

Effects of x-ray exposure on NOR and NAND flash memories during high-resolution 2D and 3D x-ray inspection

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Abstract

In this paper, we present a detailed study on the effects of x-ray exposure on data corruption in commercially available NOR and NAND flash memory devices during x-ray inspection with a high-resolution Phoenix Nanomex system from GE. We investigated role of the x-ray tube voltage, tube current, device orientation, x-ray filters and photon energy. We explored the low exposure regime in detail when the first byte errors start occurring and also determined the absorbed dose for 100% byte errors. No data corruption was observed after the normal 2D x-ray inspection and CT scans of the NOR and NAND flash memory devices under study. However, increase in the tube voltage, tube current and/or the x-ray beam size resulted in byte errors which increased exponentially with the exposure time. The byte error rate was found to be much more sensitive to the tube voltage than the tube current. It was also affected by the device orientation with respect to the x-ray beam. The NAND flash memories were found to be more susceptible to data corruption from x-ray exposure than the NOR devices examined in this work. Some NOR devices were irradiated with the monochromatic x-rays from the CHESS synchrotron facility at Cornell University. Of all the photon energies used in this study, 12 keV x-ray irradiation resulted in the highest byte error rate. In this paper, we thus present a direct proof that it is the low-energy photon absorption that plays a major role in introducing bit errors in flash memories. Commonly available low-energy x-ray filters such as Cu and Al foils were found to be effective in preventing data corruption in such devices for long exposure time. Use of lower tube voltage, lower tube current, smaller x-ray spot size, short exposure time and low-energy x-ray filters, is recommended to prevent data corruption during 2D and 3D x-ray inspection of flash memory devices and other semiconductor devices in general.

Key words

Flash memories, x-ray inspection, radiation damage, bit errors, data corruption

I. Introduction

National Transportation Safety Board (NTSB) is an independent Federal agency charged by the US Congress with investigating civil aviation accidents in the United States and significant accidents in other modes of transportation. NTSB determines possible causes of an accident and issues safety recommendations aimed at preventing future accidents. During its investigation process, the agency extracts crucial digital information from microelectronic devices, such as flash memories collected from the accident site. Oftentimes it is not possible to retrieve any data from a device because of the possible physical damage from mechanical and thermal shocks during an accident. Non-destructive testing (NDT)

techniques such as x-ray inspection, computer tomography (CT) and scanning acoustic microscopy (C-SAM), are then employed to evaluate such devices for any internal physical damage. This evaluation helps in finding ways to repair the device whenever possible, and ultimately retrieve the crucial data that can provide clues to possible causes of an accident.

During x-ray inspection and CT scans, microelectronic devices are exposed to the polychromatic x-rays for a given amount of time. X-ray irradiation depending on the absorbed dose, is known to cause bit errors in electronic storage devices such as flash memories [1]-[4] and can thus lead to corruption of the crucial data. Bit errors occur

mainly due to x-ray photon interaction with the device material that results in ionization and trapped charges within the tunnel oxide, interpoly oxide and field oxide in the floating gate cells and charge pump circuitry of the flash memory devices [2], [5].

The amount of x-ray dose during 2D x-ray inspection of microelectronic devices, is generally too low to cause any data corruption [6]-[8], but it can be a cause of concern during CT scans which require longer exposure times and higher x-ray power and flux [9]. Though there is a general understanding of the role of such parameters on data corruption in electronic storage devices [5]-[10], it is not well studied from the 2D and 3D x-ray imaging point of view. Moreover, each imaging system is different in regards to the x-ray dose imparted to the devices being examined. In this paper, we investigate effects of x-ray exposure on commercially available NOR and NAND flash memory devices commonly encountered by the NTSB. These devices were exposed to x-rays from a Phoenix Nanomex inspection system from GE and a monochromatic source from the CHESS synchrotron facility at Cornell University. Any changes in the stored bits/bytes from the Total Ionized Dose (TID) were recorded after each exposure. We investigated the role of the x-ray tube voltage, tube current, device orientation, low-energy filters, and x-ray energy on the extent of data corruption. The x-ray dose values were determined using high-dose dosimeters for the exposure conditions reported in this paper.

