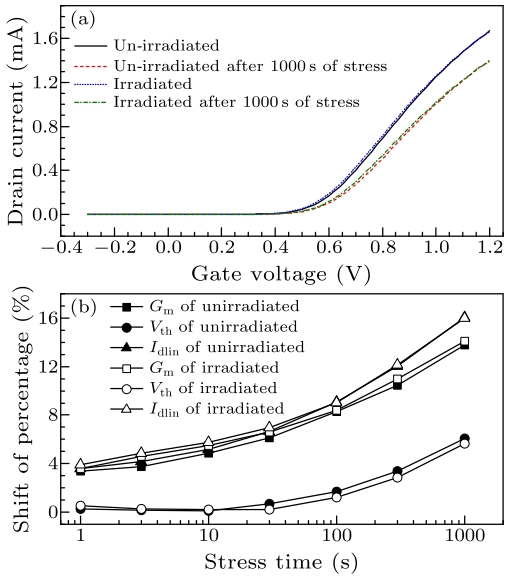

Fig. 2. (a) The I_{ds}–V_g curves of irradiated and un-irradiated wide channel devices before and after 1000 s of hot-carrier stress. (b) Altering of threshold (V_{th}), transconduction (G_m), linear saturation current (I_{dlin}) versus stress time for irradiated and un-irradiated wide channel devices.

Figure 1 shows the I_{ds}–V_g characteristics of wide and narrow channel 65 nm nMOSFETs before and after 1 Mrad (Si) of irradiation. As shown in Fig. 1, radiation has negligible impact on I_{ds}–V_g characteristics of 65 nm nMOSFETs, which is in agreement with the higher TID tolerance reported.

Hot-carrier degradations of irradiated and un-irradiated wide channel nMOSFETs are shown in Fig. 2. Seen from Fig. 2, the difference between hot-carrier degradations of irradiated and un-irradiated wide channel nMOSFETs is negligible, indicating that radiation has no impact on hot-carrier reliability of 65 nm wide channel nMOSFETs.

Figure 3 displays the hot-carrier degradations of irradiated and un-irradiated narrow channel devices. Hot-carrier stress-induced G_m and I_{dlin} degradations in irradiated narrow channel nMOSFET are enhanced, as shown in Fig. 3.

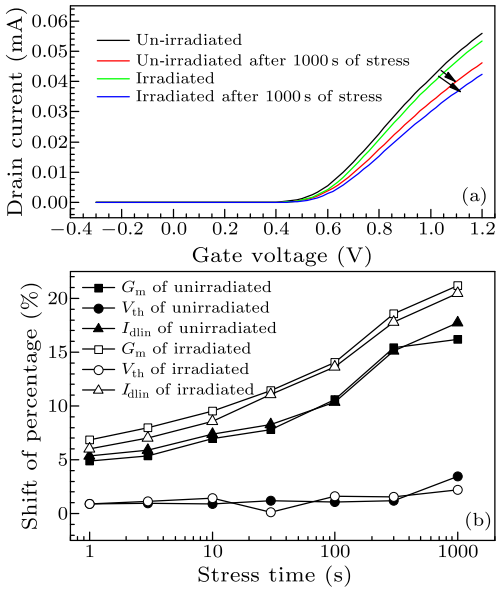

Fig. 3. (a) The I_{ds}–V_g curves of irradiated and un-irradiated narrow channel devices before and after 1000 s of hot-carrier stress. (b) Altering of V_{th}, G_m, I_{dlin} as a function of stress time for irradiated and un-irradiated narrow channel devices.

As we have shown, the degradation of irradiated narrow channel nMOSFETs under hot-carrier stress is larger than that of the un-irradiated devices. On the other hand, radiation has negligible impact on hot-carrier degradation of wide channel nMOSFETs.

Hot-carrier stress degrades the device parameters by generating defects in the gate oxide and interface traps near the drain. The main driving force of the hot-carrier generation in nMOSFETs is high electric field in pinch-off region of devices.[9] For an nMOSFET biased in channel hot-carrier stress, the lateral field rises gradually from the source side toward the drain side of the channel, with a sharp peak in the pinch-off region where the p–n junction is strongly depleted by a high drain voltage, as shown in Fig. 4. In this high field region, the electrons can gain a large amount of energy. A fraction of the hot carriers can

acquire sufficient energy to break H bonds at the interface generating defects in the gate oxide and interface traps near the drain. The extent of hot-carrier degradation is determined by the electric field in the pinch-off region, and there is enhanced degradation on the irradiated narrow channel nMOSFETs attributed to the electric field at the isolation edge.

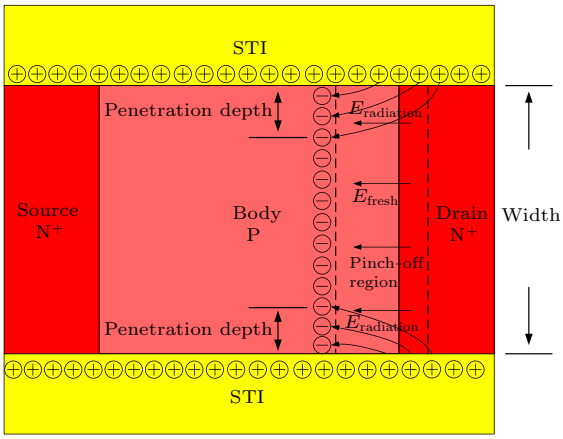

Fig. 4. Top view of an nMOSFET showing the STI charge influence.

Radiation degrades the device parameters by generating oxide traps and interface traps in oxides. For 65 nm CMOS devices, the ultra-thin gate oxide of transistors is almost not affected by TID irradiation. However, STI still has a thickness of several hundreds of nanometers and is sensitive to TID irradiation.[10] The radiation-induced charge trapping in STI can modify the electric field at the edge of the transistor. Seen from Fig. 4, there is a penetration depth, i.e., the effective area, in which the STI positive charge affects the body region potential. For wide channel nMOSFETs, the penetration depth is much less than the width of the device, thus the influence of radiation on electric field in the pinch-off region is relatively smaller. However, for narrow channel devices, the ratio of penetration depth to device width is much greater, thus the electric field in the pinch-off region is enhanced by radiation, and irradiated devices will suffer more hot-carrier degradation.

In summary, we have presented an enhanced hot-carrier degradation in the irradiated narrow channel 65 nm nMOSFETs. This observed behavior is caused by the radiation-induced charge trapping in STI. The electric field in the pinch-off region of the transistor is enhanced by radiation-induced charge trapping in STI, resulting in a more severe hot-carrier effect. As a result, additional testing must be undertaken to evaluate the reliability of 65 nm devices used in the radiation environment.

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