SPICE Model Extraction Parameters of Gamma Irradiation on Drain Current and Threshold Voltage of N-Channel MOSFETs

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Abstract - Sensitivity of an improved nMOSFET device was studied for energy dependence on cobalt-60 radiation measurement. Physical parameters including threshold voltage and drain current were investigated using a SPICE model level 3 to determine low field surface mobility and maximum transconductance parameters respectively. Measurements of increased gamma ray irradiation on n-channel metal oxide semiconductor field effect transistors (MOSFETs) were investigated for devices with a gate oxide thickness of 15 nanometers fabricated by 0.8-micron complementary metal-oxide-semiconductor (CMOS) technology. Characteristics of the pre-irradiated devices regarding gamma rays emitted by a cobalt-60 source, transient dose = 290.68 Gy/hr, GC3 centre turn: 3.9 kGy/hr at total dosage varying from 1 to 10 kGy were assessed. Results suggested that n-Channel MOSFET devices were affected by increased gamma ray exposure dosage. Our findings indicated that deviation of the threshold decreased by 36.0% for short nMOSFET and 33.8% for big nMOSFET. Threshold voltage ratios between pre-irradiation and post-irradiation were approximately 0.65 and 0.63 for short and big nMOSFETs respectively, while maximum transconductance ratios between pre-irradiation and post-irradiation were approximately 0.95 and 0.63 for short and big nMOSFETs respectively. The maximum drain current IDS of big nMOSFETs increased by 8% at the highest dose rate (10 kGy) and increased by approximately 1.5% for short nMOSFETs.

Keywords - SPICE model level 3, n-Channel MOSFETs, gamma irradiated, low field surface mobility, Maximum transconductance

I. INTRODUCTION

Gamma irradiation can modify the physical characteristics of electronic parameters of devices and materials through treatment with ionising radiation energy. This technique can alter the properties of electron-hole pairs in silicon (Si) and silicon dioxide (SiO2). Electron-hole pairs increase the wavelength of X-rays or gamma rays when they are scattered. This phenomenon is known as the Compton effect and can be applied in radiography. Several types of radiation dosimeters are currently in use including ion chamber, Geiger-Muller and proportional counters, scintillators, thermoluminescent and bubble dosimeters, activation foils, solid state or silicon detectors, calorimetric, photographic film and chemical methods.

Solid-state or semiconductor radiation detectors were studied and reviewed to assess the extraction characteristics and properties of metal oxide semiconductor field effect transistors (MOSFETs) by simulation program with integrated circuit emphasis (SPICE) models. Semiconductor transistors are extremely useful and offer fast response, high stability and small size compared with other types of dosimeter. Semiconductor radiation detectors can be used in active (positive bias on the gate during irradiation) or passive (zero bias on the gate during irradiation) mode, with detection principally by ionisation of the semiconductor and semiconductor damage.

Electrical properties of MOSFETs can vary depending on the physical parameters of dosimetry quantity. One such parameter as threshold voltage shows variation for MOS transistors depending largely on the electric field in silicon dioxide, the interface surface charge density, the flat band voltage and the channel doping. A radiation-induced buildup of electron-hole pairs is generated in silicon dioxide (SiO2) [1]. This positively-charged build-up can be attracted to a negative-biased gate electrode [2]. The nMOSFETs can be used for biological applications in dosage amounts of 1 to 10 kGy for sterilisation of fresh foods, human radiation protection and measurement of dose in both medical and industrial processes. They can also be employed to change the colour of gemstones. Previously, SPICE models were used in parameter extraction for radiation-induced equivalent lumped parasitic transistor in MOSFET or for radiation induced hardened silicon-on insulator complimentary metal oxide semiconductor (CMOS) circuits [3-4].

This study presents an in-depth review of SPICE parameters to determine radiation-induced low field surface mobility. Comparison of radiation-induced threshold voltage and drain current in test nMOSFETs was undertaken by both pre-irradiation and post-irradiation experiments.
Results were extracted by SPICE parameters level 3 as a more empirical approach, using curve fitting to describe the combined effects of enhanced dose rate and density of interface charge.

