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EFFECTS OF γ-IRRADIATION ON ELECTRICAL CHARACTERISTICS OF POWER VDMOS TRANSISTORS

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Abstract. *In this paper we present the results of both experimental investigation and analytical modelling of γ-irradiation effects on basic electrical characteristics of power VDMOS transistors. First, an analytical model that yields the drain current and transconductance dependencies on gate oxide charge density is developed. The experimental data are utilized to establish an analytical relation between the absorbed dose of γ-irradiation and corresponding effective density of gate oxide charges, as well as to extract the values of model parameters. Drain current and transconductance of VDMOS devices are then modelled as the functions of irradiation dose. Finally, the results of modelling are compared with experimental data.*

Key words: *VDMOS Transistors, γ-Irradiation, Drain Current, Transconductance*

INTRODUCTION

The electrical characteristics of MOS transistors are well-known to strongly depend on quality and purity of gate oxide and, in particular, on the presence and status of Si-SiO_2 interface defects. Certain impurities and defects are inevitably incorporated into the gate oxide either during oxide growth or during the subsequent processing steps. A consequence of this contamination is the appearance of four different kinds of charges and traps in thermally grown silicon dioxide [1]-[3]: (1) Si-SiO_2 interface trapped charges (also referred to as surface states, fast states, or interface states), which can be either positive or negative, (2) fixed oxide charges, located very near the Si-SiO_2 interface (within about 25 Å), which are positive, (3) oxide trapped charges (mainly positive), and (4) mobile ionic charges (alkali metal ions). The flat-band voltage and threshold voltage values in MOS devices, as well as the mobility of charge carriers in channel region, are directly dependent on densities and distributions of all these charges. Consequently, these

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charges have very strong influence on device current-voltage characteristics and transconductance.

Charges built-in into the gate oxide during the MOS device manufacturing process do not represent any serious difficulty from the technology standpoint, since a simple annealing process efficiently reduces their effective density to an acceptable level (approximately to 3×10^{10} cm^{-2} in state-of-the-art devices). However, the problems related to stability and reliability of operation arise in the case of devices that are either stored or operated in an ionizing radiation environment. Ionizing irradiation is known to induce the appearance of additional charges at Si-SiO_2 interface and within the oxide itself [4], [5]. This additional increase of gate oxide charge density causes a degradation of device electrical parameters (threshold voltage, leakage currents, transconductance, etc.), possibly leading to a failure of the circuit or overall system. Electronic devices used in satellite equipment are operated in radiation-hazardous space environment. Even in low-Earth orbits the total mission dose absorbed over the years of exploitation can be accumulated up to 100 Gy (1 Gy = 100 rad), while in high orbits this dose can be as high as 10 kGy [6]. The risk is even much higher in nuclear power stations where under the usual circumstances (not to mention accident situations) some devices must be able to withstand γ-irradiation from the reactor coolant system at a rate as high as 1 Gy h^{-1}, which represents a total dose of 250 kGy over 30 years [7]. On the other hand, some applications require devices that are highly sensitive to γ-irradiation. Thus, an investigation of electrical characteristics of MOS transistors exposed to irradiation is of considerable importance since it may help the development of both radiation resistant devices and devices that are radiation sensitive enough to be used as dosimeters.

Since the power MOS devices are also affected by irradiation, the subject of our current research is the influence of γ-irradiation on VDMOS transistor electrical characteristics. The results of preliminary investigations on devices irradiated up to the overall absorbed doses of 140 Gy have already been reported [8], while in this paper we extend our consideration to more realistic dose range of 500 Gy. First, we present the analytical model that yields dependencies of drain current and transconductance on an effective density of gate oxide charges. The experimental results are utilized for establishing a direct relation between the absorbed dose of γ-irradiation and effective density of gate oxide charge, as well as for the extraction of key parameters of the analytical model. Finally, results obtained by modelling are compared with the measured values of drain current and transconductance in irradiated VDMOS devices.

EXPERIMENTAL DETAILS

As the experimental samples in this study we have used the *n*-channel VDMOS transistors EFL1N10 produced by "EI-Semiconductors", Nis, Yugoslavia. Devices have been manufactured in a standard poly-silicon gate technology and encapsulated into the TO-39 metal cases. Their current and voltage ratings are 1 A and 100 V, respectively, while the values of some technology parameters that will be used in modelling of the electrical characteristics are given in Table 1.

