Transconductance increase due to charge trapping during hot-carrier stress of nMOSFETs

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Abstract

An unusual hot-carrier degradation mode characterised by a transconductance increase during hot-carrier ageing of nMOS transistors is analysed. By measuring the effects of hot-carrier stress on drain and substrate characteristics and applying alternate static injection phases performed at different gate regimes, it is proved that the degradation is mainly due to negative charge trapping in a localised region near the drain. The transconductance increase is explained in terms of an exchange of the dominant role between the damaged and undamaged portions of the channel. This model is fully corroborated by 2D device electric simulation results.

1. Introduction

In the past two decades, a lot of works have focused on the hot-carrier degradation of conventional nMOS transistors. The damage is commonly believed to result in charge trapping in the gate oxide [1] and interface-state generation at the Si-SiO₂ interface [2,3,4]. The simplest approach states that the first is responsible for a parallel shift of the full I_d vs. V_g curves, while the second leads to subthreshold slope changes and transconductance decrease due to electron mobility degradation [5]. However, the specific particularities involving the nature, extension and position of the generated damage make physical understanding of hot-carrier degradation a rather complex subject.

In this paper, an unusual hot-carrier degradation mode characterised by a transconductance increase during hot-carrier stressing is analysed. In fact, a transconductance increase has already been predicted by a few simulation works [6,7], in which the presence of

negative oxide trapped charges localised close to the drain junction has been found to result in this phenomenon. However, to our knowledge, this was neither corroborated by experimental results nor have the mechanisms giving rise to the phenomenon itself been fully analysed. A transconductance increase after long-term hot-carrier degradation has also been observed in case of hole trapping under low gate voltage stresses [8,9] or in devices with an extremely high substrate impurity concentration ($\geq 10^{18} \text{cm}^{-3}$) [10].

In contrast to the above experimental works, all of them performed under very special electric or technological conditions, the hot-carrier ageing-mode analysed in the present paper has been observed in nMOS transistors of a conventional CMOS twin-tub process, stressed at maximum substrate current condition, and it has been directly related to the presence of negative trapped charges.

Fig. 1. I_d vs. V_g ($V_d=0.1V$) curves and corresponding transconductance measured at various times of ageing.

2. Devices and experimental procedure

The n-channel devices used in this study were fabricated using a conventional twin-tub CMOS process, with a Doubly Doped Drain (DDD) structure. The nMOSFET dimensions were $L_{eff}=1.3\mu m$ and $W=75\mu m$, with a SiO_2 gate oxide thickness of 25nm.

Previous to the study of device degradation, an electrical characterisation was carried out, evaluating the most representative aspects of drain (I_d) and substrate current (I_{sub}) characteristics. The gate voltage condition leading to maximum substrate current (I_{submax}) was determined to be at $V_g=V_d/2$.

For the hot-carrier degradation analysis, the transistors were stressed at constant-voltage stress, with drain voltage (V_d) ranging from 5.5 to 7V and at the I_{submax} condition, which was experimentally found to give rise to the most severe degradation. The effect of the stress on the devices was mainly evaluated through the analysis of I_d vs. V_g curves, which were regularly measured at $V_d=0.1V$ between different stress phases.

Threshold voltage ($V_{th} \equiv V_g @ I_d=0.01W/L \mu A$), maximum transconductance (G_{mmax}) and linear drain current measured at $V_g=5V$ (I_{dlin}) were the primary degradation monitors, all of them obtained from the I_d vs. V_g curves.

The fully automated experimental set-up used for both, the electrical characterisation and the stress experiments, consisted of an HP 4142B modular DC source/monitor, an HP 4085A switching matrix and a Wentworth automatic wafer prober. All experiments were carried out in a light-proof and electrically shielded probe station.

Fig. 2. G_{mmax} and I_{dlin} relative degradation, together with ΔV_{th} , as a function of stress time.

3. Device degradation

3.1 I_d vs. V_g and transconductance increase

Fig. 1 shows typical I_d vs. V_g measured curves for an n-channel MOSFET subjected to hot-carrier stress. The degradation observed over the whole range of stress voltages is characterised by two main phases along the stress time, which have been found to be accelerated as stress voltages are increased or, alternatively, as channel lengths are reduced.

