Effects of stress conditions on the generation of negative bias temperature instability-associated interface traps*

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The exponent n of the generation of an interface trap (N_{it}), which contributes to the power-law negative bias temperature instability (NBTI) degradation, and the exponent's time evolution are investigated by simulations with varying the stress voltage V_g and temperature T. It is found that the exponent n in the diffusion-limited phase of the degradation process is irrelevant to both V_g and T. The time evolution of the exponent n is affected by the stress conditions, which is reflected in the shift of the onset of the diffusion-limited phase. According to the diffusion profiles, the generation of the atomic hydrogen species, which is equal to the buildup of N_{it}, is strongly correlated with the stress conditions, whereas the diffusion of the hydrogen species shows V_g-unaffected but T-affected relations through the normalized results.

Keywords: negative bias temperature instability, reaction–diffusion model, interface trap

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1. Introduction

As one of the most important reliability issues in modern CMOS technology, negative bias temperature instability (NBTI) manifests itself as the degradation of device parameters when subjected to a negative gate bias at high temperature.[1–5] The previous studies have shown that interface traps (N_{it}) and oxide traps (N_{ot}) are the reasons for the NBTI degradation, with N_{it} dominating the degradation.[6–8]

To investigate the buildup of N_{it} and the relevant NBTI degradation, the reaction–diffusion (R–D) model, which interprets the power-law dependence of N_{it} generation, has been employed in many studies.[9–11] Whether the exponent n of the power-law relationship is independent of the stress conditions remains in dispute due to discrepancies in experimental results.[12–14] Besides, the impact of the stress conditions on the time evolution of the exponent n requires more attention.

In this paper, a simulation based on the R–D model is implemented to investigate the effects of various stress conditions on the exponent n of the power-law dependency and its time evolution. The diffusion profiles during the reaction-limited and diffusion-limited phases of the R–D theory for N_{it} generation are noticed to reveal the connection of the evolution of the exponent n with the varied stress conditions.

2. Simulation details

The simulation is performed with the modeling interface-defect generation simulator with atomic hydrogen as the diffusion species. A pMOSFET having a gate oxide thickness of 1.6 nm is employed. To analyze the influence of the stress conditions on the NBTI degradation, the stress voltage V_g applied is changed from -1.6 V to -2.2 V with the temperature T kept at 100 °C for the V_g-varied simulation, and four temperatures are selected from 80 °C to 150 °C with $V_g = -2.0$ V for the T-varied simulation. The generation of N_{it}, the time evolution of the exponent n, and the diffusion profiles at different stress time are observed simultaneously.

3. Results and discussion

3.1. Effect of stress voltage

In order to find out whether the applied V_g affects the exponent n of the power-law degradation, the simulation is conducted under $T = 100$ °C with V_g varied. Figure 1 shows the increase of N_{it} with stress time under different V_g. Obviously as shown in the inset of Fig. 1(a), all the curves go through a two-stage process which reflects the reaction-limited and diffusion-limited phases in the R–D theory. Besides, the second stages of the curves seem to be almost parallel. The tangency point at which the slope of the degradation is close to its stabilized value (close to 0.25) is considered as the on-

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set of the diffusion-limited phase in the R–D process. Thus, the time of the onset is found to reduce with increasing V_g, as shown in Fig. 1(a).

