Overview of Radiation Dose During X-ray Inspection of Electronics

Nordson Internal White Paper

Overview

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X-ray imaging of semiconductor and electronic devices is an invaluable tool; enabling non-invasive sub-surface inspection, identification of defects and measurement of critical dimensions. Figure 1 shows a schematic and description of a typical X-ray inspection system for electronics and semiconductor devices. Unfortunately, semiconductor devices are sensitive to sustained radiation dose, which if too high, can cause current leakage, damage, and ultimately failure of the component or device. This overview paper describes the fundamental mechanism for radiation damage in semiconductor devices; typical dose tolerance limits of electronics; how to measure and model radiation dose levels; and methods for reducing dose during X-ray inspection.

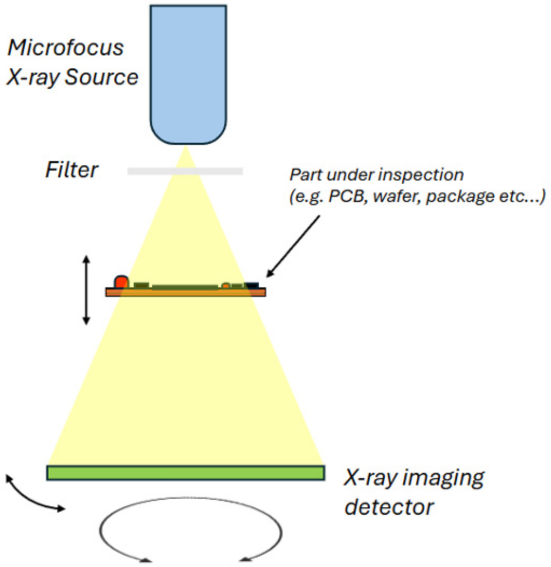

Figure 1. *Schematic of a typical electronics X-ray inspection system. A microfocus source shines X-rays on to a part under inspection (e.g. printed circuit board, silicon wafer, packaged device etc…). A detector records an image of the attenuated X-ray beam, revealing the internal structure of the object. By moving the object closer to the X-ray source, higher geometric magnification can be achieved and therefore a higher resolution image of the object can be formed. Adding a filter material into the beam is a good way of removing low energy 'soft' X-rays and reducing radiation dose. Inclined imaging (often referred to as 2.5D imaging) can be performed by tilting the part or x-ray detector. 3D imaging can be performed by rotating the detector around an axis on a plane, similar to computed tomography, to get a three-dimensional view of the internal structure of the part. This limited angle tomography is often called laminography.*

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X-ray radiation damage in semiconductor devices

X-rays are a form of ionising radiation which means they excite and eject electrons from atoms to create ions. In semiconductor materials, ionisation means the creation of electron-hole pairs (see Figure 2), promoted into the conduction and valence band, respectively. This electronic charge would normally recombine, meaning no lasting damage. However, in transistors such as Metal Oxide Semiconductor Field Effect Transistors (MOSFETs), the electronic charge can get trapped at defects and interfaces, such as at the gate oxide SiO2/Si interface. This trapped charge builds up with continued radiation exposure and starts to create its own in-built electric field. This electric field can then affect the gate voltage thresholds and therefore the performance of the transistor. If sufficient charge is built up the transistor can fail to operate. At the device level, if many transistors are rendered ineffective, the whole device will fail (1). For memory devices, such as dynamic random-access memory (DRAM), the retention time of memory cells drastically reduces with increasing absorbed dose (2), leading to a loss in memory.

Radiation dose units

Radiation dose is a measure of the amount of energy imparted to a volume of material, measured in units of Joules per unit Mass. It is traditionally reported in terms of a volume of Air – often quoted as Kinetic Energy Released per unit Mass (KERMA). Air Kerma has SI units of 1 Joule per Kilogram of Air = 1 Gray [Gy]. It is possible to convert Air Kerma to a figure for absorbed dose in another material, for example Silicon. This conversion considers the relative difference in the mass-energy attenuation coefficient of the material compared to Air. For Silicon, the conversion is approximately a factor 7.2 for X-ray energies in the 10-100 keV range, energies often used in X-ray inspection systems. Absorbed dose to Silicon is often reported in the older CGS unit of [rad], typically quoted as kilo rads of Silicon [krad(Si)]. An approximate conversion factor is: 1 Gy Air Kerma = 0.72 krad(Si). Most research studies into radiation effects in semiconductors and electronics from the likes of NASA (3), use the unit of krad(Si) when quoting dose levels to electronics. Whereas the majority of dosimeters report dose as Air Kerma in units of mGy or Gy. It is important to make the correct distinction and conversion between Air Kerma and Silicon absorbed dose when reporting dose levels.

