NEUTRON RADIATION GENERETED CHARGES TRAPPED IN MOS DEVICES

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Abstract

Metal oxide semiconductor (MOS) circuits are currently the cornerstones of the modern microelectronics industry. The primary physical effect of neutron bombarding semiconductor material is the formation of displacement defects within the crystal lattice structure. Neutron radiation causes failure of MOS devices due to two mechanisms, that is, trapped charge density buildup in the silicon dioxide layer, and an increasing in the density of trapping states at the silicon dioxide interface. The neutron radiation induced interface traps cause a degradation in mobility of the carriers in the channel of the MOS transistor, this leads to a reduction in channel conductance and transconductance for the transistor, and thus a decrease in gain.

1. Introduction

Currently most of electronics system are designed by using a structural basis of MOS (Metal Oxide Semiconductor), for as both of p-MOS, n-MOS and as CMOS (Complementary Metal Oxide Semiconductor). The superiority of this new technology of MOS is the low energy consumed and the simple fabrication of it, but in a nuclear radiation environment, the MOS structure will be sensitive and easily electrically balance disturbed, making these components having a high potential to experience malfunctioning. Therefore tested electronic components are extremely necessary to operate in such nuclear radiation environment. Today, the importance of this field to the well being of large segments of the population must not be underestimated. As investigation of radiation induced surface effects in bipolar transistor continued, proceeding from studies of gaseous-ion-induced semiconductor surface modification to studies of electronic trapping within SiO_2/Si surface region, the emphasis switched to metal oxide semiconductor (MOS) devices.[1]

2. Theoretical Foundation

Neutrons have no charge and therefore do not give rise to direct ionization when they penetrate silicon. They can only be stopped by interaction with nuclei. Neutron collisions where the neutron is absorbed by the target atomic nucleus, which in turn emits a changed particle, such as in the *(n, α)* and *(n, p)* reactions. [2]

In silicon the (n, α) reaction corresponds to

$$n + Si \longrightarrow {}^{25}_{12}\mathrm{Mg} + \alpha$$

While the (n, ρ) reaction corresponds to

$$n + Si \longrightarrow {}^{28}_{13}Al + P$$

Ionizing radiation is that which possesses enough energy to break atomic bonds and create electron/hole pairs (i.e., cause ionization) in the materials of interest, which in the case of MOS devices are primarily silicon dioxide and silicon. The effects due to these bond-breaking events are to be contrasted with those that can occur when atoms in a material structure are displaced from their original positions by the radiation (displacement damage). The typical cause of significant displacement damage is neutrons from a nuclear reactor or weapon burst. The high-energy neutron loses through ionization as it passes through a transistor's reverse-biased MOS and leaves a dense track of electron-hole pairs. To generate an electron-hole pair in silicon, energy of 3.6 eV is needed. [3] Thus the critical charge *Qc* may be formed by deposition in the critical volume of energy *Ec*:

$$Ec = 3.6\ \mathrm{eV} \times Qc / 1.6 \times 10^{-19}\ \mathrm{C} = Qc \times 2.25 \times 10^{19}\ \mathrm{eV/C}. \qquad (1)$$

The radiation damage in the silicon dioxide layers consists of three components: the buildup of trapped charge in the oxide, an increase in the number of interface traps, and an increase in the number of bulk oxide traps. Electrons and holes are created within the silicon dioxide by the ionizing radiation or may be injected into the SiO_2 by internal photoemission from the contacts. These carriers can recombine within the oxide or transport through the oxide. Electrons are very mobile in SiO_2 and quickly move to the contacts; in contrast the holes have a very low effective mobility and transport via a complicated stochastic trap-hopping process. Some of the holes may be trapped within the oxide, leading to a net positive charge. Others may move to the SiO_2/Si interface, where they capture electrons and create an interface trap.[1] Along with the electron-hole generation process, chemical bonds in the SiO_2 structure may be broken. Some of these bonds may reform when the electrons and holes recombine, whereas others may remain broken and give rise to electrically active defects. These defects can then serve as trap sites for carriers or as interface traps. Bonds associated with hydrogen or hydroxyl groups when broken can release these impurities, which are then mobile within the silicon dioxide. These impurities may then migrate to the SiO_2/Si interface, where they undergo a reaction which results in an interface trap. The defects created by the radiation may themselves migrate in the strained region near the SiO_2/Si interface and also result in the formation of an interface trap. Typically the net charge trapped in the oxide layer after irradiation is positive. The interface traps can exchange charge freely with the silicon substrate, and thus their charge state depends upon the bias applied to the device—more negative for a positive bias applied to the gate electrode than for a negative bias applied to the gate electrode.

