**Impact of Radiation-Induced Back-Channel Leakage and
Back-Gate Bias on Drain Current Transients of
Thin-Gate-Oxide Partially Depleted Silicon-On-Insulator
n-channel Metal-Oxide-Semiconductor Field-Effect Transistors**

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In this study, we analyze the impact of back-channel radiation-induced leakage and back-gate bias on switch-off drain current transients of thin-gate-oxide partially depleted (PD) silicon-on-insulator (SOI) n-channel metal-oxide-semiconductor field-effect transistors (MOSFETs). The presence of radiation-induced positive trapped charges in the buried oxide after 60 MeV proton irradiation is found to reduce the “switch-off” transient times for gate voltages above and below the front-gate threshold voltage for body-to-gate electron valence band tunnelling. An increase in steady-state drain current and an increase in the amplitude of weak inversion drain current transients are observed. A similar effect is observed when applying a positive bias to the back-gate, which is found to generate an “irradiation-like” subthreshold leakage. The observed switch-off drain current transient behavior is explained by taking into account an edge parasitic back-channel transient component, which is added to the conventional front-gate drain current transient.

KEYWORDS: buried oxide, drain current transients, floating-body effects, generation lifetime, proton irradiation, radiation effects, recombination lifetime, silicon-on-insulator (SOI) MOSFETs.

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1. Introduction

Silicon-on-insulator (SOI) metal-oxide-semiconductor field-effect transistors (MOSFETs) have several intrinsic potential advantages over their bulk Si counterparts as components to be operated in radiation harsh environments.^{1,2)} In particular, the thin semiconductor film provides better resistance against transient ionization effects such as single-event upsets or latch-up.³⁾ However, the thick SOI buried oxide introduces an additional constraint due to total ionizing dose charge trapping.³⁾ Moreover, owing to device integration requirements and intrinsic resistance constraints, no film contacts are generally provided in advanced SOI technologies. If body contacts are not present, so-called floating body effects (FBEs) arise, particularly in partially depleted (PD) SOI MOSFETs, leading to some detrimental effects on device performance.^{4,5)}

As a consequence of FB operation, after switching “on” or “off” the front gate, there is no substrate current to quickly adjust the majority carrier density and equilibrium has to be reached through generation and recombination processes. Since early times, it is known that drain current (I_D) transients are observed under these conditions⁶⁾ and their potential impact on circuit performance has been a matter of concern.⁷⁾ Originating from generation and recombination processes, I_D transients can also be a valuable tool for assessing the quality of the starting material, process-induced defects or contamination. Different techniques have been proposed for PD or fully depleted (FD) SOI MOSFETs to extract the generation or recombination lifetimes from “switch-off” or “switch-on” I_D transients, respectively.⁸⁻¹⁴⁾

Recently, with the marked decrease in front-gate-oxide thickness (t_{fox}), a new type of FBE associated with gate-body direct tunnelling has been identified in linear operation [low drain voltage (V_D)] of SOI n- and p-channel MOSFETs. This new type of FBE has a similar

influence on device and circuit operation as the classical impact-ionization-related “kink” effect. The main difference is that for thin gate oxides (t_{fox} as thin as 2-2.5 nm), electron valence band (EVB) tunnelling, occurring for a sufficiently large front-gate voltage (V_{FG})¹⁵⁾ supplies the necessary majority carriers to charge the film and forward-bias the source-body junction, inducing a “kink” in the linear $I_{\text{D}}-V_{\text{FG}}$ characteristics and a second peak in the derived transconductance.^{16,17)} Associated with this effect, an increase in low-frequency noise^{18,19)} and a change in I_{D} transient shape^{16,17,20)} have also been reported. The presence of these gate-induced FBEs (GIFBEs),¹⁶⁾ leading to history and memory effects, could be a limitation for PD SOI CMOS circuit operation.²¹⁾

Although the continuous miniaturization process has implicitly led to radiation-resistant front-gate oxides, with a thickness below the trapped-hole tunnelling limit, since the early times, there has been concern regarding total ionizing dose charge trapping in the buried oxides.^{22,23)} Studies have been carried out on SOI devices with a wide range of substrate qualities²⁴⁾ and, in a number of cases, a significant impact of buried oxide trapped charges on device front characteristics has been pointed out.^{22,25)}

The increase in gate coupling associated with the decrease in semiconductor film thickness is expected to make SOI MOSFETs more sensitive to buried oxide charge trapping.²⁶⁾ In this way, while an increase in leakage current in the subthreshold region is reported for PD SOI nMOSFETs,³⁾ which is normally associated with parasitic edge conduction in the case of LOCOS (local oxidation of silicon)-isolated devices,^{25,27-29)} a decrease in top-gate threshold voltage, due to gate coupling, is observed in fully depleted (FD) nMOSFETs.^{3,30)}

