Modeling of the Tunneling Current in MOS Devices After Proton Irradiation Using a Nonlinear Series Resistance Correction

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***Abstract*—Contrary to what is expected for a damaged device, the impact of 10 MeV-energy protons on a metal-oxide-semiconductor (MOS) structure can give rise to a significant reduction of the gate tunneling current, mainly in the high bias range. In order to simulate the observed deviation, a correction to the oxide field in the Fowler-Nordheim tunneling expression is considered. Since the nature and location of the device damaged region have not been clearly identified yet, the conduction problem is circumvented by introducing an effective nonlinear series resistance correction. Experimental and simulated data obtained as a function of the irradiation fluences supporting the proposed approach are presented. The possible origin of this nonlinear resistance and its implications for the reliability assessment of irradiated MOS devices are also discussed.**

***Index Terms*—Fowler-Nordheim, MOS, reliability, tunneling.**

I. Introduction

Degradation and breakdown of the gate oxide layer in MOS structures have received extensive attention in the past, mainly for devices subjected to electrical stress. However, because of the more demanding requirements in terms of safety and high-energy facilities, much less experimental work has been devoted to explore the consequences of particle irradiation on the leakage current characteristics of such structures [1]–[5]. The use of fundamental physics modeling to draw practical information for the design of radiation tolerant devices and circuits is a very challenging task since many experimental results are hardly repeatable often because of changes in the irradiation conditions or simply because of the time and costs involved [6] and [7]. As in the case of electrical stress, some of these practical limitations can be partially overcome by carrying out accelerated stress tests with dose rates far from those occurring in real environments like outer space. In this work, we have chosen to investigate the effect of 10 MeV proton irradiation on standard MOS capacitors with the aim of assessing oxide layer degradation when exposed to high-energy particles such as those found in the inner zone of the Earth's radiation belts [8].

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It is shown first that the initial leakage current in our devices is well represented by Fowler-Nordheim (FN) tunneling injection with parameter values in good agreement with those reported in literature [9]–[11]. However, as the degradation process caused by irradiation proceeds, the current significantly departs from that behavior, especially in the high bias range. One possible approach to deal with this deviation is to introduce a suitable correction to the oxide electric field in the FN expression. This is the standard procedure for simulating distortions in the oxide tunneling barrier caused by trapped charge or for incorporating into the conduction model radiation-induced defects in the semiconductor bulk. Since the current decreases gradually as a function of irradiation fluence and the shape of the current-voltage (I-V) characteristics are consistent in the intermediate bias range with the initial FN mechanism, we propose that the current reduction can be electrically modeled using an effective series resistance. This approach is motivated by two reasons: first, the role played by a series resistance on the tunneling current has been thoroughly investigated in the past [9]–[12] and second, because this mechanism has already been successfully invoked to model the FN current in proton irradiated devices [12]. A major difference with previous approaches is that the effect of irradiation in our devices cannot be simply accounted for by means of a constant resistance but requires a nonlinear correction. This leads to a relationship between the gate current and the applied voltage that in spite of its complexity can be analytically solved in terms of the Lambert W function [13], i.e., the solution of the transcendental equation $W\exp(W) = x$.

Although the physical link between the device degradation at microscopic level and its electrical equivalence is still unsolved, the proposed model provides a simple way to describe the effects of proton irradiation on MOS structures. It is worth pointing out that an accurate determination of the leakage current modification in tunnel oxides during or after irradiation and the corresponding oxide voltage drop is essential for any lifetime projection of MOS transistors aimed to operate in such extreme conditions [12], [14], and [15].