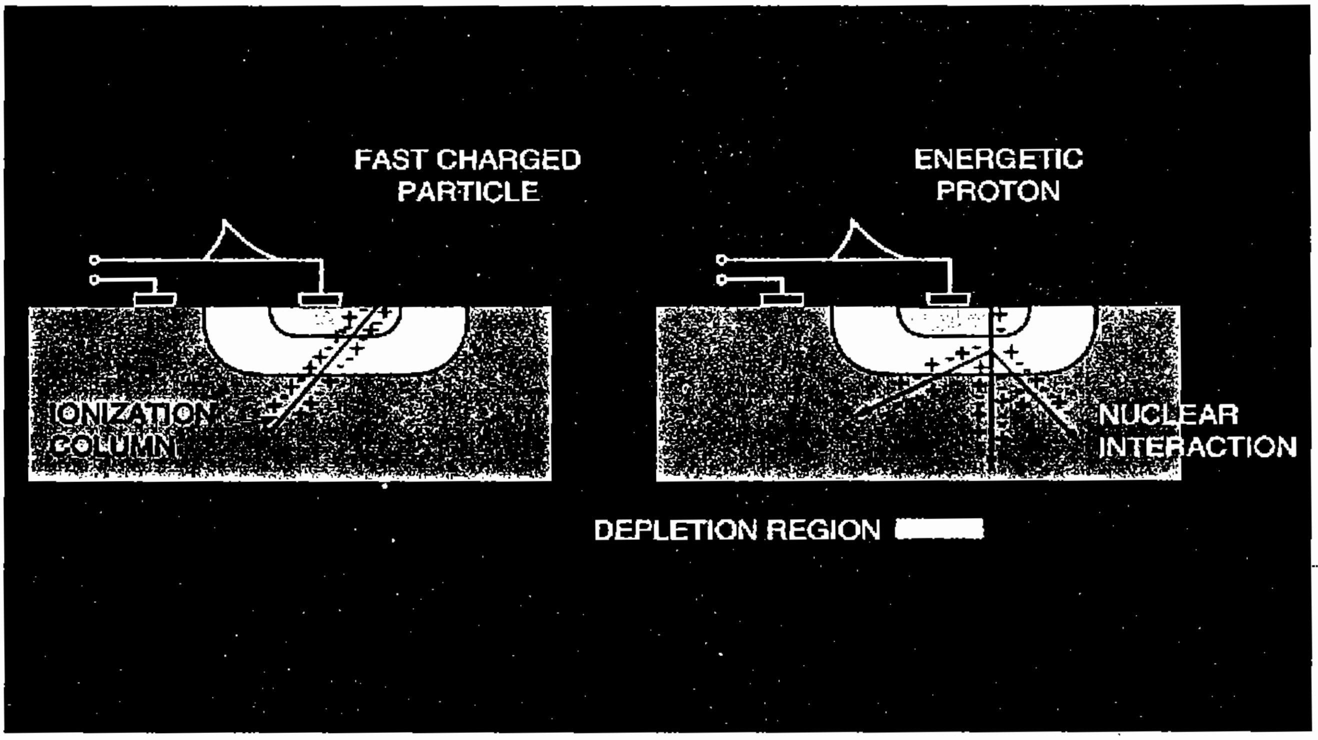

Fig. 1 Schematic showing ionizing radiation deposit energy in an MOS device

The principal processes that control the buildup of a negative voltage shift ΔV_{ot} due to hole trapping are shown schematically in Fig.2 for an MOS structure with oxide thickness d_{ox} irradiated under positive bias.

