[DOI: 10.2197/ipsjtsldm.13.56]

Regular Paper

Universal NBTI Compact Model Replicating AC Stress/Recovery from a Single-shot Long-term DC Measurement

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> Received: December 4, 2019, Revised: March 11, 2020, Accepted: April 23, 2020

Abstract: In this paper, a simple and compact Negative Bias Temperature Instability (NBTI) model is proposed. It is based on the reaction-diffusion (t^n) and hole-trapping $(\log(t))$ theories. A single shot of DC stress and recovery data is utilized to express duty cycle dependence of NBTI degradation and recovery. Parameter fitting is proceeded by considering that the amount of recovery cannot be larger than stress degradation. The proposed universal model is applied to two types of transistors in different fabrication process technologies, and evaluate its feasibility to show the universality of our proposed model. It replicates stress and recovery successfully with various duty cycles.

Keywords: negative bias temperature instability (NBTI), AC stress dependency, reaction diffusion, hole trapping

1. Introduction

Negative bias temperature instability (NBTI) is one of the most severe reliability issues for integrated circuits. NBTI is an aging degradation on negative-biased PMOS transistors. The effect of NBTI is observed as transistor performance degradation, which is expressed as threshold voltage and subthreshold swing degradation in compact models [1], [2], [3], [4], [5], [6]. The performance degradation increases path delay and it leads to malfunction due to timing violation. In circuit design, some amount of timing margin must be added to mitigate aging degradation. Inaccurate timing margin increases area and power consumption. Therefore, accurate lifetime estimation of transistors is mandatory to design circuits with adequate design margins.

NBTI degradation is accelerated by temperature and a strong vertical electric field to gate dioxide [7], [8], [9]. By removing the electric fields, the NBTI degradation recovers instantly. But some amount of degradation remains after long recovery time and remains permanently. The recovery is also accelerated by higher temperature and the positive electric field [2], [9], [10]. Physical mechanism of NBTI is modeled by the reaction-diffusion (R-D) and the hole trapping (trap de-trap (T-D)) model [2], [11], [12], [13]. The R-D model assumes that the NBTI degradation and recovery are caused by the generation of interface traps. Hydro-

gen is dissociated from Si-H at Si-SiO2 interface and diffuse toward the gate electrode during applying negative bias to gate electrode. The dissociated hydrogen recombines with dangling bond Si- when the negative bias is removed. These hydrogens become hydrogen molecules. Since the hydrogen molecule is neutral, it cannot be explained that applying positive bias to gate terminal accelerates recovery [2], [9]. The T-D model assumes that the NBTI degradation and recovery are caused by the trapping and de-trapping carriers into pre-existing defects in the gate oxide. The distribution of the time constant of carrier traps is assumed to follow a lognormal distribution. Thus the threshold voltage shift due to gate-oxide traps is also assumed to follow a lognormal distribution. The T-D model can explain a recovery acceleration applying positive bias since trapped carriers are positively charged. However, the T-D model cannot explain degradation of subthreshold slope characteristic which is widely observed in various papers. To overcome these issues, an NBTI model combining those two mechanisms was proposed in Ref. [14].

Since NBTI has not only degradation but also recovery, estimating the total amount of NBTI degradation is tough. For an accurate estimation of transistors lifetime, it is mandatory for the model to handle AC stress dependability of NBTI degradation and recovery. From a model building perspective, the modeled function and parameter extraction should be simple and fast for model builders. Universality of both the model parameters and model function is important for accurate NBTI degradation estimation.

In this paper, as an extension of Ref. [15], we propose a simple and universal NBTI degradation and recovery model which can express an AC stress dependency from a single-shot DC stress

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and recovery measurement result. This model assumes that the degradation is caused by the combination of the R-D and T-D mechanics, but only the T-D mechanism recovers from degradation. The model uses a few fitting parameters obtained by a single-shot DC stress and recovery measurement, and can express the NBTI degradation and recovery of AC stress with various duty cycles. The model development flow of the proposed model can be applied to transistors manufactured by various process technologies.

