THE USE OF LOW ENERGY X-RAYS FOR DEVICE TESTING
- A COMPARISON WITH Co-60 RADIATION*

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Abstract

Low (~ 10 keV) energy x-ray sources have been proposed as alternatives to Co-60 for device testing. Several effects caused by differences in the photon energies of the two types of sources are evaluated. Quantitative estimates of the magnitude of these effects and other factors which should be considered in setting up test protocols are presented. Several cases are defined where the differences in the effects caused by x-rays and Co-60 are expected to be small. Other cases where the differences may be as great as a factor of five are described. Lateral spreading of the collimated x-ray beam beyond the desired irradiated chip region is also discussed.

Introduction

In the past several years low energy x-ray sources have been proposed and used as convenient alternatives to Co-60 for total dose testing of MOS devices.[1,2,3] Testing with x-ray sources makes use of conventional x-ray tubes with anodes such as W and Cu to produce intense photon beams with energies of approximately 10 keV. Although the energies of these photons are much lower than those from Co-60, total dose effects occur in the surface region before the x-ray beams are attenuated greatly. One advantage of these low energy sources is that they require significantly less shielding to minimize personnel hazards than does Co-60. A second advantage is that collimation is relatively easy to perform for x-ray sources, unlike Co-60 sources where collimation is difficult. Thus, small regions of MOS structures can be irradiated selectively. As a result, it is possible to incorporate x-ray radiation testers into device fabrication lines and test individual chips on the wafers prior to dicing and packaging. Testing at the wafer level should allow significant savings to be realized in the manufacturing of radiation-hardened devices.

Because of the attractiveness of wafer level testing, several laboratories and industrial firms have begun to incorporate low energy x-ray testers into their radiation-testing programs. X-ray testers are used to monitor processing and to assist in the pre-selection of radiation-hard wafers. Nevertheless, experience with x-ray testers is limited. Further experience with x-ray testers may result in the improved selection of radiation-hard MOS devices. It may also allow for total dose qualification standards for devices to be met at the wafer level without the additional steps of packaging and testing in Co-60 cells.

When using low-energy x-rays for testing of MOS devices, the magnitude of the effects may be significantly different for x-rays as compared to those from Co-60 at the same exposure level.[2] Two of the important mechanisms leading to differences are interface dose enhancement[4] and elec-

tron-hole recombination.[5] Each of these effects must be considered in the testing environment. For x-rays, the additional problem of spreading of the deposited energy beyond the area of the collimated beam must be considered. (This spreading is not normally considered for Co-60 testing since collimation and wafer level testing is not done.)

In this paper, mechanisms which can alter the results of testing with low energy sources, as compared to Co-60, are discussed. Each of the mechanisms is analyzed and quantitative estimates of the magnitudes will be given where possible. Although absolute magnitudes depend on the specific device design, these calculated results can assist in making more accurate comparisons between x-ray and Co-60 test data. In addition, the lateral spreading of the x-ray deposition within the wafer is also considered.

Energy Deposition and Beam Attenuation

The critical regions in MOS devices for which radiation dose must be determined are the gate and field oxides. Simple dosimeters which allow the user to measure the actual absorbed dose levels in these oxides are not currently available. Although MOS dosimeters have been fabricated,[6,7] under some conditions they are not sufficiently accurate as dosimeters and are also too expensive.

In general, three things must be known to obtain an accurate estimate of the dose in the oxide region. They are (a) a knowledge of the spectral distribution of the x-ray source, (b) the dose in a radiation detector, such as a Si pin detector or CaF_2 TLD's, which can be related to the incident intensity, and (c) the structure of the device being tested.

