Monitoring Trapped Charge Generation for Gate Oxide Under Stress
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Abstract—A measurement method to extract the respective quantities and centroids of positive and negative trapped charges, i.e., $Q_p$ and $Q_n$, generated by the negative current stress for gate oxides is proposed and demonstrated. The method is based on neutralization of $Q_p$ by a low positive current stress to differentiate the effects of $Q_p$ and $Q_n$. From the extracted quantities and centroids of $Q_p$ and $Q_n$ of negatively stressed oxides, it was found that $Q_p$ and $Q_n$ are generated near the oxide/substrate interface and $Q_p$ is initially much larger than $Q_n$. After the continuous stressing, $Q_p$ saturates and moves closer to the interface, but $Q_n$ keeps increasing and moves away from the interface, especially for those oxides after the post-poly anneal (PPA) treatment. $Q_p$ is very unstable and easily neutralized, either by a small stress of opposite polarity or the same polarity. For the latter, $Q_p$ is mainly dependent on the level of the final stressing field.

I. INTRODUCTION

HIGH field stresses are commonly used to evaluate the gate oxide reliability. The stress-induced trapped charges in the oxide film result in threshold voltage shifts, excess leakage currents and even oxide breakdowns. Previously, the distributions of trapped charges were measured and discussed to analyze trapping mechanisms [1]–[8]. However, in the stress, both positive ($Q_p$) and negative ($Q_n$) trapped charges are simultaneously generated [1]–[6]. In previous studies, effects of $Q_p$ and $Q_n$ were not differentiated and their net effects were measured when stress-induced $C-V$ or $I-V$ curve shifts were analyzed. To fully understand the trapings and the related degradation mechanisms of gate oxide films, it is desirable to monitor $Q_p$ and $Q_n$ generation, respectively, during the stress.

In this paper, a new method is proposed to monitor the distributions of $Q_p$ and $Q_n$, respectively. Unlike $Q_n$, $Q_p$ is very unstable and easy to be neutralized by a low reverse bias stress [6], [9]. Thus, the respective effects of $Q_p$ and $Q_n$ on $C-V$ and $I-V$ curve shifts were differentiated by neutralizing $Q_p$. Then their individual trapping quantities and centroids in the oxide film were extracted. Thus their dependence on stressing currents and injected charges under constant current stresses was monitored. Moreover, the relations between the oxide quality and the trapping characteristics were also studied by using the post-poly-annealing (PPA) method which was to degrade the oxide film [10]. In addition, the dynamic change of trapping distributions in the oxide film under different injection conditions were also studied. It was found that $Q_p$ has a reversible characteristics, with its steady-state trapping level determined by the final oxide field [9], [11], and additional stresses only generate extra $Q_n$ but does not disturb the original $Q_n$.

II. EXPERIMENT TECHNIQUES

The samples used in this study were POCl$_3$-doped gate MOS capacitors, with an area of $2.33 \times 10^{-4}$ cm$^2$, on a p-type Si wafer. The 80 Å gate oxide was grown in diluted dry O$_2$ (O$_2$/N$_2 = 1/6$) at 900 °C and annealed in N$_2$ at the same temperature for 15 min. The poly-Si gate was metallized with Al followed by a 400 °C anneal in N$_2$ for 30 min. For some samples, the gate oxides were degraded by the PPA, before POCl$_3$ doping, in N$_2$ at 900, 950, and 1000 °C, respectively, for 10 min. HP4145B and Keithley $C-V$ analyzer were used to measure sample electrical characteristics.

