

# Investigation of Single Event Upset and Total Ionizing Dose in FeRAM for Medical Electronic Tag

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**Abstract** — We investigate the single event upset (SEU) and total ionizing dose (TID) tolerance of FeRAMs fabricated in 180-nm technology against neutron and gamma-ray radiation. Our irradiation tests reveal that the FeRAM has an SEU rate of less than  $8.5 \times 10^{-3}$  FIT/Gbit for terrestrial neutrons and a tolerance up to the dose of 100-kGy for gamma-ray radiation. These results indicate that the FeRAM is suitable for the medical electronic tags which require sterilization with 25-kGy ionization radiation.

**Keywords-component; Single event upset, Total ionizing dose, FeRAM, Medical, Electronic tag, Gamma-ray, Sterilization.**

## I. INTRODUCTION

Semiconductor memories equipped in medical electronic tags (METs) are required to be robust against single event upsets (SEUs) since METs are often associated with human life. Ionization radiation is often used for sterilization of medical equipment because it is less harmful than the antiseptic solutions which may contain carcinogens, however, this radiation can cause total ionizing dose (TID) damage in those memories. Thus, they need to have TID tolerance of at least 25-kGy for gamma-ray irradiation according to ISO11137 and ISO/TR13409 [1], [2]. However, nonvolatile memories, such as EEPROM and FLASH memory, are known to be vulnerable to ionization radiation [3]. TID tolerance of ferroelectric random access memory (FeRAM) for gamma-ray was also reported to be less than 25-kGy [4]–[7]. These reports were published before 2008 and the FeRAMs under test were manufactured in 350-nm or older technologies. Since TID tolerance generally improves with technology scaling due to thinner gate oxides [8], it is worth re-evaluating the TID tolerance of FeRAMs.

In this work, we investigated the TID tolerance of FeRAMs, fabricated in 180-nm technology, undergoing gamma-ray irradiation test. In addition, we evaluated the SEU tolerance through neutron irradiation test. From these tests, it is concluded that 180-nm FeRAMs are good candidates for METs.

## II. FERAM

A FeRAM uses a ferroelectric film for its memory capacitor. Figure 1 shows the hysteresis loop, which shows the relationship between the polarization charge (Q) and the voltage (Vf) applied to the ferroelectric capacitor. Points A and D correspond to the opposite polarization directions, where the

ferroelectric capacitor has remnant polarization  $+Pr$  and  $-Pr$ , respectively. U-term and P-term represent the quantities of output charge obtained for un-reversal and reversal polarization, respectively [9].

In the two-transistor and two-capacitor (2T2C) type FeRAM [9] in Figure 2, “0” and “1” data are written in the paired cell capacitors of F1 and F2, which are polarized in the opposite directions. For example, “0” is written by polarizing F1 to the upper state (point D in figure 1) and F2 to the lower state (point A), and “1” is written vice versa. “0” and “1” data can be read out by sensing the polarization direction of F1 and F2 capacitors. In the actual read operation, when voltage  $V_{cc}$  is given to the plate line (PL), output charges corresponding U-term and P-term flow into the bit lines of BL and BLX, respectively. The data “0” or “1” is determined by the sense amplifier according to the voltage difference between the bit lines BL and BLX.

