The As-grown-Generation (A-G) model [3] has successfully demonstrated its excellent predicting capability on device reliability and variability under DC NBTI [4] and HCl conditions [5]. This work demonstrates, for the first time, (i) both DC and AC NBTI under use-overdrive Vgst_ov can be reliably predicted from the A-G model extracted from Vg-accelerated short tests (Figs.1c-d), and (ii) the same model can also predict the NBTI under variable operational workload (Fig.2), needed for dynamic voltage scaling power management [6]. The model needs only three fitting parameters.

We emphasize that the A-G model is extracted from the accelerated short DC tests and the test data at low biases in lower panels of Figs.1c-d were not used for fitting. This success is achieved after a detailed understanding of different types of defects and their contributions to NBTI, based on direct measurements of each type of defects (Table I), as described below.

Measuring different types of defects: Devices from three different processes are used, including HKMG and SiON (Table II). Measurement with 3µs speed is used for both DC&AC NBTI under 125 °C. Early works [3] reported that as-grown hole trap (AHT) and generated defects (GD) are located below and above the energy level E(VgGD) (Fig.3) respectively, allowing their separation. For unipolar AC stress, the defects above E(Vg=0V) do not discharge once generated, but those between E(VgGD) and E(Vg=0) do. As a result, the GDs are further separated into two parts: the anti-neutralization positive charges (ANPC) above E(Vg=0V) and the cyclic positive charges (CPC) between E(VgGD) and E(Vg=0V). (Fig.3).

The Vg waveform for their measurement under DC and AC stress is given in Figs.4a&d, respectively. ‘●’ in Fig.4b is the sum of all defects. By biasing at VgGD (Fig.3), all AHTs are discharged, so that AHT (‘●’ in Fig.4c)=‘□’-‘●’. The device was then biased at Vg=0V to discharge CPC, so that CPC (‘□’ in Fig.4c)=‘□’-‘●’ and ANPC=‘●’ (Figs.4e). For AC stress, total AVth are measured on two edges: one from zero to Vgst (‘●’ as “End-of-Recovery (EoR)” and the other from the opposite edge (‘□’) as “End-of-Stress (EoS)”) (Figs.4d&c). This gives two sets of AHTs in Fig.4f: AHT EoS (‘•’=△’- ‘□’) and AHT EoR (‘□’=‘●’- ‘□’). The CPC and ANPC were evaluated in the same way as that after DC stress. Their properties and contributions to NBTI are examined next.

Anti-neutralization positive charges (ANPC): For the same effective stress time, the same ANPC was obtained for DC and AC stresses at different frequencies (Fig.5a), as ANPC does not neutralize during AC stress. ANPC generation follows power law against both stress time (Fig.5b) and stress Vgst_ov (Fig.5c) and the exponents are independent of Vg and stress time, laying the foundation for reliable prediction. ANPC are modelled with three fitting parameters: g0,m,n (eq.1, Table I).

As-grown hole traps (AHT): Under DC stress, more AHTs are charged at higher Vg (Figs.6a&b), but the normalized kinetics is the same (Fig.6c). Under AC stress, AHT EoS reduces for higher frequency (Fig.7a), because of shorter charging time, tch-period/2. With the same tch, AHT EoS agrees well with AHT DC (Fig.7c). Charging AHTs can be fully modelled by the kinetics (Fig.6c) with its saturation level taken from Fig.6b. The efficient discharging under Vg leads to AHT EoR=0 for all frequencies (Fig.7b). This explains AHT EoS=AHT DC for the same tch, since charging restarts from zero in each cycle. The discharge kinetics is independent of Vgst_ov (Fig.8a&b) and used for modelling discharge.

Cyclic positive charges (CPC): CPC is the same for DC and AC initially (<50sec, Fig.9a), but CPC DC saturates at a higher level eventually. To understand this, CPC DC was neutralized and recharged (Fig.9b). CPC can be filled to saturation much faster in the recharging compared with 1st DC stress, confirming they are generated defects. Moreover, these generated CPC clearly has two components: i) fast-charging CPC (iCPC) recharged fully within 1µs, and ii) slow-charging CPC (sCPC) only starts recharging after 5ms and reach saturation after 10s. Their different dependence on stress Vg in Fig.10a supports that they are different defects. For DC NBTI, sCPC charging is modelled by the kinetics in Fig.9b. For AC NBTI, sCPC contributes little to charging (Fig.9a) as total CPC AC=sCPC, because discharging is far more efficient than charging (Fig.10b V.S. Fig.9b). There is no need to model sCPC for AC NBTI, therefore. In contrast, charging fCPC is far more efficient than discharging (Fig.9b V.S. Fig.10b) and contributes to AC NBTI. Similar to AHTs, fCPC is modelled by the saturation level in Fig.10a and the discharging kinetics in Fig.10c.

