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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 silicon (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 International System of Units (SI) 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 and health practices and determine the applicability of regulatory limitations prior to use.*

[1] This guide is under the jurisdiction of ASTM Committee F01 on Electronics and is the direct responsibility of Subcommittee F01.11 on Quality and Hardness Assurance.

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[2] The boldface numbers in parentheses refer to the list of references at the end of this guide.

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 Quantities and Units Reports:*

ICRU Report 33—Radiation Quantities and Units[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, 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.

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

[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, 7910 Woodmont Ave., Suite 800, Bethesda, MD 20814.

[5] Available from Standardization Documents Order Desk, Bldg. 4 Section D, 700 Robbins Ave., Philadelphia, PA 19111-5094.

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 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 nanometers 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 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 (0.005 in.) 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 (0.005 in.) 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 (6 in.) of air.

NOTE 9—For irradiation of Si to SiO_2 based microelectronic devices which are unpackaged, or packaged but unlidded, 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* 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 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.

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 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), 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.

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.

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.

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:

$$D_a = D_b \frac{(\mu_{en}/\rho)_a}{(\mu_{en}/\rho)_b} \quad (1)$$

where:

D_a = equilibrium absorbed dose in the device material,
D_b = absorbed dose in the dosimeter,
$(\mu/\rho)_a$ = mass absorption coefficient for the device material, and
$(\mu/\rho)_b$ = 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 $(\mu/\rho)_{Si}/(\mu/\rho)_{SiO2}$ 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 for testing of 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):

$$\text{Relative}-\text{Effect} = \frac{\text{Number Holes (Cobalt}-60)}{\text{Number Holes (X}-\text{Ray)}} \quad (2)$$

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 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).

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 ≈ 10^6 V/cm	~0.9	Effects nearly cancel
II	Gate (Off): oxide thickness = 25–50 nm oxide field ≈ 10^5 V/cm	~ 1.2	Recombination dominates slightly
III	Thick Gate (On): oxide thickness = 100 nm oxide field ≈ 10^6 V/cm	~0.9	Effects nearly cancel
IV	Thick Gate (Off): oxide thickness = 100 nm oxide field ≈ 10^5 V/cm	~1.3	Recombination dominates slightly
V	Field: oxide thickness = 100–400 nm oxide field ≈ 10^5 V/cm	1.3 to 1.5	Recombination dominates