The key extension of this paper is adding model fitting results to different fabrication conditions. In Ref. [15], NBTI of core transistors width thin oxide is modeled. In this work, NBTI of IO transistors with thick oxide is modeled with the same modeling flow, and show same modeling process successfully model the NBTIs of the transistors in different process technologies.

The rest of this paper is organized as follows. Section 2 describes related works for the NBTI models and explains differences among our proposed model and other conventional models. Section 3 describes the proposed model and modeling guideline. Section 4 describes experimental results and model verification results with measurement data of two process technologies. Section 5 concludes the paper.

2. Related Works

To estimate the amount of NBTI degradation, many NBTI models are proposed. Reference [16] uses the two mechanisms of the R-D and T-D models and successfully estimates the AC stress dependency. The model, however, is not universal. Model parameters and modeled functions should be changed to express the duty cycle dependency of the NBTI degradation. Reference [17] also estimates the AC stress dependency, while it is too complicated to easily build a compact model. Moreover, the amount of recovery does not depend on its total amount of degradation.

The model in Ref. [16] has parameters depending on duty cycles and clock periods. In model development, extra time-consuming measurement is required to obtain those parameters. Reference [17] uses both the drain-source current and gate injection current to build a compact model. Those data are converted into model parameters. The model-building flow is also complicated and it is difficult to obtain model parameters.

In this work, we propose an NBTI compact model which can express a duty cycle dependability of the NBTI stress/recovery effect from a single-shot DC stress/recovery measurement. It is possible to obtain model parameters by periodically measuring drain-source current of transistors during a stress phase and the subsequent recovery phase. One key idea is setting the priority in the model fitting process to improve model prediction accuracy. Their model development flow is simpler than models of Refs. [16], [17].

3. Proposed Compact Model

The goal of our compact model is to express DC/AC measurement results with a unique set of fitting parameters. Proposed model uses only single shot DC measurement result to represent both DC and AC stress/recovery dependency. Both simplicity and universality of the fitting parameters are important for model building. Drawback is that model accuracy may be sacrificed by



Fig. 2 Transistors corner model of process variation and NBTI.

the model simplicity. To achieve good estimation accuracy using simple model equation, we introduce a priority fitting in model building. There are many candidates of the parameters that can replicate measurement data. Firstly, parameters to determine a total amount of recovery are extracted. Then the other parameters are extracted. The compact model developed by the proposed flow can reproduce not only a single-phase stress/recovery but also multiple-phase AC stress dependency. In addition, the proposed flow can apply to various process technologies and can reproduce AC stress dependency.

Figure 1 shows our modeling methodology. It is built from a single-shot stress-recovery DC measurement that can express AC stress dependency. Different AC stress/recovery condition can be reproduced by unique fitting parameters. In other word, developed model is universal.

Threshold voltage degradation caused by NBTI can be decomposed into initial shift and time dependent component. Time dependent component is modeled as a function to time. Initial shift should be treated as "corner model", similar to process variation. Thus, NBTI degradation can be modeled as shown in **Fig. 2**. In this work, we target to model a time dependent component, and treat initial shift as DC bias offset, which is described in Section 4.

In the model, we assume that NBTI degradation is modeled by the combination of the R-D and T-D models. Only the logarithm component from the T-D model is recoverable since the R-D model cannot explain recovery phenomenon [2].

As discussed later, our model is applied to two types of transistors with different fabrication conditions to validate its universality. **Table 1** shows the two types of transistors process technologies. The transistors used in this experience are core transistors grouped as "DUT_A" and IO transistor grouped as "DUT_B". Details are described in Section 4.1. In this section, data of transistor DUT_A is used for explanation.