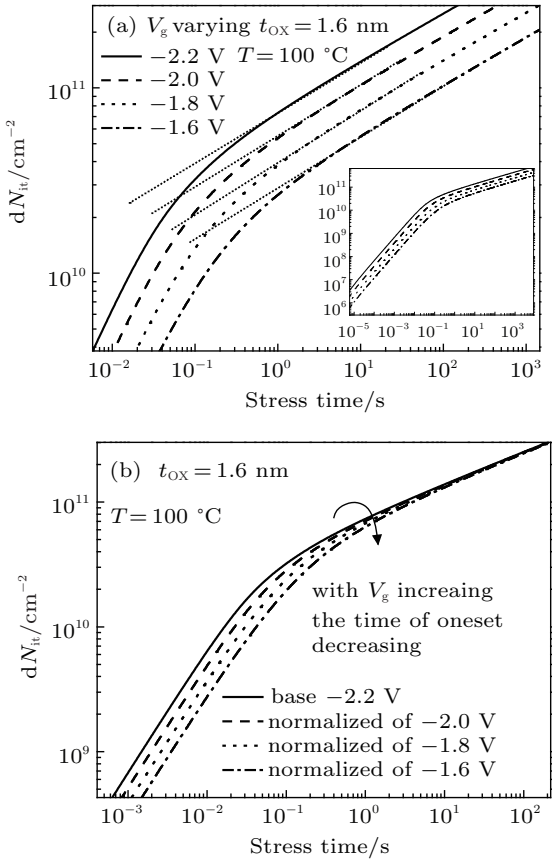


Fig. 1. Variation of N_{it} with stress time for different V_g. (a) Curves in the magnified (main figure) and original (inset) views. (b) Normalized curves.

In Fig. 1(b), the curves are parallel shift by normalizing to obtain the overlapped second stages of the curves. The slopes of the overlapped parts of the curves obtained by data fitting are listed in Table 1. The fitted slopes which correspond to the exponent n of the power-law degradation are approximately identical for the varied V_g (with ±0.08% margin). The tiny difference between the results obtained after 1 s and those at 10 s can be explained by the changing of the exponent n during the transition process before entering into the diffusion-limited phase. This is evidence for that the exponent n is independent of V_g.

Table 1. Power fitted slopes of the curves with varied V_g.

V_g/V	−1.6	−1.8	−2.0	−2.2
Fit after 1 s	0.24826	0.24840	0.24845	0.24840
Fit after 10 s	0.24606	0.24671	0.24718	0.24747

The diffusion profiles with V_g of −1.6 V and −2 V are shown in Fig. 2. Due to the difference in the amount of generated N_{it}, which is equal to the amount of generated atomic hydrogen species under the varied V_g conditions, the curves of the two V_g are quite different as shown in Fig. 2(a). Whereas, after normalizing the data of the lower V_g by multiplying with an appropriate value, the curves of the two V_g at the same time can be superposed perfectly, as shown in Figs. 2(b) and 2(c), indicating that differences in V_g only impact the amount of N_{it}, not the diffusion rate. This is believed to be another clue for the independence of V_g on the exponent n. According to the R–D model, the generation of N_{it} is associated with the forward and reverse reaction rates, which are relevant to the concentrations of the reactants and resultant in an electrochemical reaction that is a reversible process. In the reaction-limited phase, the forward reaction rate, which dominates the degradation, is determined by the applied electric field. The larger applied V_g means the higher electric field, which induces a faster reaction and hence the faster generation of the resultants as shown in Fig. 2(a). But when the process comes into the diffusion-limited phase, which corresponds to the time when the reaction process is no longer determined by V_g, the diffusion of the resultant, which is considered as an electric-neutral hydrogen species, facilitates the forward reaction and affects the net reaction rate. In addition, the diffusion of the hydrogen species is relevant to the concentration gradient but irrelevant to the electric field, leading to the V_g-unaffected degradation slope in the diffusion-limited phase.

The time evolution curves of the exponent n under different V_g are shown in Fig. 3. From right to left, the curves of different V_g are distributed with increasing V_g. The time when the exponent n approaches 0.25, i.e., the onset of the diffusion-limited phase in the R–D process, is denoted as TOD. The larger the applied V_g is, the smaller the TOD will be, which is also shown by the normalized curves in Fig. 1(b).

