Impacts of Cycle-to-Cycle Variation effects on the Prediction of NBTI Degradation and the Resulted Dynamic Variations in High-κ MOSFETs

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ABSTRACT

In this paper, the impacts of cycle-to-cycle variation (CCV) effects on the predictions of NBTI degradation and the resulted dynamic variations are studied in highly-scaled high-κ pFETs. By adopting the statistical trap-response (STR) technique, the 2-D distributions and the correlations of key parameters in compact NBTI models due to both device-to-device variation (DDV) and cycle-to-cycle variation (CCV) are extracted. Large error can be found if not considering the CCV effects in predicting the NBTI degradations and resulted time-dependent variations. Different compact NBTI models are also compared for accurate reliability-variability predictions in nanoscale device and circuit design.

INTRODUCTION

With the downscaling of device dimensions, NBTI reliability induced dynamic variations have attracted growing attentions [1-8], which would have much impact on the circuit level predictions of the device aging and resulted time-dependent variations. Whatever which compact NBTI model is used in circuit simulations, the random fluctuations of the key parameters in these models should be considered for accurate reliability-variability predictions.

Recently, we have found that, apart from conventional time-dependent device-to-device variation (DDV) during NBTI degradation, there is a new source of cycle-to-cycle variation (CCV) due to the random occupation of trap states in each operation cycle [5]. This new CCV effect adds to the total time-dependent variation of V_{th} shift (ΔV_{th}) during circuit aging, which should thus be taken into account into the prediction of NBTI degradation and the resulted dynamic variations. Therefore, in this paper, the 2-D distributions and the correlations of key parameters in compact NBTI models due to both DDV and CCV effects are experimentally extracted and analyzed. And their impacts on the reliability-variability predictions of NBTI are extensively studied.

DEVICES AND CHARACTERIZATION METHODS

The samples used in this work are highly-scaled pFETs with ultrathin SiO_2/HfO_2 gate dielectrics. The gate length is 27nm, Due to DDV and CCV combined effects, ΔV_{th} presents a 2-D distribution for each particular aging time, as shown in Fig.1 (a). Therefore, statistical trap-response (STR) technique [5-6] is adopted here, as shown in Fig.1 (b): the devices were shortly stressed and then fully recovered at a small V_g to monitor the recovery traces, which has been used for characterizing either DC NBTI [5] or AC NBTI [6]. In this work, AC NBTI of 100 kHz is taken as the stress condition for demonstration. For each device, the stress/recovery cycle is repeated 50 times for CCV analysis; and for DDV characterization, devices with the same W and L across the wafer are measured.

RESULTS AND DISCUSSIONS

Fig.2 shows the typical results of STR measurement. The mean value of ΔV_{th} varies with different devices and different cycles, which induce the DDV and CCV in NBTI degradations.

For circuit-level predictions, compact NBTI model, whatever conventional NBTI model or the recently-proposed hole trapping (HT) model, should be used. For conventional NBTI model, ΔV_{th} is as Eq. 1 [2]. In our previous study based on the HT mechanism [5], the ΔV_{th} is related to the average number of activated traps per device (N) and the effective trap occupancy probability (p_{eff}) as in Eq. 2, in which N is experimentally found to be log(t) dependent [5]. Therefore, ΔV_{th} in HT model can be simply written as the Eq. 3, which is also consistent with the theoretical results [7]. Or, one can use a slightly modified expression as in Eq. 4 [8]. In this work, Eq.3 is used in HT model for simplicity.

Therefore, whatever which compact model is used for predicting NBTI degradation and variation, we need to consider both DDV and CCV effects on the key parameters in the model, which actually induce 2-D distributions. So, the variations of conventional NBTI model are related to the fluctuations of A and n, while variations of the recent HT model are related to ϕ, A and B (or ϕ, A and C).

Fig. 3 shows the distributions of the extracted parameters in conventional NBTI model. Both A and n present the normal distribution, and they are independent. The distributions of extracted parameters in the recent HT model are also normal distributions as shown in Fig. 4, in which A and B are independent, but A shows a linear dependence on ϕ. All these parameters show non-negligible variations when taken into account of CCV effects, which can seriously impact the reliability-variability predictions.

For the circuit-level predictions, the model parameters can be randomly generated according to their normal distributions, e.g., in HSPICE Monte Carlo simulation. It is worth noting that, the dependence of A and ϕ in the HT model should be considered in the prediction. As shown in Fig. 5, for a short-term stress time, both conventional NBTI model and the recent HT model can fit the experiment data. But as will be shown later, they give different long-term prediction. Fig. 6 shows μ and σ of ΔV_{th} predicted by conventional model and the recent HT model. It can be found that, even if both models can fit the experimental data for the short stress time; however, for long-term stress, conventional model predicts larger variations than the recent HT model, which is due to the sensitivity of the parameters in conventional model.

