8. NBTI TIME DEPENDENCE: STRESS PHASE

8.1 Review/Background

In the previous chapters, we have discussed the physical origin of bulk and interface defects, as well as the charging of these pre-existing defects. A careful and optimized process ensures low defect density, therefore, charging of pre-existing defects – while important – is not necessarily a reliability concern. During operation, the transistors are turned on and off millions of times at high electric field and relatively high operating temperature. As a result, new defects are created. When these newly created defects exceed a certain threshold, the transistor cannot function and the IC fails. We will explore the mechanics of defect creation in the rest of the book. Next four chapters will focus on negative bias temperature instability (NBTI) – a mechanism of interface defect generation, thereafter four more chapters will be devoted to bulk trap generation that leads to time-dependent dielectric breakdown (TDDB).

8.2 A PMOS transistor biased in inversion shows rapid degradation

Having understood the nature and properties of interface traps, and why hydrogen atoms are used at the Si-SiO$_2$ interface during fabrication, it is now possible to understand the phenomena called NBTI (Negative Bias Temperature Instability). It has been observed that the threshold voltage of PMOS transistors shift gradually with time after applying a gate stress. This trend is accelerated with increase in temperature. Even though the device does not break down abruptly, NBTI is responsible for what is known as parametric failure. Circuit designers assume a range of threshold voltage variation while designing the circuit. Over the period of its operation, the $V_{TH}$ PMOS transistor changes due to NBTI (Fig. 7.10), causing failure in circuit operation. It thus becomes necessary to predict NBTI degradation over the period of a few years, so that a warranty time period can be specified on a product.
8.2.1 **Observation 1: NBTI breaks Si-H bonds only in PMOS transistors**

The reason why this degradation is termed as “Negative Bias” because in CMOS circuits, when the PMOS transistors are switched off, the applied gate voltage is negative with respect to source and drain.

The first observation that has been made with regards to NBTI is that it occurs only in PMOS devices in inversion, which implies that this has something to do with holes. Also, NBTI
disappears for a buried-channel PMOS device (Fig. 7.11), where the inversion layer is not formed at the interface. This implies that NBTI is primarily an interface related issue. This fact is further confirmed by the fact that Electron Spin Resonance measurements of the Si-SiO$_2$ interface show signatures of Pb centers after stress, as can be seen in Fig. 7.12. This implies that Pb centers are generated during application of the gate stress in a PMOS device. These Pb centers arise from unsatisfied Si valences at the interface. However, before the stress is applied, for a passivated surface, there is no detectable signature of a Pb center.

Fig. 7.13 shows NBTI degradation for devices having slightly different process flows than the conventional. In one case, Deuterium is used instead of Hydrogen for passivation, and in the other case, SiO$_2$ is grown in dry oxygen environment instead of using a wet H$_2$O$_2$ mixture for oxidation. NBTI degradation for both these cases was found to be lower.

![Fig. 8.3](image)

Fig. 8.3 (left) Change in saturation drain current (equivalently, change in threshold voltage) over time due to NBTI for DC and AC stress pulses. (middle) The ratio of AC to DC degradation depends on duty cycle. (right) The temperature activation of NBTI degradation can be approximated as being Arrhenius.

All these observations lead to the conclusion that the NBTI degradation mechanism has something to do with holes near the Si-SiO$_2$ interface during PMOS inversion, and with the hydrogen used for passivating dangling Si bonds near the interface.

8.2.2 Observation 2: NBTI degrades transistor performance as a power-law
NBTI degradation occurs over a period of years under normal operating conditions, and it’s not possible to characterize the degradation parameters in the laboratory over this time period. What is often done is that the degradation is accelerated in time by increasing either the stress voltage or temperature or both. Then predictions are made on lifetimes based on normal operating voltage and temperature. However, in order to make a reliable prediction, the trends of temperature or voltage acceleration must be known accurately.

$\Delta V_{TH}$ v/s time for NBTI when plotted on a log-log plot is a straight line, as can be seen from Fig. 7.14, which means that $\Delta V_{TH}$ has a power-law dependence on time, i.e. $\Delta V_{TH} = At^n$. Also from the same figure we can see that frequency has almost no dependence on the degradation, a trend which has been experimentally seen to continue till 2 GHz. Also, it is important to note that the time exponent for AC and DC characteristics are very similar.