The tendency of the leftward distribution along with the increased V_g can be understood through the R–D process. When a certain amount of N_{it} is generated, the forward reaction is restrained by the increase in the reactant, which causes a decrease in the degradation slope n. The larger V_g leads to generating more N_{it} and causes an earlier appearance of the downtrend of the exponent n. Besides, the transition from the reaction-limited phase to the diffusion-limited phase is related to the accumulation of the resultant hydrogen species. The transition of the hydrogen species produced may appear earlier due to a greater amount of N_{it} generated with the larger V_g compared to that with a smaller V_g. Thus, from the different time evolution of exponent n, we can conclude that the smaller TOD corresponds to the greater degradation with the varied V_g conditions.

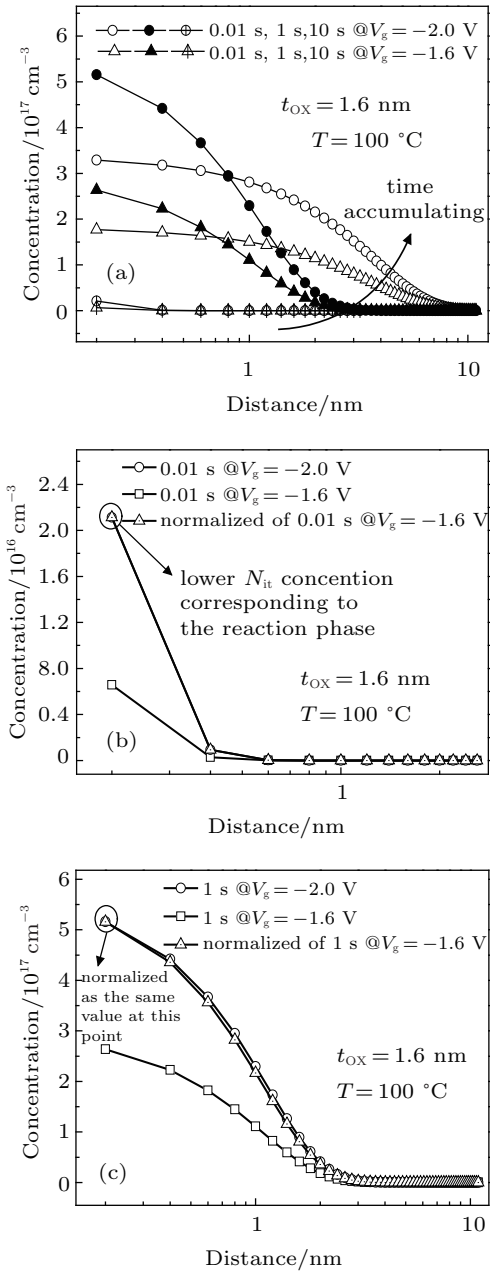


Fig. 2. Diffusion profiles at the fixed stress time for different V_g. (a) Original curves at three time points. (b) Results normalized at 0.01 s. (c) Results normalized at 1 s.

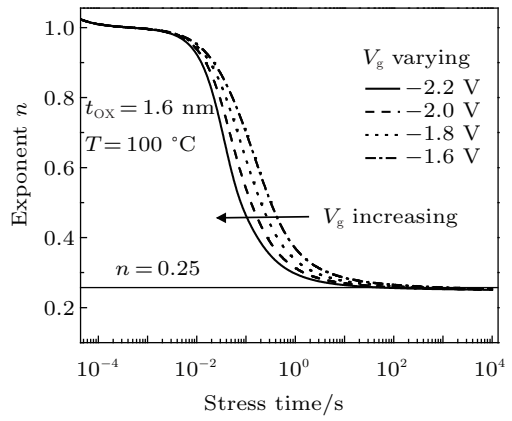


Fig. 3. Evolution of exponent n with stress time for different V_g.

