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Effect of Temperature and Electrical Modes on Radiation Sensitivity of MISFET Dose Sensors †

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Abstract: The temperature and electrical modes influences on radiation sensitivity of *n*-channel MISFETs sensors of the total ionizing dose were investigated. There were measured the MISFET-based dosimeter output voltages V as function of the radiation doses D at const values of the drain current $I_D$and the drain–source voltage V_D, as well as the (I_D–V_G) characteristics before, during and after irradiations at different temperatures T ($V_G$is the gate voltage). It was shown how the conversion function $V(D)$ and the radiation sensitivity S_D are depending on the temperature T for different electrical modes. To interpret experimental data there were proposed the models taking into account the separate contributions of charges in the dielectric Q_t and in SiO_2–Si interface Q_s. The model's parameters $\Delta V_t(D,T)$ and $\Delta V_s(D,T)$ were calculated using the experimental I_D–V_G characteristics. These models can be used to predict performances of MISFET-based devices.

Keywords: ionizing dose sensors; MISFET; temperature; electrical modes; radiation sensitivity

1. Introduction

The influence of ionizing radiation (electrons, X-rays, γ-rays, protons and heavy ions) on devices based on the metal-insulator-semiconductor structures (MIS-capacitors and field-effect transistors called as MISFETs) are being studied since 1960′ years (e.g., [1,2]). It was found that the general dose radiation effect is the irreversible change during irradiation of effective charge Q_e, summarized effective charges Q_t in an insulator and Q_s in insulator-semiconductor interface [3,4]. This effect results in the deformations of MIS-capacitors' C-V characteristics and MISFETs' I–V characteristics (CVC), what are physical basics of the MIS-based dosimeters of ionizing radiation. MISFETs possess small sizes and the best compatibility with the elements of silicon integrated circuits (SIC). So as dose-sensitive elements they seem promising to develop the integrated dose-metric sensors, as well as embedded elements in SIC to estimate degradations of SICs' electrical characteristics under irradiation. MISFET-based dosimeters are using in medicine and in space equipments.

MISFET-based sensors of the total ionizing dose D (TID) have been studied by many investigators [4–8]. Found that radiation sensitivity of sensors depend on electrical modes, structural and technological parameters of MISFET. We have previously researched *n*-channel MISFET as the dose-metric sensor at room temperature [8]. However, radiation changes of effective charges $Q_t$and Q_s at different temperatures T and electrical modes remain unexplored issues. The motivations of work are to investigate of the influence temperatures in wide ranges on the TID effects in MISFETs at

different electrical modes, and to propose models taking into account the separate contributions of $Q_t(T,D)$ and $Q_s(T,D)$ to radiation sensitivity.

Usually, sensors embedded in signal conditioning analogue or digital circuits to measure TID. Typically, MISFETs applied in dosimeters in analogue modes. The informative parameter of the volt-metric analogue circuits is the output voltage V, which consists of the initial value V_0 and dose-dependent value ΔV. The value ΔV is the result of converting the dose change ΔD in charge changes ΔQ_e. There are three basic electrical modes for volt-metric circuits: (1) the measurand V is V_G vs. Q_e at the constant I_D and V_D; (2) the measurand V is V_D vs. $I_D(Q_e)$ at the constant V_G; (3) the measurand V is V_D vs. Q_e at the constant I_D and V_G. In this paper there will be analyzed only the first type of circuit used widely in MISFET-based devices.

2. Materials and Methods

MISFETs with Al-SiO_2-Si structure were fabricated by means of conventional *n*-MOS-technology. The chip and the circuit of MISFET-dosimeter demonstrated in Figure 1. In this circuitry the voltage V is equal to the gate voltage V_G. The simplified structure of the all measuring system is shown in Figure 2a. There were measured the output voltages V as function of the total ionizing dose (TID) D of X-rays radiation for different drain currents $I_D$and source-drain voltages V_D, as well as the (I_D–V_G) characteristics before, during and after irradiations at different temperatures T in range from −50 °C to 125 °C. The constant temperatures (T ± 2 °C) were supported by thermoelectrical module (Peltier element), using the temperature control circuitry of measuring system MERA-3. The general view of *I*–*V* characteristics before and after irradiation at constant T is illustrated in Figure 2b.

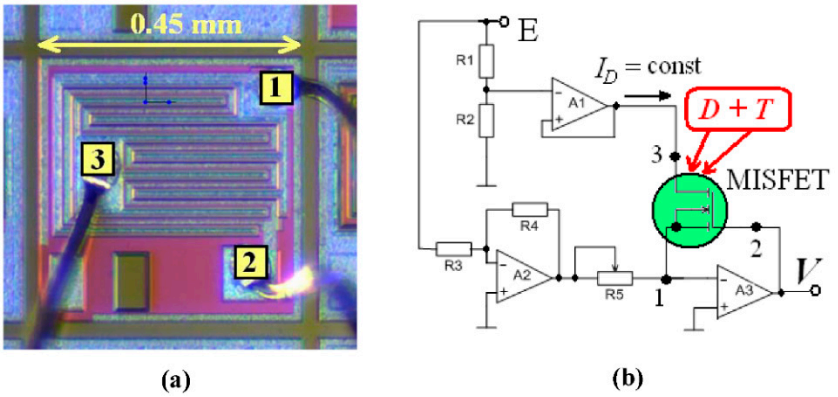


Figure 1. (**a**) MISFET's chip photo; (**b**) The MISFET-dosimeter circuit (1—source; 2—gate; 3—drain).