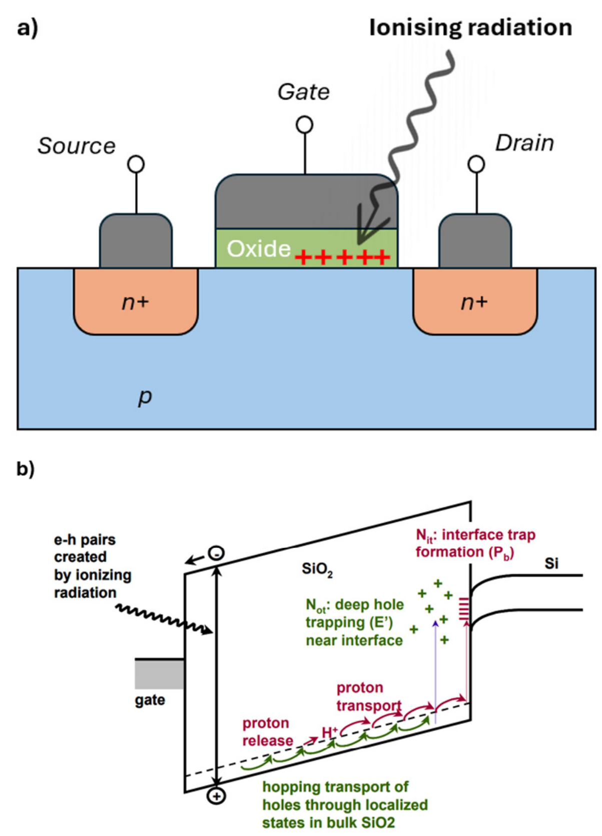


Figure 2. *Schematic of a MOSFET device under irradiation from ionising radiation. Positive charge builds-up within the oxide layer at the interface to the p-silicon. b) Band diagram of a MOSFET device with positive gate bias showing the effect of ionizing radiation on carrier generation, transporting and trapping. [Figure b) copied from (1)] .*

Dose tolerances

Understanding dose tolerances in electronic devices is a complex and in-depth topic; depending on technology (e.g. MOS, Bipolar etc), process node scale (e.g. 14nm, 10nm, 7nm etc...), and device structure. There are many published in-depth review studies, such as in references (4) (5). Much of the research has come from the aerospace community, where electronics are exposed to a myriad of space radiation (protons, neutrons, electrons, X-rays, gamma-rays) inside a satellite or space rockets. In space, there is no opportunity to replace or repair electronic components, so knowing dose tolerances is very important.

As a rough rule of thumb, so-called “rad-hard” electronics for aerospace applications are typically designed and qualified to have Total Ionisation Dose (TID) thresholds >100 krad(Si) before failure. Most commercial-off-the-shelf (COTS) electronics have dose thresholds in the range of 5– 50 krad(Si) before failure. Whereas consumer electronics would typically be reliable up to 5 krad(Si) level. Some technologies can be highly dose sensitive however, such as volatile memory (e.g. DRAM), which have low dose tolerance levels, sometimes below 1 krad(Si). (3)

It should be noted that most of the research around radiation tolerances of electronics is conducted with the devices powered-on, to simulate their operational environment (biased devices); whereas during X-ray inspection, the devices will typically be switched off (unbiased). In a biased device, the applied internal electric fields which operate the transistor act to separate electrons and holes in opposite directions, reducing their probability for recombination and therefore increasing their chances of trapping. Subsequently, the magnitude of radiation damage can be higher in biased devices than in un-biased devices. In some cases, the dose tolerances can be as much as 10 times higher in unbiased devices (6). Electronics can also have dose-rate dependencies; for example, having a lower dose tolerance at high dose rates (HDR). In some devices the phenomenon is reversed, the so-called Enhanced Low Dose Rate Sensitivity (ELDRS), whereby the limit of tolerance is lower at lower dose rates. It all depends upon the device structure and technology. X-ray inspection systems would normally be considered to deliver high dose rates, typically greater that 1 rad(Si)/s.