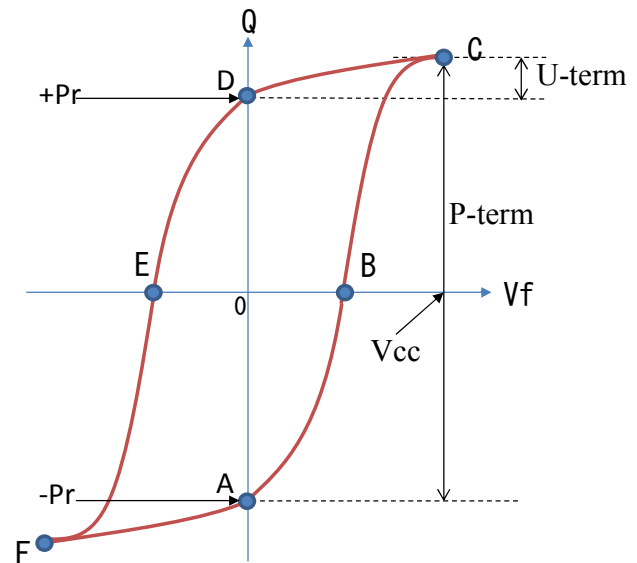


Figure 1. A hysteresis curve of ferroelectric capacitor, which shows the relationship between the polarization charge (Q) and the voltage (Vf) applied to the ferroelectric capacitor.  $+Pr$  and  $-Pr$  are the remnant polarization of positive and negative polarization states, respectively. U-term and P-term represent the quantities of output charge from the capacitors that stored “0” and “1” data, respectively.

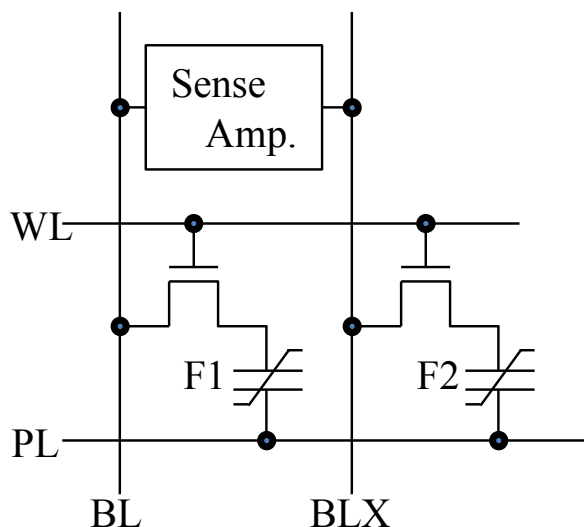


Figure 2. Schematic drawing of a 2T2C-type FeRAM cell consisting of two ferroelectric capacitors (F1 and F2), two transistors, a word line (WL), bit lines (BL and BLX), a plate line (PL), and a sense amplifier (Sense Amp.).

### III. TEST DEVICES

Ionization-radiation damages caused both in transistors and in ferroelectric capacitors can lead to bit fails of FeRAM. To evaluate the damage, we prepared two types of device for irradiation tests, which are denoted by MEMORY-DUT and MONITOR-DUT. MEMORY-DUT consists of 128-kbit 2T2C-type FeRAM array for counting bit fails. MONITOR-DUT, which includes ten monitors consisting of twelve ferroelectric capacitors, is used for separately investigating the damage caused in the ferroelectric capacitors. These devices are manufactured in 180-nm technology and assembled in plastic packages.

### IV. NEUTRON IRRADIATION TEST

To evaluate SEU rate for terrestrial neutrons, we irradiated 100 dies of MEMORY-DUT and one die of MONITOR-DUT with spallation neutron beam, which has broad energy spectrum up to 400 MeV, at Research Center for Nuclear Physics (RCNP) of Osaka University. After writing “0” and “1” stripe pattern data in the dies of MEMORY-DUT and polarizing capacitors in the MONITOR-DUT, those devices were irradiated at room temperature with neutron whose fluence was  $1.34 \times 10^{11} / \text{cm}^2$ , and then the memory data were read out and the polarization of capacitors was measured. Note that those devices were kept unbiased ( $V_{cc}=0$ ) during the exposure to the neutron beam.

Table I lists the result of this neutron irradiation test. We observed no errors in the MEMORY-DUT, which corresponds to an SEU rate of less than  $8.5 \times 10^{-3}$  FIT/Gbit at 90% statistical confidential level. The rate of SEUs from terrestrial neutrons in the storage cell is negligible. Note that the peripheral logic was not active during the test and the effect is not clear under the test. However, the effect in the peripheral logic is not critical issues for METs because the active time of peripheral logic, i.e. read and write time, is generally very short compared with the storage retention time in METs.

