JEDEC STANDARD

Test Method for Total Ionizing Dose (TID) from X-ray Exposure in Terrestrial Applications

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TEST METHOD FOR TOTAL IONIZING DOSE (TID) FROM X-RAY EXPOSURE IN TERRESTRIAL APPLICATIONS

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TEST METHOD FOR TOTAL IONIZING DOSE (TID) FROM X-RAY EXPOSURE IN TERRESTRIAL APPLICATIONS

Foreword

Within the JC-14 ‘Quality and Reliability of Solid State Products’, the Task Group on ‘X-ray Terrestrial Ionization Radiation Test Procedure’ TG141.1 committee was initiated and validated during the JC-14.1 ‘Reliability Test Methods / Packaged Devices’ meeting number 129 in January 2022. A liaison with JC- 13.4 sub-committee has been established to take advantage of its Rad-Hard’s expertise.

The test method of this standard defines the testing requirements to measure the parasitic radiation dose deposited and determine any consequential damage or effects to semiconductor devices exposed to X-ray imaging during normal manufacturing, inspections, and Surface Mount Technology (SMT) processes. The objective is to determine the Total Ionizing Dose (TID) limit (as a failure limit or a supplier limit) due to X-ray exposure in terrestrial applications.

TEST METHOD FOR TOTAL IONIZING DOSE (TID) FROM X-RAY EXPOSURE IN TERRESTRIAL APPLICATIONS

From JEDEC Board Ballot JCB-23-51, formulated under the cognizance of the JC-14 Committee on Quality and Reliability of Solid State Products.

1 Scope

This test method covers X-ray imaging for terrestrial applications on packaged devices but does not exclude the option to characterize on bare die or wafers as long as potential dose absorption or amplification effects are considered in the final assessment.

Terrestrial X-ray-imaging techniques are suitable for finding hidden defects in buried structures within Integrated Circuit (IC) packages. These techniques are complementary to the optical-inspection techniques used to find surface defects.

The X-ray system targeted for semiconductor product inspection can be used to replicate total cumulative dose for any X-ray exposure system (e.g., scanner imaging during shipping with IC devices inside, solder-joint inspection, and returned-material analysis) for characterization of dose effects.

2 References

Informative:

The following documents contain provisions that, through references in the text, are informative in this standard. At the time of publication, the editions indicated were valid. All standards are subject to revisions.

[1] T.R. Oldham, "Basic Mechanism of TID and DDD Response in MOS and Bipolar" NEPP.NASA.GOV Files, 2011

[2] D.M. Fleetwood, "Evolution of Total Ionizing Dose Effects in MOS Devices with Moore's Law Scaling", IEEE Trans. Nucl. Sc., vol. 65, nº. 8, August 2018

[3] N. Wrachien, "Investigation of Proton and X-ray Irradiation Effects on Nanocrystal and Floating Gate Memory Cell Arrays", IEEE Trans. Nucl. Sc., vol. 55, nº. 6, December 2008

[4] Md Mahbub Alam, "Impact of X-ray Tomography on the Reliability of Integrated Circuits", IEEE Trans. on device and materials reliability, vol. 17, nº. 1, March 2017

[5] A. Ditali, MICRON Tech., "Kinetic Analysis of X-ray Irradiation Induced Static Refresh Failure Mechanism in DRAM", IEEE 45th Annual Int. Reliability Physics Symposium, 2007

[6] R.K Lawrence, "TID Considerations in Space Bound Electronics Subjected to Real Time X ray Radioscopic Examinations", IEEE Radiation Effects Data NSREC Conference, 2011

2 References (cont'd)

[7] G. Borghello, "Dose-Rate Sensitivity of 65-nm MOSFETs Exposed to Ultrahigh Doses", IEEE Trans. Nucl. Sc., vol. 65, n° 8, August 2018

[8] X. Wang, "Accelerated Test of ELDRS of Ultralow Dose Rates for Bipolar Devices", 18th European Conference on radiation and its effects on components and systems RADECS, 2018

[9] W. Beezhold, "A Review of the 40-year History of the NSREC'S Dosimetry and Facilities Session 1963-2003", IEEE Trans. Nucl. Sc., vol. 50, nº. 3, June 2003

Normative:

The following normative documents contain provisions that, through reference in this text, constitute provisions of this standard. For dated references, subsequent amendments to, or revisions of, any of these publications do not apply. However, parties to agreements based on this standard are encouraged to investigate the possibility of applying the most recent editions of the normative documents indicated below. For undated references, the latest edition of the normative document referred to applies.

[10] NIST standard, J. H. Hubbell and S. M. Seltzer, Nat. Inst. Standards Technol., Gaithersburg, MD, USA, Tech. Rep., "Tables of X-ray mass attenuation coefficients and mass energy-absorption coefficients", 2004

[11] ISO/ASTM 51956 standard, "Practices for Use of a Thermoluminescence-Dosimetry System (TLD system) for Radiation Processing"

[12] JESD47 standard, JEDEC Standard Solid State Technology Association, "Stress-Test-Driven Qualification of Integrated Circuits"

3 Terminology

For the purpose of this standard, the following terms, definitions, acronyms, abbreviations, units and conversions apply.

