Comparative Analysis of TID Effects in a 65 nm FD-SOI Process under Gamma-Ray and Alpha-Ray Irradiation

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***Abstract*—Two types of ring oscillators (ROs) fabricated using a 65 nm FD-SOI process were used to compare total ionizing dose (TID) characteristics under gamma-ray and alpha-ray irradiation. By employing two ROs with nearly identical circuit structures, the electric field dependence of the TID effect was evaluated. Gamma-ray irradiation resulted in significant degradation differences between the ROs, indicating strong electric field dependence, whereas alpha-ray irradiation showed negligible differences, suggesting weak dependence. These variations are attributed to differences in initial recombination rates due to the higher linear energy transfer (LET) of alpha particles than gamma-rays. Additionally, the recovery rate under alpha-ray irradiation was lower than that under gamma-ray irradiation. These findings suggest that when using alpha-ray irradiation as an alternative to gamma-ray irradiation, compensation is mandatory.**

***Index Terms*—Total Ionizing Dose Effect (TID), FDSOI (Fully-Depleted SOI), gamma-ray, alpha-ray, Ring Oscillator**

I. Introduction

The total ionizing dose (TID) effect is a major cause of semiconductor device degradation in outer space. When a radiation strikes the device, electron-hole pairs are generated in the oxide layer. Trapped holes increase leakage current and the threshold voltage ($V_{\rm th}$) decreases [1] as shown in Fig. 1. Especially in long-term space missions, TID tolerance is mandatory to ensure device reliability.

Gamma-rays are commonly used to evaluate TID tolerance. However, dedicated facilities are required, and real-time measurements are difficult because measurement equipment cannot be installed in irradiation rooms due to the risk of degradation. In contrast, alpha-ray irradiation with sealed sources (e.g., Am-241) enables TID evaluation without beam-time constraints or specialized facilities, using compact on-chip sources. However, alpha-rays are not frequently used, and their validity remains a concern. This feature is particularly useful for satellite development, where quick and non-destructive TID evaluation during system integration is required. While X-rays can also serve as an alternative to gamma-ray irradiation, alpha-ray sources provide distinct practical advantages. They enable on-site evaluation without bulky equipment and allow direct placement on the engineering tester. Moreover, their highly-localized irradiation is suited for assessing TID effects in specific circuit regions, making them particularly useful for late-stage qualification in integrated systems.

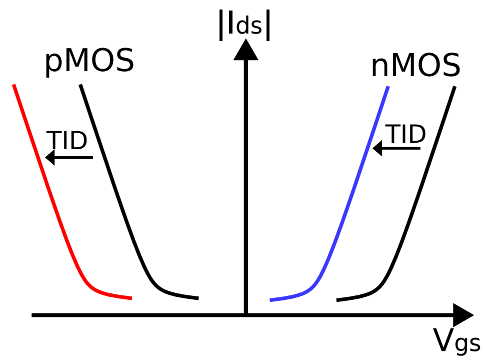

Fig. 1: Vth shift of nMOSFET and pMOSFET by TID.

Comparisons between gamma-ray and alpha-ray irradiation have been conducted using discrete components such as RADFETs [2]. We investigate the TID characteristics under gamma-ray and alpha-ray irradiation on a Fully Depleted Silicon On Insulator (FD-SOI) process, which features an SOI structure suitable to space environments. The FD-SOI structure shown in Fig. 2 is highly resistant to Single Event Effects (SEE) [3] and vulnerable to TID due to the buried oxide (BOX) layer [4]. This is because the accumulation of holes in the BOX layer causes transistor degradation. In general, TID is reduced by transistor scaling [1], but in the SOI structure, the TID effect still appears due to the BOX layer. [5] reported that the radiation properties of STI oxides are different from PMOS transistors and NMOS transistors. Therefore, to substitute gamma-ray irradiation with alpha-irradiation in SOI-based semiconductor chips, it is essential to conduct experimental evaluations using circuits fabricated in the SOI structure.

