Functional Materials 11, No.1 (2004)

Radiological characterization of metal oxide semiconductor field effect transistor dosimeter

***Chan-Hyeong Kim, Sang-Hoon Lee*[*], *Baodong Wang*[**], *X.George Xu*[**]**

Department of Nuclear Engineering, Hanyang University, Haendang-dong, Seongdong-gu, Seoul, 133-791, Korea
[*]Innovative Technology Center for Radiation Safety, Hanyang University, Haendang-dong, Seongdong-gu, Seoul, 133-791, Korea
[**]Nuclear Engineering and Engineering Physics Program, NES Building, Rensselaer Polytechnic Institute, Troy, NY 12180

This paper reports our effort to develop a detailed 3D Monte Carlo simulation model of the High-Sensitivity MOSFET dosimeter using the MCNP 4C code for radiological characterization. To determine the dosimeter response accurately, this study has taken three actions: (1) The absorbed dose to the sensitive volume of the dosimeter is calculated directly from electron trajectories; (2) The electrons are forced to make at least ten substeps in the sensitive volume; and (3) ITS-style energy indexing algorithm is used instead of the default MCNP-style energy indexing algorithm. Our results show that the developed model calculates the angular dependence, absorbed dose, and energy dependence of the dosimeter very satisfactorily when we compare the results with the measured values and theoretical values.

В статье описана попытка разработки подробной трехмерной модели Монте-Карло для высокочувствительного дозиметра на основе полевого МОП-транзистора (MOSFET) с применением кода MCNP 4C для определения радиологических характеристик. Для точного определения отклика дозиметра при исследовании были применены три приема: 1) поглощенная доза для чувствительного объема дозиметра рассчитана непосредственно из траекторий электронов; 2) электронам приписаны, по меньшей мере, 10 энергетических ступеней в чувствительном объеме; и 3) вместо алгоритма индексации энергии, применяемого в MCNP по умолчанию, использован алгоритм индексации энергии типа ITS. Наши результаты показывают, что разработанная модель позволяет весьма удовлетворительно рассчитывать угловую зависимость, поглощенную дозу и энергетическую зависимость для дозиметра, что следует из сопоставления полученных результатов с экспериментальными и теоретическими значениями.

Metal oxide semiconductor field effect transistor (MOSFET) dosimeters are increasingly utilized in radiation therapies and, more recently, in radiation diagnosis. The advantages of MOSFET dosimeters include small size, immediate readout, and ease of use, making them excellent tools for high energy photon applications. In the low energy range, however, MOSFET dosimeter response, which is mainly made of silicon, is complicated by the fact that interaction probability of photoelectric effect shows significant dependence on the atomic number of each dosimeter component. The objective of this study is to develop a detailed 3-dimensional Monte Carlo simulation model of a MOSFET dosimeter for characterizations and calibrations for low and medium energy photons.

This study models the High-Sensitivity MOSFET dosimeter (TN-1002RD, Thomson and Nielsen Electronics, Ltd., Ottawa, Canada). The High-Sensitivity MOSFET dosimeter is made of a silicon chip with 1 mm^2 area and 0.25 mm thickness. The chip is located under a layer of black epoxy bulb.

The silicon chip includes two MOSFET devices, each of which has an active area of 0.2 mm×0.2 mm and active thickness of 1 μm. The silicon chip and bulb is placed at the end of a very thin and flexible polyamide laminate cable (~0.25 mm thick, 2 mm wide) encapsulating two gold wires. Readers are referred to McKay [1] for the detailed mechanics how a MOSFET works as a dosimeter. In short, the difference in voltage shift before and after exposure is proportional to radiation dose, and it can be read out immediately.

In this study, a 3-D Monte Carlo model of the High-Sensitivity MOSFET dosimeter was developed using Monte Carlo *N*-Particle (MCNP) 4C [2]. Detailed layout and composition of the model are based on the data provided by the manufacturer. Efforts were made to accurately determine the energy deposition in the sensitive volume of the MOSFET dosimeter. The sensitive volume of the dosimeter is very thin (1 μm) and the standard MCNP tallies do not accurately determine absorbed dose to the sensitive volume. Therefore, the absorbed dose in the thin volume was directly determined by the electron track length dose estimator developed by Schaart et al. [3]. Transport of electrons in medium is complicated in that electron pathways are characterized by many interactions each having small energy loss. For example, an electron of 1 MeV can have more than 10^5 collisions in water before it completely stops. This large number of interactions makes it impractical to transport every single electron collision in Monte Carlo simulation and the so-called "multi-scattering theory" is thus adopted in MCNP. In such an approach, an electron path is broken into small energy steps and all simulation parameters are calculated on such step basis. In order to represent the electron's trajectory more accurately, these energy steps are further broken into smaller substeps by dividing the energy steps by an integer *m*. In our simulations, the values of *m* are chosen to assure that electrons make at least ten substeps in the sensitive volume of the MOSFET dosimeter. It has been documented in the literature that the default MCNP-style indexing algorithm gives much larger error than the ITS-style indexing algorithm in electron transport due to its inconsistency with the definition of energy groups [3, 4]. Therefore, this study used the ITS-style indexing algorithm for all the simulations.

