Impact of NBTI-Driven Parameter Degradation on Lifetime of a 90nm p-MOSFET

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ABSTRACT

NBTI has emerged as a major reliability concern for the electrical stability of advanced CMOS technology. We report an experimental and simulation study for the NBTI mechanism in a high-performance p-MOSFET. Various stress experiments were performed in order to analyze the degradation of the key device parameters, V_T and I_{Dsat}. The presently leading reaction-diffusion (R-D) model is used to study the interface trap generation based on the diffusion and accumulation of released hydrogen in the gate oxide. The long-time degradation was simulated in order to estimate the NBTI lifetime which depends on the applied gate voltages and frequencies. The lifetime extension under higher frequency operation was analyzed at a typical supply voltage of 1.45V with a tolerance of $\pm 50\mathrm{mV}$. An unexpected long lifetime extension between six times and twenty times of the DC lifetime was found for an operation with a 10MHz gate signal.

INTRODUCTION

Although the degradation of the Si/SiO_2 interface in p-MOSFETs caused by negative bias temperature instability (NBTI) has been known for a long time, NBTI has become a serious reliability problem for newer CMOS technologies. Nitrogen is incorporated in thinner gate oxides for the 90nm technology and beyond mainly to reduce the gate leakage current, to avoid boron penetration into the dielectric, and to improve the hot carrier injection (HCI) reliability. However, it turned out that nitrided gate oxides (SiON) exhibit a significantly higher NBTI degradation compared to pure SiO_2 for the same physical oxide thickness and voltage condition [1]. Experimental studies revealed that the thermal activation energy of interface trap generation decreases steadily with increasing the nitrogen concentration at the interface [2].

It is well known that the NBTI mechanism in p-MOSFETs depends on the applied gate voltage, temperature, and stress time. Since indirect measuring techniques have to be applied, it is difficult to correlate measurement results to NBTI induced interface degradation associated with bond breaking and chemical species. While the exact nature of the NBTI phenomenon is still unknown, it is widely accepted that interface traps are generated by breaking of hydrogen-passivated silicon bonds at the interface and subsequent diffusion of hydrogen [3, 4]. Charge pumping and gate leakage current measurements revealed that NBTI under moderate oxide fields occurs mainly due to interface traps N_{it} and that the generated oxide traps N_{ot} can be neglected [5]. The NBTI-induced interface charges cause a parameter degradation of the MOSFET firstly due to a reduction in inversion layer holes and secondly due to a mobility degradation by Coulomb scattering. NBTI degradation affects the key parameters of the MOSFET, V_T and I_{Dsat}, and therefore it is very interesting to study the impact of NBTI-driven parameter degradation on the device lifetime.

Under dynamic operation of the transistor the interface traps which are generated during the on-state are partially annealed in the off-state. Therefore the AC degradation is significantly lower than the DC degradation for any given stress time. The magnitude of the NBTI-driven parameter shift over time is significantly reduced for higher frequencies or smaller "on" duty cycles [6, 7]. In this paper we analyze mainly the impact of an operation at higher frequencies in the MHz-range at slightly different supply voltages on the AC lifetime of the transistor.

EXPERIMENTAL DETAILS

The investigated device is a p-MOSFET fabricated in a 90nm process technology with shallow trench isolation (STI). The high-performance transistor is applied in six-transistor SRAM cells. The gate oxide was annealed in an NO_x gas ambient and has a physical oxide thickness of 24Å and an equivalent oxide thickness (EOT) of 20.5Å.

Figure 1 depicts the used configuration for NBTI measurements under DC and pulsed stress conditions at a constant temperature of 125° C. Various stress experiments were performed in order to analyze the gate voltage, duty cycle, and frequency dependence of the NBTI degradation behavior. Frequency measurements were performed in the range from DC to 1 MHz and "on" duty cycles in the range of 30% to 70% were used. Voltages were applied from -1.5 V up to -2.7 V to the gate of the transistor. The MOSFET parameters were monitored for a maximum stress time of 10^5s. The collected NBTI data were then used to calibrate the numerical simulations for the 90nm device.

