Designation: F1467 – 11

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

This standard is issued under the fixed designation F1467; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

## 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*

[1] This guide is under the jurisdiction of ASTM Committee F01 on Electronicsand is the direct responsibility of Subcommittee F01.11 on Nuclear and Space Radiation Effects.

Current edition approved Oct. 1, 2011. Published October 2011. Originally approved in 1993. Last previous edition approved in 2005 as F1467 - 99(2005)$^{\varepsilon 1}$. DOI: 10.1520/F1467-11.

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

*responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

## 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.

## 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.

[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.

4.5 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 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 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, 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. 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:

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

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):

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

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 %

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

(**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**).

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.

**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 |

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):

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.

**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 | $6.68 \times 10^{12}$ | 9.8 | $6.30 \times 10^{11}$ |
| 9.5 | $6.30 \times 10^{11}$ | 10.0 | $1.32 \times 10^{12}$ |
| 9.7 | $3.62 \times 10^{12}$ | 11.3 | $9.57 \times 10^{11}$ |

[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.

**TABLE X1.2 Spectral Distribution of Tungsten X-Ray Tube Operated at 50 kV: Continuum**

| Energy (keV) | Intensity [A] keV/ (keV·sr·mA·s) | Energy (keV) | Intensity [A] keV/ (keV·sr·mA·s) |
|---|---|---|---|
| 4.0 | $1.97 \times 10^{11}$ | 22.0 | $1.69 \times 10^{12}$ |
| 6.0 | $1.09 \times 10^{12}$ | 24.0 | $1.60 \times 10^{12}$ |
| 8.0 | $1.83 \times 10^{12}$ | 26.0 | $1.52 \times 10^{12}$ |
| 10.0 | $2.18 \times 10^{12}$ | 28.0 | $1.37 \times 10^{12}$ |
| 10.2 | $2.20 \times 10^{12}$ | 30.0 | $1.29 \times 10^{12}$ |
| 10.2 | $1.65 \times 10^{12}$ | 32.0 | $1.19 \times 10^{12}$ |
| 11.5 | $1.78 \times 10^{12}$ | 34.0 | $1.05 \times 10^{12}$ |
| 11.5 | $1.58 \times 10^{12}$ | 36.0 | $9.36 \times 10^{11}$ |
| 12.0 | $1.64 \times 10^{12}$ | 38.0 | $8.24 \times 10^{11}$ |
| 12.0 | $1.50 \times 10^{12}$ | 40.0 | $6.93 \times 10^{11}$ |
| 14.0 | $1.70 \times 10^{12}$ | 42.0 | $5.74 \times 10^{11}$ |
| 16.0 | $1.78 \times 10^{12}$ | 44.0 | $4.49 \times 10^{11}$ |
| 18.0 | $1.79 \times 10^{12}$ | 46.0 | $2.75 \times 10^{11}$ |
| 20.0 | $1.75 \times 10^{12}$ | 48.0 | $1.25 \times 10^{11}$ |

[A] Note that the units for the continuum are the same as for the lines (Table X1.1) except that the intensity is per keV band out of the spectral energy distribution.

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 X-ray tube operated at 50 kV. The profiles in Fig. X1.1 and in subsequent calculations in this standard are calculated using the tungsten X-ray spectrum in Tables X1.1 and X1.2 (filtered by 0.0127 cm of aluminum) and the absorption coefficients from E. F. Plechaty et al (**24**). The results are appropriate for 'bulk' materials. That is, absorbed-dose enhancement effects, to be discussed, are not included. It is readily observable in Fig. X1.1 that the doses in $SiO_2$ behind as much as 2 μm layers of some of the more common materials such as silicon, aluminum and $SiO_2$ differ by less than 2 %.

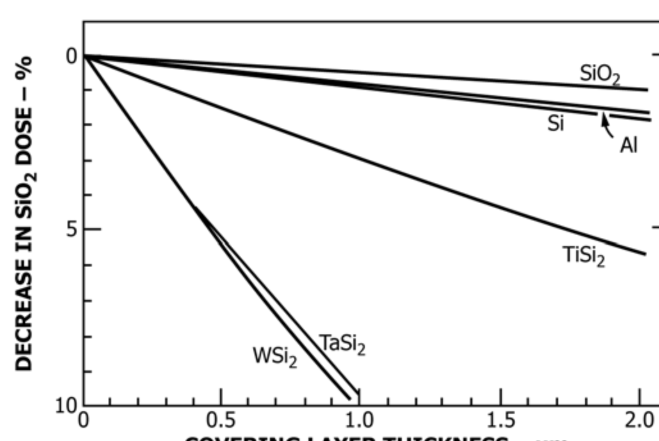



**FIG. X1.1 Decrease in the Dose in a 25 nm Oxide Caused by Loss of Energy in Materials Overlaying the Oxide**

Metal silicides can attenuate the beam more severely. However, these layers are usually only a few hundred nanometres thick so that the beam attenuation typically is less than 5 %. In general, the dose in the $SiO_2$ gate or field oxide layers is within 10 % of the $SiO_2$ dose at the surface even if metal silicide materials are used. (If much thicker silicide layers are used, corresponding attenuation calculations should be made.)

### X1.3 Absorbed-Dose Enhancement

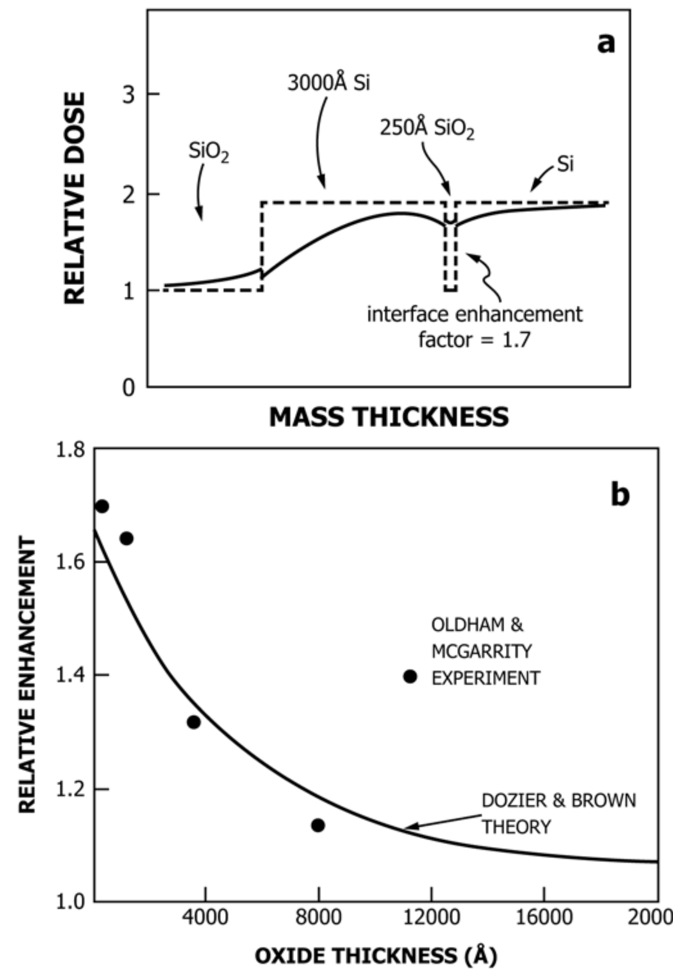
X1.3.1 Previously it was shown that attenuation of the beam within the layers covering the critical oxide layer does not lead to significant differences between the deposited energy in the oxide from X-rays and cobalt-60 gammas. On the other hand, absorbed-dose enhancement effects can cause large differences in the resulting oxide dose. In absorbed dose enhancement, electrons that are produced by the deposition processes in one layer can ultimately deposit energy in another layer, after electron transport and diffusion occur. In order for these effects to be significant, the layers must be close together in comparison with the ranges of the relevant Compton electrons and photoelectrons.

