FUSION NEUTRON IRRADIATION EFFECTS ON ELECTRIC CHARACTERISTICS OF MOSFET DEVICES

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Abstract

Ten MOSFET devices are irradiated at room temperature with 14 MeV neutron at different angles. Typical effects of neutron radiation on the electric characteristics of the devices are measured. The results of the calculation is the curve of average change. From the calculation, we can conclude that the change of MOSFET threshold voltage is 621 mV and neutron displacement damage (dpa) is 0.46×10^{-21}. These changes are called soft-error and 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.

KEYWORDS: MOSFET devices, neutron irradiation, electric characteristics, displacement damage.

Intisari

Sepuluh piranti MOSFET telah diiradiasi dengan berbagai sudut pada suhu ruang. Efek-efek perubahan karakteristik piranti MOSFET akibat radiasi neutron telah diukur. Hasil perhitungan dari rata-rata kurva perubahan dapat disimpulkan bahwa terjadi perubahan tegangan ambang MOSFET sebesar 621 mV dan kerusakan pergeseran oleh neutron sebesar $0,46 \times10^{-21}$. Semua perubahan ini disebut *soft-error*, dan tidak terjadi kerusakan permanen, karena semua piranti MOSFET telah diuji kembali setelah iradiasi dan ternyata masih berfungsi.

1. Introduction

Semiconductor devices such as diodes, transistors and integrated circuits can be found everywhere in our daily lives, e.g. television sets, computers and watches, even high sophisticated equipments in modern shuttle aircraft. We have come to rely on them and increasingly have come to expect higher performance at lower cost(1) , sometimes semiconductor devices are indispensable with many electric instruments for fusion reactor diagnostics. However, semiconductor electronic devices easily suffer performance degradation due to neutron produced displacement damage. Therefore the electronic instruments for fusion reactor diagnostics which are exposed to radiation should be designed in consideration with radiation damage, especially fusion neutron damage(2).

1.1. Why Neutron ?

It has been found that 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 (3).

In silicon the (n, α) reaction corresponds to

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

While the (n, ρ) reaction corresponds to

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

Irradiation tests by a D – T neutron source are significant, and knowledge of fusion neutron irradiation effects is directly useful for design of electronic instruments for fusion reactor diagnostics. On the other hand, as fusion reactor seem to be an alternative energy source in the future, it is important to have the data on fusion neutron irradiation effects of various components and materials[2] .

1.2. Why MOSFET Devices?

The Metal Oxide Semiconductor Field Effect Transistor (MOSFET) is the most important devices for very large scale integrated circuits such as microprocessors and semiconductor memories[4]. MOSFET has many advantages, very small size, high input impedance, zero offset voltage, better temperature stability and low noise. Their structure is easy to understand the mechanism of radiation effects[3].

The n-type MOSFET consists of a source (S) and a drain (D), two highly conducting n-type semiconductor regions which are isolated from the p-type substrate by reversed biased p – n diodes. A metal gate (G) covers the region between source and drain, but is separated from the semiconductor by the gate oxide. The basic structure of an n-type MOSFET and the corresponding circuit symbol are shown in figure 1.

