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Standard Guide for
Use of an X-Ray Tester (≈10 keV Photons) in Ionizing Radiation Effects Testing of Semiconductor Devices and Microcircuits[1]

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1. Scope

1.1 This guide covers recommended procedures for the use of X-ray testers (that is, sources with a photon spectrum having ≈10 keV mean photon energy and ≈50 keV maximum energy) in testing semiconductor discrete devices and integrated circuits for effects from ionizing radiation.

1.2 The X-ray tester may be appropriate for investigating the susceptibility of wafer level or delidded microelectronic devices to ionizing radiation effects. It is not appropriate for investigating other radiation-induced effects such as single-event effects (SEE) or effects due to displacement damage.

1.3 This guide focuses on radiation effects in metal oxide semiconductor (MOS) circuit elements, either designed (as in MOS transistors) or parasitic (as in parasitic MOS elements in bipolar transistors).

1.4 Information is given about appropriate comparison of ionizing radiation hardness results obtained with an X-ray tester to those results obtained with cobalt-60 gamma irradiation. Several differences in radiation-induced effects caused by differences in the photon energies of the X-ray and cobalt-60 gamma sources are evaluated. Quantitative estimates of the magnitude of these differences in effects, and other factors that should be considered in setting up test protocols, are presented.

1.5 If a 10-keV X-ray tester is to be used for qualification testing or lot acceptance testing, it is recommended that such tests be supported by cross checking with cobalt-60 gamma irradiations.

1.6 Comparisons of ionizing radiation hardness results obtained with an X-ray tester with results obtained with a LINAC, with protons, etc. are outside the scope of this guide.

1.7 Current understanding of the differences between the physical effects caused by X-ray and cobalt-60 gamma irradiations is used to provide an estimate of the ratio (number-of-holes-cobalt-60)/(number-of-holes-X-ray). Several cases are defined where the differences in the effects caused by X-rays and cobalt-60 gammas are expected to be small. Other cases where the differences could potentially be as great as a factor of four are described.

1.8 It should be recognized that neither X-ray testers nor cobalt-60 gamma sources will provide, in general, an accurate simulation of a specified system radiation environment. The use of either test source will require extrapolation to the effects to be expected from the specified radiation environment. In this guide, we discuss the differences between X-ray tester and cobalt-60 gamma effects. This discussion should be useful as background to the problem of extrapolation to effects expected from a different radiation environment. However, the process of extrapolation to the expected real environment is treated elsewhere (**1, 2**).[2]

1.9 The time scale of an X-ray irradiation and measurement may be much different than the irradiation time in the expected device application. Information on time-dependent effects is given.

1.10 Possible lateral spreading of the collimated X-ray beam beyond the desired irradiated region on a wafer is also discussed.

1.11 Information is given about recommended experimental methodology, dosimetry, and data interpretation.

1.12 Radiation testing of semiconductor devices may produce severe degradation of the electrical parameters of irradiated devices and should therefore be considered a destructive test.

1.13 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

1.14 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate ~~safety~~ safety, health, and ~~health~~environmental practices and determine the applicability of regulatory limitations prior to use.*

1.15 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[3]
E170 Terminology Relating to Radiation Measurements and Dosimetry
E666 Practice for Calculating Absorbed Dose From Gamma or X Radiation
E668 Practice for Application of Thermoluminescence-Dosimetry (TLD) Systems for Determining Absorbed Dose in Radiation-Hardness Testing of Electronic Devices
E1249 Practice for Minimizing Dosimetry Errors in Radiation Hardness Testing of Silicon Electronic Devices Using Co-60 Sources
E1894 Guide for Selecting Dosimetry Systems for Application in Pulsed X-Ray Sources
2.2 *International Commission on Radiation Units and Measurements Reports:*
ICRU Report 33—Quantities and Units for Use in Radiation Protection[4]
2.3 *United States Department of Defense Standards:*
MIL-STD-883, Method 1019, Ionizing Radiation (Total Dose) Test Method[5]

3. Terminology

3.1 *Definitions:*

3.1.1 *absorbed-dose enhancement, n*—increase (or decrease) in the absorbed dose (as compared with the equilibrium absorbed dose) at a point in a material of interest; this can be expected to occur near an interface with a material of higher or lower atomic number.

3.1.2 *average absorbed dose, n*—mass weighted mean of the absorbed dose over a region of interest.

3.1.3 *average absorbed-dose enhancement factor, n*—ratio of the average absorbed dose in a region of interest to the equilibrium absorbed dose.

NOTE 1—For a description of the necessary conditions for measuring equilibrium absorbed dose see the term 'charged particle equilibrium' in Terminology E170 which provides definitions and descriptions of other applicable terms of this guide. In addition, definitions appropriate to the subject of this guide may be found in ICRU Report 33.

NOTE 2—The SI unit for absorbed dose is the gray (Gy), defined as one J/kg. The commonly used unit, the rad (radiation absorbed dose), is defined in terms of the SI units by 1 rad = 0.01 Gy. (For additional information on calculation of absorbed dose see Practice E666.)

3.1.4 *equilibrium absorbed dose, n*—absorbed dose at some incremental volume within the material in which the condition of electron equilibrium (the energies, number, and direction of charged particles induced by the radiation are constant throughout the volume) exists (see Terminology E170).