3.1 Terms and Definitions

Total Ionizing Dose (TID): The absorbed cumulative dose i.e., the energy imparted by ionizing radiation per unit mass of irradiated material. The SI units for the dose is Joule per kilogram or Gray (Gy).

Kilovoltage: The energy acquired by a particle with one electron charge in passing through a potential of 1000 volts in vacuum (note: current convention is to use kV for photons and keV for electrons).

Kinetic Energy Released in Matter (KERMA): The sum of all energies released per unit mass and transferred of all the charged particles from the ionization chamber divided by the mass of the material of interest (air for example). The SI unit of air KERMA is Joule per kilogram or Gray (Gy).

3.1 Terms and Definitions (cont'd)

First Parameter to Fail: Anticipated failure to the product-specification limits during the read-out (electrical or functional). It should be noted that for a particular device type, there can be more than one parameter to fail. The first one should be used for a given part type as the limiting failure. The dose-immunity threshold is defined as the pass/fail limit based on the product specification with respect to the cumulative dose.

Supplier Limit: The supplier limit is set by the manufacturer(s) of the part. The supplier limit is typically based on the anticipated worst-case irradiation during all the X-ray inspection processes (including the in-house and customer mission profiles). It does not reflect the failure limit of the device with a stress/exposure until it fails.

Failure Limit: The failure limit is defined by the maximum dose exposure that causes the device failure according to the product-specification limits.

Enhancement Factor: The Enhancement Factor is the ratio of parametric/electrical characteristics computed between the low dose rate and high dose rate.

Bremsstrahlung: The Bremsstrahlung is the electromagnetic radiation produced by a sudden slowing down or deflection of charged particles (especially electrons) passing through matter in the vicinity of the strong electric fields of atomic nuclei.

3.2 Acronyms and Abbreviations

ATE	Automatic Test Equipment
BICMOS	Bipolar CMOS technology
CT	Computerized Tomography, X-ray system
DOE	Design of Experiment
DRAM	Dynamic Random Access Memory
DUT	Device Under Test
EEPROM	Electrically Erasable Programmable Read-Only Memory
ELDRS	Enhanced Low Dose Rate Sensitivity
FOV	Field of View
HT, RT	Hot Temperature, Room Temperature
IC	Integrated Circuit
KERMA	Kinetic Energy Released in Matter
kV, keV	kilo Volt (kV) or kilo electron Volt (keV)
LTPD	Lot Tolerance Percent Defective
μ_{en}/ρ	Mass energy-absorption coefficient (cm^2/g)
MOS	Metal Oxide Semiconductor
NIST	National Institute Standard Technology Organization
NVM	Non Volatile Memory
OSL	Optically Stimulated luminescence dosimeter
PIN diode	Positive Intrinsic Negative photo diode
PCB	Printed Circuit Board
SMT	Surface Mount Technology
t	Exposure duration time

3.2 Acronyms and Abbreviations (cont'd)

t_{REF}	Refresh time applicable for DRAM cell
TDE	Time Dependent Effects
TID	Total Ionizing Dose
TLD	Thermal Luminescence Dosimeter
Vth	Gate Voltage threshold
Zt	Sample To source distance

3.3 SI Units of X-ray Radiation

Absorbed dose unit: Gy (Gray)
Absorbed dose-rate: Gy/minute
Exposure dose unit: R (roentgen)
Exposure dose-rate: R/minute

3.4 Conversions

1 R ≈ 0.00877 Gy for X-ray absorption in air.
1 Gy = 1 joule/kg = 100 rad, 1 rad=10^{-2} Gy = 1 cGy = 10 mGy.

4 Radiation Dose Failure Mechanisms and Modes

The goal is to determine the radiation-sensitive parameters and modes after an exposure to ionizing radiation with cumulative effects. Illustrated primary parameters that can exceed specification limits after irradiation are listed in the Table 1. A radiation evaluation/assessment may be necessary to determine the level of risk or robustness. Table 1 is not exhaustive in terms of IC function/device or cell coverage nor failure modes.

Different materials absorb radiation at different rates. When the device is exposed to an X-ray source with photon energy, a parasitic dose can be deposited through the energy absorbed by the device. The cumulative or Total Ionizing Dose (TID) is the cause of failure. The induced failure mode is typically a drift in one or more electrical characteristics that causes the IC to malfunction. TID is considered to be a permanent effect on electronic devices even though some recovery may occur. Radiation damage is considered an intrinsic effect of the deposited parasitic dose.

The ionizing radiation creates electron/hole pairs. Due to low carrier mobility in dielectrics, part of these generated charges may be trapped near the Silicon/oxide interface ('border' traps) and in the volume of the gate dielectric ('bulk' dielectric traps). Apart from the built-in oxide field, having no bias applied to the device during inspection, as in case of X-ray IC packaging inspection, reduces the radiation-induced fractional-hole yield; and as such, reduces the radiation-induced damage.

These traps may modify electrical characteristics of the device or create leakage paths (within and/or between devices). Thermally-induced relaxation may be an additional consideration, with the temperature and rate depending on traps, materials, etc., but may be a consideration even at room temperature. Time-dependent effects (TDE) can be assessed (see 7.1.6) to consider such neutralization of oxide charge traps.

4 Radiation Dose Failure Mechanisms and Modes (cont'd)

To assess the critical parameter to be monitored, a full understanding of the failure modes for the products of interest need to be determined regarding the built-up dielectric charge [1], [2].