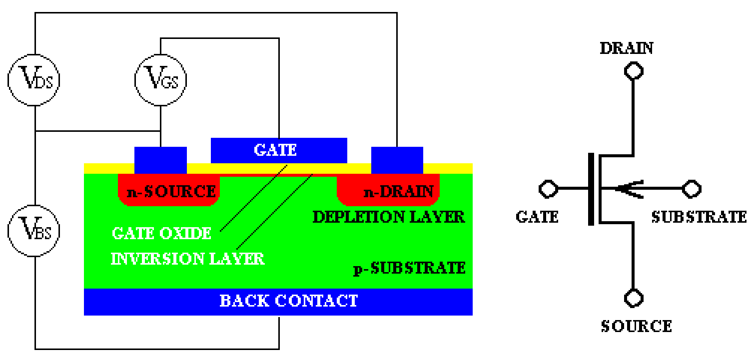

Fig.1 Cross section circuit symbol of an n-type MOSFET

The flow of electrons from the source to the drain is controlled by the voltage applied to the gate. A positive voltage applied to the gate, attracts electrons to the interface between the gate dielectric and the semiconductor. These electrons from a conducting channel between the source and the drain, called the inversion layer. No gate currents is since the gate oxide blocks any carrier flow. The net result is that the current between drain and source is controlled by the voltage which is applied to the gate. The typical current versus voltage (I_{ds} – V_{ds}) characteristics of MOSFET are shown in the figure below[5].

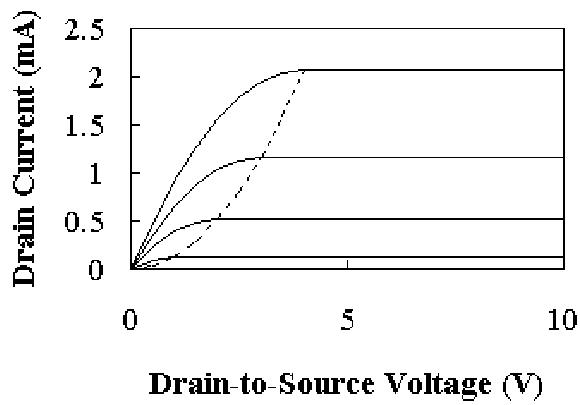

Fig. 2 I_{ds} – V_{ds} characteristic of an n-type MOSFET

2. Neutron Damage Effects

One of the principal causes of radiation damage to MOSFET devices are neutrons. Because neutron are relatively heavy, uncharged particles, instead of merely ionizing atoms or molecules, they collide with the lattice atoms of the semiconductors, displacing whole atoms from their lattice sites causing them to take up interstitial positions within the crystal. This results in distortion of the local lattice structure[3].

The principal ionizing radiation damage mechanism in MOSFET results from the creation of electron-hole pairs from the breaking of silicon-oxygen bonds in the SiO_2 insulator gate. This produces the build up of trapped positive charges (mainly holes) in the insulator, and trapped negative charges concentrated at the insulator-channel interface. Besides the electron-hole pairs that recombines following the on set of an ionizing radiation pulse, 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 gate insulator near the silicon channel interface for positive gate voltages, or near the

SiO_2 gate metal interface for negative gate voltages. These trapped positive charges are the cause for the negative shift in the $I_{ds} – V_{ds}$ characteristics curve[(6)].

3. Experimental

We use the in-situ method. The in-situ measurement of the MOSFET devices characteristics is effective in obtaining accurate data on the neutron damage. Figure 3 shows a schematic drawing of the experimental arrangement used for the in-situ measurement of the degradation of the threshold voltage of MOSFET samples.

