Dynamic Negative Bias Temperature Instability and Comprehensive Modeling in PMOS Body-Tied FinFETs

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Abstract

This paper presents a novel approach to estimate the rising and falling behavior of Nth-order on-state current by dynamic negative bias temperature instability (DNBTI). For the first time, a modified DNBTI model in PMOS body-tied FinFETs was proposed and compared with experimental data. The approach can provide a quick estimation of periodic DNBTI behavior by stress and recovery. The DNBTI behaviors dependent upon stress bias, fin width, body temperature, and substrate bias were analyzed. The proposed model closely matched with the measured static-lifetime.

Introduction

Multi-gate FinFET structures have strengths of high robustness on short-channel effects and superior scalability using conventional processes [1,2]. However, due to the scalability, NBTI starts to limit the device reliability of digital and analog circuits [3,4]. Previous studies indicate the improvement on NBTI-stress with a wide fin width (WFin) in the SOI as well as in the body-tied FinFETs because of the hole concentration reduction at the Si-SiO2 interface [5,6]. Recently, recovery of the NBTI has become a concern for the AC-lifetime prediction [7,8].

Experiments

Detailed fabrication processes of body-tied FinFETs have already been reported [2]. For the dynamic BT-stress, negative biases (V G=VTO-VStress) for stress-states and positive biases (V G=VTO+VStress) for recovery-states were applied to the gate of body-tied FinFETs for 100 sec. Additionally, the source, drain and substrate were grounded with various Temp: 50℃, 80℃, 125℃, and 150℃. A Vsub of -0.2 V was applied to ensure the virtual-floating-body effects, even in the body-tied FinFETs, which can mimic SOI FinFETs [4]. To investigate the fin width dependence of DNBTI behaviors, WFin of 30 nm, 50 nm, and 100 nm were used with a gate length of 100 nm and a gate oxide thickness of 1.7 nm. The DNBTI monitoring scheme was reported in ref. [5].

Results and Discussions

The on-current (I ON) degradation and enhancement of the PMOS body-tied FinFETs are shown in Fig. 1 with various DC stress biases (V Stress). I ON degradation represents an increment of NBTI and NBT by Si-H bond breaking; furthermore, its enhancement represents NBTI neutralization and NBTI re-passivation. [7,9]. To achieve an analytical and comprehensive understanding of DNBTI with V Stress, Temp, WFin, and floating body effects, a previous model [10] was revamped with fitting parameter, k.

Fig. 2 shows I ON variation on stress- and recovery-states. After the 1st stress, n was 0.25; n was then reduced to ±0.05 after the 1st recovery and the 2nd stress. The coefficient n=0.25 comes from the diffusion mechanism, which is the same value of planar bulk-devices [10], and the reduction of n (± 0.05) comes from the lock-in mechanism [7]. Fig. 3 shows that the exponent, n, was independent from WFin (30nm~100nm), V Stress (2.4 V~3.4 V), Temp (50℃, 125℃), and Vsub (0 V, -0.2 V). Fig. 4 and Fig. 5 show the Y-intercept of the 1st stress using Eq. 2 and the I ON degradation versus -1/kT to extract E a using Eq. 4. The coefficient m is affected by Vsub but not by WFin when the Ea decreases with the increment of Vsub and Vsub.

Fig. 6 shows the exponents for the Ea such as m1 (Vsub=0 V, FinFET); m2 (Vsub=-0.2 V, FinFET); and m3 (single-gate bulk-FET), and the activation energy of the body-tied FinFETs and the single-gate bulk-FETs, which correspond to an infinite fin width. m did not show WFin dependency, but they were dependent on Vsub. Comparing m1 and m2, an increase was seen as the number of gates increased, i.e., m1,2>m3 [10,11]. Ea was larger in the single-gate bulk planar MOSFETS than in the body-tied FinFETs [8,10-13]. Ea decreased as the WFin decreased and a negative Vsub was applied. Table 1 summarizes the extracted coefficients, A, n, m, and Ea after the 1st stress. The virtual floating body formed by applying Vsub=-0.2 V resulted in the decrement of m and Ea. Decrement of Ea caused more degradation of the device performance. Fig. 7 shows the ∆ION at Vsub=0V and -0.2V. The cross point of ∆ION between A(Ea)^n and exp(-Ea/kT) represents Ea is dominant at a low Eox field and that m is dominant at a high Eox field. The virtual floating device shows worse device performance in the low Eox region, i.e., in the m dominant region. However, the virtual floating device shows better device performance in the high Eox region, i.e., in the m dominant region. Since an actual operative region of the device is at a low Eox, the NBTI is worse at a SOI than at a bulk substrate, which is consistent with a previous report [5].

