The Effects of Proton Irradiation on 90 nm Strained Si CMOS on SOI Devices

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Abstract—**The effects of 63 MeV proton irradiation on 90 nm strained silicon CMOS on insulator is examined for the first time. The devices show no observable degradation in DC performance up to an equivalent total dose of 600 krad(Si). The performance of the strained pFETs is identical to unstrained pFETs and demonstrates the immunity of strain to displacement damage. There is no significant enhancement observed in back channel leakage for the maximum dose. Passive exposure to 2 Mrad(Si) using 4 MeV protons doesn't induce any significant performance degradation.**

***Index Terms*—strained silicon CMOS, SOI, radiation tolerance, total dose effects**

Silicon-on-Insulator (SOI) CMOS technology can provide significant improvements over bulk CMOS technology for minimizing parasitics, decreasing leakage, improving short channel effects, facilitating better noise isolation, and improving single event upset (SEU) tolerance. The use of strained-silicon techniques to enhance the current drive of advanced FETs has been recently identified as a viable path for further CMOS down-scaling into the nanometer regime [1]. While a significant amount of research has addressed the effects of radiation on conventional SOI CMOS devices [2, 3], to date, the effects of radiation on strained-silicon CMOS devices has not been reported. In particular, although the improved intrinsic tolerance to ionizing radiation damage of conventional CMOS devices with scaling is well-established, the effect of displacement damage on the induced mechanical strain in strained-silicon devices has not been investigated. In addition, the TID response of the buried oxide to ionizing radiation is clearly important for nFETs, as the back-gate threshold voltage decreases with dose and could lead to enhanced subthreshold leakage. In this work we examine, for the first time, proton radiation effects on a 90 nm partially-depleted strained silicon-on-insulator (PD-SSOI) CMOS technology. One-to-one comparisons are made with more conventional unstrained CMOS on SOI devices from the same 90 nm technology node.

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I. Experiment

The device technology investigated is a 90 nm drawn gate length, PD-SSOI technology, with a gate length (L_{poly}) of about 45 nm, a gate width (W) of 7.0 μm, and a gate oxide thickness (t_{ox}) of 1.2 nm. The devices were designed in H-Gate (edgeless) topologies with two body contacts. The strain was applied uniaxially to the channel using nitride spacers, as depicted in Figures 1a and 1b. The devices were built on a UNIBOND SOI wafer with a buried oxide thickness of 140 nm. In this experiment only the pFETs were strained. The device technology has been described in greater detail in [4, 5] and was not radiation-hardened in any way.

The devices were wire-bonded into 28-pin DIP packages and exposed to 63 MeV protons at a dose rate of 1.0 krad(Si)/sec at the Crocker Nuclear Laboratory [6] at the University of California at Davis (note: 1.00 rad(SiO_2) = 1.05 rad(Si) for 63 MeV protons). All pins were grounded during exposure and measurements were performed *in-situ* immediately after each dose point was reached, using standard measurement protocols.

Dosimetry measurements used a five-foil secondary emission monitor calibrated against a Faraday cup. The radiation source (Ta scattering foils) was located several meters upstream of the target to establish a beam spatial uniformity of about 15 % over a 2.00 cm radius circular area. Beam currents from about 20 to 100 nA allowed testing with proton fluxes from 1.0×10^9 to 1.0×10^{12} protons/cm^2-sec. The dosimetry system is known to be accurate to about 10%. The proton fluence was increased to achieve a varying equivalent

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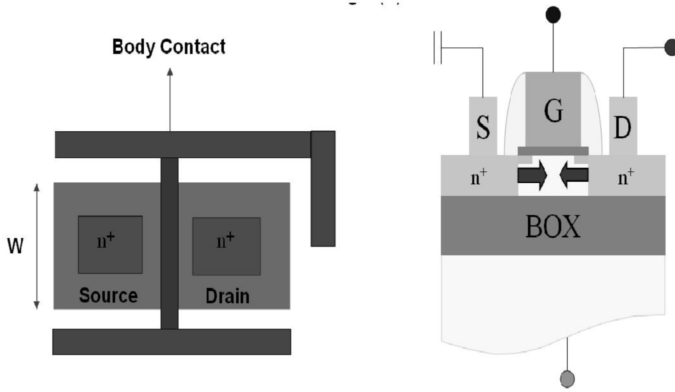

Fig. 1. Schematic (a) top view (b) cross-sectional view of the strained-silicon CMOS on SOI devices.