For much of the low energy testing of devices, W target x-ray tubes have been used. Table I contains the spectral distribution of a typical W target x-ray tube with a 0.1 cm thick Be window operated at 50 kV. The spectrum has been normalized to 1 ma tube current. Attenuation for additional filters has not been included. However, in normal use, the spectrum should be filtered, for example, by 0.0127 cm of Al to remove the softest components of the spectrum. The intensities given in Table I should then be corrected for the filtration used in a system. The spectral distribution given in Table I has been used successfully in the calculation of the dose in Si pin detectors, TLD's and several types of MOS structures irradiated by W target tubes. Agreement with measurement to better than 10 percent was achieved.

Figure 1 shows calculated deposition in a thin SiO_2 layer covered by various thicknesses of some of the more common materials which are used to fabricate MOS structures on Si. The profiles and subsequent calculations in the paper, are calculated using the W x-ray spectrum in Table I, filtered by a 0.0127 cm. Al, and the absorption coefficients from E. F. Plechety et al..[8] The results are appropriate for "bulk" materials. That is, interface enhancement effects, to be discussed below, are

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TABLE I
SPECTRAL DISTRIBUTION OF W X-RAY TUBE
OPERATED AT 50 kV

LINES

ENERGY keV	INTENSITY keV/sr/ma	ENERGY keV	INTENSITY keV/sr/ma
8.4	6.68×10^{12}	9.8	6.30×10^{11}
9.5	6.30×10^{11}	10.0	1.32×10^{12}
9.7	3.62×10^{12}	11.3	9.57×10^{11}

CONTINUUM

ENERGY keV	INTENSITY keV/keV/sr/ma	ENERGY keV	INTENSITY keV/keV/sr/ma
4.0	1.97×10^{11}	22.0	1.69×10^{12}
6.0	1.09×10^{12}	24.0	1.60×10^{12}
8.0	1.83×10^{12}	26.0	1.52×10^{12}
10.0	2.18×10^{12}	28.0	1.37×10^{12}
10.2	2.20×10^{12}	30.0	1.29×10^{12}
10.2	1.65×10^{12}	32.0	1.19×10^{12}
11.5	1.78×10^{12}	34.0	1.05×10^{12}
11.5	1.58×10^{12}	36.0	9.36×10^{11}
12.0	1.64×10^{12}	38.0	8.24×10^{11}
12.0	1.50×10^{12}	40.0	6.93×10^{11}
14.0	1.70×10^{12}	42.0	5.74×10^{11}
16.0	1.78×10^{12}	44.0	4.49×10^{11}
18.0	1.79×10^{12}	46.0	2.75×10^{11}
20.0	1.75×10^{12}	48.0	1.25×10^{11}

not included. It is readily observable that the dose in SiO_2 behind as much as $2 \mu\text{m}$ layers of some of the more common materials such as Si, Al and SiO_2 differ by less than 2 percent. Metal silicides, on the other hand, attenuate the beam more severely. However, these layers are usually only a few thousand angstroms thick so that the beam attenuation typically is less than 5 percent. In general, the dose in the SiO_2 gate or field oxide layers is within 10 percent of the SiO_2 dose at the surface even if metal silicide materials are used.

Figure 1. Decrease in the dose in a $250 \text{ \AA}$ oxide from a 50 kV W target x-ray tube that is caused by the deposition of materials over the oxide during device fabrication.

Interface Dose Enhancement and Electron-Hole Recombination

In the previous section 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 Co-60. On the other hand, interface dose enhancement effects can cause large differences in the resulting oxide dose. In interface dose enhancement, electrons which are produced by the deposition processes in one layer can ultimately deposit energy in another layer after electron transport and diffusion. In order for these effects to be significant, the layers must be close in comparison to the ranges of the relevant Compton electrons and photoelectrons.

In addition to the interface enhanced dose, the energy dependence of electron-hole recombination is included in this section. These are two of the more important physical processes which lead to energy dependence of radiation effects in MOS devices. The magnitude of the ionization charge, that is, the number of electron-hole pairs which ultimately cause the detrimental effects in MOS structures, is sensitive to interface dose enhancement and electron-hole recombination effects. Shifts in many measurable parameters, such as threshold voltage, can be related to the number of holes 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, for example, the threshold voltage if the shift vs dose behavior is saturating.)