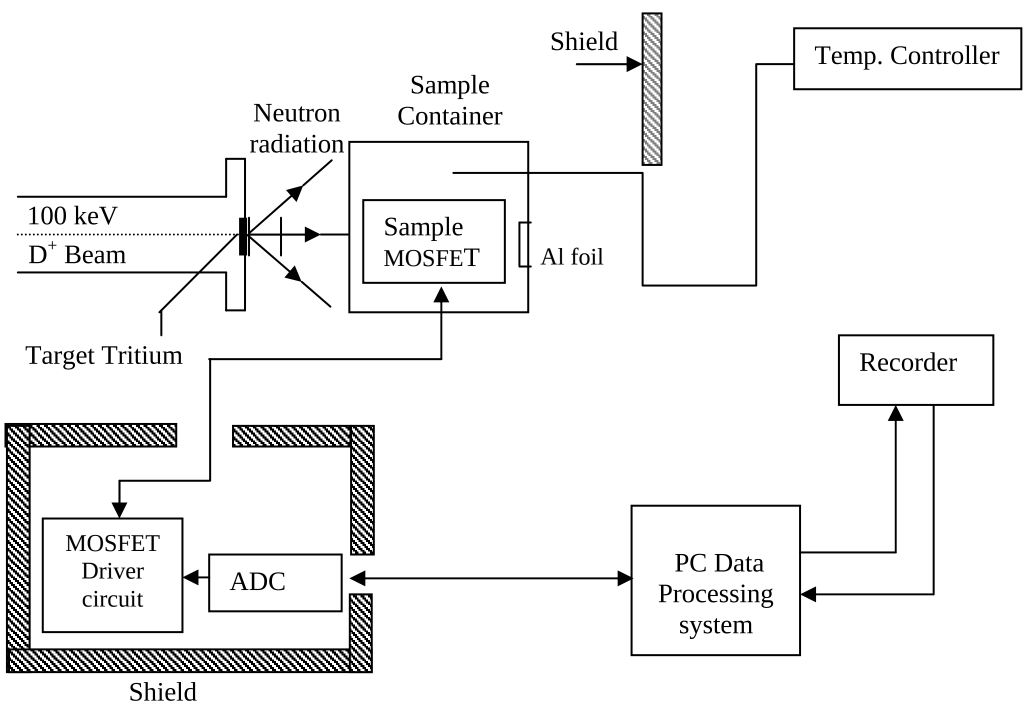

Fig.3. Schematic drawing of experimental arrangement

As shown in fig. 3, 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. Figure 4 shows the schematic diagram of the MOSFET driver circuit.