Table I. Result of neutron irradiation test.

|                            |  |
|----------------------------|--|
| Irradiated neutron fluence | $1.34 \times 10^{11} \text{ neutron/cm}^2$ |
| Error count                | 0  |
| SEU rate*                  | $8.5 \times 10^{-3} \text{ FIT/Gbit}$      |

\*The SEU rate is calculated for  $13 / \text{cm}^2/\text{h}$  (at sea level in New York [11]) at a 90% confidential level.

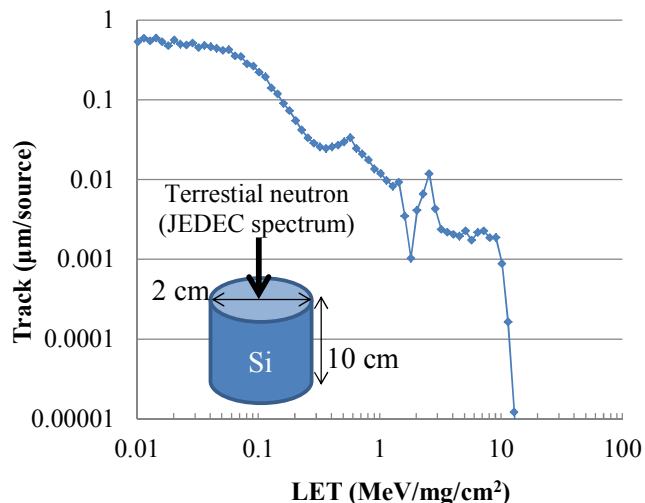


Figure 3. Average track length of an ion generated by neutron-induced nuclear reaction with silicon. This was calculated with particle and heavy ion transport code system (PHITS) [10].

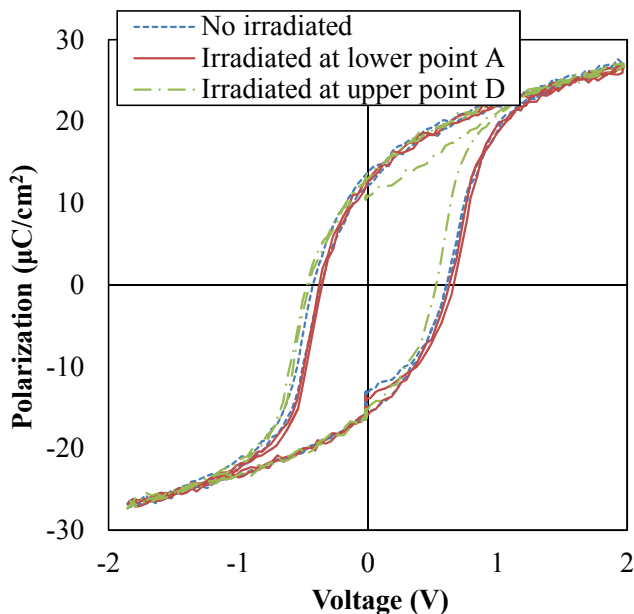


Figure 4. Polarization-voltage hysteresis curves before and after neutron irradiation.

This result of SEU rate is consistent with reference [5], where it reported that no SEU was observed for the irradiation of heavy ion whose linear energy transfer (LET) was below  $32 \text{ MeV/mg/cm}^2$ . Nuclear reaction with silicon caused by the terrestrial neutron generates few heavy ions whose LET is above  $32 \text{ MeV/mg/cm}^2$  as shown in Figure 3. Figure 3 shows the average track length of an ion generated by neutron-

induced nuclear reaction with silicon. This was calculated with particle and heavy ion transport code system (PHITS) [10]. The number of incident neutrons to the center of a silicon (Si) block is 1,079,000,000. The energy spectrum of terrestrial neutron in JEDEC [11] was assumed. The Si block is cylinder shape of 2 cm diameter and 10 cm height.