3.1.4.1 *Discussion*—

For practical purposes the equilibrium absorbed dose is the absorbed dose value that exists in a material at a distance in excess of a minimum distance from any interface with another material. This minimum distance being greater than the range of the maximum energy secondary electrons generated by the incident photons.

3.1.5 *ionizing radiation effects, n*—the changes in the electrical parameters of a microelectronic device resulting from radiation-induced trapped charge. These are also sometimes referred to as 'total dose effects.'

3.1.6 *time dependent effects, n*—the change in electrical parameters caused by the formation and annealing of radiation-induced electrical charge during and after irradiation.

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[3] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[4] Available from International Commission on Radiation Units and Measurements (ICRU), 7910 Woodmont Ave., Suite 400, Bethesda, MD 20841-3095, http://www.icru.org.

[5] Available from Standardization Documents Order Desk, DODSSP, Bldg. 4, Section D, 700 Robbins Ave., Philadelphia, PA 19111-5098, http://dodssp.daps.dla.mil.

4. Significance and Use

4.1 Electronic circuits used in many space, military and nuclear power systems may be exposed to various levels of ionizing radiation dose. It is essential for the design and fabrication of such circuits that test methods be available that can determine the vulnerability or hardness (measure of nonvulnerability) of components to be used in such systems.

4.2 Manufacturers are currently selling semiconductor parts with guaranteed hardness ratings, and the military specification system is being expanded to cover hardness specification for parts. Therefore test methods and guides are required to standardize qualification testing.

4.3 Use of low energy (≈10 keV) X-ray sources has been examined as an alternative to cobalt-60 for the ionizing radiation effects testing of microelectronic devices (**3, 4, 5, 6**). The goal of this guide is to provide background information and guidance for such use where appropriate.

NOTE 3—*Cobalt-60*—The most commonly used source of ionizing radiation for ionizing radiation ("total dose") testing is cobalt-60. Gamma rays with energies of 1.17 and 1.33 MeV are the primary ionizing radiation emitted by cobalt-60. In exposures using cobalt-60 sources, test specimens must be enclosed in a lead-aluminum container to minimize dose-enhancement effects caused by low-energy scattered radiation (unless it has been demonstrated that these effects are negligible). For this lead-aluminum container, a minimum of 1.5 mm of lead surrounding an inner shield of 0.7 to 1.0 mm of aluminum is required. (See 8.2.2.2 and Practice E1249.)

4.4 The X-ray tester has proven to be a useful ionizing radiation effects testing tool because:

4.4.1 It offers a relatively high dose rate, in comparison to most cobalt-60 sources, thus offering reduced testing time.

4.4.2 The radiation is of sufficiently low energy that it can be readily collimated. As a result, it is possible to irradiate a single device on a wafer.

4.4.3 Radiation safety issues are more easily managed with an X-ray irradiator than with a cobalt-60 source. This is due both to the relatively low energy of the photons and due to the fact that the X-ray source can easily be turned off.

4.4.4 X-ray facilities are frequently less costly than comparable cobalt-60 facilities.

4.5 The principal radiation-induced effects discussed in this guide (energy deposition, absorbed-dose enhancement, electron-hole recombination) (see Appendix X1) will remain approximately the same when process changes are made to improve the performance of ionizing radiation hardness of a part that is being produced. This is the case as long as the thicknesses and compositions of the device layers are substantially unchanged. As a result of this insensitivity to process variables, a 10-keV X-ray tester is expected to be an excellent apparatus for process improvement and control.

4.6 Several published reports have indicated success in intercomparing X-ray and cobalt-60 gamma irradiations using corrections for dose enhancement and for electron-hole recombination. Other reports have indicated that the present understanding of the physical effects is not adequate to explain experimental results. As a result, it is not fully certain that the differences between the effects of X-ray and cobalt-60 gamma irradiation are adequately understood at this time. (See 8.2.1 and Appendix X2.) Because of this possible failure of understanding of the photon energy dependence of radiation effects, if a 10-keV X-ray tester is to be used for qualification testing or lot acceptance testing, it is recommended that such tests should be supported by cross checking with cobalt-60 gamma irradiations. For additional information on such comparison, see X2.2.4.

4.7 Because of the limited penetration of 10-keV photons, ionizing radiation effects testing must normally be performed on unpackaged devices (for example, at wafer level) or on ~~unlidded~~delidded devices.

5. Interferences

5.1 *Absorbed-Dose Enhancement*—Absorbed-dose enhancement effects (see 8.2.1 and X1.3) can significantly complicate the determination of the absorbed dose in the region of interest within the device under test. In the photon energy range of the X-ray tester, these effects should be expected when there are regions of quite different atomic number within hundreds of nanometres of the region of interest in the device under test.

NOTE 4—An example of a case where significant absorbed dose enhancement effects should be expected is a device with a tantalum silicide metallization within 200 nm of the SiO_2 gate oxide.

5.2 *Electron-Hole Recombination*—Once the absorbed dose in the sensitive region of the device under test is determined, interpretation of the effects of this dose can be complicated by electron-hole recombination (see 8.2.1 and X1.5).

5.3 *Time-Dependent Effects*—The charge in device oxides and at silicon-oxide interfaces produced by irradiation may change with time. Such changes take place both during and after irradiation. Because of this, the results of electrical measurements corresponding to a given absorbed dose can be highly dependent upon the dose rate and upon the time during and after the irradiation at which the measurement takes place (see X1.7 for further detail).