Table 1. Basic parameters of VDMOS transistors EFL1N10

Parameter	Value	Units
N_{Depi}	9.0×10^{14}	cm^{-3}
N_{Dpoly}	1.0×10^{20}	cm^{-3}
N_{Amax}	3.85×10^{16}	cm^{-3}
t_{ox}	110.0	nm
t_{epi}	14.0	µm
L	2.4	µm
W	62.4	µm
S	0.10×0.10	cm^2
Number of cells	860	-

Samples were irradiated by using ^{60}Co radioactive source with a dose rate of 0.1 Gy s^{-1}. The irradiation was performed up to a desired value of overall absorbed dose in the range from 50 to 500 Gy. Transfer and output current-voltage characteristics were measured just before the irradiation and as soon as the irradiation of devices was completed. The PC driven high precision Keithley digital instruments were used for device biasing and drain current measurements in linear region, while the remaining measurements were done by means of a Sony Tektronix 370 curve tracer. Apart from enabling the readings of drain current, these measurements also enabled a simple calculation of transconductance in both linear and saturation regions of device operation.

ANALITYCAL MODEL AND PARAMETER EXTRACTION

As in the case of conventional MOS devices, there is a number of VDMOS transistor analytical models based on expressions describing the output current-voltage characteristics [2], [3], [9]-[11]. However, in contrast to conventional devices, VDMOS transistor model must incorporate not only the voltage drops along the channel and at the source and drain contact resistances, but also the voltage drops at the resistances of epitaxial layer, JFET region, and accumulation layer. Taking this into account, the voltage applied between drain and source of VDMOS transistor can be expressed as:

$$V_{DS} = V_{ch} + (R_{epi} + R_{jf} + R_{ac})I_{DS} = V_{ch} + R_{DS}I_{DS} , \tag{1}$$

where V_{ch} is the voltage drop along the channel region, I_{DS} is drain current, while the resistances mentioned above are given by following expressions:

$$R_{epi} = \frac{t_{epi}}{qN_{Depi}S\mu_{epi}} , \tag{2}$$

$$R_{jf} = \frac{A_{jf}}{\mu_{epi}} , \tag{3}$$

$$R_{ac} = \frac{A_{ac}}{\mu_{ac}(V_{GS} - V_{FB})} , \tag{4}$$

where S represents the chip active area; t_{epi}, N_{Depi}, and μ_{epi} are the thickness, impurity concentration, and carrier mobility of epitaxial layer, respectively; A_{jf} and A_{ac} are parameters dependent on device geometry only [11]; μ_{ac} is mobility of the accumulation layer carriers; V_{FB} is the flat-band voltage; and V_{GS} is the voltage applied to the gate.

According to the so-called piecewise model, VDMOS device current-voltage characteristics can be described by the following equations for drain current in the linear and saturation regions, respectively [3], [9], [10]:

$$I_{DSl} = \frac{\beta V_{DS}(V_{GS} - V_T)}{1 + (\theta + \beta R_{DS})(V_{GS} - V_T)} \ , \tag{5}$$

$$I_{DSs} = \frac{\beta}{2} \frac{(V_{GS} - V_T)^2}{(1+\delta)[1 + \theta(V_{GS} - V_T)]} \ , \tag{6}$$

where parameter β is given as:

$$\beta = n \frac{W}{L} C'_{ox} \mu_{ch} \ . \tag{7}$$

In the expressions above, n is the number of unit cells, W and L are channel width and length, C'_{ox} is gate oxide capacity per unit area, μ_{ch} is channel carrier mobility, V_T is threshold voltage, while the mobility attenuation coefficient θ represents a temperature independent parameter that is related to the electric-field-enhanced carrier scattering at Si-SiO_2 interface faults [2], [3]. Parameter δ takes into account the fact that the depletion region width varies along the channel and thus differs from its value at the source [2]. Transconductance in linear and saturation regions is obtained from Eqs. (5) and (6), respectively, as:

$$g_{ml} = \frac{\beta V_{DS}}{[1 + (\theta + \beta R_{DS})(V_{GS} - V_T)]^2} \ , \tag{8}$$

$$g_{ms} = \frac{\beta}{2(1+\delta)} \frac{2 + \theta(V_{GS} - V_T)}{[1 + \theta(V_{GS} - V_T)]^2} (V_{GS} - V_T) \ . \tag{9}$$

Expressions (5) - (9) can be used for calculations of drain current and transconductance, provided the values of threshold voltage, channel carrier mobility, series resistance R_{DS}, and parameters θ and δ are known. Besides, it is necessary to know the dependence of these five parameters on overall dose of absorbed radiation.