II. Sample Details and Irradiation Conditions

In this study, the post-irradiation conduction characteristics for a set of MOS tunneling capacitors with poly-Si gate and 11.6 nm-thick SiO_2 layers grown on p-type Si ($N_A = 1 \times 10^{16}$ cm^{-3}) were investigated. The areas of the devices are $S = 2 \times 10^{-5}$ and 8×10^{-5} cm^2. The proton irradiation was carried out at the TANDAR accelerator from the Comisión Nacional de Energía Atómica (CNEA) with a broad uniform (78 cm^2)

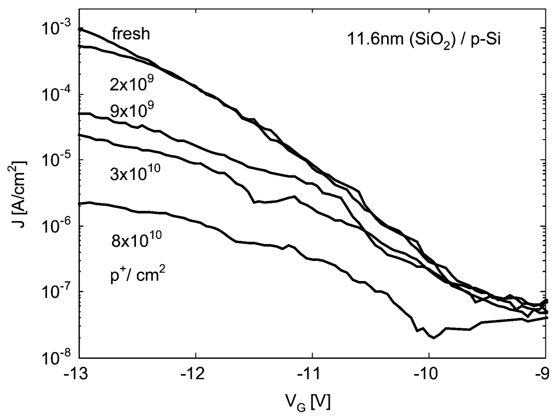

Fig. 1. Experimental J-V curves for the fresh and irradiated capacitors with 10 MeV protons and fluencies of 2×10^9, 9×10^9, 3×10^{10} and 8×10^{10} $\mathrm{protons/cm^2}$.

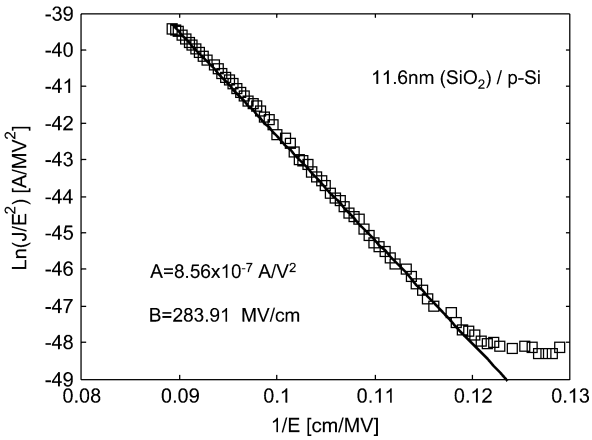

Fig. 2. Typical Fowler-Nordheim plot for the fresh samples used in this study. J is the current density and E the oxide field. The solid line is the fitting to the linear region of the experimental curve.

proton beam of 10 MeV $(\mathrm{LET} = 0.035\ \mathrm{MeVcm^{-2}/mg})$. Small dies of 1 $\mathrm{cm^2}$ were mounted perpendicular to the proton beam inside a vacuum chamber (10^{-6} Torr). The samples were exposed to proton fluences of 2×10^9, 9×10^9, 3×10^{10} and 8×10^{10} $\mathrm{p^+/cm^2}$. The device terminals were left floating during irradiation. The samples were tested using I-V (with a ramp rate of 0.25 V/s at the highest bias) and constant voltages stress (CVS @ -18 V) measurements. Electrical data was collected using a Keithley 4200 Semiconductor Device Analyzer. All measurements were performed at room temperature and dark conditions. The time elapsed between the end of the irradiation and the beginning of the characterization phase was five days.

III. Experimental Results and Model Equations

Fig. 1 shows the effects of high-energy protons irradiation on the J-V characteristics of different MOS structures for increasing irradiation fluences. It is observed that the J-V characteristics change as the accumulated damage increases. Because of the large oxide thickness ($t_{ox} = 11.6$ nm) and the noise background level of our experimental setup, the gate current can only be detected for voltages larger than approximately 9 V or equivalently for electric fields above 7 MV/cm.

In order to investigate the origin of the observed current decrease, initially detected at the largest biases and subsequently, all along the J-V curve, we start by analyzing the leakage current behavior in the fresh device. According to the FN tunneling model, the current density $J = I/S$ that flows through a thin dielectric layer when an electric field $E = V_{ox}/t_{ox}$ is applied across it, is given by the expression:

