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A Physical Based Model for Negative Bias Temperature Instability

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Abstract

An analytical time evolution model for describing the negative bias temperature instability (NBTI) is developed based on microscopic pictures. The temperature and field dependences are automatically included and show their universality under various conditions. The model parameters calculated from physics agrees well with those extracted from experimental data.

1. Introduction

The negative bias temperature instability (NBTI) degrades performances of p-MOSFETs and circuits. An accurate prediction model is required for application purpose in EDA (Electronic design automation) reliability module to limit the design window. Physical model based on atom-level is the best choice, but it is difficult to obtain analytical solution [1]. The other extreme is to develop empirical prediction model based on measurement observation even giving up any physical concepts [2]. Numerous fitting parameters may cause problem in handling complex circuit under various operation conditions. In this work, a universal model is developed based on atom-level analysis.

2. Fundamental Mechanisms of NBTI degradation

As illustrated in Fig. 1, the P_b center generation and hole-trapping in the oxide vacancies are usually considered as two original mechanisms of NBTI in p-MOSFET [1]. However, as shown in Fig. 2, none of these mechanisms are able to reproduced the device-level observations of threshold voltage shift (ΔV_{th}) over a wide range of stress time [3]. Therefore, both interface state generation (n_{it}) and oxide hole-trapping (n_{ox}) are involved (Eq. 1) as independent components for reasonable description of the measured ΔV_{th}. The physics behind the parametric shift is revealed in the following sections and universal framework is setup under different conditions of temperature, bias and technology.

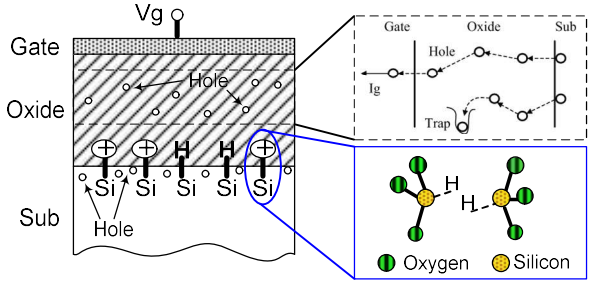

Fig. 1. Illustration of interface state generation and oxide hole-trapping.

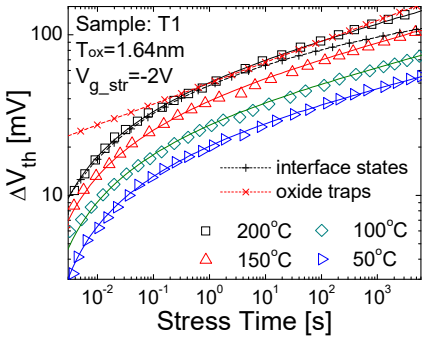

Fig. 2. Description of the observed NBTI degradation by interface state generation and oxide hole-trapping in separate and coordination.

$$\Delta V_{th} = \Delta V_{th\_it} + \Delta V_{th\_ox} = \frac{q}{C_{ox}}\left[R_{str}\log(1+\frac{t}{\tau_{str}}) + M_{ox}t^{\alpha} \right] \quad (1)$$

3. Universal NBTI Model Based on Microscopic Pictures

The interface state (n_{it}) generation is proposed originated from the breakdown of the Si-H bonds and generation rate (dn_{it}/dt) can be described using a first-order dynamic equation [4] as Eq. 2. The tunneling probability (P_{tunnel}) is mainly determined by the oxide electric field (E_{ox}) [5] and the reaction rate (k) is lowered down by dipolar coupling with the local E_{ox} and enhanced by the accumulated positive charged interface states (Eq. 3). Evolution description of the interface state generation is finally obtained as Eq. 4 with model parameters of reaction rate (R_{str}) and time constant (τ_{str}) as functions of temperature and field (Eq. 5).

$$\frac{dn_{it}}{dt} = kP_{tunnel}(N_{bond} - n_{it}) \approx kP_{tunnel}N_{bond} \quad (2)$$

$$k \propto \exp(-\frac{\Delta H_{0\_int} - aE_{ox}}{kT}) = \exp\left[-\frac{(\Delta H_0 + M \cdot n_{it}) - aE_{ox}}{kT} \right] \quad (3)$$

$$n_{it} = R_{str}\log(\frac{t}{\tau_{str}}) \quad (4)$$

$$R_{str} = \frac{kT}{M} \qquad \tau_{str} \propto \exp\left[\frac{\Delta H_0}{kT} - \left(\gamma_T + \frac{a}{kT} \right) E_{ox} \right] \quad (5)$$

Another significant NBTI mechanism, hole-trapping in the gate oxide, is caused by the holes captured by the existed oxygen vacancies and difficult to escape due a metastable state with an energy barrier of 0.2-1.2eV without field driven. Based on the dispersive transport theory, the total density of the charged oxide traps (n_{ox}) is obtained as Eq. 6 by integrating the distribution of holes with time dependent transport lifetime in the amorphous SiO_2.

$$n_{ox} = \int_0^{t_{ox}} (1-\frac{x}{t_{ox}}) \cdot p_0 \exp\left(-\frac{x}{\mu E_{ox}\tau} \right) dx \propto M_{ox} \cdot t^{kT/E_0} \quad (6)$$

