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DOSE ENHANCEMENT IN A ROOM COBALT-60 SOURCE

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Abstract

A room Co-60 source was characterized using TLDs and pMOS RADFETs. Dose enhancement was measured using RADFETs with and without gold-flashed kovar lids. A methodology was developed to predict dose enhancement vs. position and test configuration.

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I. INTRODUCTION

Room Co-60 irradiators are used extensively in total ionizing dose testing at low dose rates (≤ 1 mrad/s to 1 rads/s), e.g., in the continuing study of low dose rate phenomena in bipolar linear microcircuits [1-3]. Low dose rates can often be conveniently obtained in such sources through the use of attenuators and/or by placing test specimens at large distances from the source. In most room irradiators the Co-60 rod or slug is stored in fully shielded containers from which it can be electrically or pneumatically elevated into the room to expose the sample. Co-60 rooms are typically constructed using thick concrete walls to provide the necessary external shielding.

Unfortunately, low dose rate testing is frequently accompanied by dose enhancement phenomena that can lead to uncertainties in dose and dose rate within a test device. This is particularly true in the case of Co-60 room irradiators where backscattering from concrete walls produces low energy photons that are directly responsible for dose enhancement effects. Dose enhancement tends to become more important in environments where the scattered or low energy radiation typically becomes a larger fraction of the total gamma spectrum. This occurs as the direct or high energy (1.17 and 1.33 MeV) photon intensity is reduced disproportionately through the use of line of sight attenuators and/or increased distance from the source. At very low dose rates, the intensity of the scattered radiation may represent a significant portion of the total photon flux. Of course, actual dose enhancement produced in a semiconductor device or microcircuit from these lower energy gamma photons will depend on device packaging and chip metallization.

The various problems associated with dose enhancement during radiation testing have been known and studied for many years [4-9]. A standard test method for mitigation of dose enhancement in a test device is the use of a shielded test enclosure that completely surrounds the test object. This enclosure, which is recommended for use in all Co-60 and Cs-137 testing [10], consists of an outer layer (> 1.5 mm)

of lead and an inner layer (0.7 to 1.0 mm) of aluminum. The purpose of this box is to attenuate the low energy scattered gamma photons and secondary electrons without appreciably affecting the high energy gamma spectral component. While this Pb/Al box has proven highly effective in many high dose rate exposures, it may be much less effective in low dose rate test configurations where the low energy gamma photons become a significant fraction of the total incident gamma spectrum.

In this study dose enhancement and dose rate measurements were made for several different test configurations at the RTI Gammabeam 150 room Cobalt-60 facility. Measurements were made both within and without Pb/Al boxes as well as with and without the use of thick (2") Pb attenuators. A methodology was developed for describing dose enhancement and dose rate as a function of test configuration and position within the room.

II. DOSIMETRY

Two types of dosimeters were used in the study: standard CaF_2 chip thermoluminescent dosimeters (TLDs) and specially fabricated dual-dielectric p-channel MOSFETs (or RADFETs) [11]. TLDs packaged in aluminum to ensure electron equilibrium were provided and read by both Sandia National Laboratories (SNL) and the Naval Surface Warfare Center (NSWC) -- Crane. The TLDs were calibrated against NIST standard sources. The dual-dielectric RADFETs, also provided by SNL, were fabricated using a 370 nm thermal oxide/310 nm nitride gate dielectric, a 500 nm p^+ poly Si gate electrode, and a 950 nm low temperature thermal oxide (LTO) cap. RADFET threshold voltages were measured to the nearest millivolt at drain currents of 90 and 160 μA before and after exposure using a pMOSFET dosimeter reader obtained from Radiation Effects and Monitors (REM). The sensitivity factor for these RADFETs was determined to be -2.5 mV/rad when they were irradiated with -20 V applied to the gate with source, drain, and body grounded. These dual dielectric RADFETs are dose rate insensitive; their threshold voltage shifts are essentially linear with dose over the measurement range utilized (krad level

cumulative dose); and there were no significant threshold voltage annealing (fade) or bias instabilities due to interface state charging [11]. Typically, the RADFETs were exposed in 50 to 100 rad increments and used repeatedly until their cumulative exposure approached the krad level whereupon they were replaced with fresh samples. The RADFET dosimeters were mounted in 16-pin dual in-line packages (DIPs) with removable lids. A measure of dose enhancement was obtained by comparing the threshold voltage shifts produced in RADFETs with gold-flashed kovar lids to the voltage shifts produced in RADFETs with ceramic or epoxy lids or, in some cases, to the shifts produced in lidless devices. (There were no significant differences in RADFET response at the RTI source between bare devices and devices with ceramic or epoxy lids.)

