The transient behavior of NBTI - A new prospective

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Abstract

The Negative-Bias-Temperature-Instability (NBTI) is currently one of the most serious reliability issues in advanced CMOS technology. Specifically, the fast recovery of NBTI degradation immediately after stress is removed has recently become a hot topic. The major NBTI debates center on the responsible mechanism, the proper measurement method, and the possible impact on reliability. We show that the observed fast transient degradation is a consequence of high-field stressing and has nothing to do with "traditional" NBTI. We further show that most current NBTI experiments fail to capture an additional transient component that can potentially impact reliability more severely.

1. Introduction

NBTI is not a new phenomenon [1-4]. However, it was never a major concern because there were always plenty of other reliability problems which were more serious. The introduction of nitrided ultra-thin gate oxides changed that [5]. Currently, NBTI is the most serious reliability issue for pMOS devices. The most important characteristic of NBTI (relaxation of the degradation after the stress is removed) was reported very early on [3]. While this relaxation phenomenon has been the crucial factor which all modeling efforts must explain, it has not been properly addressed in experimental work until recently. The question of how should one account for the relaxation and therefore project lifetime correctly has become quite controversial. Much of the recent NBTI work has been devoted toward the development of better characterization of the recoverable part (relaxation) as well as the permanent part of the degradation [6-9]. These improved characterizations challenge the recently favored hydrogen-driven Reaction-Diffusion NBTI model and add merit to an old idea [3], namely hole-trapping and -detrapping. Currently, the role of hydrogen or holes, or a combination of the two is hotly debated. However, no one suspected the possibility of an additional NBTI component, namely electron trapping and -detrapping.

As CMOS technology is scaled, the operation voltage cannot follow at the same rate. The result is a steadily increasing oxide field at operation conditions. When oxides were thick, NBTI measurements were done at oxide fields less than 6 MV/cm so that the NBTI effect could be clearly separated from high-field stress effect. For state of the art CMOS technology, the operation field is already greater than 6 MV/cm. Thus, accelerated lifetime measurement conditions commonly utilize oxide fields in the range of 9 MV/cm or more. These conditions are consistent with high-field stress. Yet, most research groups use the measured results to compare with models that were developed for pure NBTI (at lower fields). The consequence is wide spread confusion.

In this study, we set out to look for the high-field stress signatures in the "common" NBTI stress conditions.

2. Experimental

Fully processed p-channel MOSFETs with 2 x 0.07 μm^2 and 2 x 0.09 μm^2 physical gate areas and 1.6 nm (physical) nitrided gate oxides were used in our experiment. Post-stress transistor characterization consists of fast I_D-V_G measurements using a setup illustrated in fig. 1 [6, 9].

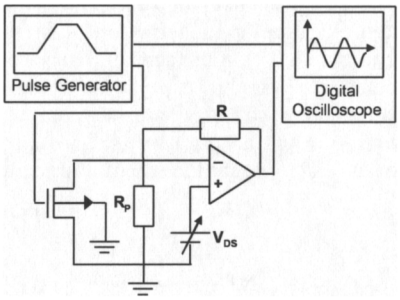

Figure 1. The fast I_D-V_G measurement setup.

The gate voltage waveform for the fast I_D-V_G measurement is shown in fig. 2.

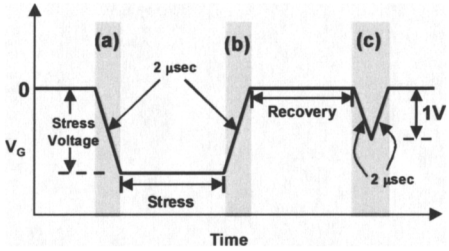

Figure 2. The gate voltage waveform

The drain current during each gate voltage transition

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(shaded region of fig. 2) was captured at very high sampling rate to produce a full I_D-V_G curve. From each curve, we extract the peak G_M value (linear) and then use the tangent at peak G_M extrapolated to zero drain current to extract V_{TH}. This standard V_{TH} extraction method is unique among all the reported fast I_D-V_G measurements. The advantage of this method is that our V_{TH} is accurate and relatively free from the G_M degradation related error which plagues many reported fast I_D-V_G experiments.

In the following discussion, ΔV_{TH} and $\%G_M$ degradations are extracted for two cases, no (negligible) recovery (ab) and post recovery (ac), as defined with refernce to fig. 2:

$$\Delta V_{TH}(ab) = V_{TH}(b) - V_{TH}(a)$$

$$\Delta V_{TH}(ac) = V_{TH}(c) - V_{TH}(a)$$

$$\%G_M \text{ Degradation } (ab) = \frac{G_M(a) - G_M(b)}{G_M(a)} \times 100$$

$$\%G_M \text{ Degradation } (ac) = \frac{G_M(a) - G_M(c)}{G_M(a)} \times 100$$

Typical high-speed I_DV_G measurements tend to be quite noisy and error prone. A Savitzky-Golay-like filter numerically cleans up our captured drain current curves. We verified our fast I_D-V_G measurement by comparing it with an I_DV_G measurement using the well-established, but slow, parametric analyzer as shown in fig. 3.