$$J(E) = AE^2 \exp\left[-\frac{B}{E}\right] \quad (1)$$

where $A = mq^3/8\pi h m^* \phi$ and $B = 8\pi\sqrt{2m^*}\phi^{3/2}/3hq$. m is the free electron mass, m^* the effective electron mass in the insulator, q the electron charge, h the Planck's constant, ϕ the cathode barrier height and V_{ox} the oxide voltage. For the sake of simplicity, we will initially consider $V_{ox} = V_G$, where V_G is the voltage applied to the gate, so that the potential drop in the semiconductor and the work function difference are neglected in (1). Although the flatband voltage was only measured for the fresh device ($\mathrm{V_{FB}} = -0.9$ V), any possible variation of this parameter is absorbed by the function f defined below. Fig. 2 shows a typical FN plot for the fresh devices used in this study. From the linear fitting, $A = 8.56 \times 10^{-7}\ \mathrm{A/V^2}$ and $B = 283.91\ \mathrm{MV/cm}$ are obtained, which yield $m^* = 0.58$ m and $\phi = 3.1$ eV. Since these values are in close agreement with the ones reported in literature [9] and [10], this preliminary analysis confirms that the conduction mechanism in the fresh device is FN tunneling.

From Fig. 1, it is clear that the J-V curves progressively depart from the initial FN regime as the degradation process caused by irradiation proceeds. However, note that whereas in the bias range from -9.5 to -10.5 V the curves are similar to the initial FN mechanism, at higher voltages the current remarkably decreases with the irradiation fluence. To deal with this deviation a correction to the gate oxide field is introduced in the FN expression (1) in the form of a potential drop across a nonlinear series resistance. As a first step, it will be assumed that the current that flows through this radiation-induced resistance is represented by the general expression $J = f(V_R)$, where f is at the moment an unknown function and V_R the voltage applied across its terminals. We are implicitly assuming that the damage is uniform over the device area, but this may not be the case as occurs for single impact events. Next, the voltage drop across the oxide layer in the MOS capacitor can be rewritten as $V_{OX} = V_G - V_R = V_G - f^{-1}(J)$, where $f^{-1}(J)$ is the inverse of function f. Inserting the new V_{ox} definition into (1), it is obtained:

$$J(V_G) = A\left(\frac{V_G - f^{-1}(J)}{t_{ox}}\right)^2 \exp\left[-\frac{Bt_{ox}}{V_G - f^{-1}(J)}\right]. \quad (2)$$

In principle, from (2) it is possible to investigate different expressions for the unknown function f. In the case of a simple linear resistor R, $f^{-1}(J) = SRJ$ [9] and [10]. Fortunately, regardless of its specific form, f^{-1} can be analytically solved as a function of J and V_G using the Lambert W function (see the Appendix):

$$f^{-1}(J) = V_G - \frac{1}{2}\frac{Bt_{OX}}{W\left[\frac{1}{2}\left(\frac{AB^2}{J}\right)^{1/2}\right]}. \quad (3)$$

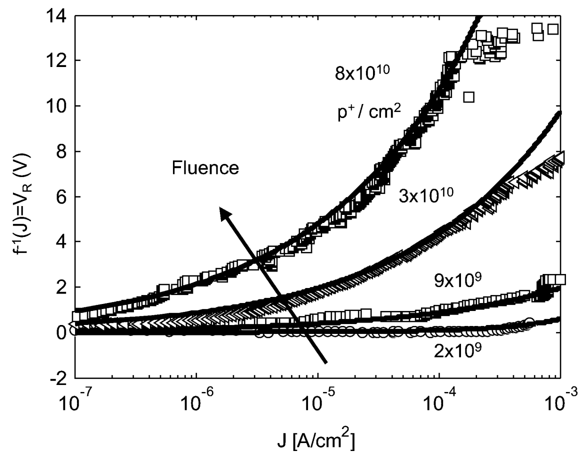

Fig. 3. Voltage drop in the series resistance as function of current density for irradiated capacitors. The symbols are experimental data obtained with (3) and the solid lines correspond to fitting results using (4).

