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

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***Abstract*—In this paper, simple and compact Negative Bias Temperature Instability (NBTI) model is proposed. The model 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 model successfully replicates stress and recovery with various duty cycles.**

Keywords—Negative bias temperature instability (NBTI), AC stress dependency, reaction diffusion, hole trapping

I. Introduction

Negative bias temperature instability (NBTI) is one of the most severe reliability issue for integrated circuits. The NBTI is an aging degradation in negative-biased PMOS transistors. The effect of NBTI is observed as transistors performance degradation, which is expressed as threshold voltage and subthreshold swing degradation in compact models [1]–[6]. The performance degradation increases path delay and it leads to malfunction due to timing violation. Accurate lifetime estimation of transistors is mandatory to design circuits with a moderate design margins.

NBTI degradation is accelerated by temperature and a strong vertical electric field to gate dioxide [7]–[9]. By removing the electric fields, the NBTI degradation is recovered 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, 11–13]. The R-D model assumes that the NBTI degradation and recovery are caused by the generation of interface traps. Hydrogen is dissociated from Si-H at Si-SiO_2 interface and diffuse toward the gate electrode during applying negative bias to gate electrode. The hydrogen dissociated from Si-H recombines with dangling bond Si- when the negative bias is removed. These hydrogens becomes 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 NBTI degradation and recovery are caused by the trapping and de-trapping the carriers into the pre-existing defects in the gate oxide. The distribution of the time constant of trap carriers is assumed to follow a lognormal distribution. Thus the threshold voltage variation 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 carrier are positively charged. However, the T-D model cannot explain a permanent component of a degradation and degradation of subthreshold slope characteristic which is widely observed in various papers. To overcome these problems, a NBTI model combining those two mechanisms was proposed in [14].

Since NBTI has both degradation and recovery, estimating the total amount of NBTI degradation is important for circuit design. For the 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, we propose a simple and universal NBTI degradation and recovery model which can expresses an AC stress dependency from a single-shot DC stress and recovery measurement result. This model assumes that the degradation is caused by the combination of both of the R-D and T-D mechanics, but only the T-D mechanism recovers the stress 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.

This paper is organized as follows. Section II describes related works for the NBTI models and explain differences among our proposed model and other conventional models. Section III describes the proposed model and modeling guideline. Section IV describes experimental results and model verification results with measurement data. Section V concludes the paper.

II. Related works

To estimate the amount of NBTI degradation, many NBTI models are proposed. Reference [15] uses the two mechanisms of the R-D and T-D models and successfully estimate 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 [16] 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.

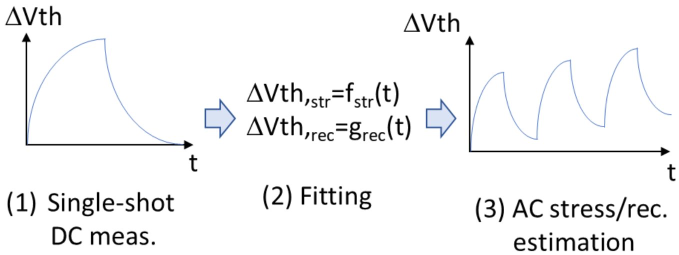


Fig. 1 AC stress estimation from a single-shot DC measurement.

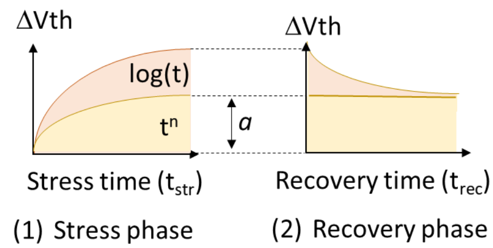


Fig. 2 Impact of the parameter '*a*' on the NBTI model. It defines the ratio of the exponential component and the logarithmic component. The exponential component must be larger than the logarithmic component in order not to recover extraordinary

Our proposed model can be developed with a simple measurement procedure and a fitting flow. The model in [15] has parameters depending on duty cycle and clock period. In model development, extra time-consuming measurement must be performed to obtain those parameters. Reference [16] uses both the drain-source current and gate injection current to build a compact model. The model-building flow is also complicated and it is difficult to obtain model parameters.

In this work, we proposes 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 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. There are many candidates of the parameters that can replicate measurement data. First 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 express not only a single-phase stress/recovery but also multiple-phase AC stress dependency.

III. Proposed Model

The goal of our compact model to express DC/AC measurement results with a unique set of fitting parameters. Furthermore, model developing process should be simple. Fig. 1 shows our modeling methodology. It is built from a single-phase stress-recovery DC measurement that can express AC stress dependency.

In the model, we assume that NBTI degradation is modeled by the combination of the R-D and T-D models. On the contrary, only the logarithm component from the T-D model is considered since the R-D model cannot explain recovery phenomenon.