It is important to investigate The behavior of radiation-induced electron-hole pairs for TID evaluation. In particular, the initial recombination rate affects device characteristics. The initial recombination rate depends on the fraction of electron-hole pairs that recombine in the oxide layer before electrons

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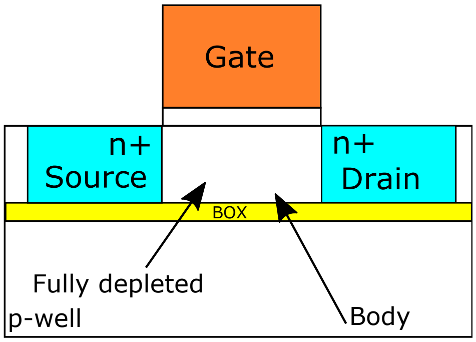


Fig. 2: Fully Depleted Silicon On Insulator (FD-SOI) transistor structure.

can leave the oxide or undergo diffusion. According to [6], the initial recombination rate strongly depends on the electric field. Under high electric field, electron-hole pairs separate quickly, which reduces the recombination rate. In contrast, under low electric field, they recombine more quickly, resulting in a different recombination rate. Moreover, [6] shows that the initial recombination rate strongly depends on Linear Energy Transfer (LET). It reports that alpha-ray, which have a higher LET, exhibit a higher initial recombination rate than gamma-ray. Therefore, we must accurately understand the differences in the initial recombination rate for various irradiation methods for TID evaluation.

In this study, we use the oscillation frequency of ring oscillators in the FD-SOI process as an indicator to evaluate TID characteristics. By comparing the frequency variations induced by TID, we perform detailed analysis of the electric field dependence of gamma-ray and alpha-ray irradiation. Additionally, we conduct experimental evaluations of the recovery characteristics following gamma-ray and alpha-ray irradiation. It has been reported that TID-induced degradation partially recovers over time after gamma-ray irradiation [7]. In the case of alpha-ray irradiation, differences in dose rate and initial recombination rate compared to gamma-ray irradiation suggest that the recovery characteristics may differ.

II. Experimental Setups

A. Test Devices

The threshold voltage shifts of transistors due to TID are evaluated using ring oscillators fabricated in a 65 nm FD-SOI process. A ring oscillator (RO) is a feedback loop of inverters. Its oscillation frequency depends on inverter delay, which shifts due to TID-induced threshold voltage changes. Measuring this shift enables TID evaluation. The RO used in this study consists of 11 inverter stages, as illustrated in Fig. 3. This configuration ensures stable oscillation and high sensitivity. TID decreases the threshold voltage of NMOS transistors and increases that of PMOS transistors. These changes affect the drive current of the transistors. In ROs, the oscillation frequency increases with a lower threshold

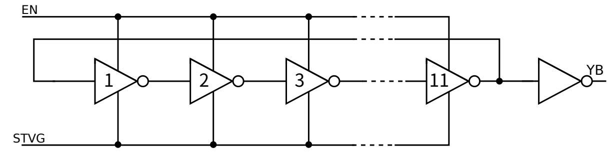
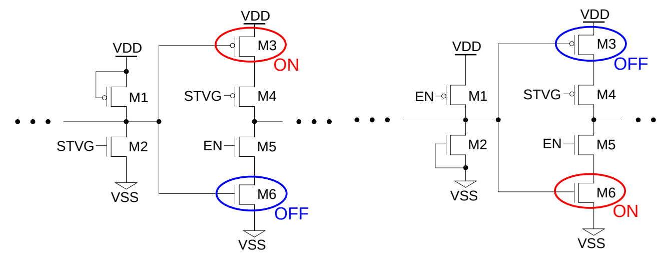


Fig. 3: Schematic of the 11-stage ring oscillator.



(a) Circuit A. (b) Circuit B.

Fig. 4: Measurement circuits.

voltage and decreases with a higher one. TID effects of FD-SOI reduces the oscillation frequency of ROs reported in [8].