This latter expression allows one to compute $f^{-1}(J)$ given the experimental value of J at each V_G. In what follows, it will be assumed that the parameters A and B in (2) remain unchanged throughout the irradiation process. This consideration is supported by the experimental observation that the leakage current density is almost insensitive to the irradiation conditions at the onset of the FN regime (at least for fluences $< 10^{10}\mathrm{p}^+/\mathrm{cm}^2$). Similar behavior for the low field FN current has been reported in [12]. Fig. 3 shows the radiation-induced voltage drop $f^{-1}(J)$ calculated from the experimental data shown in Fig. 1 using (3). The figure shows that $f^{-1}(J)$ not only increases by increasing J but also with the radiation fluence. To go a step farther and using the notation of [16], we propose that the oxide field correction can be explicitly expressed as:

$$f^{-1}(J) = \sigma J + A_0 J^{1/n} \tag{4}$$

where σ and A_0 are constants and n is a power factor associated with the nonlinear contribution $(n > 1)$. This particular dependence for the series resistance correction has been considered in a number of semiconductor systems including non-ideal diodes and junctions [16]. For instance $n = 2$ and $n = 4$ correspond to an ideal Schottky barrier diode at high forward voltages and to carrier recombination in the intrinsic layer of *p-i-n* diodes, respectively. Fig. 3 shows the fitting of (4) (solid lines) to the experimental curves (symbols). As previously reported in [12], for low irradiation fluences the main contribution to the series resistance effect comes from the linear term in (4), whereas here, it is shown that the nonlinear term dominates for higher fluences. As shown in Table I, typical values of σ for low fluences ($\leq 10^9\ \mathrm{p}^+/\mathrm{cm}^2$) range from 500 to 2200 $\Omega\mathrm{cm}^2$. In addition, A_0 shows a strong dependence on the accumulated damage with values ranging from 1 to 270 V/A$^{1/n}$ (see Fig. 4). Interestingly, a constant power factor $n = 2.85$ provides good fitting results for all the curves. In order to achieve deeper insight into the role of the linear and nonlinear corrections in (4), it is relevant to analyze the voltage drop associated with each term. Fig. 5 shows the voltage drop across the oxide V_{ox} as a function of the applied bias V_G for four particular cases. As it is observed, a linear correction term (curve with $\sigma = 500\ \Omega\mathrm{cm}^2$, $A_0 = 0$) is only suitable for small voltage corrections but that an arbitrary increment of σ (curve with $\sigma = 9\times10^4\ \Omega\mathrm{cm}^2$, $A_0 = 0$) leads to a reduction of V_{ox} incompatible with the $V_{ox} - V_G$ dependence exhibited by the experimental data (both linear and nonlinear correction terms).

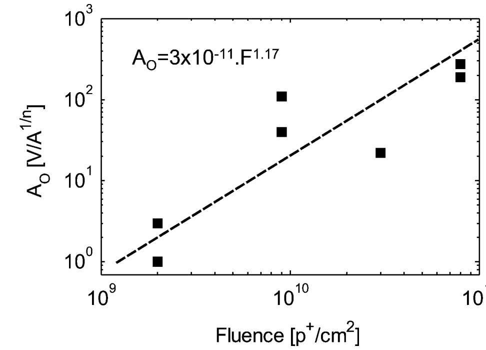

Fig. 4. Evolution of the nonlinear correction parameter A_0 as a function of the accumulated fluence. The inset shows the equation corresponding to the linear regression.

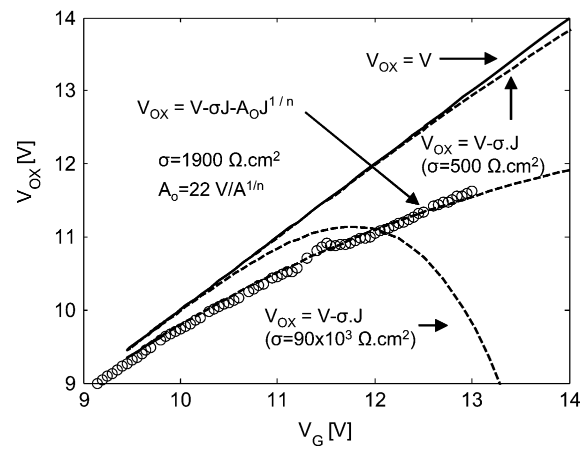

Fig. 5. Oxide voltage (V_{ox}) as a function of the applied voltage (V_G) for different models of the potential drop in the series resistance. The symbols are experimental data corresponding to the fluence $9 \times 10^9\ \mathrm{p}^+/\mathrm{cm}^2$. In all cases $n = 2.85$ was considered.