II. MECHANISMS AND METHOD

Identification of the behavior of MOSFET devices used by SPICE models was achieved by fitting simulated data with static and dynamic characterization results. SPICE models can be divided into three classes as First Generation Models (Level 1, Level 2 and Level 3 Models), Second Generation Models (BISM, HPICPE Level 28, BSIM2) and Third Generation Models (BSIM3, Level 7, Level 8, Level 49, etc.). In this paper, we used first generation models in level 3. First generation models are recommended for MOSFETs with gate lengths of 10 μm or more.

An ionizing radiation generated charge causes a threshold voltage shift. This can be defined by the sum of two voltage changes caused by the oxide-trapped charge in silica (Qot) and the interface-trapped charge (Qit). The threshold voltage can be defined by:

$$\Delta V_{th} = -e \cdot \frac{1}{C_{ox}} \cdot \Delta N_{ot} \pm e \cdot \frac{1}{C_{ox}} \cdot \Delta N_{it}$$

where e is an electron charge, $C_{ox}$ is an oxide capacitance per unit area, $\Delta N_{ot}$ represents the change in density of the oxide-trapped charge and $\Delta N_{it}$ represents the change in density of the interface charge.

The voltage shift is negative for NMOS devices. Here, densities of interface charge that induced a change of surface mobility were considered specifically for NMOS.

The next section presents the method followed for setting up the experimental procedure and results are discussed in Section IV.

These SiO2 and Si/SiO2 interface trapped charges result in a change in carrier mobility in the transistor channel of MOS and this leads to a decrease in its transconductance. This phenomenon depends on density of the trapped charge and can be expressed by a mobility model (SPICE model) via the following equation as:

$$\mu = \frac{\mu_o}{1 + \alpha_o \Delta N_{ot} + \alpha_{it} \Delta N_{it}}$$

where $\mu_o$ is low field surface mobility, $\alpha_o$ is a coefficient describing the effects of the oxide-trapped charge and $\alpha_{it}$ is a coefficient describing the effects of the interface states.

III. SET UP AND EXPERIMENTAL PROCEDURE

A. Device and Design Details

Samples were designed and fabricated at the Thai Microelectronics Centre (TMEC) in 0.8 μm complementary metal-oxide-semiconductor (CMOS) technology. The sample device was constructed with a drawn channel width at 20 μm and drawn channel length varying from 0.8 μm (short nMOSFET) as shown in Figure 1 and 20 μm (big nMOSFET).

The N-well was formed by phosphorus ion implantation with a doping concentration of $6 \times 10^{16}$ cm$^{-3}$ on a p-type substrate of 25 Ω-cm. A self-aligned n+polysilicon gate process 350 nm in thickness was used with gate oxide thickness 15 nm. A BF$_2$ ion with a dose of $1 \times 10^{15}$ cm$^{-2}$ and energy 70 keV was implemented to adjust the threshold voltage implantation process in a channel to match the threshold voltage of the NMOS and PMOS devices. The N+ region was performed by arsenic (As) ion implantation at dose $5 \times 10^{15}$ cm$^{-2}$ with energy 100 keV. Source and drain junction depth were approximately 0.4 μm with 50 Ω/square of sheet resistance. A summary of nMOSFET parameters is presented in Table I.

B. Radiation Conditions and Device Measurement

The radiation experiments were performed at the Thailand Institute of Nuclear Technology (TINT). Characteristics were collected for both pre-irradiation and
post-irradiation devices to gamma rays by cobalt-60 (Co-60) using 1.25 MeV at room temperature, transient dose = 290.68 Gy/hr, GC3 centre turn: 3.9 kGy/hr at a total dose varying from 1, 2, 4, 7 and 10 kGy. The gamma rays were produced at a dose rate of 15.38 kGy/min. Gamma radiation delivers a certain dose for a certain time period depending on the thickness and volume of the product as shown in Table II.