A. *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 candidates to express the NBTI degradation. In the R-D model, the threshold voltage degradation is modeled as an exponential 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

$$\Delta V_{th} = a\, t^{1/6} + b \log(1 + c\, t), \qquad (1)$$

where, a, b, and c are the fitting parameters, t is stress time. Exponent of time is 1/6, which is a well-known value in the R-D model. In the recovery phase only the logarithm component can be recoverable since the R-D model cannot be applied to the recovery phenomenon. The NBTI recovery is expressed as follows

$$\Delta V_{th,log} / \Delta V_{th,log\_max} = \alpha\, (t_{rec} / t_{str})^{\beta}, \qquad (2)$$

where, α, β is a fitting parameter, t_{rec} is recovery time, t_{str} is stress time.

$\Delta V_{th,log\_max}$ is the total amount of threshold voltage degradation, which is the sum of the accumulated logarithmic components of the NBTI degradation and recovery. $\Delta V_{th,log}$ 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 exponential since the threshold voltage shift on the recovery phase should not overcome that on the stress phase to prevent recovery undershoot.

Finally, the total amount of threshold voltage shift after one stress and one recovery is described as follows,

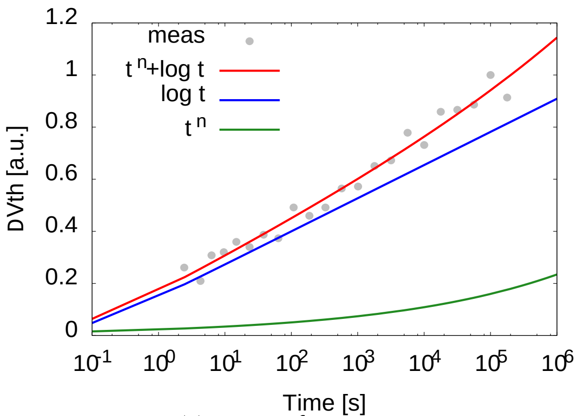
$$\Delta V_{th} = a\, t^{1/6} + b \log(1 + c\, t) + \alpha\, \Delta V_{th,log\_max}\, (t_{rec} / t_{str})^{\beta}. \qquad (3)$$

B. *Model fitting flow*

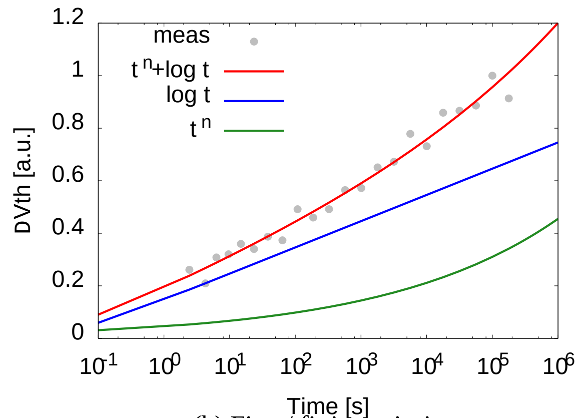
In this section, we propose a model fitting flow to obtain most appropriable parameters to express NBTI degradation and recovery.

The least square method is widely used for fitting. There are the above five parameters that must be fit from two measurement data on tress 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 extracts a set of parameters following duty-cycle dependency of stress and recovery.

In our fitting procedure, we use the assumption that the amount of recovery should be larger than zero. With this assumption, first the parameter '*a'* is extracted in the stress



(a) Fit w/o fitting priority



(b) Fit w/ fitting priority.

Fig. 3 Two different fitting results for threshold voltage degradation

Table I Measurement conditions.

	V_{GS} [V]	V_{DS} [V]	T [°C]
Stress phase	−2.0	0.0	105
Recovery phase	0.0	0.0	105
Measurement phase	−0.55	−0.10	105

Table II residual sum of squares to the fitting method.

	RSS(constant stress)
w/o priority	3.18×10^{-5}
w/ priority	3.41×10^{-5}

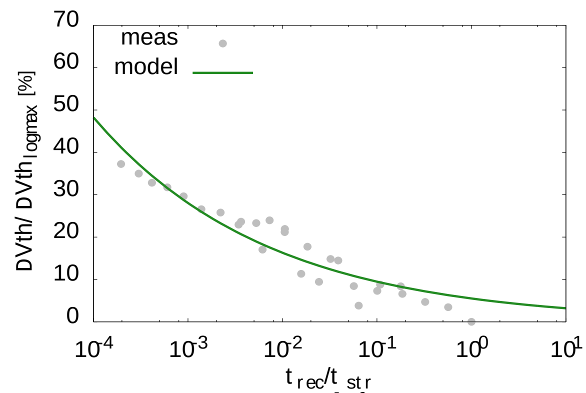


Fig. 4 Fitting result for recovery.

phase, which is a maximum value to satisfy the amount of recovery should be positive. Then, the parameters '*b*' and '*c*' are fixed by using the extracted value of '*a*'.