Figure 4 shows the hysteresis curves measured in the MONITOR-DUT before and after the neutron irradiation. We can see the hysteresis curve was almost unchanged.

### V. GAMMA-RAY DOSE TEST

We also examined the TID tolerance of the FeRAM for gamma ray radiation. After writing data into the FeRAMs of MEMORY-DUT and polarizing capacitors on the dies of MONITOR-DUT, these devices were irradiated using cobalt-60 (1.17 and 1.33 MeV gamma-ray) at Japan Irradiation Service Company (JISCO). The dose was 20, 50 and 100-kGy. All devices were irradiated at room temperature without bias ( $V_{cc}=0$ ). Note that no annealing was performed after the irradiation.

Table II lists the irradiation results of MEMORY-DUT. We observed no errors in MEMORY-DUTs (640-kbit), which indicates that the FeRAM has enough TID tolerance up to the dose of 100-kGy. This measured TID tolerance satisfies the requirement for the MET sterilization.

Table II. Results of gamma-ray irradiation to five MEMORY-DUTs (640 kbit).

| Dose | 0-kGy | 20-kGy | 50-kGy | 100-kGy |
|------|-------|--------|--------|---------|
| Fail | 0     | 0      | 0      | 0       |

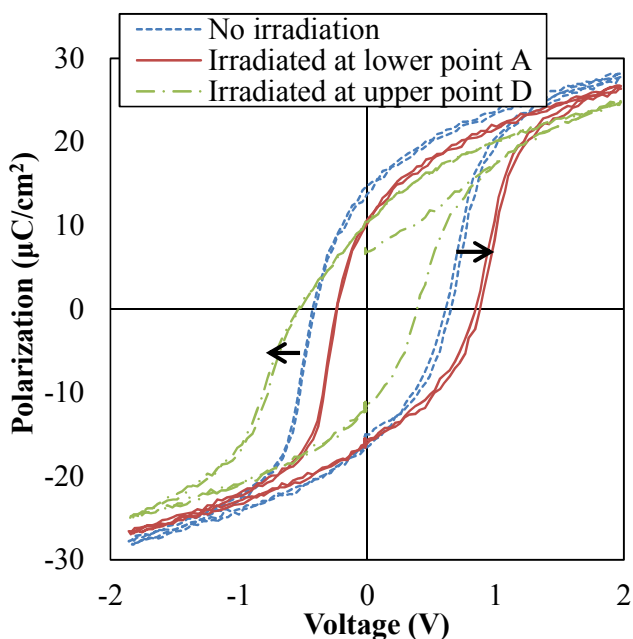
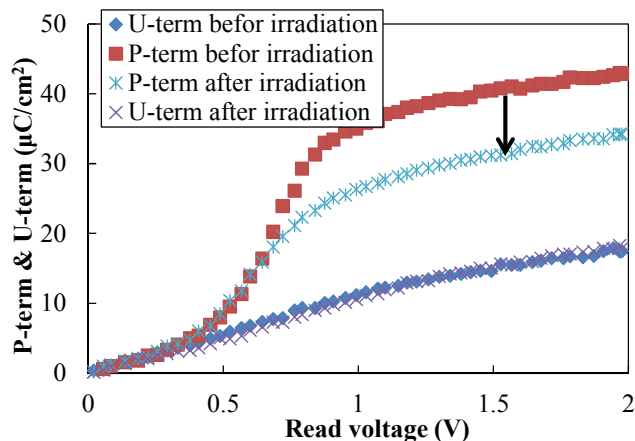
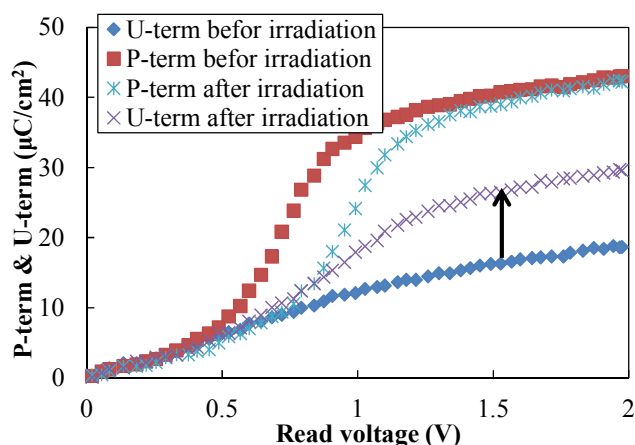