TABLE I
FITTING PARAMETERS FOR THE NONLINEAR SERIES RESISTANCE CORRECTION.

Fluence [p^+/cm^2]	*σ [$\Omega.cm^2$]*	*A_o [$V/A^{1/n}$]*	*n*
$2x10^9$	*500*	*1*	*2.85*
$9x10^9$	*1900*	*22*	*2.85*
$3x10^{10}$	*1900*	*110*	*2.85*
$8x10^{10}$	*2200*	*270*	*2.85*

Now, based on expressions (3) and (4), it is possible to obtain the theoretical V-J characteristic using the relationship:

$$V_G = \frac{1}{2}\frac{Bt_{OX}}{W\left[\frac{1}{2}\left(\frac{AB^2}{J}\right)^{1/2}\right]} + \sigma J + A_O J^{1/n} \tag{5}$$

which expresses the applied voltage as the sum of the oxide and the series resistance voltage drops. Notice that (5) is no longer an implicit equation. To compare with the experimental results, a simple exchange of the J and V axes is needed. Experimental

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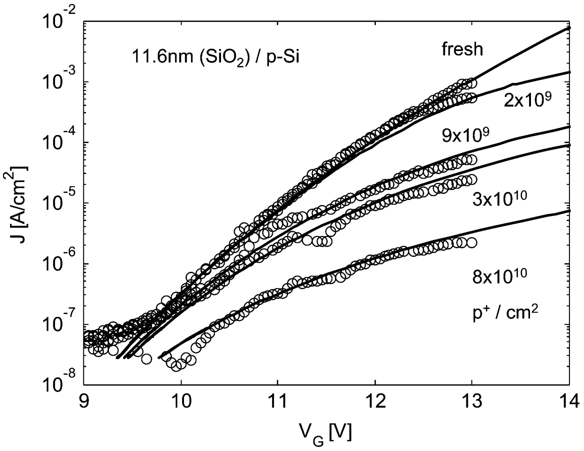

Fig. 6. Experimental (symbols) and model (solid lines) I-V curves for the fresh and irradiated capacitors with 10 MeV protons and fluencies of $2\times10^9, 9\times10^9$, 3×10^{10} and 8×10^{10} $\mathrm{protons/cm^2}$.

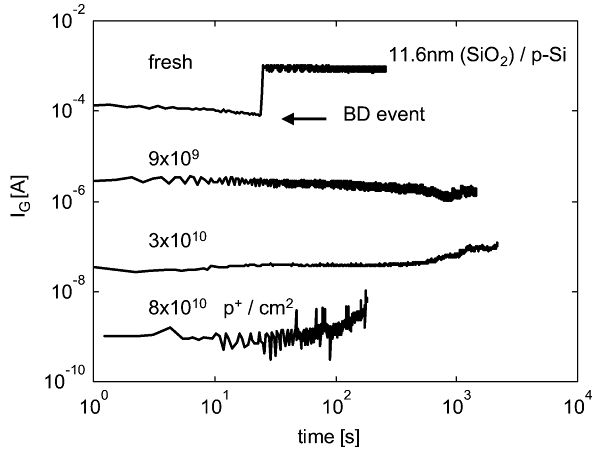

Fig. 7. Gate current as a function of the stress time during a CVS measurement in accumulation conditions at -18 V. The curves correspond to different irradiation fluences. The jump in the upper curve is a breakdown event.

and simulated curves obtained with (5) using the Padé approximation for W described in the Appendix are illustrated in Fig. 6. Notice that the agreement is very good for the voltage range investigated.