An earlier developed extraction procedure can be used to obtain the values of all parameters mentioned above [12]. First, the Ghibaudo method can be employed to determine threshold voltage and low-field carrier mobility in channel region of each sample by using Eqs. (5) and (8) and experimental data for the drain current and transconductance in the linear region [13]. In the next step, keeping these already extracted values of threshold voltage and mobility, parameters θ and δ can be calculated by combining Eqs. (6) and (9) and using experimental data for the drain current and transconductance in the saturation region. The series resistance R_{DS} can be calculated by summing up the expressions (2) - (4), though it can be also extracted from the experimental data [12]. In our experience, there was no any significant difference in the results obtained by using either of two appraches.

The above parameter extraction procedure allows us to determine the threshold voltage for each sample before and after irradiation. On the other hand, threshold voltage can be expressed as follows [1]-[3]:

$$V_T = \phi_{ms} - \frac{Q_{ox}}{C_{ox}^{'}} + 2\phi_F + \gamma\sqrt{2\phi_F} \quad , \tag{10}$$

where

$$\gamma = \frac{\sqrt{2qN_{A\max}\varepsilon_s}}{C_{ox}^{'}} , \tag{11}$$

$$\phi_F = \frac{kT}{q}\ln\frac{N_{A\max}}{n_i} , \tag{12}$$

$$\phi_{ms} = -\frac{kT}{q}\ln\frac{N_{Dpoly}N_{A\max}}{n_i^2} \tag{13}$$

In expressions (10) - (13) ϕ_{ms} represents poly-gate to silicon work function difference, Q_{ox} is the gate oxide charge density, ϕ_F is the Fermi level potential, k is the Boltzmann constant, n_i is the intrinsic carrier concentration, ε_s is the silicon dielectric constant, N_{Amax} is the maximum acceptor impurity concentration in channel region, and N_{Dpoly} is the poly-silicon donor impurity concentration. These equations, after determination of threshold voltage by extraction from the experimental data, allow obtaining the gate oxide charge density in each of our samples. That is, there is a direct relationship between the absorbed dose of radiation and the corresponding gate oxide charge density Q_{ox} in each device. Therefore, so far the effects of the overall absorbed dose of γ-irradiation on device electrical characteristics have been included in our model in an indirect way by accounting for the density of radiation induced gate oxide charge. It should be noted, however, that dependencies of device characteristics on irradiation dose can be also modelled directly, provided a suitable analytical expression for gate oxide charge density dependence on radiation dose is found. In all these considerations we are making an approximation which is common in modelling of gate oxide charge effects [3]. Namely, different types of gate oxide charges that were mentioned in our introduction are replaced by a sheet of equivalent charge with an effective density Q_{ox}. This equivalent charge is assumed to be located at the Si-SiO_2 interface and to cause the same effects as all the actual charges of unknown distribution.

A dependence of channel carrier mobility on the density of gate oxide charge is given by [14]:

$$\mu_{ch} = \frac{\mu_{ch0}}{1 + \alpha \cdot Q_{ox}} \quad , \tag{14}$$

where μ_{ch0} and α are the coefficients that depend on the peak impurity concentration in channel region. The linear regression method is used to obtain the values of these coefficients from experimental data for the mobility in irradiated devices and corresponding values of Q_{ox} by plotting the dependence $1/\mu_{ch} = f(Q_{ox})$.

Finally, after the model parameters are extracted, substituting Eqs. (10) - (14) in corresponding expressions (5) - (9) yields the dependencies of drain current and transconductance on effective density of gate oxide charge, i.e. on irradiation dose.

