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On the influence of ionizing radiation on the electrical properties of short-channel MOS transistors

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Résumé. — L'influence d'un rayonnement ionisant sur la conductance de sortie d'un transistor MOS à canal court est examinée. Les dégradations subies sont dues à la création de nouveaux états de surface à l'interface $\text{SiO}_2\text{-Si}$ et non à une éventuelle modification de la vitesse limite des porteurs.

Abstract. — The effect of ionizing radiation on the output conductance of a short-channel MOS transistor is examined. It appears that these effects are predominantly caused by the increase of the surface state density and that no noticeable effect due to the change of the carriers' saturation velocity has been detected.

1. Introduction. — The degradation of the electrical properties of MOS transistors under ionizing radiation has been generally related to the creation of both, a radiation induced surface-state density at the Si-SiO_2 interface and a density of fixed positive charges within the gate field oxide [1]. These two physical effects make the mobility and the threshold voltage V_T of the transistor evolve under irradiation.

In the case of a short-channel MOS transistor, a supplementary degradation effect has been detected. Indeed, the customary negative conductance values appear to change into positive ones after irradiation in particular for large values of the drain current. Once the experimental results have been shown, the paper discusses the physical origin of the former phenomenon. Two possibilities are compared in detail; either a change in the carrier' saturation velocity [2] or the influence of the radiation-induced surface state density.

2. Preliminary considerations. — P. Rossel *et al.* [3] have shown recently that the output dc conductance of a short-channel MOS transistor can be expressed by :

$$G \equiv R_c[Y(\omega)]_{\omega=0} = G_D - k \cdot R_{th} I_D (I_D - I_c) \quad (1)$$

where $Y(\omega)$ is the transistor admittance when it is submitted to a signal of angular frequency ω ; G_D is the high frequency conductance, R_{th} the thermal resistance and I_D the drain current. The symbol I_c stands for the drain current value that makes the admittance imaginary part $\text{Im}[Y(\omega)]$ vanish and k is a coefficient such that :

$$\text{Im}[Y(\omega)]_{\max} = -\text{Im}[Z_{th}(\omega)]_{\max} k \cdot I_D (I_D - I_c) \quad (2)$$

where $Z_{th}(\omega)$ is the transistor's thermal impedance. Relationships (1) and (2) show that in order to study the output conductance G as a function of the radiation dose it is necessary to study experimentally the two quantities : G_D and $\text{Im}[Y(\omega)]_{\max}$.

3. Experimental results. — The studied devices are V-MOS transistors of channel length $L = 1.2 \mu\text{m}$ and gate oxide capacitance per unit channel length $ZC_{ox} = 8.4 \times 10^{-8} \text{ F cm}^{-1}$. The surface orientation of the channel is $\langle 111 \rangle$. The transistors have been irradiated with X-rays up to a dose of 10 krad.

The device's complex admittance diagram has been obtained by the method described in [3] and its shape before and after irradiation is represented in figure 1. This figure clearly shows that the irradiation brings

Fig. 1. — Experimental diagram for the complex admittance values before and after irradiation ; the curve parameter is the frequency value.

about a large degradation of the dc conductance value which changes from $G_1 = -1.26 \text{ mU}$ before irradiation to $G_2 = 1.37 \text{ mU}$ after irradiation. Moreover the high frequency conductance value changes from

$$G_{D1} = 1,88 \text{ mU} \quad \text{to} \quad G_{D2} = 2.67 \text{ mU} .$$

Figure 2 shows the variation of $\text{Im}[Y(\omega)]_{\text{max}}$ as a function of the drain current value I_D . These curves show the influence of irradiation on the critical current value I_c which changes from $I_{c1} = 620 \text{ mA}$ before irradiation to $I_{c2} = 830 \text{ mA}$ after irradiation.

Fig. 2. — Measured values of $\text{Im}[Y(\omega)]_{\text{max}}$ as a function of the drain current.