In this study, we analyze the impact of back-channel radiation-induced leakage and back-gate bias on the switch-off drain current transients of thin-gate-oxide PD SOI nMOSFETs. The presence of radiation-induced positive trapped charges in the buried oxide after 60 MeV proton irradiation is found to decrease the switch-off transient times for front-gate voltages above and below the front-gate threshold voltage for body-to-gate EVB tunnelling. An increase in steady-state drain current level and an increase in the amplitude of the weak inversion drain current transients are observed. A similar effect is obtained when applying a positive bias to the back-gate, which is found to generate an “irradiation-like” subthreshold leakage. The observed switch-off drain current transients behavior is explained by taking into account an edge parasitic back-channel transient component, which is added to the conventional front-gate drain current transient.

2. Devices and Experimental Procedure

The PD SOI MOSFETs used in this study were fabricated in a 0.1 μm CMOS process using a PELOX (polysilicon-encapsulated LOCOS) isolation scheme, a 2.5 nm (t_{fox}) nitrided gate oxide (NO), a 150 nm polysilicon gate and 80 nm nitride spacers. Processing was performed on 200-mm-diameter Unibond wafers, resulting in a final film thickness (t_{si}) of 100 nm. The buried oxide thickness (t_{box}) was 400 nm. The devices received halo implantation, in order to control the short-channel effects.

The studied MOSFETs have a common gate and source configuration with separate drain pads. There is no film contact. N- and p-channel transistors with polysilicon gate lengths (L) and widths (W) ranging from 0.08 to 10 μm and 0.2 to 10 μm , respectively, were studied.

However, in order to avoid short and narrow device geometry effects on I_D transients^{16,17}, only results from long ($L = 10 \text{ }\mu\text{m}$) and wide ($W = 10 \text{ }\mu\text{m}$) transistors are reported here. Moreover, the results shown in this study focus on the n-channel devices, which showed radiation-induced degradation after 60 MeV proton exposure.

In order to enable biased irradiation, the chips were mounted in 24-pin dual-in-line packages and were subjected to two consecutive (40 days in between) 60 MeV proton irradiations at the Cyclone cyclotron facility (Louvain-la-Neuve, Belgium), each one up to a fluence of 10^{11} protons/cm², which corresponds to a dose of approximately 13.5 krd(Si), suitable for space applications such as radiation-hardness assessment.³¹ In addition, unbiased irradiations on diced chips were also performed, yielding qualitatively similar results.^{32,33}

During the irradiation, the gates of all the mounted transistors (nMOSFETs and pMOSFETs) were biased at a positive bias corresponding to the power supply voltage for this technology (+1.5 V), while all the other terminals were grounded.

All current-voltage measurements and drain current transients were measured using an HP-4156 Parameter Analyzer. During a conventional weak inversion single-gate “switch-off” experiment, the front gate was switched at $t = 0 \text{ s}$ from an ‘on’ gate bias ($V_{FG \text{ on}}$) above the front-gate threshold voltage (V_{Tf}) to an ‘off’ gate bias ($V_{FG \text{ off}}$) in the subthreshold regime. Care was taken with the duration of the ‘on’ bias level, as well as for the conditions between the two transient measurements, so that there were no device history (memory) effects. Unless, the contrary is indicated, the drain bias was kept in the linear operating regime ($|V_D| = 25 \text{ mV}$) for all measurements. All experiments were carried out in a controlled-temperature room with a lightproof and electrically shielded setup.

3. Experimental Results and Discussion

3.1 Radiation-induced back-channel leakage and V_{BG} effect on I_D - V_{FG} characteristics

Figure 1(a) shows typical I_D and transconductance (g_m) vs front-gate voltage (V_{FG}) characteristics measured at two different back-gate biases ($V_{BG}= 0$ V and -20 V) for a PD SOI nMOSFET subjected to $2 \cdot 10^{11}$ protons/cm² irradiation.³²⁾ In the same figure, characteristics corresponding to a nonirradiated nMOSFET measured at different V_{BG} values ranging from -20 to 20 V are also shown. A clear increase in subthreshold leakage current is observed after irradiation of the nMOSFETs measured at $V_{BG}= 0$ V. Moreover, this radiation-induced I_D subthreshold leakage has been found to decrease when applying a negative V_{BG} . In this way, the characteristics of irradiated devices with sufficiently negative V_{BG} are found to fit with those before irradiation [Fig. 1(a)].

