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Enhanced Proton and Neutron Induced Degradation and Its Impact on Hardness Assurance Testing

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35 WORD ABSTRACT:
Protons and neutrons can induce enhanced degradation in power MOSFETs. This degradation is caused by microdose effects associated with secondary particles produced by proton/material interactions. Hardness assurance implications are discussed.

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I. INTRODUCTION

Last year, it was shown that heavy ions can induce large shifts in the current-voltage (IV) characteristics of trench FET commercial power MOSFETs [1]. The shifts were significantly larger than the shifts induced at the same total dose using gamma rays. However, the size of the shift was found to depend on both the irradiation bias and the ion linear energy transfer (LET), suggesting that the shifts were associated with a microdose effect. Specifically, it was suggested that the ions could deposit charge along the entire length of the channel between the source and drain, leading to the development of multiple parasitic transistor structures. Based on a limited amount of data, it was also demonstrated in [1] that proton irradiation could induce large shifts in the IV characteristics that could not be explained solely by proton direct ionization. The cause of this enhanced degradation due to proton irradiation was not identified.

In this work, we conduct a more extensive investigation of the enhanced degradation observed in trench FET power MOSFETs caused by proton irradiation to identify the potential mechanism responsible for the enhanced degradation. In addition, the radiation response of these devices when exposed to neutrons is explored. The results of this work suggest that nuclear interactions between protons and neutrons and the materials in integrated circuits produce secondary ions, which induce microdose effects. These results have significant implications for hardness assurance testing of MOS devices for use in space applications.

II. EXPERIMENTAL DETAILS

Proton irradiations were performed at TRIUMF [2]. The proton energy was varied from 20 to 498 MeV. Energies from >70 to 105 MeV and ≤70 MeV were obtained by degrading a 116-MeV and 70-MeV primary beam, respectively, using a variable thickness plastic plate. Protons with energies above 105 MeV were obtained by varying the primary beam energy of a second beamline capable of a maximum proton energy of 500 MeV. The proton fluence was measured using a calibrated ion chamber. Neutron irradiations were performed using the WNR continuous spectrum neutron source at Los Alamos National Laboratory [3]. The WNR facility provides a neutron spectrum that mimics the energy distribution of terrestrial neutrons, but at several orders of magnitude higher flux. Devices were characterized using an Agilent 4156 semiconductor parameter analyzer. After each irradiation, the I-V characteristics of the trench FETs were measured with the drain biased at 10 V. In this work, we define a subthreshold voltage (V_{st}) as the gate voltage for which the drain current is equal to 1 μA.

The power MOSFETs examined include the IRF3704ZCS manufactured by International Rectifier (IR) and the FDD068AN03L manufactured by Fairchild Semiconductor. These n-channel devices are rated to a maximum gate voltage (V_{gs}) of ±20 V and a maximum drain voltage (V_{ds}) of either 20 V or 30 V. Both device types are built using a trench FET technology, which means that the gate oxide is grown on the side of a vertical trench cut in the Si wafer. The current flow is vertical along the edge of the trench from the source at the top of the wafer, through a lightly doped p-type body and into the drain, which is formed by an epitaxial layer near the bottom of the trench. The drain electrode is the backside of the wafer. The oxide thickness of the active gate region along the sidewall of the trench is ~68 nm for the IRF3701ZCS, and ~44 nm for the FDD068AN03L devices. For the IR parts, the oxide at the bottom of the trench is three to four times as thick. This was not true for the Fairchild part, where the oxide thickness at the bottom of the trench was approximately the same as gate oxide. The trench depth is approximately 1.2 μm for all devices. The IRF3704ZCS parts were packaged in D^2PAK plastic packages and the FDD068AN03L parts were packaged in SO-8 plastic packages.