NOTE 5—The dose rates used for X-ray testing are frequently much higher than those used for cobalt-60 testing. For example, cobalt-60 testing is specified by Military Test ~~Method 1019.4~~Method 1019 to be in the range of 0.5 to 3 Gy(Si)/s (50 to 300 rads/(Si)/s). For comparison, X-ray testing is commonly carried out in the range of 2 to 30 Gy(Si)/s (200 to 3000 rads(Si)/s).

5.4 *Handling*—As in any other type of testing, care must be taken in handling the parts. This especially applies to parts that are susceptible to electrostatic discharge damage.

6. Apparatus

6.1 *X-Ray Tester*—A suitable X-ray tester (see Ref (**3**)) consists of the following components:

6.1.1 *Power Supply*—The power supply typically supplies 10 to 100 mA at 25 to 60 keV (constant potential) to the X-ray tube.

6.1.2 *X-Ray Tube*—In a typical commercial X-ray tube a partially focused beam of electrons strikes a water-cooled metal target. The target material most commonly used for ionizing radiation effects testing is tungsten, though some work has been done using a copper target. X-ray tubes are limited by the power they can dissipate. A maximum power of 3.5 kW is typical.

6.1.3 *Collimator*—A collimator is used to limit the region on a wafer which is irradiated. A typical collimator is constructed of 0.0025 cm of tantalum.

6.1.4 *Filter*—A filter is used to remove the low-energy photons produced by the X-ray tube. A typical filter is 0.0127 cm of aluminum.

6.1.5 *Dosimeter*—A dosimetric system is required to measure the dose delivered by the X-ray tube (see Guide E1894).

NOTE 6—X-ray testers typically use a calibrated diode to measure the dose delivered by the X-ray tube. These typically provide absorbed dose in rads(Si).

6.2 *Spectrum*—The ionizing radiation effects produced in microelectronic devices exposed to X-ray irradiation are somewhat dependent upon the incident X-ray spectrum. As a result, appropriate steps shall be taken to maintain an appropriate and reproducible X-ray spectrum.

NOTE 7—The aim is to produce a spectrum whose effective energy is peaked in the 5 to 15 keV photon energy region. This is accomplished in three ways. First, a large fraction of the energy output of the X-ray tube is in the tungsten L emission lines. Second, some of the low-energy output of the tube is absorbed by a filter prior to its incidence on the device under test. Third, the high-energy output of the tube is only slightly absorbed in the sensitive regions of device under test and thus has only a small effect on the device. (See X1.2 for further detail.)

6.2.1 *Control of Spectrum*—The following steps shall be taken to insure adequate control of the X-ray spectrum:

6.2.1.1 *Anode Material*—Unless otherwise specified, the X-ray spectrum shall be produced by a tungsten target X-ray tube.

6.2.1.2 *Anode Bias*—Unless otherwise specified, the X-ray tube producing the X-ray spectrum shall be operated at a constant potential no lower than 40 kV nor higher than 60 kV.

6.2.1.3 *Spectrum Filtration*—Unless otherwise specified, the X-ray spectrum shall be filtered by 0.0127 cm of aluminum prior to its incidence on the device under test. Further filtration of the X-ray spectrum by additional intervening layers or by the device under test itself is to be minimized.

NOTE 8—Note that the X-ray spectrum is also filtered by the beryllium window of the X-ray tube and by ~15 cm of air.

NOTE 9—For irradiation of Si to SiO_2 based microelectronic devices which are unpackaged, or packaged but ~~unlidded,~~delidded, filtration of the X-ray spectrum by the device under test is not expected to have a significant effect (see X1.2 for further detail).

6.2.2 *Determination of Spectrum*—Generally, when using the X-ray tester for ionizing radiation hardness testing, it is not necessary to have a detailed knowledge of the X-ray spectrum. Where it is necessary to know the spectrum, data exist in the literature for some important cases. For unusual cases, experimental and computational means exist to determine the spectrum (see X1.2 for additional detail).

NOTE 10—If a thermoluminescent dosimeter (TLD) is used as a dosimeter, it is necessary to know the spectrum. This is because the spectrum of the X-ray tester is substantially attenuated in passing through a TLD. For further information on the spectrum see X1.2. Given a spectrum, a dose versus depth correction can be made for the TLD (see, for example, Ref (**4**)).

6.3 *Dose Rate:*

6.3.1 Since ionizing radiation effects can depend strongly on the dose rate of the irradiation, adequate steps shall be taken to determine and control the dose rate (see 7.1 for additional information).

6.3.2 The dose rate shall be maintained at the value specified in the test plan to a precision of ±10 %.

6.4 *Device Preparation*—The photons from the X-ray tester have a limited range in materials as compared to photons from a cobalt-60 gamma source (see X1.2 for further detail). As a result, microelectronic devices to be irradiated shall be tested either as regions on a wafer or as ~~unlidded~~delidded packaged devices. ~~Previously packaged devices must be delidded for testing.~~

6.5 *Beam Collimation*—X-ray testers may be used for irradiation of selected devices on a wafer. For this use, appropriate measures shall be taken to ensure that the X-ray beam is limited to the vicinity of the particular devices being irradiated. See X1.6 for further detail.

6.6 *Test Instrumentation:*

6.6.1 Various instruments for measuring device parameters may be required. Depending on the device to be tested, these can range from simple current-voltage I-V measurement circuitry to complex integrated circuit (IC) test systems.

6.6.2 All instrumentation used for electrical measurements shall have the stability, accuracy, and resolution required for accurate measurement of the electrical parameters as specified in the test plan.