III. SOURCE CHARACTERIZATION

The RTI Gammabeam 150-A Cobalt-60 irradiation facility is housed in a 10 ft. square concrete room as shown in Figure 1 and was rated at 177 Ci in March 1996. Three standard test configurations consisting of Pb/Al boxes designated nos. 1-3 and utilized for exposures of approximately 0.8, 9, and 85 mrads(Si)/s, respectively, were first evaluated. Here, the two lower dose rate boxes are located on a shelf in the corner of the room with the test boards in the center of the boxes at a distance of 227 cm from the source. Additionally, a two-inch thick Pb

Figure 1: RTI Cobalt-60 facility

attenuator is located in front of lowest rate box (no. 1). The highest rate box (no. 3) is located on the aluminum table such that the test board is 71 cm from the source. The test box centers are in the same horizontal plane as the center of the Co-60 source when elevated above the table. In addition to the standard test configurations (originally set up for use in low dose rate linear bipolar studies), measurements were also made in the exact same positions without the boxes, at position 1 without the wall both with and without the box, and at position 3 with the wall both with and without the box. All of these configurations all summarized in Table 1. Within each test configuration, SNL and NSWC TLDs, along with SNL RADFETs, both with and without kovar lids were mounted on a single $4\frac{1}{2} \times 6\frac{1}{2}$ inch circuit board during irradiation.

Table 1. Test configurations for dosimetry measurements (standard configurations highlighted)

Desig.	Description	Expected Dose Rate
PL1	Position 1, 2" Pb and no box	TBD
PBL1	Position 1, 2" Pb and box	0.8 mrads/s
P1	Position 1, no Pb and no box	TBD
PB1	Position 1, box and no Pb	TBD
P2	Position 2, no Pb and no box	TBD
PB2	Position 2, box and no Pb	9 mrads/s
PL3	Position 3, 2" Pb and no box	TBD
PBL3	Position 3, 2" Pb and box	TBD
P3	Position 3, no Pb and no box	TBD
PB3	Position 3, box and no Pb	82 mrads/s

IV. RESULTS AND ANALYSIS

Measurement results in terms of dose rate values determined from SNL and NSWC TLDs and RADFET dose enhancement factors are shown in Table 2 for each of the ten test configurations. The DE factor is defined as the measured threshold voltage shift of a device with kovar lid divided by the shift of a device without the lid (or with a ceramic or epoxy lid). Again, within the measurement error, RADFET threshold voltage shifts produced by the RTI source were

Table 2. Measured dose rates and dose enhancement factors

Config.	SNL TLD DR (mrads/s)	NSWC TLD DR (mrads/s)	RADFET DE
PL1	2.30	2.24	2.3 - 2.4
PBL1	0.88	0.78	1.5 - 1.8
P1	13.00	11.00	1.8 - 1.89
PB1	9.50	8.50	1.12 - 1.19
P2	12.00	10.50	1.62 - 1.79
PB2	9.20	7.86	1.09
PL3	11.20	10.40	1.5 - 1.97
PBL3	8.30	8.20	1.15 - 1.2
P3	105.00	96.20	1.17 - 1.31
PB3	88.30	78.80	1.04 - 1.07

independent of whether the device was bare or equipped with epoxy or ceramic lids.

Several observations can be made from the data in Table 2. First, there is a significant difference between the dose enhancement factor for position 3 and those for positions 1 and 2. This implies that the gamma energy spectrum at position 3 is harder than the spectra at the two more distant points. Since the direct or primary (MeV) gamma component is known to fall off as $\sim 1/r^2$, where r is the distance from the source, then one might assume that there is a background, scattered (low energy) spectral component that is approximately constant throughout the room. A second observation is that the 2" Pb attenuator causes an increase in dose enhancement at both positions 1 and 3, but particularly at the more distant position 1. Finally, it is observed by comparing in-box/out-of-box dose enhancement measurements at each position that the Pb/Al box is quite effective in reducing dose enhancement (and thus also the low energy scattered spectral component).