The overall charge buildup process (neglecting hole-removal processes other than recombination) can be expressed in the following incremental form:

$$\Delta n_{ht}(x,\Delta D) = F_h(x)\sigma_{ht}(\xi_{ox}(x()[N_{ht}(x) - n_{ht}(x)] - F_e(x)\sigma_r(\xi_{ox}(x))n_{ht}(x) \qquad (2)$$

Where n_{ht} is the local density of trapped holes; ξ_{ox} is the effective field

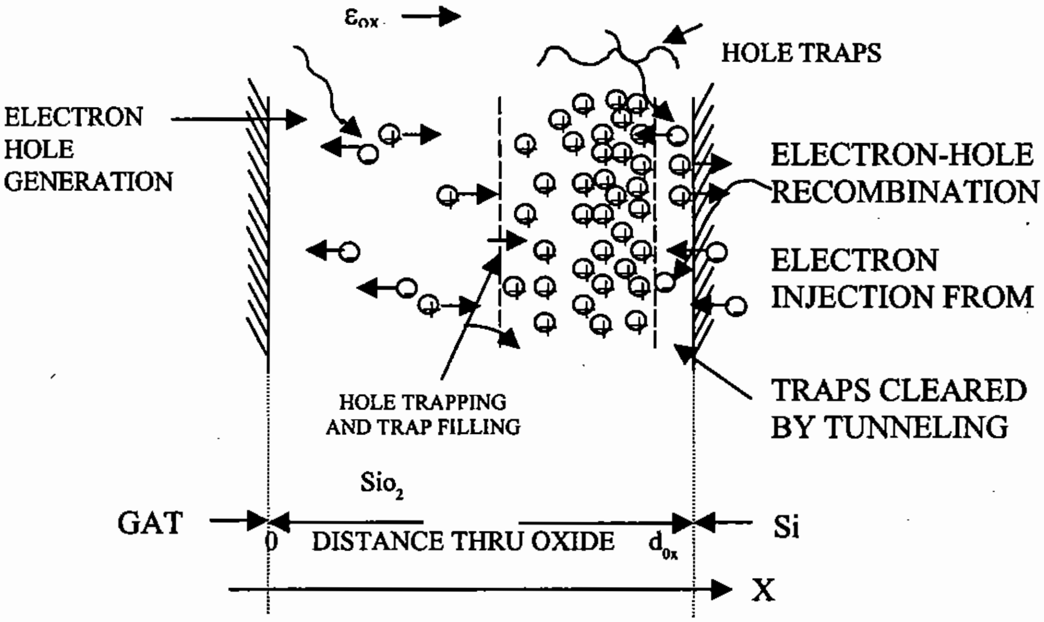

Fig.2 Oxide charge (hole) trapping and removal processes in an MOS structure under positive gate bias.

in the oxide; N_{ht} is the local density of hole traps; σ_r is the local oxide field-dependent cross-section for recombination of an electron with a trapped hole; and F_h and F_e depend upon the "upstream" generation and removal of holes and electrons in the oxide. The ΔV_{ot} that results from the trapped holes is given by

$$\Delta V_{ot}(\xi_{ox}, E) = -(q/\in_{ox})\, K_g(E)\, f_y(\xi_{ox}, E)\, ft(\xi_{ox})\, d^2_{ox}\, D(E) \qquad (3)$$

3. Experimental Setup

Many specimen MOSFET devices were irradiated with 14-MeV neutron resulting from D-T reaction. A computerized test system was used to monitor the changes in the devices. The neutron fluence measured with Al activation foils, were controlled by variation of the irradiation time, and the distance between the devices and the target. [4] To examine the neutron energy dependency, each sample MOSFET was set at different angles for the incident beam direction. The neutron energy is determined from the kinematics and slightly varies with the angle . [5]

In-situ measurements of performance degradation were carried out for the MOSFET and the information and status of MOSFET was transmitted through MOSFET driver circuit based on Analogue to Digital Converter (ADC) which was composed in a personal computer.

