THE MECHANISM OF MOSFET DAMAGE INDUCED BY NEUTRON RADIATION RESULTING FROM D-T FUSION REACTION

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Abstract

Silicon metal oxide semiconductor (MOS) devices are currently the cornerstones of the modern microelectronics industry. Neutron radiation causes significant changes in the characteristics of MOS devices by the creation of oxide-trapped charge and interface traps. The degradation of the current gain of the GF4936 dual *n*-channel depletion mode MOSFET, caused by neutron displacement defects, was measured using *in-situ* method during neutron irradiation. The average degradation of the gain of the current is about 35 mA, and the change in channel current gain increased proportionally with neutron fluence. The total fusion neutron displacement damage was found to be 4.8×10^{-21} dpa per n/cm^2, while the average fraction of damage in the crystal of silicon was found to be 1.24×10^{-12}. All the MOSFET devices tested were found to be controllable after neutron irradiation and no permanent damage was caused by neutron fluence irradiation below 10^{10} n/cm^2. The calculation results shows that (n, α) reaction induced soft-error cross-section about 8.7×10^{-14} cm^2, and for recoil atoms about 2.9×10^{-15} cm^2, respectively. Thus, it can be concluded that alpha particles induced the largest portion of error in MOS capacitor among the three kinds of charged particles.

KEY WORDS: Neutron displacement damage, Soft-error, *In-situ* method, MOS capacitor, and MOSFET.

INTISARI

Piranti silikon *metal oxide semiconductor* (MOS) telah menjadi piranti dasar dalam dunia industri mikro-elektronika modern. Radiasi neutron menyebabkan karakteristik piranti berbasis MOS berubah secara signifikan akibat penjebakan muatan pada daerah dioksida dan tertangkapnya muatan pada daerah antarmuka. Degradasi *gain* arus MOSFET GF4936 kanal-*n* tipe deplesi yang disebabkan oleh kerusakan pergeseran neutron, telah diukur dengan metode *in-situ* selama iradiasi neutron berlangsung. Degradasi rerata *gain* arus adalah sekitar 35 mA, dan perubahan pada *gain* arus kanal naik sebanding dengan kenaikan fluens neutron. Total kerusakan pergeseran oleh neutron ditemukan sebesar $4{,}8\times10^{-21}$ dpa per n/cm^2, sedangkan rerata fraksi kerusakan kristal silikon ditemukan sebesar $1{,}24 \times 10^{-12}$. Semua Piranti MOSFET telah diujicoba setelah diiradiasi, dan ditemukan dalam keadaan baik tanpa terjadi kerusakan yang permanen sampai pada fluens10^{10} n/cm^2. Hasil perhitungan simulasi menunjukkan bahwa reaksi (n, α) dan reaksi atom rekoil mengakibatkan *soft-error cross-section* masing-masing sekitar $8{,}7 \times 10^{-14}$ cm^2 dan $2{,}9 \times 10^{-15}$ cm^2, maka dapat disimpulkan bahwa patikel alpha mengakibatkan jumlah *error* paling besar pada kapasitor MOS di antara ketiga partikel tersebut.

KATA KUNCI: Kerusakan pergeseran neutron, *Soft-error*, Metode *In-situ*, kapasitor MOS, dan MOSFET.

I. Introduction

Currently most electronic systems are designed by using a structural basis of MOS (Metal Oxide Semiconductor), for as both as *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 its simple fabrication of it, but in a nuclear radiation environment, the MOS structure will be sensitive and its electrical easily 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.

II. Theoretical Foundation

One of the principal causes of radiation damage to electronic devices is due to neutron. Because neutrons are relatively heavy (1840 times heavier than electrons) uncharged particles, instead of merely ionizing atoms or molecules, they collide with the lattice atoms of the semiconductor, displacing whole atoms from their lattice sites to causing them to take up interstitial positions within the crystal. This results in disruption or distortion of the local lattice structure. The former site of the now displaced atom is called vacancy. The displaced atom is called an interstitial and the interstitial –vacancy pair is called a *Frenkel defect*. The incident neutron transfers enough energy to a silicon atom to displace it from its lattice site. This atom is also called a primary knock-on atom (PKA), *primary, primary recoil atom, recoil atom, displaced, or interstitial atom.* The mean displacement energy of a lattice site is 25 eV. That is, at least 25 eV of energy must be supplied by the incident neutron to displace a silicon atom from its site in the lattice. Displacement damage in silicon semiconductors results in significant decreases in carrier concentration, mobility, and minority carrier lifetime. [1]

The number of displaced atoms per cm^3, N_d, is given, [2]

$$N_d \cong \Phi_n \cdot \bar{n}_s / \lambda \qquad (1)$$

Where Φ_n is the fluence of neutron, $\bar{n}_s$ is the mean number of displaced atoms and λ is the neutron mean free path.