Furthermore, as shown in Fig. 1(a), the application of a positive bias to the back gate has been found to result in the generation of “irradiation-like” subthreshold conduction. In this way, there is a strong similarity between the I_D - V_{FG} characteristics of irradiated nMOSFETs measured at $V_{BG}= 0$ V and the characteristics measured on nonirradiated transistors at a sufficiently positive V_{BG} . In contrast, only a small radiation-induced degradation has been occasionally observed in the GIDL (gate-induced drain leakage)³⁴⁾ region for p-channel MOSFETs [Fig. 1(b)].

An important feature of the characteristics of these thin-gate-oxide PD SOI MOSFETs is the occurrence of a second peak in the transconductance for a $|V_{FG}|$ of approximately 1.2 V [Fig. 1 (a) and (b)]. This second g_m peak is due to the injection of majority carriers in the floating body by EVB tunnelling,^{16,17)} which is quite analogous to the classical impact-

ionization-related kink effect. The main difference is that the excess majority carriers are introduced into the film by gate-body direct tunnelling when V_{FG} surpasses the threshold voltage for EVB tunnelling. Consequently, it is observed for small drain biases (V_D) and is, therefore, present in the ohmic operation regime.

Neither the radiation-induced back-channel parasitic conduction nor the leakage obtained by applying a positive V_{BG} have been found to affect the portion of the characteristics above the front-gate threshold voltage and, in particular, the magnitude or the position of the EVB-induced second peak of g_m .³²⁾

By measuring the back-gate characteristics (I_D - V_{BG}), the observed degradation has been found to be associated with a positive back-gate threshold voltage shift ($\Delta V_{Tb} \approx 14$ V, Fig 1(a)) caused by radiation-induced hole trapping in the thick buried oxide. The effective density of trapped holes [$N_{otb} \approx \Delta V_{Tb} / (\epsilon_{ox} / t_{box})$] has been estimated to be approximately $7.5 \cdot 10^{11}$ charges/cm² for devices biased during the irradiation, whereas this has been found to be approximately three times smaller in the case of devices not biased during the irradiation.³²⁾ Evidently, no such effect is expected for the pMOSFETs, in which the back channel becomes more accumulated upon positive charging of the buried oxide, which on the other hand may be responsible for the occasionally small current increase in the pMOSFETs GIDL region [Fig. 1(b)].

In order to distinguish between parasitic conduction due to the inversion of the back channel or that mainly concentrated along the edges between the buried oxide and the PELOX field isolation,^{5,29)} the I_D subthreshold leakage dependence on gate width was investigated. The results showed no dependence on W of the subthreshold leakage current up to values of

approximately $V_{BG} = 80$ V, where the switch-on of an additional back-channel conduction path was noted. This additional conduction at very high V_{BG} is found to be dependent on W and is attributed to the creation of the inversion back-channel layer. In this way, the conduction observed for V_{BG} voltages up to approximately 80 V, which is independent of W , is associated with the parasitic conduction along the edges between the buried oxide and the PELOX field isolation.^{25,28,35)} Although shallow trench isolation (STI) provides benefits for more scaled technologies, enabling a smaller isolation spacing than with PELOX, STI can also give rise to a similar subthreshold conduction after irradiation, when not properly optimized.^{36,37)}

3.2 “Switch-off” I_D transients in thin-gate-oxide PD SOI MOSFETs and lifetime extraction

In a conventional weak inversion single gate switch-off experiment, $|V_{FG\ on}|$ is taken above V_{Tf} ($V_{Tf} \approx 0.35$ V for our long NMOSFETs), whereas $|V_{FG\ off}|$ is taken in the subthreshold regime. After switching-off the devices from $|V_{FG\ on}| = 0.7$ V to $|V_{FG\ off}| = 0.1$ V, an increase in drain current $|I_D(t)|$ is observed for 20 - 30 s until the I_D steady-state value ($I_D(t=\infty)$) is reached [Figs. 2(a) and 2(b)].

It has been shown that for a fixed temperature, the measured I_D transient time T_0 [defined as the time to reach 90% of $I_D(t=\infty)$] can be used to extract the effective film generation lifetime (τ_{geff}) of PD SOI MOSFETs, by the approximated linear relationship¹³⁾

$$\tau_{geff} \approx \frac{T_0}{K} \quad (1)$$

with K a technology and temperature-dependent factor, that under our experimental conditions and for devices with a 2.5-nm-thick gate oxide and a $5.5 \times 10^{17} \text{ cm}^{-3}$ average film doping concentration, is easily calculated to be approximately 120×10^6 .^{13,38)}

Using this procedure, a τ_{geff} of approximately 0.2 μs has been extracted for the devices under study in this work, these values being in the range of the data published in the literature for similar high-quality SOI materials and conditions.^{4,12-14,39)} In fact, the absolute lifetime value is not so important, but it arises as a useful parameter for comparison between different starting materials, processings or irradiation conditions.