It has been observed that the broken Si bonds during NBTI process, recover with the passage of time unlike other degradation processes that saturate after a period of time. So NBTI is a self-annealing process. Approximately half of the interface traps may recover during this phase. We can hence observe a very strong dependence on the duty cycle. Empirically it has been found that the interface trap density (which causes NBTI) increases with duty cycle as follows:

$$N_{IT}(t) = KS^{3.6}t^{-6}$$

where $S$ is the duty cycle, and $K$ is a proportionality constant. Dependence of NBTI degradation on duty cycle can be seen from Fig. 7.15.

8.2.3 **Observation 3: NBTI degradation increases exponentially with temperature and electric field**

Temperature dependence of NBTI degradation can be modeled using an Arrhenius relationship with an activation energy $E_A$, which has a value close to 0.1eV. When plotted on a log scale with $1/T$ on the x-axis, the slope of the straight line gives the value of activation energy (Fig. 7.16).

$$\Delta V_{TH} = A_0 \exp\left(\frac{E_A}{KT}\right)t^n$$
NBTI has been observed to depend on the oxide electric field, and not the applied gate voltage. Even for different gate voltages, but for identical electric fields, the amount of degradation has been shown to be identical. Field dependence can be modeled as either having an exponential or a power-law relationship.

\[
\Delta V_{TH} = A \exp \left( \frac{E_A}{K T} \right) \exp \left( -\frac{E_A}{K T} t^n \right) \quad \Delta V_{TH} = \Lambda E^n \exp \left( -\frac{E_A}{K T} \right) t^n \quad 8.3
\]

The time exponent however remains the same irrespective of electric field or temperature. This makes it easy to do accelerated testing, and make reliability predictions for normal operating conditions.

Since NBTI depends upon the number of unbroken Si-H bonds at the interface, it is subject to statistical variations for small devices. As we reduce the size of the transistors, threshold voltage fluctuations between each transistor becomes so large that useful data becomes next to impossible to extract. However, it is observed that the average characteristics of a large number of small transistors behave very much like a large area transistor.

8.3 **Physics of NBTI degradation as a function of time**

In last class we have seen various signatures and experimental observations regarding the NBTI (Negative Bias Temperature Instability) degradation [1]. One of the prominent characteristics of the NBTI degradation is the robust power law which is stable for several orders of magnitude of stress time. Fig. 8.1 shows experimental results regarding the NBTI degradation and the power law for various applied gate bias or stress. We note that the power law in the $V_T$ shift is extremely stable with stress time for more than 6 orders of magnitude and this very unusual characteristic indicates that there is a fundamental physical basis which gives rise to this robust power law. In this class we will explore the physics of the NBTI degradation and will analytically derive the power law with stress time.
8.3.1 **NBTI degradation involves three components**

NBTI is a PMOS specific phenomenon. During inversion, holes in the channel can be captured by Si-H bond at a level slightly below the valence band of Si, as shown in the Fig. 8.2(a). The covalent Si-H bond now involves a single electron, with reduced energy barrier for dissociation, as shown in Fig. 8.2(b). The bond is further stretched and weakened by the applied gate voltage, so that eventually H atom may dissociate under thermal activation, leaving behind a dangling Si+ atom with energy state in the midgap. The just liberated H atom can now diffuse around, diamarize with other H. A fraction of the dissociated H atoms can diffuse back to the Si surface and again react with the Si+ atom to reform Si-H bond. We will see later that this re-passivation is very important to explain the power exponent observed in the NBTI degradation. The following chemical reaction summarizes the process

\[
\text{Si-H} + h^+ \rightarrow \text{Si-H}^+ \rightarrow \text{Si}^+ + H
\]

![Fig. 8.4](image)

**Fig. 8.4** (a) Energy levels of the intermediate particles involved in the NBTI degradation mechanism. (b) The energy barrier for the Si-H bond dissociation with the description of how the barrier gets lowered due to the gate bias or the hole capture. (c) The profile of H diffusing away from the Si/SiO2 interface.
8.3.2 **NBTI degradation can be described by a Reaction-Diffusion model**

