DRAM damage due to X-Ray Inspections Post PCB Assembly

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ABSTRACT

X-ray inspection remains integral in the Surface Mount Technology (SMT) industry, persistently employed to inspect obscured and defective solder joints within ball grid arrays (BGAs) and flip chip packages. This pivotal step streamlines failure analysis activities, offering a non-destructive and effective means of ensuring the quality of printed circuit board (PCB) assemblies. However, this ubiquitous technique carries an inherent risk for BGAs housing on-package memory modules. Excessive exposure to X-rays can potentially lead to the degradation of dynamic random-access memory (DRAM), underscoring the delicate balance between inspection and the preservation of memory integrity on these BGAs. Although this balance is so critical, the limits to which these DRAMs can be exposed are not clear or readily available.

Previous research has extensively discussed the static refresh degradation of DRAM caused by X-ray irradiation. However, the radiation levels on the PCB assembly have not been thoroughly characterized for post-SMT X-ray inspection. Additionally, readily available functional test data on these BGAs with on-package memory which have undergone X-ray exposure are lacking. The characterization of X-ray exposure levels has been conducted on packages and boards of varying thicknesses. A range of materials and filter thicknesses have been evaluated in this process. Furthermore, the exposure on both automated inspection and manual inspection systems has been characterized. This comprehensive evaluation seeks to provide insights into the impact of X-ray irradiation on DRAM, shedding light on potential vulnerabilities and informing strategies for reducing X-ray exposure and improvement in manufacturing processes.

This paper also investigates the radiation tolerance of PCB assemblies housing BGAs with on-package memory, pinpointing the radiation threshold where functionality issues arise. Through exposure to different radiation levels using a manual x-ray inspection tool, the package was subjected to stress testing using open-source memory testing software to assess memory performance. The results are then discussed in the context of the refresh time degradation of such DRAMs as reported by other studies.

Key words: X-ray, inspection, DRAM, memory, assembly, SMT.

INTRODUCTION

Concerns are increasingly being raised about the potential for X-ray inspections steps during manufacturing such as post-SMT inspections to cause latent damage to semiconductor components. Several publications [1-3] have stressed the need for users to be aware of the risks associated with X-ray exposure to components, even though the radiation levels involved typically do not cause immediate failures. Defining the thresholds for any type of degradation, however, can be difficult. Users must take care to configure the inspection setup in a way that achieves the best possible imaging results while minimizing any risk of damage to the samples. Although latent damage is a possibility, it is expected to affect only a small percentage of samples, as the majority are likely to have enough tolerance in key or sensitive parameters to alleviate concerns about device failure.

One of the most significant semiconductor devices being used nowadays is the Dynamic Random Access Memory (DRAM). One major use of the DRAM in the current packaging landscape is to have an on-package DRAM close to the CPU to improve the bandwidth and lower latency. Several studies have reported that the critical device parameters of DRAM are sensitive to X-ray irradiation. The static refresh t_{ref} or retention time is the amount of time a DRAM cell or device can reliably hold data and several studies [4-6] have reported degradation in the DRAM retention time upon exposure to radiation such as X-rays. Measurement of other timing parameters, such as t_{ac} (access time) and t_{rp} (precharge time), had been made in prior X-ray experiments; however, no significant shifts were observed. As such, only t_{ref} appears to be the most sensitive parameter. Since leakage is a strong component of refresh characteristics, it is believed that the increase in reverse junction leakage is the most probable cause for t_{ref} degradation after subjecting DRAM components to X-ray radiation [1].

The DRAM damage due to irradiation poses a significant challenge to the inspections of BGAs with on-package DRAM to produce an image quality that is needed for providing the necessary information regarding the physical defects present e.g., voids in solder joints after SMT assembly. As BGA pitch reduces it is becoming increasingly necessary to go higher magnifications which reduce the distance between the package and the X-ray source and hence leads to higher dosage. In addition to developing methods to inspect the packages, it is also crucial to characterize the functional performance of DRAM upon X-ray exposure.

