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RELAXABLE DAMAGE IN HOT-CARRIER STRESSING OF *n*-MOS TRANSISTORS

M. RAHMOUN[a,*], E. BENDADA[a], A. EL HASSANI[b]
and K. RAÏS[c]

[a] *Laboratoire de la Microélectronique, de Capteurs et d'Instrumentation, Université My Ismaïl, FST, B.P. 509, Errachidia-Morocco;*
[b] *Laboratoire d'Electronique et Traitement de l'Information, Université My Ismaïl, Faculté des Sciences, Meknès-Morocco;*
[c] *Laboratoire de Caractérisation des Composants à Semiconducteur, Université Chouaïb Doukkali, Faculté des Sciences, B.P. 20 El Jadida-Morocco*

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A method for device characterization is experimented to qualify the relaxable damage in hot-carrier stressing of *n*-MOS transistors. The degradation of physical parameters of the body-drain junction of power HEXFETs is presented for applied stress condition $V_g = V_d/2$. Large decrease of the resistance series, of the ideality factor, and of the reverse recombination current are shown to be related to relaxation time, and are significant at $V_g = -V_d$. These effects are discussed and explained by the evolution of the interface states.

Keywords: Stress; relaxation; diode parameters

1. INTRODUCTION

The influence of hot-carrier on the performance of MOS transistors has been studied extensively during the last decade. With the ever shrinking device geometries, this problem will more and more become a limitation on the reliability of the devices, and therefore increased attention is being paid, not only to the modeling of the hot-carrier phenomenon, but also to the physical mechanisms that lie behind the

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[*] Corresponding author.

corresponding device degradation [1,2]. The hot-carrier effect results from the high fields in the drain region of the transistor due to applied voltages and leads to a degradation in the transconductance (and/or a shift in the threshold voltage) and a decrease in the post-threshold drain current. Published works [3 – 5] have discussed this degradation in terms of interface-states and/or of oxide trapping sites. They are based on the presence of very high field in micronic MOS structures which increase carrier injection into the thermally grown silicon dioxide layer (SiO_2) used as gate insulator.

This study shows that other parameters might be of importance to qualify commercial microelectronic devices for use in space applications. These are the junction body-drain parameters which are shown to be monitors of hot-carrier degradation.

The object of this work is to study the relaxation of stress-induced charges in the conduction processes and in the characteristic parameters of the body-drain junction. The relaxation induces large decrease of the series resistance, of the ideality factor and of the reverse recombination current. They are found to be related to the relaxation of the trapped charges.

2. EXPERIMENTAL CONDITIONS AND DEVICES

The devices used in this study are IRF *n*-channel power hexagonal field effects transistors (HEXFETs) manufactured by International Rectifier. They were stressed at $V_g = V_d/2$ and were relaxed at $V_g = -V_d$ and $V_g = -V_d/2$ during 4 hours (with $V_d = 7V$). This study are related to transistors with a gate geometry: $W/L = 1.4/0.5$.

The study of the physical processes of body-drain junction transport phenomena is performed under voltage operating conditions with the gate bias lower than the threshold voltage value V_t. This is to ensure the characterization of recombination phenomena in the junction. When the channel is turned ON (for gate voltage values close to V_t), the diode effect disappears and the direct biased transistor starts operating normally, the drain-to-source current then flows totally *via* the channel.

In our experiments, static-voltage measurements were obtained from the gate-controlled HEXFETs integral body-drain diode with

$V_g = 2V$. The transistor is reversed biased *i.e.*, the source terminal is made positive with respect to the drain (Fig. 1) so the diode is forward biased. The gate voltage is kept below the threshold voltage value, *i.e.*, these is no current through the channel.

Due to the HEXFET design, the current can flow through the source cell, across the forward biased *p-n* junction. The experimental method has been commented and detailed elsewhere [6].

On the Figure 2 are represented characteristics $I - V$ of the body-drain junction before and after 4 hours of stress at $V_g = V_d/2$ and after 4 hours of relaxation at $V_g = -V_d/2$ and $V_g = -V_d$.

These curves do not deduce of each other by a simple translation, what shows a modification of the junction to the hot-carrier stressing and to the relaxing damage. On each characteristic 100 points are measured and corresponding values (I, V) are memorized and used later for modeling these curves.

