New Insight Into NBTI Transient Behavior Observed From Fast-G_M Measurements

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***Abstract*—Fast-I_DV_G measurements have become an important tool to examine MOSFET transient degradation. The threshold voltage $(V_{\rm TH})$ extracted from fast-I_DV_G measurements is often used to infer the transient behavior of trapped charges in the gate dielectric and at the interface. In this letter, we show that the peak transconductance (G_M) can also be extracted reliably in the microsecond time scale. The transient G_M behavior provides additional insights not easily observed from an examination of $V_{\rm TH}$ alone. Specifically, transient G_M results illustrate that an electron trapping/detrapping transient component contributes to the transient behavior observed in the negative bias temperature instability. This electron trapping component has never been reported.**

***Index Terms*—Fast-G_M, fast-I_DV_G, negative bias temperature instability (NTBI).**

I. Introduction

RECENTLY, the transient response of advanced CMOS devices subject to various stress and relaxation periods has captured the attention of the reliability community [1]–[4]. Since traditional semiconductor parameter analyzer device characterizations, often referred to as "DC" measurements, are too slow to capture this transient behavior [1]–[4], alternative methods have been developed which measure the device drain current (I_D) response to a fast gate-voltage (V_G) sweep [3]–[6]. Threshold voltage $(V_{\rm TH})$ transients extracted from these fast-I_DV_G curves have had a considerable impact on the characterization and understanding of an important reliability problem called the negative bias temperature instability (NBTI) [1]–[4], [7]. In DC parameter analyzer measurements, it is common to extract the channel transconductance (G_M) from the I_DV_G curve along with the $V_{\rm TH}$ to gain channel mobility information. While both G_M and $V_{\rm TH}$ are sensitive to trapped charges in the gate dielectric and at the interface, their sensitivities are somewhat different. Monitoring both parameters ($V_{\rm TH}$ and G_M) during transient behavior is expected to provide a deeper understanding than one parameter alone. However, G_M extraction from fast-I_DV_G measurements is rarely reported.

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The nature of most transient experiments prohibits signal averaging, and the significant noise in the transient data makes $V_{\rm TH}$ extraction difficult. Since both I_D and V_G data are captured with equal time spacing (using a high-speed oscilloscope), commonly available digital filters (such as Savitzky–Golay [8]) can easily smooth the I_D and V_G data separately before mapping the I_D data onto the V_G data. The resulting fast-I_DV_G curves are sufficient to monitor transient $V_{\rm TH}$ shifts $(\Delta V_{\rm TH})$. One cannot first "build" the fast-I_DV_G curve and then apply the Savitzky–Golay smoothing filter because of the nonuniform V_G data spacing. Fast-I_DV_G G_M extraction is significantly more challenging. Direct differentiation of the raw fast-I_DV_G curve $(G_M = dI_D/dV_G)$ or even the individually smoothed I_D and V_G curves (which allows for acceptable $V_{\rm TH}$ extraction) results in unacceptably noisy G_M curves.

In this letter, we employ a filtering method that is capable of smoothing unequally spaced fast-I_DV_G data to such a degree that reliable G_M extraction is achievable. This method is similar to the Savitzky–Golay method in principle, but is far less efficient in computation. Our filtering methodology is a four-step process which proceeds as follows: 1) a polynomial function is least-squares fit to an appropriate section of the fast-I_DV_G curve; 2) the polynomial function is solved for the center value of the section resulting in a smoothed I_DV_G data point; 3) the polynomial function is differentiated; and 4) the differentiated polynomial is solved for the center value of the section resulting in a smoothed G_M data point. The chosen section of the I_DV_G curve is then incrementally stepped through the entire I_DV_G curve to produce (equally spaced) smoothed-I_DV_G and G_M curves. Our measurements utilize a third-order polynomial least squares fitting routine which allows a relatively large section of the curve to be fitted and improves the noise suppression capability of the filter. The ability to extract "fast-G_M" accurately and reliably allows for more standard $V_{\rm TH}$ extraction (extrapolation of a tangent line to the I_DV_G curve at the peak-G_M value). This method is somewhat more accurate and reliable than methods used thus far in the literature for fast-I_DV_G $V_{\rm TH}$ extraction. Thus, by developing a method to extract fast-G_M, we also improved the fast-$V_{\rm TH}$ extraction. It is important to note that, while our $\Delta V_{\rm TH}$ extraction procedure is quite reliable, it does not completely account for the $I_D - V_G$ mobility degradation [7].