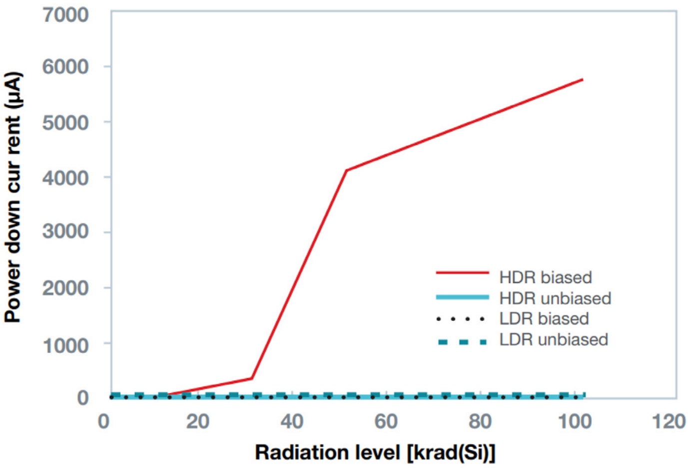


Figure 3. *Effect of bias voltage and dose-rate on a device (DAC121S101QML-SP). With the unit powered up during irradiation (biased), at high dose rates the device starts to show degradation above 20 krad(Si) (red line). Whereas if the leads are grounded during irradiation (unbiased) then the device is very dose tolerant, showing no degradation up to 100 krad(Si). At low dose rates, the device appears unaffected either biased or unbiased, up to at least 100 krad(Si). HDR corresponds to 165 rad/s and LDR corresponds to 0.01 rad/s. Figure reproduced from (6).*

Measuring dose

It is important to know how much radiation dose is being delivered to the device or component during X-ray inspection. Table 2 gives a comparison of the common types of dosimeters with their relative strengths and limitations.

The traditional way of measuring radiation dose is to use an ionisation chamber, which has a volume of air (or gas) between two metal electrodes, which are biased to high voltages. Ionised charge is generated inside the volume of gas from the incoming radiation, which gets swept towards the electrodes. A recording of the electrical current generated can then be converted to a value for dose. The ion chambers are accurate and easy to calibrate, but the downside is the requirement for a connecting electrical cable, making it difficult to do in-situ measurements.

Another type of dosimeter are solid-state diode detectors, which have small footprints and can be used with a live digital readout. They typically offer additional features such as the ability to measure beam quality metrics, such as total filtration, half value layer thickness, and peak acceleration voltage from an X-ray tube. As such, diode dosimeters are widely used for characterising X-ray tube output, particularly in the medical X-ray equipment sector. However, diode detectors are typically not sensitive to low energy ‘soft’ X-rays and in most cases require a connecting cable meaning limitations for in-situ measurements.

MOSFET detectors are a similar type of solid-state detector, based on the principal of measuring the change in capacitance of the gate insulator in a MOSFET device. They are compact and offer rapid readout but have limited lifetime (up to about 100Gy) due to radiation damage.

The final type of dosimeter discussed here are portable luminescent-based dosage tags. These are normally used for personal dosimetry in a medical or industrial environment. They work on the basis that the radiation is absorbed in a material and can be later luminescently released by either thermal stimulation (Thermoluminescent Dosimeters (TLD’s)) or optical stimulation (Optically Stimulated Luminescent dosimeters (OSL’s)). These have the advantage of being very small and highly portable and so can be attached to a PCB for example and sent through an X-ray inspection system for in-situ measurements. The downside is that they must be individually calibrated and, in most cases, sent off for measurement by a third party. They also typically report out as personal dose equivalent (absorbed dose to human soft tissue)

– either as Hp(10), absorbed dose 10mm below the surface of soft tissue; or as Hp(0.07), skin dose 0.07mm below the surface (7). Both are measured in units of milliSieverts. These figures must be converted to Air Kerma to have any relevance to X-ray inspection of electronics, but this conversion is not straight-forward and can lead to inaccuracies. There are intricacies to how these dose tags are calibrated, such as what mounting medium is used: plastic slabs, rods or cylinders to emulate back-scatter from human body parts (thorax, head or wrist), and the angle of incidence response leads to different outputs. In addition, their energy response can be non-linear, so great care must be taken to use a relevant and accurate energy calibration in-line with the spectral output of the X-ray tube.