Examples of interface enhancement effects are shown in Figures 2 and 3. The procedures for the calculations used here have been reported in an earlier paper.[9]

The device geometry used in the calculation for Figure 2 is a typical silox:polysilicon-gate: SiO_2 :Si structure. The SiO_2 gate oxide layer is $250 \text{ \AA}$ thick. The covering silox layer was assumed to be approximately $2 \mu\text{m}$ thick. The dashed lines in Figure 2a show the doses which would occur in each material far from any interface, that is, without electron transport across interfaces. The solid lines show the doses allowing for the electron transport which causes interface 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 dosimetry calculations. Figure 2b shows the interface enhancement expected in the oxide for different oxide thicknesses. For a field oxide with $\sim 10000 \text{ \AA}$ thickness, the dose enhancement for the x-ray beam is approximately a factor of 1.15.

The structure in Figure 3, based on structures currently being considered for VLSI devices, was chosen to demonstrate the large interface enhancement effects that can occur. Figure 3a shows a case with an expected dose enhancement factor of 4.5. The device geometry used in this calculation had a $250 \text{ \AA}$ oxide with a $1500 \text{ \AA}$ polysilicon layer between a $2500 \text{ \AA}$ thick tungsten silicide layer and the oxide. The covering silox layer was also assumed to be approximately $2 \mu\text{m}$ thick. Measurements by Lambert[10] of threshold voltage shifts in transistor test structures irradiated by x-rays and Co-60 have shown differences which are

Figure 2. (a) Deposition profile for W x-rays in a MOS device with a polysilicon gate. Dashed lines are dose calculated with standard absorption coefficients. (Doses are appropriate to "bulk" materials.) Solid line is the dose that occurs after electron transport and diffusion. (b) Correction to the "bulk" SiO_2 dose required for various oxide thicknesses in MOS device similar to that shown in (a). X-rays are incident from the left, and SiO_2 layer at the left is assumed to be $2 \mu\text{m}$.

consistent with enhancement factors as large as the calculated value of 4.5 in the structure described here. Figure 3b shows the effect of altering the separation of the silicide layer from the oxide. Even with 7000 Å of Si between the silicide and the oxide, an enhancement factor of 1.2 would be expected.

The effects shown in Figure 2 and 3 are caused largely by the transport of photoelectrons away from their site of generation. These processes are not as important in Co-60 irradiations where the energy deposition is dominated by Compton scattering processes. There can, however, be interface enhancement effects from Compton processes in Co-60 irradiations. A good deal of fundamental work has been done on the subject by Burke and coworkers.[4,11] Long et al.[12] and Brown and Dozier[13] have attempted to apply this work to devices. More recently, Kelly et al.[14] have measured interface enhancement effects in MOS devices irradiated with Co-60 sources. Further discussion of this effect is outside the scope of this paper.

The second factor which alters the number of electrons-hole pairs in the oxides is electron-hole recombination. Dozier and Brown[15,16] and Oldham[17] showed experimentally that under low field conditions approximately twice as much electron-hole recombination occurs for 10 keV radiation as compared to Co-60 radiation. This difference is observed at relatively low fields ($<10^5 \text{ V/cm}$). At

Figure 3. (a) Deposition profile for W x-rays in an MOS device fabricated with WSi_2 near the 250 Å gate oxide. Dashed lines are doses calculated with standard absorption coefficients. (Doses are appropriate to "bulk" materials.) Solid line is dose that occurs after electron transport and diffusion. (b) Magnitude of the interface dose enhancement that occurs with various thicknesses of polysilicon between the WSi_2 and the oxide. The interface dose enhancement factor approaches 1.8, the interface dose enhancement from the Si surrounding the oxide layer. X-rays are incident from the left, and SiO_2 layer at the left is assumed to be $2 \mu\text{m}$.

high fields ($>10^6 \text{ V/cm}$) the recombination is approximately the same for both low and high energy because the applied fields can separate the electrons and holes. As a result, for cases where the fields in the oxide are low, fewer holes remain following x-ray irradiation. Thus, at low doses, where the radiation-induced effects change linearly with the number of electron-hole pairs produced, recombination will tend to cause the results obtained with an x-ray tester to be smaller than those observed with Co-60 sources.