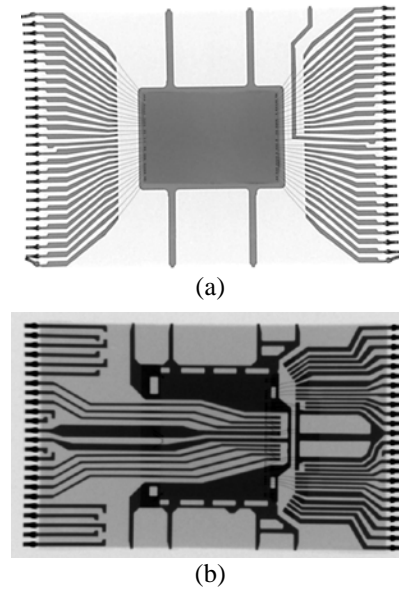
The work described in this paper is organized as follows: In section II, we present experimental details on the flash memories, the x-ray sources and the exposure set-up used in this study. Section III covers x-ray irradiation results and section IV discusses main conclusions drawn from this investigation.

II. Experimental Details

In this section we describe the devices, the x-ray sources, the exposure set-up and the data programmer used in the exposure experiments.

We used two types of flash memories, (i) 128Mb, 250 nm technology NOR devices from Intel (part number 28F128J3A), and (ii) 1Gb, 48 nm technology NAND devices from Micron Semiconductor (part number MT29F1G08ABADAWP). Both devices are thin small outline packages (TSOP) with a single wire-bonded Si die. Figs. 1(a, b) show the x-ray images of the Intel NOR and Micron NAND devices respectively. Leadframe layout looks different in the two devices, with the Cu die paddle covering the entire die from the backside in the NOR device. Two bits/cell are stored in the NOR device whereas 1 bit/cell is stored in the NAND device under study. The

Intel NOR device uses nominal 3 V, and the Micron NAND device employs 3.3V (with 2.7-3.6V full operating voltage range).



Figs. 1(a,b): x-ray images of (a) the NOR device from Intel and (b) the NAND device from Micron Technologies, acquired at the parameters (85kV, 40 μ A, spot mode 1).

These flash memory devices were pre-programmed with the full size data files using the SUPERPRO 7000 programmer from XELTEK just before each x-ray exposure experiment. Fig. 2a shows the 16 MB file pattern written in the hexadecimal format with no 00 and FF bytes employed for the NOR device study. Fig. 2b shows the same file fully corrupted after x-ray irradiation of the device. NAND devices were programmed with a 1Gb size pattern in the hexadecimal format. The devices pre-programmed with the known pattern, were then exposed to x-rays from the Nanomex x-ray inspection system for a given time. The devices were not powered-up during x-ray irradiation. After each exposure interval, the devices were immediately read and the irradiated data file was compared with the pre-programmed pattern to determine any byte changes. The x-ray exposure was continued till 1% byte changes were observed in the exposed device. Some devices were chosen for increased exposure until 100% byte changes occurred. % byte errors were plotted as a function of the x-ray exposure time.

Phoenix Nanomex x-ray inspection system employed in the current study, is capable of performing 2D x-ray imaging as well as 3D scans with a CT scanner accessory. The system produces polychromatic Tungsten x-rays with e-beam spot ranging from $\sim 10 \mu\text{m}$ (spot mode 0) to submicron (spot mode 3) in size. As the spot mode number increases, the

beam size and thus the x-ray intensity decrease. The maximum available tube voltage, current and power in the Nanomex system, is 160kV, 600 μ A and 30W respectively. To obtain the x-ray images shown in Fig. 1(a, b), x-ray tube voltage of 85kV, current of 40 μ A and spot mode size 1, were used for \sim 10 min exposure. Even with 12 hours of x-ray irradiation at these parameters, no byte changes were observed in the NOR devices.

