Detrimental impact of hydrogen passivation on NBTI and HC degradation

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***Abstract*—Numerous studies have shown that the passivation of interface states by hydrogen has a significant impact on degradation mechanisms such as the bias temperature instability (BTI) and hot carrier (HC) degradation. By varying the thickness of the titanium layer at the beginning of the back-end-of-line processing we are able to change the hydrogen content near the Si–SiO_2 interface. While the precursor density for negative BTI (NBTI) defects with large time constants, typically observed as a quasi-permanent component, is dramatically increased with the hydrogen passivation degree, the distribution of activation energies is left unchanged. For PBTI, the opposite observation is made, that is, the degradation decreases with hydrogen passivation. Interestingly, the recovery activation energy for hot carrier induced degradation is fully consistent with P_b center passivation, while the recovery of the permanent component of BTI appears to be due to a different mechanism.**

I. Introduction

Hydrogen has traditionally played an important role in the history of NBTI research [1]. In recent alternative explanations [2, 3] a considerable amount of the degradation and particularly the recovery is ascribed to switching oxide traps. This recoverable part of NBTI degradation has been demonstrated to be insensitive to hydrogen [2, 4]. On the other hand, the quasi-permanent part has been shown to be very sensitive to the hydrogen passivation degree [2, 4]. In particular, a passivation of the interface with deuterium instead of hydrogen only affects the quasi-permanent part [2].

By varying the hydrogen passivation degree, we study the impact of hydrogen on the recoverable as well as the quasi-permanent component in n- and pMOSFET with respect to N- and PBTI as well as HC degradation. Our study provides valuable information for the ongoing controversy regarding the role of hydrogen in MOSFET reliability issues.

II. Experimental

We control the amount of hydrogen near the Si–SiO_2 interface by varying the total amount of pure titanium (Ti) in the back-end-of-line stack, by making use of the hydrogen getter capability of Ti [4–6]. To quantify the passivation degree of the interface we investigate the charge pumping (CP) current of our devices before stress and observe a correlation between I_{CP} and the Ti layer thickness. Since I_{CP} is very sensitive to the interface trap density, we conclude that the interfacial defect density correlates inversely with the Ti layer thickness.

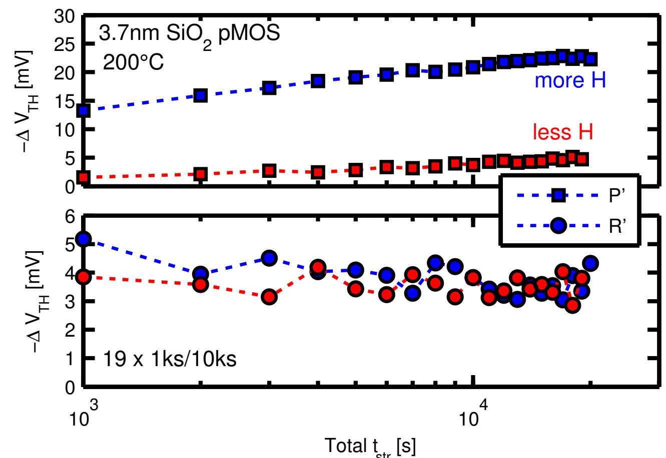

Figure 1. By varying the thickness of the Ti layer in the back end of line material stack we are able to adjust the hydrogen passivation degree at the Si–SiO_2 interface [4, 5, 9]. We then perform a continuous repetition of 1 ks stress and 10 ks recovery [10, 11] on two sample devices having more or less hydrogen at the Si–SiO_2 interface. We observe that the hydrogen content influences especially the quasi-permanent part of NBTI defined as $P' = \Delta V_{TH}(t_{rec} = 10\,\text{ks})$. A measure of the recoverable part of NBTI, defined through $R' = \Delta V_{TH}(t_{rec} = 1.5\,\text{ms}) - P'$, is largely unaffected by hydrogen. The virgin difference in the V_{TH} of the two devices is only a few mV. The large values of the drift therefore suggests that the device with more hydrogen has a larger overall drift capability than the device with less hydrogen at the interface.

We investigate negative and positive BTI and HC degradation on devices with pure SiO_2 oxides having thicknesses between 3.7 nm and 30 nm. The results are independent of the actual oxide thickness in all our experiments, consistent with previous results [7]. In order to be able to study the influence of temperature thoroughly we use the poly-heater, a simple in-situ heating structure of polycrystalline Si in the close vicinity of the device [8].

