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Impact of Voltage-Accelerated Stress on Hole Trapping at Operating Condition

Z. Y. Tung and D. S. Ang

Abstract— This paper shows that voltage-accelerated stressing (VAS), a common methodology used in gate-oxide reliability testing, can change the capture activity of a time-zero oxide trap (i.e. already active under operating condition). It is found that after VAS, a time-zero oxide trap can be rendered either significantly more or less likely to capture a hole, implying that the applied electrical stress may have changed the atomic structure of the trap. The question on whether such change is relevant to reliability testing would have to be further considered carefully given the significant impact that charge trapping/detrapping at a single oxide trap may have on the behavior of a small-area MOSFET.

Index Terms—Bias-temperature instability, gate oxide reliability, random telegraphic noise, switching oxide trap

I. INTRODUCTION

VOLTAGE-accelerated stressing is one of the most commonly used methods for assessing the reliability of electronic devices, including the degradation and breakdown of the MOSFET gate oxide. All this while, the attention has centered on the effect of the newly created oxide traps on parametric shifts and it has been assumed that the applied stress does not affect the pre-existing or time-zero oxide traps (i.e. already present under the operating condition). This assumption is generally valid for large-area MOSFETs, given 1) the usually low density of these traps ($\sim 10^{10} \text{ cm}^{-2}$); 2) the relatively insignificant perturbation a trap-occupancy change has on the overall drain current (I_d).

However, the same assumption may not hold true in the case of the small-area MOSFETs. It has been shown that the random trapping/detrapping of inversion charges by a few oxide traps in a small area MOSFET can significantly impact the I_d , especially if a trap is located near the channel percolation path arising from the random fluctuations of dopants in the channel region [1]–[7]. There have been numerous reports on the statistical analysis of such random charge trapping/detrapping events, through the momentary application of a gate stress voltage and monitoring of the post-

Fig. 1. (a) Test sequence used to study the effect of voltage-accelerated stressing (VAS) on time-zero switching oxide traps measured at $V_g = -1 \text{ V}$ (operating condition) in the monitoring step. (b) Examples of step-like drain current (I_d) recovery, due to trapped-hole emissions, in the 100-s relaxation interval ($@ V_g = -0.6 \text{ V}$) that follows the 10-s biasing interval at $V_g = -1 \text{ V}$. (c) An example of I_d evolution measured at $V_g = -1 \text{ V}$, for the same test device as in (b). Dashed lines are eye guides, delineating what appears to be an I_d degradation step due to a hole capture event at $\sim 10^{-4} \text{ s}$ amidst the “noisy” measurement data.

stress relaxation characteristics [7]–[9].

Although already inferred earlier via the analysis of the post-stress relaxation of large-area p-MOSFETs subjected to dynamic negative-bias temperature instability (NBTI) stressing [10]–[13], it was only recently confirmed that NBTI stressing can increase the hole-emission times of certain oxide traps [14]–[15], i.e. an oxide trap which can regularly emit the trapped hole within the relaxation interval would subsequently fail to do so, indicating a change from a temporary to a permanent charged state. The results imply that the nature of an oxide trap can evolve under NBTI stressing, due possibly to a change in its atomic structure. While evidence on the change of a trap’s emission characteristics has been reported, the effect of voltage-accelerated stress (VAS) on the capture characteristics has not been revealed. In this paper, it is shown that the likelihood of an oxide trap to capture a hole under operating condition can be altered after a VAS step. Our study should be distinguished from past studies (e.g. [3], [6], [7], [16]) which examined the voltage dependence of a trap’s capture characteristics. In these studies, the change in capture behavior stems from the effect of the applied gate voltage (V_g) on the capture barrier energy and local inversion charge density. In contrast, the change in capture behavior revealed here was observed at the same V_g and without any apparent change in the local inversion charge density after VAS.

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Fig. 2. Pre- (top) and post-VAS (bottom) spectral maps, derived from the corresponding monitoring steps applied on two test devices D (left) and E (right). Apparent changes in the intensity of certain clusters (see dashed and dotted lines) can be seen after a $V_g = -2$ V VAS step.