We implemented the inverters of the RO as two types of measurement circuits, as shown in Figs. 4a and 4b [9]. Both circuits share the same structure except for the two switches (M1 and M2). As shown in Fig. 5, circuit simulations show that the frequency characteristics of the measurement circuits under transistor degradation are similar. During irradiation, EN is set to 0 and STVG to 1 to stop oscillation. In this state, M3 and M6 behave oppositely. M3 and M6 transistors in circuit A are in the ON and OFF states, respectively. In contrast, M3 and M6 transistors in circuit B are in the OFF and ON states, respectively. NMOS transistor degradation increases the frequency, whereas PMOS transistor degradation decreases it as shown in Fig. 5. If the TID effect strongly depends on the electric field, M3 and M6 degrade differently and the frequency difference between two circuits becomes larger. Thus, these circuits can be used to evaluate the electric field dependence under gamma-ray and alpha-ray irradiation.

B. Gamma-ray irradiation test

The gamma-ray irradiation test (for TID characterization) was performed using a Co-60 source at the National Institutes for Quantum Science and Technology. During gamma-ray irradiation, the DUT is placed in the irradiation room with power supplied through a sleeve as shown in Fig. 6. A cable of approximately 12 m is required to connect inside and outside the irradiation room. However, signal integrity significantly degrades over such a long cable length, causing delays and attenuation. As a result, control signals cannot be reliably transmitted. While placing a controller near the DUT was considered for real-time measurement, standard control hardware lacks guaranteed radiation tolerance in Co-60 environments, and was therefore not adopted due to the risk of malfunction or damage. Therefore, it is difficult to control

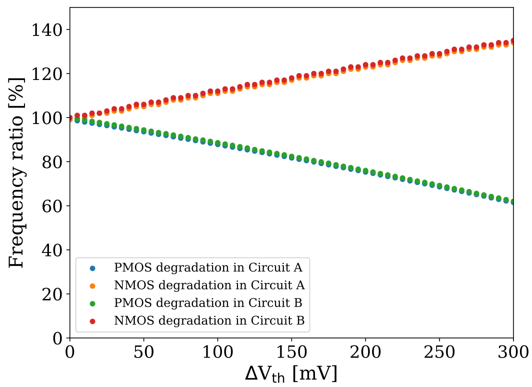


Fig. 5: Frequency ratio variation due to changes in NMOS and PMOS threshold voltages. calculated by circuit level simulations.

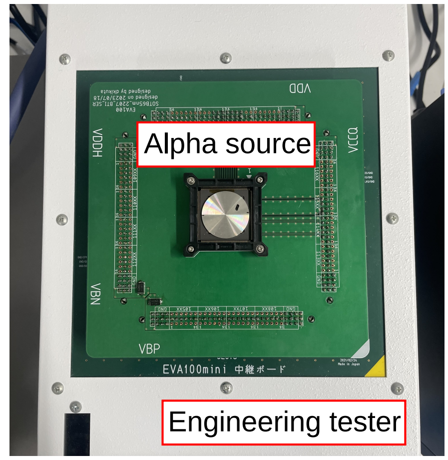


Fig. 7: Alpha-ray irradiation setup.

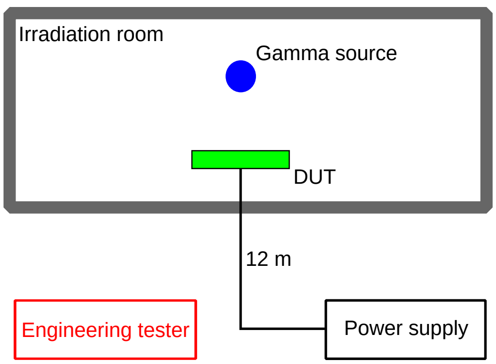


Fig. 6: Gamma-ray irradiation setup.

and measure in real time from outside. After irradiation, the DUT was connected to the engineering tester outside the irradiation room for measurement. The dose rate is 100 krad(Si) per hour. Although this gamma-ray irradiation test does not strictly comply with ESCC Basic Specification No. 22900 [10], mainly due to facility constraints such as the lack of real-time monitoring, the accumulated dose was measured using an appropriate dosimetry method, ensuring the reliability of the exposure.