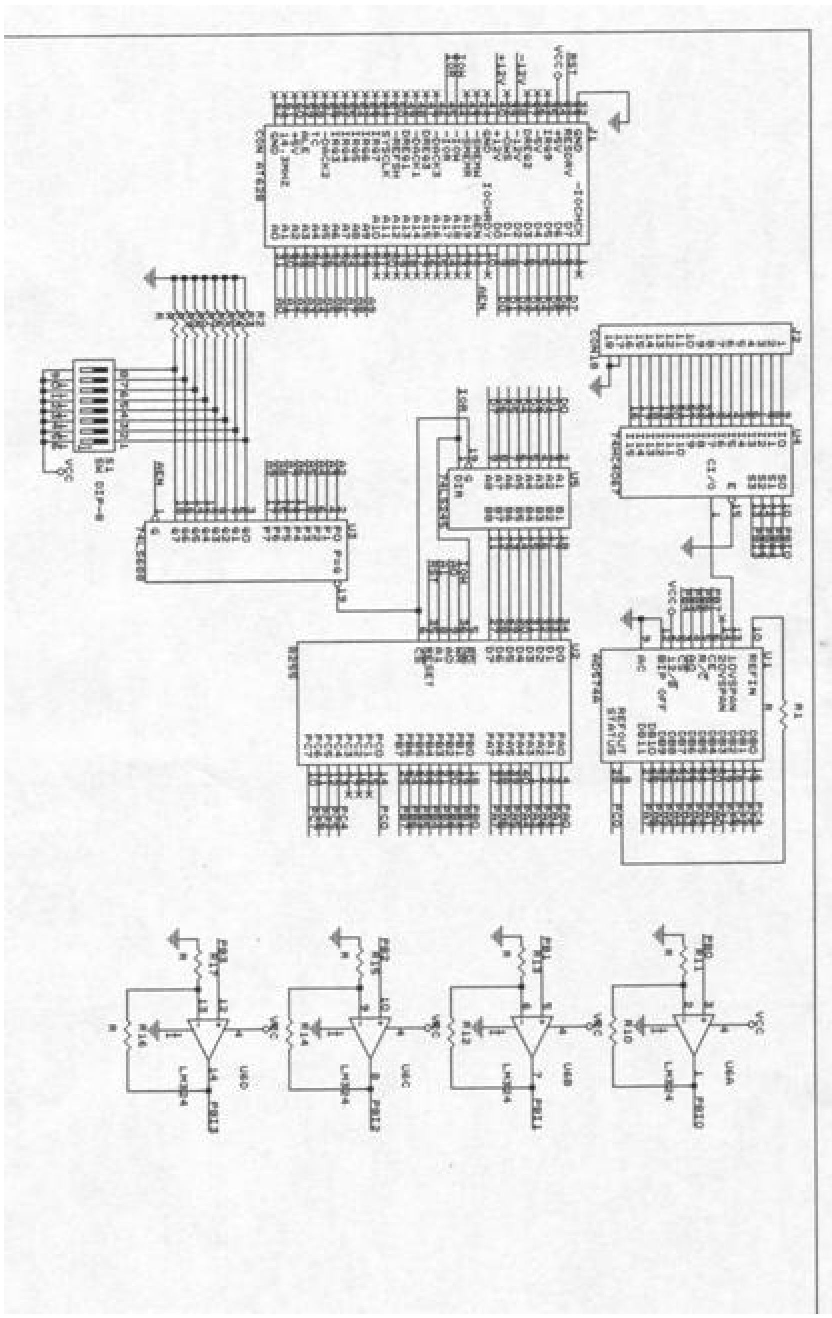

Fig.4 Schematic diagram of the MOSFET drive circuit

This circuit worked as a data dispatcher to control MOSFET samples and to receive commands from the computer system in the control room. The MOSFET driver circuit and the computer was connected with 12 m long cables. Before beginning the neutron irradiation experiment, these cables never led to any serious distortion of the shape of signals or the degradation of reliability in data communication. The MOSFET driver circuit was operated by turbo basic program.

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.

4. Calculation

As described previously, neutrons cause displacement defects in a MOSFET (Silicon Crystal) and they act as recombination centers and traps which shorten the carrier lifetime. Thus, in order to quantitatively discuss neutron damage in MOSFET, we calculate the rate of neutron displacement damage for Si. Details of a method for calculating the neutron displacement damage have been comprehensively explained(7). Neutron reactions important for causing the displacement damage were all treated as two collisions as follows.

$$A\ (n) + B\ (Si) \rightarrow C\ (PKA) + D$$

The displacement damage was caused predominantly by recoil atoms. The amount of the displacement damage by particles other than recoil atoms was much smaller and was disregarded here. The primary knock on atom (PKA) energy $E_p\ (E, E'_r, \phi)$ in the laboratory system is found from conservation of momentum and energy to be.

$$E_p\ (E, E'_r, \phi) = \mu_3 E'_r + \mu_1 \mu_4 E - 2\ (E E'_r \mu_1 \mu_3 \mu_4)^{1/4}\ \mathrm{Cos}\ \phi \qquad (1)$$