II. EXPERIMENTAL DETAILS

The test devices (DUTs) used were p^+ polysilicon/SiON gate stack p-MOSFETs, with 120-nm and 60-nm drawn channel width and length respectively. The thickness of decoupled plasma nitrided SiON gate dielectric is 1.8 nm. A total of 38 devices were tested at 100 °C based on the test sequence illustrated in Fig. 1: (1) A pristine device was first subjected to 100 monitoring cycles, each involving a 10-s interval at $V_g = -1$ V (operating voltage) followed by a 100-s relaxation interval at $V_g = -0.6$ V, during which the drain current I_d was continuously measured. An I_d recovery step in the relaxation trace (see examples in Fig. 1(b)) stems from the emission of a trapped hole and in conjunction with the emission time, they provide a means for identifying the oxide trap that captured the hole during the $V_g = -1$ V interval. It is generally difficult to identify a trap capture event through the direct measurement of I_d degradation at $V_g = -1$ V, because of the noisier I_d data due to a change of measurement range (Fig. 1(c)). (2) After the monitoring step, the DUT was subjected to VAS at $V_g = -2$ V for 100 s. (3) Following this, another 100 monitoring cycles of the same conditions as in (1) were re-applied to determine the impact of the VAS on the oxide traps identified in the pre-VAS monitoring step. Steps (2) and (3) were then repeated on the same test device with a successively higher stress voltage of -2.5 V and -3 V for each repetition. In total, 38 devices were tested.

III. RESULTS AND DISCUSSION

The emission times of an oxide trap may be fitted to the exponential distribution (not shown), in agreement with past studies [3], [7], [8]. As one would need ~ 2 -3 days on average to measure a complete trap occupancy curve (from which the capture time constant is extracted) of a test device, the complete curve was not measured so as to keep the total experimental time at a reasonable level. To probe the impact of VAS on the capture characteristics of a trap, the trap's occupancy or capture activity at $V_g = -1$ V, 10 s (defined as the number of times a trapped-hole emission event related to the trap is observed relative to the 100 monitoring cycles applied) before and after VAS are compared. The observation of a trapped-hole event linked to a particular oxide trap during the 100-s relaxation interval indicates that the trap was able to capture a hole during the prior -1 V biasing interval.

Fig. 3. Each data point represents a hole-emission event observed in a particular cycle of the pre- and post-VAS monitoring steps. Cycle numbering continues from the previous monitoring step. (a) Trap D1 of device D; (b) trap E3 of device E. Capture activity of the traps, in percent, before and after VAS are as indicated. Also shown for each case is I_d degradation at the end of relaxation, $|\Delta I_d|^{eor}$ as a function of the monitoring-cycle number (line).

A “spectral map” that allows identification of active oxide traps [7] at $V_g = -1$ V is obtained by plotting the time and the drain-current recovery step for each trapped-hole emission event in the 100 relaxation traces measured during the monitoring step (e.g. Fig. 2(a)(i)). A comparison between the spectral maps obtained before and after VAS consistently reveals two interesting outcomes; the capture activity of an oxide trap can either be increased or decreased after the VAS.

Examples where the capture activity of oxide traps at $V_g = -1$ V is visibly altered after the VAS step are given in Figs. 2 and 3 for 2 test devices (D and E). For device D, the pre-stress spectral map (Fig. 2(a)(i)) shows 2 distinct clusters, corresponding to 2 active oxide traps (D1, D2). Interestingly, the cluster for D1 has its intensity clearly decreased in the post-VAS spectral map, while the cluster for D2 is unaffected. The former is due to an obvious reduction in the number of hole-emission events for trap D1 in the post-VAS monitoring step (Fig. 3(a)). Also shown in Fig. 3(a) is I_d degradation at the end of relaxation, $|\Delta I_d|^{eor}$ (Fig. 1(b)) as a function of the monitoring-cycle number. Apart from the expected increase of $|\Delta I_d|^{eor}$ after VAS (due to the stress induced generation of new traps), $|\Delta I_d|^{eor}$ is unchanged through the post-VAS monitoring step. A clear absence of any correlated change in $|\Delta I_d|^{eor}$ at each of the 3 hole-emission events of trap D1 in the post-VAS monitoring step can be seen. This implies that the reduction in the hole-emission events of trap D1 is not because of the trapped hole failing to emit in every relaxation interval but rather the trap is now less likely to capture a hole during the $V_g = -1$ V intervals. On the other hand, an opposite outcome applies to trap E3 of device E. Prior to the VAS step, trap E3 is relatively inactive, with only 3 emission events in 100 monitoring cycles (Fig. 3(b)), and only a vague shade can be observed in the spectral map (Fig. 2(b)(i)). After the VAS step, the number of emission events is evidently increased (Fig. 3(b)), giving rise to an obvious cluster in Fig. 2(b)(ii). These observations show that trap E3 has become more likely to capture a hole during the $V_g = -1$ V intervals after VAS.