Aging Prediction: Four Vg-accelerated short (1ks) DC stresses (Fig.1c) were carried out to extract the A-G model (Table I), giving 3 fitted parameters in Table II. The model can successfully predict both DC and AC NBTI under use-Vgst_ov (Fig.1c&d), delivering the original mission of NBTI modelling. The NBTI under variable operation Vg_ov is also successfully predicted (Fig.2). Moreover, the A-G model predicts the frequency (Freq) and duty-factor (DF) dependence under operation condition well (Figs.11a&b). The contributions of different defects are also shown in Figs.11a&b. AHT is mainly responsible for the Freq- and DF-dependence of AVth EoS. A higher Freq or smaller DF reduces the charge time at ‘End-of-Stroke’ and in turn fills less AHTs (Fig.7a&b). At ‘End-of-Recovery’, however, AHTs≈0 for all frequencies due to efficient discharging (Fig.7b), resulting in the well-known frequency-independence of NBTI [7]. Over 1MHz, AHT≈0 and AVth EoR=AVth EoS. Both ANPC and fCPC are frequency independent.

Process independence: The A-G model was applied to two other processes to prove it is not process specific. The measured Freq- and DF-characteristics under low Vg ov agree well again (Figs.12a-d) with the predicted ones using A-G model extracted from the short DC stresses at high biases, in Table II.

An analysis of the success: To understand why A-G model can predict and early models [2] cannot, it is realized that the charging or generation of some defects will saturate with time during aging, like AHTs (Fig.6c) and CPCs (Fig.9b). However, ANPC does not saturate (Fig.5) and thus controls the long term aging. The A-G model’s success comes from its accurate separation of ANPC from the rest of defects, enabling the reliable prediction from accelerated Vg to use Vg.ov. Only one non-saturating aging kinetic is needed: a power law with Vg- and time-independent exponents for ANPC (Fig.5). The R-D framework [2] has to use two separate non-saturating kinetics with more fitting parameters, because the real non-saturating component was not properly separated out. The contamination of non-saturating defects by the saturated ones results in erroneous power exponents and prediction.

Conclusions: For the first time, we demonstrate that A-G model extracted from short Vg-accelerated stresses can predict both long term DC and AC NBTI under low and dynamic operation Vg. This is achieved by successfully separating non-saturating defects from the saturating ones, allowing reliable extraction of power exponents needed for long term prediction. Unlike R-D model, A-G model does not require solving differential equations for AC NBTI. This saves computation time significantly, especially for high-frequency that needs small time-step, and makes it readily implementable in SPICE-like simulators.

Acknowledgement: This work is supported by EPSRC of UK (EP/L010607/1).
For the same charging time, \( t_{\text{ch}} = \text{period} \times \text{DF} \) (duty factor).

For AC:

- \( V_{\text{gov}} = -0.7 \text{V} \) (inset).
- The extraction procedure is shown in Fig.9(b).
- ANPC extracted from DC and AC stress.

\( |V_{\text{gov}}| \) (V)

(\( \text{DC} \))

\( \Delta V_{\text{th}}(\text{ts} = 1 \text{ks}) | \text{[mV]} \)

AC stress, DF=0.5:

\( \Delta V_{\text{th}}(\text{DC}) \) regardless of frequency.

For longer stress time, CPC saturates and CPC\(_{\text{DC}} \) = CPC\(_{\text{AC}}\) regardless of frequency. For longer stress time, CPC saturates and CPC\(_{\text{DC}} \) = CPC\(_{\text{AC}}\).

\( \Delta V_{\text{th}}(\text{DC}) \) after discharging under EoS edge and end-of-recovery (EoR) edge.

In Fig.12, the extracted model parameters for both R-D and A-G models (HKMG: \( \text{a} \& \text{d}; \text{SiON: b} \& \text{d} \)).

- The extracted R-D model, however, cannot predict the \( \Delta V_{\text{th}} \) under low use-\( V_{\text{gov}} \), as shown by the difference between symbols and lines in the lower panels of a&b).
- In contrast, the extracted A-G model predicts well not only for DC, but also for AC, NBTI under the same low use-\( V_{\text{gov}} \) (the lower panels of c&d). The test data in the lower panels of a-d were not used for fitting. In the inset.

- A comparison of CPC extracted from DC and AC stress. Within 50s, CPC\(_{\text{AC}}\) regardless of frequency. For longer stress time, CPC saturates and CPC\(_{\text{DC}}\) = CPC\(_{\text{AC}}\).

\( \Delta V_{\text{th}}(\text{DC}) \) after discharging under EoS edge and end-of-recovery (EoR) edge.

In Fig.12, the extracted model parameters for both R-D and A-G models (HKMG: \( \text{a} \& \text{d}; \text{SiON: b} \& \text{d} \)).

- The extracted R-D model, however, cannot predict the \( \Delta V_{\text{th}} \) under low use-\( V_{\text{gov}} \), as shown by the difference between symbols and lines in the lower panels of a&b).
- In contrast, the extracted A-G model predicts well not only for DC, but also for AC, NBTI under the same low use-\( V_{\text{gov}} \) (the lower panels of c&d). The test data in the lower panels of a-d were not used for fitting. In the inset.

<table>
<thead>
<tr>
<th>Device</th>
<th>( E_{\text{g}} )</th>
<th>( m )</th>
<th>( n )</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1.750-3</td>
<td>3</td>
<td>0.2</td>
</tr>
<tr>
<td>B</td>
<td>4.90E-3</td>
<td>3.38</td>
<td>0.22</td>
</tr>
<tr>
<td>C</td>
<td>1.00E-4</td>
<td>4.49</td>
<td>0.25</td>
</tr>
</tbody>
</table>

The magnitude and charging/discharging kinetics of \( \text{AHT, CPC, ANPC} \) is extracted directly from experiments (Fig.6 & Fig.10).