Where

E = Neutron energy

$E'_r = E\ \mu_2/(\mu_1 + \mu_2) - Q_j$

ϕ = Scattering angle in center of mass system

$$\mu_i = \frac{M_1}{(M_1 + M_2)} \qquad i = 1, 2, 3, 4$$

M_1,M_2,M_3,M_4= Atomic weight of particles A, B, C

Q_j = nuclear energy level

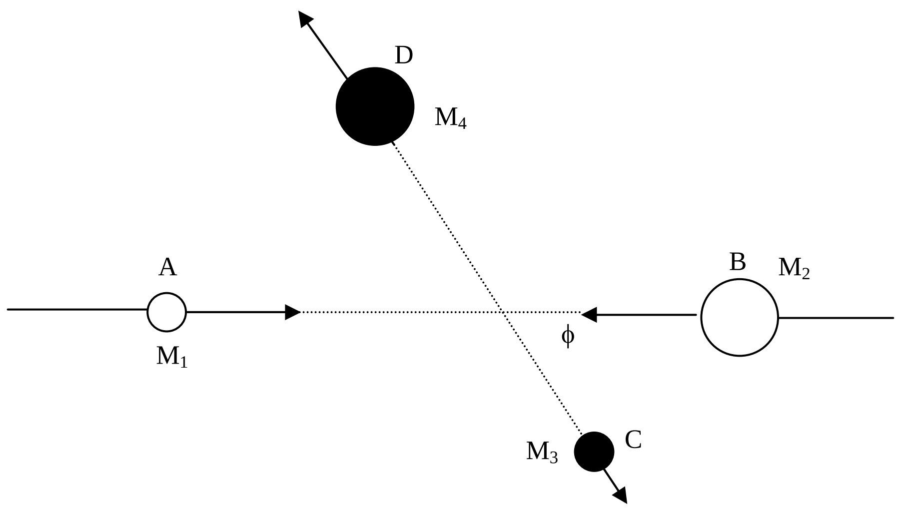

Fig. 5. Nuclear reaction in center of mass system

The amount of the neutron displacement damage C_d (displacement per atom dpa) can be calculated by

$$C_d = \sum_i \int_0^{\infty} \int_{Ed}^{EP\,max} \sigma_i(E)\, W_i(E, E_p) . \nu(E_p) \Phi(E) dE_p\, dE \qquad (2)$$

Where

$\sigma_i(E)$ = cross section for neutron reaction i

$W_i(E, E_p)$ = energy spectral function of PKAs produced by neutron reaction i

$\nu(E_p)$ = displacement damage function

Φ (E) = neutron fluence

E_d = displacement energy

Ep_{max} = maximum energy of PKAs

The displacement damage function determines the fraction of PKA energy going to displacement damage and is expressed in the following formula based on the Lindhard theory.

$$\nu\left(E_p\right)=\frac{E_p}{2E_d}\left[1+k.g\left(E_p/E_L\right)\right]^{-1} \qquad (3)$$

Where

k = 0,133745 $Z^{2/3}$ $A^{-½}$

g(ε) = 86.931 $Z^{7/2}$ (in eV)

Z = atomic number of Si

A = mass number of Si

A value of 25 eV was used for the displacement energy E_d, as for the neutron energy spectrum using the following equation.

$$N(E) = 0.373 \exp(-0.88E) \sinh(2.0\,E)^{½} \qquad (4)$$

5. Results and Discussion

Some examples of results of fusion neutron irradiation experiment on MOSFET devices are shown in figure 6(a) and (b) for output characteristic and forward transfer characteristics.

