Flat-roof phenomenon of dynamic equilibrium phase in the negative bias temperature instability effect on a power MOSFET*

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The effect of the static negative bias temperature (NBT) stress on a p-channel power metal–oxide–semiconductor field-effect transistor (MOSFET) is investigated by experiment and simulation. The time evolution of the negative bias temperature instability (NBTI) degradation has the trend predicted by the reaction–diffusion (R–D) model but with an exaggerated time scale. The phenomena of the flat-roof section are observed under various stress conditions, which can be considered as the dynamic equilibrium phase in the R–D process. Based on the simulated results, the variation of the flat-roof section with the stress condition can be explained.

Keywords: negative bias temperature instability (NBTI), reaction–diffusion model, interface traps, power MOSFET

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1. Introduction

As device dimensions continuously scaling down, negative bias temperature instability (NBTI) has been identified as one of the most important reliability issues in modern complementary metal oxide semiconductor (CMOS) technology.[1–3] For years, many attempts have been made to study the NBTI effect in terms of experiments, modeling, and mechanism with different MOS structures and measurement conditions.[4–9] The majority of those works are commonly conducted with nanometer scale devices. However, the NBTI could also be crucial for ultra-thick gate oxide devices such as the power metal–oxide–semiconductor field-effect transistor (MOSFET) as its operation condition of high current and high voltage favors the NBTI.

The underlying buildup of the NBTI degradation, which is described by the reaction–diffusion (R–D) theory, is believed to apply to the power MOSFET, as studies have shown that the degradation behavior of the power MOSFET is similar to that of nanometer scale devices.[10–12] Nevertheless, the structural and technological diversities of the power MOSFETs bring some different phenomena in NBTI experiments when compared with nanometer scale devices, which requires more analysis and investigation in order to find a reasonable explanation.

In this paper, the experiments on p-channel power MOSFETs are conducted under a static NBT stress. The phenomena of the flat-roof section are observed for the varied stress conditions. And the discrepant observations under different stress conditions are analyzed with the assistance of a simulation based on the R–D framework.

2. Experiment and simulation details

2.1. Experiment setting

The experiments are performed with commercial p-channel power MOSFETs from the IRF74×× series. For the static NBT stress, negative gate voltages $V_g = -12$ V and $V_g = -14$ V are applied with stress temperature T selected at 100 °C and 150 °C. The conventional stress-interrupted measurement methodology is adopted to characterize the NBTI effects through the observation of V_{th} shifting.

2.2. Simulation details

The generation of N_{it} contributing to the NBTI degradation is described by the R–D framework as follows:

$$\frac{dN_{it}}{dt} = k_f(N_0 - N_{it})P - k_r N_H N_{it}, \quad (1)$$

$$\frac{dN_{it}}{dt} = -D_H \frac{dN_H}{dx}\bigg|_{x=0}, \quad (2)$$

$$\frac{dN_H}{dt} = D_H \frac{d^2 N_H}{dx^2}, \quad (3)$$

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where N_{it} is the interface trap density, N_0 is the initial concentration of the Si–H bond, N_H is the hydrogen concentration, k_f/k_r are respectively the forward/reverse reaction rates, P is the hole concentration, and D_H is the diffusion coefficient of H.

According to Eqs. (1)–(3), with the relationship between k_f/k_r, D_H, and the stress variables (stress time, voltage, and temperature), the degradation of V_{th} can be obtained from the relation $\Delta V_{th} \approx q\Delta N_{it}/C_{ox}$ and expressed as

$$\Delta V_{th} = A_0 A V_g \exp\left(BV_g\right) \cdot D_0 \exp\left(\frac{-E_a}{kT}\right) t^n, \tag{4}$$

where A_0 is a constant which is determined by the process condition and technology, A and B are the fitting constants for the electric field dependency, D_0 is the diffusion prefactor, E_a is the activation energy, k is the Boltzmann constant, and n is the exponent of the power-law relationship.[5,13,14]

Based on the above model function (4), the simulations are performed with the coefficients determined by the experiment and relevant studies.