As shown in Fig. 2, the first phase (I in Fig. 2) is characterised by a weak decrease of device maximum transconductance (G_{mmax}), together with a slight but continuous decrease of I_{dlin} and a negligible positive threshold voltage shift (ΔV_{th}).

As the stress progresses, the device enters a second phase (II in Fig. 2), in which there is a significant positive V_g shift of the curves in their entirety as a function of increasing stress time, together with a gradual degradation in subthreshold slope and an unusual turn around in the transconductance behaviour, which now starts to rise, eventually reaching higher values than those corresponding to the virgin device. Finally, under the most stringent conditions, and after long stress time, a slight deceleration of the degradation, associated with a saturation of the generation of damage, is appreciated.

The classical explanation of the I_d vs. V_g characteristics degradation would be that this is due to both, trapping of electrons in the gate oxide (N_{of}) and generation of acceptor-like interface states (N_{it}). Nevertheless, since the registered transconductance increase cannot be explained merely by N_{of} or N_{it} , a more particular degradation feature is expected to be responsible for this phenomenon.

Fig. 3. I_d vs. V_d pre-stress and post-stress (16000s, $V_d=6.5$, $V_g=3.25$) characteristics for $V_g=2$, 2.5 and 3V, measured in normal and reverse configurations.

3.2 Localisation of the damage

In view of this unusual hot-carrier degradation mode, output characteristics (I_d vs. V_d) were measured before and after stress experiments, both, interchanging (reverse) and without interchanging (normal) the source for the drain relative to the configuration in which the stress was performed. It was expected that if negative charge trapping occurred in a localised region close to the drain junction, their electrical effects must be masked by the drain depletion region.

A typical result is shown in Fig. 3. As expected, initial drain curves exhibit symmetry to the source-drain interchange. In contrast, after stressing the device, I_d is lower, and a clear asymmetry between normal and reverse polarities appears.

As V_d is increased, less difference is observed between the pre-stress and the post-stress I_d vs. V_d curves measured in normal configuration, showing a marked rounded shape. On the other hand, this phenomenon is not observed when source and drain are interchanged for the I_d vs. V_d measurements.

Both phenomena can be explained by negative charge trapping occurring in a limited region near the drain junction [6,7]. In this way, the I_d reduction in both configurations is attributed to V_{th} increase in the portion of the channel lying underneath the negative trapped charge. Moreover, the lack of symmetry indicates that the trapped charges are localised near the drain junction.

In normal configuration, the damage is located close to the drain and its electrical effects become more and more masked as the drain depletion region

Fig. 4. V_{th} before (open symbols) and after (full symbols) stress (18000s, $V_d=6.5$, $V_g=3.25$) against V_d in normal and reverse configurations.

widens. On the other hand, in reverse configuration, the damage is located close to the source junction and, independently of the applied V_d , it remains always electrically active.

An additional prove for the above model was obtained by measuring I_d vs. V_g characteristics in normal and reverse configurations applying increasing V_d voltages. V_{th} results from such characteristics are shown in Fig. 4.

For low V_d values, situation in which the channel of minority carriers spreads from the source to the drain (linear regime), no difference is appreciated between V_{th} values corresponding to normal and reverse configurations. However, as V_d is increased, a marked asymmetry appears.

In the case of normal configuration, a clear V_{th} modulation associated to the widening of the drain depletion region is appreciated [11]. For sufficiently high V_d ($V_d > 1.5$ V), no significant V_{th} difference with respect to the pre-stress condition is registered, indicating that the damage has been totally shielded by the drain depletion region. In contrast, V_{th} remains independent of V_d in the case of reverse configuration, showing that the amount of electric active damage remains independent of V_d .

From the above results, as it should be expected, it can be drawn that the negative trapped charges are located in a limited region near the drain junction, which extends at most less than $L_{eff}/2$. Considering a simple approach relating applied V_d with junction depletion width [12], from the results in Fig. 4, an estimation for the length of the damaged region (ΔL) was performed. These results showed that ΔL was about the length of the pinch-off region ($\Delta L \approx 0.25 \mu m$) [2].