This paper provides an in-depth analysis of the factors influencing X-ray inspection of BGAs, focusing on key variables such as the type and thickness of the X-ray filter material, the thickness of the circuit board, and the duration of the inspection process. It also examines the impact of X-ray power and voltage settings on the inspection quality. By understanding how these parameters affect the inspection outcomes, the study aims to optimize the X-ray inspection process for better accuracy and reliability. Additionally, the paper outlines strategies for mitigating radiation damage in BGAs, considering three different construction types. These mitigation techniques are crucial for preserving the integrity and functionality of DRAM during inspection. A test setup was also developed to detect changes in functional performance of the DRAM when exposed to increasing levels of radiation.

EXPERIMENTAL METHOD

Radiation measurement was performed using a widely used Thermo-luminescent detector (TLD) with an accuracy of +/- 5% and a minimum reportable dose of 0.01 rad. TLDs are a useful dosimeter choice, as they are simple to use and good for measuring integrated dose applications. Their principle of operation is to create "color centers" within their crystal structure when ionizing radiation, the x-rays in our case, are absorbed. Subsequent heating of the TLD material releases the stored photons created by the radiation, as each color center is driven back to its lowest energy state. The results (photons = dose) from the test sample can then be referenced against a calibration table for the TLDs used [4]. The dosimeter was attached to the area of interest where radiation needed to be measured using a Kapton tape. Radiation was measured in both types of machines- Automated X-ray Inspection (AXI or 3D X-ray) and Manual X-ray Inspection (MXI or 2D X-ray).

Table 1. DOE table for radiation exposure

Filter Material	Filter thickness (mm)	Inspection time (sec)	Tube Voltage (kV)	X-ray power (W)	# of Runs	Comments
No Filter	0	55	120	14.5	2	Filter material & thickness
Aluminum	1.6	55	120	14.5	2	
Zinc	1.6	55	120	14.5	2	
Copper	1.6	55	120	14.5	2	
Aluminum	4.8	55	120	14.5	2	
Aluminum	4.8	135	120	14.5	2	Inspection Time
Aluminum	4.8	255	120	14.5	2	
Aluminum	4.8	315	120	14.5	2	
Aluminum	4.8	75	160	20.0	1	Tube Voltage& Power
Aluminum	4.8	75	140	14.5	1	
Aluminum	4.8	75	160	14.5	1	
Aluminum	4.8	75	140	17.5	1	
No Filter	0	75	160	20.0	1	
No Filter	0	75	160	14.5	1	

Three BGAs with different geometries of board and substrate were chosen for evaluation of the dosage experienced by on-package DRAM. BGA #1 had a 0.58mm thick substrate and was placed on a 10L 0.6mm thick PCB. BGA #2 had a 1.56mm thick substrate and was placed on a 16L 1.58mm thick board. BGA #3 had a 2.27mm thick substrate and was assembled on a 28L 3.175mm thick board. All three BGA construction types serve as test vehicles that have the on-package DRAM memory completely exposed. If there is a heat spreader (IHS), then it could provide additional shielding from the X-ray radiation and that is not in the scope of this paper. The radiation absorbed by the on-package DRAM was characterized for the 3 BGA construction types in a typical AXI as well as MXI scans.

A 10L 0.5mm thick PCB with BGA #1 assembled on it was used to characterize the influence of various inspection parameters on the X-ray dosage. Table1 shows the various parameters that were varied to characterize the effect of the radiation. All these DOEs were conducted in a 2D X-ray (MXI) machine so that the various parameters can be controlled more accurately. Three types of filter materials namely Aluminum, Copper and Zinc were evaluated for their efficacy in shielding radiation. The inspection time, X-ray power, tube voltage was also varied on the machine. Different board thickness was also tested under the same inspection conditions to characterize the impact of the PCB material on radiation absorption.

A functional test was set up using a validation platform hardware that contained a motherboard, heatsink, keyboard, monitor, mouse and SSD. The hardware setup is equivalent to a functional laptop or desktop installed with Windows Operating system. Functional SOC with memory on package will then be installed on this socketed motherboard and tested using MemTest86. MemTest86 is an open-source memory testing tool for memory diagnostics, was used to test if the DRAM had errors upon exposure to radiation.

Figure 1. Functional test set-up for DRAM performance

RESULTS AND DISCUSSION

Figure 2 (a) and (b) show the dosimeter locations on BGA #1. Pos A is on the PCB on the same side of the board as the BGA, Pos B is on the memory and Pos C is on the PCB on side of the board opposite to that of the BGA. Figure 2 (c) and (d) show the locations of the dosimeters with respect to the X-ray source on both the 2D X-ray and 3D X-ray machines. The 3D X-ray machine has a 0.5mm thick Aluminum on-unit filter attached to the X-ray source while additional filters can be added to the 2D X-ray machine as needed. Figure 2 (e) shows the dosage readings for the BGA #1. The readings show that PCB absorbs a significant amount of radiation and that Al filters help reducing the dosage.