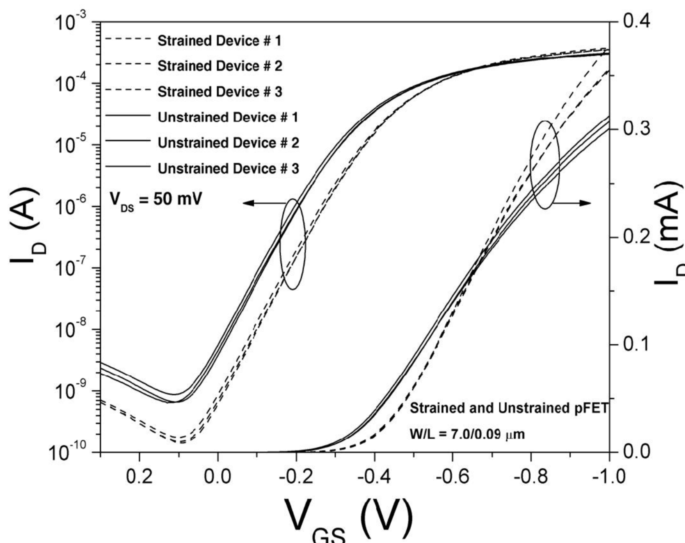

Fig. 2. Transfer characteristics of strained and unstrained pFETs.

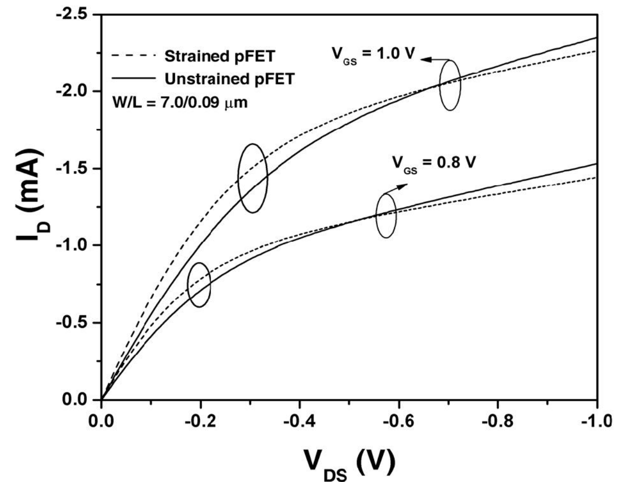

Fig. 3. Output characteristics of strained and unstrained pFET as a function of gate voltage.

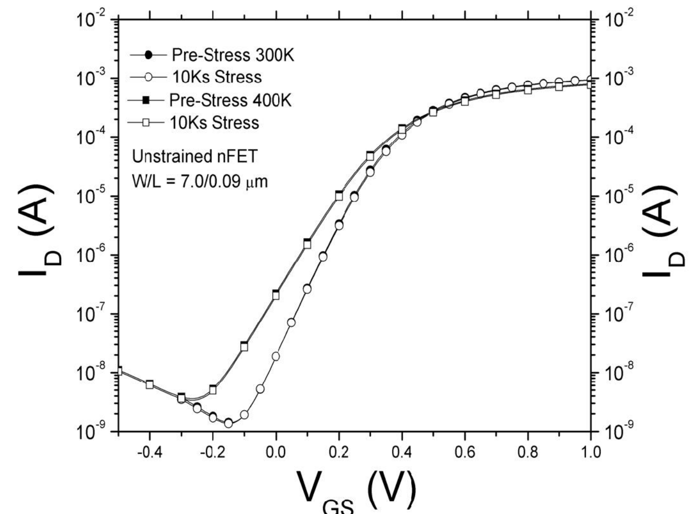

Fig. 4. Transfer characteristics of the unstrained nFET after 10,000 s stress.

total dose ranging from 20 krad(Si) up to a maximum of 600 krad(Si).

