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Semiconductor High-level Dosimeters Used in the SLAC Photon and Neutron Fields

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ABSTRACT

As part of an exploration of Semiconductor High-Level Dosimetry (SHLD) in the accelerator radiation fields, the response of SHLD system, composed of dual MOSFETs, wide-base PIN diode, and a microprocessor-controlled reader, was calibrated in photon (Co-60) and neutron (Bare-reactor) fields. The response curves for the MOSFET and the PIN diode were determined. The neutron sensitivity of the PIN diode is about a factor of 2200 times higher than its photon sensitivity. Therefore, the PIN diode can be used to measure the neutron dose and virtually ignore the photon dose contribution. The MOSFET can be used to estimate the photon dose after subtracting the ionizing effect of the neutrons. The SHLD was used in the SLAC mixed field to measure the photon and neutron doses around a copper beam dump. The photon measurements near the copper dump agreed reasonably with the FLUKA Monte Carlo calculations. The neutron measurements agreed with FLUKA calculations to within a factor of two.

INTRODUCTION

The Stanford Linear Accelerator Center (SLAC) is a high-energy physics research facility. When the GeV electron or positron beam hits a target, photons and neutrons are generated. SHLD is used to characterize this secondary radiation for two purposes. One application is to assess likely radiation damage, which is the disruption of operating characteristics in engineering materials, particularly those in electronic devices. Common units of radiation damage are absorbed ionizing dose in silicon, caused predominantly by electrons and photons, and displacement damage fluence in equivalent 1-MeV neutrons, caused predominantly by neutrons.

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Another application is to determine the source term to characterize the secondary particles directly produced by the primary beam. In this case, the unit of interest is absorbed doses in tissue for both photons and neutrons. In this paper, SHLD is investigated for the second application.

Optical absorption dosimeters have been used at SLAC for high-level dosimetry but have some drawbacks [1]. The dose received by an optical absorption dosimeter is indicated by its color change, but measurement of this change does not distinguish between doses delivered by photons and neutrons. Furthermore, no system exists for reading optical absorption dosimeters on-line. The SHLD system was developed by the Center for Medical Radiation Physics, Department of Engineering Physics, University of Wollongong, supported closely by two semiconductor suppliers. The system functions reliably in SLAC high-level mixed photon and neutron fields.

MATERIALS AND METHODS

a. Semiconductor dosimeters:

In the SHLD system, each semiconductor dosimeter probe consisted of two sensors: one p-channel MOSFET (RADFET) developed by REM Oxford Ltd., England and one wide-base PIN diode, developed by KINO and SPO, Kiev, Ukraine. The size of the probe was 0.5 cm $\times$ 0.5 cm $\times$ 1 cm. The read-out system consisted of a single reader with RS232 output, which is connected to a printer. The probe was connected to the reader by a telephone cable with length up to 50 m. The reader passed 160 μA through the MOSFET and 1 mA through the diode. A built-in 16 bit Analogue-to-Digital Converter (ADC) and a microprocessor measured the voltage drop across each sensor and displayed it on a liquid crystal display.

i. MOSFET sensor

First reported by Holmes-Siedle as a dosimetric method in 1974 [2,3], applications of the Radiation-Sensitive Field-Effects Transistor [RADFET] were becoming well-known by 1986 [4,5].

The response of the MOSFET is mostly due to ionization effects within the gate oxide. The sensing principle derives from the field produced when space-charge induced by ionization is trapped semipermanently in the gate oxide region of the FET (Figure 1).

