Influence of Bulk Bias on Negative Bias Temperature Instability of pMOSFETs with Ultrathin Plasma-Nitrided Gate Oxide

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Introduction

The negative bias temperature instability (NBTI) of p-MOSFETs has become one of the most crucial reliability issues, especially when the gate oxide thickness is scaled down to less than 2nm and nitrogen is incorporated [1]. Considerable work has been done in both dc and ac NBT stresses, in which a voltage is applied on the gate electrode (V_g) and the source/drain and substrate (bulk, V_b) electrodes are grounded. It was reported that the positive bulk bias during the NBT stress has no influence on NBTI for V_b up to 4V [2,3]. But we find that the degradation can be enhanced significantly by V_b, and the enhancement depends on both V_g and V_b. Moreover, we find, for the first time, that the degradation can be dramatically enhanced under bipolar BT stress if the bulk electrode is floating. Both phenomena suggest that the interface trap generation during the BT stress is closely related to the tunneling of hole from Si to oxide, which can be enhanced by high V_b or the transient electrons in the channel (as well as trapped electrons in the interface states) during the bipolar BT stress with V_b floating.

Experimental

The tested p-MOSFETs were fabricated on n-well of p-Si substrates using a standard CMOS process with LDD, P^+ poly gate, and plasma-nitrided gate oxide, which has a base oxide thickness of ~ 2nm and a peak nitrogen concentration of 9%. The device was stressed at 125°C, by applying a dc or ac voltage on the gate while source/drain grounded and the bulk electrode is grounded, positive biased or floating. The ac voltage has a square waveform of 50% duty factor and 4.5ns rise and fall time. Immediately after stress interruption, and I_d-V_g and a modified direct-current current-voltage (DCIV) measurement [4] were carried out at the same temperature. Each stress was carried out on a fresh device whose initial interface trap density (N_{it}) is between 1.5~ 3.0×10^9 cm^{-2} for all tested devices.

Results and Discussion

With increasing the stress time, the DCIV peak increases and the peak positive shifts to the negative direction, indicating the interface trap generation (ΔN_{it}) and the fixed oxide charge buildup (ΔN_{ot}) [4]. Figs. 1(a) and (b) show the threshold shifts (ΔV_{th}), which are extracted from the I_d-V_g curves, and ΔN_{it} data extracted from the DCIV peaks as a function of stress time under various V_g and V_b. Both figures show similar trends, i.e., at low $|V_g|$ (1.5V), ΔV_{th} (and ΔN_{it}) is almost independent of V_b (up to 2V), while at $|V_g| \geq 2.0$V, it is significantly enhanced at V_b = 2V. The enhancement magnitude depends on both V_g and V_b. The higher $|V_g|$, the lower V_b to trigger the enhancement is. It should be noted that the $|V_b|$ value to trigger the enhancement is much lower than that reported by Y. Mitani *et al.* [3] and V. Huard *et al.* [2].

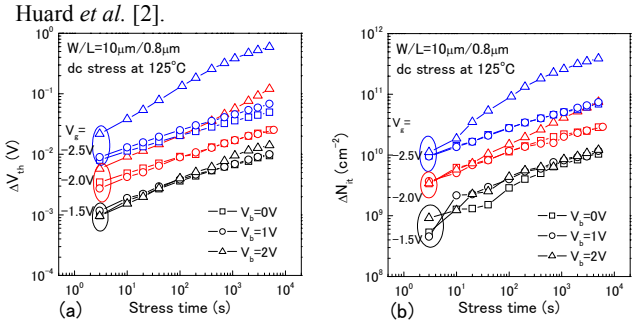

Fig. 1 (a) ΔV_{th} and (b) ΔN_{it} as a function of stress time under dc stress with various V_g and V_b

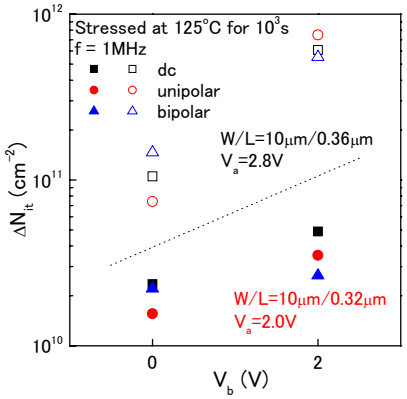

Fig. 2 The interface trap generation under dc, unipolar or bipolar pulsed stresses at V_b = 0 or 2V. The magnitude of the stress voltage V_a is 2.0V or 2.8V.