X1.3.2 Examples of absorbed-dose enhancement effects are shown in Fig. X1.2. The procedures for the calculations used here have been reported by Brown (**25**).

X1.3.3 The device geometry used in the calculation for Fig. X1.2 is a typical silox (deposited $SiO_2$)/polysilicon gate/ $SiO_2$/Si structure. The $SiO_2$ gate oxide layer is 25-nm thick. The covering silox layer was assumed to be approximately 2-µm thick. The dashed lines in Fig. X1.2a show the absorbed doses that would occur in each material far from any interface, that is, without electron transport across interfaces. These are the equilibrium absorbed doses. The solid lines show the doses allowing for the electron transport that causes absorbed dose enhancement effects. Note that the dose in the $SiO_2$ gate has been enhanced by a factor of 1.7. Thus, there would be a factor of 1.7 underestimate of the dose in the gate oxide if this effect was not included in the dosimetry calculations. Fig. X1.2b shows the absorbed-dose enhancement expected in the gate oxide for different oxide thicknesses and for the case of aluminum metallization. For polysilicon gate devices, the enhancement factor is about 10 % larger for devices with gate thicknesses of 50 to 100 nm. Note that for a thick field oxide with 1000-nm thickness, the dose enhancement for the X-ray beam is approximately a factor of 1.15.

X1.3.4 More recently, Benedetto and Boesch (**10**) have measured the absorbed-dose enhancement versus oxide thickness for aluminum gate devices. These results are presented in Fig. X1.3. These results should be compared with the results presented in Fig. X1.2b. Additionally, Brown (**26**) has presented revised calculations for the absorbed-dose enhancement factors for silicon gate devices. These new results show enhancement factors, which are about 20 % smaller than those presented in Ref (**25**).

X1.3.5 Further, Benedetto et al (**17**) have presented experimental data giving the magnitude of dose enhancement to be expected in silicided devices. Fig. X1.4 shows data giving the variation of dose enhancement with the thickness of the polysilicon layer separating the silicide layer from the gate oxide.




NOTE 1—Fig. X1.2a shows the deposition profile for tungsten X-rays in a MOS device with a polysilicon gate (**18**). Dashed lines are the doses calculated with standard absorption coefficients. (Doses are appropriate to 'bulk' materials.) The solid line is the dose that occurs after electron transport and diffusion. X-rays are incident from the left, and the $SiO_2$ layer at the left is assumed to be 2-µm thick.

NOTE 2—Fig X1.2b shows the absorbed-dose enhancement factor. This is a correction to the 'bulk' $SiO_2$ dose required for various oxide thicknesses in an MOS device similar to that shown in Fig. X1.2a except that this data is for aluminum gate devices. The enhancement factor is about 10 % larger for polysilicon gate devices of 50 to 100 nm. The experimental data are those of Oldham and McGarrity (**11**).

**FIG. X1.2 Experimental and Theoretical Corrections for Dose Enhancement**

X1.3.6 Also, Fleetwood et al (**19**) have explored dose enhancement in silicided devices. Predicted dose-enhancement factors are shown in Table X1.3. The meaning of the notation in Table X1.3 is as follows: 'Aluminum' implies a 1.07 µm metallization adjacent to the gate oxide. 'Tantalum silicide↓' implies 0.67 µm of aluminum over 0.2 µm of tantalum silicide over 0.2 µm of aluminum over the gate oxide. 'Tantalum silicide↑' implies 0.2 µm of aluminum over 0.2 µm of tantalum silicide over 0.67 µm of aluminum over the gate oxide. Note that the maximum predicted dose-enhancement factor was

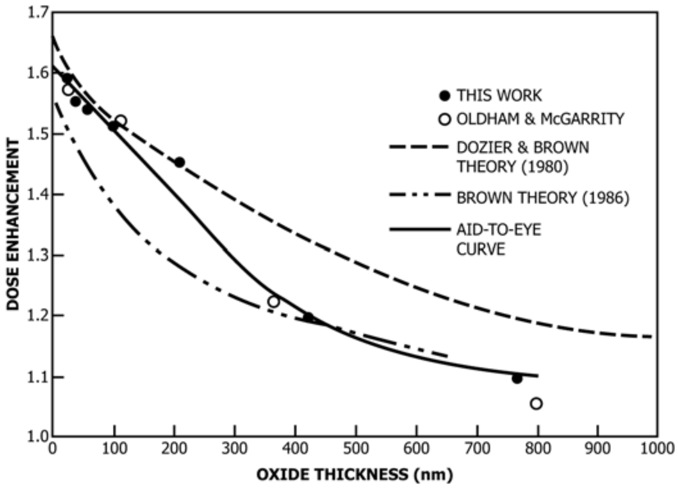



**FIG. X1.3 Dose Enhancement Versus Oxide Thickness (From Benedetto and Boesch (10)). Open Circles: Oldham and McGarrity (11). Dashed Line: Dozier and Brown (29)**

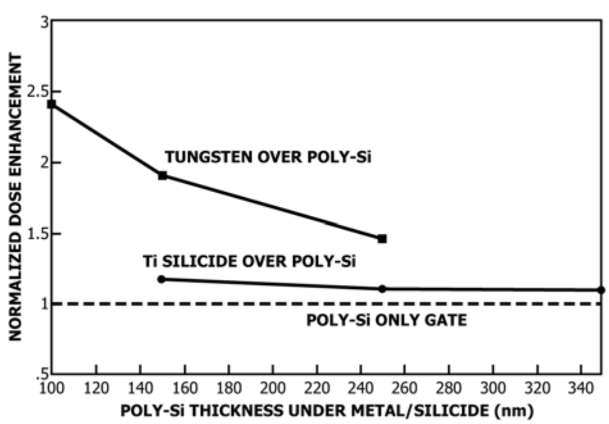



**FIG. X1.4 Dose Enhancement Versus Poly-Si Thickness Under the W or $TiSi_2$ Layer, Normalized to the Poly-Si-only Case (Benedetto et al (17))**

**TABLE X1.3 Predicted X-ray Dose Enhancement Factors as a Function of Gate-Oxide Thickness and Code**

| Material | Code | Oxide Thickness (nm) | | | |
|---|---|---|---|---|---|
| | | 35 | 98 | 356 | 1060 |
| Aluminum | TEP | 1.48 | 1.40 | 1.25 | 1.13 |
| | CEPXS/ONETRAN | 1.54 | 1.37 | 1.26 | 1.12 |
| | TIGERP | 1.59 | 1.59 | 1.26 | 1.02 |
| | TEP | 2.73 | 2.60 | 1.94 | 1.49 |
| Tantalum silicide↓ | CEPXS/ONETRAN | 2.98 | 2.69 | 2.07 | 1.54 |
| | TIGERP | 2.32 | 2.40 | 1.77 | 1.48 |
| | TEP | 1.70 | 1.57 | 1.36 | 1.21 |
| Tantalum silicide↑ | CEPXS/ONETRAN | 1.86 | 1.71 | 1.52 | 1.26 |
| | TIGERP | 1.52 | 1.52 | 1.30 | 1.13 |

about 3.0. In the worst case explored by these authors, twice the cobalt-60 gamma irradiation was required to produce a result comparable to an X-ray irradiation.