6.6.3 Cables connecting the device under test to the test instrumentation shall be as short as possible. The cables shall have low capacitance, low leakage to ground, and low leakage between wires.

7. Procedure

7.1 *Test Plan:*

7.1.1 Parties to the test must agree upon the conditions of the test, as follows, and establish a test plan.

7.1.1.1 Source and dose level to be used,

7.1.1.2 Dosimeter system to be used,

7.1.1.3 Irradiation geometry to be used,

7.1.1.4 Devices to be tested, and

7.1.1.5 Parameters to be tested, including bias conditions and required accuracy.

7.1.2 The test plan may also include a required sequence of actions for the test. A suggested sequence for the test is as follows:

7.1.2.1 Prepare bias fixtures, test circuits, and test programs.

7.1.2.2 Perform preliminary dosimetry if such measurements are not available.

7.1.2.3 Make pre-irradiation ~~parameter or functional~~ electrical measurements.

7.1.2.4 Bias the parts properly and irradiate them to the first radiation level.

7.1.2.5 Perform post-irradiation electrical ~~measurements and reinsert or switch the parts into the bias network.~~ measurements.

7.1.2.6 Irradiate the parts to the next level, if more than one radiation level is required.

7.1.2.7 Repeat 7.1.2.5 and 7.1.2.6 until all required levels have been achieved.

7.2 *Device Bias:*

7.2.1 Ionizing radiation effects depend on the biases applied to the device under test during and following irradiation (see X1.4 and X1.5 for additional information).

7.2.2 Biasing conditions for devices during irradiation shall be maintained ~~within ±10 % of the bias conditions~~ as specified in the test plan. In most cases, use worst case bias conditions.

7.2.3 If the time dependence of the behavior of the device under test is to be studied, the biasing conditions on the device following irradiation shall be maintained within ±10 % of the bias conditions specified in the test plan.

7.2.4 If it is necessary to move the device from its location in the X-ray irradiation apparatus to a remote test fixture, the device shall be handled so as to minimize changes during the transfer.

7.2.4.1 If the device is packaged (and ~~unlidded),~~ delidded), the contacts on the device under test shall be shorted during transfer.

7.2.4.2 If the device is either packaged or on a wafer, the device shall be handled so that electrical transients (for example, from static discharge) do not alter the device characteristics.

7.3 *Temperature:*

7.3.1 Many device parameters are temperature sensitive. To obtain accurate measures of the radiation-induced parameter changes, the temperature must be controlled.

7.3.2 In addition, time-dependent effects (see 5.3 and X1.7) can be thermally activated. Because of this, the temperatures at which radiation measurements and storage take place can affect parameter values.

7.3.3 Devices under test (DUT) shall be irradiated at a temperature measured at a point in the test chamber in close proximity to the DUT.

7.3.4 All radiation exposures, measurements, and storage shall be done at 24° ± 6°C unless another temperature range is agreed upon between the parties to the test. ~~At higher TIDs, the temperature within the gamma chamber will increase.~~

7.3.5 Temperature effects must also be considered in establishing the sequence of post-irradiation testing. Choose the sequence of parameter measurements to allow lowest power dissipation measurements to be made first. Power dissipation may increase with each subsequent measurement. When high power is to be dissipated in the test devices, pulsed measurements are required.

7.4 *Electrical Measurements:*

7.4.1 The X-ray tester may be used to determine ionizing radiation effects on microelectronic devices for a broad range of applications including *process control* and *research on hardening technology* (see Appendix X2 for further detail).

7.4.2 A wide range of electrical measurements may be performed in conjunction with X-ray tester irradiations. These may include current-voltage, subthreshold current-voltage, and charge pumping measurements. These pre- and post-irradiation electrical measurements shall be performed as specified in the test plan.

7.4.3 *Timing of Measurements:*

7.4.3.1 Changes in electrical parameters caused by the growth and annealing of radiation-induced electrical charge within the device under test can be highly time dependent (see 5.1 for additional detail). As a result, particular care will be given to the timing of the irradiation and electrical measurements as specified in the test plan.

7.4.3.2 Long delays between the end of irradiation and the start of electrical measurements are not recommended unless the purpose of the experiment is the study of time dependent effects (TDE). Unless otherwise specified, electrical measurements will be started within 20 min after the end of irradiation or sooner.

7.4.3.3 It is usually preferable to perform electrical testing on the device under test either during irradiation, immediately following irradiation with the device left in place in the irradiation fixture, or both. ~~For gamma tests, the change in temperature within the chamber needs to be accounted for.~~

7.5 *Dosimetry:*

7.5.1 *Measurement of Dose:*

7.5.1.1 Appropriate dosimetry techniques shall be used to determine within ±10 % the dose applied to the device.

7.5.1.2 The equilibrium absorbed dose shall be measured with a dosimeter irradiated in the position of the device before, or after, the irradiation of the device.

Note 11—The dose from X-ray testers has most commonly been measured using a calibrated PIN diode detector (**3**). This method results in a measured dose-rate in rad(Si)/s. Since there is some appreciable attenuation of the X-ray beam on penetrating to and through the sensitive layer of the detector (even with a filtered spectrum as required by 6.2.1.3), a correction needs to be made to give the dose which would have been deposited in a very thin layer of silicon. This correction is somewhat spectrum dependent. At least one manufacturer provides detectors whose calibration includes this correction. During the calibration measurement the front surface of the sensitive region of the PIN detector must be in the same plane as the front surface of the device under test. Further, care must be taken that the entire front surface of the sensitive region of the PIN detector must be illuminated by the X-ray beam.