Table 1 — Most Expected Failure Modes for Major IC Device or Cell Types

Type of Device/Cell	Category	Induced Defects / Stressed Layer	Expected Electrical Failure Mode
Device	MOS [1], [2]	Trapped charge in gate dielectric	Shift of threshold voltage of transistor expected after radiation dose
		Trapped charge in field dielectric or Shallow Trench Insulator (STI)/ dielectric	Increased leakage after radiation dose between transistors isolated with the dielectric
	Bipolar [1]	Trapped charge in dielectric	Decrease of the bipolar gain (Beta, ß) link to increased base current (Ib) after radiation dose Beta (ß)=Ic/Ib, with Ic as collector current
Cell	NVM Flash/EEPROM [3], [4]	Trapped charge in oxide-nitride-oxide and tunnel dielectrics	Shift of the margin Program/High Vth after radiation dose
	DRAM [5]	Trapped charge in gate dielectric causing changes / variability in data-retention times	Refresh-interval margin (t_{REF}) of memories decreases after radiation dose

5 X-ray System Settings and Variables

X-ray photons are produced when a target material is bombarded by high-speed electrons or beam of electrons accelerated by a voltage and focused onto a metal target such as tungsten. Electrons approaching an atomic nucleus are decelerated by the nucleus electric field, which generates Bremsstrahlung. This radiation has a continuous energy spectrum. The collision of incoming electrons with shell electrons of the target material can produce X-rays of discrete characteristic energies. These energies are characteristics radiation of the used target material (Figure 1).

X-rays are directed through and around the sample are collected on a detector in the form of a shadow image. The shadow depends on the characteristics of the absorption material (bright with poor absorption and dark with higher absorption) and the output operating parameters of the X-ray tube/system (Figure1).

The relevant critical parameters of the X-ray system must be taken into consideration to assess the critical maximum dose (Table 2) according to the settings or targeted X-ray 2D/3D technique.

3D Computerized Tomography (CT) X-ray method can improve the coverage of X-ray inspection by avoiding masking/absorption interaction by other elements in a multi-level of interconnect stack (e.g., solder bump of 100 µm width masked by BGA balls of 500 µm width). This technique is used to inspect with angle views by tilting the sample or the image detector by scanning individual 2D X-ray images from a single axis of rotation.

The critical maximum dose in Table 2 defines the worst-case irradiation to be characterized for the dose effects on the functional IC. Additionally, it is possible to set-up an X-ray system to minimize the dose during an X-ray inspection and to avoid repetitive inspections directly linked to the total exposure limit.

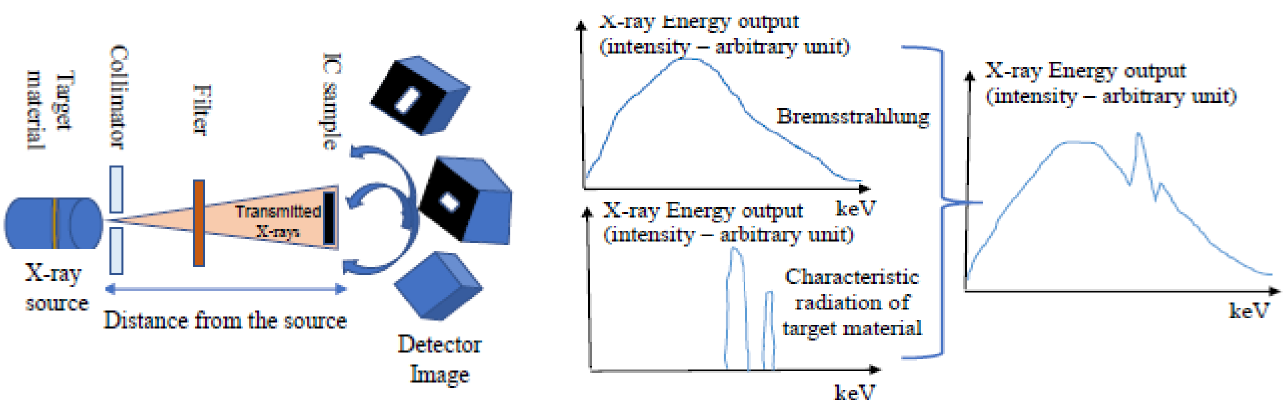

Figure 1 — Simplified Schematic of X-ray System

5 X-ray System Settings and Variables (cont'd)

The following parameters shall be considered to integrate the energy spectrum for dose-rate characterization at X-ray system level:

- **Exposure time**: The exposure time is cumulative; therefore, the total dose shall be determined by the summation of all acquired doses over the period relevant to the mission profile. The repeated X-ray inspection and any rework shall be included in the overall exposure time. Scanning operations with additional projections per field of view (FoV) can induce longer exposure times (e.g., angle of view with 3D CT technique).

- **Collimator**: A collimator is used to adjust the beam on a given region or part and to avoid secondary exposure on adjacent regions or parts during inspections. The collimator is a 'beam-limiting device,' meaning the beam dimensions of the X-ray field are restricted to the device and minimized on the surrounding regions or parts.

