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A Consistent Modeling Framework to Explain Negative Bias Temperature Instability (NBTI) DC Stress, Recovery and AC Experiments

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Introduction: NBTI is a crucial reliability issue for SiON and high-k p-MOSFETs having implications for digital and analog CMOS circuits and has attracted huge attention. Past studies have shown the following key features of NBTI: (i) it recovers after the removal of stress [1] and calls for fast or ultra-fast measurements [1-3], (ii) it shows strong gate oxide process dependence [4,5], (iii) optimized, production quality devices show universal power-law long-time degradation [6-8], (iv) recovery data measured following stress show log-like time dependence [9], and (v) AC data versus frequency and duty cycle from different groups also show universal behavior when properly normalized [10]. In this paper, a Reaction-Diffusion (RD) model [11-13] based framework is used to explain all the key features of NBTI as listed above.

Stress data analysis: Gate oxide process impacts measured NBTI V_T shift (Fig1a), pre-existing bulk traps (Fig1b) and stress induced trap generation (Fig1c). As modeled in detail in [10], NBTI is due to *uncorrelated contributions* from fast hole trapping in pre-existing, process related bulk oxide traps (ΔN_h), together with generation of interface (ΔN_{IT}) and bulk (ΔN_{OT}) oxide traps (Fig.2), where a non-dispersive H/H_2 R-D framework [13] has been used to model ΔN_{IT}. The underlying ΔN_{IT}, ΔN_h and ΔN_{OT} components of overall NBTI show consistent temperature (T) activation and oxide field (E_{OX}) dependence for devices having different gate oxide processes (Figs.3,4) [10]. Strong process dependence of NBTI can be *mostly* attributed to differences in hole trapping in pre-existing bulk traps (Figs.2-4), which can be reduced by process optimization. Contributions from ΔN_h and ΔN_{OT} become lower in properly optimized FETs close to operating bias, and long time degradation becomes ΔN_{IT} dominated (Fig.5a) [10]. Predicted degradation has same power law time dependence as measured over long stress time from various groups (Fig.5b) [6-8]. This universal power law feature of long-time NBTI can *only* be predicted by R-D model as discussed in detail in [10].

Recovery data analysis: There has been much concern that R-D model cannot explain NBTI recovery transients [9], as it fails to predict the following features: (i) start of recovery, (ii) rate of recovery, and (iii) bias dependence. As discussed in [10], bias dependence of recovery (as long as recovery bias is well above V_T and interface traps don't capture electrons) is a measurement artifact related to not taking into account the role of mobility degradation. As NBTI stress results in ΔN_h, ΔN_{OT} and ΔN_{IT}, it is inappropriate and naive to attempt prediction of measured recovery data *only* by R-D solution of ΔN_{IT}, as done in [9]. Once the early part of measured recovery is identified to hole detrapping from pre-existing and generated defects, the start time of recovery as governed by ΔN_{IT} recovery can be accurately predicted by R-D model solution. Finally, the difference in measured and predicted rate of ΔN_{IT} recovery by R-D model is identified due to difficulty associated with formulating a 3D diffusion problem in a 1D framework and can be taken into account by adopting multiple back-diffusion pathways. Once ΔN_{IT}, ΔN_h and ΔN_{OT} components are isolated by analyzing stress data, NBTI recovery data from differently processed devices and measured under different conditions can be accurately predicted using hole detrapping and R-D model as shown (Fig.6) [10]. Therefore, contrary to recent perception, NBTI recovery can be accurately predicted by R-D framework.

AC data analysis: NBTI recovery after removal of stress also makes AC degradation lower than that of DC and therefore holds promise for extra reliability margin. AC data obtained from different sources versus frequency and duty cycle show a wide spread when normalized to DC data per usual practice (Fig.7a) [14-20]. This has been identified due to differences in hole trapping contribution that affects DC stress. Interestingly, when renormalized using AC stress data at 50% duty, unique universality is observed (Fig.7b) [10]. Once again, R-D model solution can explain frequency independence and duty cycle dependence (up to ~85% duty, beyond which scatter due to hole trapping dominates). This is another proof that R-D model can accurately predict NBTI recovery.

Conclusions and Outlook: The DC stress, recovery and AC frequency and duty cycle dependence of NBTI degradation in p-MOSFETs show universal features and is explained using a R-D model for interface traps together with hole trapping in pre-existing and stress generated traps. Pre-existing bulk traps can be minimized by suitable process optimization, and generation of bulk traps are reduced close to operating voltage. Therefore for well optimized devices at use condition, NBTI is dominated by generation of interface traps, and R-D model solution can be used to extrapolate measured data to end-of-life for lifetime estimation under both DC and AC conditions.