IV. Discussion

Several physical mechanisms have been proposed to explain the degradation of the tunneling current observed in MOS structures after electrical or particle irradiation stress [17]. Even though there is wide consensus that both stress types generate defects, in the case of proton irradiation, the physical location of the damaged region is a question that has not been totally clarified yet. It has been claimed that for 10 MeV proton irradiated 0.18 μm-technology MOS transistors the most affected region of the devices are the spacer oxides and not the gate oxide itself [18]. However, there is strong evidence, such as the RILC (radiation-induced leakage current) mechanism in thin oxides ($t_{ox} < 10$ nm), that the gate dielectric is indeed severely affected by the impact of protons as well [1] and [2]. The energy and fluence of the protons and the thickness of the oxide layer seem to play a role in the final results. For example, 60 MeV-proton irradiation on ultrathin (1.4 nm) oxides resulted in much more dramatic changes than in our case since only oxide breakdown events were observed [19]. On the contrary, it has been reported that 24 GeV-proton irradiation on 2.5 nm-thick oxynitride layers is not totally destructive yielding gate current increases proportional to the proton fluence [20]. In that paper, the changes in the MOSFET characteristics were attributed to positive charge buildup in the spacers and to defects in the gate oxide. At variance with these reports, other authors locate the damaged region outside the gate insulator region and more specifically at the back contact of the structure [12] or in the semiconductor substrate [21]. In this latter case, the substrate resistivity increase is attributed to the reduction in carrier concentration due to majority-carrier trapping in the radiation-induced defects. This is closely related to the proton-induced displacement damage in semiconductors which has been identified as the cause of the device parasitic resistance increase [6], [7], [22] and [23]. In this connection, it is worth mentioning that proton irradiation has been used as a technique to suppress latchup in CMOS integrated circuits [23]. A series resistance increase from 25 Ω to 7.2 MΩ has also been reported to occur in Schottky diodes after proton exposure [24]. These irradiation effects are very appealing from the simulation viewpoint since they naturally lead to the appearance of a series resistance correction for the tunneling current.

Another possible explanation for the current deviation at high fields but that needs to be further investigated is that negative charge trapping in the radiation-induced defects can modify the tunneling barrier profile [25] or alternatively diminish the cathode electric field [26]. This in turn would lead to a higher tunneling resistance. Our experimental results indicate that fixed negative trapped charge in the oxide layer can be neglected since no parallel shift of the I-V characteristic is detected after irradiation (we have used the same A and B for all the curves). In this case, the series resistance effect should be likely regarded as a kind of feedback mechanism whose main action is to reduce the oxide voltage as the injected charge rate increases. Future work will involve a thorough analysis of the capacitance-voltage (C-V) characteristics of our devices in order to provide further information about the location of the device damaged region and the trapping dynamics in the radiation-induced defects.

For gate oxide reliability projections in rad-hard applications, it is often relevant to predict the evolution of the gate current density for one or several stress conditions as a function of the irradiation fluence. Fig. 7 shows typical results for CVS experiments performed in accumulation at -18 V on the already irradiated devices. In agreement with the behavior exhibited by the J-V curves shown in Fig. 1, a current decrease in several orders of magnitude for larger irradiation fluences is observed again. Notice that within the experimental time window, a breakdown event was only detected in the case of the non-irradiated device. This is clearly a consequence of the reduction of the oxide field and the appearance of an effective series resistance in the leakage current path. Although this behavior seems to indicate that the oxide layer was not severely damaged during irradiation it must be taken into account for reliability projections that the

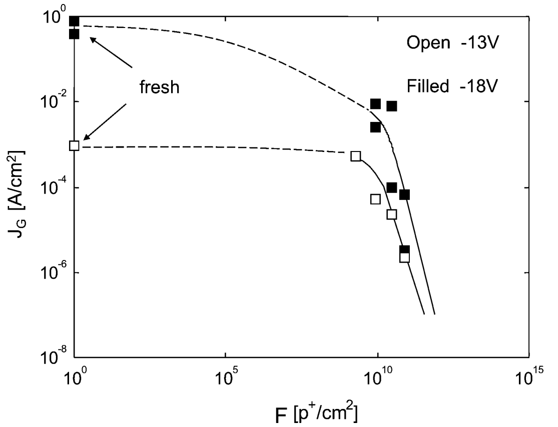

Fig. 8. Experimental (symbols) and model (solid line) gate current densities at −18 V and −13 V as a function of the irradiation fluence. The dashed lines are guides to the eye.