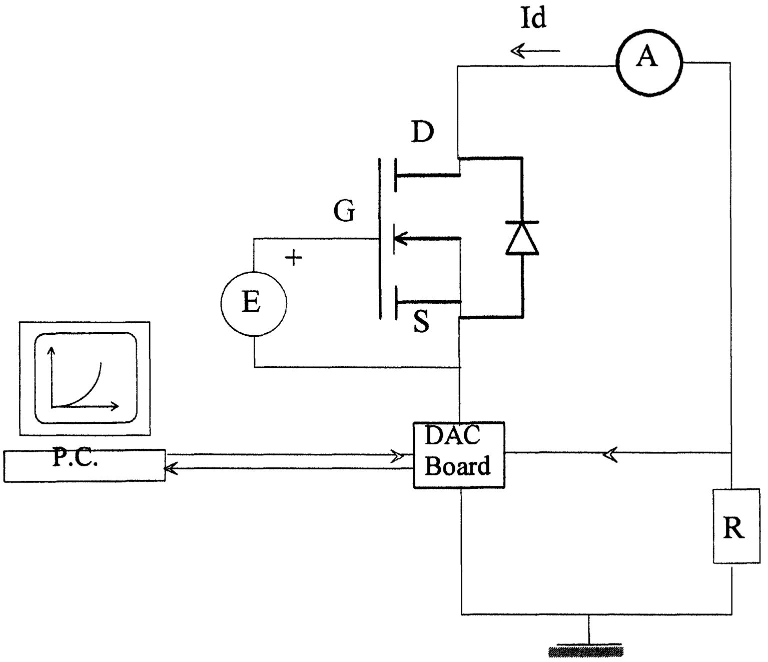

FIGURE 1 Experimental set-up with bias conditions for *n*-channel HEXFET mounted as a gate controlled diode, with data acquisistion and control (DAC) board.

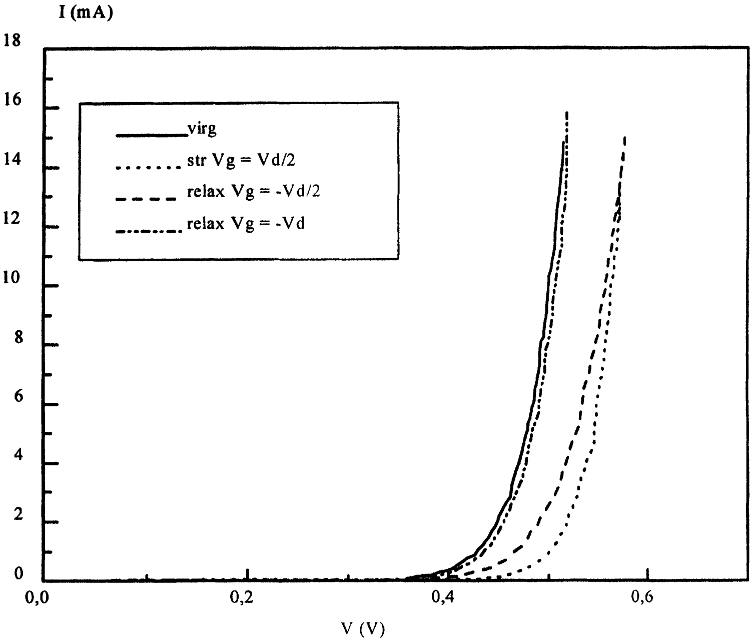

FIGURE 2 $I-V$ Characteristics of the body-drain junction during 4 hours of stress at $V_g = V_d/2$ and during 4 hours of relaxation at $V_g = -V_d/2$ and $V_g = -V_d$.

This study uses the well established model, to two exponential [7] allow to describe characteristics (I, V) of a diode by the implicit equation:

$$I = \frac{V + R_s I}{R_{\rm sh}} + I_{\rm 0d}\left[e^{\frac{q}{kT}(V+R_sI)} - 1\right] + I_{\rm 0r}\left[e^{\frac{q}{nkT}(V+R_sI)} - 1\right] \qquad (1)$$

The model introduce the series resistance R_s to take into account the power losses, the shunt resistance $R_{\rm sh}$ for the leakage currents and the diode ideality factor n. Currents $I_{\rm 0d}$ and $I_{\rm 0r}$ are the two components of the diode reverse currents.