- **Tube mode**: The tube mode determines the focal spot size, as the effective output exposure area provided by the X-ray supplier and tube characteristics (e.g., target angle with internal electron flux).

- **Tube power**: The tube power determines the intensity and range of the X-ray energy spectrum. Both current and voltage will contribute to the dose. The current will determine the number of electrons striking the target. If more electrons hit the target, more X-rays and dose are produced. The kilovoltage will determine the kinetic energy of the electrons accelerated in the X-ray tube and the full range of the photon energy spectrum will contribute to the absorbed dose. In the case where the current is not monitored, the dose-rate plotted per power (expressed in Watts) can determine the characteristics of the X-ray dose with voltage.

- **Distance**: The distance varies regarding the magnification required. For high magnification (to see smaller features), the device is placed the closest to the X-ray tube. The highest dose is obtained at the minimum distance.

- **Filter**: A filter has a direct role in attenuating the dose by absorbing a portion of the X-ray dose. A portion of the spectrum is reduced depending on the characteristics of the filter material (typically metal (e.g., copper, aluminum, and molybdenum) with a high level of absorption relative to the thickness and the atomic mass number).

- **Angle**: Angular or 3D inspection can lead to different distances from the source to the specimen (e.g., the closer the specimen is to the tube, the higher the exposed dose (see Table 2)) and to a non-uniform X-ray beam over the DUT. The irradiated area changes with the angle which can lead to secondary dose effects on other devices. Worst-case irradiation is preferred for the test set-up and can be usually achieved by an orthogonal inspection/exposure of the source to the device (as demonstrated in Figure 4). In addition, the worst-case (closest) distance should be used. If angular inspection is used for the test set-up, the actual dose to which the device is exposed should be measured and documented. In real-time applications, the impact of angular inspection and the secondary dose effects must be known.

5 X-ray System Settings and Variables (cont'd)

Tube and target characteristics can be considered and documented in case of known radiation effects such tube/target lifetime or material type of the target.

Table 2 — Critical X-ray Parameters

Critical Parameter	Dose Dependence	Critical Maximum Dose
Exposure Time	Dose ∝ Exposure dose-rate x Time	Highest exposure time
Collimator	Dose is a function of limited area exposed defined (with collimator) or diffused (without collimator)	Total diffused exposure with secondary exposure on adjacent parts
Tube mode (focal spot size from the source)	Dose function of attenuation ratio given by the datasheet of X-ray supplier or X-ray calibration report	Larger spot size
Tube Power (P) Combination of current and voltage	Power is a combination of the current and voltage settings with the induced contribution. Both contributions shall be characterized. If current not monitored, the dose-rate per Watt shall be measured.	Highest current at a given kV Highest kV at a given current
Distance (D) Source to Sample	Dose ∝ $1/D^2$	Minimum distance
Filter / absorbing Z material	Dose function of attenuation ratio of the absorbed dose regarding filter tray (thickness and density atomic number (Z))	No filter is recommended for testing
Angle	Dose function of the inspection mode (e.g., 3D)	Orthogonal inspection with minimum distance

6 X-ray System Dose Rate Characterization

The objective is to characterize the radiation output (dose-rate) of the X-ray inspection system inside the material of interest. This test requires an X-ray inspection system to generate a stable radiation, as well as an X-ray dosimeter to accurately measure the dose-rate.

X-ray system settings shall be selected to mimic typical X-ray inspection conditions following the critical parameters (Table 2). A Design of Experiment (DOE) plan is recommended to assess the dose-rate over several critical parameters such as voltage, power, and distance [6]. The dose-rate setting shall be selected to replicate the worst inspection profile in term of maximum dose received to match with the actual field X-ray-inspection settings. If a standard dose-rate used for testing is higher than 0.1 cGy(Si)/s, no additional test is required to assess the Enhanced Low Dose Rate Sensitivity (ELDRS). Only in extreme conditions approaching total dose higher than 100 Gy (e.g., long exposure time) combined with dose-rates starting at values below 10 cGy(Si)/s (e.g., with filtering absorption, large distance, and low power), a check at a second dose rate to determine the enhancement factor should be considered [7], [8]

To apply the full energy spectrum of X-rays, the characterization shall be done without a filter. If a filter is utilized for a specific test, details of the filter material (e.g., metal composition and thickness) shall be documented.

A verification of the dose to the distance relationship shall be performed, where Dose $\propto 1/(\text{Distance})^2$.

6.1 X-ray Radiation Dosimetry

The X-ray dosimeter [6], [9] should be able to measure the dose-rate of the X-ray system with an accuracy $\leq \pm 5\%$ in targeted ranges of the dose-rate and tube voltage as a pre-requisite for device exposure.

Individual dosimeter sensitivity can vary, so refer to the supplier data sheets to take the following characteristics into consideration:

- Uncertainty and correction factors if any (e.g., temperature for air-ionization chambers or linearity when saturation for high dose-rate).
- Reproducibility (e.g., by annealing for OSL/TLD re-use) within the dosimeter lifespan and assessing any potential damages due to dose-range boundaries or handling precautions.