X1.3.7 The effects shown in Fig. X1.2, Table X1.3, and Fig. X1.4 are caused largely by the transport of photoelectrons away from their site of production. These processes are not as important in cobalt-60 gamma irradiations where the energy deposition is dominated by Compton scattering processes. It should be noted, however, that there can be significant absorbed-dose enhancement effects due to the transport of Compton electrons in cobalt-60 gamma irradiations. These effects can complicate the comparison of data obtained on the X-ray tester with that obtained using cobalt-60 gamma sources. A good deal of fundamental work has been done on this subject by Burke and co-workers (**7, 27**). Long et al (**28**) and Brown and Dozier (**14**) have attempted to apply this work to devices. More recently, Kelly et al (**16**) have measured absorbed-dose enhancement effects in MOS devices irradiated with cobalt-60 gamma sources.

## X1.4 Effects of Bias

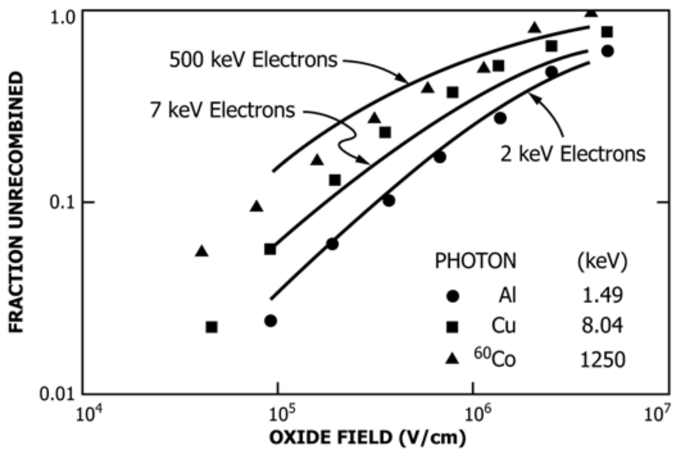
X1.4.1 It is widely understood that radiation effects may be dependent on the bias that is applied during irradiation. It is, perhaps, less widely recognized that the effect of bias may be dependent upon the energy of the incident photons. The following section (X1.5) describes such a case, electron-hole recombination. Annealing and interface-state-generation effects may also be dependent upon both photon energy and bias.

## X1.5 Electron-Hole Recombination

X1.5.1 The energy dependence of electron-hole recombination is included in this section. This and absorbed-dose enhancement are believed to be the most important physical processes that lead to an energy dependence of radiation effects in MOS structures.

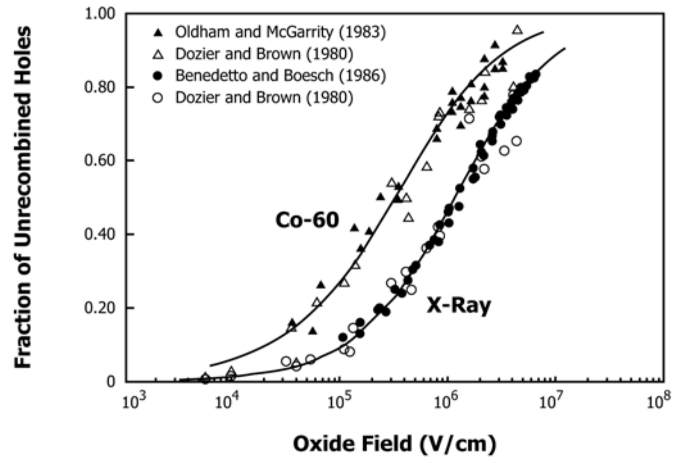
X1.5.2 Shifts in many measurable parameters, such as threshold voltage, can be related to the number of holes that are generated in the oxide and that escape subsequent recombination. This is true for two reasons. First, there is an obvious connection between the number of unrecombined holes and the number of holes that become trapped in the oxide. (Note that a factor of 3 change in the number of generated holes does not necessarily mean a factor of 3 change in the threshold voltage if the number of hole traps is saturating.) Secondly, there may be a connection between the number of unrecombined holes and the number of interface states generated. (This connection is not clearly established at this time.) The magnitude of the ionization charge, that is, the number of electron-hole pairs that ultimately cause the detrimental effects in MOS structures, is sensitive to both absorbed-dose enhancement and electron-hole recombination effects.

X1.5.3 Dozier and Brown (**29, 30, 31**) and Oldham and McGarrity (**11**) showed experimentally that under low field conditions approximately twice as much electron-hole recombination occurs for 10 keV radiation as compared to cobalt-60 gamma radiation. This difference is observed at relatively low fields ($<10^5$ V/cm). The above authors found that at high fields ($>10^6$ V/cm) the recombination approaches being the same for both low and high energy because the applied fields can separate the electrons and holes. Fig. X1.5 shows an example from this work. As a result of these recombination effects fewer holes remain following X-ray irradiation for cases where the fields in the oxide are low. Thus at low doses, where the radiation-induced effects change linearly with the number of electron-hole pairs produced, recombination will tend to cause




NOTE 1—Model predictions (lines) for three electron energies are shown with experiment data (points) for comparable photon energies.

**FIG. X1.5 Electron-Hole Pairs Escaping Recombination as a Function of Oxide Field (31)**




NOTE 1—Figure from Ref (**32**). Data are modifications of data from Refs (**29, 11,** and **10**).

**FIG. X1.7 Fraction of Holes Escaping Recombination for Cobalt-60 and 10 keV X-rays as a Function of Oxide Field**

the results obtained with an X-ray tester to be smaller than those observed with cobalt-60 gamma sources.

X1.5.4 More recently, Benedetto and Boesch (**10**) have measured the fraction of unrecombined electron-hole pairs for X-ray irradiation. These results are shown in Fig. X1.6 for comparison with the results of Fig. X1.5.