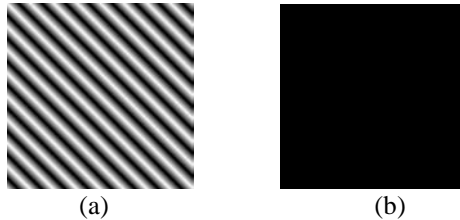


Fig. 2(a, b): (a) 16MB hexadecimal pattern used for the NOR device exposure experiments. (b) Data from an irradiated NOR device after \sim 100% byte change. 00 byte is black with grey scale 0, and FF byte is white with grey scale 255.

Since even 12 hours of x-ray exposure at the imaging conditions, was not able to introduce any byte changes in the stored data, we increased the x-ray intensity by increasing the beam size to its maximum. For most exposure experiments reported here, we used the largest x-ray spot size at mode 0. Because it is a common practice to change the tube voltage, tube current and sample orientation to optimize the image contrast in the area of interest, we varied these parameters and investigated response of the irradiated devices. Distance between the x-ray source and the device was kept constant in all experiments, and it was made sure that entire die was exposed to the x-rays. We used the following conditions in the Nanomex exposure experiments:

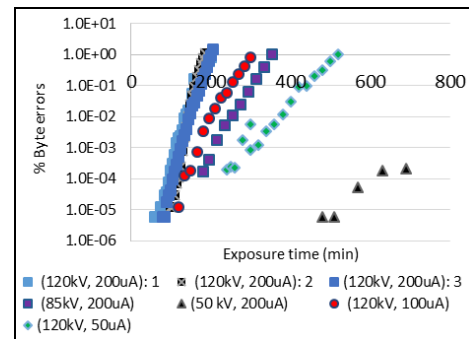
1. Tube voltage of 120kV, 85kV and 50 kV at constant current of 200 μ A; at (24W, 17W, 10W).
2. Tube current of 200 μ A, 100 μ A, 50 μ A at constant voltage of 120kV; at (24W, 12W, 6W)
3. Different sample orientations with respect to the x-ray beam.
4. Low-energy x-ray filters such as Cu and Al foils.

Changing the tube voltage changes mainly energy of the x-ray photons, whereas changing the tube current mainly changes their flux. Higher energy photons are needed for better penetration, especially during CT scans where x-rays are required to penetrate through the entire thickness of a microelectronic package. To understand the role of photon energy on data corruption in flash memories, we irradiated some NOR devices with the monochromatic x-rays of 7 keV, 12keV, 20keV and 25keV at the CHESS synchrotron facility at Cornell University. X-ray dosage at the tube

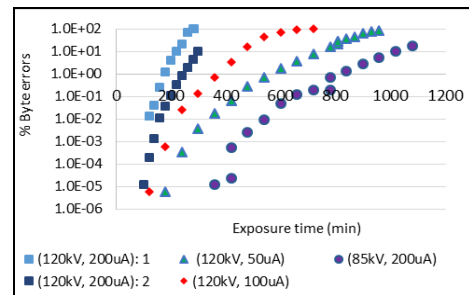
parameters given above, were determined using the high-dose LiF dosimeters from Mirion Technologies.

III. Results

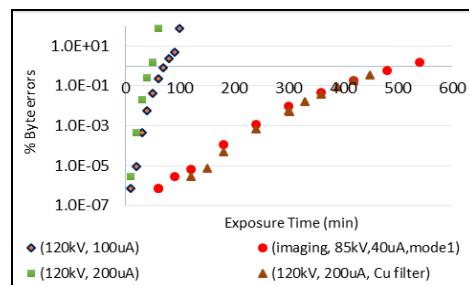
Figs. 3 (a, b) show results from the x-ray exposure experiments performed on 16 MB Intel NOR flash memory devices. Fig 3a gives the short exposure regime results with byte errors up to 1% for the voltage and current values given in the last section and the maximum beam size at mode 0. Short exposure periods were used in this set of experiments to precisely determine the time when the first byte changes occurred. Fig 3b gives long exposure results for the same V, I values where a different set of devices were exposed till 100% byte errors were observed. The memory cell array as well as the drive circuitry were exposed to x-rays straight at 0 $^{\circ}$ angle of incidence (AOI) during these experiments.



(a)



(b)



(c)

Fig 3(a, b, c): Plots of % byte errors versus the x-ray exposure time for the NOR devices (a, b) and the NAND devices (c) using different tube voltage and current values.