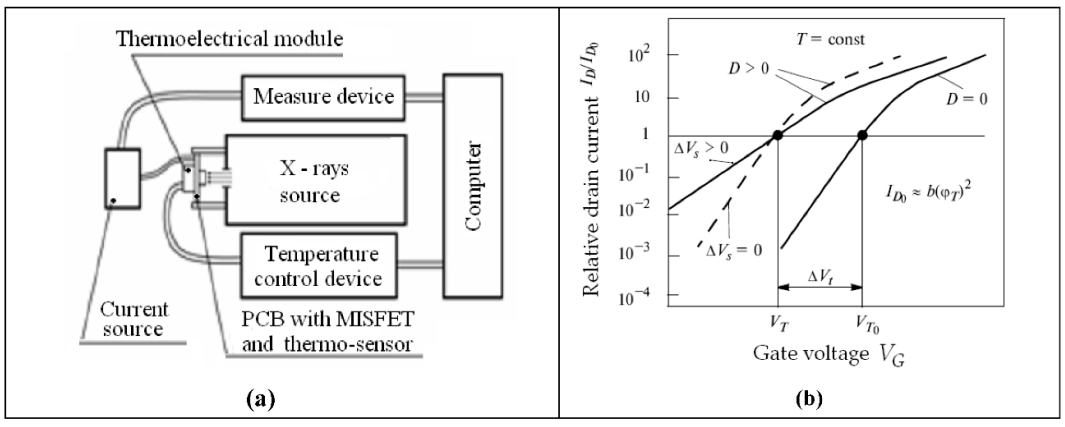


Figure 2. (**a**) The structure of system MERA-3; (**b**) MISFETs' *I*–*V* characteristics before and after irradiation.

3. Results

Experimental conversion functions $V(D)$ at various currents I_D and temperatures T are presented in Figure 3. The example of (I_D–V_G) characteristics before and after irradiations is illustrated in Figure 4a. Calculated separate contributions of model's parameters $\Delta V_t(D,T)$ and $\Delta V_s(D,T)$ at different temperatures and average values of parameters of MISFETs are presented in Figure 4b and in Table 1.

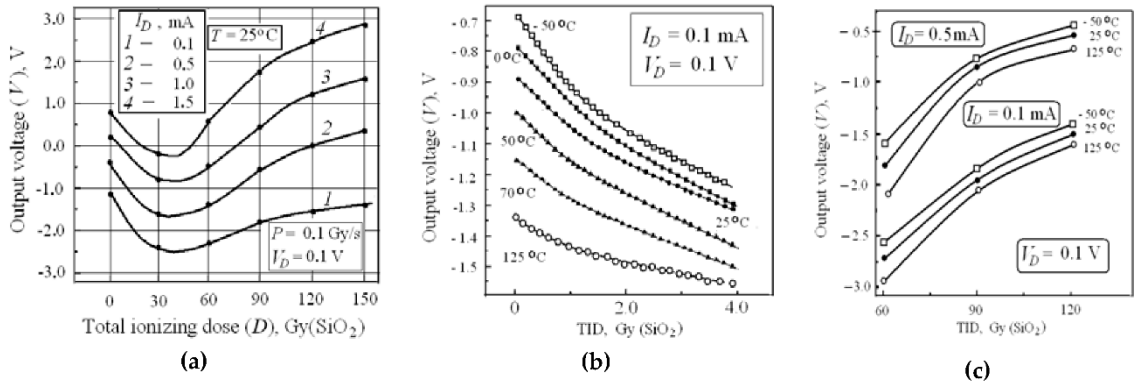


Figure 3. (**a**) Conversion functions at different I_D; (**b**,**c**) Conversion functions at different temperatures T.

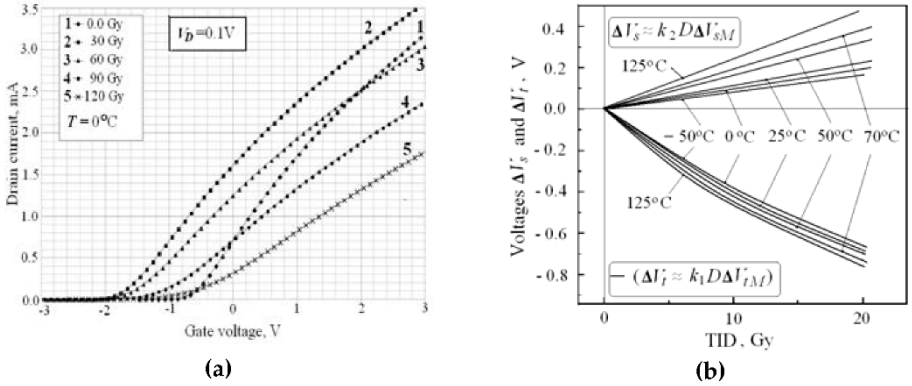


Figure 4. (**a**) I_D–V_G characteristics for different TID; (**b**) Calculated parameters $\Delta V_t(D,T)$ and $\Delta V_s(D,T)$.

