Examination of the Utility of Commercial-off-the-shelf Memory Devices as X-Ray Detectors

Travis Z. Fullem, *Student Member, IEEE*, Lawrence P. Lehman, and Eric J. Cotts

***Abstract*– An examination was conducted of the use of standard memory devices as X-ray detectors. Commercial-off-the-shelf memory devices such as flash memory, UV-EPROM, DRAM, and non-volatile SRAM units were studied. The memory states of the devices were continuously monitored as a function of time and X-ray flux. It was found that in all configurations used, the devices were not practical X-Ray dosimeters; hard fails were nearly as prevalent as soft fails.**

I. Introduction

There is significant interest in producing portable, low-cost radiation detectors for security applications [1], [2]. We report development efforts on an X-Ray detection system which utilizes various types of commercial-off-the-shelf memory devices as detectors. We have experimented with the following types of memory and will discuss their suitability for use as detectors: dynamic random access memory (DRAM), USB flash drives, erasable programmable read only memory (EPROM), and non-volatile static random access memory (NVSRAM). X-Rays can produce single-event upsets in a memory chip which changes the data stored in the chip. In the present design, a known data pattern is written into the memory device prior to irradiation. The contents of the memory are then monitored so that single event upsets can be detected while the X-Ray flux is systematically varied.

II. Background

It has been known for many years that alpha particles can induce single event upsets (SEU) in DRAM [3], and the use of DRAM as an a detector was first proposed shortly after this was discovered [4]. Cosmic rays can also induce SEUs in memories [5], [6]. The cause of single event upsets is not limited to alpha particles. Energetic photons (such as X-Rays or γ rays) can also produce electron-hole pairs in silicon via the photoelectric effect which can lead to bit flips in memory. Previously, DRAM has been successfully employed as a neutron dosimeter [14], [15]. Recent efforts have indicated that the efficiency of the systems can be significantly improved [16]. DRAM has also been used to detect photons in the visible portion of the spectrum [17]. There are also several reports in the literature of UV-EPROMs being used as dosimeters [18], [19]. Descriptions of the upset mechanisms in DRAM [3], [7], [8], SRAM [9] and floating gate memories (such as EPROM and flash memory) [10]-[12] are available in the literature. A historical overview of radiation induced soft fails is given in [13].

A brief description of the physical mechanisms involved in the upset process in DRAM will now be given. In Fig. 1a, we see a storage capacitor in a DRAM. This storage well is depleted of electrons and represents a binary one. Fig. 1b shows the storage well being struck by an energetic particle (such as an α or γ). The particle track is indicated by the thick arrow. Electron-hole pairs are generated around the track and are indicated in the diagram as '+' and '-'. A typical 5Mev α particle will penetrate approximately 25μm. Since the energy required to produce a single electron-hole pair is 3.5eV there will be approximately 10^6 electron-hole pairs produced by such an α particle. In Fig. 1c, the incident particle has been completely absorbed and we are left with an abundance of electrons and holes, which will work their way through the silicon. The electric field in the depletion region will draw electrons into the storage wells and push holes away into the bulk silicon. Fig. 1d shows the final result in which the well (which was depleted of electrons prior to irradiation) is now filled with electrons and the value of this bit will be read as a zero rather than a one. This is a soft error (since the chip itself was undamaged and will work properly in the future) and is sometimes referred to as a bit-flip.

III. Description of the Present Work

The suitability for use as an X-Ray detector of several different types of memory devices was examined, including dynamic random access memory (DRAM), USB flash drives, SD flash memory cards, erasable programmable read only memory (EPROM), and non-volatile static random access memory (NVSRAM). The X-Ray beam used in this work was generated using the X-Ray tube in a Philips X-Ray diffraction system. The tube employed a Cu target which produced an X-Ray beam whose peak intensity was at an energy of 8keV. Following is an overview of our experiments. For more detailed information, the interested reader is referred to [20].