### Table II. Gamma Radiation Exposure Dose by Cobalt-60 Gamma Ray Source, Transient Dose = 290.68 Gy/hr, GC3 Centre Turn: 3.9 kGy/hr at Room Temperature.

<table>
<thead>
<tr>
<th>Dose (min)</th>
<th>1</th>
<th>2</th>
<th>4</th>
<th>7</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Irradiation energy (kGy)</td>
<td>15.38</td>
<td>30.77</td>
<td>61.54</td>
<td>107.69</td>
<td>153.85</td>
</tr>
</tbody>
</table>

The test devices were measured both pre-irradiation and post-irradiation using a precision semiconductor parameter analyser B-1500A semi-automatic probe station cascade ALESSI REL6100 model as shown in Figure 3. The IDS-VGS characteristics were measured on the n-Channel MOSFETs with bias drain voltage at 0.1 V and bias gate voltage range of 0 to 5 V as shown in Figure 4.

The $I_{DS}$-$V_{DS}$ characteristics of the nMOSFET devices were tested using a bias drain voltage range of 0 to 5 V and bias gate voltage range of 0 to 5 V with the source terminal and substrate connected to the ground. Threshold voltage extraction was performed by linear extrapolation methodology. The threshold voltage $V_{TH}$ as the gate voltage $V_{GS}$ at drain current $I_{DS}$ was zero value on the condition of maximum slope of the drain current.  

The maximum linear conductance ($G_m$) can be defined as the maximum slope of the $I_{DS}$-$V_{GS}$ curve.

The drain current of MOSFET can be defined by:

$$I_{DS} = \mu_{eff} C_{ov} \frac{W_{eff}}{L_{eff}} \left( \left( V_{GS} - V_{TH} \right) V_{DS} - \frac{1}{2} V_{DS}^2 \right)$$  \hspace{1cm} (3)

where $\mu_{eff}$ is the effective mobility in a channel, $W$ is a channel width, $L$ is a channel length, $C_{ov}$ is gate oxide capacitance per unit area, $V_{GS}$ is gate-source bias voltage, $V_{DS}$ is drain-source supply voltage and $V_{TH}$ is the threshold voltage.

In the linear region $V_{DS}$ is small ($V_{DS} = 50$ mV) and the drain current can be defined as:

$$I_{DS} = \mu_{eff} C_{ov} \frac{W_{eff}}{L_{eff}} V_{DS} \left( V_{GS} - V_{TH} \right)$$  \hspace{1cm} (4)

The maximum transconductance ($G_m$) for the device in the linear region and mobility model [4] can be defined by:

$$G_m = \mu_{eff} C_{ov} \frac{W_{eff}}{L_{eff}} V_{DS}$$  \hspace{1cm} (5)

$$\mu_{eff} = \frac{1}{1 + \theta (V_{GS} - V_{TH})} \left( \frac{V_{DS}}{V_{max}} \right)$$  \hspace{1cm} (6)

In the saturation region $V_{DS, sat} = V_{GS} - V_{TH}$ and the saturation drain ($I_{DS,sat}$) can be defined as follows:

$$I_{DS,sat} = \mu_{eff} C_{ov} \frac{W_{eff}}{2L_{eff}} (V_{GS} - V_{TH})^2$$  \hspace{1cm} (7)

where $\mu_{eff}$ is the effective mobility in a channel due to the vertical and lateral field, $W_{eff}$ is an effective channel width,
Leff is an effective channel length, Cox is gate oxide capacitance per unit area, VGS is gate-source bias voltage, VDS is drain-source supply voltage, VTH is the threshold voltage, μv is the vertical or surface mobility due to the vertical field and θ is the gate field induced mobility reduction parameter.