III. RESULTS AND DISCUSSIONS

As mentioned previously, both positive ($Q_p$) and negative ($Q_n$) trapped charges are generated during high field stresses [1]–[6], and $Q_p$ is very unstable and easy to be neutralized by a low reverse bias stress [6], [9]. An experiment was done by applying two consecutive $-100$ mA/cm$^2$ stresses to a group of similar samples, but with some samples applied with small opposite $+0.1$ mA/cm$^2$ stresses for different times between these two consecutive stresses. The first and the second $-V_g$ stresses were both applied for 10 s. Fig. 1 shows

Fig. 1. The gate voltage shifts ($\Delta V_g$) for samples under two consecutive $-100$ mA/cm$^2$ stresses. Between these two consecutive steps of negative stresses, small opposite $+0.1$ mA/cm$^2$ stresses were applied for different times (s) to neutralize the pregenerated $Q_p$ in the oxide film.
the gate voltage shifts ($\Delta V_g$) of these samples. The first stress generated $Q_p$ which caused the initial decrease of $\Delta V_g$. The amount of generated $Q_p$ then saturated [5] and then $Q_n$, which was generated at the same time, just like that of the first stress. This indicates that the $Q_p$ generated by the first negative stress was neutralized by the reverse +0.1 mA/cm$^2$ current stress and re-generated during the second stress. For these samples, it is also seen that the decrease in $\Delta V_g$ saturates after the +0.1 mA/cm$^2$ stress for 20 s. This suggests that the precreated $Q_p$ had been completely neutralized. And in the following studies, a +0.1 mA/cm$^2$ stress for 30 s was applied to neutralize the negatively created $Q_p$ and thus differentiate the respective effects of $Q_p$ and $Q_n$.

Fig. 2 shows gate voltage shifts, $\Delta V_g$, of +0.1 mA/cm$^2$ stresses for the samples to which negative stresses of different current densities had been preapplied, but with the same total injected charges of $-1$ C/cm$^2$. For the fresh sample, which did not receive any negative stresses, the $\Delta V_g$ curve decreased due to the generation of $Q_p$ near the gate/SiO$_2$ interface [3]–[5], [8] upon $+J_g$ stressing. However, for the samples which had been prestressed with negative currents, all $\Delta V_g$ curves increased rapidly initially then saturated. These initial voltage increments were resulted from recombination of the positively injected electrons with the preexisting $Q_p$'s which were generated by the negative prestressing currents. The more $Q_p$'s generated by the higher negative current stress [7]–[9], the more the initial rising of the $\Delta V_g$ curve. The final saturation of all curves indicated that for all cases, $Q_p$ had been completely neutralized by the positive current stress. On the other hand, since the positive neutralizing stress was relatively small, only +0.1 mA/cm$^2$ stress with 0.003 C/cm$^2$ of total injected charges, it is reasonable to assume that the distribution of the preexisting $Q_n$ was not disturbed by it.

The above phenomenon can be explained with the aid of Fig. 3, in which Fig. 3(a) shows the generated $Q_p$ and $Q_n$ after the first negative stress, and Fig. 3(b) shows that $Q_p$ near the SiO$_2$/Si interface had been neutralized and small quantity of newly generated $Q_n$ appeared near the gate/SiO$_2$ interface due to the small reverse positive stress but $Q_n$ stayed undisturbed.

![Gate Voltage Shifts](image1)

**Fig. 2.** The gate voltage shifts ($\Delta V_g$) under +0.1 mA/cm$^2$ stress for samples prestressed by $-0.1$, $-1$, $-10$, $-100$, and $-500$ mA/cm$^2$ with the same total injected charges of $-1$ C/cm$^2$. The neutralization of $-I_g$ stress-generated $Q_n$ by the $+I_g$ stresses led to the initial increase of their $\Delta V_g$ curves. The higher the $-I_g$, the larger the initial $\Delta V_g$-increment, i.e., the more $Q_n$ neutralized.

![Gate Voltage Shifts](image2)

**Fig. 3.** The distributions of $Q_p$ and $Q_n$, pregenerated by a $-V_g$ stress, (a) before and (b) after application of the +0.1 mA/cm$^2$ stress. $Q_p$ near the SiO$_2$/Si interface had been neutralized and small quantity of newly generated $Q_n$ appeared near the gate/SiO$_2$ interface due to the small reverse positive stress but $Q_n$ stayed undisturbed.