An interesting feature associated with the EVB tunnelling phenomenon giving rise to the second peak in g_m [Figs. 1(a) and 1(b)] is the fact that the switch-off transients are found to change their shape from undershoot to overshoot when $V_{\text{FG on}}$ is above the V_{FG} threshold for EVB tunnelling [$|V_{\text{FG on}}| = 1.5 \text{ V}$ data in Figs. 2(a) and 2(b)]. In fact, this probes the injection of majority carriers into the substrate,^{16,17)} which disappear after switching off the device. The shape of these transients has been found to fit well with conventional (EVB-free) switch-on-type transients,⁴⁰⁾ which enable the extraction of the majority carrier recombination lifetime.¹²⁾ Since carrier recombination is usually faster than generation,^{12,41)} the transients in the EVB tunnelling regime [$|V_{\text{FG on}}| = 1.5 \text{ V}$ data in Figs. 2(a) and 2(b)], are faster compared with the normal switch-off ones [$|V_{\text{FG on}}| = 0.7 \text{ V}$ data in Figs. 2(a) and 2(b)].

3.3 Zerbst-type lifetime extraction method

The above generation lifetime measurement method, based on the relationship between the I_D transient time (T_0) and the film τ_{geff} [eq. (1)] has been successfully confirmed to be effective for PD SOI MOSFETs¹³⁾ compared with a well-established dual-gate Zerbst-type technique previously published.⁹⁾ In a dual-gate experiment, one of the two gates (usually the back gate) is switched off from depletion to accumulation, while the other is kept in strong inversion. Very close τ_{geff} values have been extracted with the two methods,

allowing to conclude that the surface component is not playing a determinant role under these conditions.¹³⁾

The dual-gate technique is based on the equation that describes the time evolution of minority and majority carriers at the front and back gates, respectively^{9,42)}

$$\frac{1}{qn_i} \left(\frac{dQ_{\text{depf}}(t)}{dt} + \frac{dQ_{\text{accb}}(t)}{dt} \right) = \frac{W(t) - W_{\infty}}{\tau_{\text{geff}}} + S_{\text{eff}} \quad (2)$$

Here, q is the electron charge, n_i is the intrinsic carrier concentration, $Q_{\text{depf}}(t)$ and $Q_{\text{accb}}(t)$ are the front-gate depletion and back-gate accumulation charges, W is the depletion region depth and τ_{geff} and S_{eff} are the effective generation lifetime and surface generation velocity, respectively.

The above formula [eq. (2)] has been found to also be appropriate for describing I_D transients in the weak inversion regime, i.e., with V_{FG} below V_{Tf} ⁴²⁾ or even to describe single-gate I_D transients observed when switching off the front gate (from $V_{\text{FG}} > V_{\text{Tf}}$ to $V_{\text{FG}} < V_{\text{Tf}}$) while keeping the back gate grounded,³⁹⁾ which is very suitable in our case to also evaluate the buried oxide interface quality.⁴³⁾

With conventional expressions for I_D and the involved charges corresponding to PD SOI devices in the weak inversion regime, the I_D transient formula of eq. (2) is found to be described by eq. (3)^{39,42)}

$$\underbrace{\frac{C_{\text{fox}}}{qn_i\beta} \frac{1}{I_D(t)} \frac{dI_D(t)}{dt}}_{\text{LHS}} = \underbrace{\frac{C_{\text{fox}}}{qN_a\beta} \text{Ln} \left(\frac{I_D(t=\infty)}{I_D(t)} \right)}_{\text{RHS}} \frac{1}{\tau_{\text{geff}}} + S_{\text{eff}} \quad (3)$$

Here, $\beta \equiv q/kT$ is the inverse of the thermal voltage, k is the Boltzmann constant, N_a is the film doping concentration and $C_{\text{fox}} \equiv \epsilon_{\text{ox}}/t_{\text{fox}}$ is the front-gate oxide capacitance density.

Plotting the left-hand side (LHS(t)) of eq. (3) as a function of the right-hand side (RHS(t)), the effective generation lifetime (τ_{geff}) and the surface generation velocity (S_{eff}) can be determined from the slope and the intercept with the vertical axis, respectively. As the front-surface potential is not pinned in the case of a weak inversion transient, some small deviation from eq. (3), associated with time-dependent S_{eff} , can sometimes be appreciated, particularly at the beginning of the transient.^{42,44)}