A. DRAM

A Dynamic RAM was chosen (TMS4116 16384 X 1 bit) which had been successfully used as a neutron dosimeter in the past [14]. This DRAM is relatively easy to work with since each cell in the memory is individually addressable and the unit is packaged in a 16 pin Dual Inline Package (DIP). A microcontroller-based control circuit was constructed and programmed so that it could produce the timing signals

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The authors are with the Physics Department, State University of New York at Binghamton, Binghamton, NY 13902 USA. (e-mail: tfullem@alumni.ithaca.edu; lplehman@binghamton.edu; ecotts@binghamton.edu).

necessary to read, write and refresh the TMS4116 DRAM. A DRAM chip was placed in the path of the X-Ray beam, and the control circuit was located outside the X-Ray chamber as shown in Fig. 2. The chip was written with all 1's prior to irradiation. The control circuit monitored the data output of the DRAM, and if a bit was found to be 0, this was counted as an error. The controller circuit read all 16384 bits in the DRAM every sixty seconds.

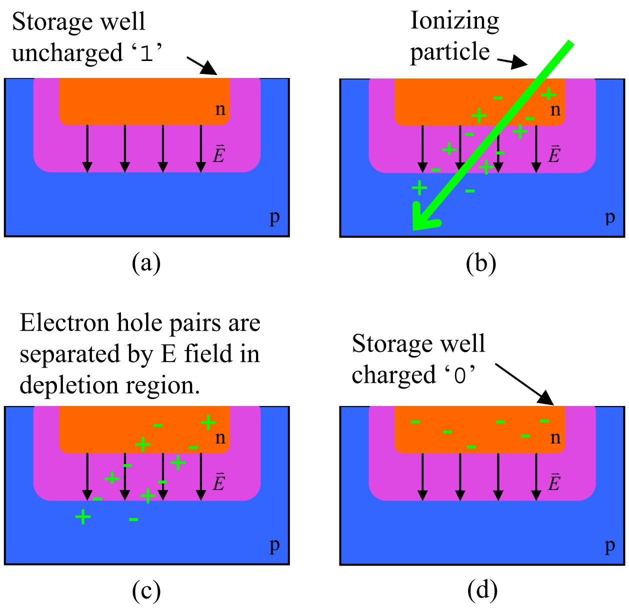


Fig. 1. The upset process in DRAM. Adapted from [3]. (a) Prior to irradiation. The uncharged capacitor represents a logical 1. (b) During irradiation. Electron hole pairs are generated along the track of the energetic particle. (c) After irradiation. The particle has been absorbed. (d) The bit has flipped; the capacitor is now charged.

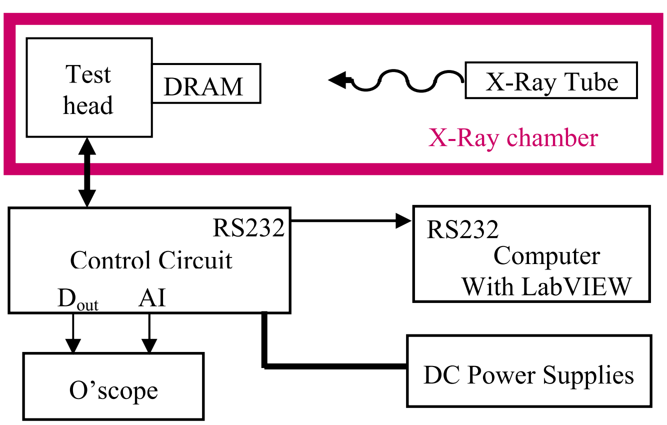


Fig. 2. DRAM detection system block diagram.