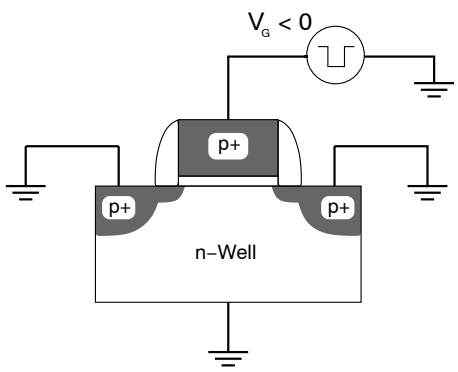

Fig. 1: Configuration for DC and pulsed NBTI stress.

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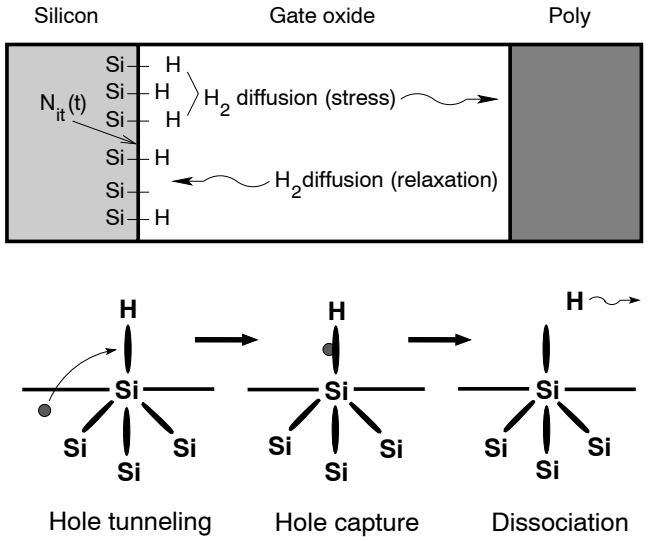

Fig. 2: Possible mechanism of breaking interfacial Si–H bonds by interaction with inversion-layer holes. The degradation is controlled by the forth-and-back motion of released hydrogen in the gate oxide.

REACTION-DIFFUSION MODEL

A reaction-diffusion (R-D) model was used for the simulation of NBTI degradation, because this model can predict static and dynamic NBTI data [8, 9]. Figure 2 shows a schematic description of the R-D model. A possible scenario for the generation of interface traps is that Si–H bonds break by interacting with holes at elevated temperatures. The upper sketch shows that released hydrogen diffuses into the gate oxide and returns back to the interface when the stress is removed [5]. In the R-D model the formation of interface traps is described by two coupled differential equations according to

$$\frac{\partial N_{it}(t)}{\partial t} = k_f\,[N_0 - N_{it}(t)] - k_r\,N_{it}(t)\,C_H(x{=}0,t) \quad (1)$$

$$\frac{\partial N_{it}(t)}{\partial t} = -D\,\frac{\partial C_H(x,t)}{\partial x}\Big|_{x=0} + \frac{\delta}{2}\frac{\partial C_H(x,t)}{\partial t} \quad (2)$$

Equation (1) states that the N_{it} generation is determined by a chemical hydrogen release reaction (const. dissociation rate k_f) and simultaneous self-annealing (rate k_r), when the p-MOSFET is biased in inversion. When the transistor is switched off, the forward rate k_f becomes zero and the reverse rate k_r stays unchanged. The parameter N_0 denotes the total Si–H bond density at the interface before stress. Equation (2) is obtained by integration of the standard diffusion equation across the silicon/oxide interface with a thickness δ. The diffusion coefficient D is the average diffusivity of the assumed atomic and molecular hydrogen diffusing species. Note that $N_{it}(t)$ is equal to the number of released hydrogen atoms at any given time t.