In order to better analyze the experimental I_D transients, this τ_{geff} extraction procedure was applied to our measurements. In this way, Fig. 3 shows the obtained LHS vs RHS plots (eq. (3)) corresponding to the “switch-off” (from $V_{\text{FG on}} = 0.7$ V to $V_{\text{FG off}} = 0.1$ V) I_D transients measured for an $L=W=10$ μm nMOSFET biased under different V_D conditions. When extending this analysis to increased V_D values, τ_{geff} is found to be markedly decreased, which can be associated with carrier generation in the increased space-charge region near the drain.^{38,45)} Naturally, for high V_D values (above ~ 0.75 V) sub-band gap impact ionisation can start introducing majority carriers into the film,⁴⁶⁾ which makes the transients faster and difficult to measure with a parameter analyzer. The corresponding τ_{geff} values extracted from eq. (3) are shown in the inset of Fig. 3 as a function of $1/V_D$. The τ_{geff} values extracted from the I_D transient time T_0 [defined at 90% of $I_D(t=\infty)$, following eq. (1)] are also given for comparison.³⁸⁾ A reasonable agreement between the two τ_{geff} extraction methods is found, enabling the estimation of effective film generation lifetime in the range of 0.2-0.3 μs .

3.4 Radiation-induced back-channel leakage and “switch-off” I_D transients

In spite of the different techniques published in the literature to extract the generation and recombination lifetimes from I_D transients, there are only few studies discussing their applicability to the investigation of radiation effects.^{11,47)} Moreover, these only concentrate on the study of the generation lifetime and, to our best knowledge, no results including the recombination lifetime degradation have been reported. Under their experimental conditions, these works pointed to a reduction in bulk generation lifetime, together with an increase in surface generation velocity after irradiation.^{11,47)}

In order to investigate the effects of radiation on SOI film generation and recombination lifetimes, switch-off I_D transients were measured on the n-channel and p-channel MOSFETs before and after irradiation, using front-gate voltages above and below the threshold voltage for body-to-gate EVB tunnelling.

As can be seen from $V_{FG\ on}= 0.7\ V$ results in Fig. 2(a), the nMOSFET’s conventional switch-off transients become much faster after irradiation,^{32,38)} which could point to a radiation-induced degradation of τ_{geff} . However, in our case, the decrease in transient time should not be directly attributed to a decrease in film lifetime, but rather associated with the radiation-induced increase in subthreshold leakage current [Fig. 1(a)]. This is supported by the fact that the I_D transients measured for nonirradiated nMOSFETs at $V_{BG}= 14\ V$, which give rise to “irradiation-like” back-channel parasitic conduction [Fig. 1(a)], are found to fit very well with those corresponding to the irradiated devices measured at $V_{BG}= 0\ V$ [Fig. 2(b)]. Furthermore, as shown in Fig. 2(b), the transients measured on the p-channel devices, with no radiation-induced leakage [Fig. 1(b)], do not show any significant change after irradiation.

As shown in the Fig. 2(a) for $V_{FG\ on}= 1.5\ V$, irradiation also seems to speed up in a similar way the recombination of the majority carriers introduced into the film during the $V_{FG\ on}= 1.5\ V$ step. However, this apparent faster hole removal in the n-channel devices may be again associated with the radiation-induced subthreshold leakage and this possibility will be analyzed in the following paragraphs.

3.5 V_{BG} and “switch-off” I_D transients

In order to investigate the impact of back-channel leakage on I_D transients, switch-off measurements were performed on irradiated and nonirradiated nMOSFETs applying different V_{BG} biases. It was envisaged that different back-channel conditions could play an important role in the I_D transient behavior (steady-state current and transient time). In the past, longer transient times were observed with the back gate in weak accumulation⁴⁵⁾ that was attributed to a reduction of some generation component associated with the back surface or device edges.⁴⁵⁾ Figures 4(a) and 4(b) show the obtained results for a nonirradiated transistor after switching off its front gate from $V_{FG\ on}= 0.7\ V$ to $V_{FG\ off}= 0.1\ V$.

As observed in Fig. 4(a), it is found that the steady-state I_D [$I_D(t=\infty)$] is markedly increased when applying V_{BG} values above the back-gate threshold voltage (V_{Tb}), which is approximately 6 V for these long and wide n-channel transistors.³²⁾ The activation of this back-channel conduction is found to be responsible for the faster I_D normalized transients observed in irradiated devices [Fig. 2(a)], as well as for the nonirradiated ones with sufficiently positive V_{BG} [Fig. 4(b)]. On the other hand, as expected, the application of a back-channel accumulation bias ($V_{BG}<0$) to the nMOSFETs has been found to result in small

changes in $I_D(t=\infty)$. However, for sufficiently negative V_{BG} (<-5 V), the transients get considerably faster and their amplitude decreases as well [Figs. 4(a) and 4(b)].

In order to better analyze the impact of V_{BG} on the transients behavior, Fig. 5 shows the extracted I_D transient times, defined as the times to reach either, 90% (undershoot) or 110% (overshoot) of $I_D(t=\infty)$, measured for irradiated and nonirradiated $L=W=10\text{ }\mu\text{m}$ nMOSFETs after switching off their front gate from $V_{FG\text{ on}}=0.7$ V to $V_{FG\text{ off}}=0.1$ V and from $V_{FG\text{ on}}=1.5$ V to $V_{FG\text{ off}}=0.1$ V, respectively.