Neutrons are capable of causing ionization in the lattice by indirect processes even though their major influence is through damage by displacement. Because neutrons are uncharged, they can not interact electrically with charge particles to ionize them. They nevertheless produce ionization through secondary processes, such as

a) neutron collisions that produce recoil atoms or ions.

b) neutron collisions that excite atomic nuclei, which de-excite by emitting gamma rays that can ionize.

c) 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, ρ) reactions.

In silicon the (n, α) reaction corresponds to

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

While the (n, ρ) reaction corresponds to

$$n + Si \rightarrow {}^{28}_{13}\mathrm{Al} + \rho$$

The neutron 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. 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. Since the number of electron/hole pairs generated is directly proportional to the amount of energy absorbed by the device material, the total damage is also roughly proportional to the total fluence of radiation received by the device. Typically the net charge trapped in the oxide layer after irradiation is positive. [3] The possible processes by which the radiation creates these charge and trap sites are illustrated in Figure 1.

To generate an electron-hole pair in silicon, energy of 3.6 eV is needed. Thus the critical charge *Qc* may be formed by deposition in the critical volume of energy *Ec*: [4]

$$Ec = 3.6\ eV \times Qc / 1.6\ X\ 10^{-19}\ C \qquad (2)$$

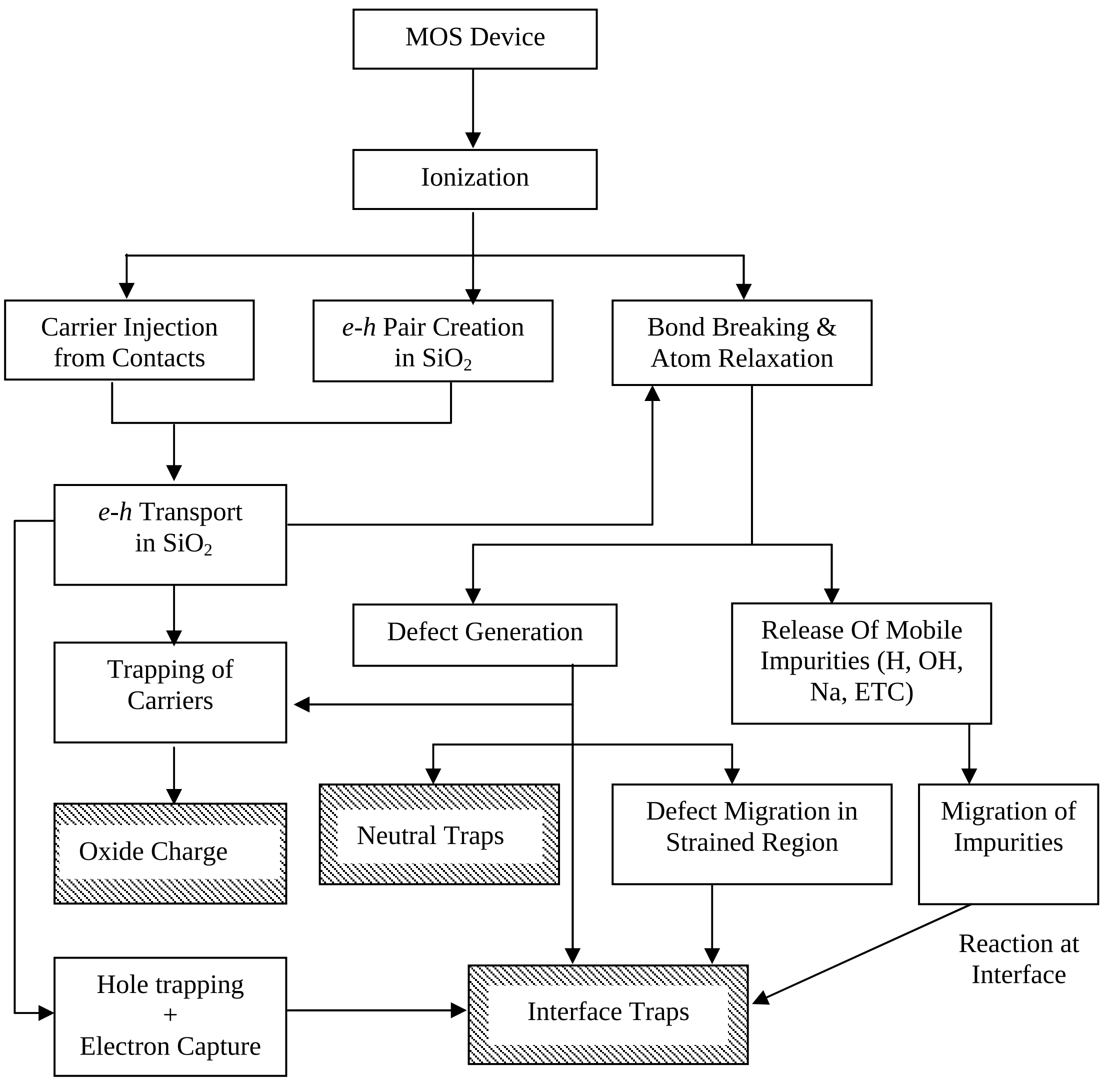

Fig. 1 Schematic diagram illustrating the possible processes by which ionizing radiation in an MOS device leads to the creation of oxide charge, neutral traps, and interface traps.

III. Experimental Method

The method that was used to observe GF4936 dual *n*-channel depletion mode MOSFET devices during irradiation with neutron results from D-T reaction is called the *in-situ* method. By using this method, changes in electric device characteristics were observed and measured directly at the time when MOSFET was irradiated**.** This method was based on two interface cards, i.e., analog to digital converter A/D and digital to analog converter D/A interface card. The *in-situ* measurement of the current gain degradation under various bias conditions is effective in obtaining accurate data on neutron radiation damage in MOSFET devices. A full and detailed relation between a change in current gain, threshold voltage, and neutron fluence can be derived with less correlation from the *in-situ* measurement. In additional to the effects on the threshold voltage, neutron radiation causes in a number of other MOS transistor parameter, the sub-threshold characteristic of the MOSFET can change markedly with irradiation. Figure 2 shows a schematic drawing of the experimental arrangement and the electronic circuit used for the *in-situ* measurements.

