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FAST ELECTRON IRRADIATION EFFECTS ON MOS TRANSISTOR MICROSCOPIC PARAMETERS – EXPERIMENTAL DATA AND THEORETICAL MODELS

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In this paper the authors propose a general and a simplified theoretical model in order to study the output MOS transistor characteristics and to compute the microscopic (the electron mobility, the Fermi energy) and macroscopic (the saturation voltage and the changing of the drain channel length) parameters, after fast electron irradiation (3 MeV, 10 MRd) of the samples. Starting from the experimental data, we used these models and an appropriate optimization method, for computer simulation of the circuit characteristics and for finding the specific parameters of three MOSFET transistors with p-induced channel (ROS 01, ROS104, ROS 05), before and after irradiation.

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1. Introduction

Due to the large employment of the devices based on MIS (metal-insulator-semiconductor) structures like MOS transistors, integrated MOS type circuits and charge coupled circuits in the last decade, it is very usefully to study the physical and chemical properties of these structures under different external conditions.

MOS based devices may be exposed to ionised irradiation during the technological manufacturing process.

The effects of the irradiation on MOS transistors were, for the first time, emphasised by Hughes and Giroux, in 1964 [1].It was showed that the most important effects of the irradiation on the MOS type circuits was the accumulation of the positive charge due to hole excess produced by the radiation and the accumulation of the positive charge on interfaces.

Our work is concerned to the study the main characteristics and the microscopic and macroscopic parameters of three MOS type transistors, before and after irradiation with fast electrons. For this purpose, we propose a theoretical background and an optimisation method for fitting the experimental data and computing the specific parameters of the studied devices: the electron mobility, the Fermi energy, the saturation voltage and the changing of the drain channel length.

2. Experimental

We have traced the transfer and output characteristics for three MOSFET transistors with p-induced channel (ROS 01, ROS104, ROS 05), using an experimental set-up which enable a direct recording of these curves.

The electric circuit contains variable voltage power supplies (which give V_{DS} and V_{GS} input voltages), an ampere-voltage converter (giving an output voltage proportional with drain current I_D), a

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KIPP-ZONEN, BD 30 type X-Y recorder and high precision digital voltmeters of HP 3480A and KEITHLEY 161 type (for measure V_{DS} and V_{GS} voltages).

In order to avoid the influence of the temperature on the data measurements, the transistors were kept at constant temperature (T=30 °C) using an U10 type thermostat.

The connection between the A-V converter and the transistor (housed in the thermostat) was made by shielded multi-wire cable. The HF oscillations which could appear due to the inductance of the connection cable, between the transistor terminals were wired 47 nF non-inductive capacitors. These capacitors short-break the transistor terminals at high frequencies, without affecting his d.c. behaviour.

In fact, we used two converters one for p-channel transistors and one for n-channel transistors.

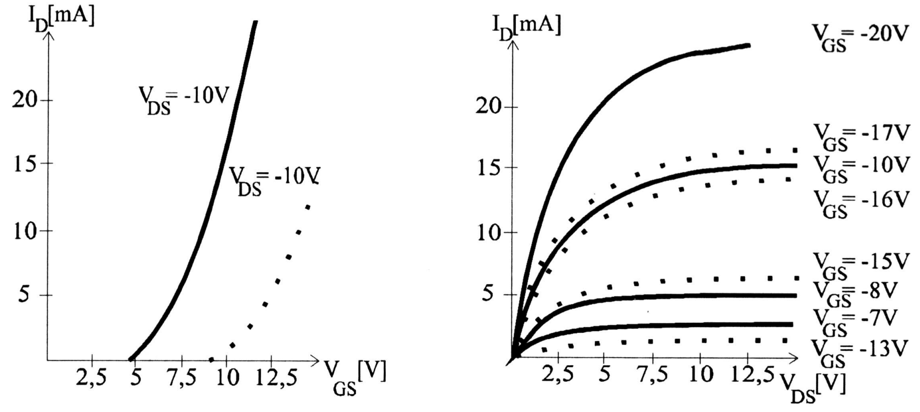
The A-V converter output voltage is applied to Y input of the recorder (at an appropriate sensibility level).

The conversion factor (ratio) was 0.2 V/mA.

At the X input of the recorder we applied V_{GS} or V_{DS} voltages for transfer or output characteristic recording, respectively. For the output characteristics recording the V_{GS} voltage was kept constant, while varying V_{DS}.

