Real Vth instability of pMOSFETs under practical operation conditions

J. F. Zhang(1), Z. Ji(1), M. H. Chang(1), B. Kaczer(2), and G. Groeseneken(2,3)

(1)School of Engineering, Liverpool John Moores University, Byrom Street, Liverpool L3 3AF, UK
(2)IMEC, Leuven B3001, Belgium; (3)Also at KU, Leuven, Belgium

Abstract

Lifetime of pMOSFETs is limited by negative bias temperature instability (NBTI). For the first time, we show that the NBTI-induced threshold voltage shift, ΔVth, measured in early works by using either the 'on-the-fly' or the conventional transfer characteristics extrapolation techniques is not the real ΔVth under practical operation. A new method is proposed for estimating the real ΔVth.

Introduction

For pMOSFETs with SiON, negative bias temperature instability (NBTI) [1-4] is limiting their lifetime. The threshold voltage instability, ΔVth, is traditionally measured from the shift of extrapolated quasi-DC Id-Vg characteristics, which is represented by ΔVth(ex) hereafter. The measurement can take seconds, resulting in substantial recovery [4-6]. To suppress this recovery, the 'on-the-fly (OTF)' technique was proposed [4]. Fig. 1 shows that ΔVth(OTF) can be one order of magnitude higher than ΔVth(ex). Both ΔVth(OTF) and ΔVth(ex) were measured at a gate bias, Vg, different from that under practical operation. The **objective of this work** is to show that the ΔVth reported in early works by either OTF or extrapolation is not the real ΔVth under practical operation conditions, ΔVth(real). A new method is proposed for estimating ΔVth(real), after a critical analysis of existing techniques. This method is insensitive to the series resistance of source and drain.

Results and discussions

A. True reference Id and gm

OTF uses the first measured point as the reference Id and assumes it being degradation-free. Its measurement can take 20~150ms for a typical parameter analyzer and it has been shown that the degradation during this period was not negligible [5]. The detailed relation between Id and time during the initial stress period has not been reported, which is needed to determine the maximum measurement time allowed for a degradation-free Id. The degradation-free trans-conductance, gm, was not reported, either.

Fig. 2 shows the Id against stress time. The first point measured by the analyzer is substantially degraded. gm is estimated by measuring Id at Vg=Vgst±DV, where Vgst is the stress Vg. Fig. 3 shows that the first gm depends on the perturbation sequence, which is again caused by degradation during the measurement. To obtain the degradation-free gm, pulsed Id-Vg with a transition time of 6 μs must be used.

Fig. 3 also shows that gm actually increases with time under a constant Vgst. This is caused by a reduction of |Vgst-Vth|, which enhances the effective mobility, despite the degradation of low-field mobility. A more detailed analysis on the variation of effective mobility during stress was given in our recent work [7]. After using the degradation-free Id and gm, Fig. 4 shows that the ΔVth(OTF) is more than doubled. However, we will demonstrate that ΔVth(OTF) is not ΔVth(real) next.

B. Impact of sensing Vg on ΔVth:

In early works, ΔVth was not measured at the typical operation voltage, say, |Vg|=1.2 V. On one hand, ΔVth(OTF) was recorded at stress bias, which was typically much higher than 1.2 V. On the other hand, the conventional ΔVth(ex) was evaluated at |Vg| less than 1.2 V. The potential impact of sensing Vg on ΔVth was not assessed before and is studied here.

To suppress the complication caused by ΔVth recovery during measurement, a stressed device was first left floating at stress temperature for 5 min, during which the initial rapid recovery took place. After this stabilization period, the traditional Id-Vg was measured in Fig. 5a. The current degradation at each Vg is ΔId(Vg) and the corresponding ΔVth(Vg) is estimated by:

$$\Delta Vth(Vg)= \Delta Id(Vg)/gm(Vg) \qquad (1)$$

where gm(Vg)=dId/dVg in Fig. 5b was obtained from the Id-Vg in Fig. 5a. Fig. 5c shows that |ΔVth| increases with sensing |Vg|. Although |ΔVth(ex)|=8.5 mV, |ΔVth| reaches 18.6 mV at |Vg|=1.2 V, an over 100% increase. To examine if this Vg effect originates from the use of high stress Vgst, Figs. 6a and 6b show that |ΔVth(Vg=-1.2V)|>>|ΔVth(ex)| is observed in both cases with Vgst=-1.2 or -3.17 V. We conclude that the classical ΔVth(ex) substantially underestimates ΔVth(real).