Fig. 2 shows the interface trap generation under dc and ac (both unipolar and bipolar) NBT stresses. Under ac NBT stress, similar V_b effect still exists, while the enhancement magnitude is slightly decreased under the bipolar stress. On the other hand, Fig. 3 shows that, with the bulk electrode floating, ΔN_{it} is

dramatically enhanced under the bipolar stress while it remains almost unchanged under the dc or unipolar stress. The increase magnitude of ΔV_{th} is larger than that of ΔN_{it} (not shown here), indicating that ΔN_{ot} is enhanced more significantly than ΔN_{it}.

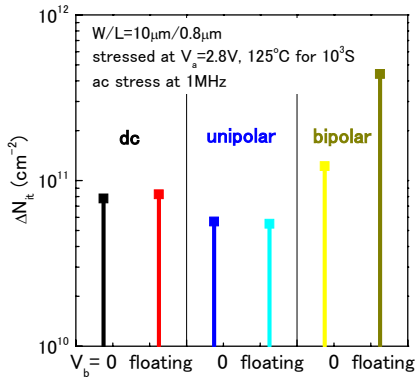

Fig. 3 The interface trap generation ΔN_{it} after static, unipoar or bipolar stress with V_b grounded or floating for 1000s. The degradation is dramatically enhanced under bipolar stress with V_b floating.

Fig. 4 shows the frequency dependence of interface trap generation under bipolar BT stresses with V_b floating. In normal bipolar BT stress (V_b=0), the ΔN_{it} enhancement occurs at frequency larger than ~ 10 kHz [5-6]. With V_b floating, the enhancement magnitude is much larger and the enhancement occurs at 1 Hz and then saturates or increases very slowly at frequency larger than 1 kHz. Fig. 5 shows the time evolution of ΔN_{it} under BT stress with V_b floating. At the early stress time, ΔN_{it} increases with time in a power-law but with the exponent n much larger than 0.25, indicating that there is an additional mechanism for both ΔN_{it} and ΔN_{ot}. The decrease of the increase rate at the longer stress time, as well as the saturation trend in higher frequency region in Fig. 4, can be ascribed to the limited amount of the Si-H bonds at the SiO_2/Si interface [2].

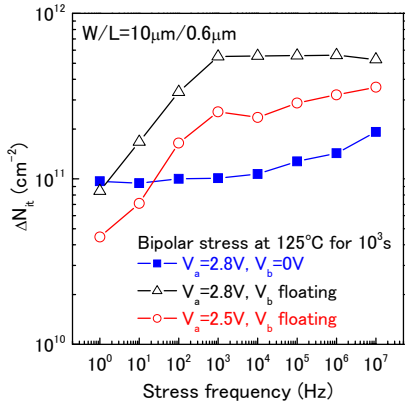

Fig. 4 The stress frequency dependence of interface trap generation ΔN_{it} under bipolar BT stress with V_b floating or grounded. Devices with W/L = 10μm/0.6μm were stressed at 125°C for 1000s by a bipolar square waveform with V_a =2.8V or 2.5V. With V_b floating, ΔN_{it} increases remarkably with frequency and then saturates at frequency larger than ~ 1kHz.

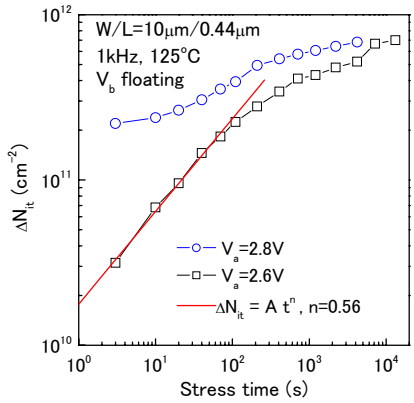

Fig. 5 The time evolutions of the interface trap generation under bipolar BT stress with V_b floating and V_a = 2.6 or 2.8V. At the early stage of the V_a = 2.6V stress, a fitting line based on the power-law dependence is displayed.