3.2. Effect of temperature

To study the relationship of T and exponent n, simulations with varied T are carried out under a fixed V_g stress. Figure 4 shows the generated N_{it} under $V_g = -2.0$ V with T ranging from 80 °C to 150 °C. The two-stage curves are partially overlapped in the initial part of the degradation, while the curves at the second stage seem to be almost parallel but with different onsets of the diffusion-limited phase. It is clear from the tangent lines in Fig. 4 that the onset of the diffusion-limited phase is delayed by the higher T.

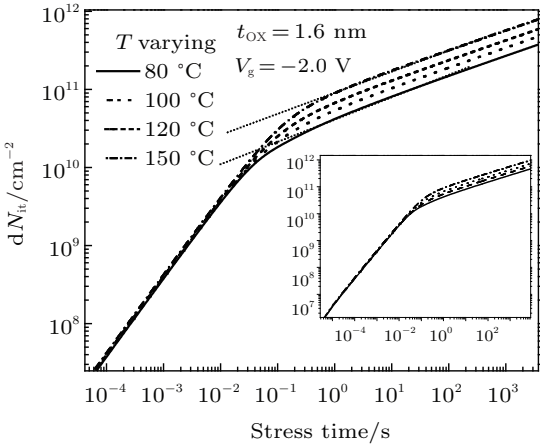


Fig. 4. Variation on N_{it} with stress time for different T in the magnified (main figure) and original (inset) views.

The exponent n of the degradation in the diffusion-limited phase obtained by data fitting is listed in Table 2, and the obtained slopes are within a margin of ±0.5%. It is indicated that the stress T barely affects the exponent n.

Table 2. Power fitted slopes of the curves with varied T.

T/°C	80	100	120	150
Fit after 1 s	0.24782	0.24716	0.24648	0.24537
Fit after 10 s	0.24880	0.24845	0.24807	0.24746

The diffusion profiles with $T = 100$ °C and 150 °C are drawn in Fig. 5. Technically, the time is selected according to the R–D process for the diffusion profile curves. At 0.01 s, corresponding to the reaction-limited phase, the normalized curve of 100 °C is lower than that of 150 °C, indicating that a higher T accelerates N_{it} generation. At 1 s and 10 s, the process comes into the diffusion-limited phase, the N_{it} concentration (equals to the concentration of the resultant hydrogen species) peaks at 150 °C are lower than those at 100 °C, though the areas under the curves of the higher T are greater than those for the lower T.

As shown in Figs. 5(b) and 5(c), to compare the resultant hydrogen species diffusion under these two stress levels, the data of 100 °C are normalized to get the same peak values as those of 150 °C. Unlike the situation of V_g-varied simulation

discussed above (the curves of different V_g are superposed after normalizing), here a divergence of the curves with varied T is observed, which suggests that different diffusion processes are induced by the varied T. Whenever the process of N_{it} generation is in the reaction-limited or diffusion-limited phase, the rightward located curves of 150 °C imply that a higher T accelerates not only the formation but also the diffusivity of the resultant hydrogen species.