4. Results and Discussion

Under the assumption that hole trapping takes place very close to the SiO_2/Si interface in an MOS structure

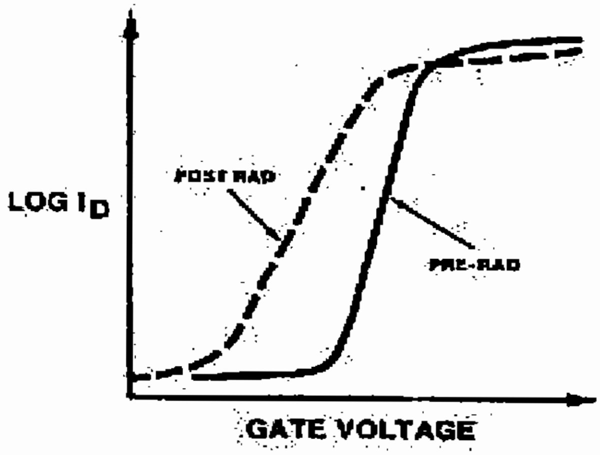

Fig.3 The changes of the threshold voltages of n- and p-channel MOS transistors as a function of radiation dose

irradiated, because the electron-hole created from the breaking of silicon oxygen bonds. This produces the build up of trapped positive charge in insulator, and trapped negative charge concentrated at the insulator-channel interface.

Besides the hole-electron pairs that recombine following the onset of an ionizing radiation, the applied gate voltage rapidly sweeps the electrons out of the oxide insulator, because of their very large mobility, compared with that of the corresponding holes. The relatively immobile holes become trapped in the SiO_2 in the gate insulator near the silicon channel interface for positive gate voltages, or near the SiO_2 gate metal interface for negative gate voltages.

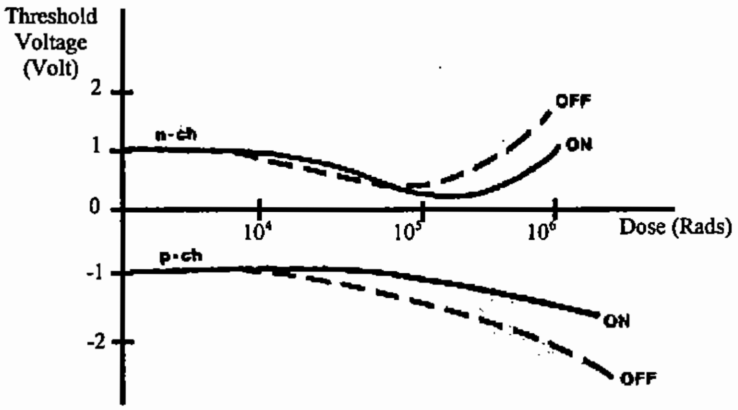

Fig. 4 Plot of the logarithm of the drain current of an n-channel MOS transistor as a function of gate voltage before and after irradiation.

Ionizing radiation induced positive charges (holes) in the insulator will then require a greater negative voltage to compensate the positive charge to achieve surface inversion, and thus transistor turn-on, the increase in turn-on voltage, or threshold voltage. Fig. 3 shows the kinds of changes that occurred in threshold voltage for n-channel and p-channel transistor biased either "on" or "of" during irradiation.

In Fig. 4 is plotted the drain current of an n-channel MOS transistor vs. gate voltage before and after the device irradiated. The curve shifts in the negative direction, this means that the threshold voltage of the transistors is more negative, or that a less positive voltage is required to turn the transistor on. The curve is also less steep; that is, a greater change in applied bias is required to cause the same change in current as before the radiation. The neutron radiation induced interface traps cause a degradation in mobility of the carriers in the channel of the MOS transistor, this leads to a reduction in channel conductance and transconductance for the transistor, and thus a decrease in gain.

5. Conclusion

Neutron radiation generates electron-hole pairs in the silicon dioxide. All the electrons are rapidly swept out of the oxide by the applied field but a fraction of the holes are permanently trapped producing a negative threshold voltage shift. The size of the threshold voltage shift varies with the magnitude and polarity of the applied gate bias during irradiation. Positive gate to substrate bias results in a large threshold voltage shift since the holes are trapped near the silicon surface where they will exert maximum influence on the devices. With negative gate bias during irradiation, the holes tend to be trapped near the metal gate where they have much smaller effect on the surface potential and mobile charge in silicon.

Displacement damage in silicon devices leads to significant decreases in carrier concentration, carrier mobility, and minority carrier lifetime. The dominant failure mechanisms in most neutrons irradiated MOS devices are a reduction in minority carrier lifetime (> 10^{11} n/cm^2) and decrease in carrier concentration (> 10^{13} n/cm^2). Mobility in silicon dose not become sever until neutron fluence exceeds 10^{15} n/cm^2. [6]

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