III. Hydrogen influence on NBTI

We perform experiments with long ($> 10\,\text{ks}$) alternating stress and recovery phases on pMOSFETs with more or less hydrogen at the interface to investigate the influence of hydrogen on the distribution of time constants of NBTI defects (cf. Fig. 1). Consistent with previous results [2, 4] we find that only defects with emission time constants larger than

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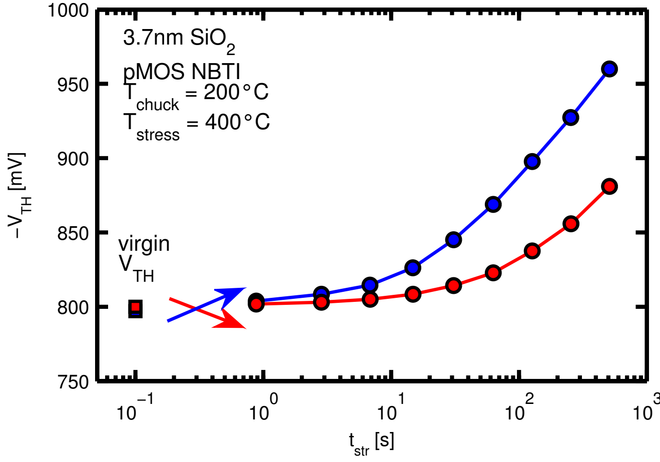

Figure 2. Result of an NBTI experiment strongly accelerated with a 500 s long stress at 400 °C [12] using the poly-heater [8]. The virgin V_{TH} of the device with more hydrogen at the interface (blue) is only a few mV smaller than that of the device with less hydrogen (red). The stress does not only reduce the difference in V_{TH} of the two devices but even inverses the order of the two. This means that the number of traps which may become charged during NBTS (i.e. the max. degradation capability) is increased through hydrogen passivation, consistent with literature [4, 5, 13, 14].

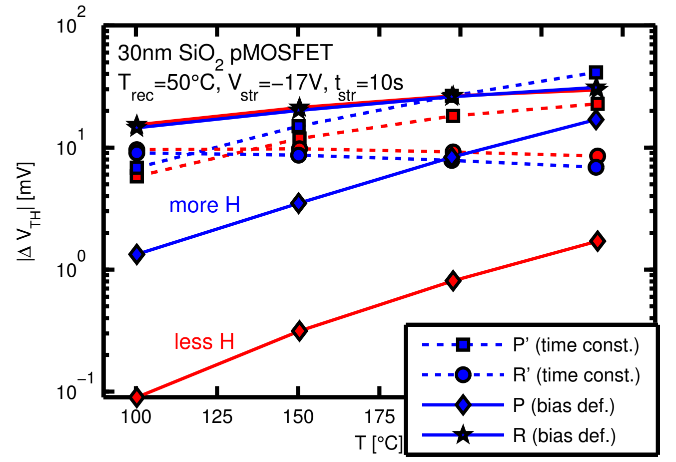

Figure 3. Stress temperature dependence of R', P', R and P measured at always the same recovery temperature of 50 °C. R' and P' are defined by the trap time constants (see the caption of Fig. 1). R and P are defined by the bias dependence (measured after applying a 1 s pulse to 0.5 V at 50 °C). Especially those defects which react to the short accumulation phase are considerably influenced by the hydrogen content at the interface. The parallel shift in the more or less hydrogen bias dependent P characteristics suggests that the hydrogen passivation changes only the amount of charges available for P and not their energetic position or effective activation barrier.

10 ks at 200 °C (which we arbitrarily define as P' in Fig. 1) are affected by the hydrogen passivation degree. We observe neither a difference in the amount of traps with emission time constants between 1.5 ms and 10 ks nor a large loss of these traps with the increase of P'. This challenges models suggesting a transfer of hydrogen to an oxide trap which locks the positive charge state of this trap [2, 3].

The amount of drift for the device with more hydrogen at the interface in the experiment of Fig. 1 is much larger than the virgin difference in V_{TH} of a few mV between those devices. In order to investigate the maximum drift potential of the two devices we accelerate only the NBTS with 400 °C using the poly-heater [8] in the experiment described in Fig. 2 [12] (the analysis temperature is kept at 200 °C). Even though NBTI degradation does not fully saturate also at this high temperature [12], the experiment shows that the amount of degradation activated in the device with more hydrogen is much larger than in the device with less hydrogen. We must conclude that the hydrogen passivation therefore increases the precursor density for NBTI [4, 5, 13, 14].