III. EXPERIMENTAL RESULT & DISCUSSION

The radiation response of FDD068A devices exposed to protons with energies from 20 to 498 MeV is shown in Figure 1. At least two devices were irradiated at each proton energy examined. Devices were irradiated with a gate bias of 15 V (all other pins were grounded). While not shown here, it is important to note that changes in the basic IV characteristics with increasing proton and neutron fluence were similar to those previously observed for trench power MOSFETs [1]. In general, changes in the IV characteristic begin as a small hump that increases in size with increasing fluence. In Figure 1, the change in V_{st} is plotted as a function of proton fluence. The fluence was increased from ~5×10^6 to ~10^{12} protons/cm^2. While there is a reasonably large scatter in the data from part-to-part, the general trend shows a monotonic increase in the voltage shift with increasing fluence. For some of the devices, a change in V_{st} of ~1 V is observed at 2×10^7 protons/cm^2 and increases to ~ 7 V at a fluence of 10^{12} protons/cm^2. To within the part-to-part variation, these results also suggest that there is no significant dependence on proton energy. This is more noticeable by looking at changes in the drain-to-source leakage current (I_{ds}) when the transistor is biased in the off condition (V_{gs} = 0 V), as illustrated in Figure 2. Changes in I_{ds} at V_{gs} = 0 V are normally more important to system designers. For all devices examined, the preirradiation I_{ds} at V_{gs} = 0 V was less than 1 nA. The trend in I_{ds} shown in Figure 2 with increasing fluence is similar to that observed for changes in V_{st}. Increases in leakage current of a few μA are observed at the lowest fluence levels and the current increases rapidly as the fluence is increased. There is ~0.01 A of leakage current after irradiating to 10^{12} protons/cm^2. Note that for 498 MeV protons this is equivalent to a total dose ~36 krad(SiO_2).

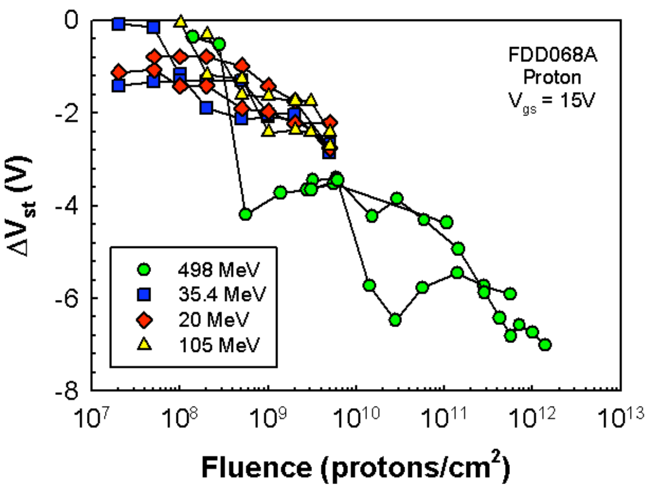

Fig. 1: A plot of the proton induced ΔV_{st} versus fluence for FDD068A devices with 15 V on the gate during irradiation.

The fluences at which the first observance of an increase in I_{ds} (or V_{st}) occurred correspond to extremely low total dose levels. For example, for the FDD068A irradiated with 35.4 MeV protons, the first increase in I_{ds} occurred at a fluence of 2×10^7 protons/cm^2, corresponding to a total dose of only ~2 rad(SiO_2). This increase in leakage current occurred at a much lower total dose level than expected based on ^{60}Co gamma ray data. No significant change in I_{ds} was observed for FDD068A devices irradiated with ^{60}Co gamma rays (biased with V_{gs} = 15 V during irradiation) until the devices were irradiated to a total dose of ~ 20 krad(SiO_2), at which ~ 10nA of leakage current was observed. In addition, at a fluence of 2×10^7 protons/cm^2 the shift in V_{st} was -1.4 V. The maximum shift in threshold voltage assuming 100% charge trapping can be calculated from [4],

$$\Delta V_{th(max)} = -1.9 \times 10^{-8} f(E_{ox}) D t_{ox}^2,$$

where $f(E_{ox})$ is the hole yield as a function of the oxide electric field, D is the dose, and t_{ox} is the oxide thickness (in units of nm). Thus, for the FDD068A, which has a ~44 nm oxide and assuming a charge yield of 1 (worst case), the maximum threshold voltage shift due to proton direct ionization at 2 rad(SiO_2) is ~74 μV. This is clearly much smaller than the experimentally observed voltage shift. Hence, the observed shifts in threshold voltage (and I_{ds}) cannot be explained in terms of direct ionization by the protons.