Figure 3 (a) and (b) show the dosimeter locations on BGA #2. Pos A is on the PCB on the same side of the board as the BGA, Pos B is on the memory and Pos C is on the PCB on side of the board opposite to that of the BGA. Figure 3 (c) and (d) show the locations of the dosimeters with respect to the X-ray source on both the 2D X-ray and 3D X-ray machines. Figure 3 (e) shows the dosage readings for the BGA #2. The readings also show that PCB absorbs a significant amount of radiation and that Al filters help reducing the dosage.

Figure 4 (a) shows the dosimeter locations on BGA #3. Pos A is on the Si, Pos B is on the memory and Pos C is on the PCB on the same side of the board as the BGA. Figure 4 (b) shows the dosage readings for the BGA #3. In the case of a 3D X-ray scan, the readings are highest for Pos C as expected as there is more material absorbing radiation on Pos A and Pos B. However, for the 2D X-ray the order of readings is reversed. Pos A sees the highest radiation even though it is the most shielded. This is because the amount of dosage absorbed also depends on the method and the actual path of the X-ray scan.

Figure 5 provides a detailed analysis of various factors affecting dosage in X-ray imaging. In Figure 5 (a), the impact of different filter materials on dosage is highlighted, showing that copper is the most effective material for reducing dosage. This suggests copper's superior filtering capability in attenuating X-rays compared to other materials. However, Figure 6 shows the image quality with the three materials of equal thickness and although Copper provides the most shielding from radiation, it is quite ineffective to produce the image quality needed for inspection. Aluminum on the other hand seems to provide effective shielding and preserve the image quality as seen in Figure 6.

Figure 5 (b) examines the influence of tube power and voltage on dosage. It reveals that while tube power significantly affects dosage at a constant tube voltage, variations in tube voltage have a minimal impact on dosage when X-ray power is kept constant. Figure 5 (c) demonstrates a linear relationship between inspection time and dosage, indicating that longer exposure leads directly to higher dosage. Lastly, Figure 5 (d) illustrates a decreasing exponential relationship between board thickness and dosage, suggesting that beyond a certain thickness increasing the thickness has diminishing effect to reduce dosage.

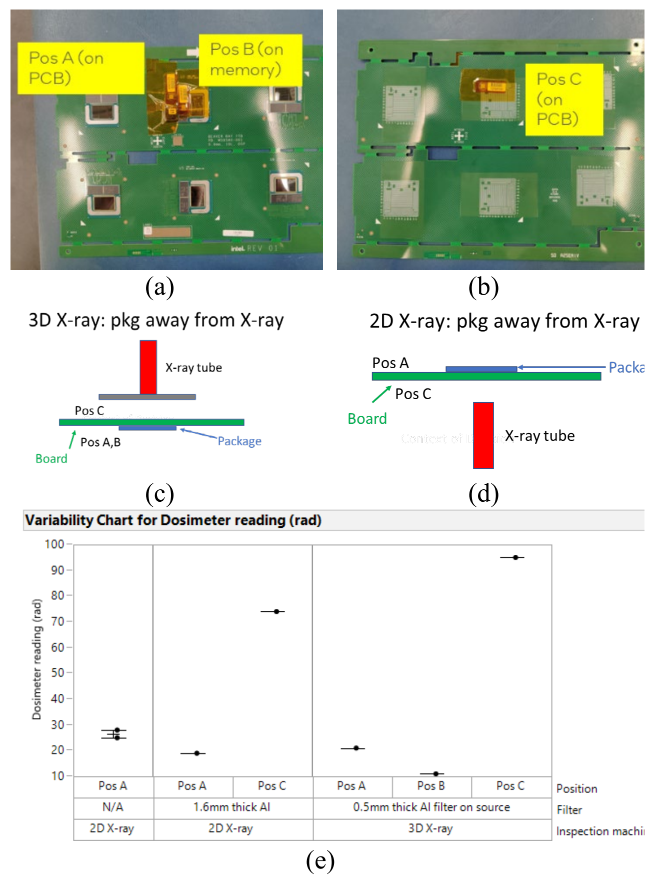
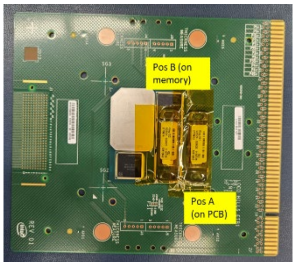
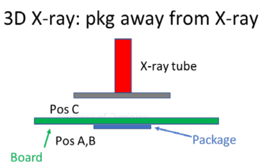