We utilize this fast-G_M capability to examine the effect of measurement time on the transient $V_{\rm TH}$ shift $(\Delta V_{\rm TH})$ and $\%G_M$ degradation in SiON pMOSFETs subject to NBTI stressing conditions. The measurement time dependence reveals an additional fast transient electron trapping component which is not apparent in previously reported $\Delta V_{\rm TH}$ measurements alone.

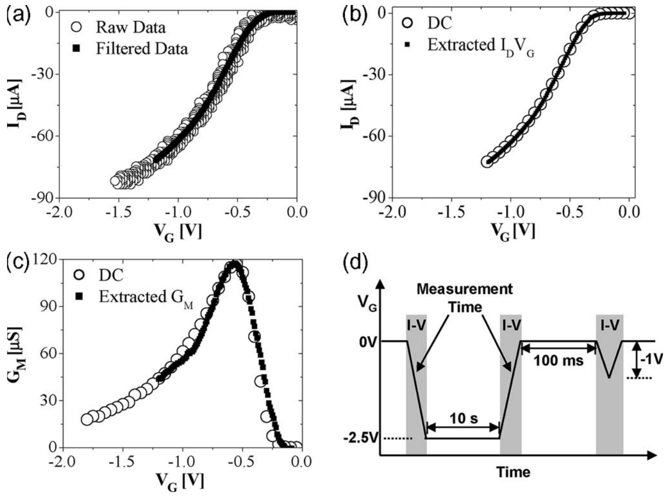

Fig. 1. Fast-I_DV_G characteristic curves are subject to significant noise. We utilize a "moving" third-order polynomial filtering procedure to extract (a) I_DV_G characteristic curves from (room temperature, 2-μs measurement time) raw data. Our extracted (b) I_DV_G and (c) G_M characteristics agree very well with DC parameter analyzer measurements [9]. We utilize this fast I_DV_G capability to study NBTI using the gate-voltage stress and sense pulses schematically shown in (d).

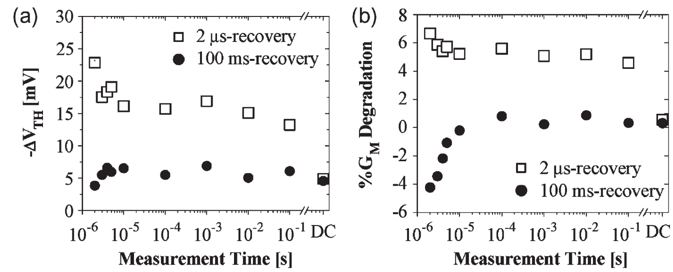

Fig. 2. Two-microsecond recovery and 100-ms recovery (a) $-\Delta V_{\mathrm{TH}}$ and (b) $\%G_M$ degradation as a function of measurement time for pMOSFETs subject to an NBTI stress of -2.5 V at 125 °C for 10 s. The 100-ms recovery G_M improvement is evidence of an additional electron trapping transient degradation component.