The input pulses are digitized, and the digital pulse height is stored in a memory location referred to as a channel, the horizontal axis is labeled as channel number. The resulting pulse height spectrum have been used to determine the energies of the radiations emitted by the source from their locations on the horizontal scale, and their relative intensities from areas of the various peaks in the spectrum. In γ-ray spectroscopy measurements, the goal is usually to determine the energy and the intensity of the radiation. Based on the energies that have determined, the flux of neutron radiation then can be calculated.

More than 25 GF4936 dual *n*-channel depletion mode MOSFET samples were irradiated at room temperature with D-T neutrons to examine the neutron-induced changes of the characteristics of electronic devices. All samples were set and tested around the target at different angles, that is, (0^o, 15^o, 30^o, 60^o, and 90^o).

As described before, fusion neutron releases high energy charged particles in almost every material by (*n*,*p*), (*n*,α) and other reactions. When these reactions take place near the sensitive region of the MOSFET device, electric charges induced by the ionization effect of the high-energy charged particles will change the bias voltage of MOSFET. However, these changes are not permanent but recoverable with control signals from the computer placed in the control room. The energy deposition during the charged particles penetration can be calculated using a computer simulation program. This experiment provides a simple alternative to predict the degree of the neutron-induced changes of the parameters of MOSFET. By measuring the electric pulse signal of the noise induced by neutron reaction in MOSFET using power line pins, it was confirmed that the neutron induced charge deposition in the MOSFETs.

Irradiations of samples have done two times in order to determine the characteristic of MOSFET, viz., first to measure the output characteristics, and second to measure the forward transfer characteristics. In output characteristics, the gate-source voltage, V_{GS}, was changed from +0.5 to -1.5 volts with changes of the applied DC supply voltage, V_{cc}, starting from 0 to 20 volts. On the other hand, the characterization of MOSFET 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 of 20 volts during irradiation time.