Figure 2 shows the impact of the parameter '*a*' in our NBTI model. The parameter '*a*' defines the ratio of the exponential component and the logarithmic component of the NBTI stress. We assume that only the logarithmic component of NBTI stress can be recovered. Thus the amount of the recoverable component is constant. Finally, the other parameters are fit by using Eq. (2) on the recovery phase.

IV. Experimental Results

In this section, we explain an experimental setup for NBTI stress/recovery measurement and validate our model. The NBTI model is obtained by single shot DC stress/recovery measurement, and verified under the different duty cycled AC stress/recovery measurement.

A. *Experimental setup*

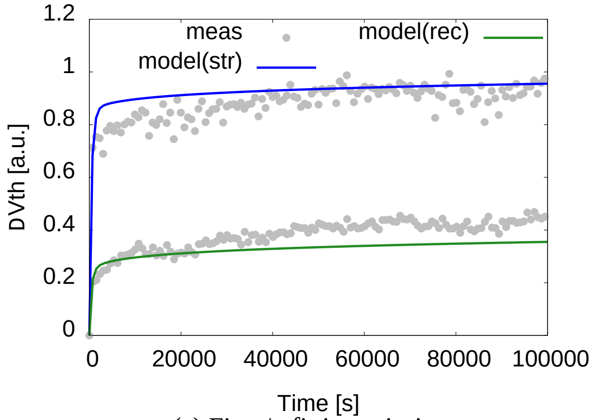
We measure the NBTI effects on a 65-nm FDSOI process for model building and verification. We measure the transistors on-current with measure-stress-measure (MSM) method. MSM method applies stress voltage only in the stress condition, and remove the stress during measurement. To prevent recovery at the 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 simulation. We first measure its initial device current, and then measure its current degradation after applying stress voltage and temperature. We apply −0.55 V for gate-source voltage, and −0.10 V for drain-source voltage to prevent the short channel effect.

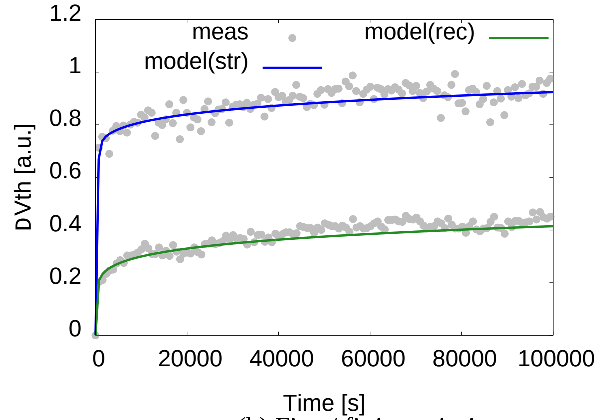
All the transistors used in this experience are W/L = 0.14 µm × 20 / 60 nm, and are regularly located on a wafer. We probe them individually and measure its on-current using semiconductor analyzer Agilent 4156C. Table I summarizes the measurement conditions.

B. *Measurement and verification for DC stress/recovery*

We measure the transistors on-current in NBTI DC stress/recovery, and construct NBTI model expressed as eq.(1) and eq.(2). Fig, 3 show the result of two model with difference fitting method. Fig. 3(a) does not use priority in fitting, simply fits the equation to the NBTI degradation. On the other hand, fig. 3(b) uses a priority in fitting. Threshold voltage in fig.3 is normalized its maximum value because of the NDA. Table II shows the residual sum of squares (RSS) in each fitting method. Results show both two set of parameters successfully fit to the measured result. However, the ratio of the exponent and logarithm component differs between the two model. Figure 4 shows the result of our model and measurement data in recovery stage. As we assume, all measured data are positive or nearly zero.



(a) Fit w/o fitting priority.



(b) Fit w/ fitting priority.

Fig. 5 AC stress results from two model building methods (t_{str}/t_{rec} = 700 s/70 s). Model with fitting priority successfully fits to the measurement data.

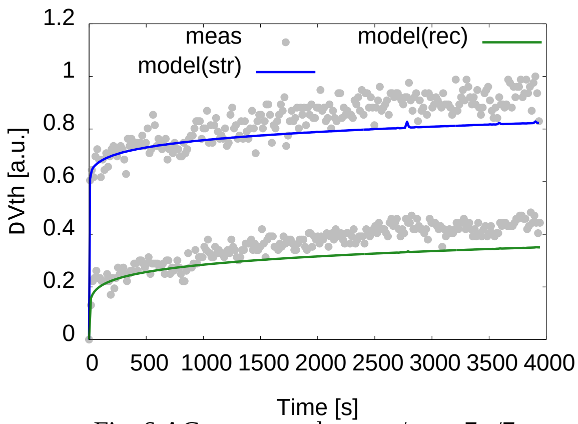


Fig. 6 AC stress results at t_{str}/t_{rec} = 7 s/7 s.