3.1 Model Function for NBTI Degradation and Recovery

Our model assumes the NBTI degradation is caused by the combination of the T-D and R-D models, which are well known

Name	DUT_A	DUT_B	
Structure	Core PMOSFET	IO PMOSFET	
Structure	FD-SOI	Bulk	
Nominal	0.55 V	2 2 V	
supply voltage	-0.33 v	-3.3 V	
Dimension	$0.14~\mu m \times 20$ / 60	$0.14~\mu m \times 20$ / 400	
(Wide/Length)	nm	nm	

Table 1 Difference of both process technologies.

candidates to express the NBTI degradation. In the R-D model, the threshold voltage degradation is modeled as a power-low function for time (t^n) , while in the T-D model, it is modeled as a logarithmic function for time $(\log(t))$. In a stress phase, the NBTI degradation is expressed as follows

$$\Delta V_{th} = \alpha t_{str}^{1/6} + \beta \log(1 + \gamma t_{str}), \qquad (1)$$

where, α , β , and γ are the fitting parameters, t_{str} is stress time. Exponent of time is 1/6, which is a well-known value in the R-D model [1]. In the recovery phase only the logarithm component can be recoverable since the R-D model is hard to model the recovery phenomenon. The NBTI recovery is expressed as follows

$$\Delta V_{\rm th,log} / \Delta V_{\rm th,log_max} = \delta (t_{\rm rec} / t_{\rm str})^{\varepsilon}, \qquad (2)$$

where, δ , ε are fitting parameters, $t_{\rm rec}$ is recovery time and $t_{\rm str}$ is stress time. $\Delta V_{\rm th,log_max}$ is the total amount of threshold voltage degradation, which is the sum of the accumulated logarithmic components of the NBTI degradation and recovery. $\Delta V_{\rm th,log}$ is the amount of threshold voltage recovery after the recovery time, which is normalized by the total amount of degradation. The function of the recovery should be power-low since the threshold voltage shift on the recovery undershoot. Finally, the total amount of threshold voltage shift after a single stress and a single recovery is described as follows,

$$\Delta V_{\rm th} = \alpha t^{1/6} + \beta \log(1 + \gamma t) + \delta \Delta V_{\rm th, \log_max} (t_{\rm rec}/t_{\rm str})^{\varepsilon}.$$
 (3)

3.2 Model Fitting Flow

In this section, we propose the model fitting flow to obtain most appropriable parameters to express NBTI degradation and recovery.

The least square method is widely used for fitting. There are the above five parameters that must be fit from two measurement data on stress and recovery. The problem is that many candidates are available for a set of parameters which can "fit" to data with a small fitting error. Putting some priority to fix those parameters can successfully extract a set of parameters following duty-cycle dependency of stress and recovery.

In our fitting procedure, we use assumption only the amount of degradation expressed by the logarithmic component can be recovered. Under the assumption, the parameter ' α ' is extracted in the stress phase, which is the maximum value to satisfy the assumption that the amount of recovery is not larger than stress degradation by the logarithmic component. Then, the parameters ' β ' and ' γ ' are extracted simultaneously by fitting to the result of stress phase without changing ' α '. **Figure 3** shows the flow chart



Fig. 3 Flow chart in fitting.



Parameter					
α		Fitting parameter for power-low component.			
Stress	β	Fitting parameter for logarithmic component			
	γ	Fitting parameter for stress time of			
		logarithmic component.			
Dagayomy	δ	Fitting parameter for the amount of recovery.			
Recovery	ε	Fitting parameter for recovery time.			



Fig. 4 Impact of the parameter '*a*' on the NBTI model. It defines the ratio of the power-low component and the logarithmic component.

of fitting. First, ' α ' is initialized. Next, fitting is performed with the result stress phase to extract ' β ' and ' γ '. We check that the assumptions are satisfied in the recovery phase and ' α ' is maximum. Then, if it satisfies both the assumption and ' α ' is maximum, breaks the loop. If the assumption is not satisfied, reduce ' α ' If ' α ' is negative value, increase ' α '. **Table 2** summarizes the variables of model. **Figure 4** shows the impact of the parameter ' α ' in our NBTI model. The parameter ' α ' defines the ratio of the power-low component and the logarithmic component of the NBTI stress. Our assumption is that only the logarithmic component of NBTI stress can be recovered. Thus the amount of the recoverable component is limited. Finally, the other parameters are fit by using Eq. (2) on the recovery phase.