IV. RESULTS AND DISCUSSION

Major models of big nMOSFETs consist of gate oxide thickness (Tox) = 150 Å, poly silicon gate thickness (Tpoly) = 3,500 Å, channel width (W) = 20 μm, channel length (L) = 20 μm, VTH = 0.7 as shown in Figure 5, low field surface mobility = 467.89 cm²/Vs, maximum transconductance = 101 μA/V², θ = 0.07 V⁻¹, channel width reduction from drawn value (W0) = 0.5 μm, channel length reduction from drawn value (L0) = 0.06 μm, drain series resistance (RD) = 88 Ω and source series resistance (RS) = 88 Ω as shown in Table III.

**TABLE III. THRESHOLD VOLTAGE, MAXIMUM TRANSCONDUCTANCE AND LOW FIELD MOBILITY AT VARIOUS GAMMA RADIATION EXPOSURE DOSES BY COBALT-60 IN THE DOSE RANGE OF 1 TO 10 KGY OF BIG NMOS.**

<table>
<thead>
<tr>
<th>Dose (kGy)</th>
<th>Parameter</th>
<th>VTH (volts)</th>
<th>Maximum transconductance (A/V²)</th>
<th>Low field surface mobility (cm²/Vs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
<td>0.700</td>
<td>1.01x10³</td>
<td>467.89</td>
</tr>
<tr>
<td>1</td>
<td></td>
<td>0.622</td>
<td>9.90x10⁴</td>
<td>458.49</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>0.600</td>
<td>9.80x10⁴</td>
<td>453.87</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>0.533</td>
<td>9.79x10⁴</td>
<td>453.58</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>0.506</td>
<td>9.69x10⁴</td>
<td>448.87</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td>0.420</td>
<td>9.66x10⁴</td>
<td>447.44</td>
</tr>
</tbody>
</table>

Values for short nMOSFETs were gate oxide thickness (Tox) =150 Å, poly silicon gate thickness (Tpoly) = 3,500 Å, channel width (W) = 20 μm, channel length (L) = 0.8 μm, VTH = 0.58, low field mobility = 195 cm²/Vs and maximum trans-conductance (Kp) = 414 μA/V² as shown in Table IV.

**TABLE IV. THRESHOLD VOLTAGE, MAXIMUM TRANSCONDUCTANCE AND LOW FIELD MOBILITY AT VARIOUS GAMMA RADIATION EXPOSURE DOSES BY COBALT-60 IN THE DOSE RANGE OF 1 TO 10 KGY OF SHORT NMOS.**

<table>
<thead>
<tr>
<th>Dose (kGy)</th>
<th>Parameter</th>
<th>VTH (volts)</th>
<th>Maximum transconductance (A/V²)</th>
<th>Low field surface mobility (cm²/Vs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
<td>0.580</td>
<td>414 x10⁴</td>
<td>194.69</td>
</tr>
<tr>
<td>1</td>
<td></td>
<td>0.568</td>
<td>329 x10⁴</td>
<td>152.43</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>0.534</td>
<td>328 x10⁴</td>
<td>151.86</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>0.454</td>
<td>293 x10⁴</td>
<td>135.90</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>0.429</td>
<td>275 x10⁴</td>
<td>127.33</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td>0.371</td>
<td>260 x10⁴</td>
<td>120.58</td>
</tr>
</tbody>
</table>

Experimental results indicated degradation of the device after irradiation of big and short nMOSFETs. Figure 6 shows the IDS-VGS characteristics of pre-irradiated and post-irradiated big nMOSFET at 10 kGy. The pre-radiation threshold voltage of big nMOSFET was 0.68 V compared with the irradiated NMOS at 4 and 10 kGy as 0.55 V and 0.45 V respectively. At the highest dose, the threshold voltage reduced significantly by 33.8% compared with the pre-irradiated big nMOSFET.

This phenomenon can be explained because the electric field in the oxide was not sufficiently strong. The threshold voltage shift was expected to be faster with an increase in positive field from the gate to the substrate.
extracted a Theta parameter from low field mobility in the linear region. The value of mobility degradation of pre-radiation big nMOSFET was 0.074 V⁻¹. As the big nMOSFET devices were increased with gamma ray exposure dose, mobility degradation values reduced compared with post-radiation big nMOSFETs with highest dose as 0.049 V⁻¹.