C. Alpha-ray Irradiation Test

The alpha-ray irradiation test (for TID characterization) was performed using an alpha source (3.0 MBq Am-241) as shown in Fig. 7. Real-time measurement was conducted with the alpha source placed above the DUT connected to the engineering tester. The dose rate is 15.4 rad/s. This rate is calculated from the following equation.

$$
\begin{aligned}
D &= F\ [\mathrm{cm}^{-2}] \times L\ [\mathrm{MeV}\cdot\mathrm{cm}^2\cdot\mathrm{mg}^{-1}] \times t\ [\mathrm{s}] \\
&= 1.6 \times 10^{-1} \times F \times L \times t\ [\mathrm{MGy}] \\
&= 16 \times F \times L \times t\ [\mathrm{Mrad(Si)}] \qquad (1)
\end{aligned}
$$

where, F is the flux of alpha-ray, t is time and L is the LET of alpha-ray. The values of F and L were set to 1.33×10^6 $\mathrm{Bq/cm^2}$ and 0.645 $\mathrm{MeV\cdot cm^2\cdot mg^{-1}}$, respectively. These values are based on [2].

III. Measurements Results

Figs. 8 and 9 show the measured oscillation frequency under gamma-ray and alpha-ray irradiation. The gamma-ray irradiation results show that circuit A degrades more than circuit B. The slopes of the fitting functions for the both circuits are -10.23 and -6.66, respectively. In contrast, the degradation rates under alpha-ray irradiation were approximately equivalent. The slopes of the fitting functions for circuit A and B are 2.78 and 2.28, respectively.

Dose rates of 700 and 4500 krad(Si) were used for gamma-ray and alpha-ray irradiation recovery evaluation, respectively. The measurements were conducted at room temperature. The alpha-irradiated sample degraded 5% more than the gamma-irradiated sample before recovery. Both circuits exhibit similar recovery trends. For gamma-ray irradiation, the 0.4% recovery was observed after 15 hours. For alpha-ray irradiation, the 0.5% recovery was observed after 15 hours. Despite the greater degradation before recovery, the alpha-irradiated sample showed the similar recovery to the gamma-irradiated sample.

IV. Discussion

A. Degradation Characteristics

Degradation due to alpha-ray irradiation is smaller than that caused by gamma-ray irradiation. The results indicate that gamma-ray irradiation exhibits strong electric field dependence. This is because the electric fields applied to M3 and M6 differ between the measured circuits, leading to asymmetric degradation. As a result, significant degradation differences are observed between circuits. In contrast, alpha-ray irradiation results in negligible degradation differences, suggesting weak electric field dependence. Since the response to the electric field is uniform across transistors, the degradation remains

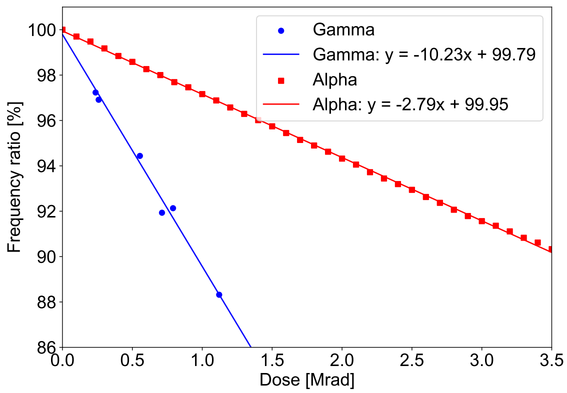


Fig. 8: Degradation of oscillation frequency in measurement circuit A.