X1.5.5 Further, Dozier et al (**32**) have performed a critical evaluation of earlier electron-hole recombination data (**29, 11, 10**). They have adjusted the values given in these three references to put them in terms of a common assumption for the energy of formation of electron-hole pairs (16.5 keV) and a common method for scaling the data to obtain the point of 100 % yield. The results of this analysis is a set of values for the fraction of holes that escape recombination at an electric field, E, across the oxide. These results are presented in Fig. X1.7. Those authors report that the fitting curves shown in Fig. X1.7 can be represented by

$$f(E)_{X-ray} = ((1.35/E)+1)^{-0.9} \quad (X1.1)$$

and

$$f(E)_{Co-60} = ((0.55/E)+1)^{-0.7} \quad (X1.2)$$

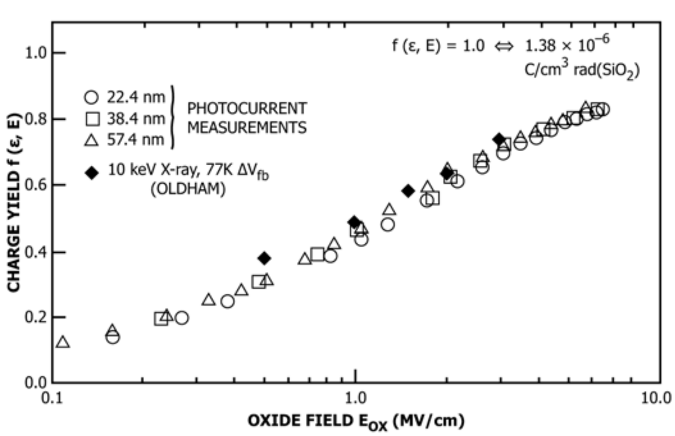
where:

$E$ = the oxide field in MV/cm.

X1.5.6 Shaneyfelt et al (**33**) have suggested that the cobalt-60 data of Fig. X1.7 are too high in the low field (<0.5 MV/cm ) region. For example, their results suggest that the fraction unrecombined at a field of 0.1 MV/cm is about 0.13 as compared with about 0.26 as shown in Fig. X1.7. Their data for the fraction of unrecombined holes for cobalt-60 irradiation are shown in Fig. X1.8. Note, in comparison, that the data of Fig. X1.5 also suggest that the fraction of unrecombined holes for cobalt-60 irradiation is about 0.12 at a field of 0.1 MV/cm.

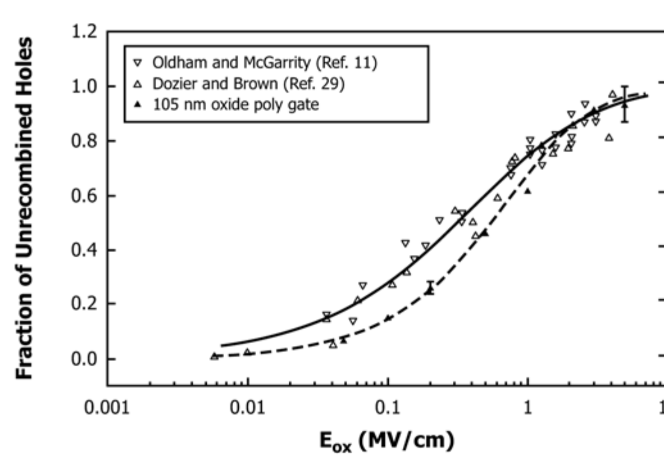
X1.5.7 An analysis of the literature data for the fraction of unrecombined holes for cobalt-60 irradiation leads to the suggestion that Eq X1.2 be replaced tentatively by

$$f(E)_{Co-60} = ((0.65/E)+1)^{-0.9} \quad (X1.3)$$




NOTE 1—Figure based on Benedetto and Boesch (**10**). Solid diamonds from Oldham and McGarrity (**11**).

**FIG. X1.6 Charge Generation and Fraction of Unrecombined Electron-Hole Pairs Versus Oxide Field**




NOTE 1—Figure from Shaneyfelt et al (**33**). Dashed line represents revised recommendation of these authors.

**FIG. X1.8 Fraction of Holes That Escape Recombination for Cobalt-60 as a Function of Oxide Field**

X1.5.8 This equation has the following characteristics: First, in comparison with Eq X1.1, it implies that the unrecombined fractions for X-ray and cobalt-60 irradiations should have a constant ratio at low oxide fields as suggested by Fig. X1.5. Second, it is a compromise between the values given in Fig. X1.5, Fig. X1.7, and Fig. X1.8. Third, the use of Eq X1.3 rather than Eq X1.2 gives predictions for the oxide field dependence for X-ray/cobalt-60 effect ratios that are in agreement with the work of Fleetwood et al (**34**).

## X1.6 Beam Spreading

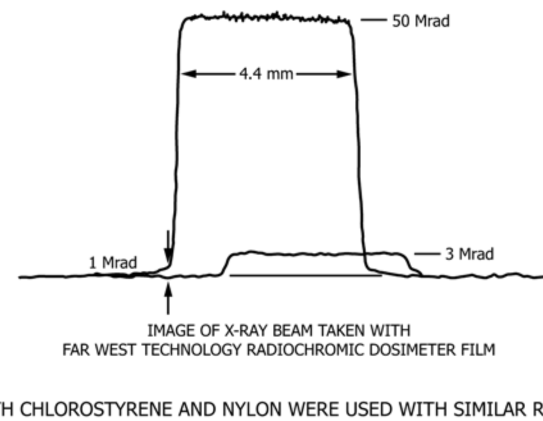
X1.6.1 One of the advantages that makes low energy X-ray testers attractive for testing at the wafer level is the feasibility of collimating the X-ray beam effectively. Collimation cannot be performed adequately for cobalt-60 gamma photons. This difference is, again, due to the different energy deposition mechanisms of high and low energy photons.

X1.6.2 Cobalt-60 gamma photons are highly scattered as they interact with materials. Not only are the photons scattered, but energetic electrons are produced that can ultimately deposit their energy in regions outside the primary beam.

X1.6.3 On the other hand, the photoelectric process dominates the deposition of 10 keV X-rays. This latter process produces electrons with much lower energies and shorter ranges. The low photon scattering and small range of secondary particles permit the collimation of 10 keV X-rays. However, even for 10 keV photons some scattering occurs. Additionally, the X-ray beam can generate fluoresced photons in the sample being irradiated.

X1.6.4 To investigate the scattering and fluorescence of the beam, exposures were made of a collimated tungsten target X-ray beam on radiochromic dye dosimeter films (**18**). These films were located in a position corresponding to the sample position of a commercial irradiator. The collimator was a chromium plated brass opening in the sample probe card approximately 1 mm above the dosimeter. Both nylon and chlorostyrene (a better match to the materials in silicon devices) dosimeter films were used. Results of the exposures of both films were similar. An example of the results is shown in Fig. X1.9. It can be seen that the spreading in the deposition extends a small distance beyond the region defined by the collimator. A rough calibration of the exposures shows that the dose measured approximately 0.1 mm beyond the edge of the collimator (as indicated by the arrows on Fig. X1.9) is 2 % of the dose that was measured in the central irradiated region. This spreading decreases in an approximately exponential fashion, becoming negligible at about 1 mm beyond the edge of the collimator. It is believed likely that the beam spreading shown in Fig. X1.9 is due to scattering of the radiation within the material being irradiated (rather than from the X-ray collimator).

X1.6.5 Significantly better results have been reported by Palkuti (**35**). He has reported that if care is used to keep high atomic number materials out of the beam (for example, beryllium copper probes were used on the X-ray tester probe card rather than tungsten probes) the intensity just outside the penumbral region of the beam is 1/1000 the intensity in the central region of the beam.




NOTE 1—Optical microdosimeter scan at 3 Mrad(Si) dose is offset for clarity.