Note 12—Other dosimetry methods that have been used include TLDs (see Practice E668 and Ref (**4**)) and X-ray photographic film.

7.5.1.3 This dosimeter absorbed dose shall be converted to the equilibrium absorbed dose in the material of interest within the critical region within the device under test, for example the SiO_2 gate oxide of an MOS device. Conversion from the measured absorbed dose in the dosimeter to the equilibrium absorbed dose in the device material of interest can be performed using Eq 1:

$$D_a = D_b \frac{(\mu_{en}/\rho)_a}{(\mu_{en}/\rho)_b}$$

(1)

where:

D_a = equilibrium absorbed dose in the device material,
D_b = absorbed dose in the dosimeter,
$(\mu_{en}/\rho)_a$ = mass absorption coefficient for the device material, and
$(\mu_{en}/\rho)_b$ = mass absorption coefficient for the dosimeter.

Note 13—If, for example, the dose is measured in a PIN detector and the dose in an SiO_2 region of the device is desired, the ratio $(\mu_{en}/\rho)_{Si}/(\mu_{en}/\rho)_{SiO2}$ is, in the photon energy range of interest, approximately 1.8. Thus, in this case, $D_{Si} \approx 1.8\ D_{SiO2}$.

7.5.1.4 A correction for absorbed-dose enhancement effects shall be considered. This correction is dependent upon the photon energy that strikes the device under test (see 8.2.1 and X1.3).

Note 14—A relatively simple case to analyze for dose enhancement is one where the dose is desired for a thin (˜<50 nm) SiO_2 layer bounded on either side by thick (˜>200 nm) layers of silicon or aluminum (see, for example, Fig. X1.2 of X1.3). For this case, the dose-enhancement factor is 1.6 to 1.8. That is, the dose in the thin SiO_2 layer is approximately the same as the dose in the adjacent silicon or aluminum. For a similar problem, but with thicker SiO_2 layers, the dose-enhancement factor is ˜<1.6 and ˜>1 (see X1.3).

7.5.2 *Measurement of Dose Rate*—Appropriate dosimetry techniques shall be used to determine within ±10 % the dose rate of the irradiation of the device under test. Typically, the dose rate will be the measured dose divided by the irradiation time.

Note 15—Determination of the significance of the dose rate for radiation effects can be quite complex (see 5.1, 8, and X1.7).

8. Comparison with Cobalt-60 Gamma Results

8.1 *Physical Processes That Affect Radiation Effects:*

8.1.1 When X-rays are used to test devices, the magnitude of the irradiation-induced changes in electrical parameters may be significantly different as compared to the changes resulting from cobalt-60 gamma irradiation at the same exposure level (**4**).

8.1.2 The causes for these differences arise from the dependence of radiation effects on the energy of the irradiating photons. Two of the important mechanisms leading to these differences are absorbed-dose enhancement (**7**) and electron-hole recombination (**8**).

8.1.3 In comparing radiation-induced effects caused by X-rays and cobalt-60 gammas, the relative magnitude of absorbed-dose enhancement and electron-hole recombination shall be assessed. The magnitude of such effects must be assessed for the specific testing environment used.

8.2 *Use of Corrections for Physical Processes to Intercompare X-ray and Cobalt-60 Gamma Measurements:*

8.2.1 *Combined Effects of Absorbed-Dose Enhancement and Electron-Hole Recombination for Si-SiO_2 Devices*—In order to compare the radiation effects caused by X-ray and cobalt-60 gamma irradiations, it is necessary to make appropriate allowance for the differences between these two sources. In order to accomplish this, it has been suggested that it is necessary and sufficient to correct for differences in absorbed-dose enhancement and electron-hole recombination (**9, 10, 11, 12, 13**). A critical assessment of this body of work suggests that X-ray versus cobalt-60-gamma comparisons often can properly be made in this fashion.

8.2.1.1 Although the methodology described in this section is predominantly based on radiation-induced hole-trapping studies, the same approach can be applied to interface state generation. (For additional discussion see X1.8.1.)

8.2.1.2 This section will present an estimate of the differences between X-ray and cobalt-60 gamma effects for several important cases. That is, an estimate will be presented of the expected values of the ratio (Eq 2):

$$\text{Relative} - \text{Effect} = \frac{\text{Number Holes} (\text{Cobalt} - 60)}{\text{Number Holes} (\text{X} - \text{Ray})}$$

(2)

8.2.1.3 The combined effects of both absorbed-dose enhancement and electron-hole recombination will be presented. In calculating the ratio of Eq 2, it has been assumed that both sources (X-ray and cobalt-60) produced the same dose (as measured by TLDs or silicon PIN detectors and corrected to dose in 'bulk' SiO_2) with the same dose rate (in SiO_2).

8.2.1.4 It should be noted that the material of this section includes the combined effects of *only* dose enhancement and recombination. If other effects (for example, time dependent interface state growth or hole annealing effects) are important, then those correction factors must be included also. Some of these other effects are discussed in X1.7.