C. Suppressing time-related recovery

Since ΔVth(OTF) was measured with zero recovery, one must suppress the time-related recovery, in order to assess the impact of Vg on ΔVth(OTF). This is achieved by using the waveform in Fig. 7a and the pulsed Id-Vg before and after stress is given in Fig. 7b. Fig. 7c shows |ΔVth(OTF)| again increases with sensing |Vg|. We conclude that the ΔVth(OTF) overestimates ΔVth(real). Fig. 8 shows that the extent of this over-estimation increases with stress |Vgst|.

The falling time, tf, in Fig. 7a is 6 μs. Fig. 9a confirms that the recovery was insignificant at tf=6 μs, broadly in agreement with early observation [8]. The Vg effect can be clearly separated from the traditional recovery effect. Fig. 9b shows that the sensing Vg does not affect the recovery.

When ΔVth is a function of Vg, our analysis shows that gm=dId/dVg should be replaced by gm=dId/d(Vg-Vth). This correction requires simulation and is small for |Vgst|=2 V (Fig. 10a), but considerable for |Vgst|=3.17 V (Fig. 10b).

D. Physical process and defects

The reduction of |ΔVth| for lower |Vg| indicates a decrease of positive charges, as illustrated in Fig. 11. Fig. 7 shows that the neutralization occurs within 6 μs. To assess the charging time, Fig. 12 shows that there is little difference between the ΔVth obtained by applying a 6 μs pulse or a quasi-DC ramp. The defects can communicate with substrate in microseconds or less and must be close to Si interface. However, they are not the traditional interface states and can charge and discharge in the range of |Vg|>|Vth|, where the charging status of traditional interface states does not change. Positive charges with energy level above the Si conduction band edge have been reported recently [9,10]. Further work is needed to understand them. The good agreement between the pulsed and quasi-DC measurement in Fig. 12 also confirms that any degradation induced by the quasi-DC measurement itself has little effect on the result.

E. Impact on lifetime

A popular definition for NBTI-induced device lifetime is |ΔVth|=50mV. Traditionally, the extrapolated threshold voltage shift, ΔVth(ex), is used. Fig. 5c shows that |ΔVth(ex)| underestimates the ΔVth under practical operation bias. This will lead to an over-estimation of device lifetime, if |ΔVth|≤50mV is required under practical operation conditions. Fig. 13 shows that lifetime can be reduced by a factor of 10^4 when ΔVth(Vg=-1.2 V), instead of ΔVth(ex), is used.

F. Insensitivity to processes

The results in Figs. 1-13 were obtained on a thermally nitrided 2.7 nm SiON. To ensure the Vg dependence of ΔVth is not process specific, Fig. 14 shows that it also occurs in a plasma nitrided 1.85 nm SiON layer.

G. Effect of series resistance of source and drain

Figs. 5 and 7 show a new method for estimating ΔVth(real). Transconductance is used in this method and the measured gm will depend on the series resistance of source and drain. The question is how the series resistance affect the ΔVth(real). To address this issue, we externally connected a resistor to the source, Rs.

As expected, Fig. 15a shows an increase of Rs leading to a reduction of gm. The variation of drain current at a given Vg, ΔId(Vg) is also reduced (Fig. 15b). However, Fig. 15c shows that the effect of Rs on ΔVth is negligible, since the reduction in gm is essentially cancelled out by the reduction in ΔId through equation (1). The method proposed for evaluating ΔVth is insensitive to the series resistance of source and drain.

Conclusions

This work shows that the ΔVth measured in early works by using either the on-the-fly (OTF) or extrapolation is different from the real ΔVth under practical operation conditions. This difference originates from the increase of |ΔVth| with the sensing |Vg|. The classical extrapolation technique uses sensing |Vg| lower than operation |Vg| and underestimates real ΔVth. The OTF typically uses higher |Vg| and consequently overestimates real ΔVth. The dependence of ΔVth on sensing Vg is not caused by either the traditional recovery or a high stress bias and is not process-specific. It can have a large impact on device lifetime and the maximum operation voltage.

