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Investigation of NBTI Recovery During Measurement

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ABSTRACT

In this work we present a rigorous investigation of the negative bias temperature instability (NBTI) recovery process during measurement intervals in comparison to the numerical solution of an extended reaction-diffusion (RD) model. In contrast to previous work, the RD model has been implemented in a multi-dimensional device simulator and is solved self-consistently together with the semiconductor device equations. This allows us to directly use many commonly approximated quantities such as the oxide electric field and the interface hole concentration in a self-consistent manner. In addition, the influence of the trapped charges can be more accurately considered by using a distributed Shockley-Read-Hall interface trap-charge model [1, 2] which has been coupled to the RD model. Thus, due to the self-consistent solution procedure, also the feedback of these charged interface-states on the Poisson equation is considered which influences the observed threshold voltage shift. Experimental data confirm the model which has been calibrated to a wide range of temperatures using a single set of parameters.

INTRODUCTION

Negative bias temperature instability (NBTI) has come to the forefront of not only academic but also industrial interest. It occurs in p-type MOS devices stressed with negative gate bias at elevated temperatures. In particular for thicker oxides, as used in high-voltage devices, the degradation can be ascribed to two major effects, the generation of interface traps N_{it} at the Si/SiO_2 interface and the generation of fixed oxide charges in the dielectric. These effects lead to a shift of important transistor parameters such as the threshold voltage V_{th}, the drain current I_D, the transconductance g_m, and the off current I_{off}. The degradation can cause timing shifts of logic circuits and thus lead to circuit failure.

Due to the need for accurate prediction of device and circuit lifetimes, modeling and simulation of the degradation physics has gained importance. There are two important factors for accurate modeling: (a) the physics of the degradation mechanisms have to be modeled as precisely as possible (b) the experimental and measurement setup must lead to an exact description of the device state. Here, especially the applied measurement technique needs special attention, as the method used for evaluating NBTI degradation can have a considerable impact on life-time extrapolation results [14, 4].

THE ORIGINAL MODEL

Our model is an enhanced version of the original work by Jeppson and Svennson [5]. Their proposed reaction-diffusion (RD) model describes the degradation process as a reaction at the Si/SiO_2 interface generating a positively charged interface state (N_{it}) as well as releasing a mobile hydrogen related species (N_X). This generation process is described as

$$\frac{\partial N_{it}(t)}{\partial t} = \underbrace{k_f (N_0 - N_{it}(t))}_{\text{Generation}} - \underbrace{k_r N_{it}(t) N_X(0,t)}_{\text{Recombination}} , \tag{1}$$

where k_f is the interface-trap generation and k_r the recombination rate. The symbol N_0 denotes the number of initially inactive interface-traps and $N_X(0,t)$ is the surface concentration of the diffusing species. The equilibrium of the generation and the recombination term is controlled by the hydrogen density at the interface ($N_X(0,t)$). Thus, the transport mechanism of the hydrogen species away from the interface characterizes the degradation mechanism, controlling for example the V_{th} shift. The original reaction-diffusion model describes the transport as a purely diffusive mechanism which is described by the regular diffusion equation

$$\frac{\partial N_X(x,t)}{\partial t} = D \frac{\partial^2 N_X(x,t)}{\partial x^2} . \tag{2}$$

Here D is the diffusivity of the hydrogen species in the dielectric.

THE EXTENDED MODEL

The basic reaction-diffusion model has been implemented in a two- and three-dimensional numerical device simulator and the model equations are coupled fully self-consistently to the semiconductor device equations. The benefits are manifold, since now the local oxide field, hole concentration, charged carriers, fast interface states (Fermi-level dependent charges), and slow oxide charges can be included in both, the device equations and the NBTI model. Due to the availability of the solution of the semiconductor equations, the trap generation rate can be expressed as a function of the surface hole concentration p_s and the oxide electric field E_{ox} as [6]

$$k_f = k_{f,0} p_s / p_{ref} \exp(E_{ox} / E_{ref}) , \tag{3}$$

instead of using estimates for p and a constant E_{ox}. The symbols $k_{f,0}$, p_{ref}, and E_{ref} denote the reference values for the generation rate, the hole concentration and the electric field.