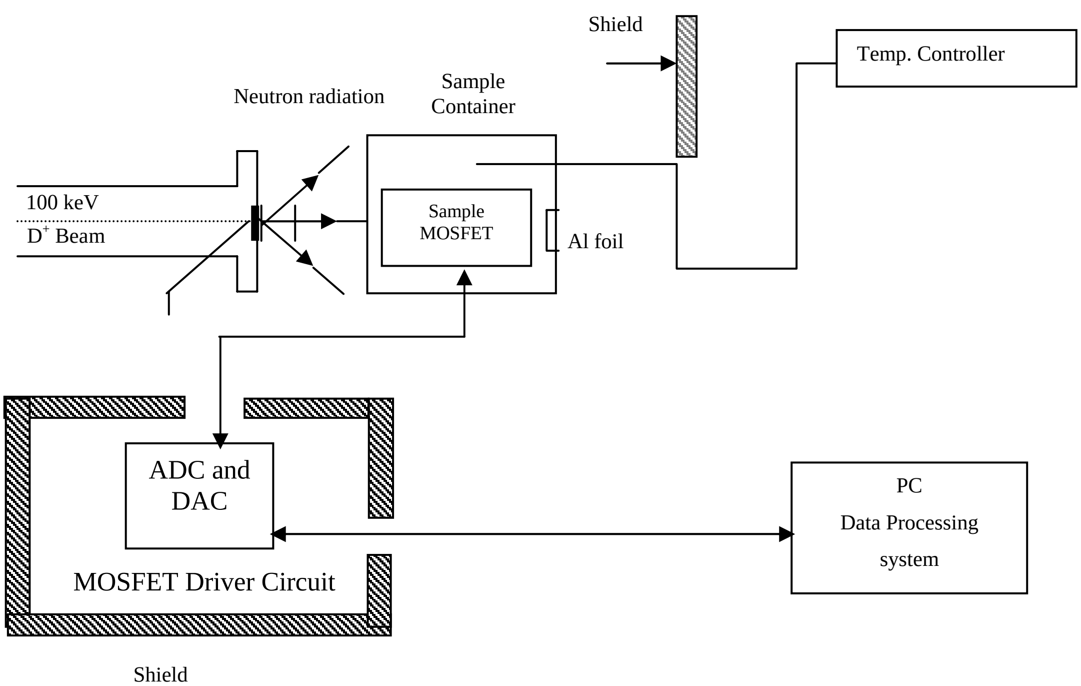

Fig. 2 Experimental arrangement and measuring system for MOSFET device irradiation experiments.

IV. Simulation Method

For the purposes of investigate the model and its resultant mechanism which have been described so far, the program based on Monte Carlo method was used. The program simulates the behavior of the secondary charged particles, which are produced by neutron induced reaction with silicon nuclei in the MOS capacitor. A Monte Carlo computer program is presented which calculates the slowing down and scattering of energetic ions in amorphous targets. This Monte Carlo program is used to calculate the range distribution of a variety of ion/target combinations. This program has been called TRIM (Transport of Ions in Matter). [5]

The D-T neutrons (14,7 MeV in the present case) bombardments in the silicon produce at least three secondary charged particles, which are alpha particles, protons, and silicon recoil atoms, through (n, α), (n, p), and silicon recoil atoms by neutron scattering respectively. The kinetic energy and range of these charged particles are different among themselves, thus the probability of hitting and changing the characteristics and parameters of the MOS capacitors are different also. This information of the effects of each charged particle is very useful in clarifying the mechanism changes of characteristics. Unfortunately, the experimental results provide only the integral of the whole kinds of effects of charged particles. [6]

There are three crucial factors in the soft error simulation calculation. They are the amount of energy that is deposited by the penetration of charged particle, the capacitor value of the sensitive volume, and the changes of the threshold voltage. The first factor, the amount of the energy deposited by each charged particle in the sensitive volume, depends on the kind of particle, its kinetic energy, and the length of the penetration path. The second factor, the capacitor magnitude of the sensitive area, is determined by the material structure of the MOS capacitor and applied bias voltage to the device. The third factor, the changes of the threshold voltage to induce the changing of characteristics of the MOS capacitor devices.

The computation of changes in the characteristics of MOS capacitor induced by neutron radiation of 14.7 MeV is done with the use of Monte Carlo method. This method can adequately explain the mechanism that takes place as well as characteristic changes in the electronic component. The computation carried out uses various single particle ions that begin with the movement of neutrons in materials until the creation of electron-hole pairs that can cause a change in electronic equilibrium in the component. Overall, this algorithmic computation consists of three modules, that is,

1. **Neutron transport in silicon.**

The application of Monte-Carlo method on neutron simulation was intended to clarify neutron particles, starting from neutron collision with silicon atoms, until the neutrons disappear, due to absorption or off limits from the medium.

2. **Charged particles transport in silicon.**

The calculation of charged particle transport in silicon was based on the TRIM 90 simulator, which has been modified for the purpose of determining the initial position of charged particle movements. The initial position of charged particle movements was obtained from the neutron transport in silicon. The results obtained from TRIM 90 indicate a number of deposition energy along the path within the geometric boundary for alpha particles, proton particles, and recoil atoms (magnesium and aluminum).

1. **Analysis of the change in MOS capacitor characteristics.**

Standard capacitance-voltage (*C-V*) estimates of oxide trap charge rely on the observation that interface traps are primarily acceptors in the upper half of the bandgap, donors in the lower half of the bandgap, and neutral at or near the midgap. The analysis of MOS capacitor characteristics has observed threshold voltage of MOS capacitor towards input parameters, that is, gate voltage, V_G, and temperature.