Rather than arbitrarily defining the quasi-permanent part as $P' = \Delta V_{TH}(10\,\text{ks})$ at the "end" of the recovery trace, we apply a positive pulse to remove a significant fraction of the trapped holes. Accumulation of electrons during recovery considerably decreases the emission time constants of most of the trapped holes [15–17]. What remains will be called P and should be closer to the quasi-permanent part. Fig. 3 demonstrates that the hydrogen content has an even stronger impact on the amplitude of P than on P'. The quasi-parallel vertical shift of the P characteristics in Fig. 3 is a strong indication that the hydrogen content only changes the number of bias independent charges and not their energetic position within the SiO_2 bandgap or their activation energy.

IV. Measurement of the Recovery of P

Detailed investigation of the quasi-permanent component of NBTI is a cumbersome task due to the long time constants [18]. Still, it has been demonstrated that most BTI degradation can be "baked" away [12, 19], clearly indicating that P' or P is not really permanent. In order to characterize the recovery of P in more detail we use the poly-heater to induce temperature accelerated recovery [12]. The high temperatures achievable with the poly-heater provide an elegant possibility to analyze the quasi-permanent part of NBTI degradation in more detail. We investigate R and P at all combinations of stress and recovery temperatures for the three values 30 °C, 100 °C and 200 °C and plot the result (cf. Fig. 4) as a function of the temperature time

$$\vartheta(T) = \tau_0 \left(\frac{t}{\tau_0}\right)^{T_{\text{meas}}/T}, \qquad (1)$$

as defined in more detail in [12]. τ_0 is the only fitting parameter of our approach and may be different for every single defect [20, 21], but we could show that also a single value for τ_0 captures the temperature dependence of an ensemble of defects reasonably well [12]. This experiment demonstrates the correlation between the hydrogen passivation and the amplitude of P. We analyze all data sets using a recently suggested analytical CET map model [10] which consists of two bivariate Gaussian distributions (one for R, one for P) and includes the distribution of the Arrhenius-like T activation of the defect time constants [12]. The fits of both data sets give consistent estimates for the emission and capture activation energy distribution of the quasi-permanent component