3. Results and discussion

3.1. Experimental phenomena

The variations in V_{th} with the varied V_g and T are present in Fig. 1. As can be seen clearly, the degradation behaviors of different device samples obey the well-known power-law relationship predicted by the R–D theory, but the time evolution of the degradation has an exaggerated time scale compared to that of the nanometer device. Besides, in spite of the changed stress condition, all the curves show a flat-roof section between the two large slope sections and the different stress condition has an influence on the time duration of the flat-roof section; the earlier appearance and longer duration of the flat-roof section can be observed with higher V_g or lower T. In addition, the slope of the flat-roof section is about 0.02516, which can be approximately regarded as following the $\Delta \sim t^0$ relation.

The phenomena here are quite different from the often-observed results in other experiments, especially those on nanometer devices. However, the time span in which the degradation changes from the first large slope section to the last large slope section is in the range of 10^3 s to 10^4 s, which has the same order of magnitude as that in the other experiments.[10–12] The results reveal that the degradation trend of the power MOSFET follows the time evolution predicted by the R–D model, though the time scale is stretched by many orders of magnitude in the coordinate of stress time when compared to that of the nanometer scale MOSFET.

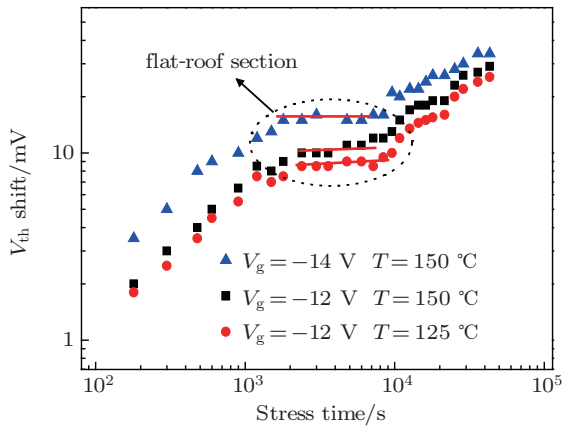


Fig. 1. (color online) Variations in V_{th} with stress time for different V_g and T.

3.2. Discussion of the flat-roof section

The function coefficients used in the simulation process are determined according to the after-transformation data which are obtained by condensing the stress time scale proportionally with the degradation shift unchanged. This transformation leads to the same shape of the degradation curve but with a small order of magnitude for the time coordinate as shown in Fig. 2, which demonstrates the comparison of the after-transformation experimental V_{th} degradation with the simulated N_{it} generation as a function of time. It is clear that the two curves have the same tendency and the same time span for the flat-roof section. However, the slope of the section after the flat-roof section is much larger in the experiment curve, which is due to the degradation slope increasing induced by the measurement delay.[5,6]

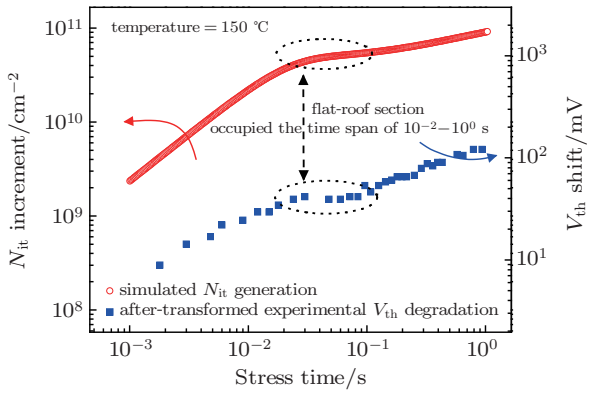


Fig. 2. (color online) Comparison between the after-transformation experimental and the simulated data.

