The As-grown-Generation (AG) model: A reliable model for reliability prediction under real use conditions

J. F. Zhang*, Z. Ji and W. Zhang
Department of Electronics and Electrical Engineering, Liverpool John Moores University,
Byrom Street, Liverpool L3 3AF, UK.
*Phone: +44-151-2312363 Email: j.f.zhang@ljmu.ac.uk

***Abstract-* Modeling the negative bias temperature instability (NBTI) can optimize circuit design. Several models have been proposed and all of them can fit test data well. These models are extracted typically by fitting short accelerated stress data. Their capability to predict NBTI aging outside the test range has not been fully demonstrated. This predictive capability for long term aging under low operation bias is what needed by circuit designers. In this work, we test the predictive capability of the well-known reaction-diffusion (RD) based framework for samples fabricated by a variety of processes. Results show that the RD model cannot make an acceptable generic prediction. The recently proposed As-grown-Generation (AG) model is then introduced. By dividing defects into two groups, as-grown and generated defects, and measuring the as-grown defects experimentally, we demonstrate that it can make reliable prediction for the same set of data where the RD model failed.**

I. INTRODUCTION

The gap between device models and real performance is one of the difficulties in optimizing circuit design. The inaccuracy in modeling aging can contribute to this gap [1, 2]. The negative bias temperature instability (NBTI) is a well-known reliability issue for both digital [3] and analog CMOS integrated circuits [4]. Although it was first reported in 1960s [5], it has become a serious aging issue only since 2000s or so, because the operation temperature and electrical field increase with downscaling [6] and nitrogen is routinely added to gate dielectric [7, 8].

Several NBTI models have been proposed, such as the two-stage model [9], reaction-diffusion (RD) based framework [10, 11], the composite model [12], and the as-grown-generation (AG) model [13-17]. In order to verify their correctness, a common practice is to demonstrate that they can fit the test data well. The tests were typically carried out at elevated Vg for a relatively short time (e.g. 1000 sec [10]) and there is little information on their capability to predict aging outside the test range used for the fitting. This predictive capability for long term aging under low operation bias is what needed by circuit designers.

The two-stage model has been extensively and critically reviewed recently [11,18]. In this paper, we will examine the predictive capability of the RD based framework and the AG models. The methodology is to test them under conditions as simple as possible, since if they do not work under the simplified test conditions, they cannot work when additional physical processes are involved. As a result, we only test the continuous stress (DC) with recovery process minimized here. It will be shown that both the RD based framework failed in the prediction assessment. In contrast, the As-grown-Generation (AG) model can predict the long-term degradation under low operation biases, based on the same set of test data.

II. DEVICES AND EXPERIMENTS

A. Devices

To test the generic predictive capability of the RD model, four processes were selected to represent different fabrication techniques (ALCVD, plasma nitridation, and thermal nitridation), and dielectric materials/structures (Al_2O_3-capped HfO_2/SiON, HfSiON/SiON, SiON), and gate materials (TiN, p+ poly-Si) as listed in Table I. Both D1 and D2 have high-k stack and metal gates. Among the four processes, Fig. 1 shows that D2 has the highest NBTI under Vg=-1.1 V, representing a process under development. D3 is a plasma nitrided SiON and has the lowest NBTI, representing an industry-grade process. D4 is a thermally nitrided SiON and is used to give a high nitrogen density and high as-grown hole traps [19] .

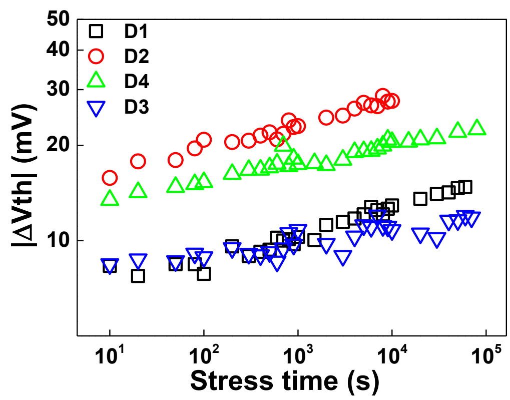

Fig. 1 A comparison of the aging of the four samples listed in table I under nominal operating bias, Vg, and 125 ºC.

