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# Effects of DD and DT neutron irradiation on some Si devices for fusion diagnostics

Yoshihiko Tanimura *, Toshiyuki Iida

*Department of Electronic, Information Systems and Energy Engineering, Graduate School of Engineering, Osaka University, 2-1 Yamadaoka, Suita, Osaka, 565, Japan*

**Abstract**

In order to examine the difference in the irradiation effects on Si devices between DT and DD neutrons, CCD image sensors, memory ICs and a Si detector were irradiated with neutrons from a deuteron accelerator. The transient effects (i.e. neutron-induced background noises) and permanent effects (i.e. neutron damage) on them were in situ measured during irradiation. Regarding the transient effects, brightening spot noises, soft-error upsets and induced-charge noises were measured for the CCDs, memory ICs and Si detector, respectively. As for the permanent effect, the number of damaged cells of the CCDs and the leakage current of the Si detector increased with neutron fluence. Also we developed a Monte-Carlo code with the TRIM code to evaluate the correlation of DT and DD neutron effects on Si devices. The calculated correlation factor of DT and DD neutron damage for Si devices agreed approximately with the correlation factor obtained from the irradiation experiments on the CCDs and Si detector. © 1998 Elsevier Science B.V. All rights reserved.

## 1. Introduction

In fusion technology, research and development of materials and components for a fusion reactor is one of the most important subjects. Irradiation experiments with intense neutron sources have been conducted for neutron damage studies on a variety of materials and components necessary for a fusion reactor. Especially data on DT and DD neutron irradiation effects are directly useful for the development and selection of materials and components for a fusion reactor.

There have been many papers discussing quantitatively neutron damage on Si semiconductor devices [1–5]. However, results from these discussions seem to have considerable uncertainty because of insufficient knowledge of the energy spectrum of the neutron irradiation field. The purpose of this paper is to show experimental data on DT and DD neutron effects in some Si diagnostic devices and to discuss the correlation of DT and DD neutron effects on them. These data and discussions are useful for the design of fusion diagnostic instruments that may be exposed to fusion neutrons.

The uniqueness of the present experiments lies in the following two points. One is that the amount of transient effects like the production of neutron-induced background noises and permanent effects i.e. damage on the Si devices was in situ measured during neutron irradiation. The in situ measurement is effective in obtaining accurate values of the production rate of the noises and damage for the samples. The other point is that the same samples were irradiated with DT and DD neutrons whose energy spectra were accurately known. This makes it possible to quantitatively discuss the correlation of DT and DD neutron effects.

## 2. Experimental procedures

Fig. 1 shows a schematic drawing of the experimental arrangement and the electronic circuits for the in situ measurements. A special sample holder with a Peltier-effect device to control the sample temperature was made and set near the tritium or deuterium target of the 300 kV deuteron accelerator OKTAVIAN [6]. The neutron flux was obtained from the measurement of the

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[*] Corresponding author. E-mail: tanimura@fnshp.tokai.jaeri.go.jp.

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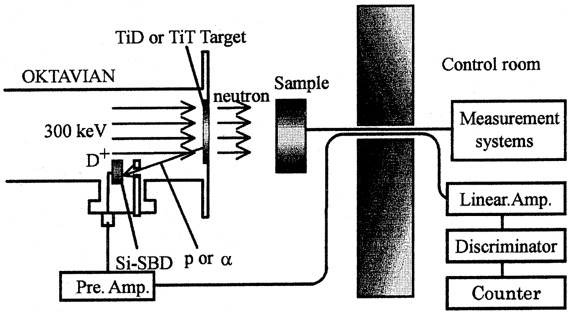

Fig. 1. Schematic drawing of experimental arrangement.

correlated particles, i.e. alpha particles for DT neutrons and protons for DD neutrons. The DT neutron flux at the position of the samples was varied from 1 to $100 \times 10^6$ n/cm$^2$ s. The neutron energy was determined from the kinetics. And in order to examine the neutron energy dependency, some samples were set at different angles for the incident deuteron beam direction. The neutron energy was varied from 13.5 to 15 MeV and from 2.0 to 3.5 MeV for DT and DD neutrons, respectively.

Interline type Charge Coupled Device (CCD) image sensors, four types of Complementary Metal Oxide Semiconductor Static Random Access Memory (CMOS SRAM) ICs and a Si Surface Barrier Detector (Si-SBD) were prepared for the neutron irradiation experiments. They are all commercially available. Video signals from the CCDs on the holder in a dark box were recorded with a video recorder during neutron irradiation. The recorded video signals were analysed with an image processing system after irradiation. Information on cell status of memory IC samples in the irradiation room was periodically transmitted through optical fibres to a data processing system in the control room. The data processing system with a computer was programmed to measure the rate and pattern of the soft-error upsets (i.e. the change of the status of memory cells) during irradiation. The erring memory cells were found out by comparing data during irradiation with data initialised before irradiation. As for the Si-SBD, the leakage current and spectra of electric charge induced by neutron reactions were measured together with neutron fluence. The Si-SBD was made of an about 3 kΩ cm n-type Si and had the effective window area of about 35 mm$^2$ and the depletion layer depth of about 150 μm.