Figure 3 represents the variation of $\text{Im}[Y(\omega)]_{\text{max}}$ as a function of $I_D(I_D - I_c)$. It appears that the two straight lines, before and after irradiation are exactly the same which shows that k is a quantity which does not depend upon irradiation. The slope of the curves

$$\text{Im}[Y(\omega)]_{\text{max}} = f[I_D(I_D - I_c)]$$

is given by $\text{Im}[Z_{th}(\omega)]_{\text{max}} \cdot k$. It has been assumed that $\text{Im}[Z_{th}(\omega)]_{\text{max}}$ does not depend upon the irradiation dose which is supported by the fact that this quantity is only controlled by the bulk semiconductor properties.

Fig. 3. — Measured values of $\text{Im}[Y(\omega)]_{\text{max}}$ versus $I_D(I_D - I_c)$.

4. Discussion of the results. — The preceding results show that the influence of irradiation on the output conductance value G is mainly due to the variation of the critical current value I_c . Indeed the slight variation of G_D ($G_{D2} - G_{D1} = 0.79 \text{ mU}$) cannot account for the much larger variations of the conductance value ($G_2 - G_1 = 2.6 \text{ mU}$). In order to specify the physical origin of this influence the meaning of k and I_c will be recalled.

It was recently shown [4] that these two quantities stand for, respectively :

$$k = - \frac{\partial \ln(v_{\text{sat}})}{\partial T} \quad (3)$$

$$I_c = ZC_{\text{ox}} v_{\text{sat}}^2 \left(\frac{\partial V_T}{\partial T} \right) \cdot \left(\frac{\partial v_{\text{sat}}}{\partial T} \right)^{-1} \quad (4)$$

Fig. 4. — Measured value of the threshold voltage V_T versus temperature before and after irradiation.

Fig. 5. — Measured values of V_T and of the carriers' mobility μ_0 versus the irradiation dose.

where T is the silicon crystal temperature and v_{sat} the carriers' saturation velocity.

By taking into account the values of both $(\partial V_T / \partial T)$ (see Fig. 4) and I_c (see text) it appears that under irradiation the variation of v_{sat} deduced from (3) and (4) :

$$v_{\text{sat}} = \frac{k}{ZC_{\text{ox}}} I_c \left(\frac{\partial V_T}{\partial T} \right)^{-1} \quad (5)$$

is less than 6 %.

This small value is to be compared with the large variations of the mobility value ($\approx 27 \%$) represented in figure 5.

This result shows that the Si-SiO₂ interface properties do not affect the carrier saturation velocity. Indeed the large variation of both V_T and μ_0 under irradiation shown in figure 5 must be interpreted in terms of a degradation of the SiO₂-Si interfaces.

Fig. 6. — Measured variations of $\mu_0 E_0$ versus radiation dose — μ_{00} and E_{00} stand respectively for the values of μ_0 and E_0 before irradiation.

However this does not mean the commonly used relation :

$$v_{\text{sat}} \approx \mu_0 \cdot E_0 \quad (6)$$

where E_0 is the longitudinal critical electric field, is not valid after irradiation.

Indeed as it can be shown in figure 6 the quantity $\mu_0 E_0$ is practically constant with the radiation dose ⁽¹⁾ (the registered variations are about 10 % for 10 krad radiation dose).

In addition the preceding results show that the sensitivity to irradiation of the output conductance values is mainly due to the radiation induced variation

of $(\partial V_T / \partial T)$ and thereby only the electrostatic effect of the surface state density on V_T ⁽²⁾ is responsible for this sensitivity.

5. Conclusion. — It has been shown that the radiation-induced variation of the output conductance of a short channel MOS transistor is mainly due to the creation of a radiation-induced surface-state density at the Si-SiO₂ interface. It has also appeared that the saturation velocity value is not sensitive to radiation doses up to 10 krad.

⁽¹⁾ E_0 has been determined from the high drain voltage section of the drain current-gate voltage curve [5].

⁽²⁾ The variation of $\partial V_T / \partial T$ cannot be attributed to electric charges within the oxide but to the building of electric charges at the SiO₂-Si interface as a consequence of the creation of new surface states by irradiation.

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