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A Model for Neutron Radiation Damage in Metal Oxide Semiconductor (MOS) Structures

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Abstract. Neutron bombardment on semiconductor material causes defects, one such primary physical effect is the formation of displacement defects within the crystal lattice structure, and such defects effectively decrease the mean free path and thus shorten the recombination time. Ionizing radiation causes creation of electron-hole pair in the gate oxide and in parasitic insulating layers of the MOS devices. Calculations show increase of the dark current in depletion region caused by a single neutron. Determination of energy and angular distribution of primary knock on atoms, with 14 MeV neutron irradiation in silicon are presented.

Introduction

Changes and disruptions of irradiated device characteristics depend on type of radiation, rate of energy deposition in semiconductor device, and the type of material the semiconductor structure is made of. Radiation effects can be divided into transient and permanent, depending on time an irradiated device needs to recover from radiation and restore its functionality [1].

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 was shown. The emphasis tends to switch to metal oxide semiconductor (MOS) devices [2]. Energetic particles creates permanent displacement damage, if that damage occurs in a sensitive region of MOS device, the issue arises whether the resulting changes in electrical properties are significant enough to be a problem. Neutron radiation induced defects in device regions increase the thermal generation rate of carriers and thereby cause the dark current to increase [3]. This effect is independent of the shape of the damage region produced by a given incident particle. If a single 14-MeV neutron interacts with a silicon atom in a depletion region which then creates several hundred stable defects in that region via displacement of atoms, each of these defects will cause an increment in dark current. The primary effect of neutron bombardment on depletion regions is the decreasing of the generation lifetime, τ_g due to the interaction of generation centers. The dark current density, J_d varies with neutron fluence, ϕ according to the expression [4].

$$J_d = \frac{qn_i x_d}{2}\left(\frac{1}{\tau_{g0}} + \frac{\phi}{k_g}\right). \tag{1}$$

where τ_{g0} is the pre-irradiation value of τ_g, x_d is the depletion width, and k_g is a macroscopic generation lifetime damage coefficient.

The neutron radiation damage in the silicon dioxide layers consists of three components: the build-up of trapped charge in the oxide, an increase in the number of interface traps, and an increase in the number of bulk oxide traps [5]. 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. Typically the net charge trapped in the oxide layer after irradiation is positive [6].

Experimental Detail

Experiments and modeling were performed for 14-MeV neutrons incident on silicon structure to evaluate neutron interactions and the nature of damage regions. Calculations were made to determine the energy and angular distributions of primary knock-on atoms (PKAs) for elastic and inelastic scattering. In this research, 25 transistors (*n*- channel depletion mode MOSFET) were operated in the dark and thermally generated current was allowed to accumulate, in the storage devices. Two accumulation times were employed, 10 sec and 20 sec. Pre- and post-irradiation measurements of dark current density were made at 303 ± 0.2K for each transistor in the array using the experimental arrangement.

Post irradiation measurements were performed 2 to 3 hours after each bombardment. *In situ* method was used to observe GF4936 dual *n*-channel depletion mode MOS transistor during irradiation with neutron results from D-T reaction. The *in situ* method was based on two interface cards, i.e., analog to digital converter A/D and digital to analog converter D/A interface card [7]. Irradiation of samples was performed twice in order to determine the characteristic of MOS transistor, viz., first to measure the output characteristics, and second to measure the forward transfer characteristics. In order to measure the output characteristics, the gate-source voltage, V_{GS}, was changed from +0.5 to -1.5 V with changes of the applied DC supply voltage, V_{cc}, starting from 0 to 20 V. On the other hand, the characterization of MOS transistor in order to determine the forward transfer characteristics of the gate-source voltage, V_{GS}, was changed from –5.0 to +5.0 volts with V_{cc} constant at 20 V during irradiation.

Results and Discussions

The number of interaction (N) between neutrons of a given energy and silicon atoms in a depletion region of cross sectional area A is given by $Ax_d P'\phi$, where P' is the neutron scattering probability per centimetre of material. For a single interaction ($N = 1$), Eq. 1 becomes

$$J_d = \frac{qn_i x_d}{2}\left(\frac{1}{\tau_{g0}} + \frac{1}{k_g A x_d P'}\right). \tag{2}$$

Thus, the additional dark current (I_{dl}) produced by one neutron interaction is given by,

$$I_{dl} = qn_i / 2k_g P' . \tag{3}$$

which is equal to $1.16 \times 10^{-9} / \; k_g P'$ amperes at room temperature.

Value for k_g at room temperature has previously been determined experimentally, to be 3.1×10^6 *n*-sec/cm^2 for 14-MeV neutron bombardment. This value allow the dark current per neutron interaction to be calculated, at 14-MeV, Eq. (3) yields 42×10^{-15} ampere, produced per interaction ($P' = 0.09$).

The predominant interactions between 14-MeV neutrons and silicon are elastic (*n*, *n*) and inelastic (*n*, *n'*) scattering. These reactions are assumed to occur with ^{28}Si which has an abundance of 92.3%. All other reaction, such as (*n*, *p*), (*n*, α), and (*n*, *np*), have much smaller cross sections. Both (*n*, *n*) and (*n*, *n'*) interactions have cross section of approximately 0.9 barns. Most interest focused on the elastic reaction, while ignoring the inelastic. Because of the high energy of the 14-MeV neutron, elastic scattering of ^{28}Si produces the typical "diffraction-like", differential elastic cross section [9].

