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Negative Bias Temperature Instability What Is It and Why Is It a Problem?

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INTRODUCTION

Negative bias temperature instability (NBTI) commonly observed in *p*-MOSFETs, when stressed with negative gate voltages at elevated temperature, is a major reliability problem. We discuss the results of such stress on device and circuit performance and review interface traps and oxide charges, their origin, present understanding, and changes due to NBTI. Next we discuss the effects of varying parameters (hydrogen, deuterium, nitrogen, water, fluorine, and boron) on NBTI and conclude with the present understanding of NBTI and its minimization.

NBTI MECHANISM

NBTI has been known since the very early days of MOS device development, having been observed as early as 1966 [1]. It occurs in *p*-channel MOS devices stressed with negative gate voltages at elevated temperatures and is the result of interface trap generation at the oxide/silicon interface and positive charge creation in the oxide. It manifests itself as absolute drain current and transconductance decrease and threshold voltage increase. The threshold voltage change typically exhibits the gate voltage, temperature, and time dependence

$$\Delta V_T = At^n \exp(\beta V_G)\exp(-E_A/kT) \qquad (1)$$

NBTI is lower, in *n*-MOSFETs biased into accumulation. Typical stress temperatures lie in the 100-250°C range with oxide electric fields below 6 MV/cm, *i.e.*, fields below those that lead to hot carrier degradation. Such fields and temperatures are typically encountered during burn in, but are also approached in high-performance ICs during routine operation. Either negative gate voltages or elevated temperatures can produce NBTI, but a stronger and faster effect is produced by their combined action. In MOS circuits, it occurs most commonly during the "high" state of *p*-MOSFET inverter operation. It leads to timing shifts and potential circuit failure due to increased spreads in signal arrival in logic circuits and matching problems in analog circuits. A fraction of NBTI degradation can be recovered by removing the stress voltage. Early MOS devices, containing only SiO_2 as the gate dielectric exhibited NBTI. Migration to nitrided oxides aggravated NBTI coinciding with a shift from research to production around 1999 after nitrided oxides became the industry standard in advanced CMOS.

NBTI-generated interface traps (D_{it}) and oxide charges also have an adverse effect on 1/f noise, which is believed to be closely related to these charges. NBTI has also been reported for HfO_2 high-K insulators [2]. Figure 1 shows typical changes of threshold voltage and transconductance as a function of stress time [3]. Transconductance is related to mobility that is degraded during the stress.

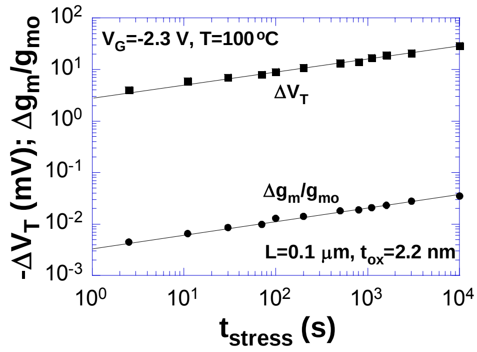

Fig. 1. Time-dependent threshold voltage and stress-induced transconductance increase. Data after Kimizuka et al. [3].

The exact model describing NBTI physics remains somewhat elusive at this time. One model assumes that *SiH* bonds at the SiO_2/Si interface are broken by a combination of electric field, temperature, and holes. First-principles calculations show that positively-charged hydrogen or protons, H^+, react directly with the *SiH* to form an interface trap, according to the reaction [4]

$$Si_3 \equiv SiH + H^+ \rightarrow Si_3 \equiv Si\bullet + H_2 \qquad (2)$$

where $Si_3 \equiv SiH$ is a hydrogen-terminated interface trap and $Si_3 \equiv Si\bullet$ is an interface trap with the dot representing the dangling bond. As shown in Fig. 2, the hydrogen is assumed to originate from phosphorus-hydrogen bonds in *n*-Si substrates. This model predicts reduced NBTI for *n*-channel devices due to the difficulty of breaking boron-hydrogen bonds in *p*-Si substrates.

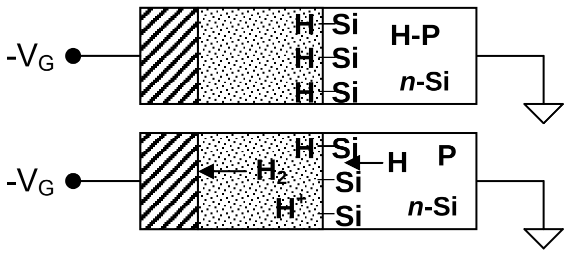

Fig. 2. Possible interface trap creation by hydrogen

The *P-H* bonds dissociate and the hydrogen on the way to the SiO_2/Si interface "picks up" a hole to become H^+, to react with the *H* from the *SiH* bond to form H_2 leaving behind a positively charged Si dangling bond (or trapping center). The H_2 diffuses from the interface into the oxide or poly-Si gate. It can later passivate a dangling bond by diffusing back to the interface when the stress voltage is interrupted. In another model, a hole, captured by a *SiH* bond, weakens the bond which then breaks to form an H_2 molecule.

In the *reaction-diffusion model* the gate voltage initiates a field-dependent reaction at the SiO_2/Si interface that is initially limited by the *SiH* dissociation and D_{it} generation rate [5]. Later, the limiting rate is hydrogen diffusion from the interface into the SiO_2.

Ambient Effects

Hydrogen is a common impurity in MOS oxides, being incorporated into the oxide during various phases of IC fabrication, *e.g.*, nitride deposition and forming gas anneal and is believed to be the main passivating species for Si dangling bonds. *Deuterium*, a hydrogen isotope, reduces NBTI due to its heavier mass or giant isotope effect. Deuterium can be introduced early or late in the device fabrication process. It is not clear yet, whether this improvement is enhanced at the low fields that are more typical of actual circuits. *Nitrogen*, commonly incorporated into gate oxides to reduce boron diffusion, improve hot carrier resistance, and increase the dielectric constant, can improve or degrade NBTI. It appears that low nitrogen densities in SiO_2 improve NBTI due to strong *SiN* bonds at the SiO_2/Si interface. However, higher nitrogen density in the oxide degrades NBTI, possibly by trap formation. *Water* and *boron* in the oxide also degrade NBTI while *fluorine* improves it.

Conclusion

NBTI has become a significant reliability problem in today's, thin-oxide integrated circuits. It degrades both digital (transconductance, delay time) and analog (current mirror, device matching) circuits. The type of circuit operation is important for NBTI, with ac degradation usually less than dc degradation because the gate voltage stress is interrupted for unipolar stress and reversed for bipolar stress. For sufficiently long dormant times, NBTI damage is totally healed. To minimize NBTI, one should start with low densities of electrically active defects at the SiO_2/Si interface, keep water out of the oxide, minimize stress and hydrogen content, and keep damage at the SiO_2/Si interface to a minimum during processing. Fluorine and deuterium improve NBTI, but it is important to ensure deuterium can get to the SiO_2/Si interface and passivate dangling bonds or replace the hydrogen with deuterium in *SiH* bonds.

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