30.0 Review

We have spent several weeks discussing NBTI and TDDB related reliability issues. Now for the next three/four classes, we will be discussing MOSFET degradation related to Hot Carrier Injection (HCI). In the last class we saw the basic physics of HCI. If we take a MOSFET which is switching, $V_G$ is changing while $V_D$ is held constant, there is a current flow through the channel. Near the drain junction, a precipitous voltage drop takes place and electrons get accelerated. This takes place in the corner, i.e., towards the drain end. So in the last class we saw a qualitative picture of the HC effect.

In this class, we will look at a possible hypothesis for way the time dependence is $t^{0.3}$ to $0.5$

30.1 Time Dependence

Stress Phase

The interface-trap generation rate for HCI can be written similarly to that of NBTI as a balance between dissociation and annealing rates of Si-H bonds

$$\frac{dN_{IT}}{dt} = k_f (N_0 - N_{IT}) - k_r N_{IT} N_H(0)$$

Generally $N_{IT}$ is small compared to $N_0$ and derivative of $N_{IT}$ w.r.t time is smaller compared to the fluxes on the right hand side (see discussion of NBTI time-exponents for details), so that

$$\frac{k_f N_0}{k_r} = N_{IT} N_H(0).$$

Fig.1 a) Co-ordinate System b) H-Diffusion profile in NBTI
For NBTI, we see that the diffusion was taking place in a right triangular prism fashion, while for HCl it is in conical fashion since it takes place only near the drain-end.

In HCl, Volume under the curve:

$$N_{it} = \frac{1}{3} \pi * (\sqrt{D_H t})^2 N_H(0)$$  \hspace{1cm} (1)

Also,

$$\frac{k_f N_o}{k_r} = N_{it} N_H(0)$$  \hspace{1cm} (2)

From equation, (1) and (2), we can write:

$$N_{it} = \sqrt{\frac{k_f}{k_r} N_o * \frac{1}{3} \pi (D_H t)}$$

So for ‘H’ diffusion, t exponent is 0.5. Remember that in the case of NBTI, we get the exponent as 0.5 only if diffusing species is positively charged (H\(^+\)).

When Hydrogen molecule (H\(_2\)) diffusion is assumed, the HCl time dependence can be found to be shown as:

$$N_{it} = \left(\frac{k_f}{k_r} N_o * \frac{1}{6} \pi \right)^{\frac{2}{3}} * (D_{H_2} t)^{\frac{1}{3}}$$

Here the time exponent is 1/3. In general therefore, we expect a time-exponent of n=1/3-1/2 for HCl degradation during the stress phase. This value of the exponent has been observed in wide variety of experiments involving NMOS transistors.
30.2 Relaxation

Degradation in HCI is larger than NBTI while the Recovery is smaller. This is due to the fact that in the case of HCI, the annealing involving passivating a broken Si-H bonds towards a 'point' of broken Si-H bonds. Now let us try to prove it mathematically.

In analogy to NBTI degradation, the amount of H annealing involves the inverted pyramid region in Fig. 3, so that

\[ N_{IT}^*(t+t_0) = \frac{\pi}{3} (\sqrt{\varepsilon D_H t})^2 N_H^* \]  
(3)

\[ N_{IT}(t+t_0) \sim \frac{\pi}{3} (\sqrt{\varepsilon D_H (t_0+t)})^2 N_H^* \]  
(4)

Also Fig. 4 allows us to write a conservation of total traps at time (t+t₀) equation:

\[ N_{IT}(t+t_0) + N_{IT}^*(t+t_0) = N_{IT}(t_0) \]  
(5)

Remaining Traps \quad Annealed Traps \quad Total Traps at the beginning of stress phase
From Eq. (3)-(4), we find

\[
\frac{N_{IT}^*(t + t_0)}{N_{IT}(t + t_0)} = \frac{\varepsilon t}{(t_0 + t)}
\]  

Substituting equation (6) in (5), we get:

\[
1 + \frac{\varepsilon t}{(t_0 + t)} = \frac{N_{IT}(t_0)}{N_{IT}(t + t_0)}
\]

\[
\frac{N_{IT}(t + t_0)}{N_{IT}(t_0)} = \frac{1}{1 + \frac{\varepsilon t}{(t_0 + t)}}
\]

For pin-hole diffusion \( e \sim (1/3 \text{ to } 1/2) \)

At \( t = t_0 \),

For \( e = 1/2 \),

\[
\frac{N_{IT}(2t_0)}{N_{IT}(t_0)} = \frac{1}{1 + \frac{1/2 t_0}{(t_0 + t_0)}} = \frac{4}{5}
\]

For \( e = 1/3 \),

\[
\frac{N_{IT}(2t_0)}{N_{IT}(t_0)} = \frac{1}{1 + \frac{1/3 t_0}{(t_0 + t_0)}} = \frac{6}{7}
\]