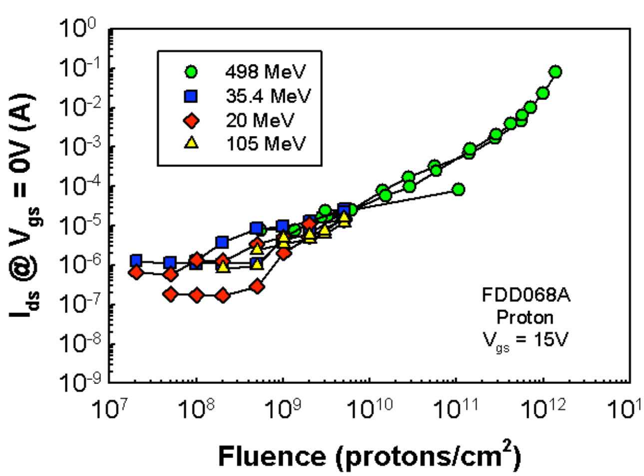

Fig. 2 A plot of the proton induced I_{ds} at V_{gs} = 0 V versus fluence for FDD068A devices with 15 V on the gate during irradiation.

Instead, it is likely that these shifts are associated with microdose effects caused by the ionization of secondary particles created by proton/material interactions. As a high-energy proton (or neutron) enters the semiconductor lattice it may undergo an inelastic collision with a target nucleus. This may result in the emission of alpha or gamma particles and the recoil of a daughter nucleus (e.g., Si emits α-particle and a recoiling Mg nucleus), or a spallation reaction, in which the target nucleus is broken into two fragments (e.g., Si breaks into C and O ions), each of which can recoil. Any of these reaction products can now deposit energy along their paths by direct ionization. Approximately one proton in 10^5 will have such a nuclear reaction in a typical 4-μm silicon device [5]. These secondary particles can have higher LETs and thus deposit more charge than the incident protons.

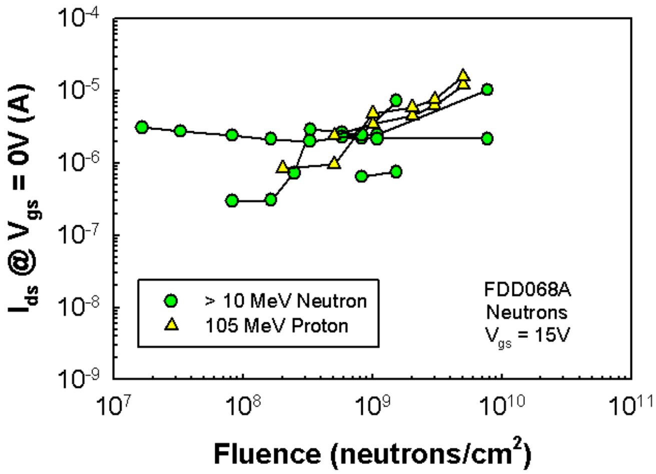

Fig. 3: A plot of the neutron induced I_{ds} at V_{gs} = 0V versus fluence for FDD068A devices with 15 V on the gate during irradiation. The 105 MeV proton data from Figure 2 is included in this plot for comparison.

This is consistent with the data of Figure 1 & 2 and the data of Ref. [1]. For example, in [1] a shift in V_{st} of ~7 V was measured after irradiating with Ne ions/cm^2 (LET = 1.8 MeV-cm^2/mg) to a fluence of 10^7 ions/cm^2. An LET of 1.8 MeV-cm^2/mg is close to the upper bound expected for alpha particles created by proton/Si interactions. Assuming it takes 10^5 protons to create one secondary alpha particle, a fluence of 10^7 Ne ions/cm^2 is roughly equivalent to a fluence of 10^{12} protons/cm^2. As discussed above, 7 V was indeed the shift in V_{st} that was measured after irradiating to a fluence of ~10^{12} protons/cm^2. Moreover, based on the active surface area of the gate, we calculate that, on average, a fluence of ~10^7 protons/cm^2 is required to create one secondary particle that would strike the active gate region. To within experimental uncertainty, this is the approximate fluence at which a shift in the IV characteristics was first observed in proton irradiations (see Figure 1 & 2). Note that the large part-to-part variation observed for the proton irradiated devices is likely due to the statistical variation in the LETs of the secondary particles and the physical location where they are created.