Table II summarizes the combined effects of both interface enhancement and electron-hole recombination. The number of holes which are produced in the oxide by the primary photon irradiation and by electron transport across interfaces and which also escape recombination was calculated for both Co-60 irradiation and 10 keV x-ray irradiation. It was assumed that the devices received the same dose (as measured by TLD's or Si pin detectors and corrected to dose in "bulk" SiO_2). The ratio of the number of holes from Co-60 to the number of holes from x-rays is presented. Note in Table II that there are cases where one would expect small differences between x-ray and Co-60 irradiation, and other cases where factor of five differences are possible.

TABLE II
SUMMARY OF INTERFACE ENHANCEMENT
PLUS RECOMBINATION FOR Si MOS DEVICES

CASE	HIGH Z PRESENT	THIN OR THICK OXIDE ^a	FIELD ^b	(# HOLES) CO-60 (# HOLES) X-RAY	COMMENTS
I	NO	THIN	LOW	1	EFFECTS CANCEL
II	NO	THICK	HIGH	1	SMALL EFFECTS
III	NO	THIN	HIGH	1/2	X-RAY DOSE ENHANCED
IV	YES	THICK	HIGH	1 - 2	CO-60 DOSE ENHANCED
V	YES	THICK	LOW	2 - 4	COMBINATION OF CO-60 DOSE ENHANCEMENT AND X-RAY RECOMB *
VI	NO	THICK	LOW	2	MORE RECOMBINATION FOR X-RAYS
VII	YES	THIN	—	2 - 1/5	ENHANCEMENT FOR FOR CO-60 = 1-3; LARGE ENHANCEMENT POSSIBLE FOR X-RAY IF HIGH Z LAYER IS "NEAR"

^a <1000 Å is "thin"; >10000 Å is "thick" except for case VII

^b <10⁵ V/cm is "low"; >10⁶ V/cm is "high"

In Case I shown in Table II, x-ray dose enhancement in Si devices with thin oxides is approximately a factor of 1.6-1.8. This dose enhancement is caused by the Si or Al gates and the Si substrate of the device. The correction at low fields for recombination is about 0.5. Thus the effects essentially cancel. Small effects are also expected in the Case II, for thick oxides, since little dose enhancement is observed for thick oxides as can be seen in Figure 2b and recombination is minimized at high fields. Based on similar considerations, it follows that in Cases III and VI the approximate factors of 1/2 and 2 should be expected. During Co-60 exposures, if high atomic number elements are present, such as Au deposited on the inside of Kovar device lids, factors between 1 and 2 in dose enhancement can occur. This enhancement has recently been demonstrated by Kelly et al.[14] This is shown as Case IV. Case V is similar except that, in addition, enhanced recombination would be expected with x-ray irradiation. Case VII is a particularly difficult problem. If there is a Au-coated Kovar cap for the Co-60 tests, but the device is otherwise like Case I, then the ratio may approach a value of 2. (Note that the Au/Kovar cap would not be present in x-ray testing because it would excessively attenuate the beam.) On the other hand, if Co-60 interface enhancement effects are small, but there is a high Z layer, such as a silicide using a high atomic number material, near the gate oxide then x-ray dose enhancement effects may cause the ratio to approach 1/5 (See Figure 3b).