3.3 Effects on lateral channel electric field ($E_{||}$)

An additional characteristic feature of this hot-carrier degradation mode is the fact that substrate current (I_{sub}), or more precisely, multiplication factor (I_{sub}/I_d), has been found to monotonously rise as the stress progresses (Fig. 5). As it is well known, I_{sub} is originated by the impact ionisation events taking place in the high field region near the drain junction, the simplest approach for I_{sub} is given by [2]:

$$\frac{I_{sub}}{I_d} \approx C \cdot e^{-\phi_i / q\lambda E_m} \quad (1)$$

Being E_m the maximum value of the lateral electric field ($E_{||}$) along the channel, C a weak function of E_m and device parameters, λ the hot-electron mean-free path and ϕ_i the minimum energy that a hot-electron must have in order to create an electron/hole pair.

Thus, as no increase of I_d is registered apart from that derived of the additional electrons from the impact ionisation events, a clear increase of E_m occurs during the hot-carrier degradation of the devices. This E_m increase is also attributed to the trapping of negative charges near the drain junction. In this situation, the trapped electrons reduce the effective V_g in the damaged region, which results in an increase of the voltage drop and of $E_{||}$ near the drain junction [6,13].

4. Alternate static injection phases

In order to investigate the connection between the registered transconductance and E_m increases with the negative charge trapping phenomenon, some devices were first aged at $V_g = V_d/2$ and then stressed under conditions which resulted in a hole-injection phase (V_d high, $V_g \approx V_{th}$) [3,9,14,15]. As expected, the hole-injection phase resulted in a partial neutralisation or compensation of negative trapped charges, and this allowed to prove the existence of a close relationship between the negative charge trapping and the transconductance and E_m increases.

Fig. 6 shows V_{th} , G_{mmax} and I_{sub}/I_d stress time evolution for a device stressed at $V_d = 6.5V$ and at different consecutive V_g voltages. From the figure, a basic correlation between these three parameters can be easily outlined. Under $V_g = V_d/2$ stress bias conditions, positive ΔV_{th} , together with G_{mmax} and I_{sub}/I_d increases are registered. On the other hand, for

Fig. 5. I_{sub}/I_d stress time evolution for devices subjected to different stress voltages.

Fig. 6. V_{th} , G_{mmax} and I_d/I_{sub} stress time evolution for a device stressed at $V_d = 6.5V$ and initially at $V_g = 3.25V$ and then at $V_g = 1.5V$, $3.25V$ and $1.5V$.

the hole-injection phases all these parameters are found to behave oppositely. In this way, V_{th} , G_{mmax} , and I_{sub}/I_d after the third stress phase ($V_g = 3.25V$) in Fig. 6 are similar to those registered after the first phase. A similar situation is observed after the second and fourth phases ($V_g = 1.5V$).

5. Two-piece analytical approach for G_m

Having discussed in previous sections about nature and localisation of the damage and having also outlined a basic correlation between negative charge trapping and the G_{mmax} increase, the ultimate reasons giving rise to this particular phenomenon can be now analysed.

According to the model proposed by Haddara et al. [16], the channel of a degraded device can be considered, as a first approach, to be composed of two conductive regions of different conductance. In the linear region, the two corresponding resistances are added and the total channel conductance is given by:

$$G = \frac{G_0 \cdot G_d}{G_0 + G_d} \quad (2)$$

$$G_0 = \frac{\mu W C_{ox} (V_g - V_{th0})}{L - \Delta L} \quad G_d = \frac{\mu_d W C_{ox} (V_g - V_{thd})}{\Delta L}$$

being G_0 the conductance of the $L - \Delta L$ long defect-free region and V_{th0} and μ their threshold voltage and effective mobility, respectively. G_d , V_{thd} and μ_d correspond to the damaged region of length ΔL and width W .

From (2), the total transconductance of the degraded device ($G_m \equiv V_d \cdot dG/dV_g$) is given by:

$$G_m = \frac{G_0^2}{(G_0 + G_d)^2} G_{md} + \frac{G_d^2}{(G_0 + G_d)^2} G_{m0} \quad (3)$$

Where $G_{md} \equiv V_d \cdot dG_d/dV_g$ and $G_{m0} \equiv V_d \cdot dG_0/dV_g$ are the transconductances associated with the damaged and the defect-free portions of the channel, respectively.