On device sizes, the NBTI models originally were proposed for large devices with a negligible statistical variation. There are efforts to adopt them for the nm-sized devices by introducing statistical distributions for the model parameters [14, 17, 20]. If the original model does not work for a large device, a revised model based on it will not work for nm-size devices. As the first step in testing their predictive capability, large devices were used in this work for simplicity with typical channel width of 10 µm and length of either 1 µm (D1) or 0.1 µm (D2, D3, D4).

TABLE I SAMPLE LIST USED IN THIS WORK

Device number	Gate dielectrics	EOT
D1	HfO2 with TiN gate	1.45nm
D2	HfSiON/SiON with TiN gate	1.53nm
D3	Plasma SiON with high N% and P+ poly gate	2.0nm
D4	Thermal SiON with poly gate	2.7nm

B. Experiment

The test follows the commonly used stress-then-sense procedure and aging is monitored by pulse Id-Vg [21,22]. It starts by recording the reference Id-Vg from a 3 µs gate pulse edge during which degradation is negligible [21]. The stress was carried out either under a constant Vg or a constant over-drive voltage, Vg_ov=Vg-Vtho-ΔVth. The threshold voltage shift, i.e. ΔVth, was monitored from the Vg shift at a constant sensing Id= 100 nA×W/L. The measurement delay is 3 µs and the recovery is minimized [21]. All tests were carried out at the typical work temperature for modern CMOS technologies, i.e. 125 °C.

The constant Vg stressing was used in Fig. 1, since circuits operate under a fixed Vg. The NBTI, however, is believed to be driven by the oxide field at the interface, Eox, so that it is desirable to carry out tests under constant Eox. Under a constant stress Vg, |Eox| reduces as the positive charges built up with time. To maintain a constant Eox, the overdrive voltage, i.e. Vg_ov=Vg-Vtho-ΔVth, was kept as a constant through increasing the stress |Vg| by the |ΔVth| measured at the last step. The upper panels in Figs. 2(a)~(d) gives the ΔVth with Vg_ov not changing with time.

III. Failure of the RD Models

The original RD model was proposed for NBTI on devices of thick SiO_2 (e.g. 95 nm) with the stress Eox low enough that hole injection was negligible [5,23]. For the thin dielectric (e.g. < 3 nm) used in current industry, however, hole injection and subsequent trapping is significant and the H/H_2 RD model has been revised [10, 11]. In the “RD based framework” [10, 11], RD process covers only the generation of interface states (ΔV_{IT}). Two other components have been added: i) As-grown hole traps (ΔV_{HT}), and ii) Generation of bulk traps (ΔV_{OT}). The filling of as-grown hole traps saturates generally within 10 sec and ΔV_{HT} becomes time-independent for longer time. The formula of the simplest R-D based framework is given in eqns. (1)-(4), which is applicable to the stress phase for a stress time over 10 sec and should have the capability to predict the long term threshold voltage shift, ΔVth, under operation Vg.

$$\Delta V_{IT}=\frac{q}{Cox}A\left(Vg-Vth0-\Delta Vth\right)^{\Gamma_{IT}}e^{-\frac{E_{AIT}}{kT}}t^{1/6} \quad (1)$$

$$\Delta V_{HT}=\frac{q}{Cox}B\left(Vg-Vth0-\Delta Vth\right)^{\Gamma_{HT}}e^{-\frac{E_{AHT}}{kT}} \quad (2)$$

$$\Delta V_{OT}=\frac{q}{Cox}C(1-e^{(-\left(\frac{t}{n}\right)^{\beta_{OT}})}) \quad (3)$$

where $$n=\eta\cdot(Vg-Vth0-\Delta Vth)^{-\frac{\Gamma_{OT}}{\beta_{OT}}}e^{(\frac{E_{AOT}}{kT\beta_{OT}})}. \quad (4)$$