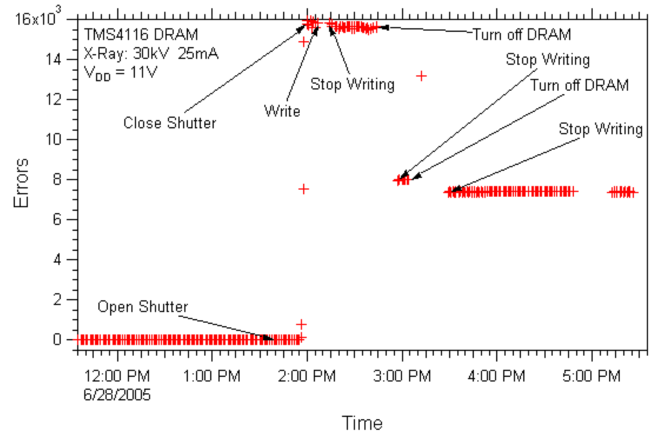


Fig. 3. DRAM error count showing ~50% soft fails.

Fig. 3 is a plot of the error count recorded by the control circuit as a function of time. After 15 minutes of irradiation, most of the bits in the DRAM had flipped. An attempt was made to rewrite 1's into the chip; however, this was not efficacious. It was found that by briefly disconnecting the power supply from the chip and then rewriting that approximately half of the bits could be rewritten. The bits that could be rewritten had experienced soft fails and those which could not be rewritten had experienced hard fails.

Our experiments have shown that X-Rays do induce soft errors in DRAM, however, they also induce hard fails which limits the reliability of such a detector. We find that the quantity of hard and soft fails are induced in the DRAM are approximately equal. DRAM is a poor choice for a dosimeter due to its need for a constant power supply and support circuitry to refresh the storage capacitors which increases cost and complexity as compared to non-volatile memory.

B. *USB Flash Drives*

The USB Flash drive that was used in this experiment was removed from its plastic housing. The circuit board had a memory chip on one side and a control chip on the other side of the board. The memory space was divided into two partitions: a main partition of 120MB and a small partition of 1.44MB. Data files consisting of a repeating string of FF00 were created to fill both of the partitions; the large file was 112305KB and the small file was 1270KB. The files were written to their respective partitions and the USB drive was placed in the X-Ray chamber. After exposure, the memory was removed from the X-Ray chamber and connected to a computer to read the data files. At low intensity, the X-Ray beam had no effect on the data. It was found that exposures at higher intensities (a tube setting of 20kV, 15mA) produced one of two results: In some cases, the computer said that a partition was not formatted; however the computer was able to reformat the partition without any difficulty. Therefore, whatever errors occurred were soft errors. In other cases, the computer produced an error message stating "The volume for a file has been externally altered so that the opened file is no longer valid", and would not allow the file to be copied. In both cases, it was not possible to determine the extent of the data corruption on this partition since the file could not be accessed.

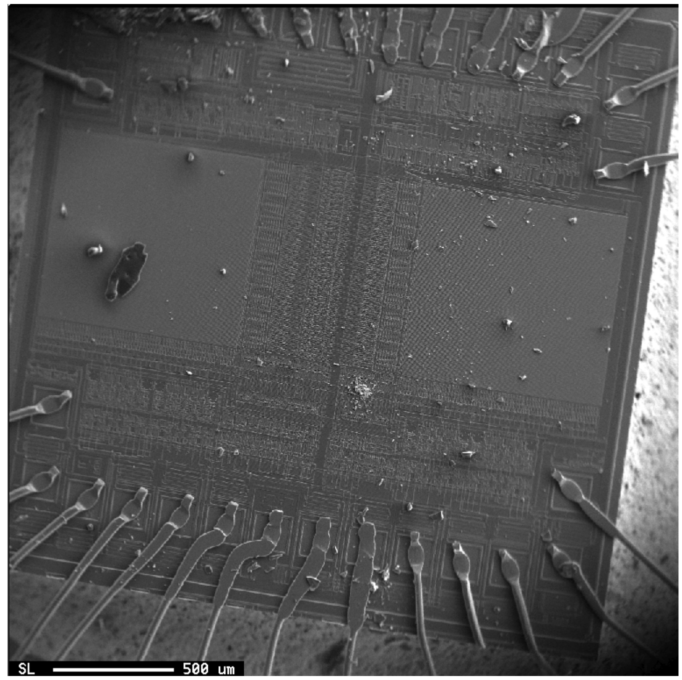
For this experiment, it is necessary to be able to view the corrupted file. The file was corrupted by the radiation, and the USB drive is able to detect this and prevents the user from accessing the corrupted file. This USB drive has too much error detection built into it for it to be used for this application. However, since soft errors did occur in this memory device (as indicated by the repairable loss of format information) the memory chip itself may be suitable if a custom control circuit is constructed.