It is well known that ΔN_{it} (also ΔN_{ot}) is closely related to the holes in the inversion layer. We speculate that it is not the total density of holes, but the density of high-energy holes that can tunnel into oxide, plays a role to the ΔN_{it} (and ΔN_{ot}). In the V_b = 0 case, the holes are the "cold" holes, and are excited only by temperature. If $V_b > 0$, the holes can be accelerated by the bulk voltage, therefore the tunneling probability is significantly enhanced even though the total hole density is reduced due to the reduction of $|V_g-V_{th}|$ [2]. In the case of bipolar stress with V_b floating, the channel electrons, as well as the electrons trapped at the interface can not follow the applied V_g variation if the transition time is less than about 1~10ms. The build-in electric field originated from these transient electrons can accelerate the hole tunneling, thus enhance the ΔN_{it} generation.

Our finding indicates that, in some cases that the bulk electrode is floating, e.g. for SOI devices without body contact, a dramatic degradation may occur under bipolar stress. On the other hand, very large V_{th} shift (e.g., >1V) can be obtained at a relatively small $|V_g|$ by floating V_b and applying a bipolar V_g.

Conclusion

The V_b (grounded, positive biased, or floating) effects on both dc and ac NBTI are studied. The positive bulk bias can enhance the ΔN_{it} generation significantly under dc and unipolar ac stresses. Moreover, a dramatic ΔN_{it} enhancement is observed under the bipolar BT stress with V_b floating. We suspect that the enhancement is due to the enhanced tunneling probability, originated from the positive V_b or the transient electrons upon V_g reversal from positive to negative in the bipolar stress.

Reference

[1] D. K. Schroder and J. A. Babcock, J. Appl. Phys. **94** (2003) 1
[2] V. Huard *et al.*, Microelectronics Reliability **45** (2005) 83
[3] Y. Mitani *et al.*, IEDM Tech. Dig. (2002) 509
[4] S. Zhu *et al.*, Jpn J. Appl. Phys. **44** (2005) L60
[5] S. Zhu *et al.*, IEEE Electron Device Letters, **25**, (2005), 387
[6] S. Zhu *et al.*, IEEE Electron Device Letters, **25**, (2005), 658

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Outline:

- **Background**
- **Experimental details**
- **Results:**
  - **V_b positive bias**
  - **V_b floating**
- **A model based on hot-hole injection**
- **Conclusion**

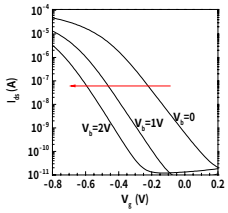
Background:

NBTI mechanism (Reaction-diffusion model):

$Si_3{\equiv}Si\text{-}H + h^+ \leftrightarrow Si_3{\equiv}Si\bullet + X_{interface}$

$O_3{\equiv}Si\text{-}H + h^+ \leftrightarrow O_3{\equiv}Si\bullet + X_{interface}$

$X_{interface} \leftarrow (diffusion) \rightarrow X_{bulk}^+$



The role of holes?

The information can be obtained from the V_b effect.

$V_b \uparrow \rightarrow V_{th} \downarrow \rightarrow |V_g\text{-}V_{th}| \downarrow$

$\rightarrow$ channel hole density $\downarrow$

V_g fixed $\rightarrow$ E_{ox} fixed

Background (continuous):

Static NBTI:

Contrary results in literature:

At the same V_g, no V_b effect up to V_b = 3V.

The lifetime decreases when V_b > 1.5V.

Dynamic NBTI:

The degradation reduces under dynamic stress.

In our previous papers, degradation under bipolar BT stress is enhanced.