As clearly seen, the I_D transient times behave in a V_{BG} -bell-shaped way, with a maximum at approximately $V_{BG}=-5$ V. In this way, as commented on the results shown in Figs. 2(a) and 2(b), both types of transients (overshoots and undershoots) are found to be significantly faster after irradiation or when a sufficiently positive V_{BG} is applied. In this case, the decrease in transient time is mainly attributed to the increased level of conduction due to the back-edge-channel leakage and the effect of the normalization, but not to the duration of the I_D excursion itself [Figs 4(a) and 4(b)].

On the other hand, the impact of back gate in strong accumulation ($V_{BG}\sim -10$ V) is found to importantly decrease the transient time without introducing significant changes in steady-state drain current [$I_D(t=\infty)$], thus, in this case, there is a clear decrease in film effective lifetime. This is explained by an electric-field-enhanced generation similar to that of the conventional front-gate GIDL mechanism,³⁴⁾ but occurring in this case in the accumulated back channel. Even at low V_D , the drain junction introduces majority carriers into the film when the film surface is strongly accumulated, thus reducing the transient time. In fact, some results in this direction were already envisaged in some early I_D transient studies.^{48,49)} This is

further supported by the exponential decrease in transient time with increasing negative V_{BG} biases (Fig. 5), which is associated with the GIDL exponential behavior, for which the back-gate-to-drain voltage drop and BOX thickness determine the relevant surface electric field.³⁴⁾

A final comment regarding Fig. 5 results corresponds to the different behavior observed after irradiation on both sides ($V_{BG} < 0$ and $V_{BG} > 0$) of the bell-shaped transient time vs V_{BG} curves. In this way, whilst a clear shift towards lower V_{BG} values is observed for the positive V_{BG} branch, which is associated with the radiation-induced back-gate threshold voltage shift (ΔV_{Tb}), no clear change is observed for the negative V_{BG} part. This is due to the fact that for this case of accumulation back-gate bias, the relevant junction to back-channel field giving rise to the BGIDL mechanism is not affected by the radiation-induced buried oxide charge trapping, because of the existing full overlap between the buried oxide and the source and drain junctions.

In order to better illustrate the impact of V_{BG} on transients behavior, eq. (3) was also applied to the I_D transients of irradiated and nonirradiated nMOSFETs. In this way, Figs. 6(a) and 6(b) show the obtained LHS vs RHS plots. From the figures, the impact of either, irradiation or accumulation V_{BG} is found to significantly reduce τ_{geff} [increase in LHS vs RHS slope in eq. (3)].

3.6 “Switch-off” I_D transients and effective gate voltage overdrives ($\Delta V_{FG\ eff}$ and $\Delta V_{BG\ eff}$)

As derived from Fig. 4(a), a very interesting feature of the I_D transients measured under different V_{BG} conditions is the fact that their amplitude is found to significantly increase for V_{BG} values above V_{Tb} . In this way, Fig. 7 shows the magnitude of the I_D

excursion ($I_D(t=0)-I_D(t=\infty)$) for irradiated and nonirradiated nMOSFETs measured under different V_{BG} conditions. From the figure, the appearance of a step in $I_D(t=0)-I_D(t=\infty)$ is found for V_{BG} values at approximately V_{Tb} , in which the back-channel parasitic conduction starts flowing along the field isolation/buried oxide edges.

In view of Fig. 7 results, one has to disregard the possibility of having only a front gate I_D transient for $V_{BG}>V_{Tb}$ conditions. If this was the case, an increase in V_{BG} should be accompanied by an increase in steady-state I_D [$I_D(t=\infty)$] but keeping a fixed amplitude for I_D transients, i.e., with $I_D(t=0)-I_D(t=\infty)$ being constant. As this is not the case in Fig. 4(a) and Fig. 7, and we have found the existence of back-channel conduction, we can assume that under $V_{BG}>V_{Tb}$ conditions the measured I_D transients are originated from both front- and back-edge-channel conduction.