Type	Description	Advantages	Limitations
Ionisation Chamber	Measure charge generated between two biased electrodes inside a chamber of gas. Often used as reference dosimetry.	Accurate Low energy dependence	Not wireless
Diode Detectors	Measure charge generated across solid-state semiconductor diode. Widely used in medical and radiation therapy sectors.	Small Live readout Beam quality metrics	Optimised for medical dosimetry Energy dependence Not wireless
MOSFET detectors	Measure the modified capacitance in the gate of the insulator of a MOSFET.	Small Live readout	Limited lifetime Energy dependence
Luminescent Dosimeters (e.g. TLD, OSL)	Release stored energy in the form of luminescence via heating or optical stimulation. Typically used for personal dosimetry.	Small Wireless Re-useable	Optimised for personal dosimetry Delayed readout Signal loss over time Energy dependence Careful calibration required

Table 2. *Comparison of common dosimeters.*

Simulation of Radiation Dose

Another strategy to understand the amount of radiation dose likely to be delivered is to simulate the X-ray physics and calculate the expected dose. The core equation for calculating Air Kerma dose is shown below:

$$K_{Air} = \Phi E \left(\frac{\mu_{en}}{\rho}\right)_{Air}$$

Where:

Φ is the photon fluence

E is the energy of the X-ray photon

$\left(\frac{\mu_{en}}{\rho}\right)_{Air}$ is the mass energy attenuation coefficient of Air.

The above equation needs to consider the full spectrum of X-ray energies released from a polychromatic X-ray tube. It is possible to use a Monte Carlo simulation of the X-ray tube emission spectrum, combined with the energy-variant mass energy attenuation coefficients for Air, to obtain a calculation of the Air Kerma. For calculating photon fluence, the simulation should consider physical parameters like the peak acceleration voltage of the X-ray tube (kVp), power of the X-ray tube (measured in Watts), the distance from the source focal spot to the object (considering the inverse square law) plus any X-ray filtration placed in the beam.

Figure 4 shows an example of the calculated radiation dose 237mm from a microfocus X-ray tube operating at 3 Watts target power, including filtration of 1mm Al. Experimental data is captured using a Raysafe X2 R/F semiconductor diode dosimeter. There is good correlation between experiment and simulation with a mean absolute percentage error of 11.5%. This plot demonstrates that it is possible to accurately simulate the radiation dose from an X-ray source, given correct input parameters.

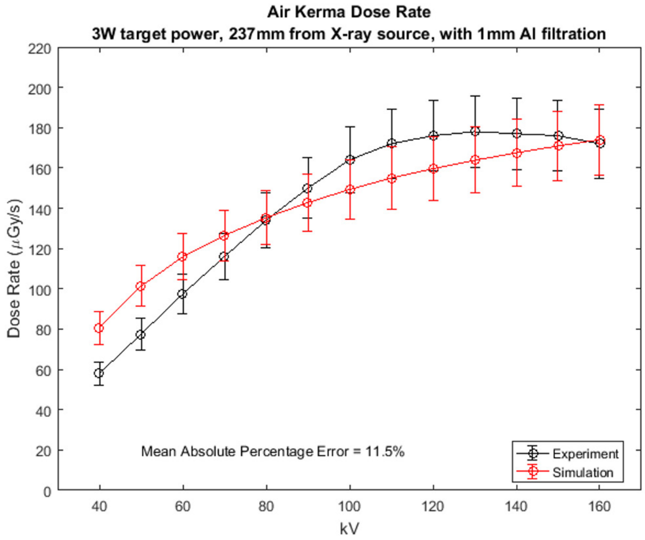
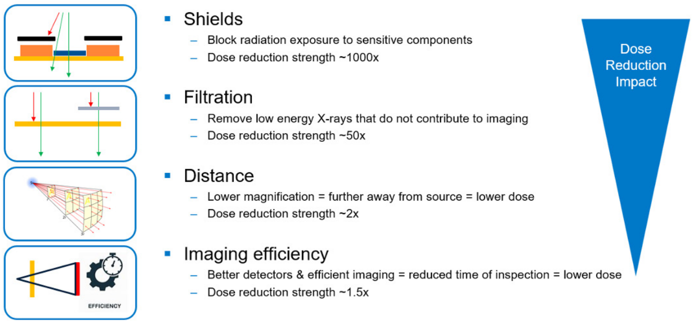