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References

[1] S. Fujieda, Y. Miura, M. Saitoh, E. Hasegawa, S. Koyama, and K. Ando, App. Phys. Lett., 82, p.3677, 2003.
[2] A. T. Krishnan, V. Reddy, S. Chakravarthi, J. Rodriguez, S. John, S. Krishnan, IEDM Tech Digest, p.349, 2003.
[3] J. F. Zhang, M. H. Chang, and G. Groesenenken, IEEE Elec. Dev. Lett., 28, p.298, 2007.
[4] M. Denais, A. Bravaix, V.Huard, C. Parthasarathy, G. Ribes, F. Perrier, Y. Rey-Tauriac, and N. Revil, IEDM Tech Digest, p.109, 2004.
[5] C. Shen, M. –F. Li, C. E. Foo, T. Yang, D. M. Huang, A. Yap, G. S. Samudra, and Y. –C. Teo, IEDM Tech. Digest, p.333, 2006.
[6] M. H. Chang and J. F. Zhang, J. Appl. Phys., 101, Art. no. 024516, 2007.
[7] J. F. Zhang and M. H. Chang, ECS Trans. Silicon Nitride, Silicon Sioxide, and Emerging Dielectrics, 6, p.301, 2007.
[8] H. Reisinger, O. Blank, W. Heinrigs, A. Muhlhoff, W. Gustin, and C. Schlunder, in proc. IRPS, p.448, 2006.
[9] J. F. Zhang, C. Z. Zhao, A. H. Chen, G. Groeseneken and R. Degraeve, IEEE Trans. Electron Dev., 51, p.1267, 2004.
[10] C. Z. Zhao and J. F. Zhang, J. Appl. Phys., 97, Art. no. 073703, 2005.

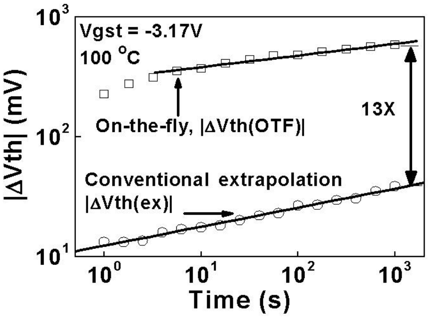


Fig. 1 A comparison of ΔVth(OTF) by the on-the-fly technique with ΔVth(ex) by the extrapolated quasi-DC transfer characteristics technique.

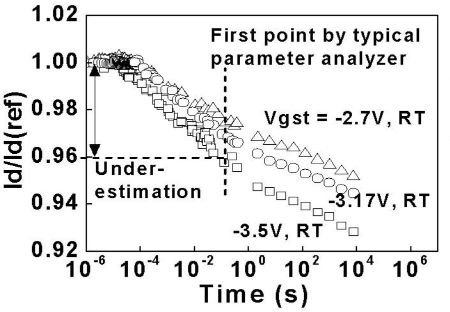


Fig. 2 The first point measured by typical parameter analyser is not degradation-free, leading to an underestimation of Id degradation.

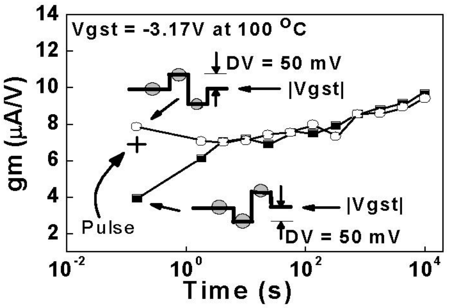


Fig. 3 The sequence of Vg perturbation has a large impact on the initial gm. '+' was obtained from the pulsed Id-Vg (6 μs) and should be used as the initial gm.

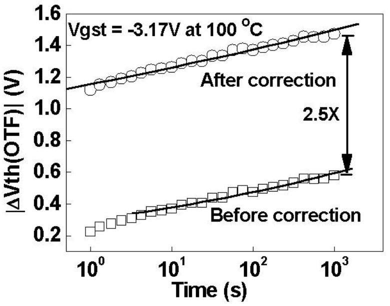


Fig. 4 After using the degradation-free Id as the reference and the correct initial gm, ΔVth(OTF) is more than doubled.