Figure 5. Hysteresis curves before and after 50-kGy gamma-ray irradiation.



(a) Irradiated at upper point A.



(b) Irradiation at lower point D.

Figure 6. P-term and U-term before and after 50-kGy gamma-ray irradiation.

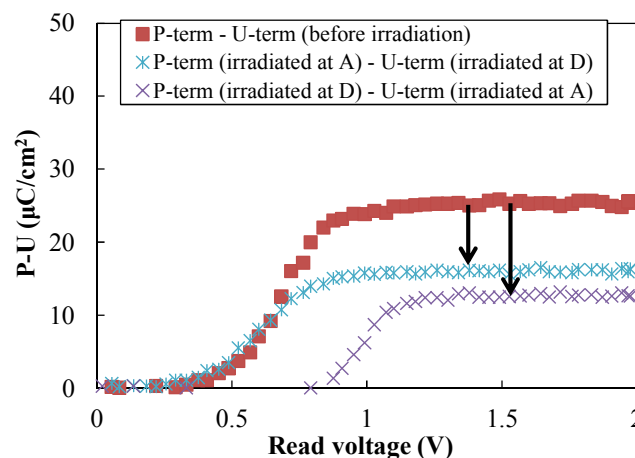


Figure 7. P-U before and after 50-kGy gamma-ray irradiation.

Figure 5 shows the hysteresis curves of MONITOR-DUT measured before and after gamma-ray irradiation. The hysteresis curves shifted to the positive or negative side depending on the initially polarized states, as shown in Figure 5. These shifts are typically due to imprint of the ferroelectric capacitor [12].

Figure 6 shows the read voltage dependences of P-term and U-term before and after irradiation. It was observed that P-term decreased and U-term increased by gamma-ray irradiation. Figure 7 shows read voltage dependences of the differences between P-term and U-term, which is denoted by P-U. This P-U value is important since it represents the readout sensing margin as explained in the Section II. The 50-kGy irradiation reduced the P-U by half. On the other hand, the 50-kGy and 100-kGr irradiation results for the MEMORY-DUTs indicate that the 50% P-U reduction did not degrade the readout reliability of FeRAM as shown in Table II.

Figure 8 shows fatigue characteristic, which is also called switching endurance, measured in the MONITOR-DUT before and after 50-kGy irradiation. The fatigue stress was given by successive pulses with a voltage of 5V and a pulse-width of 50 ns. The numbers of switching cycles (pulses) at which the polarization begins to decrease are not so different between before and after irradiation. This means that the irradiation does not largely affect the switching endurance. Although the 50-kGy irradiation degraded the initial P-U, the degradation was recovered in the first 10,000 cycles. This phenomenon is explained as follows. First, gamma-ray irradiation accumulated charge near the electrodes-ferroelectric interface, i. e. TID. On the other hand, the repetition of polarization switching released accumulated charge, and then the degradation recovered. This effect is similar to “wake-up effect” of ferroelectrics [13], [14].

Figure 9 shows the measured leakage current of MONITOR-DUT on the six dies before and after 50-kGy irradiation. The variation in the leakage current due to the irradiation was smaller than the initial variation due to manufacturing variation. The gamma-ray irradiation effect on leakage current is not visible for the usage of METs.