Fig.1 shows the distribution of primary recoil energies for elastic and inelastic interaction, while Fig. 2 shows angular distribution for both elastic and inelastic interaction. These two distributions are not independent. For each energy there is a specific angle for which a recoil occurs. The elastic energy distribution is highly peaked at low energies. These low energies PKAs will be scattered nearly perpendicular to the incident neutron direction. High energy PKAs due to elastic scattering are relatively but much more forward directed. The probability of multiple neutron interaction in MOS device can be determined using the Poisson distribution.

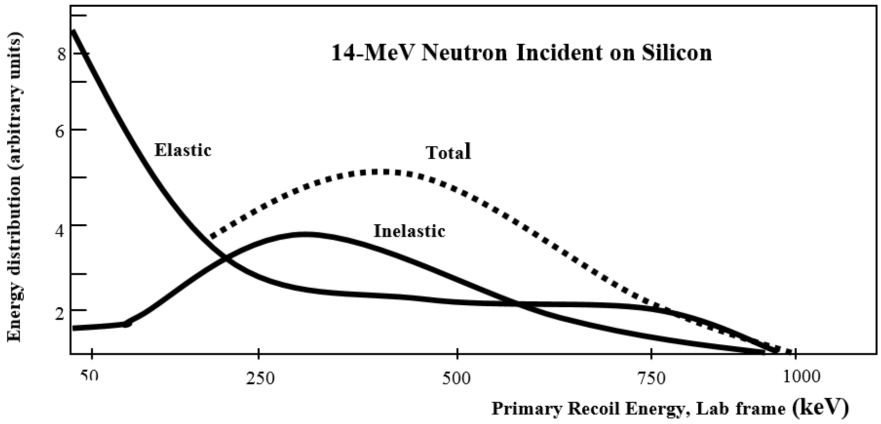

Figure 1 The distribution of primary recoil energies for elastic and inelastic interaction in 14-MeV neutron irradiated silicon.

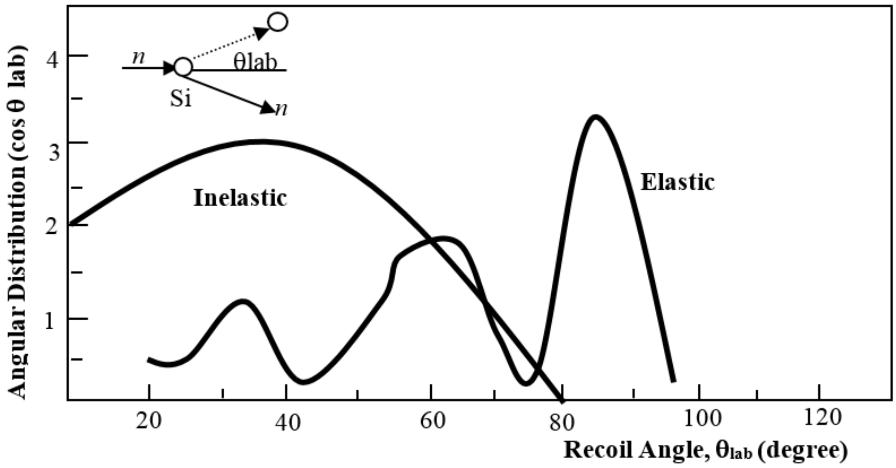

Figure 2 Angular distribution for elastic and inelastic interactions in 14-MeV neutron irradiated silicon.

The MOS devices were bombarded with a steady state 14-MeV neutron flux at room temperature. The test devices were irradiated in different angles and distances to the following cumulative fluence: 6.61×10^{9}, 1.32×10^{10}, 1.98×10^{10}, 2.64×10^{10}, and 3.35×10^{10} n/cm^2. The experimental results were examined to determine whether the number of interactions per device followed the Poisson distribution. Dark current changes experienced by each device in all seven irradiations were tabulated and the number of devices experiencing a specific number of interactions was determined. Results are shown as data points in Fig. 3.

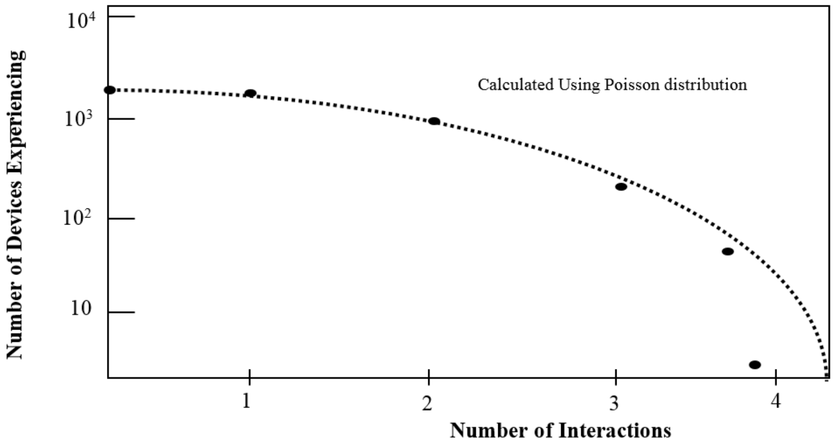

Figure 3 Comparison of measured and calculated distributions of the number of devices experiencing.

Conclusion

Calculations show interaction of neutron (single particle interactions) in device depletion regions cause an increase in the permanent dark current. However experimental verification of these predictions is required. Determination of energy and angular distribution of PKAs with 14 MeV neutron irradiated on Silicon was made. The effects of 14 MeV neutron on the characteristics of GF4936 dual n-channel depletion mode MOS devices were calculated on the basis of experimental data obtained.

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