The study on mechanism and model of negative bias temperature instability degradation in P-channel metal–oxide–semiconductor field-effect transistors*

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Negative Bias Temperature Instability (NBTI) has become one of the most serious reliability problems of metal–oxide–semiconductor field-effect transistors (MOSFETs). The degradation mechanism and model of NBTI are studied in this paper. From the experimental results, the exponential value 0.25–0.5 which represents the relation of NBTI degradation and stress time is obtained. Based on the experimental results and existing model, the reaction–diffusion model with H^+ related species generated is deduced, and the exponent 0.5 is obtained. The results suggest that there should be H^+ generated in the NBTI degradation. With the real time method, the degradation with an exponent 0.5 appears clearly in drain current shift during the first seconds of stress and then verifies that H^+ generated during NBTI stress.

Keywords: NBTI, 90nm, p-channel metal–oxide–semiconductor field-effect transistors (PMOSFETs), model

PACC: 7340Q, 7300, 7220J

1. Introduction

When the p-channel metal–oxide–semiconductor (PMOS) device is applied at strong negative gate bias and high temperature, the negative bias temperature instability (NBTI) happens usually, and the typical temperature range is 80–250 °C, just as shown in Fig. 1. During NBTI stress, the off current $I_{\rm off}$, threshold voltage $V_{\rm th}$ and sub-threshold swing S increase, while the drain current $I_{\rm ds}$ and transconductance $G_{\rm m}$ decrease. Therefore, with the rapid development of very large scale integration, NBTI has become one of the most serious reliability problems, and the whole industry is paying more attention to it.[1−8] The NBTI was found by Deal *et al.*[9] for the first time, and since then, much work has been done on the mechanism of NBTI. The generation of interface states and oxide charges are thought to be the origin of the degradation of NBTI in most models, and the mechanism of NBTI is always related to the H species.[10−15] However, some people took the H atom as the related H species, while some took the H_2 molecule. There is not a uniform opinion by now. To understand the NBTI degradation well, it is necessary to make the species clear.

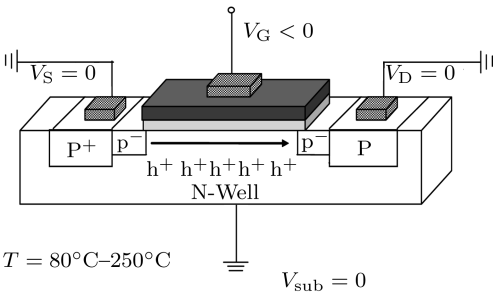


Fig. 1. The schematic diagram of NBTI stress on PMOS device.

In this paper, the effect of NBTI stress on the characteristics of PMOS devices is shown. From the results of experiments, we got the exponent representing the relation of NBTI degradation and stress time larger than 0.25 which is not consistent with the results of the neutral H related species. Based on the experimental results and the existing model, the reaction–diffusion (R–D) model with H^+ species is deduced. And then, with the help of the real-time

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measurement, it is proved that there is H^+ generated in the NBTI degradation.

2. Devices and experiments

The PMOSFETs used here are of surface channel. They were manufactured by using a 90 nm process technology with lightly doped drain structure and shallow trench isolation scheme. The gate oxides of all devices were annealed in N_2O atmosphere after thermal growth. The devices used here have an ultra-thin gate oxide thickness of 1.4 nm, gate width of 10 μm. Agilent B1500A, a high precision semiconductor parameter analyser, was used to complete the tests. The devices were stressed under NBTI stress conditions of $V_G = V_{stress}$, and $V_D = V_S = 0$ at elevated temperatures. Stress was interrupted at regular intervals, and device parameters such as threshold voltage V_{th} and sub-threshold swing S were measured.

3. Results and discussion

3.1. Results

Figure 2 shows the change of transconductance G_m and sub-threshold slope before and after NBTI stress. From Fig. 2(a), we can see that after NBTI stress, there is a clear decrease in G_m, and the peak point moves left, which shows that the gate controlling ability weakens, and there are positive charges generated in the SiO_2 or at SiO_2/Si interface. The sub-threshold slope gets smaller after NBTI stress as shown in Fig. 2(b). The decreased sub-threshold slope indicates the generation of the interface traps at the SiO_2/Si interface.