The increase or decrease in the likelihood of an oxide trap to capture a hole at $V_g = -1$ V after the VAS step is consistently observed in 17 out of the 38 devices tested. A breakdown for the two outcomes is given as follows: (1) 15 out of the 17

Fig. 4. A sequence of VAS steps involving successively higher voltages is shown to have different impacts on three oxide traps: (a) G1 and (b) G2 in the same device; (c) H2 in another device. Capture activity of the traps, in percent, are as indicated.

devices have oxide traps which are rendered less likely to capture a hole by the VAS step; (2) 11 out of 17 devices have oxide traps which become more likely to capture a hole after the VAS step. It should be mentioned that the average I_d recovery step associated with these traps are not changed after VAS (Figs. 3-5), implying that the possible role of a local inversion charge density variation on the capture characteristics may be ruled out [16].

It is also observed that a given VAS step has varying impacts on the ability of different oxide traps to capture a hole at the operating condition. Examples are given in Fig. 4. For device G (Fig. 4(a)), the $V_g = -2$ V and -2.5 V VAS steps have no apparent impact on a very active trap G1 (with hole-emission recorded in almost every monitoring cycle). The capture activity of this trap is only reduced (drastically) after the $V_g = -3$ V VAS step. This result should be contrasted against that in Fig. 3(a), where a reduction in the capture activity of trap D1 can already be seen after the $V_g = -2$ V VAS step. However, the capture activity of another trap G2 remains relatively intact even after the $V_g = -3$ V VAS step (Fig. 4(b)). Similarly, a much higher stress voltage is needed to make certain oxide traps more capture-active. For instance, trap H2 in device H becomes obviously more likely to capture a hole only after the $V_g = -3$ V VAS step (Fig. 4(c)).

A progressive reduction in the capture activity of an oxide trap is also observed after VAS steps of successively higher voltages. Fig. 5(a) shows such an example for trap J1. After the -3 V VAS step, no hole-emission events can be detected. It is unclear if the absence of hole emission of trap J1 after this VAS step is due to the trap eventually failing to capture a hole in every -1 V interval (i.e. loss of capture activity), as the absence of emission events could also arise from an increase in the emission time, as observed for another trap J2 in the same device. For the latter, regular emission events in nearly every cycle is observed after the hole-emission event at cycle 330, indicating that the absence of emission events from monitoring cycles 301 to 329 is due to the trapped hole failing to emit after the -3 V VAS step [15]. However, no emission events can be seen for trap J1 when the monitoring step was re-applied after several weeks of storage and after a

Fig. 5. (a) Gradual reduction followed by a complete loss of trap J1's activity after VAS involving successively higher voltages. (b) A brief loss of activity of trap J2 (used to emit in less than 100 s in every cycle) due to temporary increase in emission time after the -3 V VAS; activity restored after the trapped hole is emitted at cycle 330. Capture activity of the traps, in percent, are as indicated.

subsequent biasing at $V_g = +2$ V for 100 s, which saw $|\Delta I_d|^{\text{eor}}$ being reduced to 61 % of the value after the -3 V VAS step. Nonetheless, such a change in emission characteristic does not always accompany the change in capture characteristic (cf. Figs. 2 and 3), implying that they are not correlated in general.

Due to the lack of a direct evidence on the atomic nature of the oxide traps, the mechanisms behind the observed changes in the trap capture activity after VAS are not known at this stage. In view of the increasing oxide field (~ 9 MV/cm at $V_g = -2$ V) due to thickness scaling, a general explanation may be found in the possible distortion of the oxide network and the associated changes in the local atomic configuration of the trap sites that may occur upon the application of the stress, thus changing the characteristics of the traps. A more specific hypothesis on the deactivation of an oxygen vacancy defect by hydrogen released from Si-H bond dissociation at the interface has been proposed [8], [17]-[18]. It should be noted that while the capture activity of a trap is affected after VAS, no shift in its emission-time distribution is observed (Fig. 2). More study is needed to clarify whether the capture and emission characteristics must necessarily be correlated.

IV. SUMMARY

It is found that VAS can either increase or decrease the likelihood of a time-zero oxide trap (i.e. already active under operating condition) to capture a hole. Out of the 75 oxide traps probed in 38 small-area p-MOSFETs, 19 traps exhibit decreased capture activity while 11 traps demonstrate increased capture activity after the -2 V VAS step. Moreover, it is observed a given VAS step has different effects on the oxide traps, i.e. some traps can be affected by a relatively low stress voltage while others are affected only by higher stress voltages. Given that VAS is commonly used on the gate oxide and that an oxide trap can have a substantial effect on the performance of small-area MOSFETs, further consideration should be given to the possible impact the findings may have on the reliability testing of small-area devices.

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