Dose conversion (e.g., air to material) is computed with the National institute of Standards and Technology (NIST) ‘X-ray mass attenuation coefficients and mass energy-absorption coefficients’ [10] to calculate the corresponding dose inside the material of interest for a given range of energy:

- Dose in material = Dose in air x Mean Conversion Factor Material to Air [10]

6.1 X-ray Radiation Dosimetry (cont'd)

Silicon application example:

- Typical mean conversion factor based on NIST tables [10], Si/Air conversion factor is between 7 and 8 for 30 keV mean energy range reducing to 3 for higher mean energy range around 80 keV.
- Mean conversion factor = $(\mu_{en}/\rho)_{Silicon}$ / $(\mu_{en}/\rho)_{Air}$ = 7.6 for mean energy at 30 keV
  with $(\mu_{en}/\rho)_{Air}$ = 1.537E-01 cm^2/g and $(\mu_{en}/\rho)_{Silicon}$ =1.164E+00 cm^2/g
- Mean conversion factor = $(\mu_{en}/\rho)_{Silicon}$ / $(\mu_{en}/\rho)_{Air}$ = 2.9 for mean energy at 80 keV
  with $(\mu_{en}/\rho)_{Air}$ = 2.407E-02 cm^2/g and $(\mu_{en}/\rho)_{Silicon}$ = 6.896E–02 cm^2/g

6.1 X-ray Radiation Dosimetry (cont'd)

The key types of dosimeters are listed in Table 3. Ionization-chamber and semiconductor-based dosimeters are active devices: they typically measure a radiation-induced current and, thus, can give a real-time readout of the dose. Luminescence-based dosimeters have passive elements and store the dose into the device. Post-processing with temperature or light is required to measure the dose and the read-out is not immediately available after irradiation. When using this kind of dosimeter, careful conditioning is required. Storage and transportation time shall be minimized by protecting dosimeters from elevated temperature and ultra-violet light, since these can alter the dose. Normal temperature and normal natural underground storage are recommended. In case of known conditions affecting the dosimeter response, corrections shall be applied to the measured dose. The dose due to unwanted/spurious effects, can be monitored by an additional reference dosimeter, and subtracted from the dose of dosimeter used for X-ray calibration. Reader calibration within the energy range shall also be taken into consideration. ISO/ASTM 51956 standards, such as 'Practices for Use of a TLD System for Radiation Processing,' can be used as guidelines [11].

Table 3 — Dosimeter Types

Dosimeter Type	Typical Dosimeter Type	Description	Real-Time Dose Reader
Ionization chamber	Spherical Ionization chamber	Consists of measuring current between two electrodes biased with ion pairs created within the chamber of a gas volume	Yes
Semiconductor-based	PIN diode	Consists of measuring the induced current across a junction diode	Yes
	Single Crystal Diamond	Consists of measuring the induced current across a Schottky diode	Yes
	MOS	Consists of measuring the capacitance modified by the induced trapped charge in gate dielectric	Yes
Luminescence-based	TLD (Thermo-luminescent Dosimeter)	Consists of heating the material to release trapped energy in the form of luminescence	No
	OSL (Optically Stimulated Luminescence)	Consists of applying light energy to the material to release trapped energy in the form of luminescence	No

6.2 X-ray Inspection System Set-up

The X-ray inspection system needs to provide a stable and uniform dose-rate during the testing at the selected voltage and power.

- Stability: Following the user manual of the X-ray inspection system, the X-ray target shall periodically be rotated on open tubes to a fresh region before the X-ray test is started, to ensure that irradiation occurs from a fresh section of the target. For closed tubes used in automatic X-ray inspection systems, an equivalent procedure shall be utilized. After the system warm up, a minimum waiting time shall be considered to ensure that the system is stable prior to starting the X-ray test.
- Uniformity: The dosimeter and the DUT(s) shall be placed (Figure 2) in the center zone during the test with a DUT(s) to source distance (Zt) (Figure 3) greater than what is typically used for X-ray inspection conditions, if necessary, to establish a more uniform center zone test area and keeping the DUT(s) fully exposed with the same dose-rate range. The number of DUTs that can be irradiated simultaneously is determined by the radiation center zone area and a DUT size. A single test with the same beam spot and without any movement is recommended to avoid any secondary dose effects (scattering). This prevents any side effects and eliminates the need for subsequent dose correction. A collimator can also be used as shielding to avoid secondary dose effects. Film dosimetry can be used to determine the actual exposed area during X-ray irradiation when a collimator is used for testing individual parts.
- Packaged sample-inspection side: Consider all possible configurations (e.g., bottom/top/side sources, dead-bug or live-bug packages, samples mounted on a printed circuit board (PCB) or placed on carriers/tray and tapes). A replication of the typical inspection configuration or use-case shall be set-up during the exposure test prior to performing electrical testing. Absorbing package material could interact with the X-rays (e.g., plated ceramic lid of PCB (Figure 4)) and play a role by minimizing the induced X-ray dose. If no configuration limitations exist, the worst-case irradiation shall be selected by the supplier based on the product construction.