According to the R–D theory, the increase of N_{it} results from the stress-initiated reversible electrochemical process with the forward and reverse reaction rates limited by the stress condition and the concentrations of the reactants and the resultants.[15,16] In the initial reaction-limited phase, as the resultants increase and the local electric field decreases, the occurrences of the restrained forward reaction and the enhanced

reverse reaction cause the decrease in the degradation slope. When the comparable forward and reverse resultants are produced, the dynamic equilibrium phase appears and leads to a flat-roof section following the $\Delta \sim t^0$ relation. Then with the hydrogen species sufficiently generated, the diffusion of the resultant hydrogen species breaks the reaction equilibrium and makes the net reaction rate limited by the diffusion, which implies the onset of the diffusion-limited phase. Thus, based on the experimental and the simulated results in Figs. 1 and 2, it is reasonable that the sections before and after the flat-roof can be regarded as the reaction-limited and the diffusion-limited phases, respectively, and the flat-roof section observed is referred to as the dynamic equilibrium phase in the R–D process.

To analyze the emergence of the flat-roof section in the degradation curves, the simulations of N_{it} generation are implemented with the coefficients in the model function (4) obtained from our data and references.[5,10–14] For the temperature-dependent term, the fixed coefficients D_0 and E_a are adopted, while for the electric field-dependent term, the coefficients A and B are in the range of 10^{-6} to 10^{-5} and 0.37 to 0.8, respectively. Thus, $A_1 = 10^{-5}$, $A_2 = 10^{-6}$, $B_1 = 0.75$, and $B_2 = 0.5$ are selected and their four different groups of combinations are considered as the simulation conditions, which are $(A_1,\ B_1) = (10^{-5},\ 0.75)$, $(A_1,\ B_2) = (10^{-5},\ 0.5)$, $(A_2,\ B_1) = (10^{-6}, 0.75)$, and $(A_2, B_2) = (10^{-6}, 0.5)$.

Figure 3(a) shows the simulation results of the N_{it} increment. The variation in N_{it} in the case of (A_1, B_1) exhibits three distinct stages with different slopes, which accords with our experimental observation in Figs. 1 and 2. Whereas the case of $(A_2,\ B_2)$ exhibits two obvious phases which are the reaction-limited and the diffusion-limited phases, respectively. Additionally, an obscure appearance of the flat-roof section with an extremely short time duration can be recognized in the case of (A_1, B_2) or (A_2, B_1).

The time evolutions of degradation slope n are drawn in Fig. 3(b). In the case of $(A_1,\ B_1)$, the value of n undergoes a non-monotonous evolution, which appears as a valley-like region with a near-zero value of 0.12 as the minimum, it indicates the appearance of the dynamic equilibrium phase. However in the case of $(A_2,\ B_2)$, the monotonous decrease in the slope can be seen, which means the absence of the flat-roof section. In the case of the left two conditions, shallower and smaller valley regions are present, implying the short and unapparent flat-roof sections.

Thus, from our simulation above, the disunity of the flat-roof section observation can be explained by different coefficient groups which are determined by various device conditions. The transformation of the time coordinate enables the application of the R–D model to degradation characterization for the power MOSFET.