According to (2) and (3), the total conductance and transconductance of the degraded transistor is equal to zero before the turn-on of the damaged region. Just after this turn-on point ($V_g \approx V_{thd} \equiv V_{th0} + \Delta V_{th}$), the total transconductance is dominated by G_{md} term in (3), since G_d is still very low whereas G_0 is much higher. In this situation, and because of the small $\Delta L/L$ ratio giving rise to $G_{md} > G_{m0}$, the total transconductance of the device can exceed the values registered before the stress. As V_g is increased, G_d rapidly surpasses G_0 and the effect of ΔV_{th} in (3) becomes negligible. Consequently, the total transconductance (G_m) decreases towards values similar to those of the fresh device.

6. Bidimensional device electric simulation

In order to better analyse the above effect on G_{mmax} , 2D device electric simulations were carried out by means of TMA MEDICI, accordingly to previous results obtained from TMA SUPREM-3 process simulations [17].

Fig. 7. Simulated G_m vs. V_g curves ($V_d = 0.1V$).

Fig. 8. Simulated I_d vs. V_g and corresponding G_m from Fig. 7 results ($V_d = 0.1V$).

The results from those studies are shown in Fig. 7 and Fig. 8. In this way, Fig. 7 shows transconductance (G_m) vs. V_g curves for six different simulations. The first one corresponds to a fresh device ($N_{of} = 0 \text{ cm}^{-2}$) while the others correspond to a device in which different values of a spatial-uniform density of negative oxide trapped charges ($N_{of} = 2 - 10 \cdot 10^{11} \text{ cm}^{-2}$) were placed at the Si-SiO₂ interface in a region $0.25 \mu\text{m}$ -long close to the drain. The simulated transconductances corresponding to each of the two different channel regions (G_{m0} and G_{md}) are also plotted in Fig. 7. As it can be seen, just after the turn-on point, the total transconductance (G_m) is clearly influenced by G_{md} . However, as V_g is increased, the total transconductance approaches that of the fresh device.

Finally, Fig. 8 shows I_d and G_m vs. V_g simulated curves corresponding to Fig. 7 cases. As it can be seen, these simulation results qualitatively and quantitatively agree very well with the experimental degradation results (Fig. 1). So, the fact that the transconductance increases with N_{of} can

Fig. 9. Simulated distributions of $E_{\parallel}$ ($0.25 \cdot 10^5$ V/cm-spaced contours) and current flow, together with impact ionisation contour lines (R_G , 0.25-spaced contours), for (a) a defect-free device and (b) a device with $N_{ot} = 6 \cdot 10^{11} \text{ cm}^{-2}$ near the drain junction.

be fully explained by means of the interaction between the damaged and the undamaged portions of the channel.

The above simulations were also analysed in terms of lateral channel electric field ($E_{\parallel}$) and electron/hole pair generation rates. Following this trend, Fig. 9(a) shows contours of $E_{\parallel}$ together with mean flow path and impact ionisation rate contours (R_G , $10^{R_G} = \text{generated } e^-/h^+ \text{ pairs}/(\text{cm}^3 \cdot \text{s})$) for a given polarisation ($V_{ds} = 6.5\text{V}$, $V_{gs} = 3.25\text{V}$) corresponding to a defect-free device.

Fig. 9(b) shows the same information but in this case corresponding to a device in which a spatial-uniform density of negative oxide trapped charges ($N_{ot} = 6 \cdot 10^{11} \text{ cm}^{-2}$) was placed at the Si-SiO₂ interface in a region which extended $\Delta L = 0.25 \mu\text{m}$ near the drain junction.

Comparing these two figures, one can easily notice that the presence of the negative trapped charges near the drain increases the lateral electric field and the impact ionisation rate. The magnitude of the $E_{\parallel}$ increase (about 10%) is compatible with the measured I_{sub}/I_d increase (Fig. 5 and Eq. (1)).

6. Conclusions

In this paper, an unusual hot-carrier degradation mode characterised by a transconductance increase during hot-carrier stressing of n-channel MOS devices has been analysed. By means of studies of localisation and nature of the damage, this phenomenon is explained in terms of an exchange of the dominant role between the damaged and the undamaged regions of the channel. This degradation model is corroborated by 2D device electric simulation results.

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