Determination of an Absorbed Dose of MOSFET Dosimeter using Monte Carlo N-Particle Simulation with Different Tallies and Response Functions

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I. Introduction

Metal-Oxide-Semiconductor Field Effect Transistor (MOSFET) dosimeters have been used to verify dose in many fields ranging from industry to radiation therapy[1,2]. However, it is difficult to experimentally measure the detailed MOSFET dosimeter response. Thus, many studies[1,2] of MOSFET dosimeter modeling using Monte Carlo have beeen performed previously to obtain the dose response. Wang *et al*[2] studied Monte Carlo modeling of MOSFET dosimeter for low-and medium-energy photon sources. However, they determined the absorbed dose of MOSFET dosimeter by using only the track length estimator F4 tally in MCNP 4C.

In this paper, we performed MOSFET dosimeter simulation using the latest MCNP version code (MCNP 6)[3,4,5]. In order to determine the absorbed dose, we set the four source positions of 0° , 90° , 180° and 270° directions as in the previous study[2]. And, the absorbed dose traversed by electrons in the sensitive volume of extremely thin layer (1μm) was determined by both F4 tally (i.e., track length estimator) and *F8 tally (i.e., energy deposition tally). However, the accurate determination of the absorbed dose in the very small volume is quite difficult due to the extremely small sensitive volume, which results a large variance in the tally with the typical number of source particles. To resolve this difficulty, we used MCNP [ESTEP][5] option and F4 tally. The ESTEP option provides the subdivisions of the major steps to accurately represent the electron's trajectory in space, which substantially reduce the variance in the tally. In this work, we evaluated the restricted mass electronic stopping powers by using the dose response function given by Schaart *et al*[6] . They are used as the response function in F4 tally. In addition, we considered a different restricted mass electronic stopping power from the MCNP 6 output (i.e., print table 85). Then, we compared the absorbed doses calculated with these two different the restricted mass electronic stopping powers.

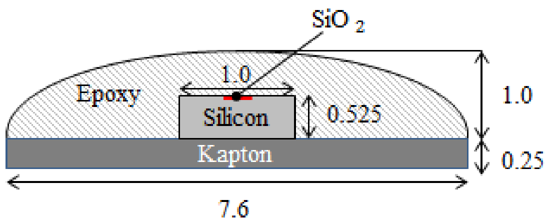
In Sec. II, the model of the MOSFET dosimeter and the dose response functions are described. Sec. III gives the results of the simulations. Finally, the summary and conclusion are given in Sec. IV.

II. Monte Carlo simulation of MOSFET dosimeter

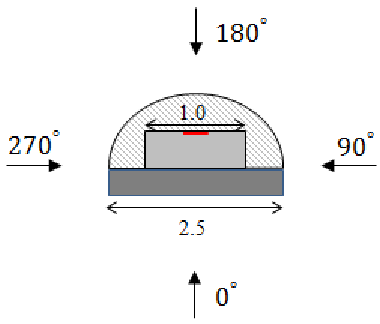
II.A. Layout of MOSFET dosimeter

The schematic diagram of the MOSFET dosimeter[1,2] is shown in Fig. 1. The structure and materials were simulated using the MCNP6 Monte Carlo particle transport code. As shown in Fig. 1.(a), the sensitive volume ($\mathbf{SiO_2}$) (0.2×0.2 $\mathbf{mm^2}$ in area, 1μm thick) is located on the top of the silicon substrate and under the epoxy bulb. The epoxy bulb is modeled as a semi-ellipsoid attached at the end of a flexible kapton cable (0.25 mm thick and 2.5 mm wide). It encloses the silicon substrate (1.0 × 1.0 $\mathbf{mm^2}$ in area, 0.525 **mm** thick).

Also, we used four typical source directions which are $\mathbf{0^{\circ}}$, $\mathbf{90^{\circ}}$, $\mathbf{180^{\circ}}$ and $\mathbf{270^{\circ}}$ that are shown in Fig. 1. (b).



(a)



(b)

Fig. 1. Schematic diagram of the MOSFET dosimeter (Unit: mm). (a) The cross-section along the wire axis. (b) The cross-section perpendicular to the wire axis.

II. B. Specification of the MOSFET dosimeter material

The MOSFET dosimeter simulated in this paper is comprised of four different materials, which are silicon, kapton, epoxy and SiO_2. They are specified in Table 1. These materials have the densities of $2.33 g/cm^3$, $1.42 g/cm^3$, $1.3 g/cm^3$ and $2.32 g/cm^3$, respectively.

Table 1: Specification of the materials used in MOSFET dosimeter

Material name	Density (g/cm^3)	Weight fraction
silicon	2.33	Si 1.0
kapton	1.42	H 0.026362 C 0.691133 N 0.073270 O 0.209235
epoxy	1.3	H 0.023062 C 0.806111 O 0.170827
SiO_2	2.32	O 0.532565 Si 0.467435

II. C. Specification of the source

In this paper, a surface source for photons is used, which is emitting energy of 0.662MeV. Also, the upper electron energy limit and the electron cutoff energy are set to 20MeV and 1.0265keV respectively. The area of the source is $0.01 cm^2 (0.1 cm \times 0.1 cm)$. And, the four source directions we considered are located in 0°, 90°, 180° and 270° directions individually that are shown in Fig. 1. (b). The distance between the source and the MOSFET dosimeter is fixed into 0.5cm and we used mono-direction source to improve the computational efficiency.