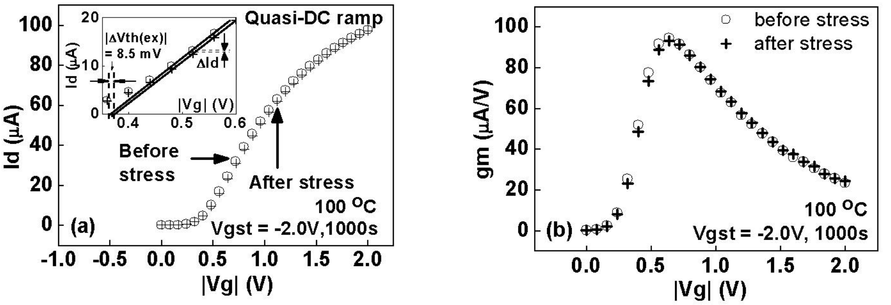
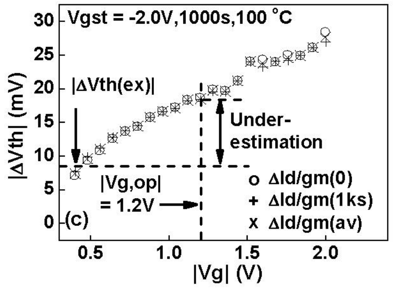


Fig. 5 (a) The quasi-DC Id-Vg before and after stress. The inset shows the conventional ΔVth(ex) measured from the shift of extrapolated Id-Vg. (b) The transconductance, gm=dId/dVg, evaluated from the two Id-Vg in (a).



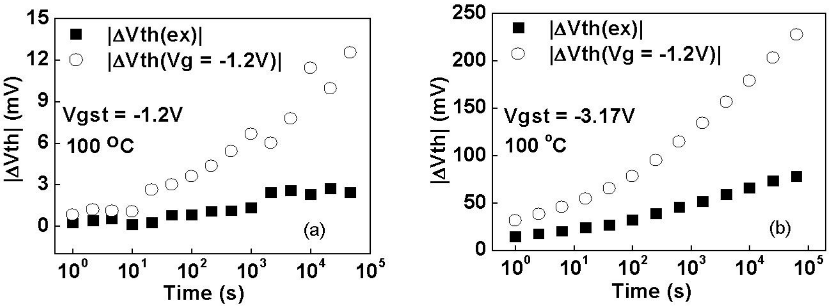


Fig. 5c Dependence of ΔVth on sensing Vg. ΔVth at each Vg was evaluated by using ΔId in Fig. 5a and gm in Fig.5b. gm(0) and gm(1ks) is the gm before and after stress and gm(av) is the average. The choice of gm only has a weak effect on ΔVth.

Figs.6 A comparison of ΔVth(ex) with ΔVth(Vg= –1.2 V) during the stress under a gate bias of Vgst= –1.2 V (a) and -3.17 V (b). |ΔVth(Vg= –1.2 V)|>>|ΔV(ex)| occurs at a stress bias as low as –1.2 V.