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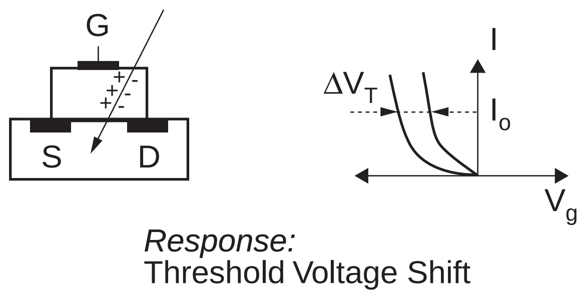

Figure 1 Radiation and MOSFET

Taking into account the following factors:

1. the channel transconductance is not significantly modified by atomic displacements
2. neutrons are not effective in the ionization process due to low efficiency of interaction with the thin gate oxide in comparison with photon.

aided by the choice of design parameters, the sensitivity of MOSFET ionization detectors to fast and slow neutrons can be expected to be low [6].

ii. Wide-base PIN diode sensor

The principle of the PIN dosimetric diode is based on the increase of the forward voltage drop measured under constant current after the production of atomic displacements (radiation damage) in the base region. Irradiation induce spectrum of radiation defects in silicon. The types of these defects depend on the type of incident radiation and on the energy of the incident particles. Radiation defects in the base of the diode lead to recombination of injected electron hole pairs and changing the resistivity in the diode base [7]. Both of these effects effectively increase the forward voltage of the diode (Figure 2).

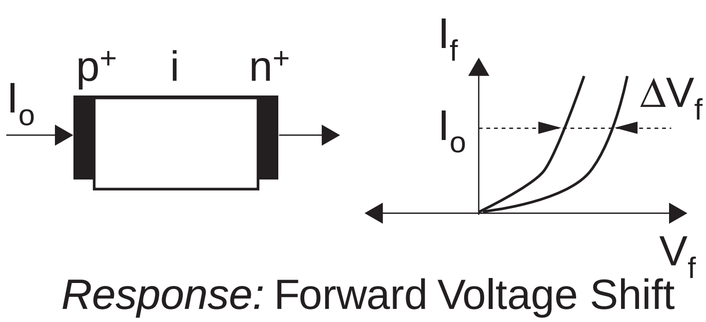

Figure 2 Radiation and P-I-N diode

The low sensitivity of the Si dosimetric diode to photon ionizing radiation is explained by the very low efficiency for the production of radiation defects (displacements) in silicon by photons in comparison with that produced by fast neutrons. The defects induced by photon radiation are mostly point defects produced by secondary particles of certain energy, mainly Compton electrons. Fast, massive particles, such as fast neutrons introduce a spectrum of defects that range from point defects to large clusters of displaced atoms. Neutron-induced defects are three orders of magnitude more effective in the degradation of the forward I-V characteristics of the diode than photon-induced defects under the condition of equal incident absorbed ionizing doses [8-12].

b. Dosimeter calibration:

The SHLD system was calibrated by a photon source at the Lockheed Martin Missiles & Space, Sunnyvale, CA and by Sandia Pulse Reactor at Sandia National Laboratories, Albuquerque, NM.

i. photon calibration

The photon calibration source was a ^{60}Co irradiation device (GammaCell 220) at Lockheed Martin Missiles & Space. The dose rate of the source was 9.2 rad-air/s (± 5 %) in the center chamber during the exposure [13]. The dose rate was calculated using the original dose rate provided by the manufacture company and the decay time. The dose rate was confirmed by a Rad-Cal air ionization chamber. The rad-air is converted to rad-tissue by timing a factor of 1.05. Total dose in given times was confirmed by TLDs (CaF_2Mn based TLD-400s from Harshaw) obtained from Sandia National Laboratories.

The SHLD probe, containing both the MOSFET and the PIN diode, was placed in the center of the chamber. The probe was connected to the reader by a cable. The reader automatically read out each voltage change of two sensors at presented times. In this experiment the readout time was every 30 seconds. The integrated absorbed dose varied from 0 to 3,000,000 rad-tissue linearly as the exposure time changed. The photon reponses of the MOSFET and PIN were obtained by plotting the voltage changes as the functions of the corresponding integrated absorbed doses.

ii. neutron calibration

The neutron responses of the SHLD were studied in Sandia Pulse Reactor (SPR) Facility at Sandia National Laboratories. The Sandia Pulse Reactor III is an unmoderated, fast-burst reactor. The reactor is designed to produce a neutron spectrum very similar to a fission spectrum. The primary experiment chamber is a large central cavity that extends through the core. The neutron tissue dose in the cavity is about seven times higher than the photon tissue dose.