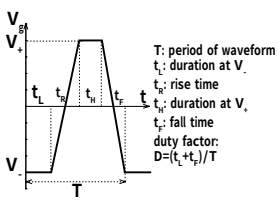
No reports about the V_b effect on dynamic NBTI.

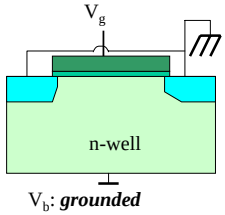
Experimental details:

Devices: pMOSFETs with p+ poly-Si gate, plasma-nitrided SiON gate.

T_{ox}=2.0nm, N%=12%, W=10μm, L=0.28 ~ 0.44μm.

Stress configuration:





V_b: ***grounded***

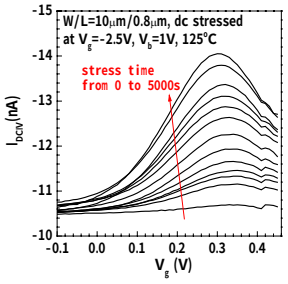
positive biased

floating

Measurement:

I_d-V_g curves for V_{th};

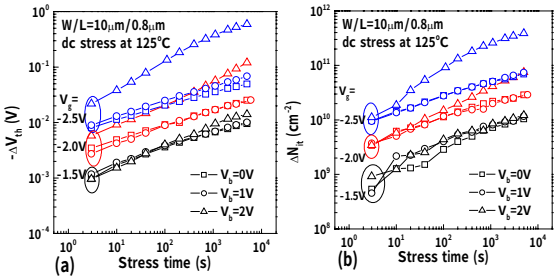
Modified DCIV (direct-current current-voltage) curves for N_{it}.

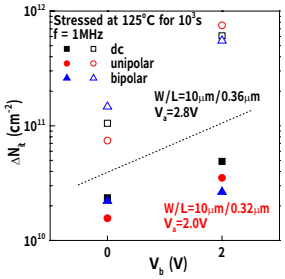


Results:

------ V_b positive bias

Device degradation under various V_g and V_b. The degradation enhancement depends on both V_g and V_b.



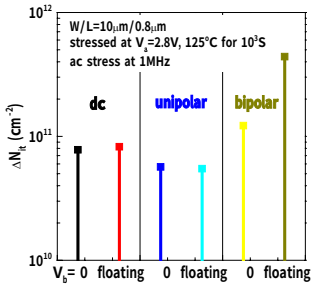


- At low V_g, the degradation is independent on V_b up to 2V.
- At high V_g, the degradation can be significantly enhanced by V_b.
- At dynamic stress with both unipolar and bipolar waveforms, similar V_b effect displays.

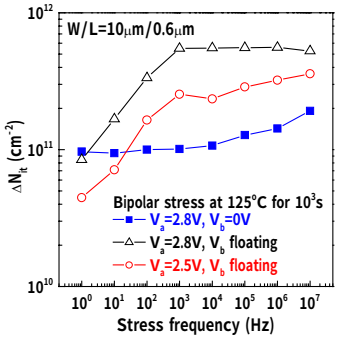
Results:

------ V_b floating

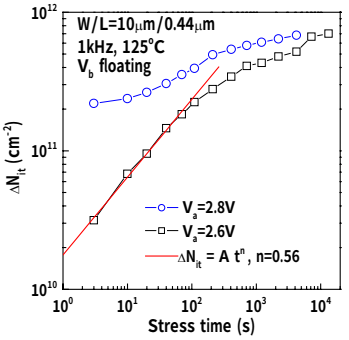
Under bipolar BT stress with Vb floating, the degradation is significantly enhanced.



Frequency dependence of degradation under bipolar stress with V_b grounded or floating.



Time evolution of degradation under bipolar BT stress with V_b floating



Conclusion

- Significant degradation enhancement is observed by **applying a positive bulk bias** or by **V_b floating in the bipolar BT stress**.
- The degradation enhancement is attributed to an additional degradation related with the **hot hole injection**.
- The holes are energized by the electrical field provide by the positive bulk bias V_b or, in the case of bipolar BT stress with V_b floating, by the **transient electrons** in the channel upon V_g switched from positive to negative.