Figure 4. *Simulated vs experimentally measured Air Kerma dose rate. Error bars are plotted as +/- 10%.*

There are certain limitations to simulating the radiation dose, for example it is difficult to simulate scattered radiation without a full 3D CAD model of the inspection system and product to be inspected, which would also require a full Monte Carlo simulation. This calculation would be complex and computationally expensive. However, in most cases the scattered radiation can be ignored, since it is likely to be a low proportion of the total radiation. The reason for this is that semiconductor and electronic devices generally have thin cross sections (<1cm) and are made of higher atomic number materials, where the main interaction mechanism is photelectric absorption and not scattering.

Dose Reduction Strategies

In an X-ray inspection system, there are many ways in which to reduce the radiation dose delivered to an electronic component. Figure 5 gives an infographic summary of the main methods for reducing dose in an X-ray inspection system.



- Shields
  - Block radiation exposure to sensitive components
  - Dose reduction strength ~1000x
- Filtration
  - Remove low energy X-rays that do not contribute to imaging
  - Dose reduction strength ~50x
- Distance
  - Lower magnification = further away from source = lower dose
  - Dose reduction strength ~2x
- Imaging efficiency
  - Better detectors & efficient imaging = reduced time of inspection = lower dose
  - Dose reduction strength ~1.5x

Figure 5. *Infographic showing the strongest strategies for reducing dose in an X-ray inspection system.*

The strongest way to reduce dose is to block the direct radiation from hitting the electronics. This can be achieved by using high density radiation shields to protect sensitive parts that do not need to be inspected. Using a shielding material of Tungsten placed in strategic locations - for example on top of High Bandwidth Memory (HBM) modules - can spare the HBM modules from excessive radiation dose. Tungsten is a high atomic number element with a very high density and dose reduction factors >5000 times can be achieved with sub-millimetre thick shields. The main limitations of using shields are that it limits the X-ray inspection to areas that are not shielded and there is no dose reduction to the regions that you are inspecting.

An effective dose reduction strategy is to use X-ray filtration which removes the lower energy X-rays from the tube emission spectrum. These low energy X-rays cause high levels of radiation dose because they are easily absorbed inside silicon, meaning more ionising radiation damage. The thickness and material of the X-ray filter must be carefully considered; too thin and the dose will not be reduced by an appreciable amount, whereas too thick and the X-ray beam quality will be degraded, making inspection difficult. Typical filtration materials are medium density elements, such as Aluminium, Copper, Zinc or Tin. Figure 6 shows the impact of adding an X-ray filter to the beam prior to the sample, removing the low energy X-rays at around 10keV that do not contribute to imaging and only cause a high radiation dose.