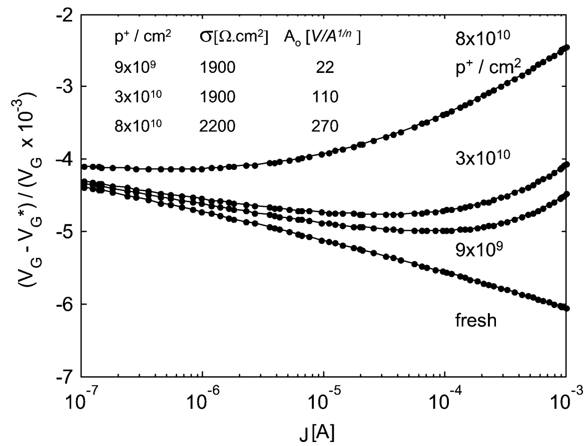

Fig. 9. Relative error of the calculated gate voltage as a function of the current density J for different fluences. The voltage V_G is calculated using the Lambert W function implemented in MATLAB, whereas V_G^* is computed using the approximate expression W^* (8) described in the Appendix.

oxide field at a given applied voltage is no longer constant as a function of the proton fluence. According to our model, a gate voltage $V_G = 13$ V corresponds to $V_{ox} = 12.6$, 11.7, 11.0 and 10.1 V for the four irradiation fluences reported in Table I.

Finally, it is possible to obtain a relationship between the current density and the particle fluence at a given gate voltage. This can be achieved neglecting the linear term in (3) so that $f^{-1}(J) \approx A_0(F)J^{1/n}$ and considering the dependence of J on F reported in Fig. 4. This relationship is illustrated by the solid lines in Fig. 8 for a CVS ($V_G = -18$ V) experiment and for data extracted from the J-V characteristics in Fig. 1 ($V_G = -13$ V). An acceptable agreement between the proposed model and the measurements is obtained. Again, this representation reflects the fact that the leakage current reduces with the irradiation fluence.

V. Conclusion

The effects of 10 MeV protons irradiation on the tunneling current of MOS capacitors with 11.6 nm-thick SiO_2 layers were investigated. It was observed that at high biases the current in the irradiated devices significantly decreases, whereas in the intermediate bias range the current does not change too much with respect to the initial FN current. Based on this observation, a simple model for the FN tunneling mechanism in the damaged devices in which the oxide field is modified by a nonlinear series resistance correction was proposed. This correction leads to a reduction of the oxide voltage, which in turn reduces the magnitude of the leakage current flowing through the device. This feedback mechanism can have important consequences for the long-term reliability analysis of irradiated devices since it strongly affects the oxide voltage drop.

Appendix

The Lambert W-function is the solution of the equation:

$$W(x)e^{W(x)} = x \tag{6}$$

and has the Taylor series expansion:

$$W(x) = \sum_{n=1}^{\infty} \frac{(-1)^{n-1} n^{n-2}}{(n-1)!} x^n = x - x^2 + \frac{3}{2}x^3 - \frac{8}{3}x^4 + \frac{125}{24}x^5 - \frac{54}{5}x^6 + \cdots. \tag{7}$$

Unfortunately (7) oscillates between ever larger positive and negative values for real $x \geq 4$ so it cannot be used for practical numerical computation. For $x \geq 0$, (7) can be approximated by the Padé approximation [27]:

$$W^*(x) \approx \ln(1+x)\left\{1 - \frac{\ln[1+\ln(1+x)]}{2+\ln(1+x)}\right\}. \tag{8}$$

This expression was used for the computation of the Lambert W function throughout this work. $W^*(x)$ approximates W(x) for real $x > 0$ with a relative error less than 10^{-2} [27].

To conclude this Section, Fig. 9 shows the relative error of the gate voltage drop calculated using the built-in Lambert function W from MATLAB and the Padé approximation W^* (8). It can be observed that the relative variation is small for all irradiated samples. Moreover, except for the fresh sample, the error decreases for the largest currents and highest irradiation fluences. This is a consequence of the particular dependence of V_G on J expressed by (5). The Lambert W function is numerically implemented in MATLAB with approximations from series expansions followed by root-finding. Halley's method and a fourth-order extension of Newton's root-finding method are used for computation [28]. Convergence is very fast, usually requiring fewer than five iterations to reach machine accuracy.

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