Additionally, the devices were exposed to 4 MeV protons at a dose rate of 1 krad/sec at the Accelerator Laboratory of Auburn University. Hydrogen beam currents of approximately 20 nA from a 2 MeV tandem Pelletron accelerator equipped with a SNICS II source was used. The beam current was measured using a biased National Electrostatics Corporation Faraday cup. Beam uniformity is known to be accurate to about 12% over an irradiated circular target area of radius 2.5 cm.

II. Results and Discussion

A. Pre-irradiation Results

Typical transfer characteristics for the strained-silicon pFETs are shown in Figure 2, along with those for an unstrained control device for direct comparison. The devices have identical subthreshold swings of 85 mV/decade and the extracted threshold voltages (defined at a constant current of 0.1 μA/μm) are -0.25V and -0.19V for the strained and unstrained devices, respectively. The slight difference in threshold voltage for the two devices can be attributed to slight (unintended) differences in processing. From the slope of the drain current (I_D) in the linear transfer characteristics shown in Figure 2, one can clearly see the strain-induced improvement in effective mobility. The extracted values of the low field mobility (extracted using the techniques in [7]) for the strained and unstrained pFETs are 53.9 and 40.3 cm^2/V-s, respectively. The extracted mobility for the nFET is 197 cm^2/V-s. The improvement in mobility for the strained pFET translates to a 29% improvement in the output drive current at a gate voltage (V_G) of -1.0 V, after taking into account the difference in threshold voltage between the two devices. The improvement in drain currents is reflected in Figure 3, where we plot the output characteristics for two gate voltages; V_G = -0.8V and V_G = -1.0V. The difference in output conductance in the

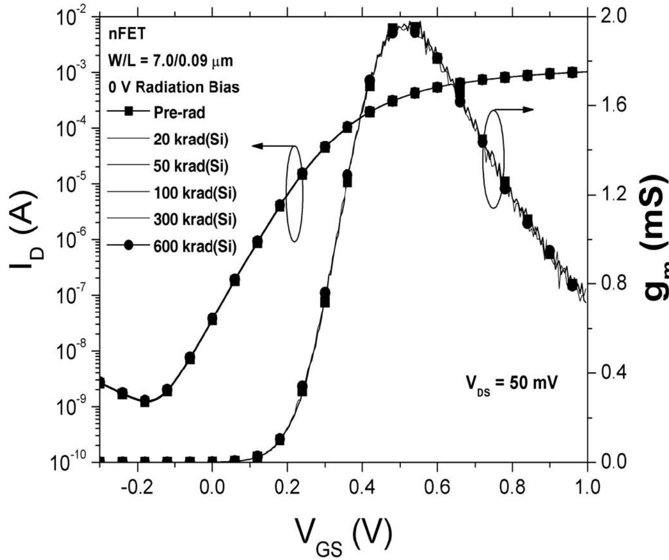

Fig. 5. Transfer characteristics and g_m of nFET as a function of dose.

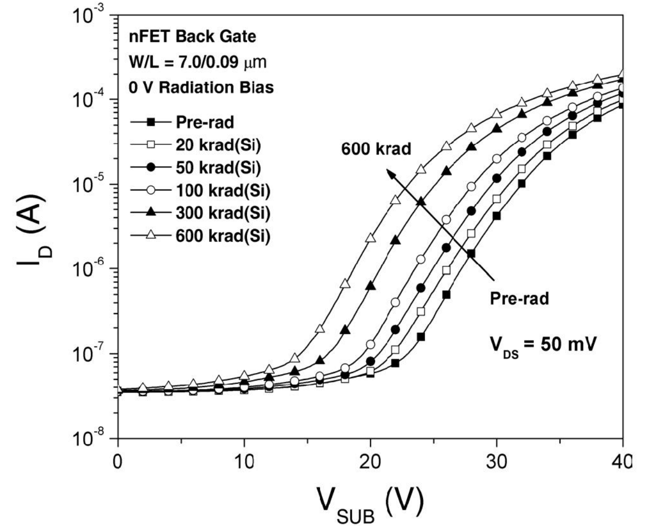

Fig. 7. Back-gate transfer characteristics for an unstrained nFET as a function of dose.