![Gate Voltage Shifts](image3)

**Fig. 4.** The shifts of quasi-static $C$–$V$ curves after the $+J_g$ neutralizing stresses applied for samples prestressed with different $-J_g$ (mA/cm$^2$) stresses with the same total injected charges of $-1$ C/cm$^2$. The curves labeled with (R) were for samples neutralized.
left with the −100 mA/cm²-stressed curve shifting most. After the \( Q_p \)-neutralization, all curves shifted right. This exhibits the same results of the \( C-V \) curves.

From the shifts of the above \( C-V \) and \( I-V \) curves, before and after \( Q_p \)-neutralization, we can derive the quantities and locations of centroids for \( Q_p \) and \( Q_n \), respectively. This can be done in the following way: Comparing the \( C-V \) curves of a sample, before and after its \( Q_p \)-neutralization, we can derive the flat band difference \( \Delta V_{fb} \) of these two curves. Similarly, we can derive the gate voltage shift \( \Delta V_{fb-I} \) of the negative \( I-V \) curves of the sample, before and after it was neutralized. During measuring this \( \Delta V_{fb-I} \), the \( I-V \) curves were measured at a current level of \(-10^{-6}\) A/cm² to prevent disturbing the unstable \( Q_p \) in oxide film. The obtained \( \Delta V_{fb} \) and \( \Delta V_{fb-I} \), mainly due to the existence and nonexistence of \( Q_p \) can be used to be \( \Delta V_{fb} \) and \( \Delta V_{fb-I} \), respectively, in the following equations to compute the quantity and the location of \( Q_p \) [12]

\[
Q_p(x) = -\varepsilon_{ox} \times (\Delta V_{fb}(x)^+ + \Delta V_{fb}(x)^-) / T_{ox} \tag{1a}
\]

\[
d_p(x) = T_{ox} \times (\Delta V_{p(x)}^- - (\Delta V_{p(x)}^+ + \Delta V_{p(x)}^-)) \tag{1b}
\]

where \( d_p(x) \), \( \varepsilon_{ox} \), and \( T_{ox} \) are the centroid of \( Q_p(x) \) measured from the substrate, the oxide dielectric constant and the oxide thickness, respectively.

On the other hand, after the \( Q_p \)-neutralization, nearly only \( Q_n \) existed in the oxide film. We can also derive the quantity and the centroid of \( Q_n \) by computing \( \Delta V_{fb} \) and \( \Delta V_{fb-I} \) from the curves of Figs. 4 and 5. In these figures, the curves marked with \((R)\) are curves corresponding to the case where only \( Q_n \) is present in the oxide film. And comparing the \((R)\) curves with the curve of the fresh sample, we can derive \( \Delta V_{fb} \) and \( \Delta V_{fb-I} \), which are used to be \( \Delta V_{fb} \) and \( \Delta V_{fb-I} \), respectively. In this case, \( \Delta V_{fb-I} \) was extracted at a current level of \(-10^{-1}\) A/cm² to minimize the amount of undetectable charges trapped in the tunneling distance of negative \( I-V \) measurement. With the obtained \( \Delta V_{fb} \) and \( \Delta V_{fb-I} \), the quantity and the location of the centroid of \( Q_n \) can be computed by using the similar formulas of (1).

It has to be mentioned that the above method can only be applied to monitor distributions of trapped charges generated by negative gate voltage stresses. This is because the trapped charges are mostly generated near the SiO₂/Si interface [3]–[5], [8] under the \(-V_g\) stress. They can be detected by the \( C-V \) and the negative \( I-V \) curve shifts. However, for the positive stress, the generated charges are mostly near the gate/SiO₂ interface. The \( C-V \) curves and negative \( I-V \) curves are not sensitive to their existence. And thus the positively created charges can not be fully and correctly detected by our method. This is also the reason that, in Fig. 3(b), although a comparatively small quantity of \( Q_p \) were unavoidably generated near the gate/SiO₂ interface during the \(-0.1\) mA/cm² neutralizing stress, they were neglected in the previous computation for determining \( Q_p \) and \( Q_n \). Moreover, for the positive stress, an opposite \(-0.1\) mA/cm² stress is needed to neutralize the precreated \( Q_p \). This \(-0.1\) mA/cm² stress will also inevitably generate new \( Q_p \) near the SiO₂/Si interface. And this can not be neglected as in the negative stress case, since errors will be introduced in the extracted data.