Each dissociated H atom contributes an interface trap, the density of which is denoted by $N_{IT}$. The dynamics of the trap generation is described by the following reaction diffusion equation:

$$\frac{dN_{IT}}{dt} = k_F(N_0 - N_{IT}) - k_R N_H(0) N_{IT} \quad \text{Reaction} \quad 8.5$$

$$\frac{dN_H}{dt} = D_H \frac{d^2 N_H}{dx^2} + N_H \mu_H E + \frac{\delta}{2} \frac{dN_{IT}}{dt} \quad \text{Diffusion} \quad 8.6$$

where, $N_0$ is the total Si-H bond density at the interface, $N_H$ is the density of ‘free’ Hydrogen, $D_H$ and $\mu_H$ are the diffusion constant and the mobility, respectively, of the same. $E$ is the electric field and $\delta$ is the width of the small region near the interface where the bond-breaking reaction takes place. In all the analysis in this lecture, $x = 0$ denotes the Si-SiO$_2$ interface and positive x-direction directs towards the oxide as shown in **Fig. 8.4**.

The first term on the right hand side of Eq. 8.8 denotes the forward reaction (i.e. breaking of bonds to increase the trap density). Hence it has been set proportional to the density of the unbroken bonds ($N_0 - N_{IT}$). The second term denotes the reverse reaction (i.e. restoration of the bond) and has been set proportional to the trap density (broken bond density) and the available Hydrogen at the interface. Equation 8.9 is the continuity equation for the ‘free’ Hydrogen at the interface. The first term on the left hand side of this Eq. 8.9 denotes the generation rate of ‘free’ Hydrogen due to the bond-breaking and the term inside the parenthesis denotes the current of Hydrogen at the interface (**Fig. 8.4**). The difference of these two terms is proportional to the rate of increase of Hydrogen concentration at the interface, which is zero at steady state.

Another convenient form of eq. (8.2) is its integral form:

$$N_{IT}(t) = \int_0^f(t) N_H(x, t) dx \quad 8.7$$

where, the upper limit of the integration is a function of time and will parametrically depend on $D_H$ and $\mu_H$ for the case of diffusion and drift respectively. This equation merely states that the total amount of ‘free’ Hydrogen inside the oxide is equal to the trap density. The exact functional
form of \( f(t) \) will become clearer as we proceed further into the discussion. We will now consider the solution of the reaction diffusion equation under different condition.

### 8.3.3 Reaction diffusion models can be solved by elementary methods

We can neglect \( N_{IT} \) in comparison to \( N_0 \) in Eq. 8.5 and also neglect the second term on the right hand side of Eq. 8.8 as much of the bonds remain intact and not much ‘free’ Hydrogen is produced. With these approximations we get from Eq. 8.5:

\[
\frac{dN_{IT}}{dt} = k_FN_0 \rightarrow N_{IT}(t) = k_FN_0 t
\]

which is a power law variation with an exponent of 1.

After a small period of applied stress although the concentration of dissociated hydrogen atom, \( N_H(0) \), is small enough that diffusion is yet to start and we can neglect Eq. (8.2) assuming constant \( N_H(0) \) but the back reaction term in Eq. 8.5 becomes equal to the forward term and hence Eq. 8.8 Eq. (8.1) becomes:

\[
\frac{dN_{IT}}{dt} = 0 = k_FN_0 - k_RN_H(0)N_{IT} \Rightarrow N_{IT}(t) = \frac{k_FN_0}{k_RN_H(0)} t^0
\]

However, the duration of this regime of operation is very small and soon the diffusion of \( H \) becomes very important. Now, \( N_{IT} \) is not that small to be discarded in the way as we did before as considerable amount of bonds, by now, are broken and there is significant amount of ‘free’ Hydrogen at the interface. \( N_{IT} \) is still small compared to \( N_0 \) as in the previous case. But, unlike the previous case we cannot assume constant \( N_H(0) \) and we need to couple the diffusion equation with Eq. 8.5. Moreover, the net rate of increase of trap density becomes very small as the reverse reaction starts. We get, with all these assumptions, from Eq. 8.5:

\[
\frac{k_FN_0}{k_R} \approx N_{IT}(t)N_H(x = 0,t)
\]

We will now derive a relationship between \( N_{IT}(t) \) and \( N_H(x = 0,t) \) using Eq. (8.3). But before that we need to solve for the \( N_H(x,t) \) from Eq. 8.6 and we consider the following four cases to get the profile of \( N_H(x,t) \):
**Fig. 8.5** (a) ‘Free’ Hydrogen density dominated exclusively by diffusion. (b) Free Hydrogen profile dominated exclusively by drift.