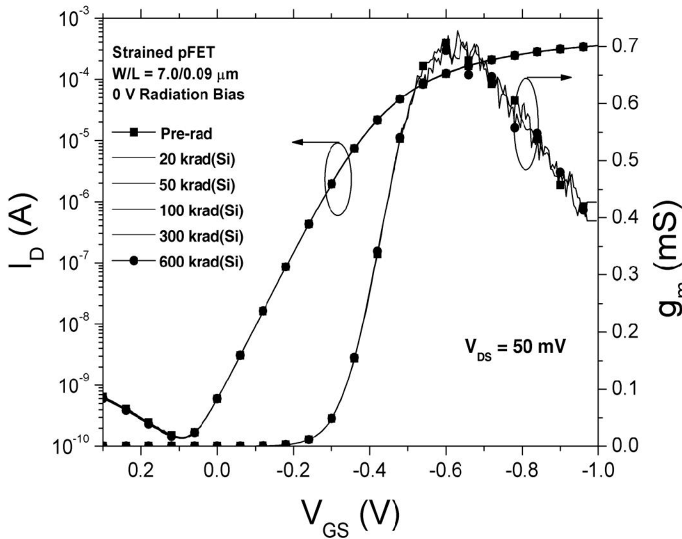

Fig. 6. Transfer characteristics and g_m of the strained pFET as a function of dose.

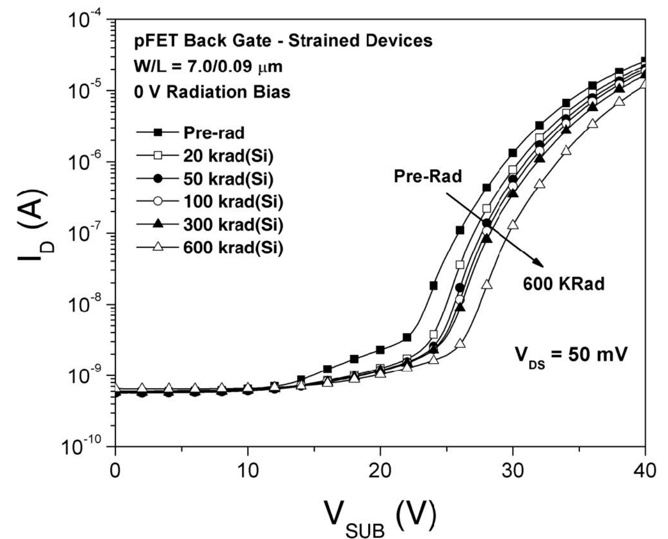

Fig. 8. Back-gate transfer characteristics for a strained pFET as a function of dose.

saturation region is due to unintended processing related differences.

B. Stress Results

The immunity of the front gate oxide to ionizing radiation damage was initially tested by stressing the device at maximum substrate current bias at 300 K and 400 K. As can be seen from Figure 4, the device shows no sign of degradation in performance after 10,000 seconds of stress. The devices, when similarly stressed at 77 K, did not show any damage. This immunity to stress damage is expected considering that the thickness of the gate oxide is only 1.2 nm, which precludes any charge collection in the volume of the oxide. In light of these results, the devices were not biased during radiation as we did not expect significant charge collection in the front gate.

C. Radiation Results

Typical front-gate characteristics and the transconductance (g_m) for the nFETs and the pFETs are shown in Figures 5 and 6, respectively. The devices did not show any degradation in performance after 63 MeV proton irradiation, up to the equivalent maximum dose of 600 krad(Si). This is extremely encouraging, as it demonstrates the robustness of the process-induced strain to any displacement damage associated with proton exposure. An examination of the unstrained device characteristics (not shown here for brevity) gives identical results (i.e., essentially no radiation-induced degradation). In addition, the front-gate characteristics of the nFETs do not