The above method was used to extract the quantities and locations of the centroids of generated \( Q_p \) and \( Q_n \) in the oxide stressed by different negative current densities. Fig. 6(a) and (b) shows the extracted data for \( Q_p \) and \( Q_n \).
Fig. 7. The calculated (a) quantities \( Q_{p(n)} \) and (b) centroids \( d_{p(n)} \) of both positive and negative trapped charges generated by \(-10 \text{ mA/cm}^2\) stresses with \(-1, -5, \text{ and } -10 \text{ C/cm}^2\) of total injected charges. In which, oxides of some samples were degraded by the PPA at 900, 950, or 1000 °C for 10 min.

respectively, for the total stressing charges of \(-1, -5, \text{ and } -10 \text{ C/cm}^2\). Both generated trapped charges are found to be near the anode [3]–[5], [8], while the higher the stressing current density, the more away the centroid is from the substrate, in addition to the larger generated quantities [7]–[9]. This is easy to be understood since the higher current density needs a higher applied field which gives more energy to injected electrons to generate traps in the oxide. On the other hand, \( Q_{p} \) increases rapidly at the initial stress and is larger than \( Q_{n} \) for this range of stressing current. While when increasing the injected charges, \( Q_{p} \) saturates after the injected charges reaches 5 C [5], but \( Q_{n} \) keeps increasing. This suggests that, initially in the oxide, hole traps are much more than electron traps. Upon stressing, these hole traps are easily filled up, which depends on the stressing field, and afterward electron traps are continuously generated by the stressing current.

The above method was also used to investigate the reliability of oxides for the samples subjected to post-poly-annealing (PPA) at 900, 950, and 1000 °C, respectively, by monitoring the stress generated charges. Fig. 7(a) and (b) shows the quantities of \( Q_{p} \) and \( Q_{n} \), and their respective centroids, \( d_{p} \) and \( d_{n} \), of the samples stressed by \(-10 \text{ mA/cm}^2\) with \(-1, -5, \text{ and } -10 \text{ C/cm}^2\) of total injected charges. These figures show that more \( Q_{p} \) and \( Q_{n} \) are generated for the samples applied by PPA at the higher temperature [10], and \( Q_{n} \) is more susceptible to the PPA. This indicates that PPA does degrade the quality of the oxide and the factor to cause oxide breakdown is mainly associated with the \( Q_{n} \) generation. Also, for the higher PPA temperature or the larger injected charges, the centroid of \( Q_{n} \) is more far away from the substrate, i.e., more near the injection interface. This also indicates that a shorter accelerating distance is sufficient for the injected electrons to generate \( Q_{n} \) trapping states in the degraded oxide which probably has more weak spots in it after PPA. But for \( Q_{p} \), the trend is opposite. In which, its centroid, \( d_{p} \), becomes closer to the substrate for the higher PPA temperature or the larger injected charges.