The SHLD probe, containing both the MOSFET and the PIN diode, was installed in the SPR center cavity. The probe was connected to the reader by a cable. Neutron calibration data was taken under two exposure conditions,

1. Low-power exposure: reactor power of 0.75 W, the estimated neutron dose = 2.26×10^{-3} rad-tissue/s in center of cavity, total exposure time = 3000 seconds. The integrated absorbed neutron dose changed linearly from 0 to 6.78 rad-tissue as the time increased. The printer printed the voltage changes of the MOSFET and PIN diode in every 30 seconds. In this exposure, 100 points were obtained.
2. High-power exposure: reactor power of 170 W, the estimated neutron dose = 0.5 rad-tissue/s in the center of cavity, total exposure time = 18,000 seconds. The integrated absorbed neutron dose changed linearly from 0 to 9000 rad-tissue as the time increased. The printer printed the voltage changes of the MOSFET and PIN diode in every 300 seconds. In this exposure, another 60 points were obtained.

Four Sandia neutron-sensitive ^{32}S sulfur sensors and four Sandia photon dosimeters (CaF_2Mn based TLD-400s from Harshaw) were installed near the probe during each exposure.

After the exposure, the Sandia dosimetry group reported the photon doses from the exposure based on the CaF_2Mn TLDs and the neutron exposure as a ^{252}californium-equivalent fluence based on neutron sensors $^{32}S(n,p)^{32}P$ activity. The ^{252}californium-equivalent fluence was converted into a neutron tissue dose based on the methodology [14] which utilized a measured neutron spectrum at the test location. The neutron spectrum in the center of cavity was shown in Figure 3. It was obtained by exposing a series of activation and fission foils in the center of cavity [14].

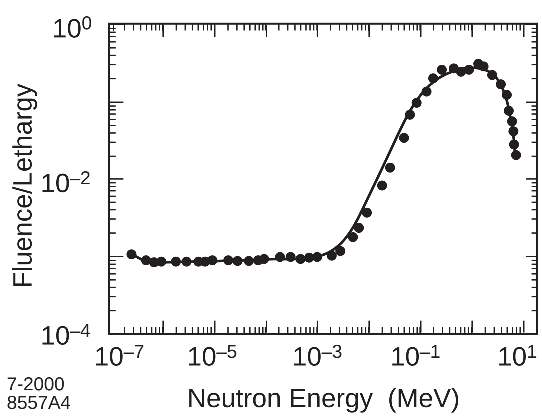

Figure 3 Neutron Spectrum in the SPR-III Central Cavity

The ENDF/B-VI cross sections for the isotopes of hydrogen, oxygen, carbon, and nitrogen was used to calculate the energy dependent responses rad (hydrogen), rad(oxygen), rad(carbon), and rad(nitrogen). Then these isotopic responses were combined to obtain a rad (tissue) response using ICRU four-tissue composition. By folding the energy-dependent neutron spectrum into the rad (tissue) response, rad (tissue) dose metric was generated (Figure 4).