**(A) Trap generation with Diffusion of Atomic H:**

Diffusion is the dominant process when the ‘free’ Hydrogen is not ionized. Assuming that there is not any kind of recombination of Hydrogen inside the oxide we get a linear profile of ‘free’ Hydrogen density inside the oxide as shown in Fig. 8.5. At any time \( t \) the profile extends to a distance of \( \sqrt{2D_H t} \). This is the functional form of \( f(t) \) in Eq. 8.7. Substituting this value of \( f(t) \) in Eq. 8.5 and considering a linear profile as shown in Fig. 8.5, we get:

\[
N_{IT} = \int_0^{\sqrt{2D_H t}} N_H(x,t)dx = \frac{1}{2} \sqrt{2D_H t} N_H(x = 0,t)
\]

Dividing Eq. 8.8 by Eq. 8.7, and then solving for \( N_{IT}(t) \) we get:

\[
N_{IT} \approx \frac{[k_F N_0]^{1/2}}{[k_R \sqrt{2}]} (D_H t)^{1/4} = At^{1/4}
\]

which is again a power law variation with a fractional exponent of 1/4.

**(B) Trap generation with charged H Diffusion:**

Drift becomes the dominant process when the Hydrogen is ionized (proton). In this case the Hydrogen density profile looks flat all the way up to the edge of the profile at \( x = \mu_H E_{ox} t \) (Fig. 8.5). So, the functional form of \( f(t) \) is \( \mu_H E_{ox} t \). Substituting it in eq. (8.3) and considering a flat profile as shown in Fig. 8.5 we get:
\[ N_{IT} = \int_0^{\mu H E_{ox} t} N_H(x, t) \, dx = \mu H E_{ox} t N_H(x = 0, t) \quad 8.13 \]

Dividing Eq. 8.13 by Eq. 8.10 and solving for \( N_{IT}(t) \) we get:

\[ N_{IT}(t) = \left[ \frac{k_F N_0 \mu_H E}{k_R} \right] t^{1/2} \quad 8.14 \]

which is a power law with a fractional exponent of 1/2.

**C) Trap generation with Diffusion of \( H_2 \):**

Since the \( H_2 \) molecules are charge neutral diffusion is the dominant process and the profile of \( N_{H_2}(x, t) \) is exactly similar as drawn for case A in Fig 8.4. So we get:

\[ N_{IT} = 2 \int_0^{\sqrt{2D_{Ht}}} N_{H_2}(x, t) \, dx = \frac{1}{2} \times 2 \sqrt{2D_{Ht}} N_{H_2}(x = 0. t) \quad 8.15 \]

The reason for multiplying the integral by 2 is that there are two Hydrogen atoms in a Hydrogen molecule and hence each H molecule is equivalent to 2 interface traps. We also need a relation between \( N_H(x, t) \) and \( N_{H_2}(x, t) \) using the law of mass action for the following reaction

\[ H + H \rightleftharpoons H_2 \quad \Rightarrow \quad \frac{N_{H_2}(x = 0, t)}{[N_H(x = 0, t)]^2} = k \quad 8.16 \]

Finally, from Eqs. 8.10, 8.15, 8.16, we get:

\[ N_{IT} \sim t^{1/6} \quad 8.17 \]

**D) Trap generation with Diffusion of \( H_2^+ \):**
Since the $H_2^+$ is charged molecule, hence drift is the dominant process. The concentration profile for $H_2^+$ is flat, same as in case (ii), with the edge of the profile given by at $x = \mu_{H_2^+}E_{ox}t$ So we get:

\[
N_{IT} = 2 \int_0^{\mu_{H_2^+}E_{ox}t} N_{H_2^+}(x,t)dx = 2 \mu_{H_2^+}E_{ox}t N_{H_2^+}(x = 0,t)
\]

8.18

The reason for multiplying the integral by 2 is that each H molecule is equivalent to 2 interface traps. We also need a relation between $N_H(x = 0,t)$ and $N_{H_2^+}(x = 0,t)$ from the law of mass action.

\[
H + H^+ \rightleftharpoons H_2^+ \quad \Rightarrow \quad \frac{N_{H_2^+}(x = 0,t)}{(N_H(x = 0,t))^2} = k
\]

8.19

Finally, from Eqs. 8.10,8.18, and 8.19, we get:

\[
N_{IT} \sim t^{1/3}
\]

8.20

![Image](Fig. 8.6) Interface trap generation with stress time for different models of Hydrogen diffusion.