Figs. 3(a, b) suggest that the byte errors (changed bytes) increase exponentially as the exposure time increases. When the tube voltage or current is decreased, the byte error rate decreases as expected. It is much more sensitive to changes in the tube voltage than changes in the tube current. Though the x-ray power at (50kV, 200 μ A, 10W) is higher than at (120kV, 50 μ A, 6W) exposure conditions, the byte error rate is much lower because of the lower tube voltage. Some exposure experiments, especially at low tube voltage or current, spanned for more than a day. Overnight rest from the x-ray exposure, resulted in slight deviation from the smooth curve; possibly due to a relaxation mechanism [5]. At the full exposure level when 100% byte changes occurred, bits changed to the “0” state in the Intel NOR devices (refer to Fig 2b). For repeatability studies, the exposure experiments at (120kV, 200 μ A, mode 0) were performed on five devices, three for the short exposure experiments given in Fig. 3a, and two for the long exposures shown in Fig. 3b. Three devices show moderate repeatability with a slight difference in the byte error rate in the short exposure regime. But the full exposure level experiments under the same conditions on two devices, exhibit different byte error rates as indicated by Fig. 3b. This result suggests that there may not be a high repeatability in the response of a flash memory device to x-ray irradiation especially at higher dose levels.

Fig. 3c gives the exposure results from 1Gb NAND devices at imaging conditions (85kV, 50 μ A, mode 1); (120kV, 200 μ A, mode 0, with and without Cu filter); and (120kV, 100 μ A, mode 0). The byte error rate is found to be higher in the Micron NAND devices in comparison to the Intel NOR devices. The byte error rate is very low under the imaging conditions and with incorporation of the Cu filter. At 100% byte errors, bits changed to the “1” state in the NAND devices. Further exposure experiments on these devices are in progress.

Exposure results given in Fig. 3 were performed with the devices kept stationary at AOI=0⁰ with respect to the x-ray source. However, during a CT scan the device rotates through 360⁰ under the x-ray source. We performed CT scan of a NOR device at (120kV, 100 μ A, mode 0) for a maximum of ~ 1 hr exposure time, the average CT scan time for the Phoenix machine. No byte change occurred during these CT scan conditions. We investigated the impact of changing the device orientation with respect to the x-ray source while keeping V, I and beam size constant at (120kV, 200 μ A, mode 0). The sample orientations used in this study were (i) die facing x-rays in direction perpendicular to the beam (AOI = 0⁰) (ii) die tilted to AOI of 45⁰ w.r.t the x-ray beam (45-a) (iii) die tilted to AOI of 45⁰ w.r.t the x-ray beam but rotated by 90⁰ in the die plane

(45-b) (iv) Cu paddle facing x-rays straight at AOI of 180⁰. Fig. 4 gives plot of % byte errors against the exposure time at orientations (i) to (iv) for the Intel NOR device. The byte error rate is maximum for orientation (i) with die circuitry facing x-rays directly through the mold. Fig 4 suggests that orientations (ii) and (iii) result in different response from the device when compared to AOI of 0⁰. Orientation (iii) causes higher byte error rate than orientation (ii) (figure shows data from 2 devices exposed at orientation ii). This can be explained by the presence of metallization in the die circuitry. Fig 5 shows such features in the SEM images of a memory cell row in the Intel NOR device exposed by micro cross-sectioning of a decapsulated package in the world line (5a) and bit line (5b) directions using the FIB-SEM system from FEI. Apart from the floating gate structure of the memory cells lined-up in a row, the metallization lines and the metal-filled vias can be seen in both images. This metallization can work as an internal x-ray filter during irradiation, resulting in lower byte error rate at angled positions. When the die paddle faced x-rays straight-on in orientation (iv), no byte change occurred in the NOR devices even after 6 hrs of x-ray exposure at (120kV, 200 μ A, mode 0). This is because the x-rays were first filtered by the Cu paddle before reaching the circuitry side of the die.