**FIG. X1.9 Lateral Spreading of the X-ray Deposition at the Sample Position as Recorded by Radiochromic Dye Film Dosimeters**

## X1.7 Time-Dependent Effects

X1.7.1 It is well known that radiation-induced defects may grow in or be annealed out on a time scale of seconds to years.

X1.7.1.1 The key processes are hole trapping, interface state growth, hole annealing (or compensation), and interface state annealing. These processes take place both during and after the irradiation.

X1.7.1.2 Ionizing irradiation of MOS devices results in two major species of defects, trapped holes in gate (and field) oxides, and interface states at the Si-$SiO_2$ interface. Hole trapping occurs rapidly (< 1 s) and interface state density builds up slowly (seconds to days). The relative magnitudes of these defects determine the effects on operation of the device and its post-irradiation time dependence. The quality of the oxide determines the relative densities and saturation levels of the defects.

X1.7.1.3 Trapped holes in the silicon dioxide result in a negative shift in the gate threshold voltage for both *n*- and *p*-channel devices (negative gate threshold shift).

X1.7.1.4 Trapped holes are removed or compensated in time while interface states increase. As hole trapping occurs rapidly, initial gate threshold shifts in both *p*- and *n*-channel devices are negative under irradiation at moderate to high dose rates. As time passes, the gate threshold voltage shift of *n*-channel devices becomes less negative and, if interface states build up, can eventually become positive. Whether *p*-channel gate shifts become more or less negative with time depends on the relative rates of formation of the negatively charged interface states and the removal of trapped holes, but the shift always remains negative.

X1.7.1.5 The interactions of these competing effects that shift with time cause the sometimes confusing behavior of MOS parts following irradiation. This complex behavior explains observed effects previously thought anomalous: 'reverse annealing,' in which parts degrade with time following cessation of irradiation rather than 'anneal;' the rebound effect, in which *n*-channel devices 'anneal' back past their pre-radiation gate threshold values to fail due to a positive gate threshold voltage shift when initially the gate threshold shift was negative; extremely 'hard' parts at particular dose rates that are softer at dose rates either above or below the 'hard' dose rates because at the 'hard' dose rate defect introduction was balanced by time dependent hole compensation and interface state buildup; etc.

X1.7.2 There exists scattered evidence that annealing of radiation-induced effects may be dependent on the energy of the incident photons. Evidence that differences in annealing exist between MeV electrons and cobalt-60 gammas, on one hand, and alpha particles and protons, on the other hand, has been presented by Brucker et al (**36**). Also, Griscom has observed differences in annealing of E' centers in fused silica for irradiation with cobalt-60 gammas and with X-rays (**37**). On the other hand, Fleetwood et al (**1**) show effects due to hole trapping and to interface states caused by three different radiation sources (linac, X-ray, and cesium-137) merging to a common postirradiation response at long times. At this point we can only urge caution about the possibility of such effects.

X1.7.3 *Dose-Rate Effects and Time-Dependent Effects:* There is a second way in which annealing effects may complicate the comparison of X-ray and cobalt-60 gamma irradiations. This is not a true photon energy dependence, but rather a reflection of the fact that X-ray irradiation and measurement is usually done more quickly than comparable cobalt-60 gamma irradiation and measurement. Because different amounts of annealing may occur in the different exposure times, this difference in test protocol may lead to an apparent energy dependence. Such effects can be large and must be allowed for in cases where annealing is important (**1, 2**). See 7.1 for additional information.

### X1.8 Areas of Uncertainty

X1.8.1 *Interface States*—At present there is some uncertainty in the mechanisms for the production of interface states. The results of some studies suggest that interface-state generation should show the same dependence on photon energy and on bias as does hole generation. For example, the data of Winokur and Boesch (**38**) and the interface state generation model of McLean (**39**) (later expanded by others (**40, 41, 42**)) suggest that interface-state generation should be a function of the number of holes generated. Further, Dozier and Brown (**18**) exposed MOS capacitors fabricated on *n*-type substrates with both cobalt-60 gammas and X-rays from a copper target tube. That experiment showed that the interface-state growth had the same 2/3 power dose dependence as observed by Winokur and Boesch. Several workers have attempted to compare X-ray and cobalt-60 gamma effects by making similar corrections for trapped hole production and interface state generation. These studies are reviewed in 8.1.1 – 8.2.6. Dozier et al (**12**), applying such an approach, have indicated that hole trapping and interface-state generation cannot be treated in the same fashion. On the other hand, studies by Dozier et al (**13**) and by Benedetto and Boesch (**10**) have indicated that hole trapping and interface state generation can be treated in a similar fashion. The data of Fleetwood et al (**9**) show a difference between the ratio of X-ray effect to cobalt-60 gamma effect for interface states as compared to the same ratio for hole trapping. The difference is less than 15 % for fields greater than 2 MV/cm. However, the difference was as great as 60 % for some lower fields. It seems simplest at this time to assume that the correction factors for hole trapping and for interface-state generation are similar. However, further investigation of the mechanisms for interface state generation is needed to resolve the uncertainties.

X1.8.2 *Hardened Field Oxides*—It is somewhat less clear that the discussion of physical processes contained in 8.1, X1.3, and X1.5 is adequate to handle hardened field oxides (**43**) because there is a relatively small amount of published data on the differences between X-ray and cobalt-60 gamma irradiation for this type of field oxide (**6**). This is an area where additional work would be helpful. As a result of the paucity of data, some caution is prudent. However, in the absence of contrary evidence, it seems appropriate to apply dose-enhancement and electron-hole-recombination corrections as described in 8.2.1 to 8.2.6. An example supporting this approach can be found in Ref (**6**).

X1.8.3 *Non-Silicon Devices*—Low-energy testers have largely been used with silicon devices. However, it is expected that these testers may be applied to technologies other than silicon. Mercury cadmium tellurium (HgCdTe), for example, is a material on which metal insulator semiconductor (MIS) structures are fabricated. The atomic numbers of some of the insulating materials, such as zinc sulfide (ZnS), are much larger than that of $SiO_2$, and the resulting absorption of radiation is much greater than for X-rays. Additionally, with the abundance and close proximity of other high-atomic-number materials, such as HgCdTe, dose-enhancement effects could also be large. A calculation of the deposition profiles for a 'typical' HgCdTe device was made. The device structure was assumed to have a metallization of 200 nm of gold and 10 nm of chromium, an insulator of 500 nm ZnS and a substrate of $Hg_{0.7}Cd_{0.3}Te$. The absorbed-dose enhancement factor caused by the nearby gold and HgCdTe layers for a tungsten X-ray spectrum was only 1.1, comparable to the absorbed dose enhancement of 1.2 that would be expected with cobalt-60 gammas. In this one case, a low-energy tester would not have introduced large errors. The dose in ZnS without absorbed-dose enhancement is a factor of 7.25 times that of $SiO_2$. Had $SiO_2$ been used as the insulator, absorbed-dose enhancement factors of 5 or greater would have been expected. Large effects such as this are possible in non-silicon devices and thus extra care should be exercised in their testing.

## X2. APPLICATIONS

### X2.1 Brief Summary of Potential Applications

X2.1.1 In order to lay the groundwork for recommendations on the use of X-ray testers, the possible applications of X-ray testers will be split into five application areas that are defined as follows:

X2.1.1.1 *Process Control*—This consists of the monitoring of some process to detect the onset of an undesirable change in the ionizing radiation hardness of the product. Also, the selection of wafers into classes, based on their ionizing radiation hardness is required. For this case, the hardness test does not need to be accurate. It does need to be adequately reproducible and sensitive.