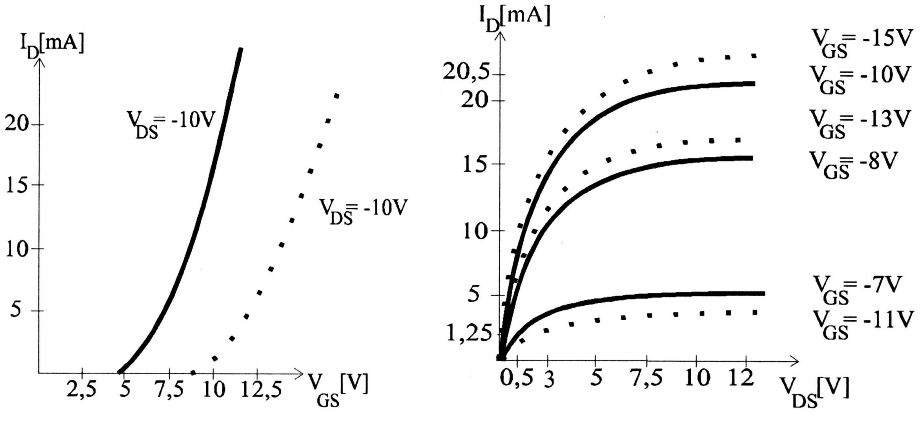
The irradiation was performed using fast electrons (3 MeV); the dose was 10 MRd (10^5 Gy) and the irradiation time, 16 min.

Figs. 1-3 show the experimental characteristics for ROS 01, ROS104 and ROS 05 transistors, respectively, before and after irradiation.



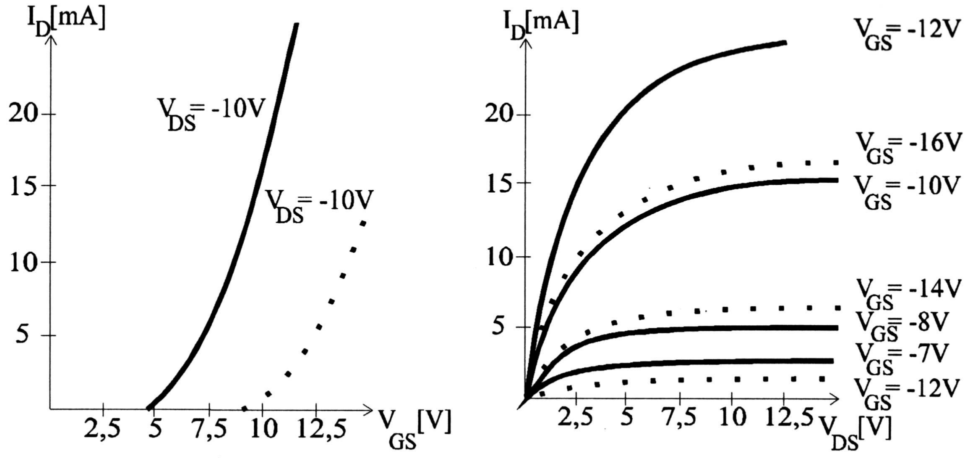
(a) (b)

Fig. 1. The transfer (a) and output (b) characteristics for ROS 01 transistor, before (full line curves) and after irradiation (dot line curves).



(a) (b)

Fig. 2. The transfer (a) and output (b) characteristics for ROS 104 transistor, before (full line curves) and after irradiation (dot line curves).



(a) (b)

Fig. 3. The transfer (a) and output (b) characteristics for ROS 05 transistor, before (full line curves) and after irradiation (dot line curves).

3. Theoretical models

First, we use a general model in order to study the intensity-voltage characteristics of the transistors. In the frame of this model, we propose for the drain current the following general expression:

$$I_D = \sum_{i=0}^{2} P_i V_{DS}^{i} + P_3 (V_{DS} + P_4)^{3/2}, \tag{1}$$

where V_{DS} is the voltage which appears on the surface of the semiconductor, while a positive voltage is applied on the drain, P_i (i=0, 4) are parameters chosen as:

$$P_0 = -\frac{2}{3} x_1 x_2 x_3^{3/2}, \tag{2}$$

$$P_1 = V_{GS} x_1, \tag{3}$$

$$P_2 = -\frac{1}{2} x_1, \tag{4}$$

$$P_3 = -\frac{2}{3} x_2 x_1, \tag{5}$$

$$P_4 = x_3, \tag{6}$$

with

$$x_1 = \frac{\mu_n \varepsilon_d B}{L w_i}, \tag{7}$$

$$x_2 = \frac{w_i}{\varepsilon_d} \sqrt{2 e \varepsilon_s N_a}, \tag{8}$$

$$x_3 = 2\Phi_F. \tag{9}$$

We used above the common notations: V_{GS} –the “gate” voltage, μ_n –the electron drift mobility, ε_d and ε_s –the dielectric constants of the dielectric and semiconductor layer, respectively, B –

the MOS transistor width, w_i –the dielectric thickness, e –the electron charge, L –the length of the channel between source and drain contact, Na –the acceptors concentration, Φ_F –the Fermi potential.

Substituting Eqs. (2)-(9) in Eq. (1), we obtain the well-known [2] expression of the drain intensity:

$$I_D = x_1\left\{V_{GS}V_{DS} - \frac{1}{2}V_{DS}^2 - \frac{2}{3}x_2\left[(V_{DS}+x_3)^{3/2} - x_3^{3/2}\right]\right\}. \tag{10}$$

The results of the simulation based on Eq. (10) for the values of the microscopic parameters lead us to the conclusion that for analysed MOS transistors the hypothesis VDS<<2 Φ_F is verified [3].

In this peculiar case, we can simplify the general model of the intensity-voltage characteristics by choosing:

$$P_j = 0, \qquad j = 3, 4, \tag{11}$$

$$P_1 = x_2(V_{GS} - x_1), \tag{12}$$

$$P_2 = -\frac{1}{2}x_2. \tag{13}$$

The drain current intensity becomes:

$$I_D \cong x_2\left[(V_{GS} - x_1)V_{DS} - \frac{1}{2}V_{DS}^2\right], \tag{14}$$

where

$$x_2 = \frac{Z}{L}\mu_n C_0 \tag{15}$$

and

$$x_1 = 2\Phi_F + \frac{1}{C_0}\left[2\varepsilon_s q N_a (2\Phi_F)\right]^{1/2}. \tag{16}$$

where the Fermi potential was measured with respect to the middle of the un-allowed energy band.

The parameters Pi (i=1, 4) were obtained from the comparison of the experimental and theoretical I-U curves, by minimizing the test function

$$F \equiv \sum_{i=1}^{N}\left[I_D(V_{DS}^i) - I_D^i\right]^2. \tag{17}$$

Here, V_{DS}^i and I_D^i are the experimental values, N the number of the experimental data, and the function $I_D(V_{DS})$ was defined first, by the theoretical general model Eq. (10) and second, by the simple model Eq. (14).

We used a Levenberg-Marquart type method for optimization the test function (17) and we compute the mobility (μ_n) and the Fermi energy (Φ_F) values, before and after the irradiation process, for different V_{GS} voltage values.

Using this values, we can find the conductance for $V_{DS} \approx 0$ and the threshold voltage (the minimum voltage applied to the “gate” electrode up to which the voltage on the semiconductor surface vanish) from the equations, respectively

$$G_0 = \frac{\mu_n \varepsilon_d B}{L w_i}\left[V_{GS} - \frac{w_i}{\varepsilon_d}\sqrt{2e\varepsilon_s(2\Phi_F)}\right] \tag{18}$$

and

$$V_{GS}^{th} = \frac{w_i}{\varepsilon_d}\sqrt{2e\varepsilon_s(2\Phi_F)}. \tag{19}$$

Moreover, using a dependence of the type [3]

$$V_D^{sat} \cong \left(\frac{2L}{Z} \frac{I_D^{sat}}{\mu_n C_0} \right) \tag{20}$$

we can compute the saturation voltages (V_D^{sat}), for the experimentally measured saturation drain currents (I_D^{sat}). Consequently, we can find the decreasing of the drain channel length from the equation [3]

$$\Delta L \cong \left[\frac{1}{qN_a} 2\varepsilon_s \left(V_{DS} - V_D^{sat} \right) \right]^{1/2} . \tag{21}$$

Figs. 4, 5 illustrate the application of the previous models for I-U characteristics of MOS transistor ROS 05, at V_{GS} =-12 V. Similar results were obtained for ROS 104 and ROS 01, at different V_{GS} values [4].