Based on these observations, a general formula can be used to describe dose rate as a function of position and test configuration (i.e. with or without attenuator and/or Pb/Al box). If R is the dose rate, then R can be expressed as the sum of primary and scattered components,

$$R = R_P + R_S \quad (1)$$

where

$$R_P = A_{PB} A_{PL} k_P / r^2 \quad (2)$$

and

$$R_S = A_{SB} A_{SL} (K_{SBG} + k_S / r^2). \quad (3)$$

Here A_{PB} and A_{PL} are the attenuation factors for the primary (MeV) beam (P) for the Pb/Al box (B) and the lead (L) attenuator, respectively, and k_P is the primary gamma source term. A_{SB} and A_{SL} are the attenuation factors for the scattered (S) component for the box (B) and lead (L) attenuator, respectively; K_{SBG} represents the constant background scattered radiation rate and the term k_S / r^2 has been added to account for any scattered radiation originating within the Co-60 source itself [12]. If it is assumed that dose enhancement is caused only by the low energy scattered components, then DE can be defined as

$$DE = \frac{R_P + m R_S}{R_P + R_S} \quad (4)$$

where m is the low energy or scattered radiation enhancement factor. These equations were then applied to each of the ten measurement configurations defined in Table 2. When present, the 2" thick Pb attenuator was assumed to block all of the scattered radiation originating at the source and 1/6 of the omni directional scattered background, K_{SBG} (i.e. $A_{SL} \equiv 0$). The remaining parameters (A_{PB} , A_{PL} , k_P , A_{SB} , K_{SBG} , k_S and m) were then adjusted for a best fit to the median dose rate and DE values measured at each position. The fit required minimization of the sum of the difference between calculated and measured values squared divided by the measured value. The results of this iteration are given in Table 3. This methodology will be discussed further in the full paper.

There is reasonably good agreement between experimental dose rate and DE values (Table 2) and the values derived from the analytical expressions (Table 3). Moreover, it is clear that, the greater the ratio of scattered (R_S) to primary (R_P) radiation, the greater is the dose enhancement. It would therefore appear that dose rate and dose enhancement can be approximated

Table 3. Dose rate, dose enhancement, and parametric values obtained from data fit to equations 1-4.

Config.	R_p (mrads/s)	R_s (mrads/s)	R (mrads/s)	DE
PL1	0.81	2.13	2.95	2.52
PBL1	0.75	0.34	1.09	1.66
P1	9.05	4.00	13.05	1.64
PB1	8.33	0.64	8.97	1.15
P2	9.05	3.47	12.52	1.58
PB2	8.33	0.56	8.88	1.13
PL3	8.03	2.67	10.70	1.52
PBL3	7.39	0.34	7.73	1.09
P3	89.27	11.13	100.40	1.23
PB3	82.13	1.78	83.91	1.04

$A_{PB} = 0.92$, $A_{PL} = 0.09$, $k_p = 4.5 \times 10^5$ mrads cm^2/s , $A_{SB} = 0.16$, $K_{SBG} = 3.2$ mrads/s, $k_s = 4.0 \times 10^4$ mrads cm^2/s , $m = 3.1$

for any 2-inch Pb attenuator-Pb/Al box configuration in the room using the general formulas in equations 1-4, and that this methodology can be used to minimize dose enhancement effects in low dose rate testing.

V. CONCLUSIONS

In this study, dose enhancement was measured for various test configurations in RTT's low dose rate room Co-60 source using RADFET dosimeters with and without kovar lids. The highest DE factor of 2.3-2.4 was measured at the greatest distance from the source behind a 2-inch Pb attenuator. This was reduced to 1.5 to 1.8 when using a Pb/Al shielded test box. Enhancement factors were much lower at the higher dose rates associated with test configurations that were located closer to the source and/or which did not employ the two-inch Pb attenuator. An analytical expression was developed to calculate the dose rate and dose enhancement factor for an arbitrary test configuration. This expression gave good agreement with measured values for ten test configurations. The study demonstrated that dose enhancement may be a significant problem, even for irradiation inside the recommended Pb/Al

shield, for low dose rate experiments where the scattered gamma component of dose rate becomes comparable to (or even greater than) the primary beam.

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