This simulation program has been written in C^{++} language. The software used to run this process is developed in Borland C^{++} for window version 5.02 programming language from Borland International Inc. that has the capability to support object oriented programming under Microsoft Windows operating system (Win 32). This object-oriented programming is intended to simplify subsequent development and process. This computation process is illustrated on figure 3.

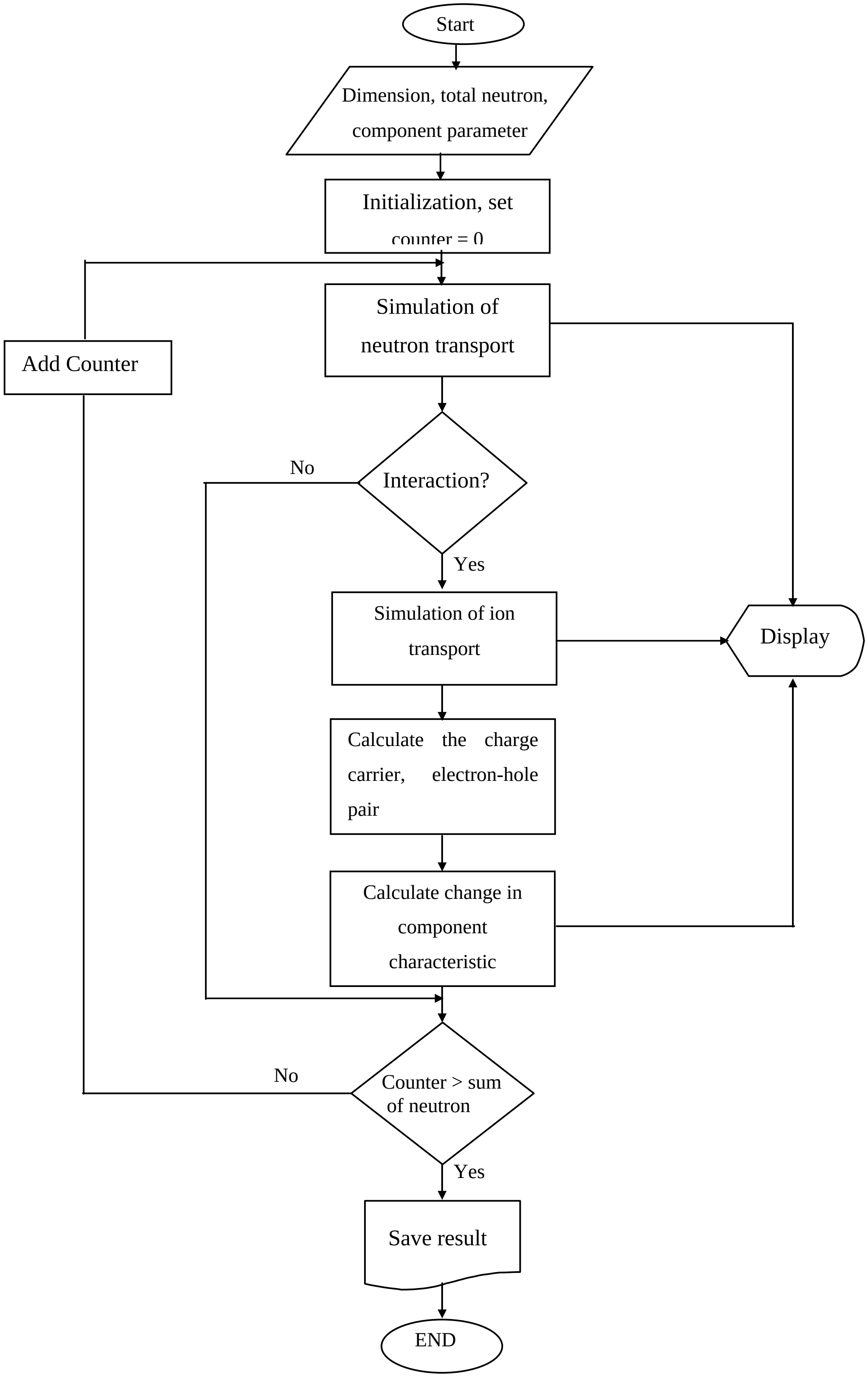

Fig.3 Main flowchart of calculation of the threshold voltage of MOS capacitor induced by a 14.7 MeV neutron.

V. Results and Discussion

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

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. 4 shows the kinds of changes that occurred in threshold voltage for n-channel and p-channel transistor biased either “on” or “off” during irradiation.