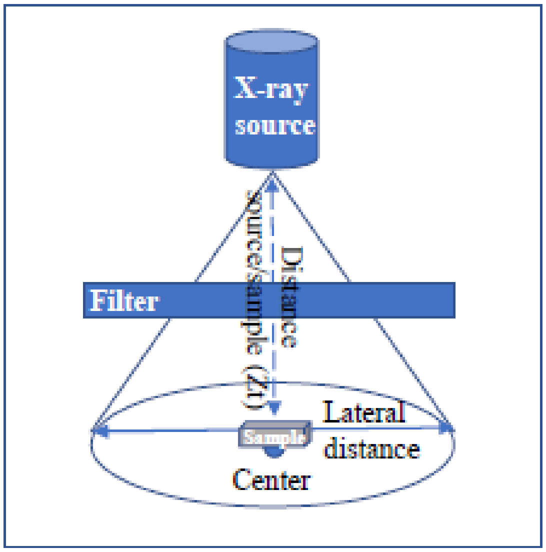

Figure 2 — Illustration of an X-ray Center Zone

6.2 X-ray Inspection System Set-up (cont'd)

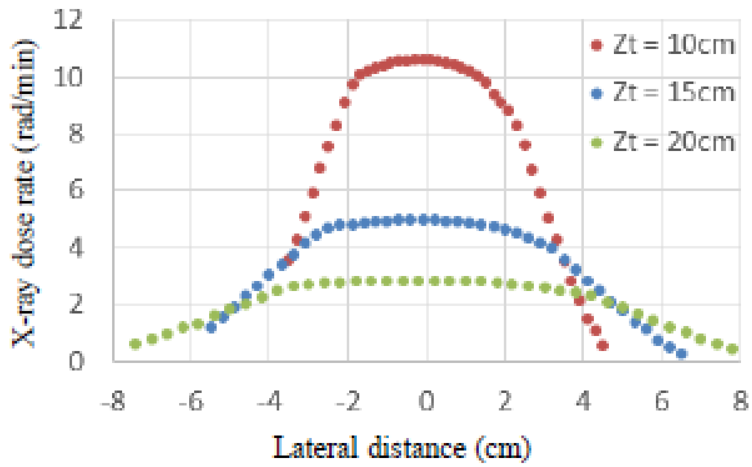

Figure 3 — Illustration of Lateral Decay of Measured X-ray Dose-Rate at Various Sample-to-Source Distances (Zt)

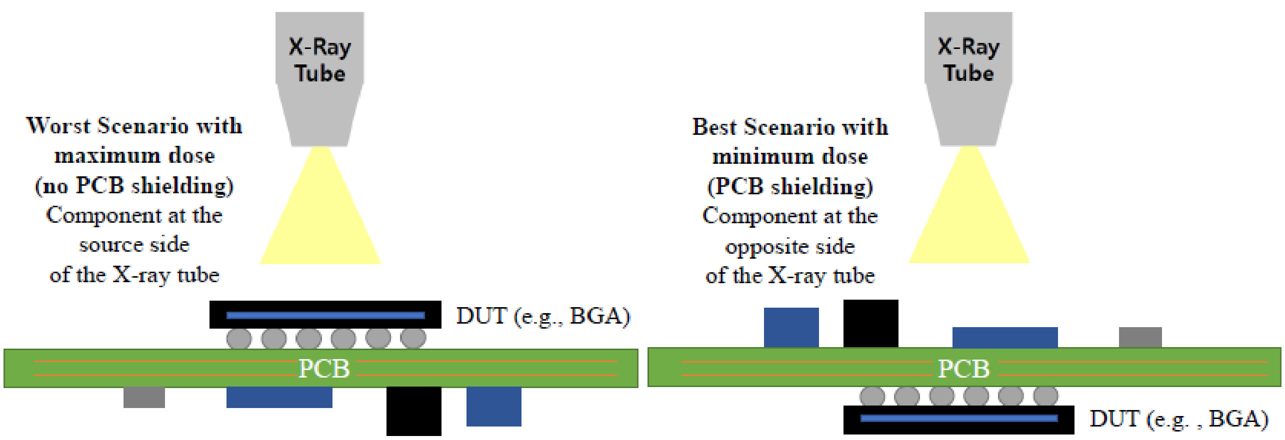

Figure 4 — Example of Shielding Effect Defining Worst-Case Irradiation for a BGA Device

7 Test Method for TID Characterization

7.1 Test Flow

The X-ray TID test flow is illustrated schematically in Figure 5.

Two characterization modes can be performed and shall be documented in the summary report (9 h) 4)). The first one is to characterize up to the supplier limit, and the second one is to characterize the failure limit.

- For the supplier limit, the anticipated worst-case irradiation for all inspection processes (including the in-house and customer mission profiles) shall be targeted based on X-ray critical parameters (Table 2). If any in-house rework inspection is performed, extra exposure time must be considered into the supplier limit.
- For the failure limit, the maximum irradiation shall be determined by the evaluation mode (7.1.4) by assessing the ‘first parameter to fail’ (device pass/fail limit with respect to the irradiation).

The characterization of time-dependent effects (TDE) is optional to replicate the post-exposure thermal budget (storage, burn-in, DUT mounting is optional, depending on the manufacturing post-exposure environment profile).

Lidless parts shall receive the maximum dose if no other shielding is utilized. For any lidded parts, the package type shall be fully documented to take into consideration any shielding effect (e.g., metal lid). Die and package type shall be an inseparable part of the final evaluated dose level. In case of pre-applied Thermal Interface Material (TIM) or heat spreader, thickness and material type shall be documented.