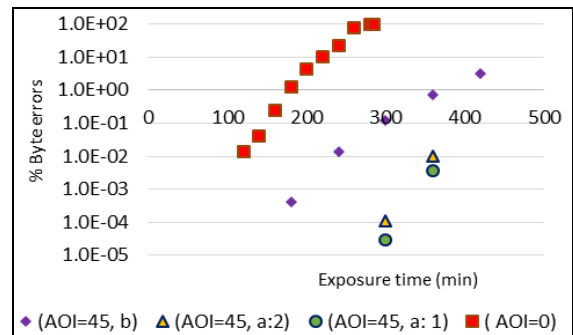


Fig. 4: % Byte errors vs x-ray exposure time plots for various device orientation with respect to the x-ray beam.

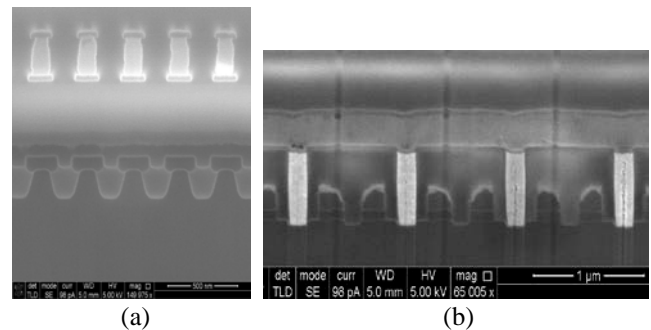


Fig 5: SEM images of the FIB micro cross-section along the world line (a) and the bit line (b) of the Intel NOR device.

If the Cu paddle does not cover the entire die in a device such as the NAND device in this study, an external filter can be employed for filtering x-rays before they enter the circuit side of the die. We used commonly available metals such as the Cu and Al foils for this purpose. 0.4 mm thick Al foil was able to prevent any byte change in the NOR device even after 6 hours of x-ray exposure at (120kV, 200uA, mode 0). 0.3 mm thick Cu filter was able to prevent any byte change for up to 9 hrs under the same x-ray conditions. Cu was found to be more effective in preventing data corruption than the Al filter.

In all experiments reported above, flash memories were exposed to the polychromatic W x-rays from the Nanomex system. In order to determine the photon energy that causes the maximum data damage, we exposed some NOR devices to monochromatic x-rays of 7 keV, 12 keV, 20 keV and 25 keV energy at the CHESS synchrotron facility at Cornell University. Since the x-ray spot size was smaller than the silicon die, the beam was scanned fast to cover the entire die. These exposure results are given in Fig 6. At low energy of 7keV, no byte change was observed even after 65 min of x-ray irradiation. At 12keV, first byte errors started occurring in just 9 min and by 24 min of exposure almost 100% byte errors occurred. At 20keV, first byte errors occurred around 11 min, and 43 min of x-ray irradiation caused 100% byte errors. At 25keV, first errors started occurring around 24 min and it took ~ 86 min to cause 100% byte changes. These results clearly show that the byte error rate is dependent on the photon energy and is highest around 12keV for the energy values investigated. This provides a direct proof that it is the low energy photons that are a major cause of data corruption in flash memories and other microelectronic devices. Al and Cu filters absorb x-rays in this spectral range and thus are effective in preventing data errors for a long time.

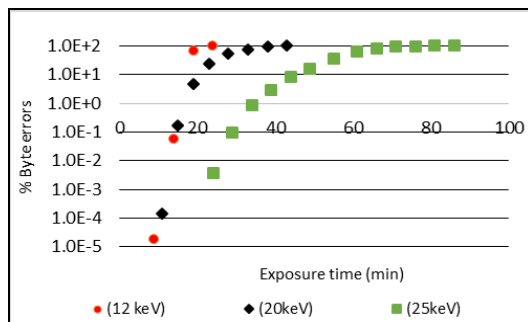


Fig 6: % Byte errors vs exposure time plots for the monochromatic x-ray irradiation of the Intel NOR device at various photon energies.