In order to explain the observed transient behavior under $V_{BG}>V_{Tb}$ conditions, one may think to replace the original $dQ_{accb}(t)/dt$ factor in eq. (2) by a new $dQ_{deplb}(t)/dt$ factor that would take into account the change in the depletion charge associated with the back channel. However, owing to $t_{fox} \ll t_{box}$, giving rise to $C_{fox} = \epsilon_{ox}/t_{fox} \gg C_{box} = \epsilon_{ox}/t_{box}$, this would only result in a negligible additional LHS term in eq. (3).⁴²⁾ This can also be seen by analyzing the expected impact on back-channel conduction due to the induced film potential (ΔV_{bs}) when switching off the front gate. From the amplitude of the I_D transients measured under V_{BG} conditions near 0 V, it is found that they are generated by an effective front-gate voltage overdrive ($\Delta V_{FG\ eff}$) in the range of 40-50 mV, which can be associated with a change in the film potential in the range of 200 mV [Fig. 8(a)]^{5,40)}

$$\Delta V_{FG\ eff} \approx -\Delta V_{bs} \frac{C_{wf}}{C_{fox}} \quad (4)$$

Here, $C_{wf} = \epsilon_{Si}/w_f$ and $C_{fox} = \epsilon_{ox}/t_{fox}$ are the front-channel depletion and front-gate oxide capacitance densities, respectively; ϵ_{Si} and ϵ_{ox} are the corresponding permittivities and w_f is the front channel depletion width [w_f (at $V_{FG}=0.1$ V) ≈ 42 nm)]. These results are in agreement with the estimated induced ΔV_{bs} values when taking into account the depletion widths corresponding to $V_{FG}= 0.7$ V and $V_{FG}= 0.1$ V conditions, as extracted from C-V measurements on MOS capacitors fabricated with the same process but on bulk wafers.⁴⁰⁾

Based on the above ΔV_{bs} values induced when switching off the front gate, one may estimate the effective back-gate voltage overdrive ($\Delta V_{BG \text{ eff}}$) according to [Fig. 8(a)]⁵⁾

$$\Delta V_{BG \text{ eff}} \approx -\Delta V_{bs} \frac{C_{wb}}{C_{box}} \quad (5)$$

Here, $C_{wb} = \epsilon_{Si}/w_b$ and $C_{box} = \epsilon_{ox}/t_{box}$ are the back-channel depletion and back-gate oxide capacitance densities, respectively.

According to eq. (5), an $\Delta V_{BG \text{ eff}}$ value in the range of 10 V would be expected for these PD SOI devices, which is, of course, not observed. Moreover, if ΔV_{bs} was introducing important changes in the whole back channel depletion width, i.e., in the neutral film width, one should also expect significant changes in the second g_m peak of the I_D - V_{FG} characteristics measured at different V_{BG} values, as well as on the amplitude of the I_D transients.⁴³⁾

Taking into account the fact that the back-channel leakage is associated with a parasitic conduction along the edges between the buried oxide and the PELOX field isolation, it has been shown by device simulation that under the presence of positive trapped charges in either the field isolation edge or the buried oxide, a narrow region close to the field isolation

edge operates in the fully depleted mode, giving rise to coupling between the front and back gates (Fig. 8(b)).^{27,29)} This is also in agreement with the V_{Tb} behavior observed in narrow channel devices, in which the regions close to the PELOX isolation become dominant.³²⁾

Under these circumstances, the relevant coupling factor for the parasitic back-channel conduction is dictated by the C_{eq} capacitance.^{5,50)}

$$C_{eq} = \frac{C_{fox} \cdot C_{si}}{C_{fox} + C_{si}} \quad (6)$$

Here, $C_{si} = \epsilon_{si}/t_{si}$ is the silicon film capacitance density.

Taking into account C_{eq} , the effective back gate voltage overdrive values ($\Delta V_{BG \text{ eff}}$) when switching off the front gate can be estimated from eq. (7) [Fig. 8(b)].

$$\Delta V_{BG \text{ eff}} \approx -\Delta V_{FG \text{ eff}} \frac{C_{eq}}{C_{box}} \quad (7)$$

Following this approach, the step in the I_D current transients amplitude [$I_D(t=0)$ - $I_D(t=\infty)$] as a function of V_{BG} (Fig. 7) can be explained by the onset of the back-channel parasitic current transient component, which is added to the conventional front-gate I_D transient. The V_{BG} position of the step in the transients amplitude is shifted after irradiation according to the shift in the I_D - V_{BG} characteristics (ΔV_{Tb}). The magnitude of this back-channel contribution to the I_D transients amplitude at the different V_{BG} biases can be easily extracted from the estimated $\Delta V_{BG \text{ eff}}$ [eq. (7)] and the measured I_D - V_{BG} characteristics (Fig. 7), being these results in good agreement with the measured $I_D(t=0)$ - $I_D(t=\infty)$ data in Fig. 7.