Figure 2. BGA #1 results. (a) and (b) Position of dosimeters on the BGA. (c) and (d) Positions of dosimeters with respect to the X-ray source. (e) TLD readings in 2D X-ray (MXI) and 3D X-ray (AXI) machines with different filters.



(a)

(b)



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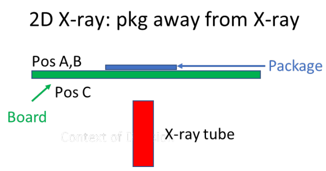

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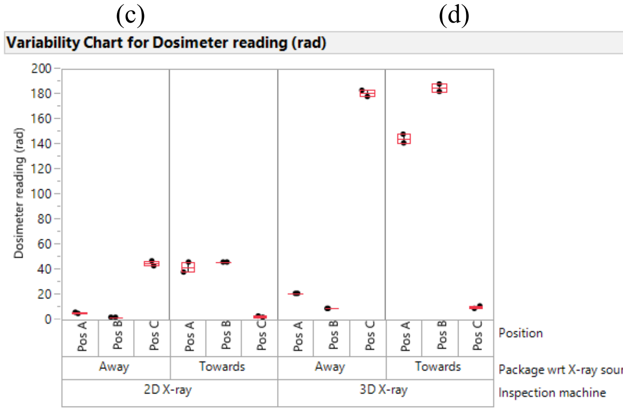
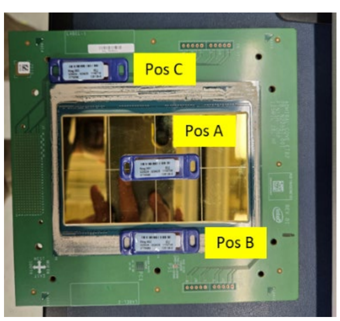
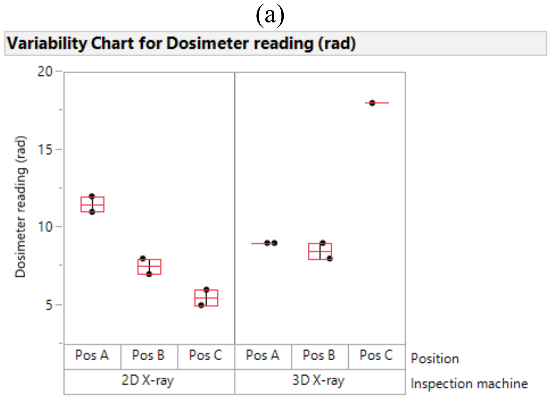


(e)

Figure 3. BGA #2 X-ray dosage results.

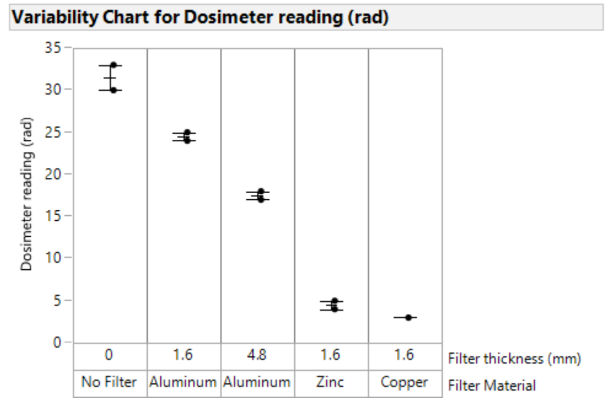


(a)

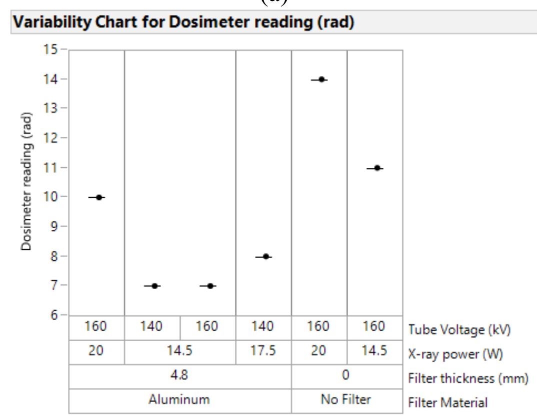


(b)

Figure 4. BGA #3 X-ray dosage results. Package is facing away from X-ray source in both machines.