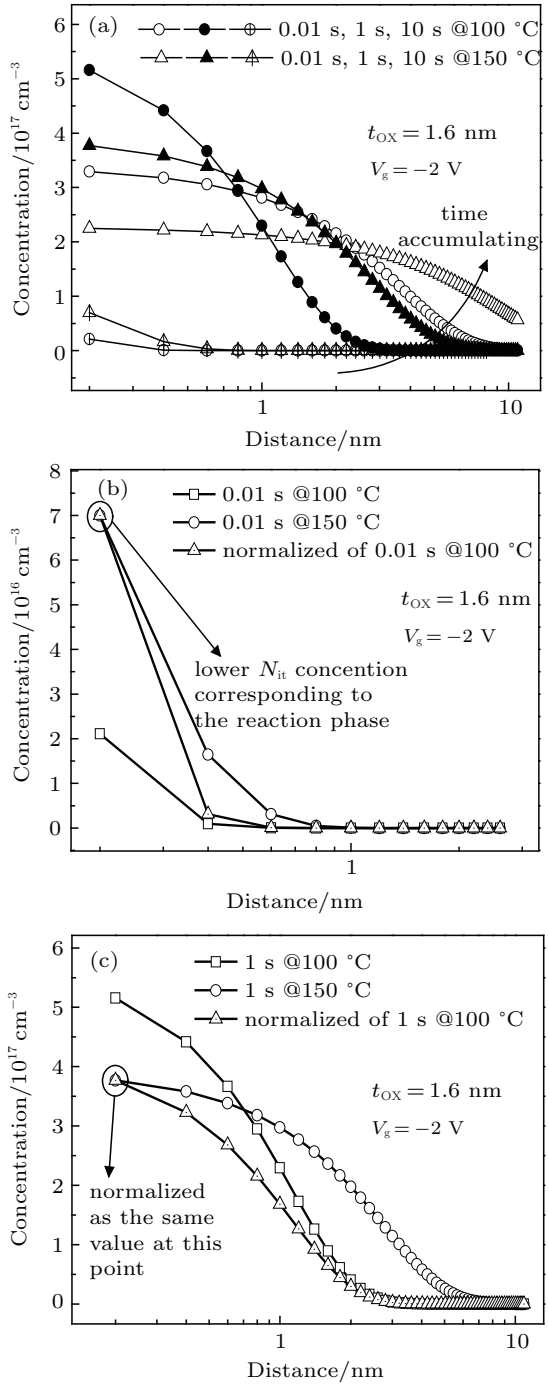


Fig. 5. Diffusion profiles at fixed stress time for different T. (a) Original curves at three time points. (b) Results normalized at 0.01 s. (c) Results normalized at 1 s.

Actually, based on the R–D model, either the reaction or diffusion process is influenced by T. The higher T weakens the energy of the Si–H bond and promotes the electrochemical reaction, leading to the increase in the amount of generated N_{it}. Besides, the diffusion of the resultant hydrogen species is accelerated due to the enhanced diffusivity, which is a constant affected by the concentration gradient and T.

Figure 6 shows the time evolution of the exponent n, revealing that the TOD is smaller with a lower T, which is in accord with the phenomenon that the larger degradation appears under the higher T condition in Fig. 4. It can be seen that the transition phase takes a shorter duration for the higher T, which implies that the higher T defers the time for the diffusion-limited phase, resulting in the aggravated degradation. A possible explanation for the rightward distributed tendency with higher T is that the accelerated diffusion of the resultant does not benefit the accumulation of the hydrogen species, resulting in the delay of the oncoming of the diffusion-limited phase.

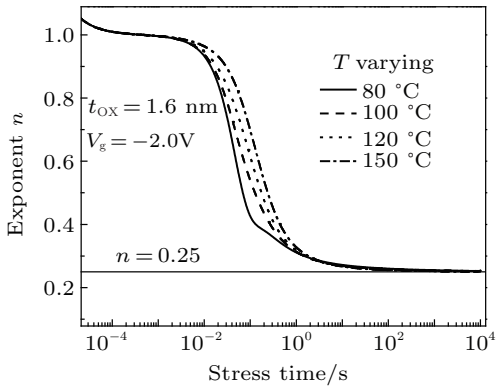


Fig. 6. Evolution of exponent n with stress time for different T.

4. Conclusion

An investigation of the exponent n of the power-law degradation and its time evolution is performed with varied V_g and T stress. The irrelevancy of the stress condition to the value of the exponent n in the diffusion-limited phase of the degradation process is verified by the simulated results. However, the time evolution of the exponent n is influenced by different stress conditions. The onset of the diffusion-limited phase is advanced by a larger V_g, while postponed by a high T. From the diffusion profile results, we can see that the process of N_{it} generation is impacted by both V_g and T stress, but the diffusion of the resultant hydrogen species presents V_g-unaffected but T-affected relations through the normalized results.

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