The single exponential model (SEM: where $I_{\rm 0d} = 0$) gives a global description of the physical processes in the operating diode. For an ideal junction $n = 1$, the reverse diffusion-recombination current $I_{\rm 0r}$ is low (its area-normed value is of the order of $10^{-14}\,{\rm A\,cm^{-2}}$) which implies a predominant diffusion process. Values of the ideality factor n greater than unity [8] are related to carrier recombination *via* traps.

The increase of n is correlated with an increase of the reverse I_{0r} current.

The double exponential model (DEM: $I_{0d} \neq 0$ and $I_{0r} \neq 0$) separates electronic diffusion-recombination phenomena (I_{0d}) in the quasi-neutral regions of the junction from the surface and space-charge region recombination current (I_{0r}). This practice is acknowledged for through its implantation in the SPICE model of the diode. A specifically conceived software [6], extracts the values of I_{0r}, I_{0d}, n, R_s, and R_{sh} from the experimental $I - V$ diode measurements. The selection of the best-descriptive set related to this specific conduction mechanism model (Eq. (1)) is made *via* the calculation of the qualification factor Q, that is the root-mean square of the distances separating the experimental points from the calculated curve.

Using the classical method with normally operating transistor and keeping the HEXFET in saturation, the threshold voltage is obtained from the intercept of the extrapolated square-root drain-current to gate-voltage curve with the voltage axis. The oxide trapped charge (ΔN_{0x}) and the interface trapped charge (ΔN_{ss}) were determined using the subthreshold charge separation technique of McWhorter and Winokur [9].

3. RESULTS AND DISCUSSION

Figure 3 shows the density of oxide trapped charge and of the interface trapped charge variation during stress and during relaxation. During stress, the density of interface trapped charge is much larger than the density of oxide-trapped charge. The relaxation damage causes a significant decrease in these densities and this decrease is monotonous during the entire relaxing time.

The density of interface charge is $\Delta N_{ss} = 13.7\,10^{11}\,\mathrm{cm}^{-2}$ after 4 hours of stress and is respectively $\Delta N_{ss} = 11.07\,10^{11}\,\mathrm{cm}^{-2}$, $\Delta N_{ss} = 2.8\,10^{11}\,\mathrm{cm}^{-2}$ after 4 hours of relaxation at $V_g = -V_d/2$ and $V_g = -V_d$.

The series resistance, ideality factor and reverse recombination current were extracted with our sotware [6] from measurements performed on the HEXFETs for stress and for different relaxation conditions. They were obtained from the double exponential model which

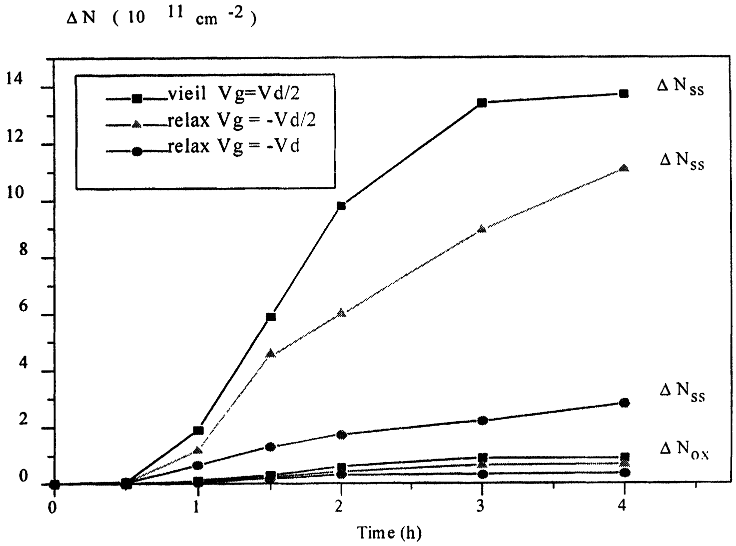

FIGURE 3 Density of interface states (ΔN_{ss}) and oxide trapped charge (ΔN_{0x}) during stress at $V_g = V_d/2$, and during relaxation at $V_g = -V_d/2$ and $V_g = -V_d$.

gives the best results according to the minimum value of the criterion factor Q. The reverse diffusion (I_{0d}) is not studied in this work since it has been found independent the stress [10].