X2.1.1.2 *Quality Conformance Testing*—This consists of comparison of measured ionizing radiation hardness with a requirement specified by contract or by a standard. In this case, there will be a strong incentive for accuracy provided by contractual obligations.

X2.1.1.3 *Comparison with Cobalt-60 Gamma Irradiations*—In this case ionizing radiation hardness measured with the X-ray tester and with cobalt-60 gamma irradiation must be compared. In this case the details of both irradiation processes must be understood.

X2.1.1.4 *Research on Hardening Technology*—This case is similar to X2.1.1.1 in that the effects of processing changes on device hardness can be tracked even if the measured dose is not accurate. This assumes, however, that the processing changes do not affect electron and photon transport and deposition significantly.

X2.1.1.5 *Research on Radiation Effects*—This case may require a very strict control and complete knowledge of the irradiation environment.

### X2.2 Guidelines for the Use of 10 keV X-Rays in Five Application Areas

X2.2.1 *Introduction*—This section is designed to give the reader an estimate of the importance of various physical processes for a series of practical problems. For discussion of the physical processes that affect radiation effects see Appendix X1. The five application areas defined in X2.1 will each be treated in turn. For each application area the effects of principal importance will be discussed. In addition, the techniques available for the correction of experimental biases introduced by these effects will be indicated.

X2.2.2 *Process Control and Wafer Selection*—The use of the X-ray tester for process control is thought to be on a fairly solid basis. The key presumption is that an experimental measurement based on the use of the X-ray tester will allow one to test for a process change of interest, even if the measurement is not quantitatively accurate. It is further assumed that a quantitatively correct correlation between an X-ray test and radiation effect can, if desired, be obtained through calibration with some independent method. For example, a correlation between the effect due to cobalt-60 gamma irradiation and that due to an X-ray tester irradiation can be experimentally established for a specific device. In this case, the cobalt-60 gamma irradiation may provide the standard or calibration experiment (**6**). It should be borne in mind that a field oxide and a gate oxide within the same device may show different effects, and thus may require independent calibration. It should also be borne in mind that a different calibration may be required for different devices. Further, it may be necessary to recalibrate if the device geometry changes. Finally, it will be necessary, if annealing effects are important, that the experimental times be carefully controlled in order to obtain reproducible and meaningful results.

X2.2.3 *Quality Conformance Testing:*

X2.2.3.1 When a product is to be tested for compliance with a requirement mandated by a standard or by a contract, it becomes necessary to perform all corrections to the dosimetry to ensure that the device under test is exposed at the specified level. If, for example, a certain deposited dose in the gate oxide is required, the most difficult corrections to apply are those for absorbed-dose enhancement. As outlined in X1.3 and 8.2.1 – 8.2.3, the correction for dose in a thin gate oxide may be as high as a factor of 1.8, even in the absence of high atomic number materials. An absorbed-dose enhancement factor as high as 5 is possible in the presence of high-atomic-number layers such as gold, tantalum, tantalum silicide, etc. In some cases, it will be necessary to establish the magnitude of these corrections using calculations, such as those described in Ref (**25**), or using measurements on appropriately designed test devices. The possibility of an energy dependence of annealing effects and of interface-state generation effects should be considered, as discussed in X1.7.

X2.2.3.2 Because of the relatively small body of experience with the use of the X-ray tester it is recommended that when an X-ray tester is used for qualification testing or lot acceptance testing it should first be cross checked against cobalt-60 gamma irradiations of the device type in question. The reader is reminded that X-ray to cobalt-60 gamma correlations may vary with device type. Also, different correlations may apply for field and gate oxides. Finally, if annealing effects are important, a careful control of experimental times is required.

X2.2.4 *Comparison with Cobalt-60 Gamma Testing:*

X2.2.4.1 Because of the convenience of total dose testing with cobalt-60 gamma sources, and because of the predominance of testing with such sources in recent years, it may become necessary to compare the results of testing done with the X-ray tester with similar testing done using cobalt-60 gamma sources. In order to make valid comparisons it will, of course, be necessary to make all of the necessary dosimetry corrections for *both* sources. Again, the most difficult corrections to make will be those for absorbed-dose enhancement. It is estimated that absorbed-dose enhancement factors as high as 2 may be present for cobalt-60 gamma irradiations where high-atomic-number materials are present (**15**). An informative experimental test of such effects has been published by Kelly et al (**16**). It must be borne in mind that even for the same deposited dose, the radiation effects for X-ray and cobalt-60 gamma irradiations may be different because of electron-hole recombination effects. Estimates of the maximum errors to be expected, taking into account (*a*) dose enhancement for X-rays, (*b*) dose enhancement for cobalt-60 gammas, and (*c*) electron-hole recombination can be found in 8.2.1 – 8.2.6. Once again it may be necessary to establish the magnitude of the appropriate corrections by calculations, such as those of Ref **(25)** and **(14)** or by measurements on suitable test devices.

X2.2.4.2 In addition to the corrections just described, the reader is reminded that other precautions may be necessary for a valid comparison between the results of X-ray tester and cobalt-60 gamma source experiments. Perhaps the most important is an adequate consideration of possible time dependent effects **(44)**. This is particularly a problem because cobalt-60 gamma irradiations often require longer time periods than are necessary with the X-ray tester. The experimenter must ensure that annealing effects are negligible, or that they are adequately compensated for. Finally, the tester should consider the possibility that X-ray and cobalt-60 gamma irradiations may result in different annealing and interface state generation effects due to an energy dependence of the physical mechanisms. This is briefly discussed in X1.7.

X2.2.5 *Research on Hardening Technology*—Appropriate treatment for research on hardening technology is very similar to that for process control described in X2.2.2, and the remarks there are largely applicable to this case. It should be emphasized again that the assumption being made here is that process changes do not alter energy deposition within the critical regions of the device. The addition of a heavy metal silicide, for example, *would* significantly alter energy deposition and thus would require special treatment.

X2.2.6 *Research on Radiation Effects*—The same kinds of precautions described in X2.2.3 and X2.2.4 also apply to research work. Moreover, even greater forethought and caution are called for because (*a*) the range of device materials and geometries is likely to be much greater in a research environment, (*b*) there may be a smaller background of experimental and theoretical experience to support some types of research project, (*c*) in research it is particularly important to avoid confusion introduced by physical effects that are not accounted for, and (*d*) research results may have higher standards for precision and accuracy. It may be necessary to do careful measurements or calculations to correct for the effects described in 8.2.1 – 8.2.6. Such calculation may however be somewhat more practical for research work where specimen and experimental geometry can be very well known, controlled, and simplified.

**X2.3 Summary and Recommendations**

X2.3.1 The use of 10 keV X-rays is a useful technique for ionizing-radiation-effects testing of the ionizing-radiation hardness of devices. There are a number of differences between the effects of 10 keV X-rays and cobalt-60 gamma radiation. The fact that these two sources lead to different radiation effects does not preclude comparison of results, but appropriate allowance must be made for differences in such effects as absorbed-dose enhancement and electron-hole recombination.