Fig. 8 shows an estimation of the I ON variation using the measured data under the DNBT-stress. Guidelines of ∆ION/I ON,0 under the NBT-stress are increased according to E a, the power time law. One guideline after the 1st stress was extracted from t1 and t2 and it was proportional to the exponent, n=0.25. Similarly, the other guideline was extracted from t2 and t3 and it was proportional to the exponent, n=0.5. At the Nth-order, ∆ION/I ON,0 follows the guideline of the 2nd stress [14]. Periodic ∆ION/I ON,0 behavior after the Nth-order stress and recovery is well matched with the proposed DNBTI modified model (Eq. 1) by using parameters in Table 1, the 1st stress measurement data, the 1st and the 2nd guidelines from the 1st and 2nd stress measurement data, and the fitting parameter, k. The solid lines of Fig. 9(a)(b) represent the DNBTI profiles modeled using the proposed method. Even using the 1st and 2nd stress-state measurement data, the modeled Nth-order stress and recovery profiles are well matched with the measurement results. The stress bias effects show a different value of k due to the different Eox dominant region. Fig. 10 shows the static-lifetime predicted by the modified DNBTI model at WFin=50 nm & 100 nm and Vsub=0 V & -0.2 V with different VStress. The virtual device is lifetime defined at 10% of the drain saturation current. The root-mean square error of measured lifetime (τme) and modeled lifetime (τmod) was approximately 16% (Eq. 5).

Conclusions

A modified DNBTI model and extraction method were developed to predict the Nth-order DNBTI profile with various VStress Temp, WFin, and Vsub. The stress time exponent, n, was 0.25 at the 1st stress-state and was changed to ±0.05 after the 1st recovery-state. A decrement of Ea with a narrower WFin represented the increment in NBT and device degradation. A virtual floating body indicated a decrement of the coefficients m and Ea. The modeled static-lifetime coincided well with the measured static-lifetime, showing a root-mean square error of 16%.

References

\[ \Delta \omega = A \times \gamma (E_{\text{ox}})^{n} \exp(-E_{a}/k_{B}T) \]  
Eq. 1

\[ \log(\Delta \omega) = n \log(\gamma) + Y \]  
Eq. 2

\[ Y = m \log(E_{\text{ox}}) + Y_{1} \]  
Eq. 3

\[ \log(\Delta \omega) = E_{k}(-1/k_{B}T) + Y_{1} \]  
Eq. 4

Fig. 5. \( I_{\text{ON}} \) degradation versus \(-1/k_{B}T\) to find the coefficient \( E_{k} \), the activation energy. \( E_{a} \) decreases with the increment of fin width and as the substrate bias is applied.

Table 1. Extracted coefficients \( A, n, m \), and \( E_{a} \) after the 1\textsuperscript{st} stress with \( W_{\text{Fin}}=50\) nm, 100 nm and \( V_{\text{sub}}=0 \) V, \(-0.2\) V. \( E_{a} \) shows \( W_{\text{Fin}} \) dependency, and \( A, m \), and \( E_{a} \) show \( V_{\text{sub}} \) dependence.

<table>
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<th>( W_{\text{Fin}} )</th>
<th>( V_{\text{sub}} )</th>
<th>( A )</th>
<th>( n )</th>
<th>( m )</th>
<th>( E_{a} )</th>
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<td>100nm</td>
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<td>Bulk FET</td>
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Fig. 9. \( I_{\text{ON}}/I_{\text{ON},0} \) of DNBTI versus stress/recovery time with various (a) \( V_{\text{stress}} \), \( W_{\text{Fin}} \) (b) Temperature and \( V_{\text{sub}} \). Solid lines represent the DNBTI profiles modeled using the proposed method.

Fig. 10. Measured and modeled static-lifetime at \( W_{\text{Fin}}=50\) nm, 100 nm and \( V_{\text{sub}}=0 \) V, \(-0.2\) V versus \( V_{\text{stress}} \) according to Eq. 1 and the parameters in Table 1. The root-mean square error is 16%.

Acknowledgments

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