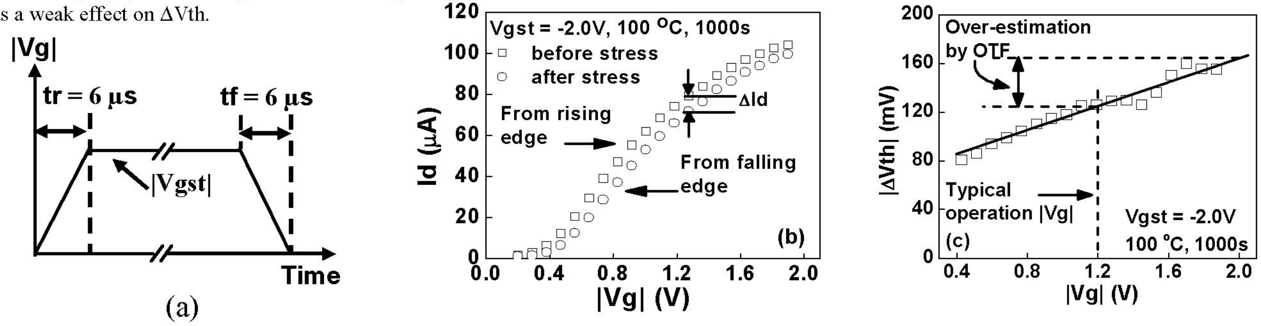


Fig. 7 (a) The Vg waveform used to suppress the recovery when assessing the Vg effect on ΔVth(OTF). (b) The pulsed Id-Vg, corresponding to the rising and falling edges in (a). The ΔId here is higher than that in Fig. 5a after the same stress, because the recovery is suppressed. A rising time of 6 μs gives the degradation-free Id as reference (see Fig. 2). (c) ΔVth evaluated by using ΔId in (b) and the average gm from the two Id-Vg. The feature of Vg effect is the same before and after recovery (see Fig. 5c). The justification for using a falling time of 6 μs is given in Fig. 9.

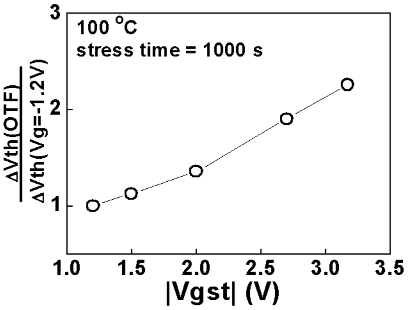


Fig. 8 The ΔVth(OTF) measured at the stress gate bias overestimates ΔVth at Vg=-1.2 V. The higher the stress bias, the larger the overestimation becomes.

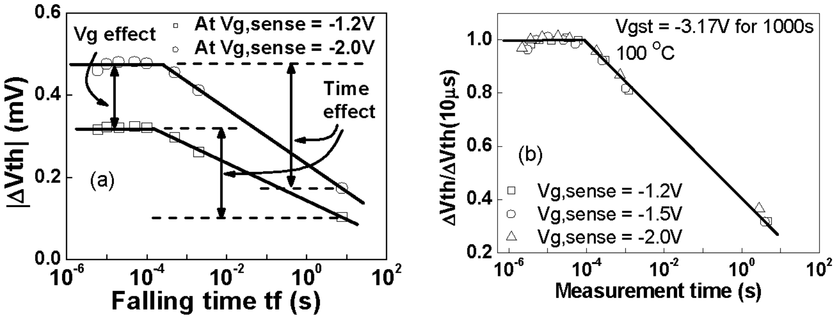
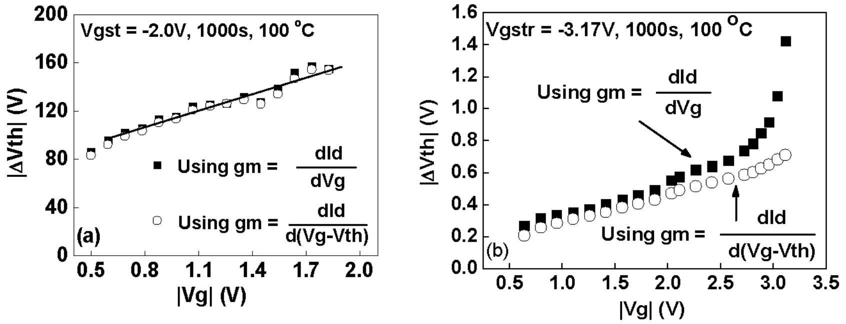


Fig. 9 (a) Separation of Vg effect from the conventional time-related recovery. The recovery is suppressed when the pulse falling time is less than 10 μs approximately. (b) After removing the Vg effect through normalisation against the value at 10 μs, the time-related recovery is insensitive to the sensing Vg.