## 3. Calculation

In order to quantitatively discuss the difference in the irradiation effects on Si devices between DT and DD neutrons, we developed a computer program based on Monte-Carlo method and tried to calculate the amount of neutron effects for Si. The program calculates the transportation of charged particles produced by neutron reactions in the devices. As for the soft-error upsets of memory ICs, for example, the upset is considered to be caused when high LET particles traverse a sensitive region in the memory cell and the induced electric charge is effectively collected to change the potential condition of the cell [7,8]. Thus, the trajectories of the neutron-induced charged particles in the sensitive region [9] that was considered to be the depletion layer under the drain of the MOS transistor were calculated by the Monte-Carlo method for the evaluation of the soft-error upset rate. Nuclear data from ENDF/B-VI [10] were used for the calculation. The number of neutron reactions generated in Si sphere with a radius of 1 mm including the sensitive region was more than one billion. The energy spectral function of the charged particles was given on the assumption that the neutron reactions were all isotropic. Moreover, the amount of electric charge induced in the sensitive region was calculated by using the Monte-Carlo code for ion transport, TRIM-90 [11] only when the charged particle traversed the sensitive region. The flow-chart of the program is shown in Fig. 2.

For the discussion of the permanent effects, we also calculated the amount of displacement damage for the CCDs and Si-SBD by similar Monte-Carlo codes described in the above. The displacement damage is caused

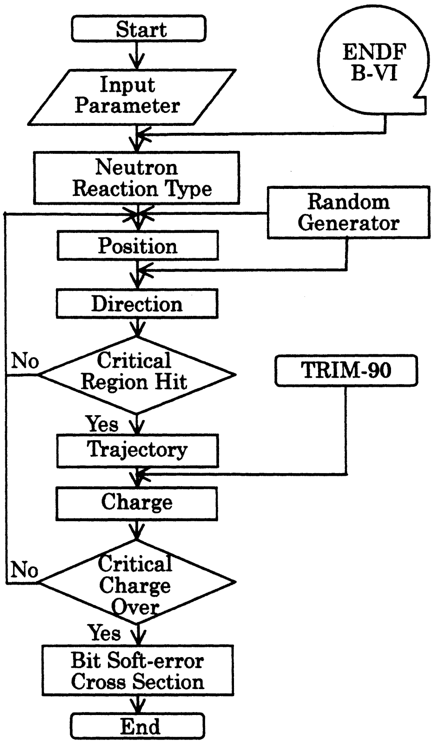

Fig. 2. Flow-chart of soft-error calculation program.

mainly by recoil atoms. The energy spectra of recoil atoms were given by the kinematics calculation with the nuclear data under the isotropic treatment. And the amount of the displacement damage for the Si devices was calculated using the TRIM code.

## 4. Results and discussions

In the irradiation experiment on CCDs, brightening spot noises were observed during neutron irradiation. An example of the transient noises is shown in Fig. 3. These transient noises were induced by neutron reactions in the CCDs themselves. Naturally the production rate of the transient noises was proportional to the neutron flux and the rate for DT neutrons was one or two orders larger than for DD neutrons. Moreover, the size of the brightening spot noises for DT neutrons was much larger than for DD neutrons. These are because DT neutrons release a larger amount of higher energy charged particles of protons, alpha particles and others from materials of the CCDs than DD neutrons, and these particles induce large transient noises inside the CCDs. Also the CCDs had many unrecoverable specks, i.e. damaged cells after irradiation as shown in Fig. 4. Fig. 5 shows an example of the relation between the number of the damaged cells and the neutron fluence. The neutron damage constant for the CCDs are given by the slope of the lines in Fig. 5, and it can be seen that in contrast to the transient noises, the permanent damage from DT neutrons is only slightly higher than from DD neutrons. The correlation factor for DT and DD neutron damage for the CCDs is given by the ratio of the DT and DD neutron damage constants and was found to be about 1.2. Results of the experiments and calculations on the CCDs are summarised in Table 1.

In the experiments on the CMOS SRAM ICs, the number of the soft-errors increased proportionally with neutron fluence and the soft-error upset rate was given as the number of soft-error per unit neutron fluence. An example of results of the DT and DD neutron irradiation experiments is shown in Fig. 6. The bit soft-error cross section is obtained by dividing the neutron induced soft-error rate by the number of memory cells in the IC and this means the probability that one incident neutron per square centimetre will cause the soft-error in one memory cell. It is clear from the figure that the soft-error upset rate for DT neutron is about two orders larger than that for DD neutrons. Experimental data on many other samples and discussions on their bit soft-error cross sections are described in our other papers [7,8]. All memory cells were controllable after irradiation and no permanent damage was caused by neutron fluence irradiation below about $10^{12}$ n/cm$^2$.