![Figure 8. Gm-VGS characteristics of pre-post irradiation of big nMOSFETs at 4 and 10 kGy.](image)

The maximum transconductance (Gm) extracted from the maximum slope of the IDS-VGS curve in the saturation region is shown in Figure 7. Maximum transconductance (Gm) of big nMOSFETs decreased for irradiated NMOS at 4 and 10 kGy as 3.1% and 4.5% compared with pre-irradiation nMOSFETs. This phenomenon can be explained because interface trapped charges resulted in a change of mobility in the charge carried in the channel of NMOS which led to a decrease in maximum transconductance (Gm) as shown in Figure 8.

The results in Table V show that deviation of the threshold decreased by 36.0% for short nMOSFETs and 33.8% for big nMOSFETs. The VTH ratio between pre- and post-radiation was approximately 0.65 and 0.63 for short and big nMOSFETs respectively. The Gm ratio between pre-irradiation and post-irradiation was approximately 0.95 and 0.63 for short and big nMOSFETs respectively. Deviation of the maximum transconductance (Gm) process was around 3.1% for short nMOSFETs and 4.5% for big nMOSFETs. The drain saturation current gave various VGS for big nMOSFETs. Results showed that maximum drain current IDS of big nMOSFETs increased 8% at the highest dose rate (10 kGy) and increased approximately 1.5% for short nMOSFETs. These increases resulted from the channel length reduction (LD), drain/source resistance (RDS), channel length effect on drain current (KAPPA) and the maximum carrier velocity (VMAX).

### TABLE V. SUMMARY OF THRESHOLD VOLTAGES, MAXIMUM TRANSCONDUCTANCE AND SATURATION DRAIN CURRENT FOR PRE- AND POST-RADIATION (10 KGy) OF SHORT AND BIG nMOSFETs.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Big nMOSFET (W/L=20/20)</th>
<th>Short nMOSFET (W/L=20/0.8)</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>VTH (pre rad)</td>
<td>0.70</td>
<td>0.58</td>
<td>V</td>
</tr>
<tr>
<td>ΔVTH</td>
<td>-0.28</td>
<td>-0.21</td>
<td>V</td>
</tr>
<tr>
<td>VTH (post)</td>
<td>0.65</td>
<td>0.63</td>
<td>V</td>
</tr>
<tr>
<td>Gm (pre rad)</td>
<td>10.1</td>
<td>414</td>
<td>µA/V</td>
</tr>
<tr>
<td>Gm (post)</td>
<td>0.95</td>
<td>0.63</td>
<td></td>
</tr>
<tr>
<td>IDS,sat (pre rad)</td>
<td>650×10⁻⁶</td>
<td>8.9×10⁻⁶</td>
<td>A</td>
</tr>
<tr>
<td>IDS,sat (post)</td>
<td>1.06</td>
<td>1.01</td>
<td></td>
</tr>
</tbody>
</table>

V. CONCLUSIONS

Our results revealed that nMOSFET irradiation showed good dose linearity and significant fading effect to improve dosimetry and/or radiation detection. However, response of the nMOSFET gave low field surface mobility which was dependent on the dose rate of Cobalt-60 gamma irradiation for the density of interface charge. Threshold voltages and drain currents of big and short n-Channel MOSFETs were investigated by a SPICE model level 3. Low field mobility and device trans-conductance were extracted. Threshold voltage shift was expected to be faster with an increase in the positive field from the gate to the substrate. When big nMOSFET devices were subjected to increased gamma ray exposure dosage, values of mobility degradation reduced compared with the highest dose at 0.049 V⁻¹. Deviation of the threshold decreased by 33.8%. Decreases in deviation of the maximum transconductance (Gm) process and low field mobility were around 4.5%. However, drain saturation current dramatically increased by 8% at the highest dose compared with the pre-irradiated n-Channel MOSFETs.

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