Refs: [1] Rangan, p.331, IEDM 2003, [2] Varghese, p.684, IEDM 2005, [3] Kumar, p.809, IEDM 2007, [4] Mahapatra, p.1, IRPS 2007, [5] Maheta, p.1630, TED 2008, [6] Islam, p.329, IEDM 2006, [7] Haggag, p.452, IRPS 2007, [8] Chen, p.704, IRPS 2005, [9] Grasser, p.16, IEDM 2010, [10] Mahapatra, p.614, IRPS 2011, [11] Chakravarthy, p.273, IRPS 2004, [12] Alam, p.853, MR 2007, [13] Islam, p.2143, TED 2007, [14] Mitani, p.6, TDMR 2008, [15] Huard, p.33, IRPS 2010, [16] Fernandez, p.337, IEDM 2006, [17] Chen, p.734, EDL 2002, [18] Islam, p.733, IEDM 2009, [19] Reisinger, p.7, IRPS 2010, [20] Grasser, p.28, IRPS 2008

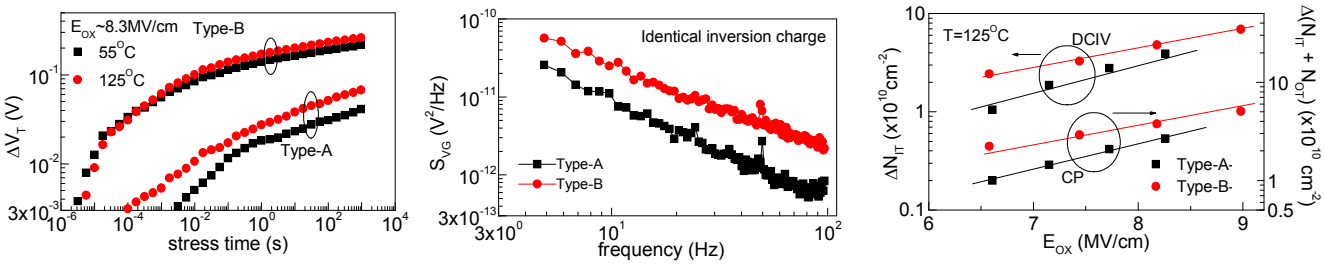


Fig1. (a) NBTI time evolution measured using ultra-fast method, (b) estimation of pre-stress existing traps from flicker noise measurement, and (c) trap generation due to stress measured using charge pumping and DCIV for optimized (Type-A) and un-optimized (Type-B) devices.

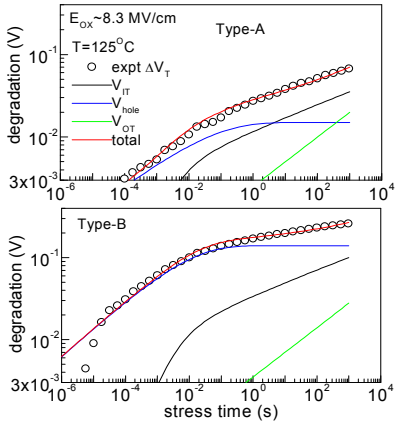
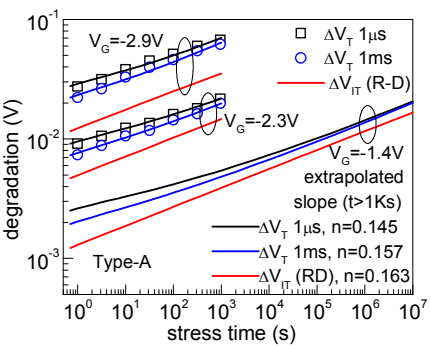


Fig2. Estimation of overall NBTI using ΔN_{IT}, ΔN_{hole} and ΔN_{OT} components.



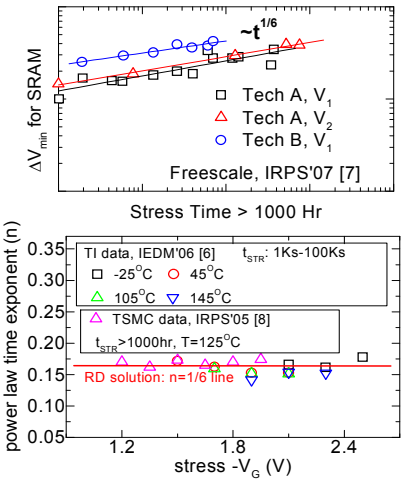


Fig5. (a) Prediction of long time NBTI and extrapolation to use condition, (b) very long time degradation and (c) very long time n published by different groups.