4. Experimental Results

In this section, we explain an experimental setup for NBTI stress/recovery measurement and validate our model for two process technologies, that have different structure and nominal sup-



Fig. 5 Two different fitting results for threshold voltage degradation for DUT_A.

Table 3Measurement conditions.					
Phase	V _{GS} for	V _{GS} for	$V_{DS}[V]$	T [°C]	
	DUT_A	DUT_B			
	[V]	[V]			
Stress	-2.0	-7.0	0.0	105	
Recovery	0.0	0.0	0.0	105	
Measurement	-0.55	-3.3	-0.10	105	

ply voltage. Two transistors show different degradation trends and different model parameters are extracted. The NBTI models are obtained by a single shot DC stress/recovery measurement, and verified under the different duty-cycled AC stress/recovery measurement. It is noted that data obtained by a long stress and recovery measurement is required to extract parameters.

4.1 Experimental Setup

NBTI of the two types of transistors is evaluated and modeled individually with our model and validate its feasibility. We measure the transistors on-current with measure-stress-measure (MSM) method. MSM method applies stress voltage only in the stress condition, and removes the stress during measurement. To prevent recovery during the measurement, we use 1 ms integration time for current measurement.

We measure the degradation of transistors on-current, and convert them into threshold voltage shift using circuit simulations. We first measure its initial device current, and then measure its current degradation after applying stress voltage and temperature.

The transistors used in this experience are core transistors grouped as "DUT_A" and IO transistors grouped as "DUT_B" are regularly located on a wafer. Their device are manufactured by different process technologies. Table 1 summarizes the difference of each process technologies. DUT_A is W/L = $0.14 \,\mu\text{m} \times 20/60 \,\text{nm}$ and DUT_B is $0.14 \,\mu\text{m} \times 20/400 \,\text{nm}$.

We probe them individually and measure its on-current using semiconductor analyzer Agilent 4156C. **Table 3** summarizes the measurement conditions. Temperature and the drain-source voltage are same in each process technologies, but the gate-source voltage is different. In DUT_A, we apply -2.0 V to gate source during stress phase, and -0.55 V during measurement phase. In DUT_B, we apply -7.0 V to gate source, and -3.3 V during mea-

 Table 4
 Residual sum of squares to the fitting method.

RSS(constant stress)



surement phase. we apply -0.10 V for drain-source voltage during measurement phase to prevent the short channel effect.

4.2 Measurement and Verification for DUT_A

In this section, NBTI of DUT_A is modeled and verified. First, we measure DC stress/recovery data, extract model parameter and develop models. Next, the models are verified for AC stress/recovery data.

4.2.1 Measurement and Verification for DC Stress/recovery

We measure the transistors on-current in NBTI DC stress/recovery, and construct a NBTI model expressed as Eq. (1) and Eq. (2). Figure 5 show the result of two models with difference fitting method. Figure 5 (a) does not use priority in fitting, simply fits the equation to the NBTI degradation. On the other hand, Fig. 5 (b) uses a priority in fitting. Threshold voltage in Fig. 5 is normalized its maximum value. Table 4 shows the residual sum of squares (RSS) in each fitting method. Results show both set of parameters successfully fit to the measured results. However, the ratio of the power-low and logarithm component differs between the two model. Figure 6 shows the result of our model and measurement data in recovery stage.



Fig. 7 AC stress results from two model building methods $(t_{str}/t_{rec} = 700 \text{ s}/70 \text{ s})$. Model with fitting priority successfully fits to the measurement data for DUT_A.