Figures 4(a, b, c) points out an increase of the parameters (R_s, n, I_{0r}) of the stressed device, compared to the virgin device that reflects the hot carrier damage in the transient region of the junction and at the oxide-semiconductor interface near the junction.

The increase of (R_s, n, I_{0r}) is consistent with the carrier mobility reduction produced by the stress [11] and may be related to the high electric field in the channel near the drain junction. The high field imparts enough energy to the electrons which generate, through impact ionization, electron-hold pairs. The electrons are swept toward the drain and the holes are attracted to the body terminal, resulting in a body current. Then it may be inferred that the increase of (R_s, n, I_{0r}) reflects, the increase of the induced trapped charge density (Fig. 3).

An increase of *p-n* junction ideality factor implies carrier recombination *via* traps at the interface and in the junction space-charge region. These higher than unity [12] ideality factor values indicate high values of the traps density and denote a degradation in

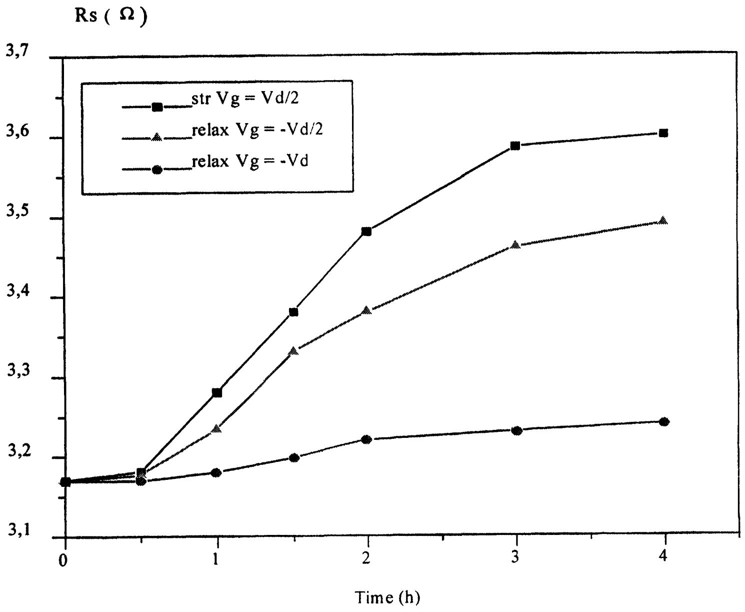

FIGURE 4a Extracted series resistance (R_s) *versus* time plots for device stressed at $V_g = V_d/2$, and relaxed at $V_g = -V_d/2$ and $V_g = -V_d$.

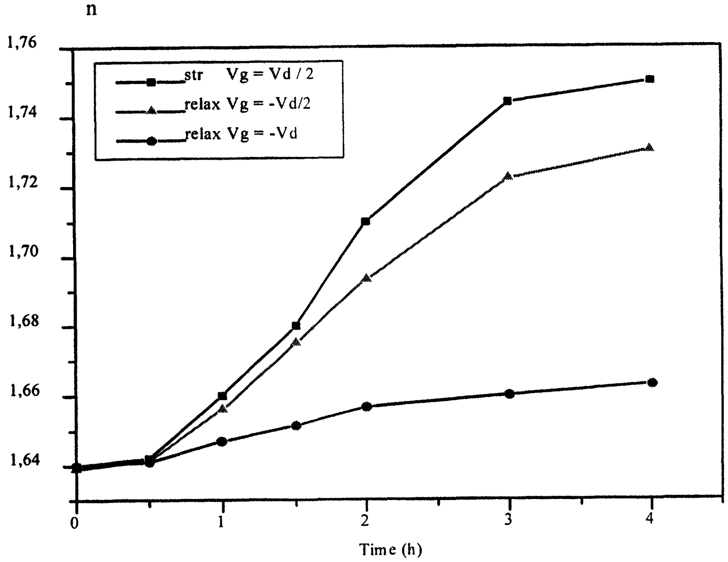

FIGURE 4b The body-drain junction ideality factor (n) *versus* time plots for device stressed at $V_g = V_d/2$, and relaxed at $V_g = -V_d/2$ and $V_g = -V_d$.