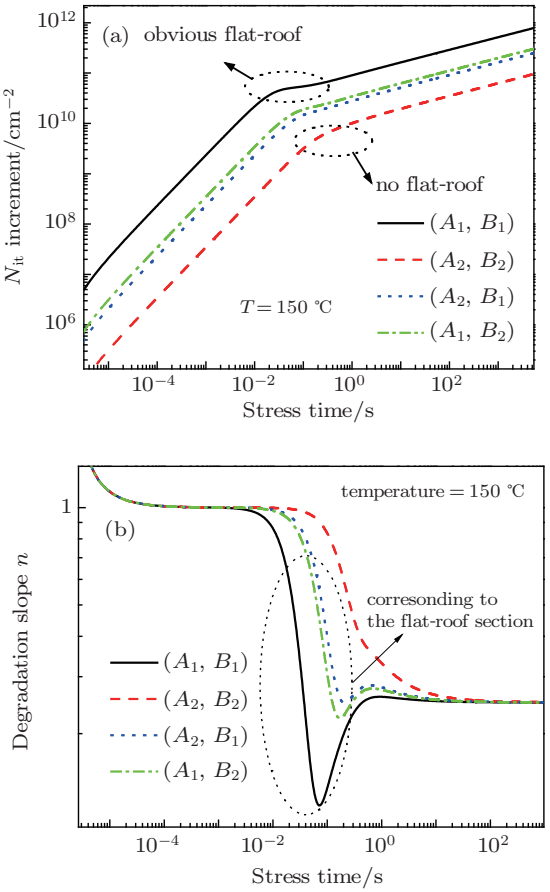


Fig. 3. (color online) Variations in (a) N_{it} generation and (b) degradation slope n as a function of time with the changed simulation coefficients. It is clear that in the case of $(A_1,\ B_1)$, the curve of N_{it} increment exhibits three distinct stages which represent the reaction-limited, dynamic equilibrium, and diffusion-limited phases in the R–D theory, respectively. The value of n rapidly decreases from 1 to the minimum value of 0.12 and then increases to 0.25, which seems as a valley-like region corresponding to the flat-roof section of the degradation curve.

3.3. Impact of stress condition on the flat-roof section

To illustrate the difference in the flat-roof section with the varied V_g and T, the simulations are performed and the results are shown in Fig. 4. As V_g increases, the time duration of the dynamic equilibrium phase is getting longer with its beginning time shifting in the negative direction of the time coordinate as shown in Fig. 4(a). Moreover, the minimum value of n is becoming smaller with the increased V_g. While in Fig. 4(b), the onset of the flat-roof section is postponed with the increased T, indicating a shorter duration of the dynamic equilibrium phase. And n has a larger minimum value when T is elevated.

The above simulations are in accordance with the result shown in Fig. 1, explaining the influence of the stress condition on the time duration of the flat-roof section.

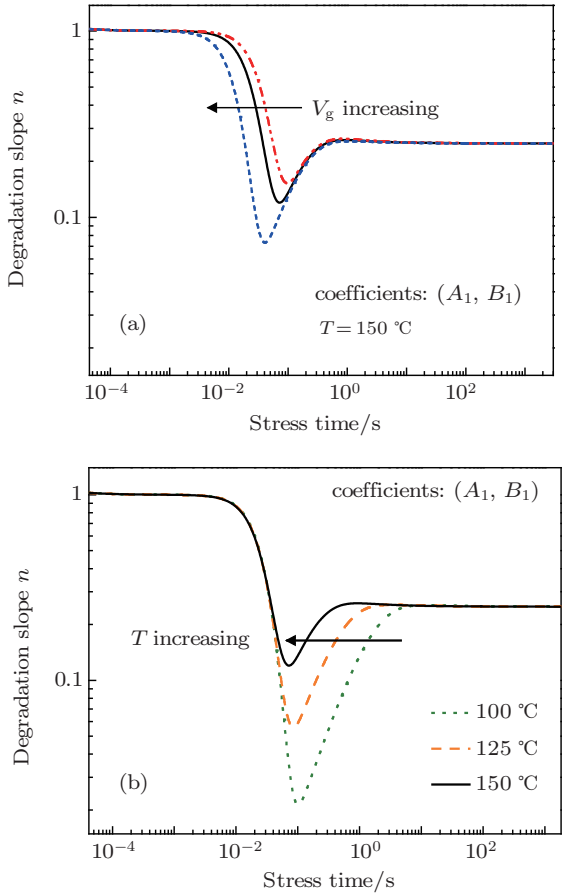


Fig. 4. (color online) Simulated results of the time evolution of n with various (a) V_g and (b) T. The coefficients of the electric field-dependent term are selected as $A_1 = 10^{-5}$ and $B_1 = 0.75$. The solid curves in both figures have the same simulation condition.

4. Conclusion

In this paper, the experiments of NBTI degradation on the power MOSFET are performed with various stress conditions. The V_{th} shift as a function of time obeys the power-law relationship predicted by the R–D theory. However, the degradation has the similar trend but with an exaggerated time scale compared to that of the nanometer MOSFET. Peculiarly, a flat-roof section is observed, which can be considered as the dynamic equilibrium phase in the R–D process. The time duration of the flat-roof section is effected by the stressed V_g and T, which has been verified by the simulation results.

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