Lateral X-ray Scattering

One of the advantages that makes low energy x-ray testers attractive for testing at the wafer

level is the ability to collimate the x-ray beam effectively. Collimation cannot be performed well for Co-60 photons. This difference is again due to the different energy deposition mechanisms of high and low energy photons. Co-60 photons are highly scattered as they interact with materials. Not only are the photons scattered, but energetic electrons are produced which can ultimately deposit their energy in regions outside the primary beam. The photoelectric process, on the other hand, dominates the deposition of x-rays. This latter process produces electrons with much lower energies and shorter ranges. However, even at these energies some scattering of photons occurs. Additionally, the x-ray beam can cause some fluorescence in the sample being irradiated. To investigate the scattering and fluorescence of beam, exposures were made of a collimated W target x-ray beam on radiochromic dye dosimeter films.[18] These films were located in the sample position. The collimator was a chromium plated brass opening in the sample probe card approximately 1 mm above the dosimeter placed in the sample position. Both nylon and chloro-styrene (a better match to the materials in Si devices) dosimeter films were used. Results of the exposures of both films were similar. An example of the results is shown in Figure 4. It can be seen that the spreading in the deposition extends out to approximately 1 mm beyond the region defined by the collimator. A rough calibration of the exposures shows that the exposure at the edge of the collimator is approximately 2 percent of the dose recorded in the central irradiated region. These exposures show that during irradiation to high doses of one device transistors near the edges of neighboring devices may receive an undesirable level of

BEAM SPREADING IN X-RAY TESTER

(BOTH CHLOROSTYRENE AND NYLON WERE USED WITH SIMILAR RESULTS)

Figure 4. Lateral spreading of the x-ray deposition at the sample position as recorded by radiochromic dye film dosimeters. Optical microdosimeter scan at 3 Mrad(Si) dose is offset for clarity.

irradiation. To avoid this problem, it may be necessary to either sacrifice the neighboring devices or to design the wafer masks so that a radiation test area is isolated from other chips.

Discussion

Surface States: At present there is insufficient data to predict the effects of photon energy dependence of interface state production. The data of Winokur and Boesch[19] and the interface state generation model of McLean[20] suggests that interface state generation should be a function of the number of holes generated. We exposed MOS capacitors fabricated on n-type substrates with both Co-60 and x-rays from a Cu target tube. This test showed that the interface state growth had the same 2/3 power dose dependence as observed by Winokur and Boesch. However, it is not clear that the test was sufficient to eliminate concern about other energy related differences that may occur. Further investigation of the possible differences that may occur for surface states is needed and care should be exercised in comparing results of devices irradiated by Co-60 and x-rays.

Non-Si Devices: Low energy testers have been used with only Si devices to date. However, it is expected that these testers may be applied to technologies other than Si. HgCdTe, for example, is a material on which MIS structures are fabricated. The atomic number some of the insulating materials, such as ZnS, are much larger than that of SiO₂, 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 metalization of 2000 Å Au and 100 Å of Cr, an insulator of 5000 Å ZnS and a substrate of Hg_{0.7}Cd_{0.3}Te. The interface dose enhancement factor caused by the nearby Au and HgCdTe layers for a W x-ray spectrum was only 1.1, comparable to the interface dose enhancement of 1.2

that would be expected with Co-60. In this one case, a low energy tester would not have introduced large errors. The dose in ZnS without interface dose enhancement is a factor of 7.25 times that of SiO₂. Had SiO₂ been used as the insulator, interface dose enhancement factors of 5 or greater would have been expected.

Conclusion

There are a number of differences between the effects of 10 keV x-rays and Co-60 radiation. These differences do not preclude comparison of results taken from these two sources, but appropriate allowance must be made for effects such as interface dose enhancement and electron-hole recombination.