### VI. CONCLUSIONS

We investigated the SEU rate and the TID tolerance of FeRAMs fabricated in 180-nm technology, undergoing neutron and gamma-ray irradiation tests. Our investigation reveals that the SEU rate of FeRAM for terrestrial neutrons is less than  $8.5 \times 10^{-3}$  FIT/Gbit, when tested under static conditions, and have TID tolerance up to a 100-kGy gamma-ray. We also found that the gamma-ray irradiation did not affect the switching endurance nor leakage current. Therefore, the 180-nm FeRAM satisfies the gamma-ray sterilization requirement of a TID of 25-kGy.

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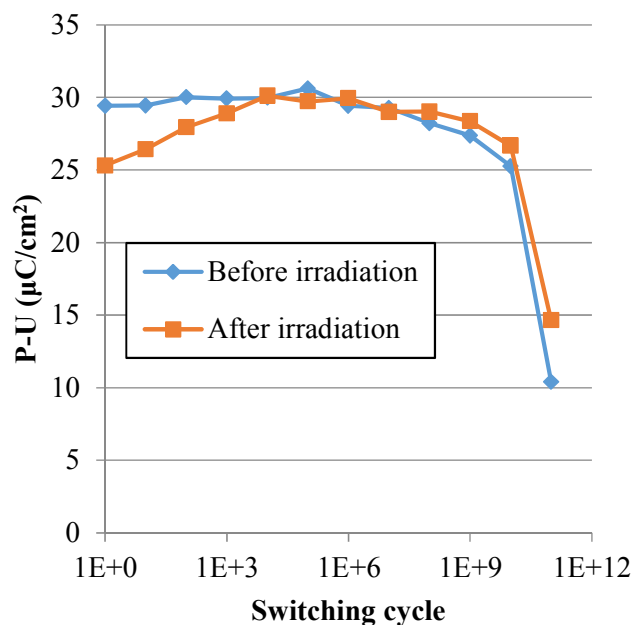


Figure 8. Fatigue characteristic before and after 50-kGy gamma-ray irradiation. This polarization switching experiment was performed with successive pulses whose magnitude was 5V and pulse width was 50 ns.

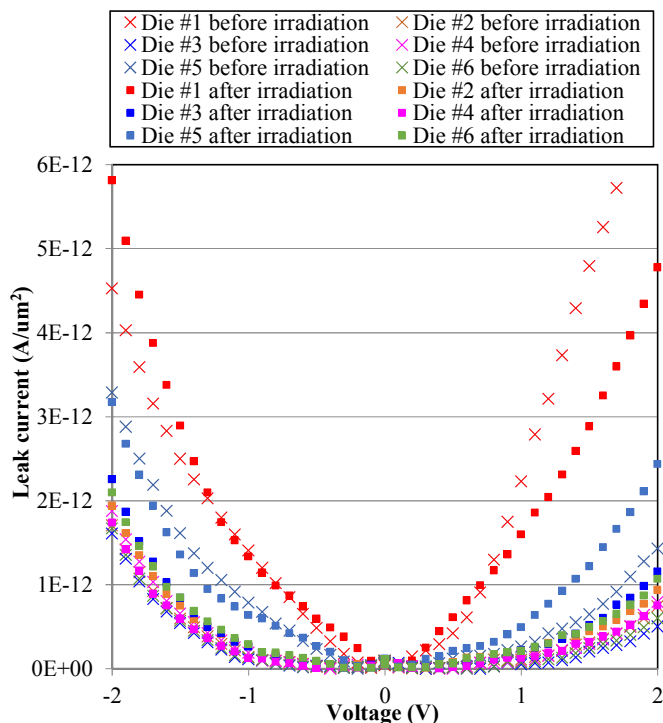


Figure 9. Leakage current of the ferroelectric capacitors on the six dies of MONITOR-DUT (#1 to #6) before and after 50-kGy gamma-ray irradiation. The cross and square marks show the leakage current before and after the irradiation, respectively. Each color corresponds to each die.

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