Remember that for NBTI,

\[
\frac{N_{IT}(2t_0)}{N_{IT}(t_0)} = \frac{2}{3}
\]

Hence we see that the recovery is slower in the case of HCl (because the H has to diffuse towards a point). Over a period of time, the frequency response with AC stress is:
30.3 Frequency Dependence

Just like NBTI, Hot carrier effect is also frequency independent.
A general property is:

If ,

\[ N_{IT} = A\cdot t^n \]

\[ \frac{N_{IT}(2t_o)}{N_{IT}(t_o)} = a \]

\[ R_2 = a\cdot R_1 \]

then, one can write the recursive relation as:

\[ R_{2k-1}^{1/2} = ak \]

\[ \frac{N_{IT,1}(T)}{N_{IT,2}(T)} = \frac{N_{IT}(k_1t_1)}{N_{IT}(k_2t_2)} = \left(\frac{k_1t_1}{k_2t_2}\right)^n = 1 \]

Here,

\[ N_{IT,1}(T) : N_{IT} \text{ generated for the total time } T \text{ with AC frequency } f_1 \]

\[ N_{IT,2}(T) : N_{IT} \text{ generated for the total time } T \text{ with AC frequency } f_2 \]

To sum up:

**HCl is a localized effect with higher diffusion slope but lower recovery compared to NBTI. However, both NBTI and HCl is frequency independent.**

So far we have talked about the time behavior of Hot carrier effect. Going ahead, we will now talk about the physics of \( k_f \). This will prepare us for the next lecture which will discuss the voltage dependence of HCl degradation during the stress phase.

30.4 and Physics of \( k_f \)

A good experiment involving usage of Deuterium instead of Hydrogen revealed the physics behind ‘\( k_f \)’

For the experiment, a Silicon wafer was taken and put in the high vacuum MBE chamber. People were predicting various properties of bare surface of Silicon and how it would be reconstructed once it is passivated with Hydrogen. The STM based experiments was supposed to probe the dynamics of surface reconstruction as H is absorbed or desorbed from the surface. However, when similar experiment involving Deuterium instead of Hydrogen was performed. It was found that the number of hydrogen produced per injected electron (called yield or Y in Fig. 5a) reduced significantly when deuterium was used. The reduction was of the order of 10-100 times.

This observation from STM experiments inspired a group from Illinois to propose replacing H by D for passivation of Si/SiO2 interface. Si-D would be more difficult to break at a given stress – they reasoned – and it would increase HCl lifetime. Indeed, this hypothesis was proven correct with a factor of 3-4 reduction in trap-generation rate with Si-D bonds and almost a factor of 20 increase in overall HCl lifetime.
Although the general hypothesis was proven correct, one might wonder why Fig. 5(a) and 5(b) has such significant differences in dissociation rates. The likely reason is that HCl in MOSFET breaks both Si-H and Si-O bonds. The amount of broken Si-O bonds ($N_O$) can be deduced from the following argument. The ratio of interface bonds created with Si-H and Si-D is given by (see Fig. 5b)

$$\frac{N_{IR}^H}{N_{IR}^D} = \frac{N_D + N_H}{N_O + N_D} = 4$$

From Fig. 5(a)

$$N_D \sim 0.1N_H,$$ so that

$$4N_O + 0.4N_H = N_O + N_H \quad \text{and} \quad N_H \sim 3N_O.$$

In other words, three-fourth of broken bonds are Si-H and therefore the dynamics of Si-H bond dissociation governs the time-exponent of HCl, as discussed in Sec. (30.1-30.3).

One could ask the reason why Si-D bonds are more difficult to break compared to Si-H bonds. Initially people thought that since D is heavier, a given force (HCl injection) can not displace it far from its equilibrium location (bonded to Si) and therefore bond dissociation is more difficult for D compared to H. More precise calculations later showed that the proper explanation is somewhat more subtle. It was realized that since Deuterium has higher mass compared to Hydrogen, the vibrational spectra is for Si-H and Si-D are somewhat different (see Fig. 6(a)). The vibrational frequency of Si-D bond happens to be far closer to frequency of the transverse optical (TO) mode of the bulk Si than that of the Si-H bond as shown in Fig 6(b). As a result, the vibrational mode of the Si-D is more strongly coupled to Si(TO) than that of the Si-H mode and thus the vibrational energy of the Si-D bond can flow/decay into the TO mode of bulk Si at a faster rate than that of Si-H bond. So cascading (which eventually leads to bond dissociation) in Si-H is much easier than that in Si-D since immediate relaxation takes place in the latter due to good coupling.
30.5 Conclusion

Today we saw the temporal dependence of Hot carrier effect. Also we noticed the frequency independence as we have previously seen in NBTI. Going ahead we will see the Electric field and Temperature dependence in the next two classes.