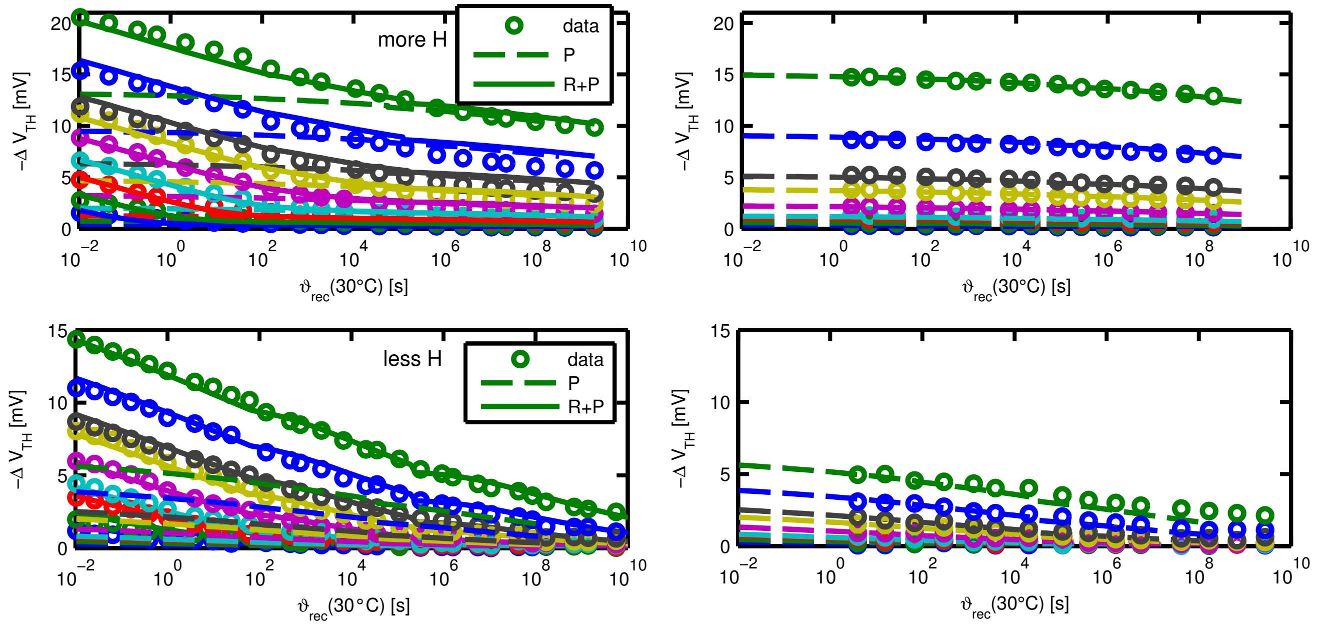

Figure 4. Temperature accelerated measurement for an analytical capture-emission-time (CET) map [10] using an abstract temperature time ϑ [12] which remaps measurements taken at different T to different times assuming a distribution of activation energies of the time constants, $\tau = \tau_0 \exp(E_\mathrm{A}/kT)$. The recovery temperature (30 °C, 100 °C, 200 °C) is increased during continuous application of the readout bias $V_\mathrm{rec} \approx V_\mathrm{TH}$ to the gate. The top (bottom) row shows the result for a device with more (less) hydrogen at the interface. On the left hand side, a full measurement is depicted while for the measurement on the right hand side we applied a short 1 s +0.5 V pulse to the gate right after stress. The remaining recovery can be fitted by a single bivariate Gaussian distribution of activation energies and serves as a initial point for the fitting of the full CET map by only adjusting the parameters of R.

of NBTI (mean (2.0 ± 0.5) eV and variance (0.3 ± 0.1) eV). These values are larger than the values for passivation of hydrogen with a Si dangling bond (P_{b0} and P_{b1} centers) at the (100) Si–SiO_2 interface (P_{b0}: mean 1.51 eV and variance 0.14 eV, P_{b1}: mean 1.57 eV and variance 0.15 eV) [22].

V. Hydrogen influence on PBTI

Quite interestingly, the influence of hydrogen on the positive BTI in an nMOSFET is the *opposite* compared to NBTI, meaning that a better hydrogen passivation *decreases* PBTI (cf. Fig. 5). In order to avoid hole trapping from the gate we use devices with a rather thick gate oxide and n^{++} gate poly doping [23–25]. One possible reason for the positive impact of hydrogen on PBTI is that hydrogen passivates also positive border traps [9, 26–29] (cf. Fig. 6). These positive traps are neutralized through PBTS which appears spuriously as negative charge increase [9].

VI. Hydrogen influence on hot carrier degradation

It has frequently been speculated that P of NBTI is due to interface states [2, 30]. Similar claims exist for the degradation build up during hot carrier stress [31–33]. In order to investigate the link more closely we study the recovery of HC degradation through bake using the poly-heater (cf. Fig. 7). We analyze the data with the generalized simple thermal (GST) model suggested by Stesmans [22], which assumes a Gaussian distribution of the activation energy for P_b center passivation by hydrogen. The GST model is mathematically equivalent to

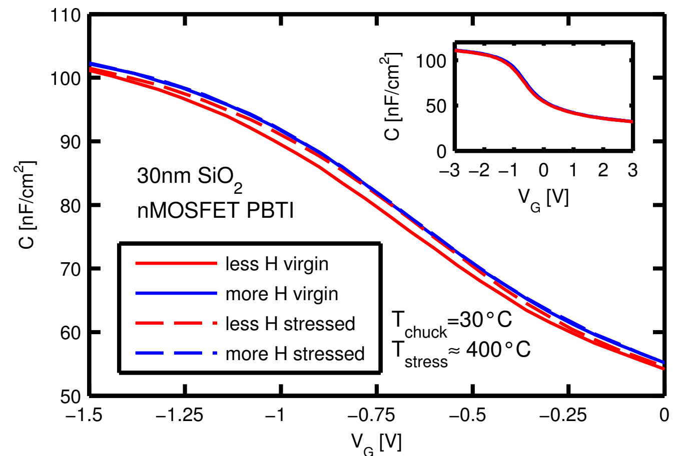

Figure 5. MOS capacitance CV curve for two devices with more or less hydrogen at the interface before and after PBTI accelerated with 400 °C. The virgin difference in the flat-band voltage between the two devices shows that positive charge is passivated through hydrogen. Both devices approach the theoretical flat-band voltage value (an oxide without any charges) through PBTS. Consequently, hydrogen passivation decreases the precursor density for PBTI on nMOSFETs [9].

the analytical CET map model for NBTI [10] for one single Gaussian distribution. The values we obtain for the emission activation energy after hot carrier stress reproduce roughly the values for P_b center passivation [22]. This is a strong hint that the recovery of HC induced damage is reaction limited [31–33] rather than diffusion limited [34]. We therefore must