Instead of using the standard diffusion equation [5, 7] or the commonly used non-equilibrium approximation [8, 3], hydrogen transport has been extended to dispersive transport by fully dynamic multiple trapping equations [9]. Transport of the diffusing species away from the Si/SiO_2 interface is therefore governed by bulk traps in the dielectric. As the bulk traps are

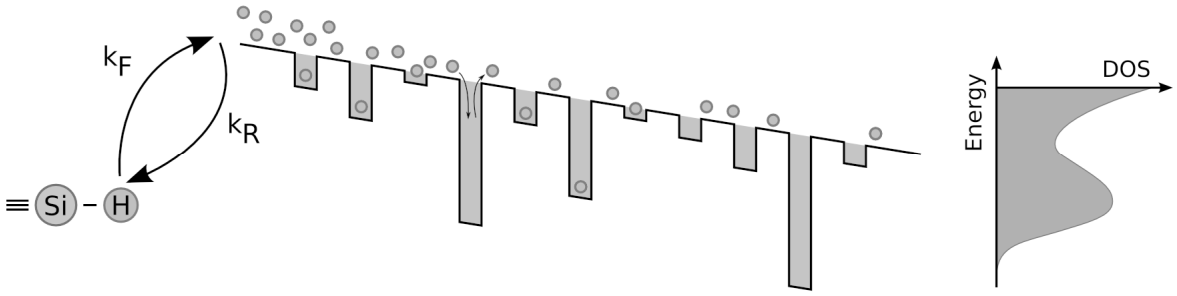

Figure 1: Schematic illustration of the dispersive transport model. Hydrogen is disassociated from the interface and transported into the SiO_2 via a diffusive mechanism. Trapping in the oxide leads to dispersive transport. The energy diagram on the right hand side shows the density-of-states (DOS) energy distribution of the hydrogen traps.

distributed in energy they can give raise to dispersive transport. The trap distribution has shown to be a combination of a shallow band-tail part, which forms the fast traps, and a deep Gaussian contribution which forms slow traps (Figure 1).

The kinetics of the hydrogen species can be adjusted for either H^0 for direct trapping/de-trapping or H_2 which is formed after de-trapping and cracked right before trapping [10]. Generation of fixed oxide charges is modeled by trapping of the diffusing species at oxide defects [11] forming slow positive charges. H_2 is cracked first [10] while H^0 is trapped right away. These distributed, fixed oxide charges are modeled separately and do not obey a fixed relation to interface traps. Although for ultra-thin oxides the importance of oxide charges is controversial [12, 13], for thicker oxides as used in power and high-voltage devices they are fundamental.

MEASUREMENT CYCLES AND THEIR SIMULATION

One of the key figures of interest is the shift of the threshold voltage (ΔV_{th}) as result of NBTI stress. The shift is typically measured by determining the transistors I_D-V_G characteristic during short interruptions of the stress conditions. The degradation caused by NBTI stress can anneal very quickly during the first few milliseconds of a measurement cycle. As this method can take up to several seconds, the full gate voltage sweep might not be a good method for evaluating the actual degradation. Figure 2 depicts such a measurement cycle and emphasizes the importance of an instantaneous measurement.

An enhanced measurement method is depicted in Figure 3, where instead of a full gate voltage sweep only a single voltage has to be used. This procedure can decrease the measurement time to a few hundred milliseconds [14]. An important assumption is that the degraded I_D-V_G characteristic has a very similar subthreshold slope.

For the comparison of measurements to simulation results the complete dynamics of degradation and annealing during the measurement intervals have to be taken into account. In our simulations we mimic the whole measurement procedure as closely as possible to reflect the real world conditions. Assuming that the influence of the measurement delay is properly accounted for, the importance to keep the delay as short as possible is minimized.