4. NBTI Model Verification

The universal property of the proposed NBTI model including temperature and electrical field is validated by various samples of T1 to T5 [3, 6-9]. The NBTI model parameters are calculated theoretically and compared with the extraction from various samples. As derived in Eq. 5, the interface state generation amplitude R_{str} reveals a linear dependence of T with slope of k/M. With M~1e-12eV·cm^2 (coefficient of charge enhanced active energy), the slope of qR_{str}/C_{ox} vs. T is calculated around 5.59e-6V·K^{-1} theoretically with the proposed framework. As shown in left figure of Fig. 3, R_{str} extracted from samples T1-T3 shows perfect linear dependence on temperature with slopes range from 7e-6V·K^{-1} to 4e-6V·K^{-1}. The interface state generation time constant τ_{str} is identified exponentially relative to the temperature, as derived in Eq. 5. With reasonable quantities of the physical parameters (ΔH_0=0.3eV, a=1.2eÅ), the slope of $\log(\tau_{str})$ versus $1/T$ ($(\Delta H_0$-$aE_{ox})/k$) is calculated as 2365.2. The measurement extraction results are shown in right figure of Fig. 3, $\log(\tau_{str})$ shows a linear dependence to $1/T$, and slopes are extracted in the range of 5300 to 1700.

For the oxide hole-trapping, the time exponent shows linear dependence of temperature, which is consistent with theoretical derivation ($\alpha=kT/E_0$), as shown in Fig. 4. E_0 is extracted ranging from 100mV to 230meV, reflecting the quality of the amorphous gate oxide [10]. The theoretical results consist well with the experimental results, indicating the validation and universality of the proposed framework for complex technology and circuit operation conditions.

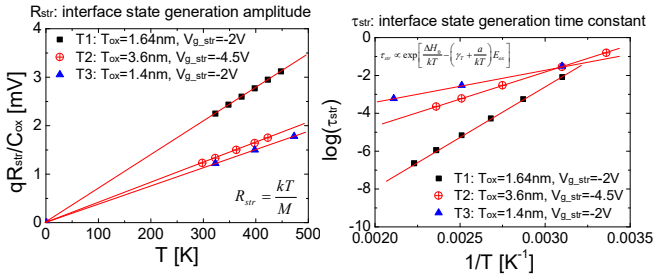

Fig. 3. Temperature dependence of left: the interface state generation magnitude R_{str} and right: the interface state generation time constant τ_{str}.

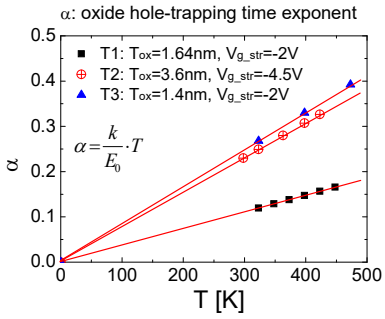

Fig. 4. Temperature dependence of the time exponent α in the gate oxide trap model (ΔV_{th}~t^{α}).

The universality of model parameter (τ_{str} and N_{ox}) dependence on electrical field (E_{ox}) is also validated in Figs. 5 and 6. Without additional fitting parameters, $\log(\tau_{str})$ extracted from various samples shows linear dependence on E_{ox} as derived in Eq. 5. With initial physical parameters of ΔH_0=0.3~1.3eV, a=1.2eÅ, γ_T~0.3cm/MV and T=300K, the theoretical slope of $\log(\tau_{str})$ versus E_{ox} is 7.6e-9, which is consistent well with the extraction results [11-13]. Meanwhile, the hole density (N_{ox}) injected into the gate oxide is relative to the gate leakage, thus shows an exponential dependence on $1/E_{ox}$ based on HiSIM model.

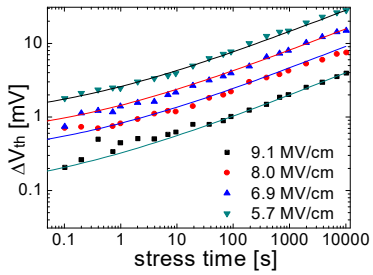

Fig. 5. NBTI induced ΔV_{th} under different electrical field. Lines are prediction results with the proposed universal NBTI model. Data is from [13].

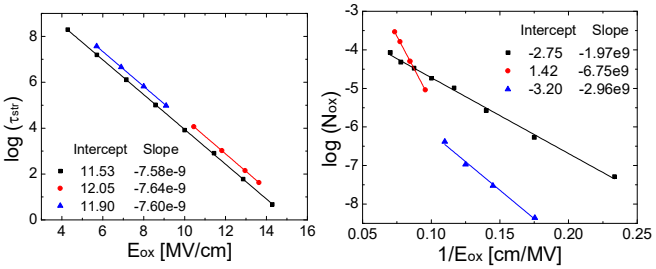

Fig. 6. Electrical field dependence of left: the interface state generation time constant τ_{str} and right: hole injection density into the gate oxide.

5. Conclusions

In conclusion, an analytical device-level NBTI model is derived from atomic-level microscopic pictures. The model parameters are identified as universal framework of temperature and electrical field. The theoretical calculation using the proposed model consists well with the measurement extraction without additional fitting parameters.

Acknowledgement

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