The summary of interface trap generation in all the regimes of stress phase is shown in
Fig. 8.7, where we have also plotted the various cases of resulting power laws. The exact value of the slope depends on the underlying mechanism of Hydrogen flow inside oxide and the mechanism of reaction.

Fig. 8.7 Interface trap generation with stress time for different models of Hydrogen diffusion.

8.3.4 Discussion

A remarkable feature of the reaction-diffusion model is the prediction of power-law solution. Power-laws reflect scale invariance, i.e., the solution from t=1 to t=100, looks exactly the same as t=100 to t=10000, and I know of no other equation that produces the same feature. Spatially distributed Reaction-diffusion model has also been used with great success in explaining pattern formation in nature and how structures emerge out of random materials – apparently in violation of the second law (Prigiorine, Haken). The reaction-diffusion model we used is a special form where diffusion is distributed, but reaction is confined to the interface.

Reaction-diffusion model explains interface trap generation. In addition, trapping in pre-existing states (Chapter 7) and newly generated defects (Chapter XX), will contribute to threshold voltage shift. One must carefully deconvolve various contributions before comparing to experiments.

8.4 NBTI degradation is partially compensated by mobility improvement

The On-current of a transistor is given by

\[ I_D \sim C_{ox}\mu_{eff}(V_G - V_T) \]  

8.21
where $\mu_{eff}$ is the effective mobility and $V_T$ is the threshold voltage. Correspondingly, the normalized change in the drain-current as a function of time is given by

$$\frac{\Delta I_D}{I_{D,0}} = \frac{\Delta \mu_{eff}}{\mu_{eff,0}} - \frac{\Delta V_T}{V_G - V_{T,0}}$$

where subscript ‘0’ indicates pre-stress parameters (e.g. points A in Fig.8.7). We know $\Delta V_T(t) = q N_{IT}(t)/C_0$ increases with time, $E_{eff} (\propto (V_G - V_T(t)))$ decreases for a given $V_G$. Therefore, even though $\mu$ decreases with $N_{IT}$ at constant $E_{eff}$, as expected (point B in Fig. 8.8), the reduction in $E_{eff}$ increases the mobility to point C. Depending on the shape of the curve, the overall $\Delta \mu_{eff} = \mu_C - \mu_A$, can reduce, stay the same, or improve. For typical Si MOSFET operated at room temperature, the relative shallowness of the universal mobility curve requires that $\Delta \mu_{eff} < 0$, so that $I_D$ always decreases due to $V_T$ shift. However, for transistors with steeper mobility-field characteristics (Si-Ge strain transistors or transistors at lower temperature), the increase in mobility can perfectly cancel the increase in the threshold voltage – thereby, keeping the $I_D$ constant, independent of time. This is the key idea of the degradation free transistor [3].

![Fig. 8.8 Universal Mobility curve with and without interface trap.](image)

### 8.5 Conclusions:

NBTI degradation exhibits a robust power law with the stress time and the physical origin of this characteristic can be explained with the reaction diffusion model. Reaction diffusion model is a wide-ranging approach for many natural systems (like morphogenesis) which exhibits some kind of power law. In the particular case of NBTI the Si-H bond breaking is
the reaction part and the transport of the broken H atom is the diffusion part. Depending on the nature of the transport mechanism of the H atom or H molecule different time exponent emerges from the solution of the reaction diffusion equations, and these time exponents can be used to reverse understand the physical origin of NBTI degradation. Finally, the real concern with the NBTI degradation is the reduction in ON current due to the increase in threshold voltage. Interestingly, in some cases, the increase in $V_T$ due to NBTI degradation get compensated by the increase in the mobility (due to the reduction of effective electric field) and this makes a transistor free from consequences of NBTI degradation.

REFERENCES:


Question/Answer:

**Q. In case of un-passivated PMOS, why NBTI should be an issue?**

**Ans.** In case of unpassivated PMOS, there will be lots of trap to begin with, which implies $N_{it}=N_{t0}$, same as $t\rightarrow\infty$. 