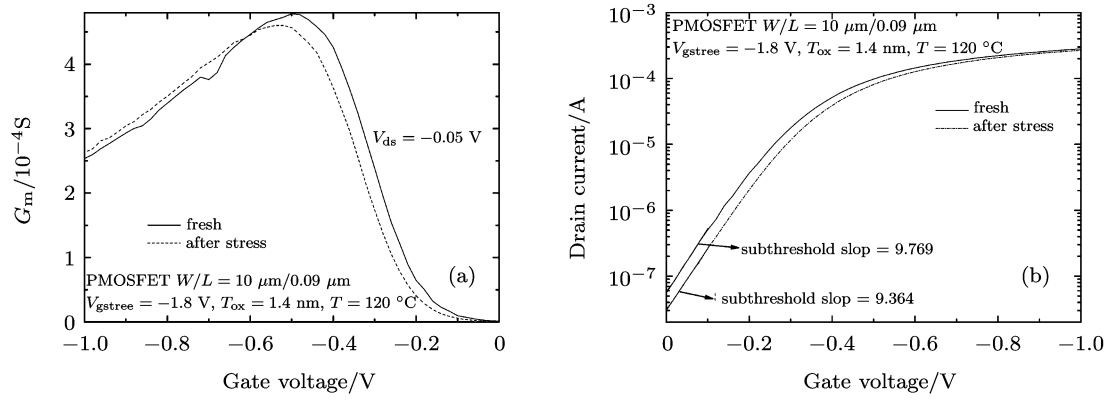


Fig. 2. The change of transconductance G_m (a) and sub-threshold slope (b) before and after NBTI stress.

The change of drain current in linear region I_{dlin} and that in saturated region I_{dsat} before and after NBTI stress are shown in Figs. 3(a) and 3(b). The drain currents are both decreased after stress and the threshold voltage moves negatively. The decrease of the drain currents will cause the decrease of the drive power and increase of the delay time, which will affect the circuit severely.

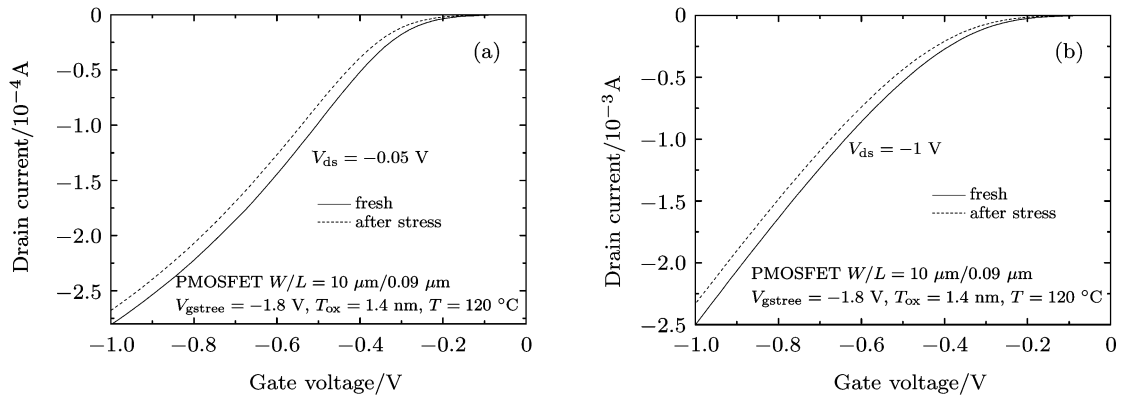


Fig. 3. The change of drain current before and after NBTI stress: (a) in linear region I_{dlin}; (b) in saturated region I_{dsat}.