(a)



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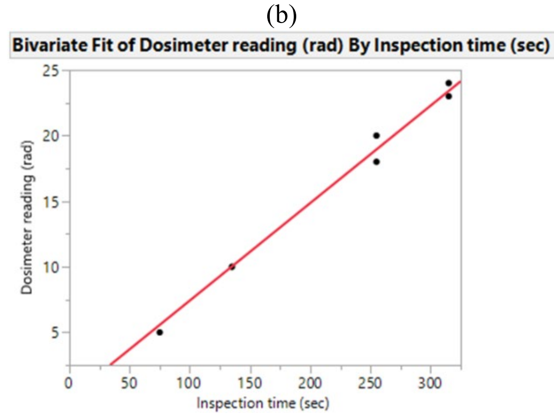

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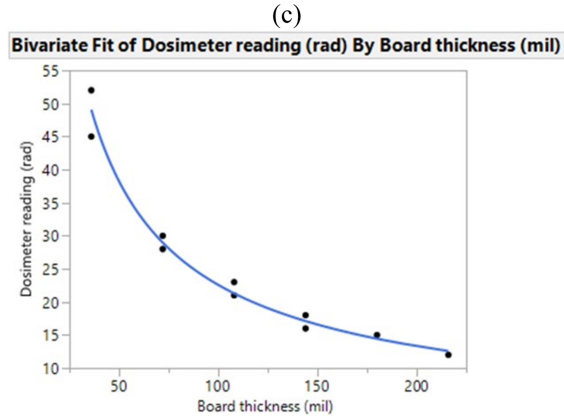

(d)

Figure 5. Dependence of dosage on (a) Filter material and thickness, (b) Tool parameters for inspection, (c) Inspection time and (d) Board thickness.

The results from the functional test are shown in Figure 7. The BGA with on-package DRAM was exposed in increments of 50 rad and after subsequent exposure the performance was measured using the test setup shown in Figure 1. There were no errors recorded by MemTest86 after any of the exposures as shown in Figure 7. Even after total exposure of 350 rads, MemTest86 gave no errors on the DRAM. The results indicate that even after overexposure to 3 times the limit provided by DRAM manufacturer, no infant mortality failures were observed. However, the reliability of the DRAM over longer periods of usage may be reduced.

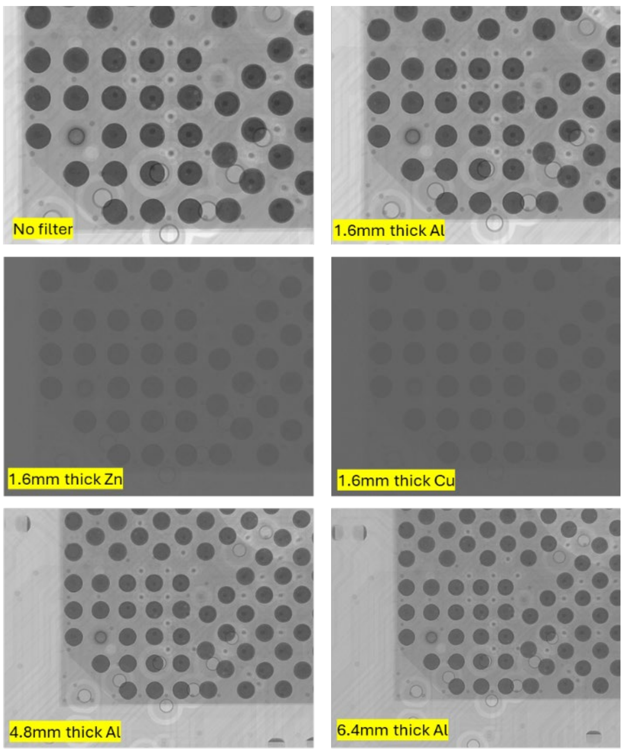

Figure 6. 2D X-ray images with various filter materials and thicknesses.