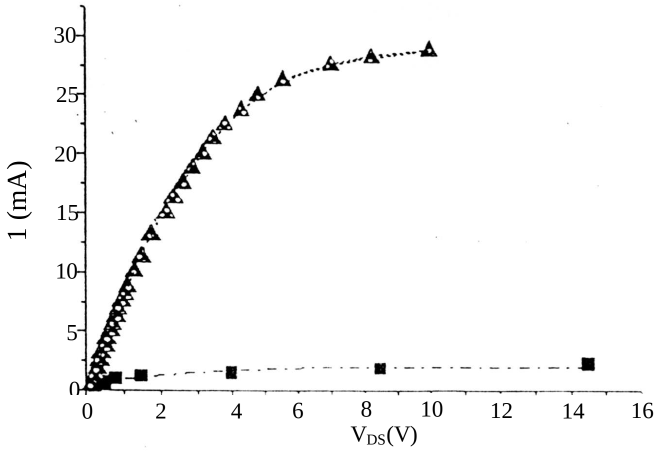


Fig. 4. Experimental and theoretical characteristics (general model) for ROS 05 transistor, at

V_{GS} =-12 V. Δ -before irradiation, ■ –after irradiation.

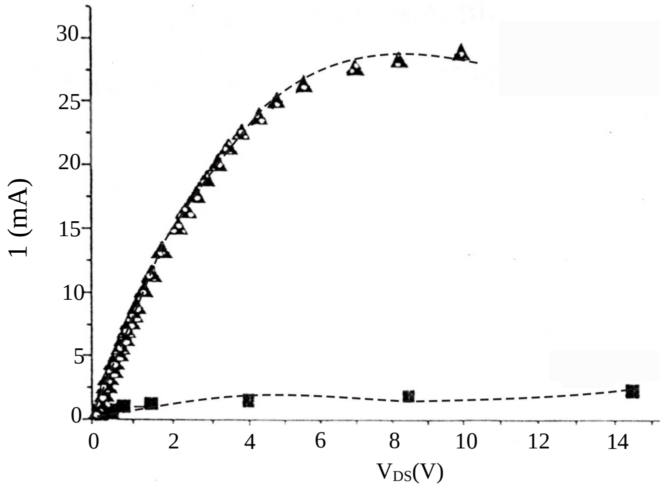


Fig. 5. Experimental and theoretical characteristics (simplified model) for ROS 05 transistor, at V_{GS} =-12 V. Δ -before irradiation, ■ –after irradiation.

4. Results and discussion

After irradiation with fast electrons, the transfer characteristics for all studied transistors proved to have a strong displacement in the sense of increasing the threshold voltage from 4-5 V up to approx. 9-10 V.

The slopes of the curves were practically unmodified and this seems to be a result of the accumulation of the positive charge in the oxide layer placed between the “gate” and the substrate of the transistors. The fast electrons crossing this layer during the irradiation process produce the ionization of the atoms [5]. Consequently, a secondary electron emission from the oxide layer took place, which finally leads to accumulation of the positive charges in the oxide substrate. This positive charge creates an electric field which has a major contribution in the transfer characteristics displacement towards high voltage values.

The theoretical curves derived from the general and simple models are in good agreement with the experimental I-U characteristics for all studied transistors.

We have computed the Fermi potential and the parameters x_1, x_2 for ROS 05 transistor and we found that the values of the Fermi potential (0.021 eV) and of the parameter x_1 ($1.0428\cdot10^{-6}$), which depends on the acceptors concentration, remain unchanged after the fast electron irradiation.

By contrast, the electron mobility was proved to be modified as a result of the irradiation process, its value decreasing from 0.17004 $m^2/$ Vs down to 0.00322 $m^2/$ Vs, for V_{GS} =-12 V. The change of the drain channel length was $\delta\Delta L=12.014$ Å, showing a good agreement with the experimental data and the phenomenological analysis.

5. Conclusions

In our work we propose two theoretical approaches for study the changes of the intensity-voltage characteristics of MOS transistors subjected to fast electron irradiation.

We have computed the microscopic and macroscopic parameters of these devices, under the same conditions, also.

We have found that the electron mobility decreased after irradiation process, while the Fermi energy was not changed, both parameters depending on the “gate” voltage values. These theoretical results are in good agreement with the experimental measurements.

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