4. Conclusions

The impact of back-channel radiation-induced leakage and back-gate bias on switch-off I_D transients of thin gate oxide PD SOI nMOSFETs has been analyzed. The presence of radiation-induced positive trapped charges in the buried oxide after 60 MeV proton irradiation has been found to reduce the “switch-off” I_D transient times for V_{FG} values above and below the threshold voltage for body-to-gate EVB tunnelling. An increase in steady state I_D and an increase in the amplitude of the weak inversion I_D transients has been found. A similar effect has been observed when applying a positive V_{BG} , which has been found to generate an “irradiation-like” subthreshold leakage. The observed I_D transient behavior is explained by taking into account an edge parasitic back-channel transient component, which is added to the conventional front-gate I_D transient.

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FIGURE CAPTIONS

Fig. 1: (a) I_D and corresponding g_m versus V_{FG} characteristics measured at $V_{BG} = 0$ V and $V_{BG} = -20$ V for an irradiated $L=W = 10$ μm nMOSFET (after 2×10^{11} protons/ cm^2) and for a nonirradiated one measured at different positive and negative V_{BG} values. (b) I_D and corresponding g_m versus V_{FG} characteristics measured at $V_{BG} = 0$ for an $L=W = 10$ μm pMOSFET before and after 2×10^{11} protons/ cm^2 irradiation.

Fig. 2: (a) Normalized “switch-off” I_D transients measured at $V_{BG} = 0$ V on a $L=W = 10$ μm nMOSFET before and after 10^{11} protons/ cm^2 irradiation, together with the results obtained for a nonirradiated one measured at $V_{BG} = 14$ V. (b) Normalized switch-off I_D transients measured at $V_{BG} = 0$ V on a $L=W = 10$ μm pMOSFET before and after 10^{11} protons/ cm^2 irradiation.

Fig. 3: Plot for effective generation lifetime (τ_{geff}) extraction based on eq. (3) method (LHS-RHS). The different curves correspond to the data from “switch-off” (from $V_{FG \text{ on}} = 0.7$ V to $V_{FG \text{ off}} = 0.1$ V) I_D transients measured for an $L=W = 10$ μm nMOSFET biased at different V_D values. The corresponding τ_{geff} extracted values are shown as functions of $1/V_D$ in the inset, together with the ones extracted using eq. (1) (T_0 90%).

Fig. 4: (a) Non-normalized and (b) normalized “switch-off” (from $V_{FG \text{ on}} = 0.7$ V to $V_{FG \text{ off}} = 0.1$ V) I_D transients measured at different V_{BG} conditions for a non-irradiated $L=W = 10$ μm nMOSFET.

Fig. 5: Measured I_D transient times (defined as the time to reach either, 90% (undershoot) or 110% (overshoot) of $I_D(t=\infty)$) versus V_{BG} for irradiated and nonirradiated $L=W=10\text{ }\mu\text{m}$ nMOSFETs after switching off their front gate from $V_{FG\text{ on}}=0.7\text{ V}$ to $V_{FG\text{ off}}=0.1\text{ V}$ and from $V_{FG\text{ on}}=1.5\text{ V}$ to $V_{FG\text{ off}}=0.1\text{ V}$.

Fig. 6: Plot for effective generation lifetime (τ_{geff}) extraction based on eq. (3). The different curves correspond to the data from “switch-off” (from $V_{FG\text{ on}}=0.7\text{ V}$ to $V_{FG\text{ off}}=0.1\text{ V}$) I_D transients measured for (a) irradiated and (b) nonirradiated $L=W=10\text{ }\mu\text{m}$ nMOSFETs at different V_{BG} values.

Fig. 7: Amplitude ($I_D(t=0\text{ s})-I_D(t=\infty)$) of “switch-off” ($V_{FG\text{ on}}=0.7\text{ V}$ to $V_{FG\text{ off}}=0.1\text{ V}$) I_D transients measured for irradiated and nonirradiated $L=W=10\text{ }\mu\text{m}$ nMOSFETs at different V_{BG} biases. The corresponding I_D vs. V_{BG} characteristics measured at $V_{FG}=0\text{ V}$ are also given and the quantitative effects associated with the back-channel component (extra back gate bias, eq. 7) are also indicated.

Fig. 8: Schematic representation of the impact of a switch-off-induced film potential (ΔV_{bs}) on the front- and back-gate voltage overdrives ($\Delta V_{FG\text{ eff}}$ and $\Delta V_{BG\text{ eff}}$, respectively) through the involved capacitances. (a) Nonirradiated PD SOI nMOSFET case. (b) Irradiated PD SOI nMOSFET or nonirradiated one measured at sufficiently positive V_{BG} , giving rise to back-channel edge leakage current and full depletion near the field isolation edges.

Fig. 1(a)

Fig. 1(b)

Fig. 2(a)

Fig. 2(b)

Fig. 3

Fig. 4(a)

Fig. 4(b)

Fig. 5

Fig. 6(a)

Fig. 6(b)

Fig. 7

Fig. 8(a)

Fig. 8(b)