If this test method is performed on bare die or at wafer level, it shall be documented in the summary report (9 d). If a device is modified or packaged in a way that is known to have an impact on the X-ray robustness, a repetition of this test method is recommended to assess any effects; alternatively a delta may be applied if the effects due to similar modifications or packaging are already known.

7.1 Test Flow (cont'd)

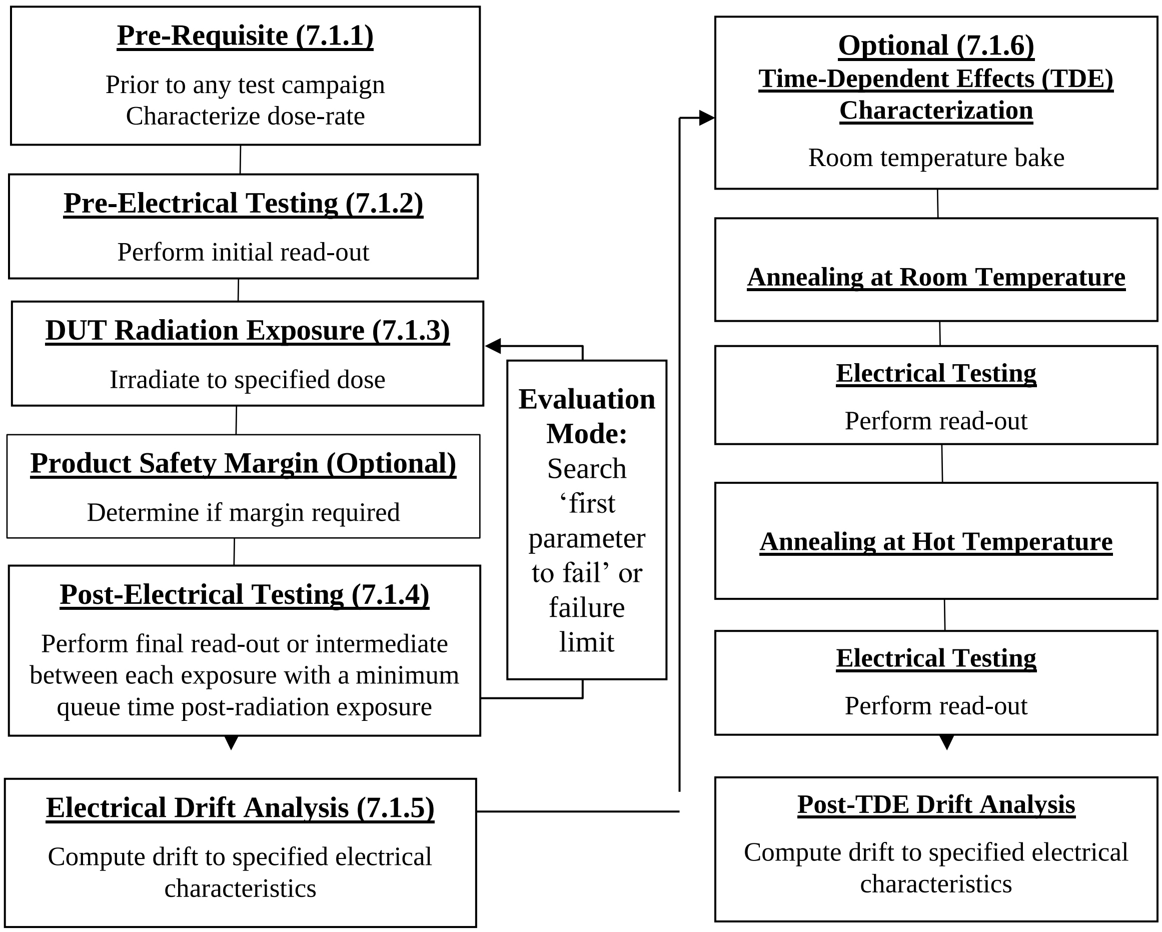

Figure 5 — Flow-Chart for TID Characterization

7.1.1 Pre-Requisite

Characterize the dose-rate (6) with appropriate dosimetry techniques to determine the Total Ionizing Dose required to characterize the supplier limit or the failure limit.

7.1.2 Pre-Electrical Testing

An initial read-out at room temperature (RT) shall be performed on all parts (DUTs) targeted for exposure, along with unirradiated control parts (7.2). A sufficient sample size shall be used to account for statistical variation and ensure that differences can be detected.

The worst-case temperature may be chosen to characterize the critical expected failure mode and effect (e.g., 85°C or extended temperature for refresh time t_{REF} on DRAMs (Table 1)).

7.1.3 DUT Radiation Exposure

Based on the desired or specified total dose and measured X-ray dose-rate, the DUT X-ray exposure time 't', where t = (specified total dose) / (dose-rate), is calculated. The DUTs are irradiated for the time 't' calculated above at room temperature. An exposure with several intermediate dose steps and read-outs up to the total dose specified is reached can be done to verify the cumulated effects on the drift.

If no specified total dose is documented from the worst-case irradiation, an evaluation with a reduced sampling can be done to determine the dose-threshold immunity before the complete characterization with several steps of exposure.

For the safety margin of X-ray inspection, where the goal is to yield zero post-inspection radiation-induced fails within the allowed total dose, it is recommended to set the upper bound of the X-ray exposure to a level below the characterized failure level. The upper bound can be technology, package, or device dependent. The safety margin shall account for dosimetry uncertainty.