Table 1. Average values (dispersion <10%) of parameters of MISFETs and models at I_D = 0.1 mA.

T, °C	V_0, V	ΔV_{tM}, V	ΔV_{sM}, V	k_0, nF/cm²	k_1, 10^{-2}Gy^{-1}	k_2, 10^{-2}Gy^{-1}	S_{DM1}, mV/Gy	S_{DM2}, mV/Gy
−50	−0.67	2.59	3.8	46	2.4	0.22	−51.7	31.4
0	−0.78	2.46	4.2	42	2.5	0.26	−51.0	31.6
25	−0.87	2.46	4.4	40	2.7	0.30	−53.3	32.2
50	−0.92	2.49	4.45	40	2.8	0.40	−53.1	33.5
70	−1.12	2.51	4.6	38	2.9	0.43	−53.0	35.0
125	−1.32	2.37	4.9	35	3.1	0.51	−48.5	37.2

4. Discussion

The conversion functions $V(D)$ have two areas (the negative and positive sensitivities). To interpret the results the following 3-component model of voltage $V(D,T,I_D)$was used:

$$V(D,T,I_D) = V_0(T,I_D) - \Delta V_t(D,T,I_D) - \Delta V_s(D,T,I_D), \quad (1)$$

$$\Delta V_t(D,\, T,\, I_D) = \Delta Q_t/C_0 = \Delta V_{tM}[1 - \exp(-k_1 D)];\ \Delta V_s\,(D,T) = \Delta Q_s/C_0 = \Delta V_{sM}[1 - \exp(-k_2 D)]; \quad (2)$$

$$\Delta V_{tM}(T, I_D) = (\Delta Q_{0M} + k_0 U)/C_0]; \text{ at } U = (V - V_T) > 0, \quad (3)$$

where V_0 (T,I_D) is an initial output voltage, being independent on TID, determined by experiments (see Table 1). Value C_0 is the dielectric capacitance per unit area. Value V_0 depends on temperature, electrical mode, structural and technological parameters of MISFET. The average temperature coefficient of initial output voltage α_0 being equal to $\Delta V_0/(V_0 \Delta T)$ ×100 can be estimated as (−0.3%/K).Value V_T is the threshold voltage of MISFET. The radiation sensitivity determined as

$$S_D = dV/dD = k_2 \Delta V_{sM} \cdot \exp(-k_2 D) - k_1 \Delta V_{tM} \cdot \exp(-k_1 D). \quad (4)$$

If temperature increase, that maximum sensitivity S_{DM} decreases for low TID and increase for high doses. The temperature coefficient of radiation sensitivity was estimated as $\alpha_T = \Delta S_D/(S_D \Delta T)$ × 100 being equal to 0.12%/K. The parameters of models (1)–(4) were calculated from the experimental I_D–V_G characteristics as in [9].

To measure low doses (up to 10 Gy), it is recommended to use the initial conversion function areas in its linear region (the negative sensitivity area), where the maximum sensitivity slightly dependent on the electric mode. To measure doses over a wider range (up to 100 Gy), the conversion function areas with positive sensitivity can be used by pre-irradiating with a dose of ~50 Gy. In this case, the average radiation sensitivity is more dependent on the operating drain current and may even exceed the maximum sensitivity in the negative sensitivity area. However, the increase of operating current leads to increased power consumption and probability of "effect of self-heating", when the temperature of the chip exceeds the temperature of the environment, and result in additional errors of doses' measurement. For example, at V_D = 0.1 V and the permissible power dissipation of 1 mW, the drain current should not exceed 10 mA, and the output voltage would be positive throughout the conversion range, the drain current should be greater than 1.5 mA. The drain current I_D = 2.0 mA, corresponding to the average sensitivity S = 40 mV/Gy, can be considered optimal for the area of positive sensitivity of theMISFET-dosimeter.

5. Conclusions

The temperature influences on radiation sensitivity of *n*-channel MISFETs sensors of the total ionizing dose were investigated at different electrical modes. There were measured the MISFET-based dosimeter output voltages as function of TID at constant values of the drain currents, as well as the CVC before,during and after irradiations at different temperatures in range −50 °C to 125 °C. It was shown how the conversion function $V(D)$ and the radiation sensitivity S_D are depending on the temperature for different electrical modes. To interpret experimental data there were proposed the models taking into account the separate contributions of charges in the dielectric Q_t and in SiO_2–Si interface Q_s. The model's parameters of $\Delta V_t(D,T)$ and $\Delta V_s(D,T)$ were calculated using the experimental I_D–V_G characteristics. These models can be used to predict performances of various types MISFET-based dosimeters.

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Conflicts of Interest: The authors declare no conflict of interest.

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