The change of output characteristics before and after NBTI stress is presented in Fig. 4. After stress, the output characteristics are measured forwards and reversely. From the results, we can see that the output drain current gets smaller clearly and the curves presenting the forward and reverse measurement are superposed. The superposition shows the difference of NBTI and hot carriers injection (HCI) mechanisms. Unlike the unsymmetry effect of HCI, the effect of NBTI stress on the whole channel is uniform and the degradations in drain and source regions are symmetrical.

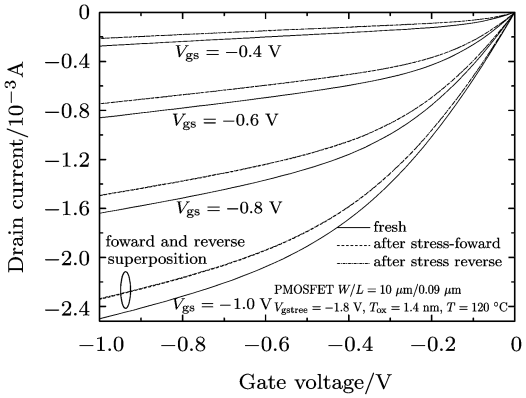


Fig. 4. The change of output characteristics before and after NBTI stress.

From the results above, we can see that the degradation of device caused by NBTI is severe. The NBTI degradation has been one of the most serious reliability problems of MOSFETs and should be paid much attention to. Next, the basic mechanism and model will be studied to get a better understanding of NBTI.

The relationship of $V_{\rm th}$ shift and stress time is shown in Fig. 5. The data are plotted in the log–log scale. The $V_{\rm th}$ shift shows excellent accordance to t^n. The degradation of $V_{\rm th}$ is caused by the generation of interface traps and oxide charges. The interface traps are generated by the breaking Si–H bonds which is the original reason for the degradation of device.[11,12] And the products of breaking Si–H bonds can also lead to degradation. Therefore, the kind of products after breaking Si–H bonds is important for us to understand the mechanism of NBTI degradation well.

When the products are neutral,[16,17] it will lead to an exponent of the interface traps to the stress time in the scale of 0.16 to 0.25. In another word, the exponent n with 0.16–0.25 indicates the neutral product. Therefore, we can focus on the interface traps degradation to the stress time to identify the products.

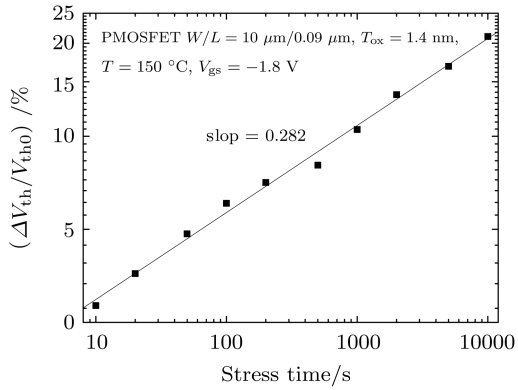


Fig. 5. The relationship of $V_{\rm th}$ shift and stress time.

Here, we utilized $\Delta S/S$ to show the change of interface traps.

When taking no account of interface traps effect:

$$S_0 = \frac{kT}{q} \ln 10 \times (1 + C_{\rm d}/C_{\rm i}), \tag{1}$$

where $C_{\rm d}$ is the depletion capacitance, $C_{\rm i}$ is the oxide capacitance.

When taking account of interface traps effect:

$$S = S_0 \times \frac{1 + (C_{\rm d} + C_{\rm it})/C_{\rm i}}{1 + C_{\rm d}/C_{\rm i}}, \tag{2}$$

where $C_{\rm it}$ is the interface trap capacitance.

After deduction, we can obtain

$$\frac{\Delta S}{S_0} = \frac{\Delta N_{\rm it} \times q}{C_{\rm d} + C_{\rm i}} \propto \Delta N_{\rm it}, \tag{3}$$

where $\Delta N_{\rm it}$ is the change of interface trap density.

Therefore, we can utilize $\Delta S/S$ to show the change of interface traps.