7.1.4 Post-Electrical Testing

Following each irradiation exposure or step, a queue time as short as possible is recommended to minimize any time-dependent recovery effects for the annealing. The read-out shall be performed at room or worst-case temperature in compliance with the product electrical specification per the supplier datasheet.

In case of failure limit evaluation mode, to anticipate the failure mode or search for the 'first parameter to fail', a loop-back between X-ray exposure (7.1.3) and post-exposure read-out (7.1.4) can be introduced to determine the acceptable electrical limits or expected functionality defined in the product specification by considering that the cumulative effects take place through continuous radiation exposure. Several loops of exposure with intermediate read-outs shall be conducted for drift analysis on the critical parameters of the failure modes (parameter to fail) compared to cumulative dose. Alternatively, different sets of parts can be exposed for different doses up to the desired dose specification or to failure and measured.

TID effects for terrestrial X-ray applications could induce similar space-level dose in the range of several gray. As a result, an initial study should start with a reduced exposure using the following exposure steps 0.1 Gy, 1 Gy, or 10 Gy in Air KERMA or directly at the highest dose level, with intermediate read-outs to determine the level of immunity of the packaged device. A loop-back with additional exposure can be done to search for the 'first parameter to fail' in an evaluation mode to search for the immunity TID-threshold level in a cumulative way (e.g., search levels: 0.1 Gy, +0.9 Gy to reach 1 Gy, +9 Gy to reach 10 Gy on the same group of samples) or alternatively, to search the threshold level with several groups of samples exposed directly at different dose level (e.g., 0.1 Gy, 1 Gy, 10 Gy).

7.1.5 Electrical Drift Analysis

In order to quantify the change in values induced by radiation, a drift analysis is required to characterize cumulative effects.

An engineering-mode test program shall be set-up to override any electrical or functional failures to perform the drift analysis in case of evaluation mode/loop.

7.1.6 Optional: Time-Dependent Effect (TDE) Characterization

The objective of the TDE characterization step is to take into consideration the back-end manufacturing thermal profile/budget at test and assembly prior to field use. The final irradiation responses (recovery or adverse effects) is not necessarily predictable over time and temperature; characterization testing is necessary to assess the effect of any thermal steps. Evaluation at room temperature is recommended after time intervals, e.g., 24 hours, 48 hours, and 168 hours. Accelerated or slow annealing is recommended to be done after a bake of 168 hours at 100°C. Electrical testing in both cases shall be taken at room temperature if no specified product requirements are available.

The bake temperature (without voltage bias) can be modified and documented to be fully matched with the manufacturing thermal budget (e.g., reflow, soldering process) post-X-ray exposure prior the critical electrical test.

For any burn-in studies and bias-assisted TDE (short operating-life test with bias), initial pre-electrical testing (7.1.1) shall be conducted prior to burn-in in order to exclude resultant infant-mortality failure modes post-exposure. This will allow delineation of the failures induced by radiation exposure considered to be intrinsic failures. To this end, annealing at high temperature can be replaced by a burn-in step (e.g., 168 hours burn in) to align with the manufacturing back-end flow (e.g., for automotive or aerospace) applications, if there is a burn-in requirement following the assembly and X-ray steps.

7.2 Sample Size

Samples have to be randomly selected from the parent population on a typical lot with a chosen quantity and additional unirradiated control samples.

8 Safety

All testing shall follow X-ray system and ATE manufacturer's safety recommendations, local safety regulations, and ESD control.

9 Final Report for X-ray Radiation TID Test

The following items shall be contained in the final report for X-ray radiation TID test:

a) Description of X-ray system, including:
   1) Facility, vendor, model type, X-ray target type
   2) X-ray setting and dose-rate
   3) Filter thickness and material if filter is used
   4) Distance between X-ray tube and test devices
   5) Orientation in respect to the X-ray source

b) X-ray dosimeter description, including vendor, model type, dose-rate measurement range, and corresponding tolerance of accuracy range.

c) Device description; including process node, product name, lot #, date code, etc.

d) Package type and thermal-interface material type if any. In case of non-packaged unit (bare die or wafer level) or lidless/package decapsulated, this shall be noted.

e) Total number of devices tested, including control (unirradiated) devices.

f) Ambient temperature used for electrical testing.

g) Time interval between exposure and read-out and annealing conditions in case of TDE characterization.

h) The total amount of X-ray dose irradiated on each DUT:
   1) Dose in air
   2) Dose in material, if applicable
   3) Dose conversion factor from air to material, if applicable
   4) Characterization mode: failure limit or supplier limit

i) Electrical testing results.

Standard Improvement Form **JEDEC** **JESD22-B121**

The purpose of this form is to provide the Technical Committees of JEDEC with input from the industry regarding usage of the subject standard. Individuals or companies are invited to submit comments to JEDEC. All comments will be collected and dispersed to the appropriate committee(s).

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1. I recommend changes to the following:

☐ Requirement, clause number __________

☐ Test method number __________ Clause number __________

The referenced clause number has proven to be:

☐ Unclear ☐ Too Rigid ☐ In Error

☐ Other ____________________

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2. Recommendations for correction:

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3. Other suggestions for document improvement:

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Submitted by

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