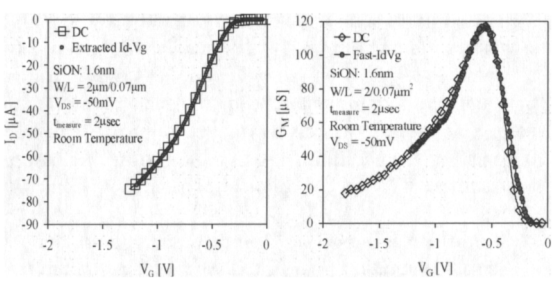

Figure 3. Comparing the measured I_D-V_G curves (left) and the G_M curves (right) from fast and slow (parametric analyzer) methods.

3. Results and Discussions

Figure 4 shows the no recovery ΔV_{TH} as a function of stress voltage (-1.2V to 2.7V) for various stressing times (0.1 to 1000 seconds). It is clear from these ΔV_{TH} results that a large initial ΔV_{TH} is only observable at *exceedingly high* stress voltages and long stress times. This is also an indication of the excellent quality of the gate dielectrics used in this study. The observed trend illustrates that higher stress voltage and longer stress time produce larger ΔV_{TH}. As the stress voltage decreases, ΔV_{TH} drops rapidly, even for the longest stress time. At around -1.8 V, the ΔV_{TH} is down to our measurement uncertainty level.

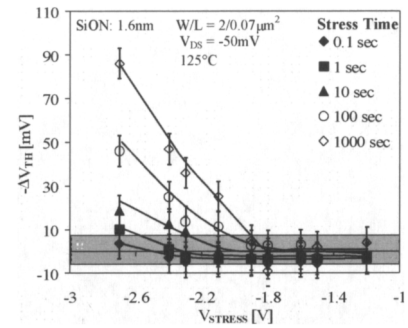

Figure 4. No recovery ΔV_{TH} as a function of stress voltage for various stress times.

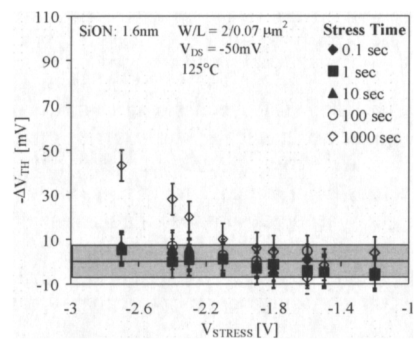

Figure 5. Post (5 s) recovery ΔV_{TH} as a function of stress voltage for various stress times.

Fig. 5 shows the post recovery ΔV_{TH} for the same set of stress conditions. The relaxation (recovery) time was 5 s. Other than the longest stress time result, all ΔV_{TH} recovered to within our experimental error.

Fig. 6 shows the no recovery G_M degradation. It basically mimics the no recovery ΔV_{TH} trend.

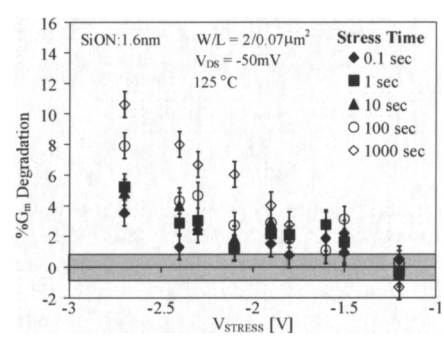

Figure 6. No recovery G_M degradation as a function of stress voltage for various stress times.

Fig. 7 shows the post recovery (5 s) G_M degradation. Notice that the $\%G_M$ degradation is negative, meaning that the G_M is **better** than before stress. This surprising result is key evidence that something other than the traditional NBTI mechanism is at work.

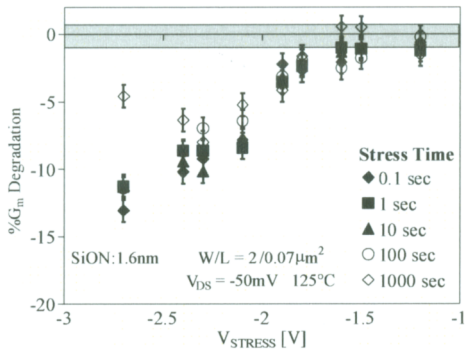

Figure 7. Post recovery (5 s) G_M degradation as a function of stress voltage for various stress times.