II. D. Electron track length estimator of absorbed dose

The average absorbed dose in a small volume of material traversed by electrons can be calculated from

$$\mathrm{D} = \int_{\Delta}^{\infty} \Phi(E) \frac{1}{\rho} L_{\Delta}(E) dE + D_{\Delta} \qquad (1)$$

where $\Phi(E)$ is the energy spectrum of the electron fluence, $L_{\Delta}(E)/\rho$ is the restricted mass electronic stopping power, D_{Δ} is the dose deposited at below cutoff energy and Δ is electron cutoff energy.

The F4 tally is a track length estimator that can be used to determine the average particle fluence in a volume. The fluences determined by F4 tally can be modified by response function in MCNP with [DF card] as a function of energy [DE card] to calculate the absorbed dose. Each time an electron produces a score, and the value of the score is multiplied by the value of the dose response function at the energy of the electron, which gives the result of the absorbed dose. The dose response function, given by Schaart $et\ al$[6], can be calculated from

$$f(E_n) = \begin{cases} \frac{1}{\rho} L_{\Delta}(E_0) & if\ n = 0 \\ \frac{1}{\rho} L_{\Delta}(kE_{n-1}) & if\ 0 < n \le N-1 \\ \frac{1}{\rho} L_{\Delta}(kE_{n-1}) + \frac{E_N}{S_{N-1}} & if\ N-1 \le n \le N \end{cases}, \qquad (2)$$

where n is the index of the energy step and N is the total number of the energy steps, E_0 is the upper electron energy limit, E_N is the electron cutoff energy, and S_{N-1} is the path length of the last major step in units of mass per area (see the DRANGE in print table 85 of MCNP 6 output). Also, the energy steps is calculated from

$$\frac{E_n}{E_{n-1}} = k \qquad (3)$$

where E_n equals the electron energy at the end of the n'th major step and k equals $2^{-1/8}$ which means the average energy loss per major step is ~ 8.3%. For having a very small material region like the sensitive volume (1μm thick), the division of the energy may not accommodate enough substeps for an accurate simulation of the electron's trajectory. In order to represent the electron's trajectory in space more accurately, the major steps are subdivided into a number of m substeps. The integer m entered in MCNP [Material data card] through following option 'ESTEP=m'. First, we calculated the dose response function for SiO_2 by using Eq. (2). The dose response function calculated with Eq. (2) was compared with the mass electronic stopping power from MCNP 6 output (print Table 85) in Fig. 2. Except for the lowest two data points, the differences between the two curves increase as the energy increases. The biggest difference between the two curves is 32.65% in this result. This is because more secondary electrons above the cut-off energy will be liberated as electron energy increases. The values at the two lowest points of the dose response function are artificially increased to account for the additional amount of energy below the cut-off energy, which is explained through the second term of the last condition in Eq.(2).

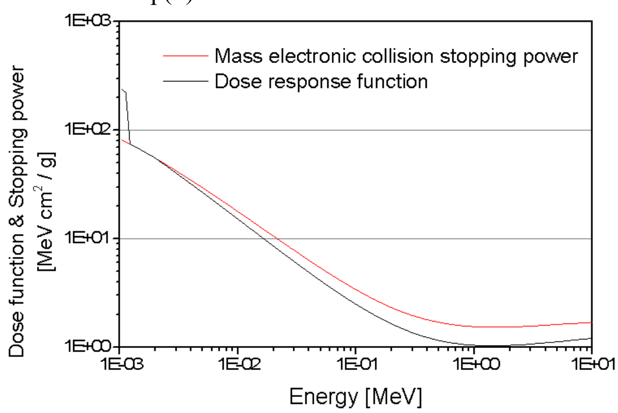


Fig. 2. Comparison of the dose response function calculated with Eq. (2) and MCNP

III. Simulation Results

III.A. Determination of absorbed dose in sensitive volume using F4 tally

We calculated the absorbed dose in sensitive volume along the four directions of photon source as shown Fig. 1. (b). It was performed using MCNP F4 tally. And, the number of source particles (NPS) is $\mathbf{5 \times 10^8}$. We applied the large number of source particles to reduce the variance of the tallied absorbed dose to below 2.0%. In case of using F4 tally, the determination of the absorbed dose of small sensitive volume using standard MCNP tallies is not accurate because of the extremely small sensitive volume. For accurate estimation of the absorbed dose, the major steps are subdivided into a number of *m* substeps. The integer *m* entered in MCNP [Material data card] through following option 'ESTEP=*m*'. Then, the absorbed dose was calculated by multiplying electron fluence calculated from F4 tally by the restricted mass electronic stopping power. The restricted mass electronic stopping power calculated with Eq.(2) was inputted into MCNP [DE card], [DF card]. In addition, we also used the mass electronic stopping power generated by MCNP for comparison.