In the Si-SBD, electric charge (i.e. electrons and holes) liberated by the ionization process of incident high-energy particles is collected at the boundary electrodes under an applied electric field. The amplitude of output signals from the Si-SBD is proportional to the energy of incident high-energy particles. Fig. 7 shows the spectra of electric charge produced by high energy particles due to neutron reactions in the Si-SBD sample.

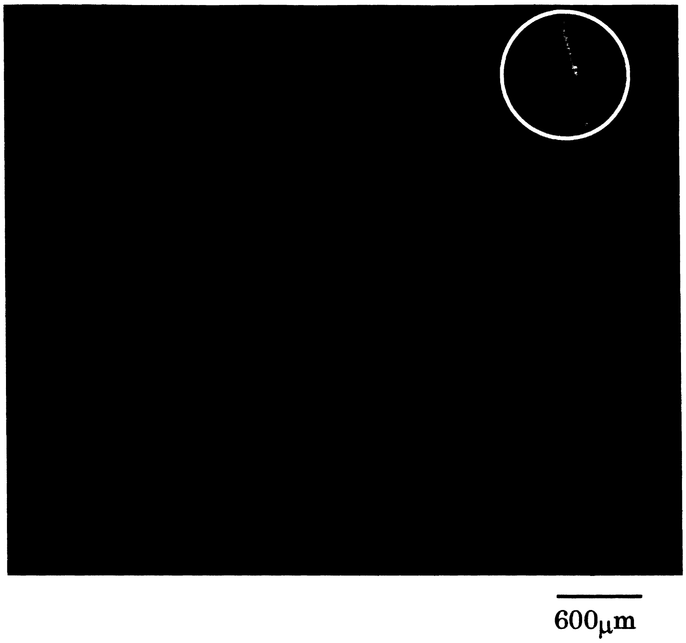

Fig. 3. Transient noises of CCD image sensor (DT neutron flux: 1.0 × $10^4$n/cm$^2$ s, CCD sample: IC × 054).

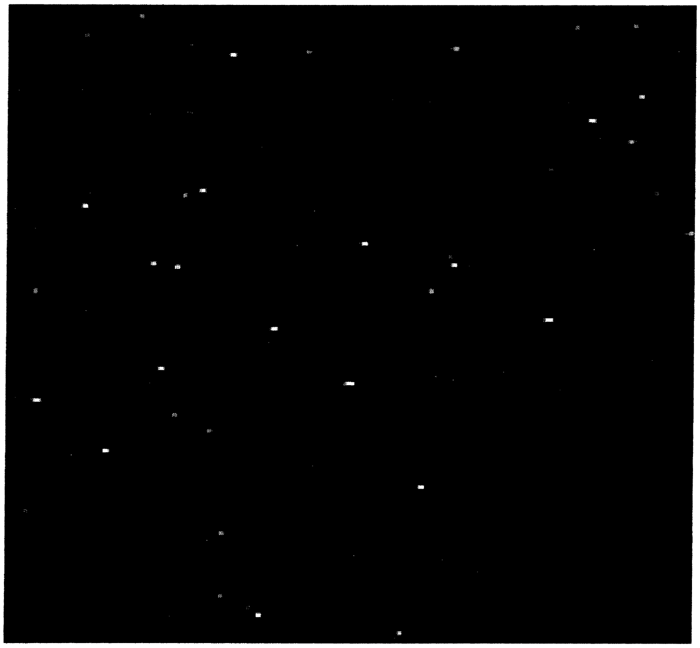

Fig. 4. Unrecoverable specks of CCD image sensor (DT neutron fluence: 8 × $10^7$ n/cm$^2$, CCD sample: IC × 054).

The energy calibration was made with a standard $^{241}$Am alpha source ($E_\alpha = 5.49$ MeV). It is clear from the figure that DT neutrons induce much larger background noises than DD neutrons for the detector. These backgrounds are formed from (n, p), (n, α) and other reactions in the detector. The large difference in the noises between DT and DD neutrons was consistent with results from calculations with the above code. Also the leakage current of the Si-SBD increased proportionally with neutron fluence like the case of the CCDs. The neutron damage constant for leakage current of the Si-SBD was found to be 4.1 × $10^{-9}$ nA/n/cm$^2$ for DT neutrons and 1.8 × $10^{-9}$ nA/n/cm$^2$ for DD neutrons. And the correlation factor of the DT and DD neutron damage for the Si-SBD was determined from the ratio of each damage constant and was found to be 2.3. This result agreed with the result of the correlation factor of the displacement damage on Si obtained by the use of the above calculation code.