X2.3.2 For some test configurations, as was shown in Table 1, the differences between cobalt-60 gamma and low energy X-ray irradiations are expected to be small, and reasonable comparisons between tests on the two sources should be expected even without applying any corrections. Further, as was discussed in 8.2.1 – 8.2.2, when radiation effects are saturated, the differences between cobalt-60 gamma and X-ray irradiations are expected to be small. However, as was shown in Table 1, there are device structures, packaging materials, and irradiation conditions that are expected to result in significant differences between the results of X-ray and cobalt-60 gamma testing.

X2.3.3 There are three techniques that are useful for obtaining comparable test data, each with its advantages and disadvantages:

X2.3.3.1 Comparative tests of devices with X-ray and cobalt-60 gamma irradiation can provide calibration data between the two sources.

X2.3.3.2 Dose enhancement and electron-hole recombination can be estimated by methods similar to those reviewed in X1.3 – X1.5 and 8.2.1 – 8.2.6.

X2.3.3.3 It is possible to fabricate simple calibration test structures such as MOS transistors or capacitors that could gage the magnitude of the combined effects of absorbed-dose enhancement, electron-hole recombination, etc. In the design of test structures, care must be taken to ensure that the radiation effects are similar to those in the real devices. Note that these structures will not provide the absolute dose, but only relative values. This comparison may be adequate for some applications. Some structures can be incorporated on the chips or wafers to be tested.

X2.3.4 In order to treat interface state generation, it is reasonable at this time to assume that similar corrections can be made for interface state generation as are made for hole trapping (see X1.3 – X1.5 and 8.2.1 – 8.2.6). This assumption should be regarded as tentative. Improved understanding of interface state generation processes may result in a need for a modified correction procedure.

X2.3.5 In cases where time dependent effects are important, the different dose rates of X-ray and cobalt-60 gamma irradiations can lead to *apparent* differences between the effects of the two sources which are, in fact, a reflection of the different times available for defect growth and annealing.

X2.3.6 For some non-silicon devices, X-ray testers may also provide a useful tool for evaluation at wafer levels. However, caution needs to be exercised. The cobalt-60 gamma versus X-ray corrections are not well defined at this time. Moreover, it is believed that some forms of device construction may result in large absorbed-dose enhancement effects with X-ray irradiation. (For further discussion see X1.8.3.)

X2.3.7 X-ray and electron scattering in the irradiated region of the die or wafer can produce dose in areas beyond the boundaries of the region defined by the collimator. This can result in doses in regions other than that which was intended to be irradiated. The magnitude of the dose approximately 0.1 mm beyond the edge of the region defined by the collimator was found to be 2 % of the dose in the central region of the collimator. This dose decreases to negligible levels approximately 1 mm beyond the edge of the collimator. (For additional discussion see X1.6.)

## REFERENCES


(1) Fleetwood, D. M., Winokur, P. S., and Schwank, J. R., "Using Laboratory X-Ray and Cobalt-60 Irradiations to Predict CMOS Device Response in Strategic and Space Environments," *IEEE Transactions on Nuclear Science*, Vol 35, 1988, pp. 1497–1505.

(2) Brown, D. B., Johnston, A. H., and Jenkins, W. C., "Application of a Model for Treatment of Time Dependent Effects on Irradiation of Microelectronic Devices," *IEEE Transactions on Nuclear Science*, Vol 36, 1989, pp. 1954–1962.

(3) Palkuti, L. J., and LePage, J. J., "X-Ray Wafer Probe for Total Dose Testing," *IEEE Transactions on Nuclear Science*, NS-29, 1982, pp. 1832–1837.

(4) Dozier, C. M., Brown, D. B., and Sandelin, J. W., "Dose and Dose Rate Dependence of 8080A Microprocessor Failures," *IEEE Transactions on Nuclear Science*, NS-27, 1980, pp. 1299–1304.

(5) Farmer, J. W., and Lee, R. S., "Photocurrents and Photoconductive Yield in MOS Structures During X Irradiation," *Journal of Applied Physics*, Vol 46, 1975, pp. 2710–2715.

(6) Fleetwood, D. M., Beegle, R. W., Sexton, F. W., Winokur, P. S., Miller, S. L., Treece, R. K., Schwank, J. R., Jones, R. V., and McWhorter, P. J., "Using a 10-keV X-Ray Source for Hardness Assurance," *IEEE Transactions on Nuclear Science*, NS-33, 1986, pp. 1330–1336.

(7) Wall, J. A., and Burke, E. A., "Gamma Dose Distributions at and Near the Interface of Different Materials," *IEEE Transactions on Nuclear Science*, NS-17, 1970, pp. 305–309.

(8) Curtis, O. L., Srour, J. R., and Chiu, K. Y., "Hole and Electron Transport in $SiO_2$ Films," *Journal of Applied Physics*, Vol 45, 1973, pp. 4506–4513.

(9) Fleetwood, D. M., Winokur, P. S., Beegle, R. W., Dressendorfer, P. V., and Draper, B. L., "Accounting for Dose-Enhancement Effects with CMOS Transistors," *IEEE Transactions on Nuclear Science*, NS-32, 1985, pp. 4369–4375.

(10) Benedetto, J. M., and Boesch, Jr., H. E., "The Relationship Between Co-60 and 10-kev X-Ray Damage in MOS Devices," *IEEE Transactions on Nuclear Science*, NS-33, 1986, pp. 1318–1323.

(11) Oldham, T. R., and McGarrity, J. M., "Comparison of $^{60}$Co Response and 10 keV X-Ray Response in MOS Capacitors," *IEEE Transactions on Nuclear Science*, NS-30, 1983, pp. 4377–4381.

(12) Dozier, C. M., Brown, D. B., Throckmorton, J. L., and Ma, D. I., "Defect Production in $SiO_2$ by X-Ray and Co-60 Radiations," *IEEE Transactions on Nuclear Science*, NS-32, 1985, pp. 4363–4368.

(13) Dozier, C. M., Brown, D. B., Freitag, R. K., and Throckmorton, J. L., "Use of the Subthreshold Behavior to Compare X-Ray and Co-60 Radiation-Induced Defects in MOS Transistors," *IEEE Transactions on Nuclear Science*, NS-33, 1986, pp. 1324–1329.

(14) Brown, D. B., and Dozier, C. M., "Reducing Errors in Dosimetry Caused by Low Energy Components of Co-60 and Flash X-Ray Sources," *IEEE Transactions on Nuclear Science*, NS-29, 1982, pp. 1996–1999.

(15) Kerris, Klaus G., and Gorbics, S. G., "Experimental Determination of the Low-Energy Spectral Component of Cobalt-60 Sources," *IEEE Transactions on Nuclear Science*, NS-32, 1985, pp. 4356–4362.

(16) Kelly, J. G., Luera, T. F., Posey, L. D., Vehar, D. W., Brown, D. B., and Dozier, C. M., "Dose Enhancement Effects in MOSFET IC's Exposed in Typical $^{60}$Co Facilities," *IEEE Transactions on Nuclear Science*, NS-30, 1983, pp. 4388–4393.

(17) Dozier, C. M., and Brown, D. B.," The Use of Low Energy X-Rays for Device Testing—A Comparison with Co-60 Radiation," *IEEE Transactions on Nuclear Science*, NS-30, 1983, pp. 4382–4387.