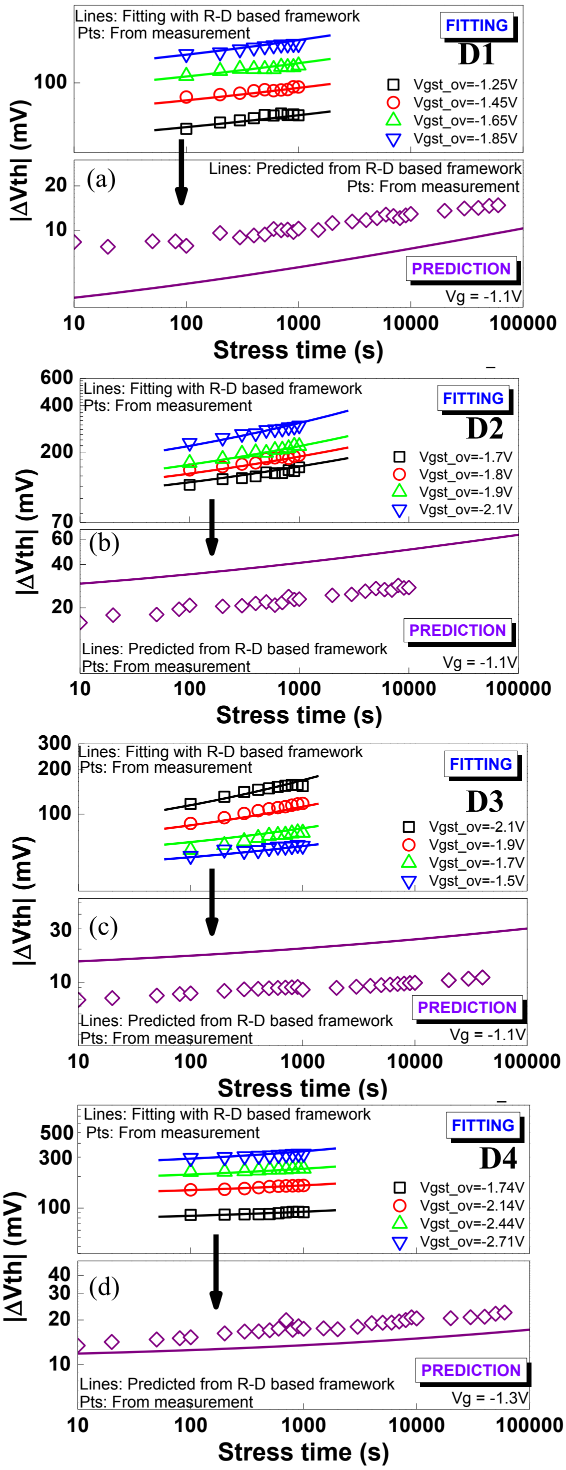

Fig. 2 Predictive capability assessment of the R-D based framework in eqns. (1)-(4). The symbols are test data. (a), (b), (c), and (d) are for the sample D1, D2, D3 and D4 given in table I, respectively. The upper panels of (a)-(d) give the ΔVth measured from short accelerated stresses and the lines are computed by using the fitted parameters in table II. The extracted model was then used to predict ΔVth under low operating Vg in the lower panels. The prediction (lines) does not agree with the test data.

Before testing the prediction capability, four parameters: A, B, C, and $\Gamma_{IT}=\Gamma_{HT}$ must be fitted for the RD based framework. The other parameters in eqns. (1)-(4) are constant and given in ref. [10]. To verify the program we used for fitting the parameters, the test data given in ref. [10] were first used and the same values were obtained as those reported in ref. [10]. This RD based framework was then fitted with the NBTI data in the upper panels of Figs. 2(a)-(d) for the