8.2.1.5 Further, it is important to note that the values presented in this section (see Table 1) do not treat saturation effects. That is, they are appropriate for cases where the effects are approximately linearly related to dose. Clearly, as one approaches the limiting case where hole trapping is completely saturated, the ratio (Number Holes (cobalt-60))/(Number Holes (X-Ray)) must approach unity. Thus the *differences between X-ray and cobalt-60 gamma irradiation are most serious for relatively low doses.* This caution is important to bear in mind for doses approaching the failure dose for a device, where hole trapping may be showing signs of saturation.

8.2.1.6 Finally, the methodology of this section is appropriate for the calculation of effects within the gate or field oxide layers of individual transistors. To apply these methods to the radiation-induced failure of microcircuits, it is necessary to apply them to the critical devices that result in the microcircuit failure.

8.2.2 *Corrections for Standard MOS Devices:*

8.2.2.1 Table 1 presents estimates of the combined effects of absorbed-dose enhancement and electron-hole recombination for several important cases for standard MOS technology. In order to systematize these results, the problem has been split into five cases of practical interest.

8.2.2.2 The results of Table 1 have been calculated assuming that the cobalt-60 gamma data are taken using a lead-walled test box (14, 15). The use of such a test box for cobalt-60 gamma irradiations is recommended, and thus the data of Table 1 should be regarded as representing the results to be expected using best experimental practice (see Practice E1249).

NOTE 16—The effects of using the lead-walled test box for cobalt-60 testing are especially important for cases where high atomic number materials are present. An example is the presence of a gold flashing on the interior surface of the lid. For additional details see Ref (14).

8.2.2.3 Note first, in Table 1, that there are cases where one would expect small differences between X-ray and cobalt-60 gamma irradiation, and other cases where a factor of 1.5 differences are expected.

8.2.2.4 During cobalt-60 gamma exposures, if high atomic number elements are present, such as gold deposited on the inside of Kovar device lids, additional dose enhancement can occur. This may raise the numbers in Table 1 by 10 to 20 % (15, 16). (This estimate is for the case where a lead-walled test box is used. The increase may be a factor of 1.5 to 1.7 in the absence of this spectrum filtration.)

8.2.3 *Example*—The calculations for Case I are now treated in greater detail to clarify how to handle cases not treated explicitly in Table 1. The data sources and calculations leading to the results shown in Table 1 are as follows:

8.2.3.1 First, the X-ray absorbed-dose enhancement factor can be obtained from the literature. See, for example, Fig. X1.2b and Refs (11), and (17). Note, from Fig. X1.2b, that a 50-nm oxide corresponds to an enhancement factor of about 1.6.

8.2.3.2 Second, the cobalt-60 gamma absorbed-dose enhancement factor was assumed to be 1.0 (no enhancement). This is reasonable in the absence of high-Z material such as a gold-flashed lid. Estimates of the cobalt-60 gamma absorbed-dose enhancement factor in the presence of high-Z material can be found in Refs (14) and (15).

TABLE 1 Estimate of the Ratio of the Relative Effects of Cobalt-60 and X-Ray Irradiations for Silicon MOS Devices (Using a Lead-Walled Test Box with Cobalt-60)

NOTE 1—These ratios of cobalt-60 to X-ray effects do not account for saturation. As radiation effects begin to saturate, cobalt-60 and X-ray effects become more similar and, thus, the ratio of their effects approaches unity.

NOTE 2—The estimated values in this table are intended to give the reader a rough value of the experimental results that should be expected. The number of significant digits used are not representative of what would be appropriate for reporting experimental results.

Case	Description of Case	Number of Holes (cobalt-60) / Number of Holes (X-ray)	Comments
I	Gate (On): oxide thickness = 25–50 nm oxide field $\approx 10^6$ V/cm	~0.9	Effects nearly cancel
II	Gate (Off): oxide thickness = 25–50 nm oxide field $\approx 10^5$ V/cm	~1.2	Recombination dominates slightly
III	Thick Gate (On): oxide thickness = 100 nm oxide field $\approx 10^6$ V/cm	~0.9	Effects nearly cancel
IV	Thick Gate (Off): oxide thickness = 100 nm oxide field $\approx 10^5$ V/cm	~1.3	Recombination dominates slightly
V	Field: oxide thickness = 100–400 nm oxide field $\approx 10^5$ V/cm	1.3 to 1.5	Recombination dominates

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8.2.3.3 Third, the recombination correction factor can be obtained from Eq X1.1 and Eq X1.3 of X1.5. Consider the data of these equations for a field of 10^6 V/cm. Note that a comparison of the fraction of unrecombined holes for a cobalt-60 gamma source to the fraction of unrecombined holes obtained using an X-ray tube shows a difference of about a factor of 1.4 (for example, at 10^6 V/cm the ratio is about 0.64/0.46 = 1.4).

8.2.3.4 Using these numbers, the combined difference in effect is about $(1.0/1.6) \times (1.4) = 0.9$. Such calculations are the source of the numbers given in Table 1.

8.2.3.5 Calculations similar to the ones just described can, of course, be carried out for values of oxide thickness and field that are intermediate to the limiting cases used in Table 1.

8.2.4 *Corrections for Devices with Heavy-Metal Silicides:*

8.2.4.1 Devices are now being manufactured with heavy metal metallization layers such as tungsten or tantalum silicide.

8.2.4.2 The presence of such layers is expected to result in significant dose enhancement in adjacent SiO_2 gate oxides for X-ray irradiation (**17, 18, 19**). For example, Fleetwood et al (**19**) suggest dose-enhancement factors in excess of 2.5 for some cases. These results are summarized in Table 2 as Case VI.