II. Experimental Details

This study involves 2×0.07 $\mu\mathrm{m}^2$ (physical gate area) fully processed pMOSFETs with SiON gate dielectrics ($t_{\mathrm{ox}} = 1.6$ nm). Our fast-I_DV_G measurements involve a voltage pulse applied to the gate electrode while the drain current is monitored with a fast operational amplifier circuit. Both gate-voltage and drain–current waveforms are captured with a digital oscilloscope. Our minimum measurement time (time required for a complete gate-voltage sweep) is 2 μs. All measurements were performed with -50 mV on the drain electrode while the source and substrate terminals were both grounded. All reported V_{TH} values are derived from a tangent line drawn at the peak-G_M position. All $\%G_M$ degradation data reflect changes in the peak G_M values. The details of the measurement apparatus and methodology have been discussed elsewhere [3].

III. Results and Discussion

Fig. 1(a) and (b) shows the raw and filtered I_DV_G curves collected using our fast-I_DV_G apparatus as well as a conventional parameter analyzer (DC). As previously mentioned, the raw fast-I_DV_G curve is quite noisy. The effectiveness of the filter is clearly illustrated in the agreement between the filtered-I_DV_G and DC curves. Fig. 1(c) shows the $G_M - V_G$ characteristic curves from the filtered fast-I_DV_G and DC measurements. Again, we observe very good agreement, particularly in the peak-G_M value and position.

To illustrate the advantage of fast-G_M extraction, we utilize this newly developed capability to examine transient NBTI degradation. We apply an NBTI stress to our devices using a sequence of gate-voltage pulses schematically shown in Fig. 1(d). The pulse train consists of a trapezoidal "stress" pulse and a triangular post-recovery "sense" pulse separated by a 100-ms recovery time period where the gate voltage is held at 0 V. The insertion of a recovery period is used to examine the well-established transient recovery of NBTI degradation [1]–[4]. Fast-I_DV_G measurements were taken at all rising and falling edges of the pulse train to obtain pre-stress (falling edge), poststress (rising edge), and post-recovery V_{TH} and peak-G_M measurements. The extracted V_{TH} and G_M values corresponding to the rising and falling edges of the post-recovery sense pulse are quite similar. Consequently, we simply report the average of the rising and falling edge V_{TH} and G_M values. We refer to the pre-stress/post-stress comparison as "2-μs recovery" (due to the measurement time) and the pre-stress/post-recovery comparison as "100-ms recovery." Recently, we have successfully utilized a similar experimental approach to examine the effect of stress voltage on the V_{TH} and G_M NBTI transients [9].

Fig. 2 shows the 2-μs recovery and 100-ms recovery ΔV_{TH} and $\%G_M$ degradations as a function of measurement (rise/fall) time for devices subject to an NBTI stress of -2.5 V at 125 °C for 10 s. Each data point represents an average of 12 measurements, and a fresh device is used for each measurement time. As shown in Fig. 2(a), the 2-μs recovery ΔV_{TH} measurement is dependent on the measurement time with larger $|\Delta V_{\mathrm{TH}}|$ observed at shorter measurement times. After 100-ms recovery, the ΔV_{TH} is essentially independent of the measurement time (with a small hint of variation at very short measurement time) and is almost completely recoverable. It is also clear that conventional parametric analyzer measurements (denoted as DC in Fig. 2) are too slow to capture the full extent of the transient degradation. This transient ΔV_{TH} behavior has been well established [4] and has greatly contributed to the controversy surrounding NBTI. Fig. 2(b) shows the corresponding 2-μs recovery and 100-ms recovery $\%G_M$ degradation as a function of measurement time. While the 2-μs recovery $\%G_M$ degradation mimics the 2-μs recovery ΔV_{TH} trend (increased degradation at shorter measurement times), the 100-ms recovery $\%G_M$ degradation surprisingly exhibits negative values at shorter stress times. The negative values (beyond the $\pm 1.1\%$ experimental error) represent an increase in G_M to values better than before stress. This behavior is further illustrated in the pre-stress, post-stress, and post-recovery G_M characteristic curves in Fig. 3, with post-recovery G_M improvement when the measurement time is 2 μs [Fig. 3(a)]. The observed G_M improvement is also in agreement with our recent work [9] reporting the transient G_M response to higher stress voltages.