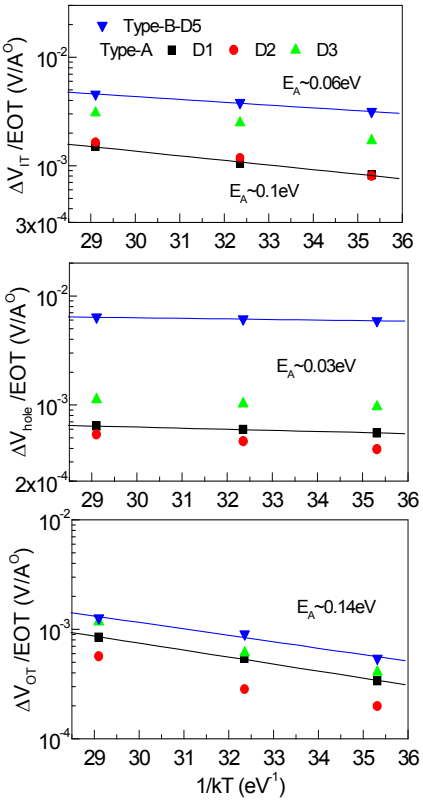


Fig3. Extracted NBTI components for different devices for different T.

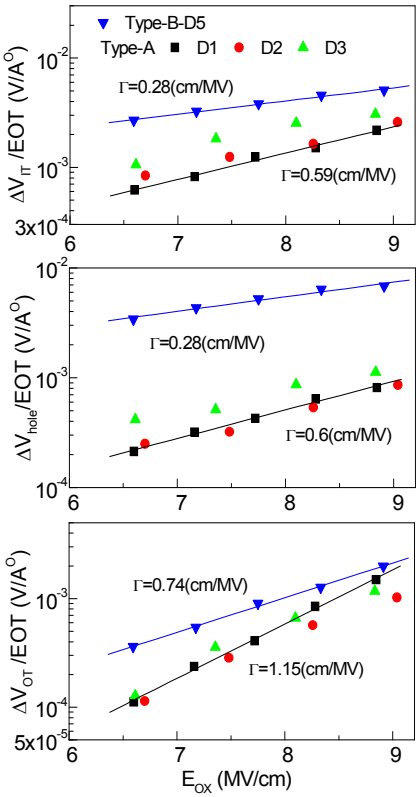


Fig4. Extracted NBTI components for different devices for different E_{OX}.

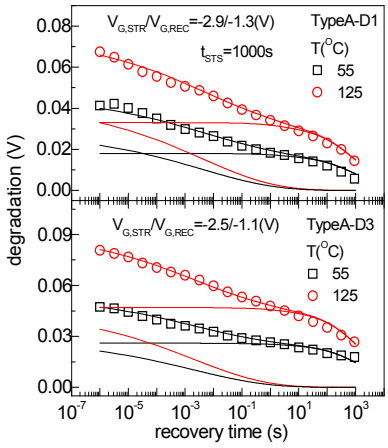


Fig6. Prediction of measured recovery using hole detrapping and R-D model for different type-A devices [10].

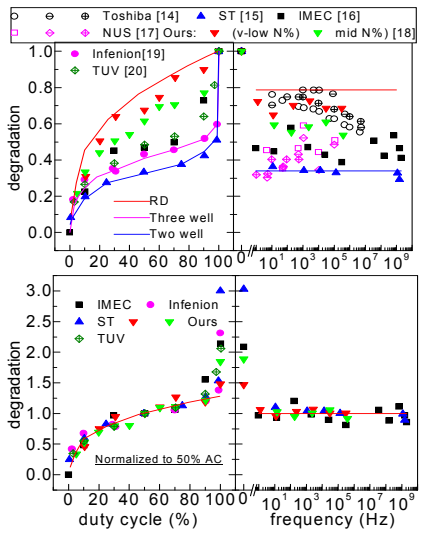


Fig7. AC duty cycle and frequency dependence data normalized to DC (top) and renormalized to 50% AC (bottom). RD solutions are shown by red line.