During NBTI stress, $\Delta S/S$ is measured by interrupting the stress. The measured data are plotted in Fig. 6(a) as linear scale and in 6(b) as log–log scale. The change of interface traps shows similar tendency to the threshold voltage. However, the exponent 0.268 of interface traps is smaller than the 0.28 of threshold voltage. This is because that there is other factor to degrade threshold voltage which we will not discuss here. The exponent of interface traps change we got is larger than that in Ref. [17], which indicates that there should be some different kind of H species generated in the NBTI process.

Besides H and H_2 which are naturally generated in the NBTI process, the positive charged H^+ may be also produced. In the following, we will deduce the H^+ related model to identify whether there is H^+ related species.

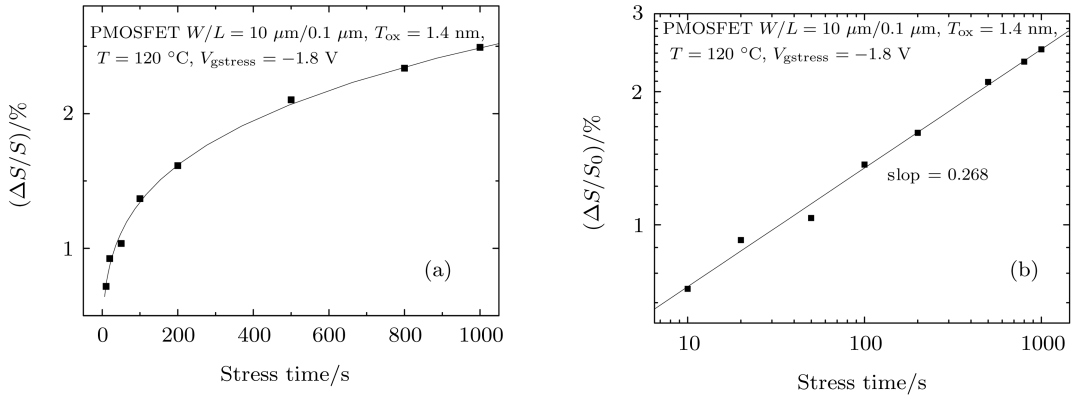


Fig. 6. The relationship of $\Delta S/S\%$ and stress time in linear scale (a) log–log scale (b).

3.2. Discussion

On the basis of the neutral H species related model, the positively charged H^+ model is deduced.

Firstly suppose the interface of SiO_2/Si as zero coordinate, namely, $x = 0$. Then, the R–D model functions with H species are founded as follows:

$$\frac{\mathrm{d}[N_{\mathrm{it}}]}{\mathrm{d}t} = k_{\mathrm{f}} \times h \times (N_0 - [N_{\mathrm{it}}]) - k_{\mathrm{r}}[N_{\mathrm{it}}]N_{\mathrm{H}^*}(x=0), \quad (4)$$

$$\frac{\mathrm{d}[H^*]}{\mathrm{d}t} = D_{\mathrm{H}^*}\frac{\mathrm{d}^2[H^*]}{\mathrm{d}x^2} + \mu_{\mathrm{H}^*}\xi_{\mathrm{ox}}\frac{\mathrm{d}[H^*]}{\mathrm{d}x}, \quad (5)$$

where [•] is the density of the matter '•', N_{it} is interface traps, H^* is H related species which is the products of breaking the Si–H bonds, k_{f} and k_{r} are respectively the forward and reverse reaction rate constants, D_{H^*} and μ_{H^*} are respectively the diffusion coefficient and mobility of H^*, ξ_{ox} is the electric field, h is the density of holes in inversion layer, N_0 is the initial density of the Si–H bonds at the interface, and $N_{\mathrm{H}^*}(x = 0)$ is the density of H related species at the interface.

In the previous work, the product of the NBTI is always regarded as neutral H. However, the experimental results we got are not consistent with that of neutral H. Therefore, there may be some other generated kind of H related species, namely, the positively charged H^+.