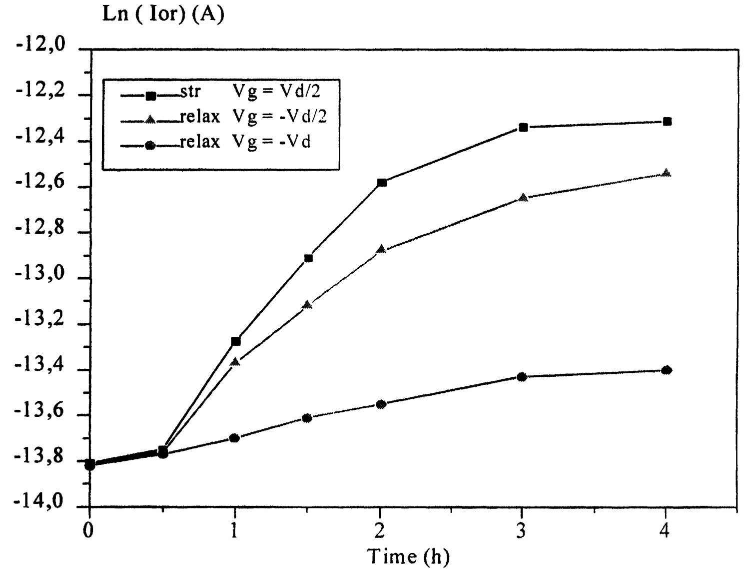

FIGURE 4c The reverse recombination current (I_{0r}) of the body-drain junction *versus* time plots for device stressed at $V_g = V_d/2$, and relaxed at $V_g = -V_d/2$ and $V_g = -V_d$.

the junction due to recombination losses. This is confirmed by the high sensitivity, shown in Figure 4c, of the reverse current I_{0r}, to the stress. We obtained an increase of the reverse current from 1 μA to 4.5 μA when the devices is stressed at $V_g = V_d/2$ after 4 hours.

Furthermore, the values of these parameters are strongly decreased after relaxation. This decrease is monotonous during the relaxation time and is more important after a $V_g = -V_d$ that after a $V_g = -V_d/2$. These results, clearly demonstrates that it is possible to return the physical parameters of the HEXFETs to its pre-stress values when the relaxation of $V_g = -V_d$ is applied for 4 hours. It is also justified by Figure 2 that shows the evolution of $I(V)$ characteristics of the body-drain junction with the stress and the relaxation. Indeed after a time of 4 hours of relaxation to $V_g = -V_d$ the characteristic $I(V)$ is approximately superposed to that before stress. The exploitation of these characteristics by our software gives approximately the same values of R_s, n, I_{0r} before stress and after 4 hours of relaxation to $V_g = -V_d$.

The results presented in Figures 3 and 4 demonstrate that there is a relationship between the parameters (R_s, n, I_{0r}) and the density of charge ($\Delta N_{ss}, \Delta N_{0x}$). This is the main result of this work: the variation of the parameters is mainly due to a variation of interfaces states (ΔN_{ss}). As clearly shown on Figure 3, these is a modest variation in the number of oxide trapped charge (ΔN_{0x}) during stress and relaxation. Figures 3 and 4 show that the parameters as well as the interface strates (ΔN_{ss}) increase and decrease with time during stress and relaxation respectively. The relaxation at $V_g = - V_d$ causes a significant decreases of trapped charges effects. These decreases of traps then can be explained by a phenomenon of neutralization that it is associated to the trapping of holes with electron that cross the oxide by tunnel effect.

These results confirm again that the relaxation damage of physical parameters transistors depends on the applied relaxation bias condition.

4. CONCLUSION

In this paper we have characterized the relaxation of stress-induced changes in the conduction processes and in the characteristics parameters of the body-drain junction of D-MOS power HEXFETs.

The effects of stress and of relaxation on the body-drain junction have been pointed out. As a consequence, physical properties of this junction have been shown to be modified. Extraction parameters methods applied to diode structures appear as a powerful tool to investigate the relaxation of stress damage. It is clearly show that, the relaxation results in large decreases of the series resistance, of the ideality factor and of the reverse recombination currents. This large decrease of these parameters has been observed as a consequence of relaxation trapped charges.

The relaxation of stress effects on the physical parameters may be considered, in the future, as a means of measuring the performance of power MOSFET.

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