8.2.4.3 Although the mechanisms for dose enhancement are expected to be the same as for Si-SiO_2 devices, the greater magnitude of this effect in silicided devices require modification of the method outlined in 8.2.1. Fleetwood et al (**19**) give some suggestions on how to make such corrections. See, for example, X1.3 for suggested dose-enhancement factors (**19**). In particular, note Table X1.3 that shows the variation of dose enhancement with gate oxide thickness, and Fig. X1.3 that shows the variation of dose enhancement with the thickness of the polysilicon layer separating the silicide layer and the gate oxide.

8.2.4.4 Electron-hole recombination corrections are expected to be similar under fields of interest in devices with heavy-metal silicides as in more conventional devices (see X1.5). Thus, recombination corrections may be taken from, for example, Eq X1.1 and Eq X1.3 of X1.5.

8.2.5 *Corrections for Silicon on Insulator (SOI) Devices:*

8.2.5.1 There is evidence that the back-gate threshold voltage in SOI devices can be particularly sensitive to photon energy. The top gates on SOI devices are expected to behave in the same manner as for more conventional devices if back-gate leakage is suppressed.

8.2.5.2 A comparison of X-ray and cobalt-60 gamma effects on SOI devices has been presented by Fleetwood et al (**20**). This paper compared zone melt recrystallization (ZMR) devices having 2 μm-thick buried oxides with separation by the implantation of oxygen (SIMOX) devices having 0.4 μm-thick buried oxides.

8.2.5.3 This work showed major differences for back-gate threshold-voltage shift with devices built with ZMR material. At zero back-gate bias, a given back-gate threshold-voltage shift required three times the X-ray dose in comparison to the cobalt-60 gamma dose. This was the worst case of the experimental situations explored. These results are summarized in Table 3 as Case VII.

8.2.5.4 The differences were smaller for SIMOX devices. In this case, X-ray exposures greater by a factor of approximately 1.5 were required to give the same shift as was obtained with cobalt-60. It was inferred that this difference resulted from the smaller thickness of the buried oxide (0.4 μm) for the SIMOX devices.

8.2.5.5 The differences between the results for ZMR and SIMOX devices was attributed to the field dependence of electron-hole recombination in the buried oxide.

8.2.5.6 Note that the correlation factor for SOI or silicon on sapphire (SOS) devices can be strongly affected by the bias on the train of the top gate transistor during irradiation (**20**). In particular, it is expected that the two radiation sources should agree more closely for the case in which the drain of the top gate transistor is biased during irradiation (with zero back gate bias) because the field in the buried insulator is greater than for zero drain bias and, hence, the differences in electron-hole recombination can be smaller.

8.2.5.7 Additional data in Fleetwood et al (**20**) may be helpful in comparing X-ray and cobalt-60 gamma results on SOI devices.

8.2.6 *Corrections for Recessed Field Oxides and Base Oxides in Bipolar Devices*—Titus and Platteter (**21**) have shown that X-ray and cobalt-60 gamma irradiations produce factor of two differences in radiation effects due to recessed field oxides. These differences have been attributed to differences in electron-hole recombination in oxides with low fields (see Fig. X1.5). That is, this is comparable to Case V (in Table 1) for standard MOS devices. Similar differences are expected for the oxides that overlie the base-emitter junction of many linear bipolar technologies. Such oxides often limit their total dose response.

9. Report

9.1 As a minimum, report the following information (where relevant):

TABLE 2 Estimate of the Ratio of the Relative Effects of Cobalt-60 and X-Ray Irradiations for Cases of Silicon MOS Devices with Heavy Metal Silicides

Case	Description of Case	Number of Holes (cobalt-60) / Number of Holes (X-ray)	Comments
VI	Gate with Heavy Metal Silicide: gate oxide thickness = 25–50 nm, gate oxide field ≈ 10^6 V/cm	0.4 to 0.9	Substantial dose enhancement possible for X rays if heavy-metal layer is "near"— enhancement of factor of 2.5 possible

TABLE 3 Estimate of the Ratio of the Relative Effects of Cobalt-60 and X-Ray Irradiations for SOI Devices

Case	Description of Case	Number of Holes (cobalt-60) / Number of Holes (X-ray)	Comments
VII	SOI Back Gate: buried oxide thickness = 0.4–2.0 μm	1.0 to 3.0	Substantial reduction of effect for X-rays for small back-gate bias

9.2 *Source*—State the source type, target material, operating voltage, fluence rate, and any information on a measured or calculated energy spectrum. State the position, thickness, and composition of spectrum filtration materials, if any,

9.3 *Dosimeter System*—State the dosimeter type, calibration data, relevant environmental conditions during the irradiation, dose enhancement and recombination corrections used;

9.4 *Device*—State the manufacturer, device type number, package type, controlling specification, date code, other identifying numbers given by the manufacturer, and any available information on its specific construction;

9.5 *Irradiation Geometry*—State the position and orientation of source and device under test;

9.6 *Electrical Bias*—State the electrical bias conditions used and provide a schematic for the bias circuit;

9.7 *Parameter Measurements*—Provide a tabulation of test parameter measurement data, and

9.8 *Statistical Bias and Precision*—State any experimental conditions that might lead to a bias or lack of precision in the measured results. State an estimate of the precision and bias for the measured results.