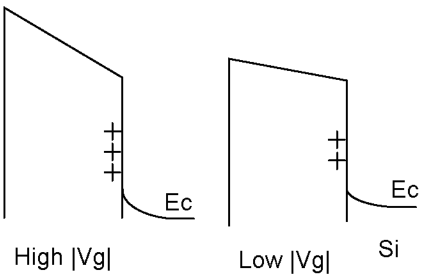
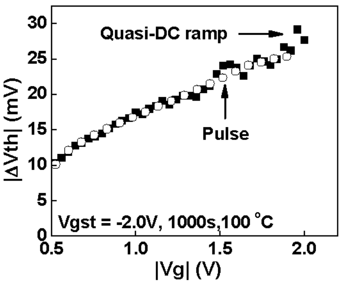
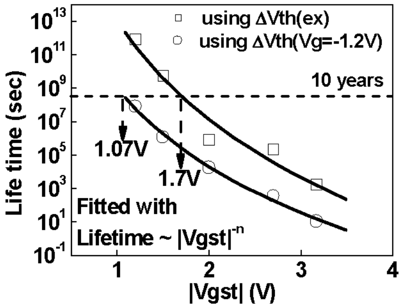


Fig. 10 The gm evaluation is corrected by taking the ΔVth dependence on Vg into account. The impact of the correction on ΔVth is weak when stressed at relatively low |Vgst|=2 V (a), but becomes considerable for |Vgst|=3.17 V (b). However, the feature of the Vg dependence of ΔVth is not changed by either the stress bias used or the gm correction.

Fig. 11 Schematic diagram showing that positive charging reduces for lower sensing |Vg| through more effective neutralisation, resulting in lower |ΔVth|.





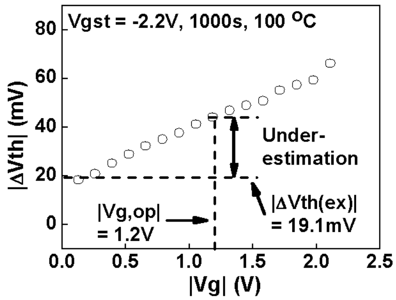


Fig. 12 After recovery, the same |ΔVth|-|Vg| was obtained from a quasi-DC Id-Vg and a pulsed Id-Vg (6 μs), indicating that the charging was completed within 6 μs.

Fig. 13 Lifetime for limiting |ΔVth|≤50 mV. Replacing ΔVth(ex) by ΔVth(Vg=-1.2 V) leads to a reduction of the maximum operation |Vg| from 1.7 to 1.07 V.

Fig. 14 Insensitivity of the |ΔVth|-|Vg| relation to fabrication process. The result corresponds to that in Fig. 5c. The SiON is 1.85 nm nitrided by DPN here. It is 2.7 nm and thermally nitrided in Fig. 5c.

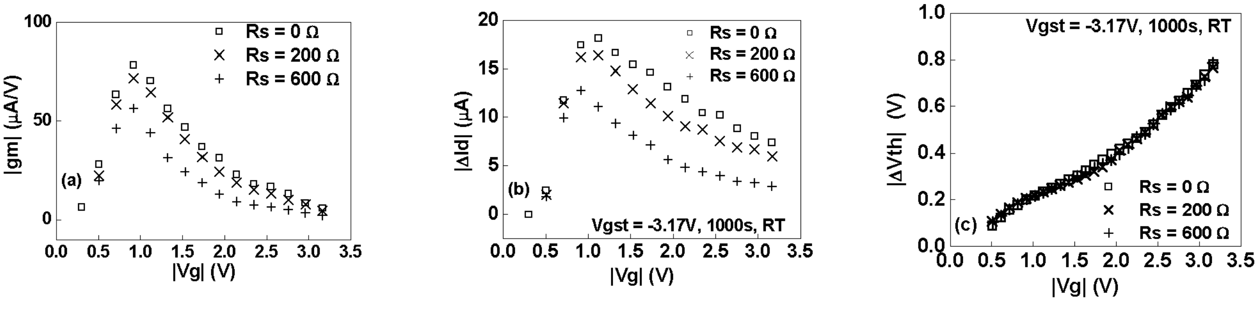


Fig. 15 The effects of the series resistance of source and drain on gm (a), ΔId(Vg) (b), and ΔVth (c). The Rs is a resistor externally connected to the source. An increase of Rs reduced both gm and ΔId(Vg), but has little effect on the ΔVth. The evaluation of ΔVth through equation (1) with gm=dId/d(Vg-Vth) is not sensitive to the series resistance of source and drain, therefore.