Table 2 shows the absorbed dose values in the sensitive volume along the four source directions.

Table 2 : Absorbed doses in the sensitive volume along the four directions of the source determined by the F4 tally

	Mass electronic collision stopping power from MCNP output		Dose response function obtained using Eq.(2)		**RE**^{b} (%)
	Absorbed Dose [**A**] (MeV/g)	SD^a (%)	Absorbed Dose [**B**] (MeV/g)	SD (%)	
0°	1.65	0.81	1.26	0.86	23.64
90°	0.325	1.95	0.251	2.05	22.77
180°	2.31	0.71	1.77	0.76	23.38
270°	0.345	1.97	0.267	2.07	22.61

^{a} Standard deviation
^{b} Relative percent error between **A** and **B**

Table 2 shows that the mass electronic collision stopping power from MCNP output gives higher absorbed doses by 22~23.6% than the dose response function does for all the directions considered. Actually, these differences in the absorbed dose can be understood by observing the differences in the response function values which are given in Fig. 2 because the absorbed dose is proportional to the response functions. Also, it is shown that the beams at the 0° and 180° directions give much higher absorbed doses than the beams at the 90° and 270° directions. Especially, when the source located at the **180°** direction, the absorbed dose has the highest value because the source is located at the nearest position with the MOSFET dosimeter. Also, the sensitive volume is located just below the epoxy cover, which allows relatively large amount of particles emitted by the source to reach the sensitive volume. Also, it is noted that the standard deviations in the tallied absorbed dose are lower than about 2.0% for all the cases.

*III.B. Determination of absorbed dose in sensitive volume using *F8 tally*

We also calculated the absorbed dose using *F8 tally. The *F8 tally was performed in the same conditions as the cases using F4 tally. The *F8 tally is the energy deposition tally and its unit is MeV. However, the unit of the absorbed dose is MeV/g. Thus, we multiplied the deposited energy by the product of the density and the volume of the sensitive volume for the conversion of the *F8 tally to the absorbed dose. Table 3 shows the absorbed dose in the sensitive volume along the four directions of the source determined by the *F8 tally and the relative percent errors between the *F8 and F4 tallies. The comparison with the absorbed doses given in Tables 2 and 3 shows that the absorbed doses tallied with *F8 are between the absorbed doses tallied by using F4 with the mass electronic collision stopping power from MCNP output and with the dose response function obtained using Eq.(2). The standard deviations in the absorbed doses tallied with *F8 are less than 3% for all the directions. Also, it was shown that the absorbed doses tallied with F4 and *F8 have very the similar distributions over the directions.

Table 3: Absorbed doses in the sensitive volume along the four directions of the source determined by the *F8 tally and the relative percent errors between the *F8 and F4 tallies

	Absorbed Dose (MeV/g)	SD (%)	Relative percent errors between *F8 and F4 tallied absorbed doses (%)	
			Mass electronic collision stopping power from MCNP output	Dose response function obtained using Eq.(2)
0°	1.48	1.46	-11.55	14.82
90°	0.298	2.92	-9.11	15.74
180°	2.04	1.17	-13.27	13.21
270°	0.315	2.79	-9.38	15.35

IV. Summary and Conclusions

In this paper, we performed Monte Carlo simulation of MOSFET dosimeter using MCNP6. In particular, the F4 track length and *F8 energy deposition estimators coupled with the ESTEP option in MCNP [Material data card] were used to accurately estimate the absorbed doses in the extremely small sensitive volume. In order to calculate the absorbed dose in the sensitive volume, we used MCNP F4 tally which is referred to the track length estimator and *F8 tally. The ESTEP option in MCNP accommodates enough number of sub-steps for an accurate simulation of the electron's trajectory. Also, MCNP [DE card] and [DF card] are used in the track length estimator to determine the absorbed dose over the sensitive volume. Also, we considered two different response functions in the F4 track length tally to calculate the absorbed doses. The first one is calculated with the formulations suggested by Schaart *et al* and the second one is the mass electronic collision stopping power which was extracted from MCNP output.

The simulation results with F4 tally showed that the mass electronic collision stopping power extracted from the MCNP output gives higher absorbed doses by 22~23.6% than the dose response function does for all the directions considered, which is resulted from the differences in the response function values. It was shown from the comparison of the absorbed doses tallied with F4 and *F8 tallies that the absorbed doses tallied with *F8 are between the absorbed doses tallied by using F4 with the mass electronic collision stopping power from MCNP output and with the dose response function obtained using the formulation suggested by Schaart *et al*. Also, the simulations showed that the F4 tallies give the absorbed doses with smaller standard deviation than the *F8 tally although all the absorbed doses obtained with all the tallies are obtained with the standard deviations less than 3%.

Acknowledgement

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