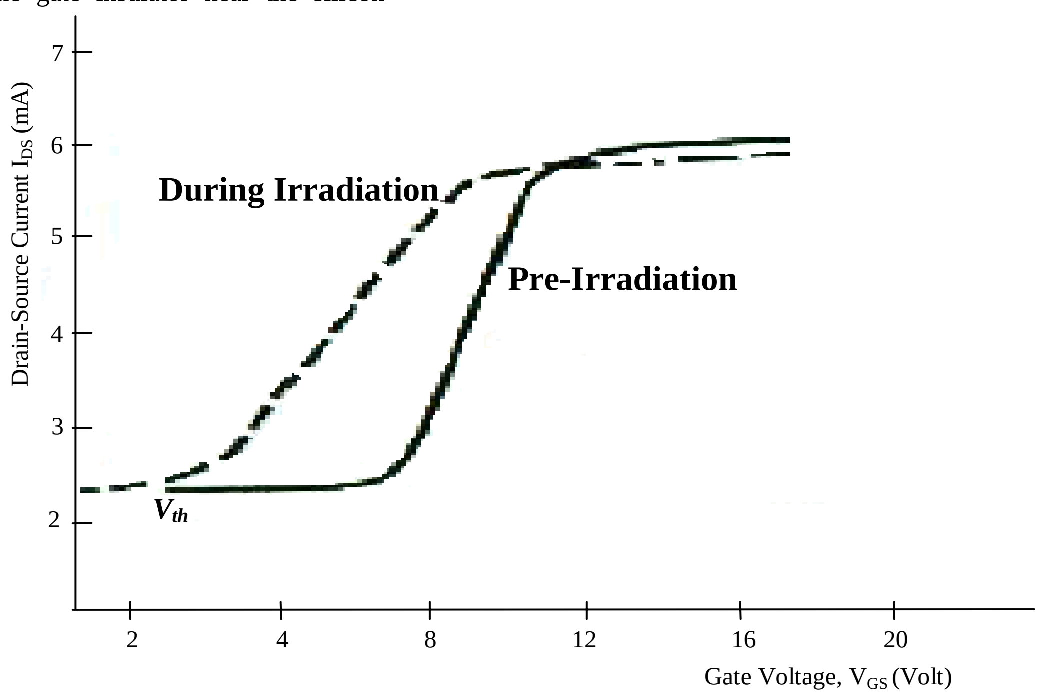

Fig. 4 Plot of the drain current of an *n*-channel MOS transistor as a function of gate voltage before and during irradiation.

When interface traps are generated by neutron irradiation, the shapes of the current-voltage characteristics are affected. As the voltage is swept, interface traps empty or fill, and they modify the electric field by requiring more (or less) charges on the gate to create a given surface field in the MOSFET. Typical changes that occur in the output characteristics for *n*-channel depletion type MOS transistor is shown in Figure 5. In general, these I_{DS}-V_{GS} characteristics are seen to shift to the left, a direct consequence of the buildup of positive oxide-trapped charge and decrease in slope. Decreasing slope is analogous to the distortion of the capacitance voltage.

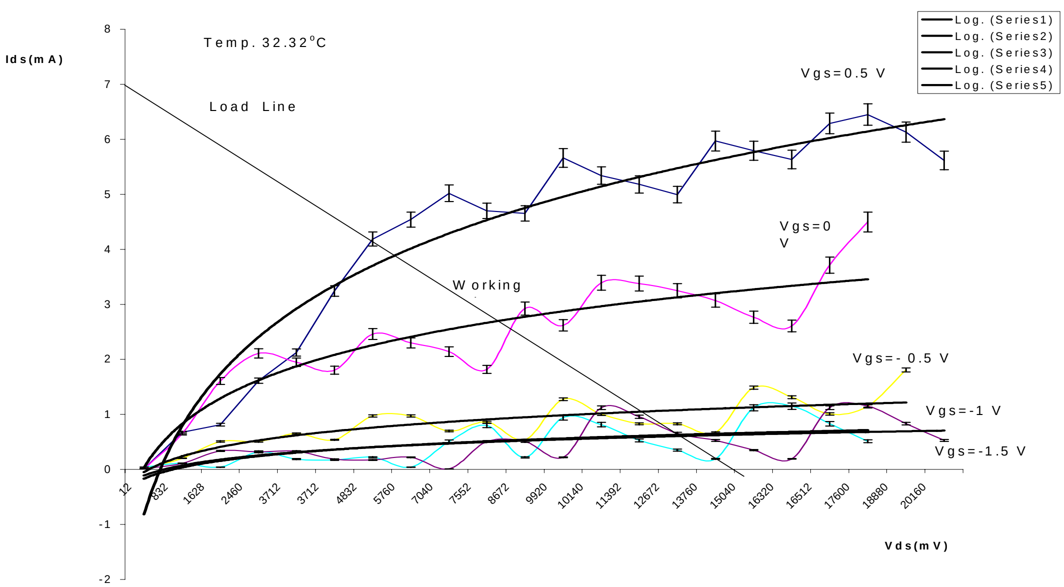

Fig. 5 The output characteristics of n-channel depletion type MOS transistor during irradiation with 14 MeV neutrons.