4.2.2 Verification Results for AC Stress/recovery

The models obtained from the single shot DC stress/recovery measurement are verified by the stress/recovery iteration measurement. Figure 7 (a) shows the measurement results and the model without fitting priority. In this case, the duty ratio is set to 91% ($t_{str}/t_{rec} = 700 \text{ s}/70 \text{ s}$). The model without considering fitting priority cannot express the measured duty cycle dependency. Figure 7 (b) shows the measured results and the model considering fitting priority (hereafter called proposed model). In this case, the proposed model can express tendency of iteration data which is appeared as accumulation of degradation. Similarly, we verify the proposed model with different iteration conditions. Figures 8, 9, 10 depict the iteration measurement data for $t_{str}/t_{rec} = 7 \text{ s}/7 \text{ s}, 700 \text{ s}/700 \text{ s}, 1,260 \text{ s}/140 \text{ s}$ with the proposed model. Since each transistor is suffered from NBTI variations, some amount of DC bias offset is applied to the model equation. In this case, there are two set of model equations in Figs. 9, 10. Note that the amount of DC bias offset is determined to fit the model equation to the initial degradation, as illustrated in Fig. 11.

This DC bias offset is also used to compensate the NBTI variability on each transistor. **Figure 12** shows duty ratio dependence. The sum of stress and recovery time is 1,400 seconds. #iter means iteration numbers of unit cycle (1,400 s). S-shape is obtained as seen in other papers. There are some gaps between measurement and our model. Fluctuation in measured results



Fig. 9 AC stress results at $t_{str}/t_{rec} = 700 \text{ s}/700 \text{ s}$ for DUT_A.



Fig. 10 AC stress results at $t_{str}/t_{rec} = 1,260 \text{ s}/140 \text{ s}$ for DUT_A.

shown in Fig. 7-Fig. 10 is one main reason of this difference.

Table 5 summarizes the iteration conditions of stress/recovery time, calculated duty ratios and these Root Mean Square Errors (RMSE). Table 5 (a) shows comparison between model with priority and without priority and Table 5 (b) shows comparison between model with DC bias and without DC bias. Result of 7 s/7 s and 700 s/70 s in Table 5 (b) means that the model without DC bias matches with the initial degradation. RMSE becomes small by considering priority and adding the bias voltage. We conclude that the proposed model has ability to express NBTI degradation and recovery by changing only the DC bias with the other



Fig. 11 Add DC bias offset for compensation of the variety of NBTI in each transistor.



Fig. 12 Duty ratio dependence for DUT_A (T = 1,400 s).

Table 5RMSE to compare models and measurement for DUT_A.(a) Compare w/ Priority and w/o Priority

Str/Rec time	Duty	RMSE [a.u.]		
		w/o Priority	w/ Priority	
7 s/7 s	50	0.39	0.25	
700 s/70 s	91	0.37	0.20	
140 s/1260 s	10	0.19	0.22	
700 s/700 s	50	0.71	0.53	
1260 s/140 s	90	1.00	0.97	

(b) Compare	w/o DC	bias and	w/	DC bias
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Str/Rec time	Duty	RMSE [a.u.]		
		w/o DC bias	w/ DC bias	
7 s/7 s	50	0.26	0.26(w/o DC Bias)	
700 s/70 s	91	0.20	0.20(w/o DC Bias)	
140 s/1260 s	10	0.22	0.18	
700 s/700 s	50	0.54	0.31	
1260 s/140 s	90	1.00	0.31	

fixed parameters in the case that the exponent component becomes smaller by setting priority.

4.3 Measurement and Verification for DUT_B

In this section, NBTI of DUT_B is modeled and verified.

4.3.1 Measurement and Verification for DC Stress/recovery

We measure the transistors on-current in NBTI DC stress/recovery, and construct NBTI model. **Figure 13** shows the result of two model with difference fitting method. Figure 13 (a) does not use priority in fitting. Figure 13 (b) uses a priority in fitting. **Table 6** shows the RSS in each fitting method. Results

Table 6 Residual sum of squares to the fitting method.

	RSS(constant stress)
w/o priority	5.58×10-4
w/ priority	6.02×10 ⁻⁴

Table 7 The model parameter "a" with each fitting method.

Process and fitting flow	Value of " α " [a.u.]
DUT_A w/o priority	1.0
DUT_A w/priority	19.5
DUT_B w/o priority	1.0
DUT_B w/priority	0.71

show both two set of parameters successfully fit to the measured result.