The discretization of the differential equations is based on a one-dimensional finite differences method. The simulation domain is the gate oxide with the boundary condition of a partially absorbing wall at the oxide/poly interface. The differential quotients are approximated using the spatial and temporal increments h and Δt. Grid points (x_i, t_j) with resolution $m = \frac{T_{ox}}{h}$ are used for an oxide thickness T_{ox}, and $x_i = ih$ for $i = 0, 1, \ldots, m$ and $t_j = j\Delta t$ for $j = 0, 1, \ldots$

We are solving for the next time step $(n+1)$ in order to calculate the hydrogen diffusion profile $C^j_{H,i} = C_H(x_i, t_j)$ and the interface trap concentration $N^j_{it} = N_{it}(t_j)$ at the next instant according to

$$C^{n+1}_{H,0} = C^n_{H,0} + \frac{2\Delta t\gamma^n}{\delta} + \frac{2\lambda h}{\delta}\left(C^n_{H,1} - C^n_{H,0}\right) \quad (3)$$

$$N^{n+1}_{it} = N^n_{it} + \gamma^n\,\Delta t \quad (4)$$

$$\gamma^n = k_f\,(N_0 - N^n_{it}) - k_r\,N^n_{it}\,C^n_{H,0} \quad (5)$$

$$\lambda = \frac{D\Delta t}{h^2} \quad (6)$$

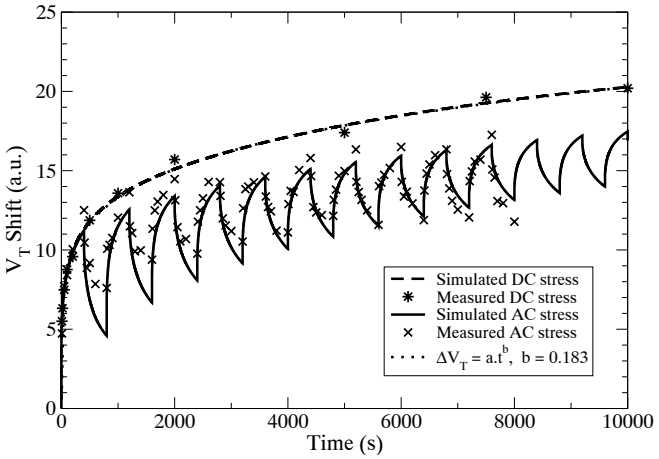

Fig. 3: The numerical solution of the R-D model is compared to NBTI data under DC and AC stress (stress: 400s, relaxation: 400s).

Figure 3 compares the numerical solution of the calibrated R-D model for DC and AC operation to experimental data of the investigated MOSFET. The V_T degradation under static and dynamic NBTI stress was simulated with the same model parameter set.

Chakravarthi et al. found that the atomic hydrogen model exhibits the typical power-law time dependence $V_T \propto t^{0.25}$ whereas the molecular hydrogen model predicts a time dependence of $t^{0.165}$ [4]. We found a time exponent of 0.183 for our measurement data, which supports that both atomic and molecular hydrogen is present. The hydrogen distribution in the oxide is calculated for every time step. The final simulation result is the defect density N_{it} and the corresponding shift $\Delta V_T \propto N_{it}$. The left diagram in Figure 4 shows four snapshots of hydrogen profiles $C_H(x, t_i)$ during the first stress phase. After 400s the transistor is switched off. The right diagram shows the corresponding profiles during relaxation. When relaxation starts the free hydrogen near the interface can now rapidly anneal broken Si–H bonds. The consumption

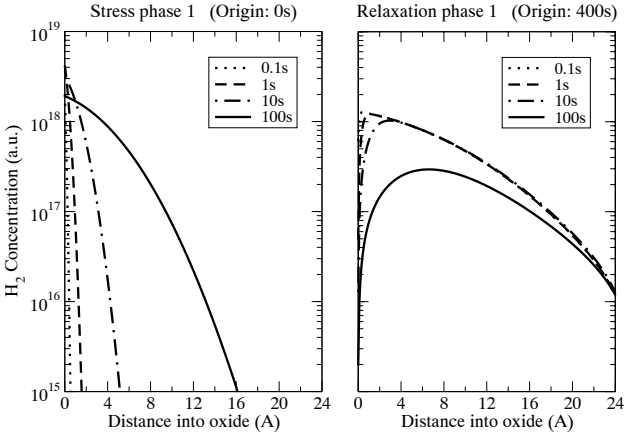

Fig. 4: Snapshots of hydrogen diffusion profiles in the gate oxide during the first stress-relaxation cycle.