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A comprehensive model for PMOS NBTI degradation: Recent progress

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Abstract

Negative bias temperature instability (NBTI) is a well-known reliability concern for PMOS transistors. We review the literature to find seven key experimental features of NBTI degradation. These features appear mutually inconsistent and have often defied easy interpretation. By reformulating the Reaction–Diffusion model in a particularly simple form, we show that these seven apparently contradictory features of NBTI actually reflect different facets of the same underlying physical mechanism.

1. Background

Design of any digital circuit is based on the presumption that transistor parameters will remain bounded by a certain margin (typically ±15%) during the projected lifetime of the IC. This margin consists of initial manufacturing tolerance encapsulated in C_P^K numbers as well as other time-dependent parameter shifts due to various transistor degradation mechanisms like hot carrier degradation (HCI), gate dielectric breakdown (TDDB), negative bias temperature instability (NBTI), etc. Among them, NBTI has been a persistent (and perhaps most significant) reliability concern for CMOS technology generations below 130 nm node [1–8]. Two factors – increasing oxide field (to enhance transistor performance without scaling gate oxide) and the use of oxynitrides (to prevent Boron penetration and to reduce gate leakage) [9,10] – appear to have exacerbated this PMOS-specific reliability issue. Specifically, NBTI causes systematic reduction in transistor parameters (e.g., drain current, transconductance, threshold voltage, capacitance, etc.) when a PMOSFET is biased in inversion ($V_S = V_D = V_B = V_{DD}$ and $V_G = 0$). Since this NBTI-specific biasing condition arises universally in inverting logic, SRAM cells, I/O system, dynamic logic, etc. [11–13], it is not surprising that the concern about NBTI is pervasive in the semiconductor industry.

Since NBTI has been a reliability concern from the very early days of integrated circuits in mid 1960s [14,15], there are many reports on various aspects of NBTI degradation over the last 40 years [3]. An extensive review of the state-of-art of the pre-2003 experimental results and the possible theoretical foundations has been made in our previous article in Microelectronics Reliability [1]. After correcting for artifacts arising from incorrect stress condition leading to spuriously high degradation exponent at later stages of degradation, resolving controversies involving oxide field vs. gate voltage dependence, and addressing process specific NBTI degradation issues, the essence and consensus regarding NBTI phenomena until 2002–2003 can be summarized as follows:

(1) The degradation is field-driven and is related to interface traps at the Si/SiO_2 interface [4].
(2) Threshold voltage degradation due to NBTI is given by $\Delta V_T \sim A\exp(-nE_D/kT)t^n$ with $n \sim 0.25$ (see Fig. 1) and $E_D \sim 0.5$ eV [1,4,6].
(3) Once NBTI stress is removed, a fraction of interface traps can self-anneal [6,16–18].
None of the pre-2003 reports, however, seemed to have realized that the values of n and E_D of NBTI

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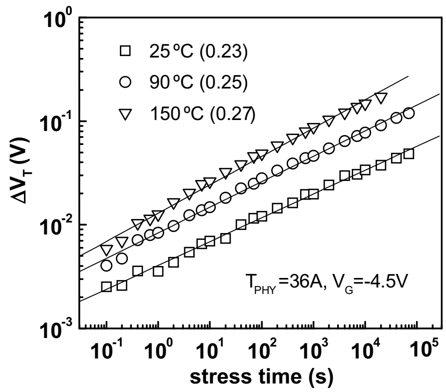

Fig. 1. Measurement of NBTI degradation at different temperatures show $n \sim 0.25$ and $E_D \sim 0.5$ eV.

are self-contradictory and mutually inconsistent. Since 2003, there have been reports about four additional features of NBTI degradation that have further complicated the classical understanding of this degradation phenomenon:

(4) As NBTI became a long-term reliability concern, many research groups looked for and *found* long-term reduction (quasi-saturation?) of NBTI time-exponent n from 0.25 to 0.13–0.16 [5,8,17].