Table 1 gives the x-ray dose values for the Phoenix

Nanomex source measured using the high-dose LiF dosimeters from Mirion Technologies. The dosimeters were exposed at the x-ray conditions reported in this work and then sent back to the manufacturer for measurements. The table suggests that the x-ray dose rate during the imaging conditions of (85kV, 40uA, mode 1) is very low compared to the ones used in most experiments in this paper. The dose rate is highest at (120kV, 200uA, mode 0), but incorporation of the Cu or Al filters, reduces it considerably. Cu filter is found to be more effective than the Al filter as indicated by the dose rate values as well as the exposure experiments. As expected, decrease in tube current and/or tube voltage reduces the dose rate and hence the byte error rate. The dose rate is found to be much more sensitive to the tube voltage than the tube current. This trend is also observed in the exposure experiments where the byte error rate is found to be more sensitive to the tube voltage than the current. Based on these dosage measurements, we conclude that the NOR devices used in the present study, start showing up first byte errors at the x-ray dose values of 250-450 Gy. 2D x-ray inspection of flash memories for ~ 30 min usually provides a dose of only ~ 15 Gy.

#	Mode	Tube Voltage (kV)	Tube Current (μ A)	Power (W)	x-ray dose rate (Gy/min)
1	Mode 0	120	200	24	3.85
2	Mode 0	120	100	12	2.72
3	Mode 0	120	50	6	1.909
4	Mode 0	85	200	17	2.1
5	Mode 0	50	200	10	0.48
6	Mode 1	85	40	3.4	0.49
7	Mode 0, Cu filter	120	200	24	0.19
8	Mode 0, Al filter	120	200	24	0.86

Table 1: X-ray dose rates for the Nanomex x-ray source at various tube voltage and current.

IV. Conclusions

In this paper, we reported a detailed investigation on the effects of x-ray exposure on data corruption in NOR and NAND flash memory devices during 2D x-ray inspection and 3D CT scans using a high-resolution Nanomex system. We investigated the role of the x-ray parameters such as the tube voltage, tube current, photon energy, sample orientation and low-energy x-ray filters. No data corruption occurred during the normal 2D x-ray inspection and CT

scans of the devices under study. But as the x-ray power and flux are increased, we observed byte errors which increased exponentially with the exposure time. Byte errors are found to be more sensitive to changes in the tube voltage than changes in the tube current. This may be because increasing the tube voltage increases the photon energy as well as the flux, which then creates more primary and secondary interactions thus leading to more trapped charges within the tunnel/interpoly/field oxide in a memory cell [5]. Increasing the tube current, on the other hand, mainly increases the x-ray flux. The sample orientation also affected the byte error rate, where the maximum damage was observed when the circuit side of the die faced the x-rays directly head-on. As the sample is tilted to other orientations, in-built metallization and metal-filled vias worked as x-ray filters and reduced the byte error rate. In this paper, we provided a direct proof that it is the low-energy photon absorption (by the tunnel/gate oxide in a memory cell) that plays a major role in introducing data corruption in flash memories [5]-[10]. Incorporation of commonly available low-energy x-ray filters such as the Al and Cu foils, is found to be effective in preventing data errors for a long exposure time. Cu filters are found to be more effective than the Al filters. Finally, dose measurements at the x-ray parameters reported in this paper, supported the x-ray exposure results. We plan to continue to do more irradiation experiments on NAND devices from Micron and other flash memory devices.

For the Intel NOR devices reported in this paper, first byte changes occurred around x-ray dose values of 250-450 Gy. Micron NAND devices started showing first byte errors at a lower dose of 75-150 Gy. X-ray dose level that can initiate data errors thus depends on the design of the device being irradiated. X-ray parameters used during 2D x-ray inspection of such devices, provide total ionized dose of only ~ 15-20 Gy in the Nanomex system, which is much lower than the one needed to induce byte changes in both devices. But CT scans, which require longer exposure time, higher x-ray power and flux, can impart an x-ray dose of 150-200 Gy with the same machine. It is recommended that 2D x-ray inspection and CT scans should be performed at lower tube voltage, lower tube current and short exposure time that can provide the optimum image quality. The die must face away from the x-ray source and use of the low-energy x-ray filters such as Cu, Al and Zn foils is recommended.

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University where most experiments were performed.

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