I. For some test configurations, as was shown in Table II, the differences between Co-60 and low energy x-rays are small, and reasonable comparisons between tests on the two sources should be expected. However, there are other device structures and packaging materials which cause significant differences between x-ray and Co-60 testing. Three solutions to obtaining comparable test data may be possible. First, comparative tests of devices with x-ray and Co-60 sources can provide calibration data between the two sources. Secondly, it is possible to fabricate simple calibration test structures such as MOS transistors or capacitors which could gauge the magnitude of the dose enhancement effects. Note that these structures will not provide the absolute dose, but only relative values. This comparison may be adequate for some applications and such structures can be incorporated on the chips or wafers to be tested. And finally, the deposition profiles can be calculated in a manner similar to that used here, and the dose enhancement and electron-hole recombination estimated.

II. X-ray and electron scattering in the irradiated region of the chip can produce dosed areas beyond the irradiated chip boundaries. The magnitude of the dose just beyond the edge of the chip was found to be approximately 2 percent of the dose in the irradiated area, and decreases to negligible levels approximately 1 mm beyond the chip edge.

III. Results from devices which exhibit large effects due to surface states should be monitored closely for potential differences. Insufficient data currently exists to judge whether or not energy dependent effects may occur in the production of surface states as has been observed in the production of electron-hole pairs.

IV. Finally, for some non-Si devices, x-ray testers may also provide a useful tool for evaluation at wafer levels. However, caution needs to be exercised since the use of some insulators may result in large errors in the insulator dose.

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References

- [1.] L. J. Palkuti and J. J. LePage, IEEE Trans. Nuc. Sci. NS-29, 1832 (1982)
- [2.] C. M. Dozier, D. B. Brown, and J. W. Sandelin, IEEE Trans. Nuc. Sci. NS-27, 1299 (1980)
- [3.] J. W. Farmer and R. S. Lee, Jour. Appl. Phys. 46, 2710 (1975)
- [4.] J. A. Wall and E. A. Burke, IEEE Trans. Nuc. Sci. NS-17, 305 (1970)
- [5.] O. L. Curtis, J. R. Srouf, and K. Y. Chiu, Jour. Appl. Phys. 45, 4506 (1973)
- [6.] L. Adams and A. Holmes-Siedle, IEEE Trans. Nuc. Sci. NS-25, 1607 (1978)
- [7.] W. R. Dawes, Jr. and J. R. Schwank, IEEE Trans. Nuc. Sci. NS-28, 4152 (1981)
- [8.] E. F. Plechaty, D. E. Collea, and R. J. Hower-ton, UCRL-50400 Vol 6, Rev. 2 (1978)
- [9.] D. B. Brown, IEEE Trans. Nuc. Sci. NS-27, 1465 (1980)
- [10.] R. J. Lambert, Private Communication
- [11.] L. F. Lowe, J. R. Cappelli and E. A. Burke, IEEE Trans. Nuc. Sci. NS-29, 1992 (1982)
- [12.] D. M. Long, D. G. Millward, and J. Wallace, IEEE Trans. Nuc. Sci. NS-29, 1980 (1982)
- [13.] D. B. Brown and C. M. Dozier, IEEE Trans. Nuc. Sci. NS-29, 1996 (1982)
- [14.] J. G. Kelly, T. F. Luera, L. D. Posey, D. W. Vehar, D. B. Brown and C. M. Dozier, Presented and the IEEE Conf. on Nuc. and Space Rad. Effects, Gatlinburg, TN, July 18-20, 1983
- [15.] C. M. Dozier and D. B. Brown, IEEE Trans. Nuc. Sci. NS-27, 1694 (1980)
- [16.] C. M. Dozier and D. B. Brown, IEEE Trans. Nuc. Sci. NS-28, 4137 (1981)
- [17.] T. R. Oldham and J. M. McGarrity, Presented at IEEE Conf. Nuc. and Space Rad. Effects, Gatlinburg, TN, July 18-20, 1983
- [18.] Radiochromic dye films obtained from Far West Technology, Inc., Goleta, CA
- [19.] P. S. Winokur and H. E. Boesch, Jr., IEEE Trans. Nuc. Sci. NS-27, 1647 (1980)
- [20.] B. McLean, IEEE Trans. Nuc. Sci. NS-27, 1651 (1980)