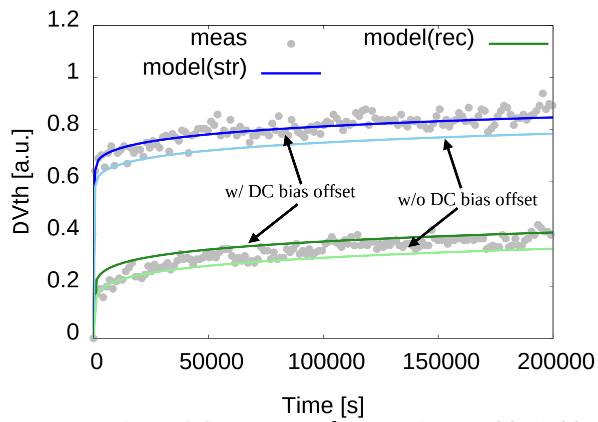


Fig. 7 AC stress results at t_{str}/t_{rec} = 700 s/700 s.

C. *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. Fig. 5(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 s/70 s). The model without considering fitting priority cannot express the measured duty cycle dependency. Fig. 5(b) shows the measured results and the model considering fitting priority (hereafter called PM). The measurement data is equivalent in Fig. 5(a) and 5(b). In this case, the proposed PM can express tendency of iteration data which is appeared as accumulation of degradation. Similarly, we verify PM with different iteration conditions. Figures 6-8 depict the iteration measurement data for t_{str} / t_{rec} =7 s/7 s, 700 s/700 s, 1260 s/140 s with PM. Since each transistor is suffered from different process variation, some amount of DC bias offset is applied to the model equation. In this case, there are two set of model equations in Figs. 7, 8. Note that the amount of DC bias offset is determined to fit the model equation to the initial degradation, as illustrated in Fig. 9. This DC bias offset is also used to compensate the NBTI variability on each transistor. The proposed PM can express the AC dependability of NBTI from the single shot DC measurement.

Table III summarizes the iteration conditions of stress/recovery time, calculated duty ratios and these Root

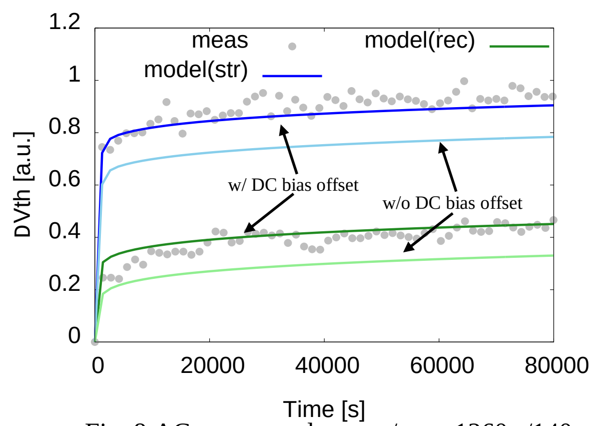


Fig. 8 AC stress results at t_{str}/t_{rec} = 1260 s/140 s.

Mean Square Errors (RMSE). RMSE becomes small by adding the bias voltage. We conclude that the proposed PM have ability to express NBTI degradation and recovery by changing only the DC bias with the fixed other parameters.

Table III RMSE to compare models and measurement

Stress/recovery time	Duty ratio [%]	RMSE [a.u.]
7 s/7 s	50	0.26
700 s/70 s	91	0.21
700 s/700 s (w/o DC bias)	50	0.54
700 s/700 s (w/ DC bias)	50	0.31
1260 s/140 s (w/o DC bias)	90	1.00
1260 s/140 s (w/ DC bias)	90	0.31

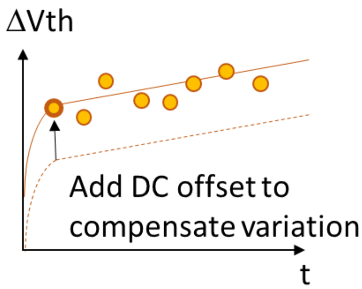


Fig. 9 Add DC bias offset for compensation of the variety of NBTI in each transistor.

V. CONCLUSION

In this paper, we propose the 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 successfully extract a set of parameters to express an AC stress dependency. The developed model can express not only DC stress/recovery but also AC stress/recovery.

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