10. Keywords

10.1 ionizing radiation effects; microcircuits; radiation hardness; semiconductor devices; X-ray testing

APPENDIXES

(Nonmandatory Information)

X1. PHYSICAL PROCESSES THAT AFFECT RADIATION EFFECTS

X1.1 Introduction

X1.1.1 This appendix will contain a discussion of four classes of physical processes that are of concern to the user of an X-ray tester.

X1.1.2 First are the processes of attenuation and filtration of the incident spectrum before it strikes the region of interest within the device-under-test. These are important because of their bearing on the question of whether the conversion from the measured dose in a detector (PIN, TLD, etc.) to the required dose in the region of interest (such as the SiO_2 gate oxide) within the device under test must be determined for each type of device. That is, will each type of device require determination of a correction for spectrum absorption and filtration, or are these corrections negligible? It will be shown that these are usually not major effects.

X1.1.3 The second class of physical processes involves the increase or reduction of radiation-induced effects within a gate oxide or a field oxide caused by electron-hole recombination (**8**) and absorbed-dose enhancement (**7**). Both of these phenomena are dependent on photon energy and device geometry. In addition, electron-hole recombination is dependent on the bias applied during irradiation. It will be shown that these phenomena can, in some cases, lead to major changes in the correlation between incident radiation flux and the measured effect on the device.

X1.1.4 The third class of physical processes is concerned with the possibility of improper localization of the incident X-ray beam caused by scattering or fluorescence. This is believed to be a manageable problem.

X1.1.5 The fourth class of physical processes to be discussed includes phenomena that are less well understood than those treated in the first two classes. Included in this class are interface state generation effects and annealing effects.

X1.1.6 Radiation-test personnel must give consideration to each of the above listed classes of physical processes. This may be accomplished by applying corrections for each of the four classes based on the current best understanding of the nature and

magnitude of the effects caused by the physical processes. Alternatively, the tester may resort to experiment—thereby determining the effects found on the devices under test using the radiation sources of interest.

X1.1.7 The critical regions in MOS devices for which radiation dose must be determined are the gate and field oxides. MOS structures within bipolar devices may be considered in an analogous fashion. Simple dosimeters that allow the user to measure the actual absorbed dose levels in these oxides are not currently available. Although MOS dosimeters have been fabricated (**22, 23**) their accuracy for this application has not been established and they may also be too expensive.

X1.1.8 In radiation-effects work one is, in general, faced with the problem of measuring an incident spectrum and correlating it with a radiation-induced effect. The dosimetry required to accomplish this task may be broken into four steps:

X1.1.8.1 measurement of the dose in a dosimeter,

X1.1.8.2 conversion from dose in the material of the dosimeter to dose in material of the region of interest within the device under test,

X1.1.8.3 correction for absorbed dose enhancement effects,

X1.1.8.4 correlation between the deposited radiation dose and the measured radiation-induced effect on the device.

X1.2 Attenuation and Filtration of the Incident Beam

X1.2.1 In this section, we shall deal with attenuation and filtration processes. This discussion will be particularly relevant to the first two of the dosimetry steps.

X1.2.2 In general, three things must be known to obtain an accurate estimate of the absorbed dose in the oxide region (ignoring, for this section, absorbed-dose enhancement effects). They are (*a*) a knowledge of the spectral distribution of the X-ray source, (*b*) the dose in a radiation detector, such as a silicon PIN detector, which can be related to the incident intensity, and (*c*) the structure of the device being tested. Such information can be used to calculate the attenuation and filtration of the X-ray beam as it passes through intervening material on its way to the critical oxide layer. It will be demonstrated in this section that such calculations are not necessary for most practical radiation tests.

X1.2.3 For much of the low-energy X-ray testing of devices, tungsten target X-ray tubes have been used. Table X1.1 and Table X1.2 contain the spectral distribution of a typical tungsten target X-ray tube with a 0.1-cm thick beryllium window operated at 50 keV. Attenuation for additional filters used with the X-ray source has not been included. In normal use, the spectrum should be filtered, for example by 0.0127 cm of aluminum, to remove the softest components of the spectrum. The intensities given in Tables X1.1 and X1.2 must be corrected for the filter used in the test apparatus. The purpose of this filtration is to reduce the attenuation of the beam by the device itself. An example of such attenuation effects will be given in the next paragraph. The spectral distribution given in Tables X1.1 and X1.2 have been used successfully in the calculation of the dose in silicon PIN detectors, TLDs, and several types of MOS structures irradiated by tungsten target tubes. Agreement with measurement to better than 10 % was achieved.

X1.2.4 Fig. X1.1 shows calculated deposition in a thin SiO_2 layer covered by various thicknesses of some of the more common materials that are used to fabricate MOS structures on silicon. The results in Fig. X1.1 are for irradiation with a tungsten target

TABLE X1.1 Spectral Distribution of Tungsten X-Ray Tube Operated at 50 kV: Characteristic Lines

Energy (keV)	Intensity [A] keV/(sr·mA·s)	Energy (keV)	Intensity [A] keV/(sr·mA·s)
8.4	6.68×10^{12}	9.8	6.30×10^{11}
9.5	6.30×10^{11}	10.0	1.32×10^{12}
9.7	3.62×10^{12}	11.3	9.57×10^{11}

[A] The term 'intensity,' though commonly used, is not very precise. The NBS Technical manual, Note 910-2, implies the use of 'radiant intensity per milliamp' in this context. Alternatively, this is the energy per second emitted into a unit solid angle for a current of 1 mA.