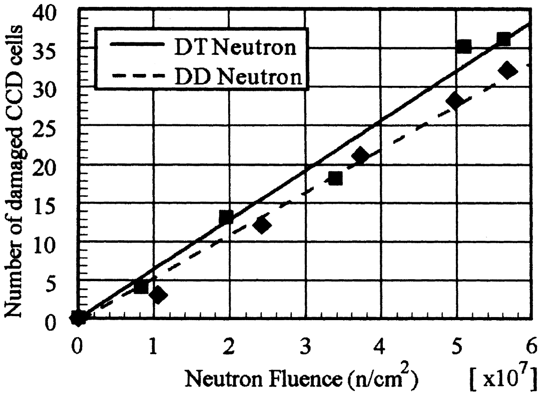

Fig. 5. Relation between the number of damaged CCD cells and fusion neutron fluence (CCD sample: IC × 054).

## 5. Conclusion

The transient and permanent effects on the CCD image sensors, Si-SBD and CMOS SRAM ICs were in situ measured during DT and DD neutron irradiations. Regarding the transient effects, brightening spot noises, soft-error upsets and induced charge noises were measured for CCDs, memory ICs and Si-SBD, respectively. The production rate of these effects for DT neutrons was one or two orders larger than that for DD neutrons. Moreover, the amplitude of the transient noises caused by DT neutrons was much larger than that by DD neutrons. These are because DT neutrons release a larger amount of higher energy charged particles than DD neutrons and these particles induce large background noises inside the Si devices. As for the permanent effects, the leakage current of the Si-SBD and the number of the damaged cells of the CCDs increased with neutron fluence. The correlation factor of the DT and DD neutron damage on the Si-SBD and CCDs was obtained from the ratio of the DT and DD neutron damage constants and was found to be 1–2. We also

Table 1
Neutron damage constants and correlation factor of DT and DD neutron damage on CCDs (CCD sample: IC × 054)

| | Damage constant (cm$^2$/n) | | Correlation factor |
|---|---|---|---|
| | DT neutron | DD neutron | |
| Experiment | $6.5 \times 10^{-7}$ | $5.6 \times 10^{-7}$ | 1.1 |
| Calculation | $1.1 \times 10^{-6}$ | $8.9 \times 10^{-7}$ | 1.2 |

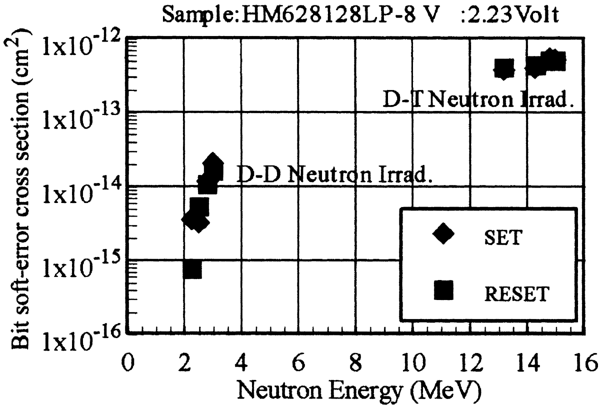

Fig. 6. Bit soft-error cross section for 1 Mbit CMOS SRAM.

calculated the rate of DT and DD neutron displacement damage for Si devices. The correlation factor of DT and DD neutron damage from the calculation approximately agreed with that obtained from the irradiation experiments on the Si-SBD and CCDs. The data in the present experiments and the discussion on the correlation of the DT and DD neutron effects are useful for the estimation of lifetimes and background noise-levels of fusion diagnostic systems with Si devices.

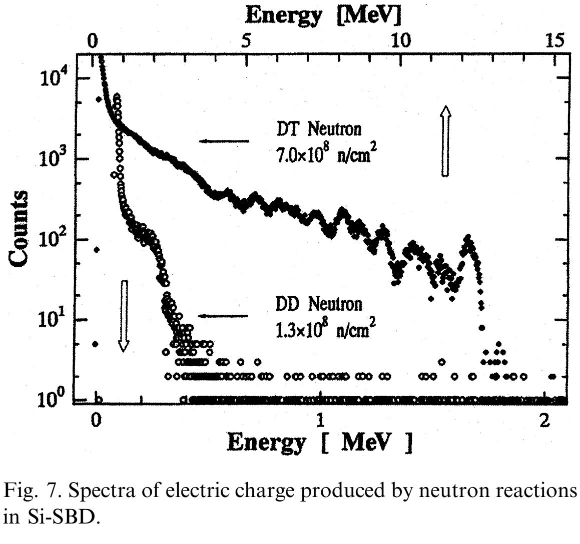

Fig. 7. Spectra of electric charge produced by neutron reactions in Si-SBD.

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