When taking H^+ as the product, H* will be replaced by H^+. As H^+ is positively charged, the electric field effect can not be ignored which is the key difference from the neutral H model. The model function of H^+ can be rewritten as follows:

$$\frac{\mathrm{d}[N_{\mathrm{it}}]}{\mathrm{d}t} = k_{\mathrm{f}} \times h \times (N_0 - [N_{\mathrm{it}}]) - k_{\mathrm{r}}[N_{\mathrm{it}}]N_{\mathrm{H}^+}(x=0),$$

$$\frac{\mathrm{d}[H^+]}{\mathrm{d}t} = D_{\mathrm{H}^+}\frac{\mathrm{d}^2[H^+]}{\mathrm{d}x^2} + \mu_{\mathrm{H}^+}\xi_{\mathrm{ox}}\frac{\mathrm{d}[H^+]}{\mathrm{d}x}. \quad (6)$$

In which there are similar definitions for parameters as those in Eqs. (4) and (5).

The D_{H^+} and μ_{H^+} meet Einstein's relation:[18]

$$D_{\mathrm{H}^+} = \mu_{\mathrm{H}^+} \times kT/q, \quad (7)$$

where k is Boltzmann constant. Then Eq. (7) can be rewritten as

$$\frac{\mathrm{d}[N_{\mathrm{it}}]}{\mathrm{d}t} = k_{\mathrm{f}} \times h \times (N_0 - [N_{\mathrm{it}}]) - k_{\mathrm{r}}[N_{\mathrm{it}}]N_{\mathrm{H}^+}(x=0),$$

$$\frac{\mathrm{d}[H^+]}{\mathrm{d}t} = D_{\mathrm{H}^+}\frac{\mathrm{d}^2[H^+]}{\mathrm{d}x^2} + D_{\mathrm{H}^+} \times \frac{q}{kT}\xi_{\mathrm{ox}}\frac{\mathrm{d}[H^+]}{\mathrm{d}x}. \quad (8)$$

The quasiequilibrium method can be still used here,[17] namely, $\mathrm{d}[N_{\mathrm{it}}]/\mathrm{d}t \approx 0$. And then we can get

$$k_{\mathrm{f}} \times h \times (N_0 - [N_{\mathrm{it}}]) \approx k_{\mathrm{r}}[N_{\mathrm{it}}]N_{\mathrm{H}^+}(x=0). \quad (9)$$

In the R–D model, one interface trap is generated while one H^+ is produced. Therefore, the density of interface traps equals the integral of corresponding H^+ density vertically distributing to the interface in the oxide (the x direction above):

$$[N_{\mathrm{it}}] = \int_0^{t_{\mathrm{ox}}} [H^+]\mathrm{d}x. \quad (10)$$

However, the distribution of H^+ in the oxide can not be thought as right-angled triangle used for the neutral H model as the H^+drift motion caused by electric field is much larger than the diffusion motion. Based on Einstein's relation, we know that the mobility of H^+ is much larger than its diffusion coefficient. Then we can ignore the diffusion effect and make the

distribution of H^+ in the oxide as the rectangle. The base of the rectangle is the depth H^+ got into the oxide, namely $\mu_{H^+} * \xi_{ox} * t$. And the height of the rectangle is the density of H^+ at the interface. Then, Eq. (10) can be changed into:

$$[N_{it}] = \mu_{H^+} \times \xi_{ox} \times t \times N_{H^+}(x = 0). \quad (11)$$

After the analysis and simplification, we obtain

$$k_f \times h \times (N_0 - [N_{it}]) = k_r[N_{it}]N_{H^+}(x = 0),$$
$$[N_{it}] = \mu_{H^+} \times \xi_{ox} \times t \times N_{H^+}(x = 0). \quad (12)$$

When $N_0 >> [Si^+]$, we obtain

$$[N_{it}] = \left(\frac{k_f h N_0}{K_r}\right)^{1/2} \times (\mu_{H^+}\xi_{ox}t)^{1/2}. \quad (13)$$

From the calculation and analysis, we can get the conclusion that the exponent of interface traps to the stress time is 0.5 when the product is H^+. Compared with the natural H, the exponent is larger. And only H^+ consisted in the products, there is possibility for the exponent to be larger than 0.25. Therefore, combined the analysis and the experimental results together, we find that H^+ should be produced in the products during the NBTI degradation process.