The radiation response of the FDD068A exposed to neutrons was similar to the radiation response of devices exposed to protons. This is illustrated in Figure 3. In this figure, changes in I_{ds} are plotted as a function of neutron fluence. The devices were biased with V_{gs} = 15 V during irradiation. The 105 MeV proton data from Figure 2 is included in this plot for comparison. To within experimental uncertainty, there is no difference between the radiation response induced by protons or neutrons for the fluences examined. This is not unexpected given the similarity between proton and neutron reaction cross sections for particle energies greater than 50 MeV. The neutron data also provides additional support to the argument that observed changes in the IV characteristics are due to ionization by secondary particles. Neutrons do not do lose energy by direct ionization as do protons. The only possible mechanism by which neutrons can cause total dose effects is by the ionization of secondary particles generated by nuclear interactions.

IV. Hardness Assurance Implication

Test guidelines have been developed for total dose hardness assurance qualification (e.g., MIL-STD-883, Method 1019). These guidelines depend on laboratory tests that do not always match the exact conditions of the use environment because of time, cost, and facility limitations. For example, TM1019 specifies the use of gamma ray sources for total dose testing. However, based on the results discussed above, performing total dose qualification testing of power MOSFET devices using gamma ray sources does not reproduce the mechanisms for device degradation caused by protons. Thus, if trench FET power

MOSFETS are going to be used in proton-rich space environments, gamma ray testing of the devices could significantly underestimate the radiation-induced degradation, leading to unexpected failures in proton-rich space environments.

While we have limited our discussion to the response of trench FET power MOSFETs so far, it is possible that similar effects could happen in other technologies. Microdose effects have been observed in many different device types [7-9]. As an example, it has been suggested that stuck bits observed in SDRAMs could be caused by microdose effects [7, 9]. Others have suggested that in addition to microdose effects, bulk defects caused by proton and ion induced displacement damage can lead to significant changes in the refresh rates in SDRAMs [9,10]. We have also taken data on SDRAMs using both protons and neutrons (not shown here) that show changes in refresh rates similar to those observed by Shindou [10]. Whether these changes are associated with microdose effects or bulk defects is irrelevant when considering the total dose hardness assurance implications. Regardless of the mechanism, qualification testing performed using gamma rays will not reproduce the device degradation that will be observed in space.

These data strongly suggest that if devices are going to be used in proton-rich environments, total dose qualification testing must be done using proton radiation sources as well as using TM1019. The TM1019 qualification still needs to be done to address annealing effects and dose rate issues (e.g., ELDRS). In addition, it is much cheaper to screen devices for total dose degradation using ^{60}Co gamma rays than it is to use protons. These results will also provide a baseline for how much total dose degradation will be induced by direct ionization of the protons. It is possible that the direct ionization effects could be worse than any indirect ionization effects that could be observed in a proton environment. If additional degradation is observed during the proton testing, it will indicate that there are microdose or displacement damage effects that impact the device response. For proton qualification testing, devices should be irradiated to the maximum fluence expected for the system. The bias conditions during irradiation should be selected to maximize microdose effects (i.e., the maximum operating voltage or approximately 1-2 MV/cm across the sensitive oxide). Other issues could also impact the microdose or displacement damage effects, like angle of incidence and dose rate. It was shown in Ref. [1] that the angle of incidence associated with heavy ion irradiations had a significant impact on the amount of degradation observed. Work is currently being conducted to explore the impact of proton angle of incidence and will be presented in the final paper. Because annealing effects could also be important when considering the impact of microdose and/or displacement damage effects on the device performance, it is a good idea to anneal the device using the same bias conditions with time to understand the annealing properties of these effects.

V. SUMMARY

It is shown that both protons and neutrons can enhance degradation in trench FET power MOSFETs. This enhanced degradation can occur at extremely low fluence\total dose levels. The mechanism responsible for the enhanced degradation is consistent with microdose effects. The impacts of these results on hardness assurance qualification testing are discussed. It is recommended that total dose qualification of any devices that are going to be used in a proton-rich space environment be done using both TM1019 and testing at a proton facility.

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