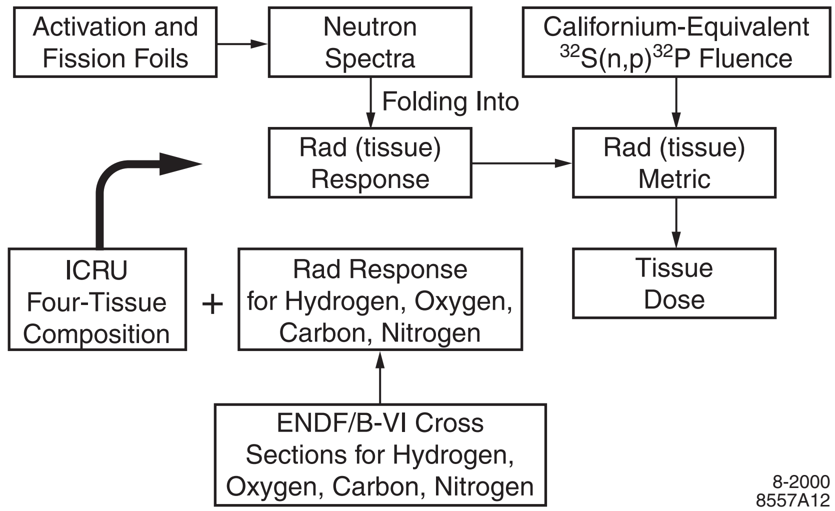

Figure 4 Neutron tissue dose report method

Neutron dose (tissue) was calculated by folding the californium-equivalent $^{32}S(n,p)^{32}P$ fluence into the rad (tissue) dose metric [14].

In the calculations of the neutron responses of the MOSFET and PIN diode, the following formulas may be used:

neutron voltage change ΔV[neut] = measured total voltage change in reactor ΔV[reac] – estimated photon voltage change ΔV[phot]

photon voltage change ΔV[phot] was estimated by using photon dose provided by the Sandia dosimetry group and the photon response curve measured in the Lockheed ^{60}Co irradiation device.

The neutron reponses of the MOSFET and PIN diode were obtained by plotting the voltage changes as the functions of the corresponding integrated absorbed doses.

c. Test in SLAC high-energy mixed field:

A 20-GeV electron beam with a spot size of approximate 1 cm was parked on a water-cooled copper beam dump. The dump size was 2 inches in radius and 10 inches in length. The beam parameters during the test were listed as follows: beam energy of 20 GeV, beam intensity of 2×10^{10} e^- / pulse @ 30 Hz, beam power of 2 kW.

Four semiconductor dosimeter probes were installed around the dump at 84°, 90°, 112°, and 120° to the beam injection point. The distance from the probes to the beam injection point was about 1 meter. The probes were connected to the reader by four cables. The voltage outputs were recorded every 30 minutes.

During the test, a total of 1×10^{16} electrons, as measured by a toroid in the beamline, was deposited into the dump.

d. <u>FLUKA Monte Carlo to simulate the test:</u>

The measured results were compared with FLUKA Monte Carlo code calculations. The geometry for the FLUKA calculations is shown in Figure 5. A 20-GeV electron beam hit a cylindrical copper target. Four pure silicon blocks (0.5 cm × 0.5 cm × 1 cm) were used to simulate the probes and were located about 1 meter away from the target in different angles. A cylindrical concrete enclosure, containing air, surrounded the target and probes. The tissue-dose to the probe was calculated by the neutron fluence to tissue-dose conversion factors.

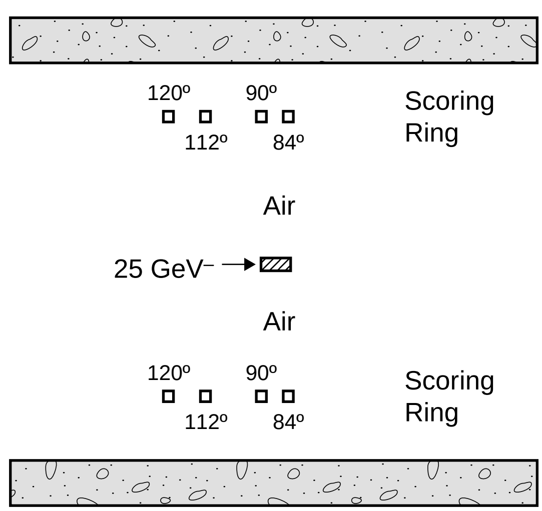

Figure 5 Geometry for FLUKA simulation.