As mentioned previously, \( Q_{p} \) and \( Q_{n} \) of \(+V_{g}\) stressed oxides can not be derived by our proposed method. It is interesting also to investigate these trapped charge distributions in the oxide. Fig. 8 shows the changes of normalized quasi-static \( C-V \) curves (\( C_{FB}/C_{ox} \)) for MOS capacitors after they were stressed by \(-10 \text{ or } +10 \text{ mA/cm}^2\), both with 1, 5, 10, and 20 C/cm² of total charges injected. The larger distortions of negatively stressed curves reveal that the interface states generated by \(-V_{g}\) stress were more than those by \(+V_{g}\) stress, especially for large injected charges. This could be attributed to that, upon \(-V_{g}\) stressing, electrons were injected from the gate and thus more damages were created at the oxide/substrate interface to generate interface states [13]. On the other hand, at the initial stage of \(-V_{g}\) stresses, i.e., the \(-1 \text{ C and } -5 \text{ C stresses, the curves shifted to the negative due to a large amount of } Q_{p} \text{ generated near the oxide/substrate interface. When increasing the injected charges, } Q_{p} \text{ remained almost constant and } Q_{n} \text{ was continuously generated. But the effect of } Q_{n} \text{ was not felt in the curves’ shifts, since } d_{p} \text{, the centroid of } Q_{p} \text{, moved closer while } d_{n} \text{ moved away from the oxide/substrate interface. However, for the } +V_{g} \text{ stresses, the more the stress, the more the curves shifted to the positive. This probably indicates that } Q_{p} \text{ and } Q_{n} \text{ were generated near the gate/oxide interface with their centroids,}}
$d_p$ and $d_n$, shifting to the gate/oxide and the oxide/substrate interfaces, respectively. Moreover, the $\Delta V_g$ curves during the neutralization process by applying an opposite small stress can also give some hint on the quantity of positively generated $Q_p$. Fig. 9 shows the gate voltage shifts of $-0.1$ mA/cm$^2$ neutralizing stresses (in open dot curves) for the PPA treated samples which were prestressed by $+10$ mA/cm$^2$ with $1$ C/cm$^2$ of total injected charges. The initial rapid increase of the curves indicate that $+V_g$ stress created $Q_p$ was neutralized by the latter $-J_g$ stress. And the higher temperature PPA, the more $Q_p$'s were generated upon $+V_g$ stressing. For comparison, similar samples were applied with $-10$ mA/cm$^2$ stress but neutralized by $+0.1$ mA/cm$^2$, and their $\Delta V_g$ curves corresponding to this $-0.1$ mA/cm$^2$ neutralizing stress are also plotted in Fig. 9 (in black dot curves). Comparing the initial increments of these $\Delta V_g$ curves, we find that the $+V_g$ stressed curves have smaller initial increments than those of $-V_g$ stressed curves, i.e., $Q_p$ generated by $+V_g$ stress is less than that of $-V_g$ stress. This may also be one of the reasons for that $-V_g$ stresses result in smaller breakdown charges than $+V_g$ stresses [14].