C. SD Flash Memory Cards

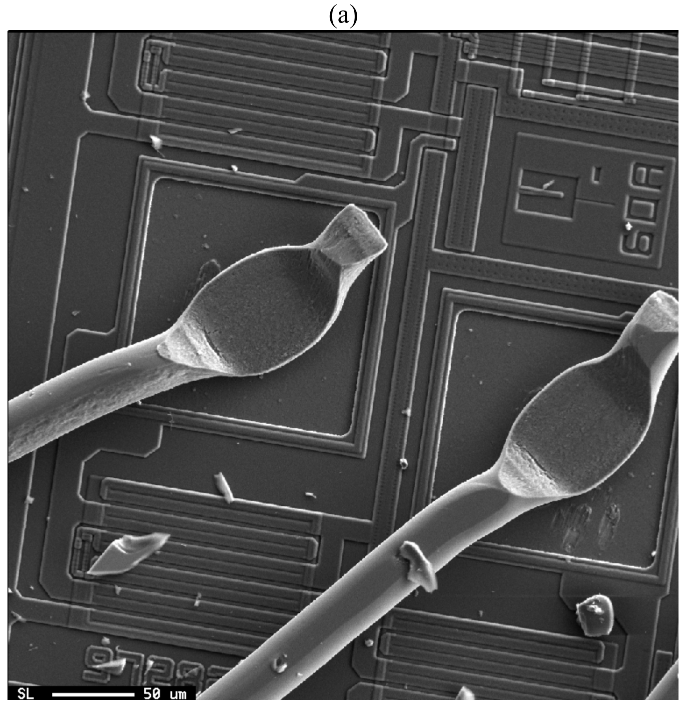
A 128MB SD card (such as found in a digital camera) was utilized. A single file which consisted of a repeating string of FF00 was stored on the memory device. The card was then irradiated at several different X-Ray intensities. After each exposure, the card was removed from the X-Ray chamber and the data file was copied onto a computer using a standard card reader. For low X-Ray intensities, no bit flips occurred. Exposure to higher intensities resulted in a hard fail that prevented the computer from recognizing the card.

D. UV-EPROM

The 27C128 EPROM, used in this experiment, consists of a ceramic DIP package with a quartz window positioned directly above the chip to facilitate erasure via UV light. In our experiments, the quartz window was removed so as to minimize attenuation of the X-Ray beam. When fully erased, all of the bits are in the '0' state (uncharged.) An EPROM programmer was used to store 1's in all of the bits of the memory, and then the chip was placed in the X-Ray beam. Several different chips were exposed to a variety of X-Ray intensities. In the instances in which the memory was erased by the X-Rays, the erasure was permanent (i.e. the programmer was unable to re-write 1's into the erased bits). It should be noted that the X-Rays did not cause total erasure of the memory; in our tests, between 3k and 8k bits were erased. Since X-Rays induce hard fails in these EPROMs, they are not a good candidate for X-Ray dosimetry, although they could be classified as a single use sensor. Furthermore, removal of the quartz window breaks the hermetic seal of the package, which adversely affects device reliability. Secondary electron images of the EPROM chip after removal of the quartz window are shown in fig. 4.