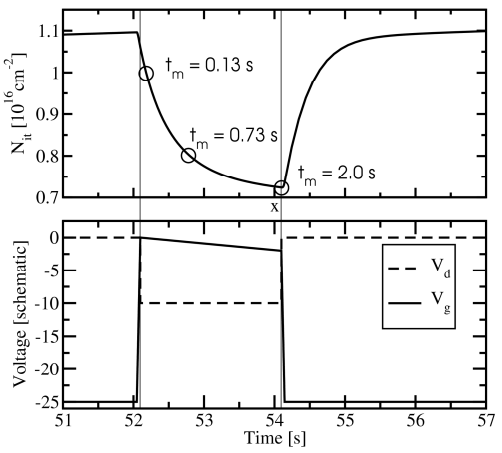

Figure 2: Measurement cycle performing a full I_D-V_G sweep to determine the V_{th} shift. Recovery can be significant and any delay can greatly influence the measurement results, as shown for three different measurement delays.

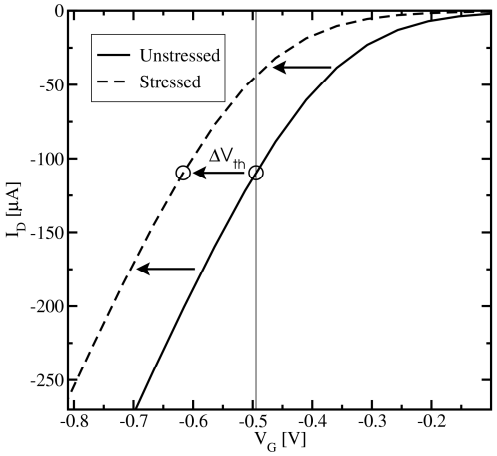

Figure 3: Fast method for determining the threshold voltage shift from a single point measurement. The drain current I_D is measured for $V_G \approx V_{th}$. The estimated value of ΔV_{th} is extracted from horizontally shifting the initial I_D-V_G curve.

EXPERIMENT AND RESULTS

The device under test was a 48 nm high-voltage oxide stressed for 1000 seconds at V_G = -25 V at four different temperatures (100, 125, 150, and 175°C). A 1000 seconds relax phase with V_G = 0 V followed the stress phase. To determine the threshold voltage shift ΔV_{th}, the stress was interrupted for two seconds at each measurement point to perform a gate voltage sweep from 0 V to -2 V. During this period a remarkable amount of relaxation can be observed. Thus, it is crucial to include the recovery process in the model. The important advantage is that the threshold voltage can now be extracted from the simulation results in the same way as in the measurements. There is no need for simplistic V_{th} estimations via the generated interface states like $\Delta V_{th} \approx$ -q N_{it}/C_{ox} which cannot properly account for two-dimensional geometry effects or the dynamics of charging and de-charging of interface traps.

Figure 4 depicts the measurement data and the simulation results with and without the inclusion of oxide traps in the H_2 model. Very good agreement to measurement data can be seen when the measurement delays are accounted for.

Figure 5 shows the good agreement for a wide range of temperatures, which can be achieved using a single set of model parameters. During the faster process within the first few seconds the annealing is attributed to re-passivation of dangling Si/SiO_2 interface bonds. This process is governed by the availability of mobile hydrogen near the interface. After the consumption of all available hydrogen new hydrogen can only be provided by de-trapping in the oxide bulk, which is a slow process. To properly capture the relax phase, the density-of-states used in the dispersive transport equation is modeled by an exponential tail for shallow traps for fast trapping and de-trapping, while the slow process is governed by deep traps given by an additional Gaussian peak well below the hydrogen conduction band (as seen on the right hand side of Figure 1).