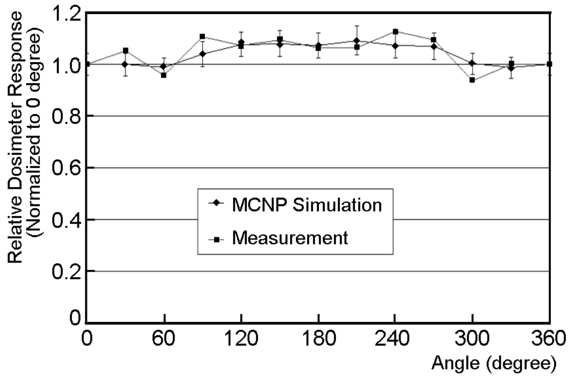

Fig. 1. Angular dependence of the MOSFET dosimeter for Cs-137 source. The 0 degree corresponds to photon incident perpendicularly on the silicon side and 180 degree is on the epoxy side.

This study performed three experiments to validate the MCNP model: 1) comparison with the measurement of a Cs-137 source; 2) computational experiment to validate the dose estimator; and 3) comparison of calculated energy dependence with the predicted value from theory. First, the MOSFET dosimeter response from different photon directions was measured using a Cs-137 source emitting 662 keV gamma ray photons. The dosimeter was rotated along its axial every 30-degree and the exposure time was one hour in each case. The same setup was simulated in MCNP and the direction of photon beam was rotated using the coordinate transformation (TR) card. Fig. 1 shows that the simulation and measurement results are in a good agreement. Both the simulation and measurement results indicate that the MOSFET dosimeter shows higher response (by ~8 %) for photons coming from the epoxy side.

The MCNP model may become unrealistic if the sensitive volume is very thin and electron steps are frequently interrupted by the cell boundaries. To check this out, a block of SiO_2 cylinder was defined in MCNP. Electrons were generated uniformly throughout the entire volume of the block. A small "tally" or detection volume was defined at the center of the block. With this configuration, we can calculate the "exact" value of the absorbed dose to the tallying volume assuming radiation equilibrium. In MCNP, the absorbed dose to the detection volume was determined by using the electron track length estimator developed in this study. This study calculated the percentage difference between the MCNP result and "exact" value for detection volume thickness varying from 0.1 μm to 1 cm. Generally, out results show that the differences are less than 3 % for all the photon energies and thickness considered in this study. The differences are larger for thinner volumes, but do not show any specific tendency or bias.

Finally, we simulated the MOSFET dosimeter response for various photon energies ranging from 15 keV to 6 MeV. The energy dependence was then compared with the theoretical values that are calculated from the ratio of the mass energy absorption coefficient of silicon to that of air. Fig. 2 shows that the MCNP result is in a good agreement with the theoretical values. There is small difference between these two curves, which is due to the lack of charged particle equilibrium at the interface of silicon and epoxy. This result shows that there is significant self-shielding effect where the photon energy is very low (<50 keV). For high energies (>1 MeV), the dosimeter underestimate the absorbed dose since charged particle equilibrium (CPE) does not exist at the sensitive volume of the dosimeter. This problem can be avoided by adding a build-up layer on the top of the dosimeter.

The authors thank the Innovative Technology Center for Radiation Safety (ITRS) at Hanyang University in Korea for supporting this study.

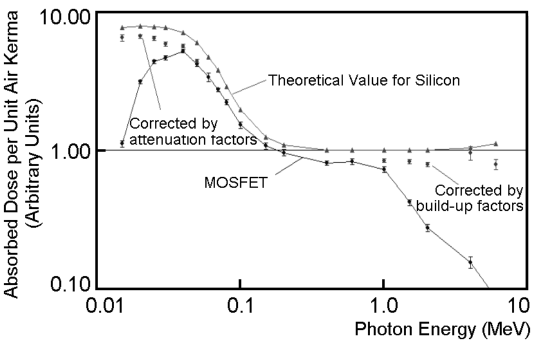

Fig. 2. Energy dependence of the MOSFET dosimeter. The relative dosimeter response agrees with the predicted value from theory, but decreases dramatically below 50 keV due to self-attenuation of the silicon.

References

1. G.MacKay, Thomson and Nielsen Electronics Ltd. Technical note, No.4, Thomason and Nielsen Electronics Ltd., Ottawa, Canada (1996).
2. J.F.Breismeister, MCNP — a General Monte Carlo *N*-Particle Transport Code Version 4C, Los Alamos National Lab., Los Alamos, NM (2000).
3. D.R.Schaart, J.T.M.Jansen, J.Zoetelief, P.F.A.Leege, *Phys.Med.Biol.*, **47**, 1459 (2002).
4. R.Jeraj, P.J.Keall, P.M.Ostwald, *Phys.Med. Biol.*, **44**, 705 (1999).

Радіологічні характеристики дозиметра на основі польового МОП-транзистора

Чан-Хіонг Кім, Санг-Гун Лі, Баодонг Ванг, Кс.Джордж Цзю

В роботі описано спробу розробки детальної тривимірної моделі Монте-Карло для високочутливого дозиметра на основі польового МОП-транзистора (MOSFET) з застосуванням коду MCNP 4C для визначення радіологічних характеристик. Для точного визначення відгуку транзистора при дослідженні було застосовано три прийоми: 1) поглинену дозу для чутливого об’єму дозиметра розраховано безпосередньо за траєкторіями електронів; 2) електронам приписано щонайменше 10 енергетичних ступенів у чутливому об’ємі; і 3) замість алгоритму індексації енергії, застосованого в MCNP за відсутності застережень, використано алгоритм індексації енергії типу ITS. Наші результати вказують, що розроблена модель дозволяє цілком задовільно розраховувати кутову залежність, поглинену дозу та енергетичну залежність для дозиметра, що витікає із зіставлення одержаних результатів з експериментальними та теоретичними значеннями.