The fraction of damage has been calculated based on the formula $FD = N_d / N$, and the results are shown on table 1. This seemingly small fraction is enough to cause appreciable damage evidenced by the degradation of the macroscopic properties of the MOSFET devices. Fig. 6 shows the relation between the fraction of damage in the crystal of silicon and the different neutron fluence results from D-T reaction.

Table 1. The fraction of damage in the crystal of silicon induced by 14-MeV neutron.

N_d atoms/cm^3 (Average)	$FD = N_d / N$
$2.46 \times 10^{12} \pm 6.3 \times 10^4$	$4.92 \times 10^{-11} \pm 6.3 \times 10^4$
$1.42 \times 10^{12} \pm 5.32 \times 10^4$	$4.84 \times 10^{-11} \pm 5.32 \times 10^4$
$2.8 \times 10^{11} \pm 5.6 \times 10^3$	$5.6 \times 10^{-12} \pm 5.6 \times 10^3$
$1.2 \times 10^{11} \pm 5.48 \times 10^3$	$2.4 \times 10^{-12} \pm 5.48 \times 10^3$
$6.2 \times 10^{10} \pm 3.5 \times 10^3$	$1.24 \times 10^{-12} \pm 3.5 \times 10^3$

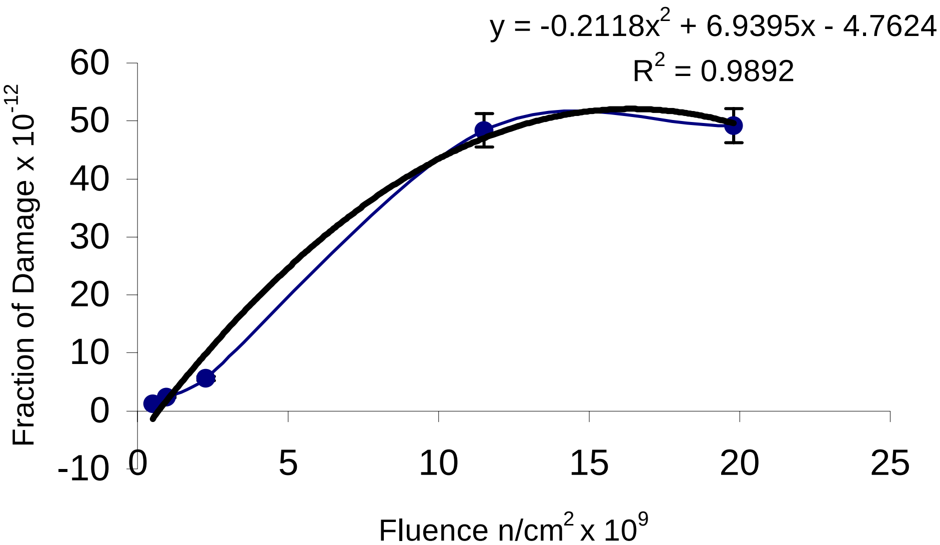

Fig. 6 Relation between fraction of damage in the crystal of silicon induced by 14-MeV neutron and the different fluence.

During the simulation calculation, it was found that there were no soft-errors induced by proton hits until 10^{10} n/cm^2 of neutron fluence. It is evident that even though proton hits are the largest among particles, proton energy transfer is not sufficient enough to induce soft-error of the MOS capacitor. From simulation results, it was also found that soft-error cross-section of the MOS capacitor with V_{cc} 5 volt and the temperature calculated at 30^{o}C was about 9×10^{-14} cm^2. Table 2 shows the simulation results for each reaction model. From the table we can conclude that the (n, α) reaction induced larger soft-error cross-section than recoil atoms.

Until the neutron fluence of $10^8 n$/cm^2, it was measured that proton hit the sensitive volume as much as 9×10^4 times, almost two orders of magnitude larger than the hits by alpha particles, which was only about 1.3×10^3 times.

Table 2 The simulation calculation results of the MOS capacitor.