RESULTS

a . Responses on MOSFET and PIN diode sensors

The photon response of MOSFET (photon dose from 0 --- 3,000,000 rad-tissue) is shown in Figure 6. The minimum photon-dose detection limit is 100 rad-tissue. Uncertainties of the response curve are ± 10 %. The neutron response of MOSFET is less than 5% of its photon response.

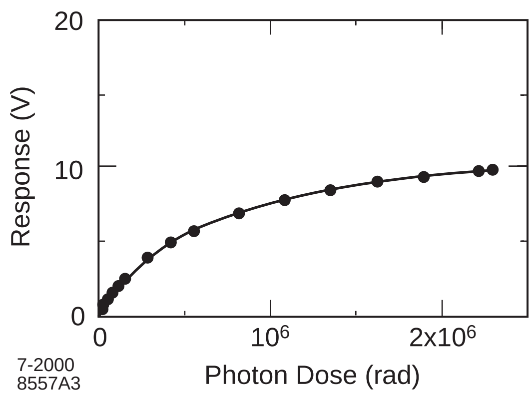

Figure 6 Photon Response of MOSFET

The neutron response of PIN diode (neutron dose from 0 --- 8000 rad-tissue is shown in Figure 7. The minimum neutron-dose detection limit is 40 rad-tissue. Uncertainties of the response curve are ± 20 %. The photon response of PIN diode is less than 0.05% of its neutron response.

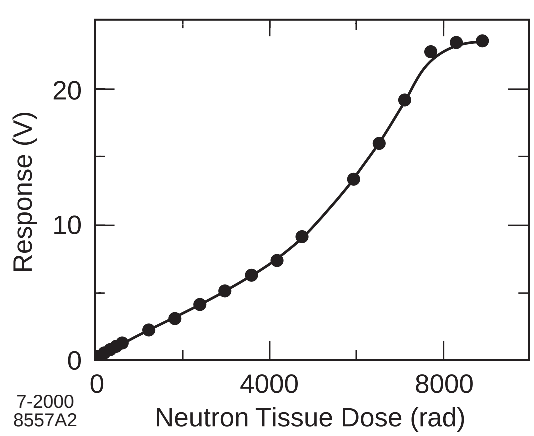

Figure 7 Neutron Response of PIN Diode

Measured characteristics of MOSFET and PIN diode is summarized in Table 1.

Table 1 Measured characteristics of MOSFET and PIN diode

Sensor	MOSFET	PIN diode
Dose range Rad (Tissue)	100 – 3,000,000	40 - 8000
Discrimination	γ/ N = 20	N / γ = 2000
Fading* in one month	< ± 5 %	< ± 5 %

* Measure voltage changes every week after irradiation.

b. Procedures to use SHLD in the mixed gamma and neutron fields:

The photon response of PIN diode is less than 0.05% of its neutron response so that the voltage change contributed by the photons could be ignored when it is used in the mixed photon and neutron filed. The following procedures are used for the SHLD in the mixed field:

1. Install a semiconductor dosimeter (composed of a MOSFET and a PIN diode) in the photon and neutron mixed field.
2. Irradiate the semiconductor dosimeter.
3. Read the voltage change of the MOSFET and the PIN diode after the irradiation.
4. Convert the voltage change of the PIN diode to neutron dose using Figure 7 (neutron dose range is from 0 --- 8000 rad-tissue), ignore the contribution of photons to the voltage change of the PIN diode.
5. Convert the neutron dose to the voltage change of MOSFET using Figure 6. Time this voltage by 0.05, which is approximate equal to the voltage change of MOSFET contributed by neutrons
6. Calculate the net voltage change of MOSFET contributed by photons.
7. Convert the voltage change of MOSFET contributed by photons to photon dose using Figure 6 (photon dose from 0 --- 3,000,000 rad-tissue)