RESULTS AND DISCUSSION

The analysis of our results will begin with the extraction of model parameters. On the basis of the measured transfer characteristics in the linear region, the corresponding values of threshold voltage were extracted and plotted in Fig. 1 versus the irradiation dose (triangles). The effective densities of gate oxide charge, calculated by means of expressions (10) - (13) for each corresponding value of threshold voltage, are also shown in Fig. 1 (circles). The relation between the radiation dose and the corresponding effective density of gate oxide charge in the first approximation can be represented by a simple linear function [8]. This linear approximation yielded quite acceptable results in the case of sample irradiation up to a rather low dose of 140 Gy [8]. However, the dose range in our current study has been extended up to 500 Gy, and the second order polynomial approximation represents better fit to the experimental data. This approximation, given by

$$Q_{ox} = (a_0 + a_1 D + a_2 D^2)\times 10^{10} \quad (\text{cm}^{-2}), \qquad (15)$$

where the irradiation dose D is given in Gy, is shown by the dotted line in Fig. 1. The values of coefficients a_0, a_1, and a_2 have been found to be 2.8111708, 0.10003805, and -0.0000725, respectively. It becomes straightforward now to include Eq. (15) into the model presented in previous section and to get dependencies of drain current and transconductance on the overall absorbed radiation dose.

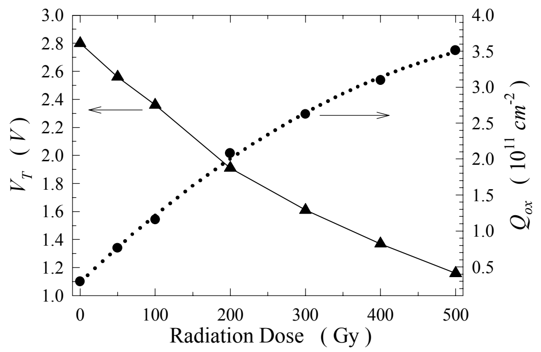

Fig. 1. Measured dependencies of threshold voltage (left axis) and corresponding extracted effective density of gate oxide charge (right axis) on irradiation dose in VDMOS transistors EFL1N10. Dotted line represents the empirical dependence given by Eq. (15)

The fact that threshold voltage decreased with irradiation dose indicated that γ-radiation caused an increase of the effective density of positive charge in gate oxide of our samples. As a consequence, the channel carrier mobility decreased [4], [5], [14]. For our samples, this is illustrated in Fig. 2, which shows the extracted values of mobility (circles) versus the gate oxide charge density, as well as the dependence given by Eq. (14). In the case of our samples, values of the fitting parameters in expression (14) as obtained by linear regression method were $\mu_{ch0} = 726$ cm^2 V^{-1} s^{-1} and $\alpha = 1.074\times10^{-12}$ cm^2.

Regarding parameters θ and δ, the extraction procedure performed either before or after irradiation in most of our samples yielded the values which were approximately equal to 0.08 V^{-1} and 0.4 for θ and δ, respectively. Some discrepancies were found in few samples, but there was no any indication of the possible influence of irradiation and radiation-induced gate oxide charge on the values of these two parameters. Hence, we have adopted the values of $\theta = 0.08$ V^{-1} and $\delta = 0.402$ for all our samples.

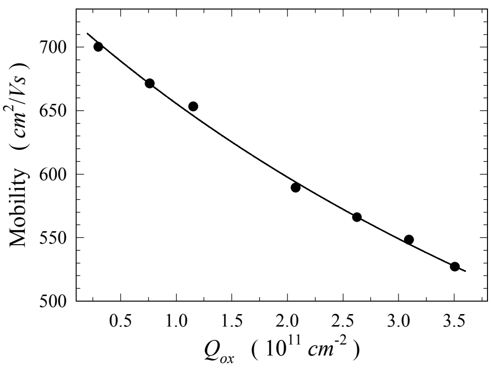

Fig. 2. Channel carrier mobility versus gate oxide charge density in VDMOS devices EFL1N10. Symbols denote extracted values; solid line represents dependence (14) with $\mu_{ch0} = 726$ cm^2 V^{-1} s^{-1} and $\alpha = 1.074\times10^{-12}$ cm^2

Measured and modelled dependencies of the drain current and transconductance on irradiation dose in EFL1N10 devices operated in the linear region are shown in Figs. 3 and 4, respectively. It can be seen in Fig. 3 that drain current at low gate voltage considerably increases with irradiation dose (that is, with the effective density of gate oxide charge), while at gate voltages higher than 5 V this increase becomes almost negligible. In contrast, Fig. 4 shows that transconductance at low gate voltage decreases with irradiation dose. However, at higher gate voltages, the transconductance behaves in a similar manner as the drain current and it almost does not depend on the absorbed dose. The latter figure also shows that transconductance in linear region decreases with the increase of gate voltage.