In the end of this work, the reversible characteristics of trapped charges, with their trapping levels being irrespective to the previous stresses but only determined by the final stressing field [9], [11], is investigated. In this study, samples were first stressed by a $J_1$ of different densities of $-500$, $-100$, $-10$, $-1$, and $-0.1$ mA/cm$^2$, all with $-0.5$ C/cm$^2$ of total injected charges, to generate trapped charges in the oxides. Then they were stressed again by a following second $J_2$ of $-0.1$ mA/cm$^2$ stress. During this $J_2$ stress, the gate voltage shifts, $\Delta V_g$, were plotted in Fig. 10. For fresh sample, which was not $J_1$ stressed, the initial decrease of its $\Delta V_g$ curve indicates that $Q_p$ was generated upon $J_2$ stressing. However, the other samples with $J_1$ prestresses have initial increments on their $\Delta V_g$ curves, indicating $Q_p$'s generated in the first $J_1$ prestressing step were neutralized by the following $J_2$ stress. Also for the samples with higher $J_1$ stresses, the larger initial increments are observed. It is because the magnitude of the following $J_2$ stress was comparatively smaller than that of $J_1$ ($-1$ mA to $-500$ mA, except $0.1$ mA) and hence $J_2$ did not generate $Q_p$, instead, neutralized the $J_1$ pregenerated $Q_p$ near the oxide/substrate interface. This can be further verified by observing the $\Delta V_g$ curves of the samples applied with a $+0.1$ mA/cm$^2$ stress to neutralize the remaining $Q_p$'s after the $J_2$ stress. The $\Delta V_g$ curves are shown in Fig. 11 (in open dot curves). For comparison, the $\Delta V_g$ curves of $+0.1$ mA/cm$^2$ neutralizing stresses for another similar set of samples, which were not applied with the $J_2$ stress to neutralize the $J_1$ stress created $Q_p$'s, are also shown in Fig. 11 (in black dot curves). The black dot curves have much larger initial increments, especially for the higher $J_2$ stress, indicating more $Q_p$'s were neutralized by the $+0.1$ mA/cm$^2$ stress. On the contrary, the three open dot curves have much smaller initial increments and almost coincide together. This again verifies that a large portion of $Q_p$ had already been neutralized by the $J_2$ stress.
The quantities of $Q_p$ and $Q_n$ of the above samples after they were just $J_1$ stressed and then $J_2$ neutralized, respectively, were also extracted by using our proposed method. Fig. 12 shows the extracted quantities of $Q_p$ and $Q_n$ for the above samples. It can be seen that just after $J_1$ stresses (the circular dot curves of total injected charge of 0.5 C and the square dot curves of total injected charge of 1 C), the higher $J_1$ stressing current or the larger injected charges resulted in the larger $Q_p$ and $Q_n$. However, when the $J_2$ stress was applied (the diamond dot curves of the total injected charges for $J_1$ of 0.5 C followed by $J_2$ of 0.5 C), the pregenerated $Q_p$ is found to decrease, especially for higher $J_1$ current densities. And the resulted $Q_p$’s for all $J_1$ densities are very close in their quantities. This indicates that $Q_p$’s generated by $J_1$ stresses were neutralized by $J_2$ and their final quantities depend somehow on the level of the final $J_2$ stressing current. That is, $Q_p$ is irrespective to the previous stresses but only determined by the final stressing field. On the other hand, $Q_n$ keeps increasing for the additional $J_2$ stress. This also indicates that precreated $Q_n$, not like $Q_p$, is very stable and not easy to be disturbed by the following stress.

**IV. CONCLUSION**

In this paper, a measurement method was proposed to monitor the respective quantity and centroid of charges, $Q_p$ and $Q_n$, which were generated by the negatively applied high field stress. The method was based on the $Q_p$-neutralization by a low positive current stress to differentiate the effects of $Q_p$ and $Q_n$ on $C - V$ and $I - V$ curves. By using this method to extract the quantities and centroids of $Q_p$ and $Q_n$, we found that $Q_p$ and $Q_n$ are generated near the oxide/substrate interface by the negative stress. And higher fields or more injected charges generate larger quantities of $Q_p$ and $Q_n$. During stressing, $Q_p$ is initially much larger than $Q_n$, but then $Q_p$ saturates in its quantity and moves closer to the oxide/substrate interface, while $Q_n$ keeps increasing and moves away from the interface, especially for those PPA treated oxides. $Q_p$ is very unstable and easy to be neutralized, either by a small stress of opposite polarity or the same polarity. For the latter, it is the so called “reversible characteristics” of $Q_p$, i.e., the quantity of $Q_p$ is mainly dependent on the level of the final stressing field.

**REFERENCES**


Yung Hao Lin was born in Taichung, Taiwan, R.O.C., in 1969. He received the B.S. and Ph.D. degrees from the Department of Electronics Engineering, National Chiao-Tung University, Hsinchu, Taiwan, in 1991 and 1996, respectively. He is currently continuing postdoctoral research at National Chiao-Tung University. His research interests include the fabrication technology and the reliability analysis of thin gate dielectrics.

Chung Len Lee (S’70–M’75–SM’92), for a photograph and biography, see p. 159 of the January 1997 issue of this *Transactions*.

Tan Fu Lei, for a photograph and biography, see p. 159 of the January 1997 issue of this *Transactions*. 