(a)



(b)

Fig. 4. (a) Backscattered electron image of the EPROM chip. Debris from the removal of the quartz window is on the surface of the chip. (b) Close up of a wirebond on the EPROM chip. Fragments from the quartz window are clearly visible in this image.

E. Non-volatile Static RAM (NVSRAM)

The NVSRAM consists of an SRAM chip and a battery encapsulated in a single package. In our experiments Dallas DS1225 NVSRAMs (64k bit) were used. The memory was filled with a repeating string of `00FF` prior to irradiation. Our experiments yielded mixed results; however, they seem to reveal a progression of failure as the duration of the X-Ray exposure increased. Exposures of less than 5 minutes had no effect on the data stored in the memory. Longer exposures led to erasure of the memory (all of the data was `FFFF`); such erasure was a soft fail and the chip could be reprogrammed. Further exposure caused the chip to contain random data, as shown in fig. 5; this was hard fail and the chip could not be reprogrammed.

```
1   00000000  A0 DB D2 9F 7B EF DF FF F9 EF D1 E3 F5 F1 AB A3
2   00000010  C3 CF C3 F7 F2 ED 83 3A 93 BB FF AF C3 FB AA DF
3   00000020  8C 9C B0 39 C3 E9 C1 F7 C5 6D 06 13 74 ED 80 F1
4   00000030  2C CF C7 44 81 A1 01 FD 64 B3 91 8B 83 93 93 D5
5   00000040  A1 FF CF F7 F1 BB 83 CD 0B BF B9 BB D2 DD 2B DF
6   00000050  C7 0F 99 8F EC 8F B9 FB EB F9 C7 FF 95 BD A3 8B
7   00000060  33 84 A1 9F 6C 8F D7 95 84 49 61 F9 83 DD F1 A3
8   00000070  27 21 03 E5 8C 97 83 35 8B E5 8D C7 29 85 C5 83
9   00000080  8C 79 F5 FF D0 E6 99 7F 29 D7 F1 DF D9 9B 07 EB
10  00000090  90 8F AB E7 0F 73 AD CB C5 B9 25 C3 BD E5 87 FA
11  000000A0  9D 01 C3 E5 91 AC 6C D3 85 EE C0 A1 E9 FA E9 DB
12  000000B0  75 2B 56 9B C5 B5 E2 DF E1 AF 32 D5 AC C1 F1 E7
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Fig. 5. NVSRAM data after a hard fail.

IV. Conclusions

Experiments have been conducted to determine the propensity of various types of memory chips to experience single event upsets as a result of X-Ray irradiation. Memory based detectors are not well suited for use in security applications due to their low sensitivity; the X-Ray intensities that were required to elicit a response were high enough to cause injury to humans. However, flash memory based detectors may find use in dosimetry applications that involve high radiation intensities. Non-volatile memory is a much stronger candidate than DRAM for low-cost dosimetry due to the passive nature of the devices. As with DRAM a mix of hard and soft fails was observed with the non-volatile memories. We were unable to quantify the results from the flash memories since the commercial-off-the-shelf (user friendly) readout systems detected the errors and restricted access to the memory's contents. It may be possible to employ flash memory as a dosimeter if customized readout circuitry is used to access the data.

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References

[1] J. C. McDonald, B. M. Coursey, M. Carter, "Detecting Illicit Radioactive Sources," *Physics Today*, vol. 57, no. 11, pp. 36-41, 2004.

[2] R. T. Kouzes, "Detecting Illicit Nuclear Materials," *American Scientist*, vol. 93, no. 5, pp. 422-427, 2005.