Measured and modelled dependencies of drain current and transconductance on irradiation dose in EFL1N10 transistors operated in the saturation region are shown in Figs. 5 and 6, respectively. As one can see, the drain current in the saturation region increases with irradiation dose at all gate voltages. In contrast to the linear region, the drain current curves in saturation seem to be simply shifted toward the higher values as the gate voltage is increased.

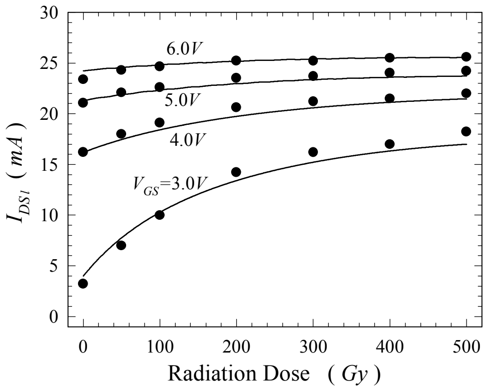

Fig. 3. Dependence of drain current on absorbed dose of γ-irradiation in VDMOS transistors EFL1N10 - linear region, V_{DS} = 50 mV. Symbols denote measured values

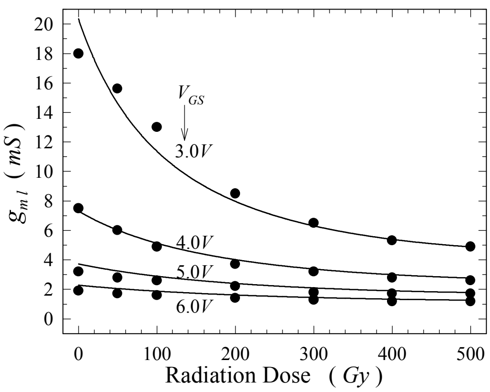

Fig. 4. Dependence of transconductance on absorbed dose of γ-irradiation in VDMOS transistors EFL1N10 - linear region, V_{DS} = 50 mV. Symbols denote measured values

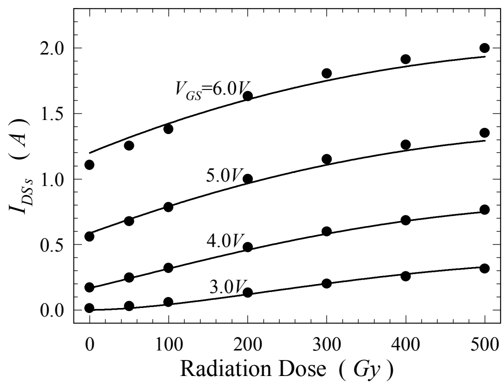

Fig. 5. Dependence of drain current on absorbed dose of γ-irradiation in VDMOS transistors EFL1N10 - saturation region, V_{DS} = 5 V. Symbols denote measured values

In comparison to the linear region, the behaviour of transconductance in saturation is quite the reverse: as shown in Fig. 6, transconductance in the saturation region increases with increase of both the irradiation dose and gate voltage.