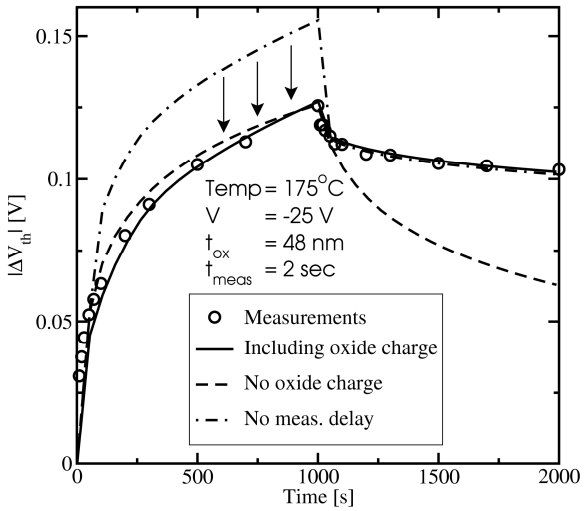

Figure 4: Comparison of the measurements to simulation results using the H_2 model. The measurements can only be described by properly accounting for the two second measurement delays during the stress phase and by including the generation of oxide charges in the dielectric.

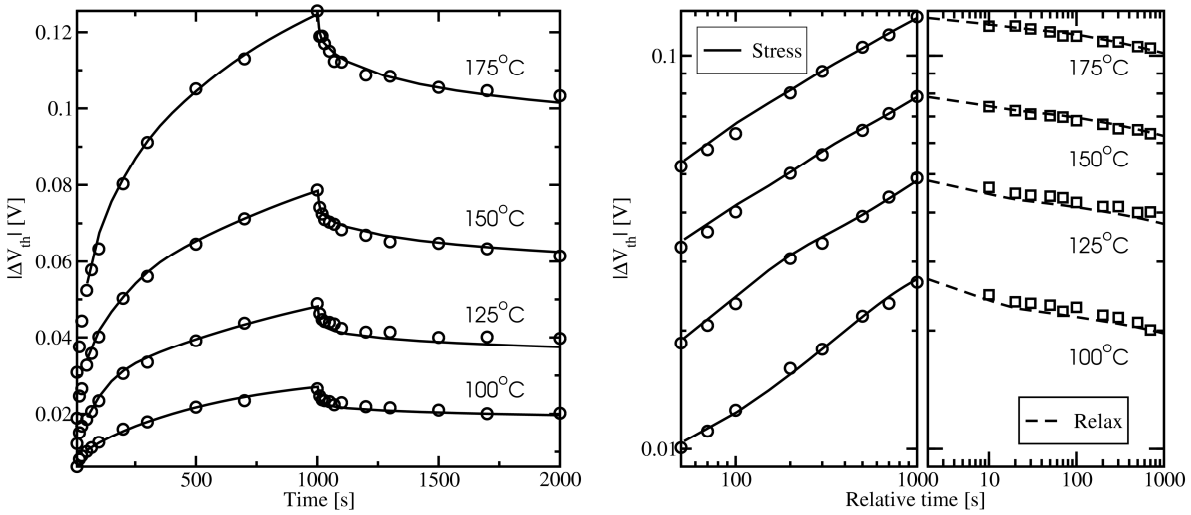

Figure 5: Comparison of the measurements to the simulation results at different temperatures in lin-lin (left) and log-log scale. One set of model parameters fits nicely to a wide range of temperatures.

CONCLUSIONS

We have presented an enhanced NBTI reaction-diffusion model with dispersive transport and fully self-consistent coupling to the semiconductor device equations. The implementation of the model in a multi-dimensional numerical device simulator allows us to directly use many commonly approximated quantities such as the oxide electric field or the interface hole concentration in a self-consistent manner. Due to the numerical investigation, highly sophisticated modeling of hydrogen trapping in the dielectric could be performed and complex density-of-states for the traps could be used.

The model has been calibrated to measurement data of a high-voltage MOSFET structure at a wide range of temperatures for both, a stress and a relax cycle. Here the full measurement setup has been taken into account and very good agreement has been shown.

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