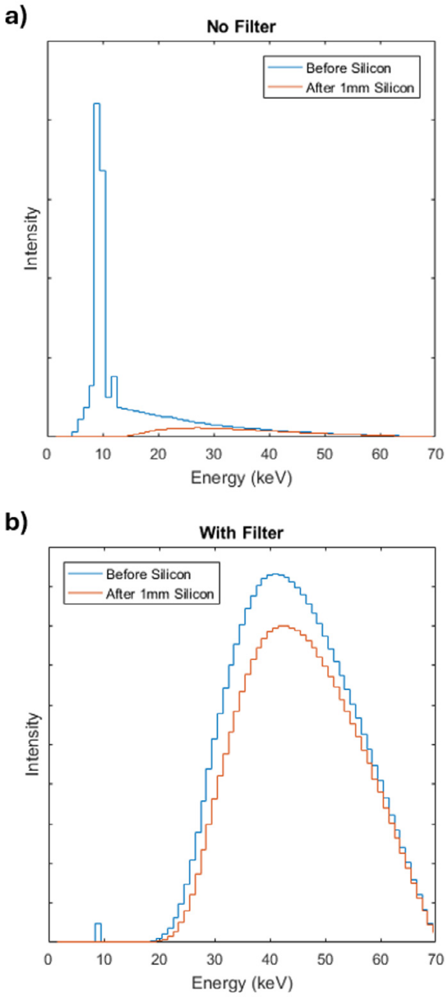


Figure 6. *Impact of an X-ray filter on the transmitted X-ray spectrum through 1mm of Silicon (70kVp, 3W, 50mm SOD). Without an X-ray filter (a) there is a large proportion of low energy X-rays around 10keV that do not make it through the silicon. These low energy X-rays are therefore completely absorbed inside the silicon and contribute a high level of radiation dose. Whereas by adding a 0.2mm of Cu filtration (b) the low energy X-rays are removed from the beam prior to hitting the sample, meaning the dose rate is reduced by a factor of about 200 times.*

An often-overlooked factor for reducing radiation dose is having high performance X-ray detectors coupled with a fast and efficient imaging chain. This enables the X-ray system to rapidly capture the inspection images with little deadtime and reduce the overall time the part is exposed to radiation. Small pixel detectors also have an advantage; they enable high resolution without the object being close to the X-ray source (lower geometric magnification). Considering the inverse square law, if the object can be moved 2x times further away from the source, then the dose would be reduced by 4x times. This can be facilitated by small pixel high resolution, high efficiency and low noise detectors.

Another consideration is which side of the component you are inspecting. For example, consider a printed circuit board with dose sensitive components facing upwards, as shown in Figure 7. If the X-ray imaging chain is in a top-down configuration (with X-ray tube on top, pointing downwards, and detector underneath) - then the components are exposed to a full radiation field. However, if the PCB is flipped over such that the dose sensitive components are underneath, then the X-ray beam must travel through the bulk of the PCB prior to interacting with the dose sensitive components. In effect, the PCB substrate acts as an additional X-ray filter, removing lower energy X-rays and therefore reducing the dose delivered to the components.

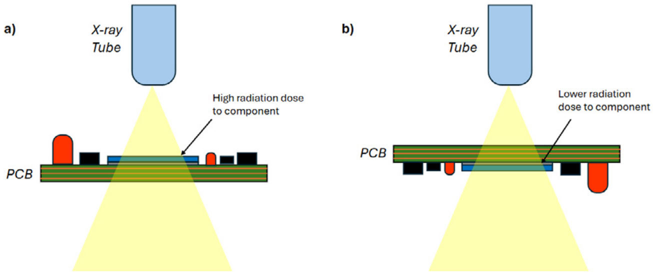


Figure 7. *A) Top-down imaging set-up.*
B) PCB is flipped over (bottom-up imaging).

Finally, having an in-situ dose management and monitoring system, where a live readout of the dose rate and total accumulated dose, ideally with spatial mapping. Having the ability to quickly switch off X-rays once a dose threshold is reached, or if there is a pause in the inspection routine, is a useful tool to reducing the total exposed dose of the part under inspection.

Conclusion

This paper has given an overview of radiation dose during X-ray inspection of electronics and semiconductors. The mechanism for radiation damage in semiconductor devices is via the creation of trapped charge inside the transistor, which in turn affects the performance of the device. Dose tolerances for different types of electronics varies widely; depending upon device technology, architecture and process node size. Generally speaking, radiation hardened electronics for aerospace applications typically have dose tolerances greater than 100 krad(Si). On the other end of the scale, memory devices are much more dose susceptible, where tolerances can be as low as 1 krad(Si). Measuring radiation dose is another in-depth topic; with a range of dose units available, whether you are measuring Air Kerma or absorbed dose, and differences in measuring equipment. This paper has also described how it is possible to simulate the expected radiation dose delivered during an inspection and presented results on the accuracy of the simulations to experimental data. Finally, methods for reducing dose during X-ray inspection have been described, such as using X-ray filters or high-density radiation shields.

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