Fig. 7 shows the DDV for different cycles predicted by conventional model and the recent HT model for long stress time. The CCV effects have large impacts on the variations of parameter n and ϕ in each model respectively. It can be found that the $\sigma(\Delta V_{th})$ increases with the increasing stress time and the predicted DDV in the best cycle can be less than 25% of that in the worst cycle, which evidently indicate that the CCV effects must be considered in the evaluation of dynamic variations, whatever which compact NBTI model is used in the predictions.

SUMMARY

In this paper, the impacts of CCV effects on the predictions of NBTI degradation and the resulted dynamic variations are studied. By adopting the STR measurement, the variations of key parameters in compact NBTI models due to both CCV and DDV are shown to be normal distributions. It is found that the CCV effects must be taken into account in the predictions of NBTI degradation and its aging-induced dynamic variations, for the reliability-variability-aware design in nanoscale devices and circuits.

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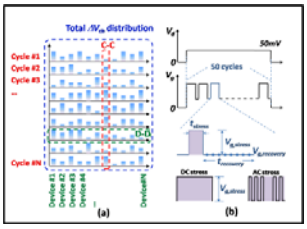


Fig.1 (a) Illustration of the 2-D total ΔV_{th} distribution in NBTI among different devices and cycles for a fixed aging time. (b) Measurement schematics of the STR technique.

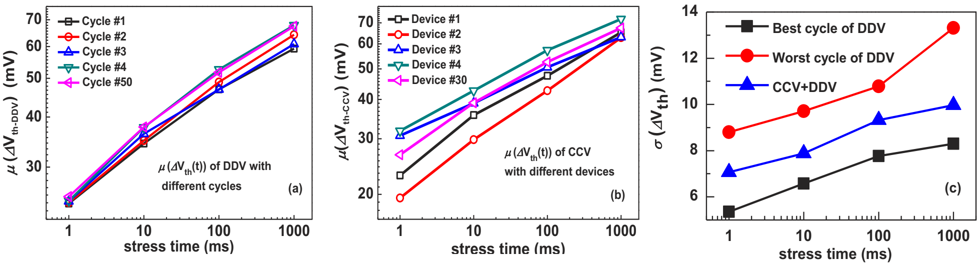
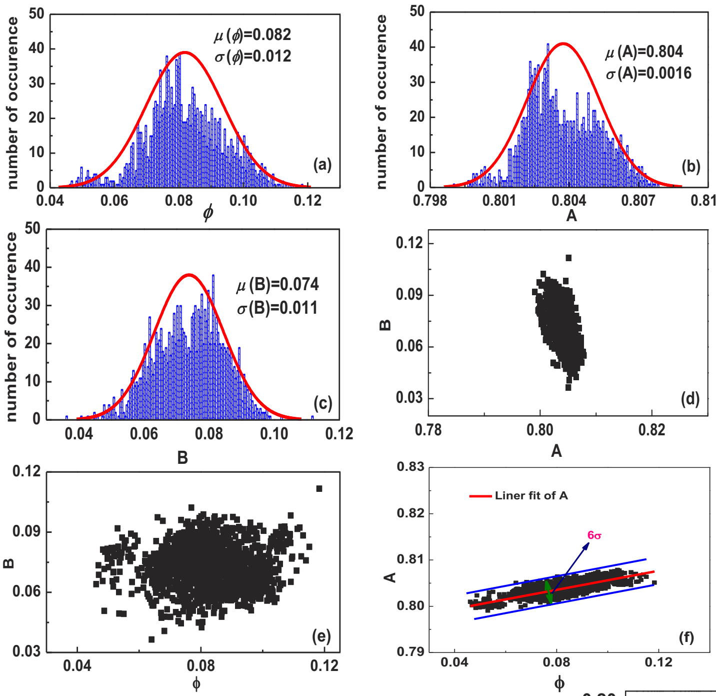


Fig.2 Experimental results of the (a) $\mu(\Delta V_{th\text{-}DDV}(t))$ with different cycles and (b) $\mu(\Delta V_{th\text{-}CCV}(t))$ with different cycles. (c) The experimental results of the variance σ due to the total ΔV_{th} variation. The variance due to device-to-device (D-D) ΔV_{th} variation (for the best and worst cycle) is also shown. The stress conditions were $V_{g,stress}$ = -2V, $V_{g,recovery}$ = -0.8V, T=125℃.