Table 7 shows the model parameter "a" which indicates the ratio of power-low degradation component for DUT_A and DUT_B with each fitting method. They are normalized by their values without priority of each device. The ratio of the exponent and logarithm component differs between the two model. In DUT_A, parameter "a" of model with priority is larger than without priority. It means that power low component of model with priority is larger than model with priority is larger than model without priority to DUT_B. In other words, model with priority can express DC measurement data regardless of which ratio of degradation component changes.

4.3.2 Measurement and Verification for AC Stress/recovery

The models obtained from the single shot DC stress/recovery measurement are verified by the stress/recovery iteration measurement. Figure 14 shows the measured results and models with and without fitting priority. In this case, stress time and recovery time are 700 s/700 s. In Fig. 14 (a), since the model without fitting priority has smaller logarithmic component, the model cannot cover the amount of recovery. Therefore, all of degradation component is considered as recoverable. The model without considering fitting priority cannot express the measured duty cycle dependency. Figure 14(b) shows the measured results and the proposed model. The proposed model can express tendency of iteration data which is appeared as accumulation of degradation. Figures 15 and 16 depict the iteration measurement data for $t_{str}/t_{rec} = 7 \text{ s}/7 \text{ s}$, 1,260 s/140 s with the proposed model. The DC bias offset is used to compensate variability. Figure 17 shows duty ratio dependence. The sum of stress and recovery time is 1,400 seconds. Almost same characteristics are observed as DUT_A in Fig. 12.

Table 8 summarizes the iteration conditions of stress/recovery time and these RMSE. Table 8 (a) shows comparison between model with priority and without priority and Table 8 (b) shows comparison between model with DC bias and without DC bias. RMSE can be small by considering priority and adding the DC bias voltage to compensate the effect of NBTI variation. We conclude that the propose d models have ability to express NBTI degradation and recovery by changing only the DC bias with the fixed other parameters for different process technologies in the case that the exponent component becomes bigger by setting priority.



Fig. 13 Two different fitting results for threshold voltage degradation for DUT_B.



Fig. 14 AC stress results from two model building methods $(t_{str}/t_{rec} = 700 \text{ s}/700 \text{ s})$. Model with fitting priority successfully fits to the measurement data for DUT_B.



Fig. 15 AC stress results at $t_{str}/t_{rec} = 7 \text{ s}/7 \text{ s}$ for DUT B.



Fig. 16 AC stress results at $t_{str}/t_{rec} = 1,260 \text{ s}/140 \text{ s}$ for DUT_B.

5. Conclusion

In this paper, we propose the universal NBTI degradation model which can express an AC stress dependability from a single-shot DC stress/recovery measurement. We assume that the NBTI degradation is a combination of the R-D and T-D models, and only the degradation by T-D can be recovered. Putting some priorities in fitting parameters, we can successfully extract a set of parameters to express an AC stress dependency. The method can be used regardless of the ratio of each degradation component. The developed model can express not only DC stress/recovery but also AC stress/recovery.

Acknowledgments This work has been partly supported by Renesas Electronics. This work is also partly supported by VLSI Design and Education Center (VDEC), the University of Tokyo in collaboration with Synopsys, Inc.



Fig. 17 Duty ratio dependence for DUT_B (T = 1400 s).

Table 8	RMSE to compare models and measurement for DUT_B
	(a) Compare w/ Priority and w/o Priority

Str/Rec time	Duty	RMSE [a.u.]		
		w/o Priority	w/ Priority	
7 s/7 s	50	0.94	0.38	
140 s/1260 s	10	0.46	0.27	
700 s/700 s	50	0.33	0.17	
1260 s/140 s	90	1.00	0.47	

(b) Compare w/ DC bias and w/o DC bias

Str/Rec time	Duty	RMSE [a.u.]		
		w/o DC bias	w/ DC bias	
7 s/7 s	50	0.80	0.32	
140 s/1260 s	10	0.57	0.33	
700 g/700 g	50	0.26	0.36(w/o	
/00 8//00 8	50	0.30	DC Bias)	
1260 s/140 s	90	1.00	0.63	

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