The semiconductor dosimeters were test in the SLAC high-energy mixed field around a copper beam dump. The photon and neutron tissue-doses to four dosimeters were reported by the procedure discussed above.

c. Measurements to be compared with FLUKA calculations:

The measurements of the semiconductor dosimeters in the mixed field were compared with the calculations from the FLUKA code. The photon-tissue-dose comparison is shown in Figure 8. The uncertainties of the photon-tissue-dose calculations are ± 5 %. The uncertainties of the photon-tissue-dose measurements are less than 15%. The measurements agreed with the FLUKA calculations within ± 50 %. The good agreements were consistent with previous studies [15], which indicated that the photon spectra at 90^{o} produced in thick targets by electron beams with high energy have one important characteristic: 90 % of the photons have energies lower than 5 MeV. The photon response of the MOSFET does not change in this energy region.

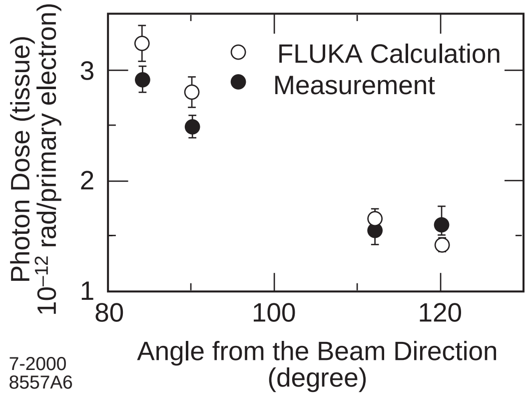

Figure 8 Comparison of Measured and Calculated Photon Dose

The neutron-tissue-dose comparison is shown in Figure 9. The uncertainties of the neutron-tissue-dose calculations are ± 7 %. The uncertainties of the neutron-tissue-dose measurements were less than 25 %. The measurements agreed with the FLUKA calculations within a factor of two. The neutron spectra in the high-energy mixed field have two peaks [16], one peak at 1 MeV, which is similar to the fission spectrum, one peak at 100 MeV. The difference between the measurements and the calculations may be due to the neutron energy spectrum effects. The PIN diode response may have lower neutron sensitivity in the 100-MeV region. Further investigations on high-energy neutron field will be done in the future to compare PIN diode response with silicon Kerma.

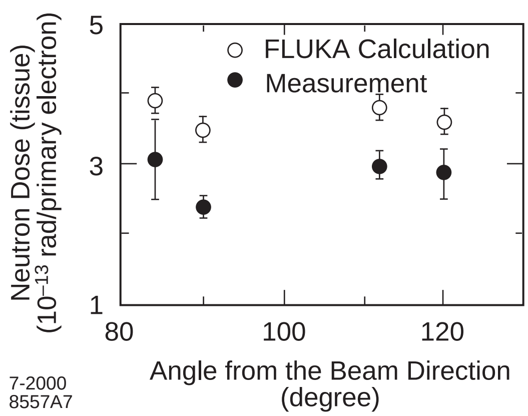

Figure 9 Comparison of Measured and Calculated Neutron Dose

CONCLUSIONS

Semiconductor high-level radiation dose monitoring system was calibrated at Lockheed Martin Missiles & Space and Sandia Pulse Reactor Facility at Sandia

National Laboratories. The calibration shows that that the dosimeter (MOSFET and PIN diode) can measure gamma dose from 100 to 2,500,000 rads and neutron dose from 40 to 8000 rads in a mixed photon and neutron field. The calibration shows that the PIN diode has a good neutron/photon dose sensitivity ratio of 2200.

The semiconductor dosimeters were tested in SLAC high-energy mixed field shows that the MOSFET can measure photon dose with uncertainty of 50 % and PIN diode can measure neutron dose with a factor of two. It was demonstrated that the MOSFET and the PIN diode measurements agreed within the expected limits with FLUKA simulation.

Acknowledgment

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