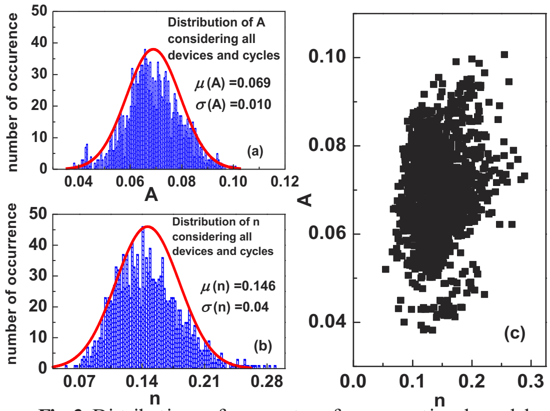


Fig.3 Distributions of parameters for conventional model, (a) A, (b) n. (c) A and n are independent. Both A and n are shown to be normal distribution. Large variations of A and n can be seen due to DDV and CCV.

Eq.1 $\left|\Delta Vth(t)\right| = At^{n}$ **Eq.2** $\mu\left(\left|\Delta Vth(t)\right|\right) = \lambda p_{eff} N$

Eq.3 $\left|\Delta Vth(t)\right| = \phi\left(A + B\,log(t)\right)$

Eq.4 $\left|\Delta Vth(t)\right| = \phi\left(A + log(1 + Ct)\right)$

Fig.4 Distributions of parameters for the recent HT model, (a) ϕ, (b) A, (c) B. ϕ, A and B are shown to be normal distributions. Relations of these parameters for HT model, (d) A and B are independent, (e) ϕ and B are independent, (f) A and ϕ are dependent.

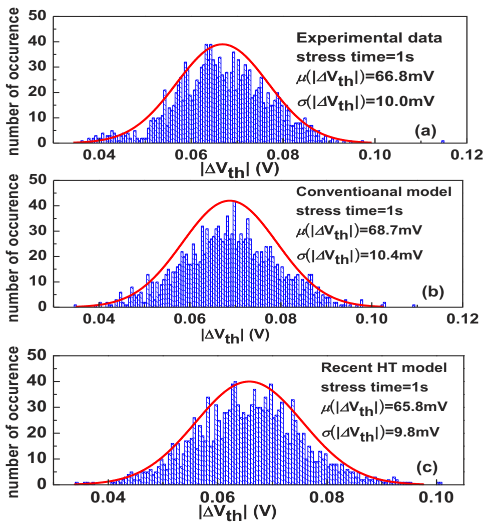


Fig.5 The total ΔV_{th} distribution of (a) experimental results, (b) conventional model and the recent HT model.

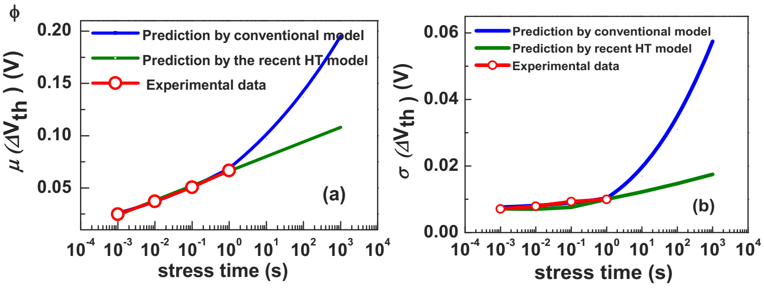


Fig.6 (a) Mean value and (b) stand deviation of ΔV_{th} predicted by conventional model and recent HT model. For short stress time, both the conventional model and the recent HT model can fit the experiment data, while for long stress time, both μ and σ value predicted by the two models deviate from each other.

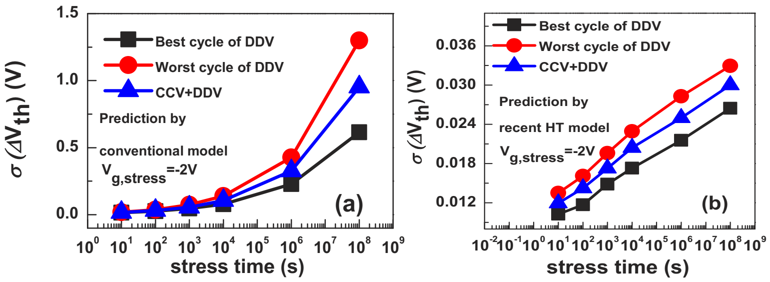


Fig.7 The prediction by (a)conventional model and (b) recent HT model of the variance σ due to the total ΔV_{th} variation. The variances due to device-to-device (D-D) vth variation (for the best and worst cycle) are also shown.