Test Start Time	2024-07-10 12:01:37
Elapsed Time	2:04:06
Memory Range Tested	0x0 - 87F800000 (34808MB)
CPU Selection Mode	Parallel (All CPUs)
CPU Temperature Min/Max/Ave	-/-/-
Lowest memory speed	7200 MT/s (80-68-68-152)
Highest memory speed	7200 MT/s (80-68-68-152)
# Tests Completed	36/36 (100%)
# Tests Passed	36/36 (100%)

Test	# Tests Passed	Errors
Test 0 [Address test, walking ones, 1 CPU]	3/3 (100%)	0
Test 1 [Address test, own address, 1 CPU]	3/3 (100%)	0
Test 2 [Address test, own address]	3/3 (100%)	0
Test 3 [Moving inversions, ones & zeroes]	3/3 (100%)	0
Test 4 [Moving inversions, 8-bit pattern]	3/3 (100%)	0
Test 5 [Moving inversions, random pattern]	3/3 (100%)	0
Test 6 [Block move, 64-byte blocks]	3/3 (100%)	0
Test 7 [Moving inversions, 32-bit pattern]	3/3 (100%)	0
Test 8 [Random number sequence]	3/3 (100%)	0
Test 9 [Modulo 20, ones & zeros]	3/3 (100%)	0
Test 10 [Bit fade test, 2 patterns, 1 CPU]	3/3 (100%)	0
Test 13 [Hammer test]	3/3 (100%)	0

Figure 7. Reference test from Memtest86 showing the DRAM passing with no errors after an exposure of 350 rads.

SUMMARY

This paper outlines several mitigation strategies for minimizing radiation dosage during X-ray inspections, particularly in the context of printed circuit boards (PCBs). One key observation is that the PCB itself acts as an effective shield, significantly reducing radiation exposure. This relationship is shown in Figure 8. This protective effect was clearly demonstrated in the experimental results, highlighting the importance of considering the board's material properties during inspection. The study also examined the impact of inspection time on dosage, revealing a direct correlation—longer inspection times result in higher radiation exposure. This finding emphasizes the need to optimize inspection duration to minimize dosage without compromising the thoroughness of the inspection. Another critical factor discussed is the choice of filter material. Copper was identified as the most effective filter for shielding radiation, significantly reducing dosage levels. However, this reduction in dosage comes at a cost, as the images produced with copper filters were of very poor quality due to the diminished X-ray penetration.

Additionally, the paper explores the relationship between material thickness and dosage, finding that this relationship follows a decreasing exponential trend. As material thickness increases, the reduction in dosage becomes marginal, indicating diminishing returns with further thickness enhancements.

This paper also investigated the radiation tolerance of PCB assemblies housing BGAs with on-package memory. It was noted that there was no initial degradation of the performance of the DRAM observed even after over exposure to several times the recommended limit of DRAM exposure from manufacturer.

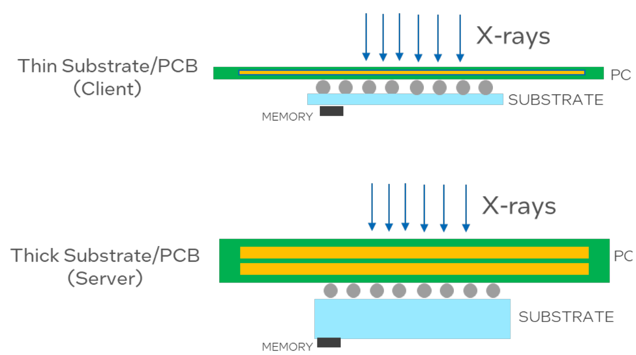

Figure 8. Effect of board and substrate geometries on the X-ray dosage absorbed by DRAM.

FUTURE WORK

More extensive research is needed to fully understand how overexposure affects the functional performance of DRAM. This includes conducting detailed failure analyses to identify specific performance degradation that may occur. Additionally, it is crucial to perform aging studies to assess the long-term reliability of these devices. Such studies will help determine how DRAM components behave over time after being initially exposed to radiation.

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