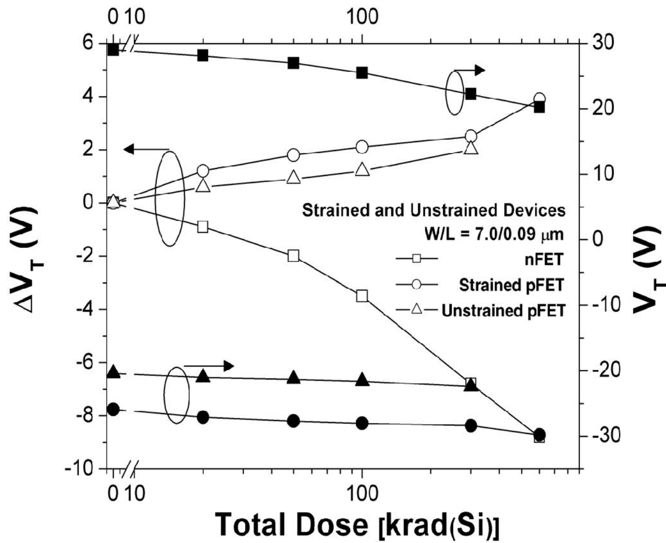

Fig. 9. Back gate threshold voltage and threshold voltage shift as a function of dose for strained and unstrained nFETs and pFETs.

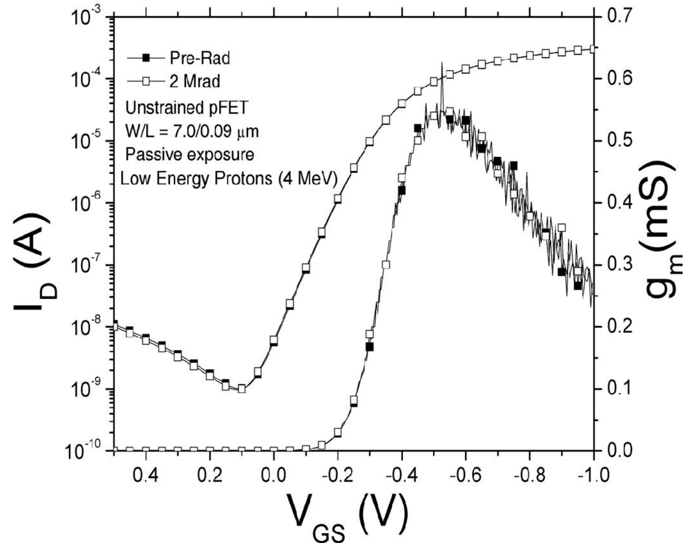

Fig. 10. Transfer characteristics for unstrained pFET after 2 Mrad(Si) of low energy (4MeV) proton exposure.

reveal any enhanced leakage due to the charge collection in the back gate, a known potential problem with standard SOI CMOS devices. An examination of the nFET back-channel characteristics (Figure 7) shows an expected significant change in the back-gate threshold voltage, but remains acceptably high for the maximum dose used. For the pFET (Figure 8), the shift in the threshold voltage is significantly smaller and is due to the negative bias applied to the gate during measurements. Moreover, the threshold voltage shifts to higher substrate voltages and is therefore not a cause for concern for increased parasitic leakage. The shift in threshold voltage with radiation dose is shown in Figure 9 for both the pFETs and the nFETs.

These results for the back-gate radiation response are qualitatively consistent with previously reported data for an earlier generation standard SOI CMOS technology [2]. From the back-gate transfer characteristics one can also see that the subthreshold swings do not change significantly with increasing radiation dose, indicating the absence of radiation-induced interface trap formation. The back-gate subthreshold swing for the nFET changes marginally from 4.4 V/decade to 4.2 V/decade after a 600 krad(Si) equivalent dose. The pFETs similarly show a change from 2.4 V/decade to 2.2 V/decade after a 600 krad(Si) equivalent dose.

The unstrained pFETs were also passively exposed to low-energy (4 MeV) proton radiation up to 2 Mrad to check for displacement damage. As can be seen in Figure 10, the devices do not show any signs of displacement damage and are radiation hard even to highly damaging low energy protons. The strained pFETs (not shown here) also did not show any noticeable change after 1 Mrad(Si) of 4 MeV proton irradiation.

III. Summary

90 nm strained CMOS on SOI devices have been examined for proton radiation tolerance and found to be radiation hard to a total dose of 600 krad(Si). The strained silicon pFETs do not show any difference in proton radiation response compared to its unstrained comparison. This indicates that the strain is resistant to displacement damage in the dose range used in this work. These results are very encouraging from a space applications perspective.

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