Recent reports have invoked a hole trapping/detrapping mechanism (positive charge accumulation) to explain the transient ΔV_{TH} [10]. While an examination of our ΔV_{TH} data

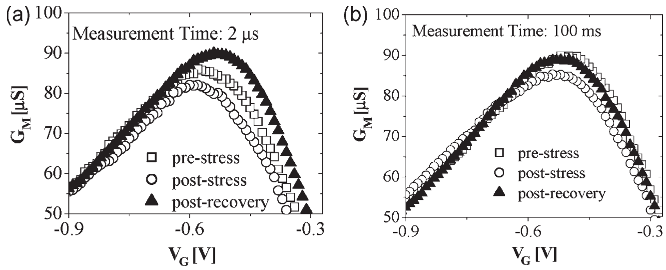

Fig. 3. Pre-stress, post-stress (−2.5 V at 125 °C for 10 s), and post-recovery (100 ms) fast-G_M measurements for (a) 2-μs and (b) 100-ms measurement times. The 2-μs measurement time exhibits post-recovery G_M improvement.

would also suggest a hole trapping/detrapping mechanism (negative recoverable ΔV_{TH}), the corresponding fast-G_M improvement suggests the presence of an additional transient component involving electron trapping and detrapping. Our NBTI stress condition, while rather common for NBTI studies of ultrathin gate dielectrics, represents an electric field which is traditionally categorized as high-field stressing. Under high-field stress, it is well known that both holes and electrons will get trapped [11], [12], and they both detrap once the stress is removed [11], [12]. However, it is also known that holes will detrap faster than electrons [2], [13]–[15]. At the conclusion of stress, both trapped holes and trapped electrons are present, along with positively charged interface states (I–V measurement condition). This combination results in maximum G_M degradation (2-μs recovery measurement). However, after the 100-ms recovery period, a large fraction of the holes have detrapped, leaving trapped electrons and positively charged interface states. The trapped electrons can compensate the positively charged interface states, leading to a reduction in Coulombic scattering and an increase in peak-G_M. While G_M improvement due to electron trapping is rare, it is not without precedent. Charpenel *et al.* [16], for example, observed G_M improvement after injecting electrons into the gate dielectric. Additionally, Weber *et al.* [17] suggest that trapped electrons could effectively "tie up" interface states and prevent them from charging or discharging. It is also important to note that slower measurement times allow the trapped electrons to be annihilated by holes tunneling from the inversion layer (pMOSFET). Inversion layer formation and hole tunneling take a finite time. Thus, one would only expect to observe G_M improvement at very short measurement times where the inversion layer holes are less effective in annihilating the trapped electrons [Fig. 2(b)].

A careful examination of Fig. 2 reveals some additional interesting observations. In the 2-μs recovery case, the V_{TH} and G_M behaviors closely correspond, and both exhibit increased degradation at shorter measurement times. However, in the 100-ms recovery case, the V_{TH} and G_M behaviors very weakly correspond. The 100-ms recovery V_{TH} does exhibit a hint of improvement (similar to G_M) at shorter measurement times, but this improvement is within the error of the experiment. The lack of V_{TH} and G_M correspondence in the 100-ms recovery case is very likely due to the relatively low V_{TH} signal-to-noise ratio (magnitude of the ΔV_{TH} is relatively small). This lack of correspondence also suggests that the fast-G_M measurement is more sensitive to transient degradation than the fast V_{TH} measurement.

IV. Conclusion

We have demonstrated a new methodology to accurately extract G_M values (fast-G_M) from fast-$I_D V_G$ measurements to study device transient behavior. We have also demonstrated that fast-G_M extraction can be more sensitive to charge trapping and detrapping than fast-V_{TH} (at least for NBTI in this letter). The additional information gained from the fast-G_M measurement provides new insight into the NBTI mechanism.

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