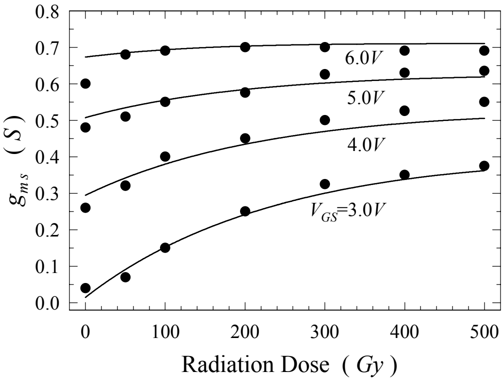

Fig. 6. Dependence of transconductance on absorbed dose of γ-irradiation in VDMOS transistors EFL1N10 - saturation region, V_{DS} =5 V. Symbols denote measured values

Taking into account given theoretical model, the observed behaviour of drain current and transconductance in both regions of device operation can be ascribed to the simultaneous effects of threshold voltage decrease and mobility lowering with the increase of gate oxide charge density caused by γ-irradiation. Because of the threshold voltage decrease, it is quite obvious from Eqs. (5) and (6) that drain current should increase with gate oxide charge density in both linear and, especially, in the saturation region of device operation. In the linear region, however, the mobility at high gate voltages is reduced further owing to the additional effect of high vertical electric field. The effect of threshold voltage decrease is thus cancelled, and drain current almost does not change with the increase of gate oxide charge density, i.e. irradiation dose. In accordance with Eq. (6), this does not happen to drain current in the saturation region since in that region of device operation the drain current is more considerably dependent on threshold voltage. As for transconductance, our results show that at high gate voltages the simultaneous influences of mutually opposite threshold voltage decrease and mobility degradation effects almost completely cancel each other not only in the linear but also in the saturation region. Consequently, the transconductance is almost independent of irradiation dose at high gate voltages in both regions of device operation.

The proposed model, though rather simple, yielded a reasonable agreement with measured values of drain current and transconductance for gate bias in the range between 3 and 6 V. It should be noted, however, that the model already at $V_{GS} = 7$ V overestimated the values of both drain current and transconductance, especially in saturation region. It is not likely that much lower measured than model-predicted values of drain current were obtained owing to measurement errors or poor ratings of the devices used. It is more certain that these discrepancies at higher gate voltages are associated with the drawbacks of the model itself and parameter-extraction method as well [12] - [14]. Special attention must be paid to the determination of the proper values of parameters θ and δ in order to achieve an acceptable compromise between the accuracy and simplicity of the model. Better accuracy can be achieved by including some additional effects (such as the effect of the lateral field on carrier mobility), while the final fitting to experimental data may be done by using an optimization technique with the extracted parameter values treated as an initial guess [3]. After all, it was not our intention to propose using the analytical modelling instead of sophisticated numerical device simulators, but we believe that the presented simple model may be convenient and easy-to-use tool for getting the first insight into the effects of γ-irradiation on electrical characteristics of VDMOS devices.

CONCLUSION

This paper analyzed γ-irradiation effects on drain current and transconductance of VDMOS transistors EFL1N10. An appropriate analytical model, based on the parameter extraction, was developed. The empirical relation between the absorbed dose of γ-irradiation and the corresponding effective density of gate oxide charge in investigated devices was established, and electrical characteristics were modelled as the functions of absorbed dose. It was found that drain current in both linear and saturation regions increased with radiation dose. On the other hand, transconductance in the linear region decreased, while in the saturation region it increased with the increase of gate oxide charge density caused by radiation effects. A reasonable agreement of the results of modelling with experimental data for the drain current and transconductance in both linear and saturation regions was achieved in spite of model simplicity.

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UTICAJ EFEKATA γ-ZRAČENJA NA ELEKTRIČNE KARAKTERISTIKE VDMOS TRANSISTORA SNAGE

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U ovom radu prikazani su rezultati eksperimentalnih istraživanja i analitički model uticaja efekata γ-zračenja na strujno-naponske karakteristike u linearnoj oblasti i oblasti zasićenja, kao i transkonduktansu VDMOS tranzistora snage. Najpre je razvijen analitički model zavisnosti struje drejna i transkonduktanse od gustine naelektrisanja u oksidu gejta. Eksperimentalni rezultai iskorišćeni su da bi se odredila analitička zavisnost izmedju apsorbovane doze γ-zračenja i gustine efektivnog naelektrisanja u oksidu gejta i izvršila ekstrakcija parametara koji su korišćeni u modelu. Zatim je izvršeno modeliranje struje drejna i transkonduktanse u funkcije doze γ-zračenja. Na kraju je izvršeno poredjenje modeliranih karakteristika sa eksperimentalnim rezultatima.