4. Experimental verification

Here, we adopted the real time measurement method[19] to avoid the effect of measurement time and showed more predictive results. In the real time measurement, a very small drain voltage is applied while gate voltage stress is applied and the other terminals are grounded. As the drain voltage is small enough, the effect of the drain voltage on the NBTI degradation can be ignored. Therefore, we can sample the drain current in real time.

From the experimental results as shown in Figs. 7(a) and 7(b), we can see that the degradation is segmented. The first segment shows a 0.5 exponent clearly, and consists with the phenomenon of H^+ products perfectly. After the first segment, namely, several seconds later, H^+ translated into natural H species, and the exponent becomes 0.28 more or less. Therefore, with the real time measurement, we can observe the segment of H^+ products and segment of translation of $H^+$to natural H.

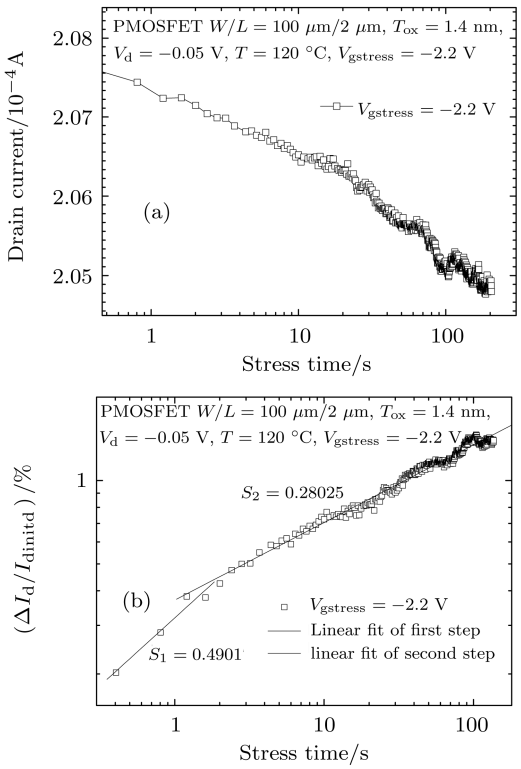


Fig. 7. During NBTI stress, the relationship of I_d (a) and $\Delta I_d/I_d$% (b) versus stress time in log–log scale.

Figure 8 shows the relationship of $\Delta I_d/I_d$% and stress time under different NBTI stresses. From the results, we can see that the $\Delta I_d/I_d$% of drain current all show two segments of degradation under different gate stresses. And the exponent of the first segment is 0.5, which shows the process of H^+ generation. Therefore, the two segment translations are testified to be universal.

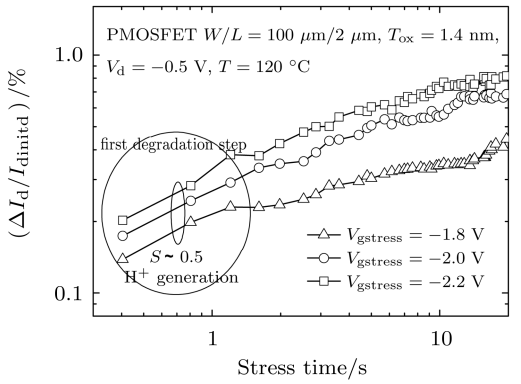


Fig. 8. The relationship of $\Delta I_d/I_d$% versus stress time under different NBTI stresses.

5. Conclusion

In this paper, the degradation mechanism of NBTI is studied. Based on the existing model, the

R–D model with H^+ related species is deduced. And we got the exponent 0.5 of H^+ related species. As the change of interface traps to the stress time in the experiments shows an exponent larger than 0.25, we concluded that there should be H^+ generated during the NBTI stress in comparison with the exponent 0.16–0.25 of natural H species. From the experimental results of the real time method, we got that the degradations of drain current all show two segments in which the exponent 0.5 of the first segment shows the process of H^+ generation. Based on this, we can get the solution that there is H^+ generated in the NBTI degradation.

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