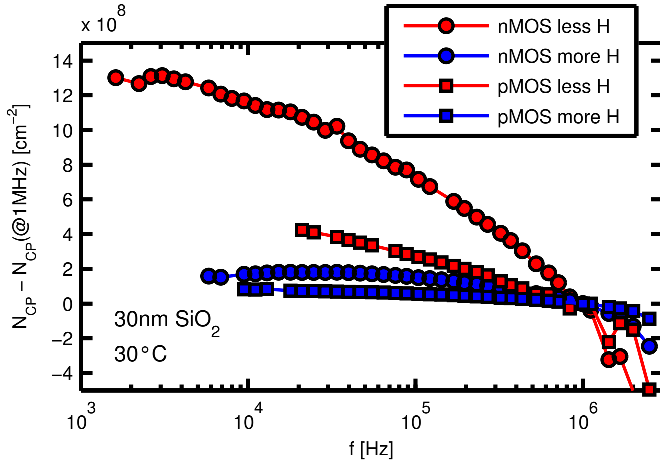

Figure 6. Charge pumped per cycle ($N_{\mathrm{CP}} = I_{\mathrm{CP}}/(qfA)$) over CP frequency. The N_{CP} measured at 1 MHz is subtracted to account for the large difference in the interface trap density for different hydrogen passivation. Ideal interface traps should be independent of f. An increase of N_{CP} with decreasing f is usually attributed to border traps with larger time constants. We observe a large decrease of the density of border traps with hydrogen passivation.

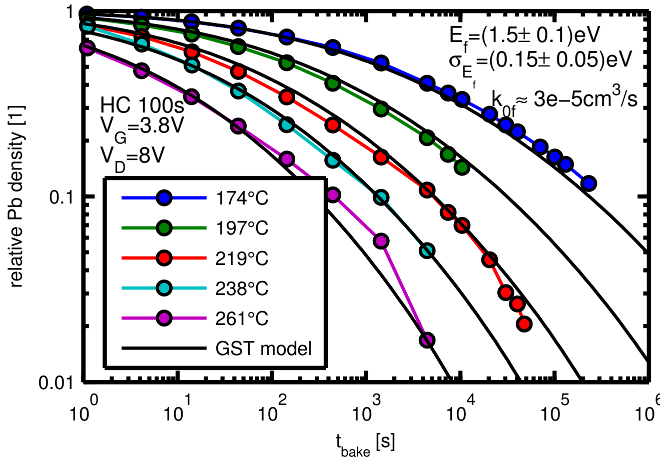

Figure 7. The degradation induced through a hot carrier stress on an nMOSFET can be healed through continuous baking with the poly-heater at zero gate bias. The relative density of dangling bonds at the Si–SiO$_2$ interface (P_b center family) is monitored using charge-pumping during short interruptions of the bake at the chuck temperature 30 °C. The recovery can be perfectly modeled when assuming a passivation equation $[P_b]/N_0 = \exp(-k_f[\mathrm{H}_2]t_{\mathrm{bake}})$, where the forward rate constant is based on $k_f = k_{0f}\exp(-E_f/kT)$ and E_f is assumed to be Gaussian distributed with a spread σ_{E_f} [22]. The values obtained from a self-consistent fit of all data resample the values given for the passivation of P_b centers at the (100) Si interface to SiO$_2$ grown at low temperatures ([22]: P_{b0}: $E_f \approx 1.51$ eV, $\sigma_{E_f} \approx 0.14$ eV and $k_{0f} \approx 1.4\times10^{-6}$ cm^3/s, P_{b1}: $E_f \approx 1.57$ eV, $\sigma_{E_f} \approx 0.15$ eV and $k_{0f} \approx 1.4\times10^{-6}$ cm^3/s).

conclude that, while HC is consistent with P_b passivation, P after NBTI is not fully due to passivation of P_b centers through hydrogen.

While investigating hot carrier recovery through bake, we observe that increased hydrogen passivation also changes the impact on hot carrier reliability. The device with more hydrogen experiences much more change in I_{CP} than the device with less hydrogen. Similarly to the NBTI case, this is due to the increased Si–H density susceptible to HC degradation.

VII. Conclusion

By varying the thickness of the Ti layer at the beginning of the BEOL processing we are able to change the hydrogen content near the Si–SiO$_2$ interface. We find that the available amount of hydrogen at the interface has a considerable impact on the quasi-permanent part of the NBTI degradation. The precursor density for NBTI defects with large time constants and/or bias independence is dramatically increased with the hydrogen passivation degree. Our experiments show a larger mean and a larger variance of the quasi-permanent part than expected from P_b centers passivation kinetics. This strongly suggests that the quasi-permanent part is not only due to interface traps. On the other hand, the impact of hydrogen on PBTI is the opposite: more hydrogen at the interface results in a decreased number of precursors for PBTI. Finally, the distribution of the recovery activation energy for hot carrier induced degradation is fully consistent with P_b center passivation. As with NBTI, hydrogen passivation also increases the precursor density for hot carrier degradation.

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