(5) A number of groups reported that NBTI is smaller for AC stress compared to DC stress, and the ratio of AC to DC NBTI degradation is frequency independent [6,9,18] at least for low frequencies (<10–100 kHz).

(6) Careful analysis of temperature-dependent NBTI data (see Fig. 1) shows characteristics of dispersive transport [1,2,19]. If this is indeed the case, lifetime projections at various temperatures would be more difficult than previously presumed.

(7) Classical NBTI models are based on dynamics of broken Si–H bonds and these models are often validated against charge pumping data, yet charge pumping technique probes both broken Si–O and Si–H bonds and can not distinguish between them [7]. This raises important concerns regarding the validation of NBTI models. Moreover, the significance of hole trapping in determining the NBTI degradation continues to be an important issue.

Since the original R–D analysis of NBTI [1] did not address these post-2003 issues, there is an incorrect presumption that these new features are incompatible with the R–D model and must be interpreted with new models of NBTI [5,20,21]. The goal of this paper is to show that the seven features of NBTI degradation discussed above (to be referred to as Issues 1–7 for the rest of the paper) can be interpreted within the same intuitively simple framework of NBTI degradation discussed in Ref. [1], with a straightforward generalization of the R–D model. And the seven features represent various aspects of the same degradation mechanism. Although the four post-2003 NBTI features of saturation, frequency independence, dispersive temperature dependence, and indistinguishability between Si–O and Si–H bonds appear to have complicated the physical picture of NBTI, in reality they hold the key to the puzzle of the pre-2003 NBTI results. In Section 2, we analyze the nature of the puzzle of the three observations in pre-2003 literature. In Section 3, we show how the post-2003 observations regarding saturation and frequency independence actually help resolve the conceptual inconsistencies. This model then allows us to connect NBTI and HCI degradation and anticipate the degradation in reduced geometry devices, as well as seek resolution of NBTI challenges through circuit techniques. Our Conclusions regarding these issues are summarized in Section 4.

2. The R–D model of NBTI degradation: definition of the puzzle

In the Reaction–Diffusion (R–D) formulation of NBTI degradation [1,8,22], one assumes that NBTI arises due to hole-assisted breaking of Si–H bonds at the Si/SiO_2 interface (see Fig. 2, top illustration). The rate of trap generation is given by,

$$\frac{dN_{IT}}{dt} = k_F(N_0 - N_{IT}) - k_R N_H(0) N_{IT} \qquad (1^*)$$

where N_0 is the initial number of Si–H bond at the Si/SiO_2 interface. N_{IT} is the fraction of these Si–H bonds broken at time t due to NBTI stress. The dissociation rate constant k_F is proportional to the number of inversion layer holes that are captured by Si–H bonds. The two-electron Si–H covalent bond is weakened once a hole is captured and this weakened bond (assisted by the electric field) is easily broken at relatively moderate temperature. The broken Si bonds acts as a donor trap [23,24] and contributes to the shift in threshold voltage and reduction in transconductance. The H atoms released in the process can anneal

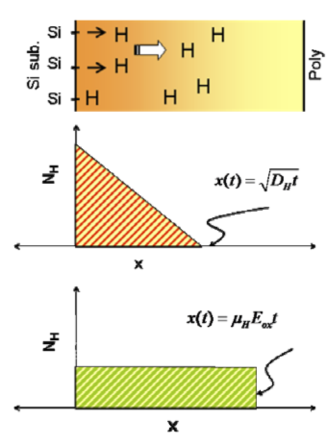

Fig. 2. (Top) Schematic view of hole-assisted dissociation of Si–H bond at the Si/oxide interface. The dissociation and passivation of Si–H bonds at the Si/SiO_2 interface is described by (1*) or (1). The H may diffuse (middle) or drift (bottom) away from the interface depending on the charge state of the diffusing species.