Reaction Type	**Soft-error cross-section**
(n, α)	8.7×10^{-14}
Recoil Atoms	2.9×10^{-14}
Total	9.0×10^{-14}

The conductance measurement of the SiO_2 insulator-Si bulk channel was determined using four variables, i.e., the channel width, channel length, threshold voltage and the gate voltage. A comparison of the conductance versus the gate voltage with corresponding *C-V* curves plot is given in Figure 7.

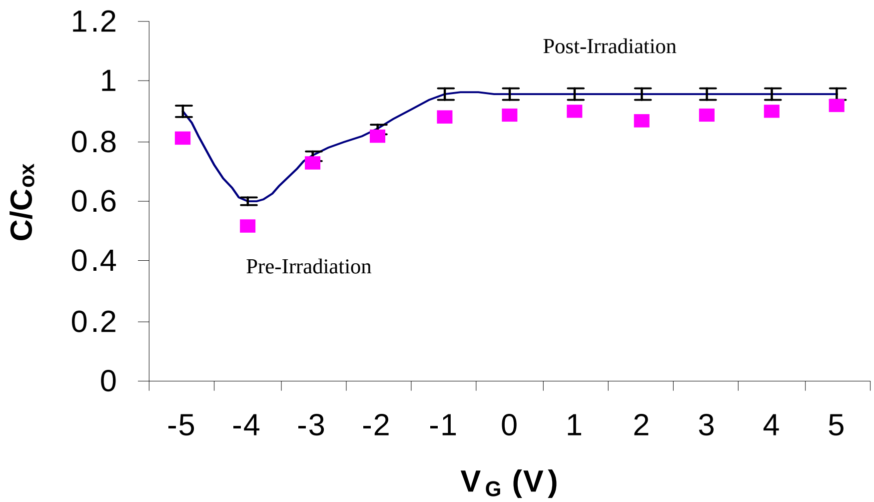

Fig. 7 Channel conductance and gate capacitance of a MOS capacitor.

VI. Conclusion

Neutron ionizing 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 larger threshold voltage shift since the holes are trapped near the silicon surface where they will exert maximum influence on the MOSFET.

The calculation of the experimental results on the effects of 14-MeV neutron induced changes of the characteristics in GF4936 dual *n*-channel depletion mode MOSFET devices can be concluded as follow,

1. The change in channel current gain increased proportionally with neutron fluence. The average degradation of the gain current about 35 mA at maximum fluence 2.0×10^{10} n/cm^2, and the average degradation of the gain current about 25mA at minimum fluence 5.0×10^8 n/cm^2.
2. The effect of neutron radiation on the drain current/ gate voltage curve of an *n*-channel MOSFET, are plotted, as the radiation fluence increases, the I_{DS}-V_{GS} curves shifted to more negative voltage.
3. High-level and low-level output voltages hardly changed, but the threshold voltage was seriously affected. The reason for the small change in high-level and low-level output voltages is that a very small current flows in the MOSFET gate and the change of channel resistance hardly affected the output voltages.
4. The average fusion neutron damage constant was found to be 1.6×10^6 n s/cm^2 for monoenergetic neutrons of energy. The value of fusion neutron damage constant depends on the structure parameters of the device and the neutron fluence.
5. On the assumption of an isotropic neutron reaction, we also calculated the rate of the fusion neutron displacement damage for Si by using the damage energy formula and the ENDF/B-IV neutron cross-section data. The total fusion neutron displacement damage was found to be 4.8×10^{-21} dpa per n/cm^2. This value depends extremely on the primary knock-on atoms.
6. Transconductance is a gain parameter of the MOSFET, the transconductance degraded proportionally with neutron fluence. The average degradation was found to be 15.85 S, and the amplification factor also decreased by 10%.
7. The average of the fraction of damage was found to be 6.2×10^{10} atoms/cm^3. This value has been calculated at different angles, because the fraction of damage depends on the angle of the neutron incident.
8. The calculation results shows that (n, α) reaction induced soft-error cross-section is about 8.7×10^{-14} cm^2, and for recoil atoms about 2.9×10^{-15} cm^2, respectively. Thus, alpha particles induced

the largest portion of error numbers in MOS capacitor among three kinds of charged particles.

9. There was no error of the MOS capacitor device configuration induced by proton particles until 1.0×10^{10} n/cm^2 neutron fluence (simulation).

10. The results of simulation calculation on the total soft-error cross-section for MOS capacitor gave about 9.0×10^{-14} cm^2 for 5 volts of the bias voltage.

11. Oxide trapped charge causes a negative shift in capacitance-voltage (*C-V*) characteristics. These changes are the results of increasing trapped positive charge in the oxide, which causes a parallel shift of the curve to more negative voltages, and of increasing interface trap density, which causes the stretch-out in the curve

VII. References

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