Taking all the data (figures 4 to 7) together; the picture of high-field stress dominated degradation emerges. In traditional NBTI stress, the oxide is thick and tunneling current is practically non-existent. In modern day NBTI stress, the oxide is thin and there is a huge tunneling current density. Even though the stress voltage is low, the electron flux can create a high density of hot holes in the anode and hole injection from the anode is not negligible [10]. Thus, we have both electrons and holes flowing across the oxide and the trapping of both are inevitable. The steep dependence of ΔV_{TH} on stress voltage in fig. 4 is entirely consistent with high-field stress. The trapping efficiency in SiON is known to be much higher than SiO_2, further increasing the effect. Furthermore, the hot electrons and hot holes at the anode will create interface states. These are well known consequence of high-field stress.

For pMOS, holes and interfaces states shift the V_{TH} in the same direction (more negative) while electrons shift it to the opposite direction (more positive). At the end of stress, there are trapped holes, trapped electrons and interface states. The net charge is positive and the V_{TH} shifts more negative. It is well known that hole-detrapping, once the stress condition is removed, is rapid [11-13]. Much of the fast recovery of ΔV_{TH} is consistent with hole-detrapping. Electrons, on the other hand, detrap slower. After the recovery period, holes are largely gone from the bulk of the oxide, leaving electrons to counter the positive charges at the interface. The net result is reduced Coulomb scattering and improved G_M. Note that at this point the net charge may or may not be negative, but it must be small.

Electron-trapping has never played a role in any NBTI modeling effort. This is true even in recent times when hole-trapping and –detrapping is often linked to the transient NBTI behavior. Although once we recognize that the modern day NBTI stress condition is similar to high-field stress, we would expect electron-trapping and –detrapping to be a natural part of the phenomena. However, these electron-trapping/-detrapping arguments still require further investigation.

If our interpretation is correct, then we would expect the $\%G_M$ degradation will return to positive values at longer recovery times. After all, the trapped electrons will eventually detrap as well. This is indeed the case as shown in fig. 8.

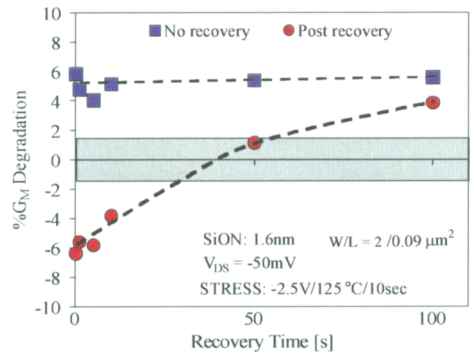

Figure 8. G_M degradation as a function of recovery time for one stress condition.

Further evidence of a trapped electron derived G_M improvement was observed when we studied the G_M behavior as a function of measurement time. Since pMOSFET inversion conditions produce holes at the interface, these holes can tunnel into the oxide to neutralize the trapped electrons. So, if we slow our measurements to allow this to happen, we should expect the G_M improvement to disappear. This is indeed the case as is shown in fig. 8.

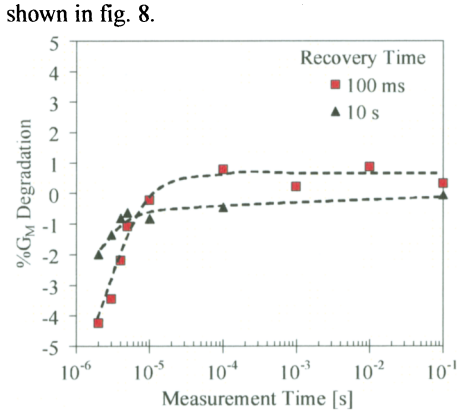

Figure 8. G_M degradation as a function of measurement speed for two recovery times.

From fig. 8 we see that if we slow the measurement speed (the sweep time of the gate voltage pulse) to longer than 10 μs, no improvement can be detected. From the tunneling front model, the depth reachable by tunneling in 10 μs is about 1.6 nm [13], the full thickness of our oxide.

4 Conclusions

Using fast I_D-V_G measurements and accurate V_{TH} and G_M extraction, we show that the transient V_{TH} shift (and its recovery) observed in modern NBTI experiments is consistent with high-field stress instead of the traditional NBTI. The high-field stress dependent nature of the degradation, transient as well as permanent, is what one would expect from high-field stress. Our data suggests that at operation voltage, the transient component may not exist – making the debate on whether the transient component should be included in lifetime consideration a moot point.

The ability to extract G_M from fast measurements allows us to observe, for the first time, the transient G_M behavior after NBTI stress. The surprising discovery of G_M improvement, albeit only for a transient period, strongly suggests an electron trapping component. This component has never been associated with the NBTI mechanism. Its presence supports our contention that modern day NBTI stress is dominate by high-field effect. However, since the operation condition is approaching "high-field", one cannot exclude the high-field effect in NBTI studies. While hole-trapping may disappear at operation voltage, electron trapping may not. The slower detrapping rate of electrons can complicate the lifetime projection. At the least, it requires a whole new consideration of the measurement methodology.

Acknowledgments

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