[3] T. C. May and M. H. Woods, "Alpha Particle Induced Soft Errors in Dynamic Memories," *IEEE Trans. Electron Devices*, vol. ED-26, no. 1, pp. 2-9, 1979.

[4] G. Cerofolini and G. Ferla, "A Proposal: Dynamic RAMs as Particle Detectors," *Nuclear Instruments and Methods*, vol. 169, pp. 125-128, 1980.

[5] L. W. Massengill, "Cosmic and Terrestrial Single-Event Radiation Effects in Dynamic Random Access Memories," *IEEE Trans. Nucl. Sci.*, vol. 43, no. 2, pp. 576-593, 1996.

[6] H. H. K. Tang, "Nuclear physics of cosmic ray interaction with semiconductor materials: Particle-induced soft errors from a physicist's perspective," *IBM J. Research and Development*, vol. 40, no. 1, pp. 91-108, 1996.

[7] L. Z. Scheick, S. M. Guertin, and G. M. Swift, "Analysis of Radiation Effects on Individual DRAM Cells", *IEEE Trans. Nucl. Sci*., vol. 47, no. 6, pp. 2534-2538, 2000.

[8] D. Shaw, G. Swift, D. Padgett and A. Johnston, "Radiation effects on five volt and advanced lower voltage DRAMs," *IEEE Trans. Nucl. Sci*., vol. 41, pp. 2452-2458, 1994.

[9] P. E. Dodd, L. W. Massengill, "Basic Mechanisms and Modeling of Single-Event Upset in Digital Microelectronics," *IEEE Trans. Nucl. Sci*., vol. 50, pp. 583-602, 2003.

[10] G. Cellere, P. Pellati, A. Chimenton, J. Wyss, A. Modelli, L. Larcher, and A. Paccagnella, "Radiation effects on floating-gate memory cells," *IEEE Trans. Nucl. Sci*., vol. 48, no. 6, pp. 2222-2228 Part 1, 2001.

[11] G. Cellere, and A. Paccagnella "A review of ionizing radiation effects in floating gate memories," *IEEE Trans. Device and Mater. Rel*., vol. 4, no. 3, pp. 359-370, 2004.

[12] G. Cellere, A. Paccagnella, A. Visconti, and M. Bonanomi, "Ionizing radiation effects on floating gates," *Appl. Phys. Lett.*, vol. 85, no. 3, pp. 485-487, Jul. 19 2004.

[13] J. F. Ziegler et al., "IBM experiments in soft fails in computer electronics (1978-1994)," *IBM J. Research and Development*, vol. 40, no. 1, pp. 3-18, 1996.

[14] J. L. Davis, "Use of Computer Memory Chips as the Basis for a Digital Albedo Neutron Dosimeter," *Health Physics*, vol. 49, no. 2, pp. 259-265, 1985.

[15] J. C. Lund, F. Sinclair and G. Entine, "Neutron Dosimeter using a Dynamic Random Access Memory as a Sensor," *IEEE Trans. Nucl. Sci*., vol. 33, no. 1, pp. 620-623, 1986.

[16] G. W. Phillips et al., "Feasibility of a Neutron Detector-Dosemeter Based on Single-Event Upsets in Dynamic Random-Access Memories," *Radiat. Prot. Dosim.,* vol. 101, pp. 129-132, 2002.

[17] S. A. Ciarcia, "A 64K-bit dynamic RAM chip is the visual sensor in this digital image camera," *BYTE Magazine*, pp. 21-31, Sept. 1983.

[18] L. Z. Scheick, P. J. McNulty, and D. R. Roth "Dosimetry Based on the Erasure of Floating Gates in the Natural Radiation Environments in Space," *IEEE Trans. Nucl. Sci*., vol. 45, no. 6, pp. 2681-2688, 1998.

[19] P. J. McNulty, N. Rajaram, K. F. Poole, K. R. Freeman, J. P. Dyar, L. Z. Scheick, M. Alkhafazi, and M. G. Mandall, "Simplified Readout of UVPROM Dosimeters for Spacecraft Applications", *IEEE Trans. Nucl. Sci.*, vol. 53, no. 4, pp. 1859-1862, 2006.

[20] T. Z. Fullem, "Radiation Detection Using Single Event Upsets in Memory Chips", MS Thesis, Binghamton University, ISBN: 9780542784842, 2006.