(18) Benedetto, J. M., Boesch, Jr., H. E., Oldham, T. R., and Brown, G. A., "Measurement of Low-Energy X-Ray Dose Enhancement in Silicided MOS Devices," *IEEE Transactions on Nuclear Science*, NS-34, 1987, pp. 1540–1543.

(19) Fleetwood, D. M., Beutler, D. E., Lorence, Jr., L. J., Brown, D. B., Draper, B. L., Riewe, L. C., Rosenstock, H. B., and Knott, D. P., "Comparison of Enhanced Device Response and Predicted X-Ray Dose Enhancement Effects on MOS Oxides," *IEEE Transactions on Nuclear Science*, NS-35, 1988, pp. 1265–1271.

(20) Fleetwood, D. M., Tsao, S. S., and Winokur, P. S.," Total-Dose Hardness Assurance Issues for SOI MOSFETs," *IEEE Transactions on Nuclear Science*, Vol 35, 1988, pp. 1361–1367.

(21) Titus, Jeffery L., and Platteter, D. G., "Wafer Mapping of Total Dose Failure Thresholds in a Bipolar Recessed Field Oxide Technology," *IEEE Transactions on Nuclear Science*, NS-34, 1987, pp. 1751–1756.

(22) Adams, L., and Holmes-Siedle, A., "The Development of an MOS Dosimetry Unit for Use in Space," *IEEE Transactions on Nuclear Science*, NS-25, 1978, pp. 1607–1612.

(23) Dawes, Jr., W. R., and Schwank, J. R., "An IC Compatible Ionizing Radiation Detector," *IEEE Transactions on Nuclear Science*, NS-28, 1981, pp. 4152–4155.

(24) Plechaty, E. F., Collea, D. E., and Howerton, R. J., Report No. UCRL-50400, Vol 6, Revision 2, Lawrence Livermore Laboratory, Livermore, CA, 1978.

(25) Brown, D. B., "Photoelectron Effects on the Dose Deposited in MOS Devices by Low Energy X-Ray Sources," *IEEE Transactions on Nuclear Science*, NS-27, 1980, pp. 1465–1468.

(26) Brown, D. B., "The Phenomenon of Electron Rollout for Energy Deposition and Defect Generation in Irradiated MOS Devices," *IEEE Transactions on Nuclear Science*, NS-33, 1986, pp. 1240–1244.

(27) Lowe, L. F., Cappelli, J. R., and Burke, E. A., "Dosimetry Errors in Co-60 Gamma Cells Due to Transition Zone Phenomena," *IEEE Transactions on Nuclear Science*, NS-29, 1982, pp. 1992–1995.

(28) Long, D. M., Millward, D. G., and Wallace, J., "Dose Enhancement Effects in Semiconductor Devices," *IEEE Transactions on Nuclear Science*, NS-29, 1982 , pp. 1980–1984.

(29) Dozier, C. M., and Brown, D. B.," Photon Energy Dependence of Radiation Effects in MOS Structures," *IEEE Transactions on Nuclear Science*, NS-27, 1980 , pp. 1694–1699.

(30) Dozier, C. M., and Brown, D. B.," Effect of Photon Energy on the Response of MOS Devices," *IEEE Transactions on Nuclear Science*, NS-28, 1981, pp. 4137–4141.

(31) Brown, D. B., and Dozier, C. M., "Electron-Hole Recombination in $SiO_2$ Using a Microdosimetry Model," in *Radiation Protection, Eighth Symposium on Microdosimetry*, J. Booz and H. G. Ebert, eds. (Commission of the European Communities, Luxembourg, 1983), p. 943.

(32) Dozier, C. M., Fleetwood, D. M., Brown, D. B., and Winokur, P. S., "An Evaluation of Low-Energy X-Ray and Cobalt-60 Irradiations of MOS Transistors," *IEEE Transactions on Nuclear Science*, NS-34, 1987, pp. 1535–1539.

**(33)** Shaneyfelt, M. R., Fleetwood, D. M., Schwank, J. R., and Hughes, K. L., "Charge Yield for Cobalt-60 and 10-keV X-Ray Irradiations of MOS Devices," *IEEE Transactions on Nuclear Science*, NS-38, 1991, pp. 1187–1194.

**(34)** Fleetwood, D. M., Winokur, P. S., Dozier, C. M., and Brown, D. B., "Effect of Bias on the Response of Metal-Oxide-Semiconductor Devices to Low Energy X-Ray and Cobalt-60 Irradiation," *Applied Physics Letters*, Vol 52, 1988, pp. 1514–1516.

**(35)** Palkuti, L. J., "Lateral Scatter in 10 keV X-Ray Tester," Advanced Research and Applications Corp., Sunnyvale, CA, 1 June 1987.

**(36)** Brucker, G. J., VanGunten, O., Stassinopolous, E. G., Shapiro, P., August, L. S., and Jordan, T. M., "Recovery of Damage in Rad-Hard MOS Devices During and After Irradiation by Electrons, Protons, Alphas, and Gamma Rays," *IEEE Transactions on Nuclear Science*, NS-30, 1983, pp. 4157–4161.

**(37)** Griscom, D. L., Stapelbroek, M., and Friebele, E. J., "ESR Studies of Damage Processes in X-Irradiated High Purity a-$SiO_2$:OH and Characterization of the Formyl Radical Defect," *Journal of Chemical Physics*, Vol 78, 1983, pp. 1638–1651.

**(38)** Winokur, P. S., and Boesch, Jr., H. E., "Interface-State Generation in Radiation-Hard Oxides," *IEEE Transactions on Nuclear Science*, NS-27, 1980, pp. 1647–1650.

**(39)** McLean, F. B., "A Framework for Understanding Radiation-Induced Interface States in $SiO_2$ MOS Structures," *IEEE Transactions on Nuclear Science*, NS-27, 1980, pp. 1651–1657.

**(40)** Boesch, Jr., H. E., "Time-Dependent Interface Trap Effects in MOS Devices," *IEEE Transactions on Nuclear Science*, Vol 35, 1988, pp. 1160–1167.

**(41)** Griscom, D. L., Brown, D. B., and Saks, N. S., "Nature of Radiation-Induced Point Defects in Amorphous $SiO_2$ and Their Role in $SiO_2$-on-Si Structures," *The Physics and Chemistry of $SiO_2$ and the Si-$SiO_2$ Interface*, C. Helms and B. Deal, Eds., Plenum Press, New York, 1988, pp. 287–298.

**(42)** Saks, N. S., and Brown, D. B., "Interface Trap Formation via the Two-Stage $H^+$ Process," *IEEE Transactions on Nuclear Science*, Vol 36, 1989, pp. 1848–1857.

**(43)** Hu, G. J., Aitken, J. M., and Dennard, R. H., "A Hardened Field Insulator," *IEEE Transactions on Nuclear Science*, NS-28, 1981, pp. 4102–4104.

**(44)** Winokur, P. S., Kerris, K. G., and Harper, L., "Predicting CMOS Inverter Response in Nuclear and Space Environments," *IEEE Transactions on Nuclear Science*, NS-30, 1983, pp. 4326–4332.