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A4 8 Nuclear Camera Disintegration

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Abstract

This paper examines the time it takes for a CMOS image sensor from a typical remote monitoring camera to cease functioning due to the radiative environment within a nuclear reactor. We have found that the total ionisation dose rate would make the device stop working at ≈ 3.3 hours, whilst the effects of displacement damage from neutrons would be ≈ 2.1 hours. The internal environment of a nuclear reactor is lethal to semiconductor electronics, and it shortens the lifetime of digital devices.

Introduction

The nuclear industry relies on remote monitoring within reactors due to the highly radioactive environment, which poses significant risks to operational safety and human health. This environment contains high levels of neutrons, alpha, beta, and gamma rays, contributing to a high dose rate that demands radiation-resistant cameras.

The purpose of this paper is to investigate the time it takes for a representative radiative environment in a typical High-Temperature Gas-Cooled Reactor (HTGR) to perform significant degradation to a CMOS Active Pixel Sensor (APS), which is the core electronic system of a typical remote monitoring camera [1].

Theory

Defect production occurs when incident particles transfer energy via ionising processes (electron-hole pairs) and non-ionising processes (displacement of atoms).

Displacement damage creates point defects, primarily vacancies (absent atoms) and inter-

stitials (displaced atoms resting between lattice sites). These defects can form clusters—regions where Si displacement sets off a cascade to local Si atoms.

Discrepancies in the lattice result in higher energy levels within the bandgap, which leads to issues with the electrical and optical behaviour of the semiconductor material. The discrepancies create noise by generating electrons from random heat energy and interfering with the signal by trapping electrons.

There are various processes involved in the interference of electronics. Thermal generation is the primary cause of noise, as electron-hole pairs create an energy shortcut in the Si, allowing heat to generate electron-hole pairs and resulting in leakage current. Recombination occurs when the defect causes free electrons and holes to annihilate each other, resulting in gain degradation. Trapping occurs when a defect temporarily holds charge carriers, causing a signal lag. These effects, along with others, impact the signals of devices and apply to the electronics used in nuclear reactors [2].

CMOS APS are widely used due to their high level of integration and dynamic range, but they are susceptible to radiation damage. The buildup of positive charge in the gate dielectric and the increase in interface states result in the failure of electronics.

Experiments have been conducted that investigate the displacement damage effects on CMOS APS image sensors from neutron irradiation. The neutron displacement damage results in a dark signal, noise, and a dark signal spike increase (caused by displacement energy), as well as a decrease in the ratio of saturation output signal to noise [3].

Calculations

Case 1: Total Ionisation Dose

The time it takes for a commercial CMOS image sensor to fail when exposed to a highly radiative environment relies on the device specification of the failure dose threshold (D_{fail}) and the dose rate from the reactor (\dot{D}).

The failure dose rate is the cumulative dose that the CMOS can absorb before the sensor's image becomes saturated to the point of being unusable due to leakage current. Current CMOS sensors exhibit a tolerance of 250 krad [4], whereas the camera system remains operational until 280 krad [1]. To get a representative time to failure, an average of the two tolerances is taken as 265 krad = 2.65 kGy. The unit Gray (Gy) is the SI unit for absorbed dose, where 1 Gy is equal to 100 rad.

The calculated shutdown dose rate inside a HTGR, 6 cm from the center, after 1 day, is 666.2 Gy hr⁻¹ [5]. Research on radiation-hardened sensors involves testing in environments greater than 1 kGy hr⁻¹ [6]. As with the failure dose rate, we can take a representative average, to model a typical, non-specific reactor environment, which yields ≈ 800 Gy hr⁻¹.

The time-to-failure (T_{fail}) from the total ionisation is given by:

$$T_{fail} = \frac{D_{fail}}{\dot{D}}.$$

Using the average tolerance $D_{fail} = 2.65$ kGy and the representative dose rate $\dot{D} \approx 800$ Gy hr⁻¹, we calculate a duration of approximately 3.3 hours until the camera is saturated with noise and permanently unusable. A more conservative approach uses the lower threshold of 2.5 kGy, yielding $T_{fail} \approx 3.1$ hours, and a more optimistic situation uses the higher threshold of 2.8 kGy, yielding $T_{fail} \approx 3.5$ hours.

Case 2: Displacement Damage

An alternative approach we can take is to determine the time of failure for a CMOS image sensor due to the effects of displacement damage. The time-to-failure with this approach depends on the failure fluence threshold (Φ_{fail}) and the neutron flux in the reactor (ϕ). This approach considers the damage from the neutrons interacting with the Si lattice.

The failure fluence threshold is the total number of neutrons that pass through an area. Studies have sensors exposed to a fluence up to 1×10^{12} neutrons cm⁻² [3].

The neutron flux is the number of neutrons which would be interacting with the sensor which we take as $\approx 1.3 \times 10^8$ neutrons cm⁻² s⁻¹ [3].

The time-to-failure for neutron dose is calculated from:

$$T_{fail} = \frac{\Phi_{fail}}{\phi}.$$

We calculate an approximate time of ≈ 2.1 hours until the pixels are saturated.

Conclusion

We have found that the time it takes for a CMOS sensor, used in cameras, is ≈ 3.3 hours with a range of ≈ 3.1 to 3.5 from the total ionisation dose and ≈ 2.1 hours due to displacement damage. We can conclude that the internal environment in a reactor would be lethal to electrical appliances and have an impact on the semiconductor lifetime.

The values used are representative and will vary between reactors and sensor specifications, but the underlying principle that CMOS sensors are quickly susceptible to this level of radiation remains consistent.

References

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