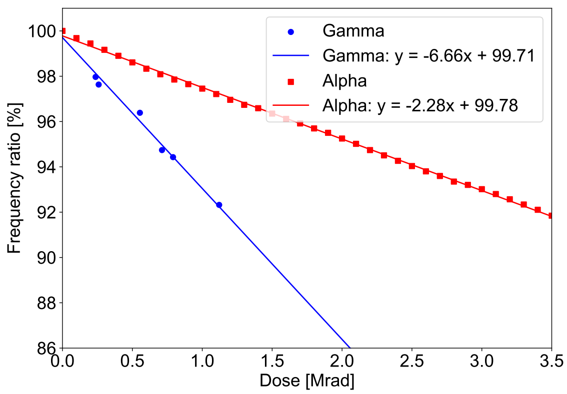
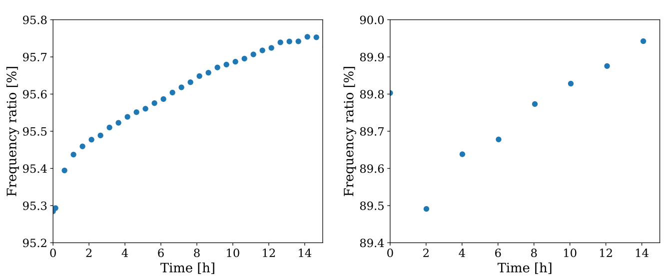


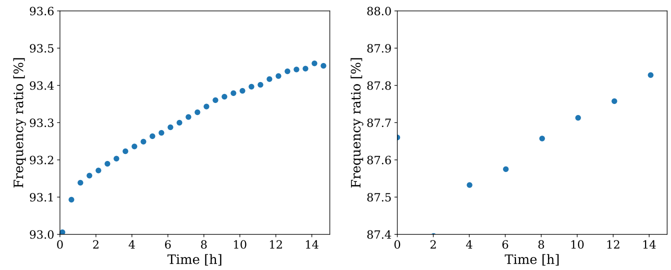
Fig. 9: Degradation of oscillation frequency in measurement circuit B.



(a) Gamma-ray irradiation result. (b) Alpha-ray irradiation result.

Fig. 10: Recovery characteristics of oscillation frequency in measurement circuit A.

similar. According to [11], the electric field affects the initial recombination rate in oxides, which in turn influence the TID effect. Under gamma-ray irradiation, the fraction of holes contrbuting to TID varies significantly with the electric filed, ranging from 0 to 1.0. Conversely, for alpha-ray irradiation, this fraction remains relatively constant, below approximately 0.1. Since the initial recombination rate is higher under alpha-ray irradiation, charge trapping is less influenced by the electric filed, leading to negligible degradation differences. As a result,



(a) Gamma-ray irradiation result. (b) Alpha-ray irradiation result.

Fig. 11: Recovery characteristics of oscillation frequency in measurement circuit B.

even under the same electric field, TID-induced degradation differs between gamma-ray and alpha-ray irradiation. The weak dependence on the electric field in alpha-ray irradiation explains the reasson why the degradation differences between the two circuits remains small.

B. *Recovery Characteristics*

In this measurement, the sample irradiated with alpha-ray showed greater initial degradation than the gamma-irradiated sample. However, both samples exhibited a similar recovery amount. This is because alpha-ray have a low dose rate with high LET, which causes slower degradation during irradiation. Therefore, the recovery rate with alpha-ray irradiation is expected to be higher than that with gamma-ray irradiation. It should be noted that the dose rates differed, which may affect recovery behavior. Future work should align dose rates to better isolate radiation-type effects.

V. Conclusion

In this work, we compared the TID characteristics under gamma-ray and alpha-ray irradiation using ring oscillators fabricated in a 65 nm FD-SOI process. To use alpha-ray irradiation as an alternative to gamma-ray irradiation, it is necessary to compensate for differences of LET. In the 65 nm FD-SOI process, the TID effect by gamma-ray irradiation strongly depends on the transistor state. In contrast, alpha-ray irradiation shows no such dependence. Therefore, compensation of the difference is required. In future work, we will propose an electric field compensation method and improve the accuracy of TID evaluation using alpa-ray sources.

VI. Acknowledgment

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