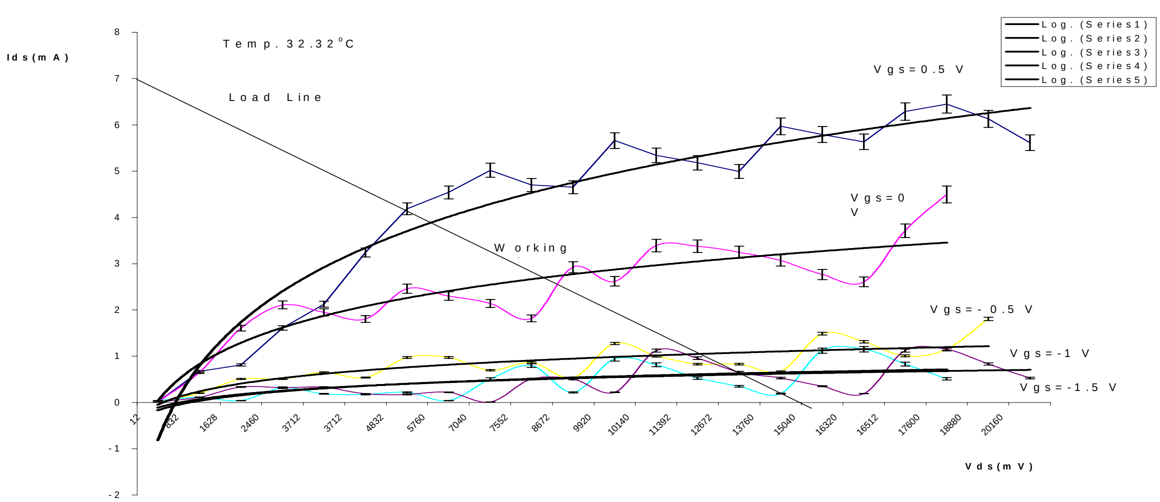

Fig. 6(a) Output characteristics of MOSFET

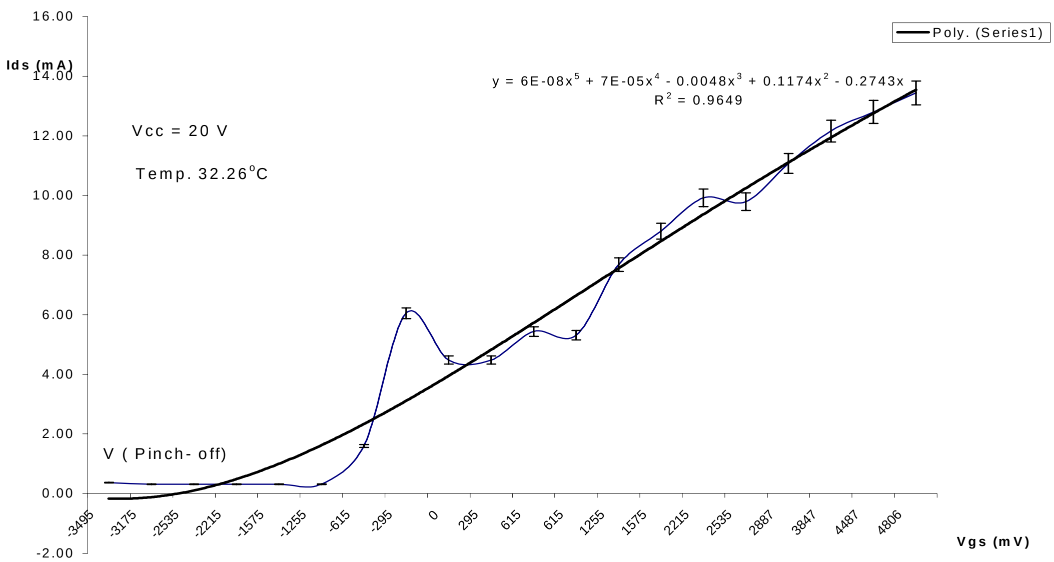

Fig. 6(b) Forward transfer characteristics of MOSFET

In the D-T neutron irradiation experiment, the output voltage and the output current of the MOSFET ($V_{ds} - I_{ds}$) of measuring electric circuit clearly changed, which depends on duration of irradiation and the angle between samples and target (T). The values in parentheses in table 1 are the average of data on the ten samples.

Table 1. Changes in Threshold Voltage Induced by Neutron Irradiation

Neutron fluence n/cm²		Threshold Voltage (mV)
	1.23×10^{10}	295
	1.85×10^{10}	615
	2.78×10^{10}	935
Average	1.95×10^{10}	621

Results of the neutron displacement damage calculation for silicon are summarized in table 2. The amount of displacement by each neutron reaction is given in dpa per unit fluence.

Table 2. Neutron Displacement Damage in Si (Ed = 25 eV)

Nuclear Reaction	Neutron Displacement Damage ($dpa/n/cm^2$)
(n, p) (n, α)	0.47×10^{-21} 0.45×10^{-21}
Average	0.46×10^{-21}

6. Conclusion

In order to experimentally clarify the mechanisms of fusion neutron induced soft-error on MOSFET, ten MOSFET devices were irradiated with D – T neutron. It was found that the interaction of neutron with silicon material in the MOSFET induced significant electrical changes. From the calculation, we can conclude that the change in MOSFET threshold voltage is 621 mV and neutron displacement damage (dpa) is 0.46×10^{-21}. These changes are called soft-error and all the MOSFET devices tested were found to be controllable after neutron irradiation and no permanent damage was caused by neutron fluence irradiation below about 10^{10} n/cm^2.

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