32.0 Review

So far, in this course we have discussed some of the major reliability concerns in Semiconductor devices. We have mainly discussed physics behind some of the device performance degradation mechanism leading to permanent or parametric failures. Today, in the last class of this course, we like to wrap up our discussions with a brief summary of what we have learned so far. Then, we conclude this course mentioning a couple of general controversies in this field. This will be of great help to involve people and engage to meaningful discussion with the experts of semiconductor reliability.

32.1 Summary of reliability issues

There are two basic aspects of reliability: (a) the forces you apply and average behavior of the system in response to that force; and (b) statistics of failure distribution. Statistics brings the key difference to reliability phenomena from purely Physics based analysis, which is centered to mean behavior. At the beginning we talked about the ‘Fish in the River with Waterfall (FRWF)’ problem in details. We have seen that how the water velocity affects the distribution and statistics (Poisson). This simple example helped us to see many common but important aspects of reliability. The forcing function, time dependence and the statistics governing the mechanism for several reliability issues are summarized in Table. 1. This table also includes key measurement techniques to use to explore these phenomena, as discussed in previous lectures.

<table>
<thead>
<tr>
<th>Time function</th>
<th>Force</th>
<th>Temp.</th>
<th>Statistics</th>
<th>Measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>FRWF</td>
<td>-</td>
<td>Velocity ($v$)</td>
<td>-</td>
<td>covered</td>
</tr>
<tr>
<td>NBTI</td>
<td>Time ($t^{0.6}$)</td>
<td>Voltage, $\xi$</td>
<td>Temp</td>
<td>Poisson</td>
</tr>
<tr>
<td>TDDB</td>
<td>Thick: Log(t), thin: $t^{0.5-0.7}$</td>
<td>$V_g$</td>
<td>T (today)</td>
<td>Weibull</td>
</tr>
<tr>
<td>HCI</td>
<td>$t^{0.3-0.5}$</td>
<td>$\xi$</td>
<td>T (today)</td>
<td>Poisson (Today)</td>
</tr>
</tbody>
</table>

In this class we quickly discuss a few things about statistics, temperature dependence, and measurement issues of HCI events before moving onto more general discussion.

32.2 Statistics, Measurement, and Temperature Dependence

32.2.1 HCI Statistics

As shown in Figure 31.1, due similar geometry of active region of HCI with that of NBTI, at they follow same statistics (Table 1). The statistics of NBTI has already been discussed in great detail in Lecture 13 – one can use the same results. Remember that NBTI/HCI...
statistics differs from TDDB statistics which is governed by Weibull statistics, due to localized breakdown of gate oxide (See Lecture 22).

32.2.2. HCl Measurement

It is worth noting that, in NBTI relaxation caused a great problem in measurement. However, in HCl the relaxation is very limited due to its inverted cone property (previous class). Hence the HCl measurement is less complicated than that of NBTI effects. However, HCl involves both SiO and SiH bonds – therefore both classes of the measurement techniques (SiH in NBTI and SiO in TDDB) are useful to study HCl degradation. We have already discussed the physics of these measurement techniques in earlier lectures.

![Fig 31.1 Active area of HCl; pinch-off region](image)

32.2.3 Temperature-Dependence of HCl, NBTI, and TDDB Degradation

A. Arrhenius vs. non-Arrhenius Activation

NBTI has the following relationship for interface trap-generation:

\[ N_{IT} = \left( \frac{k_f N_0}{k_i} \right)^{1/2} \left( D_H t \right)^n \text{ where } (D_H = D_0 \exp^{-E_0/kT}) \]  

(1)

where, \( E_D \) is the Hydrogen hopping energy, \( D_H \) is short of trapping depth for hydrogen. This expression of \( D_H \), with a constant \( (D_0) \) followed by an exponential is called Arrhenius relationship. Note that, NBTI is a phenomenon that is closest to Arrhenius but not exactly. Others like TDDB is not at all Arrhenius at all, as shown below

\[ T_{BD} = \frac{N_{BD}}{k_f \alpha T_h} \neq \exp^{+E_0/kT} \exp^{-\beta T} = T^{-1} \exp^{+E_0/kT} \]  

(2)

where, \( N_{BD} \) is the number of defects needed for breakdown (calculated from percolation theory), \( \alpha \) is the impact ionization coefficient, \( T_h \) is tunneling rates for hot holes. Empirically it is known that \( T_{BD} \) has \( \exp(-\beta T) \) dependence rather than the Arrhenius like \( \sim \exp(E_0/kT) \) dependence. A better insight can be obtained if we individually analyzed various terms of \( T_{BD} \) in eqn. (2). Neither \( N_{BD}, k, J_e \) nor \( T_h \) have Arrhenius temperature dependence, therefore overall TBD could not be described by Arrhenius activation. More
specifically you may remember that in the last class we derived an expression of $\alpha$ based on the hot-electron theory to find that

$$\alpha = \alpha_0 \exp^{\frac{-\Phi}{e m_E}} \text{ where } \lambda_E = k_B \tau_e$$  \hspace{1cm} (3)

Such that temperature dependence of $\alpha$ reflected the temperature dependence of energy relaxation rates and was not related to any Arrhenius activated transport problem.

Hot carrier effect also results from a set of similar properties, like electron heating, impact ionization, hole injection. None of these effects are activation based. Hence the overall HCI effect can’t be Arrhenius type to the 0$^{th}$ order.

In reliability analysis, usually the overall degradation from all the effects, NBTI, TDDB, HCI are considered together. Contrary to common belief this is not exactly Arrhenius type. If total degradation obeys Arrhenius relation, then at different temperature the degradation plots should have been parallel. However, based on very careful measurement data, obtained over one year of experiments, shows that the degradation curves at different temperature are not parallel (Fig. 31.2) as predicted by the eqn. (4). 

$$D = D_o \exp^{\frac{E}{kT}} \Rightarrow \ln(D) = -\frac{C}{kT} + \ln D_o$$  \hspace{1cm} (4)

where D stands for a particular degradation mechanism.

**B. Arrhenius (1896) vs. Eyring model**

After the discovery and development of Quantum mechanics (QM), lots of older concepts were generalized and modified. For example, the Boltzmann distribution was found to be an approximation of Bose-Einstein or Fermi-Dirac distribution at higher temperature. Similarly, a generalization of Arrhenius model – called a Eyring model -- was also formulated from quantum mechanics principles. Eyring used Transition Rate theory to modify Arrhenius equation to describe the temperature dependence of any reaction rate. Using Eyring equation, eqn. (1) can be expressed as:

$$D_H = \left(\frac{k_B T}{h}\right) \exp^{\frac{E_H}{kT}}$$  \hspace{1cm} (5)
where, $k_B$ is the Boltzmann const. and $h$ is the Plank’s constant. This formula can be also arrived from other approaches like a dimensional analysis. Note the pre-factor is a linear function is a temperature rather than independent of it. In general, the temperature dependence of the pre-factor can easily be incorporated as an effective (weak) temperature dependence of Arrhenius activation, Eyring equation is seldom used in Electrical engineering and is much more broadly used in Chemistry and other disciplines. Indeed, the use of proper Eyring-like formula sometime can help resolve pedagogical issues in various contexts (e.g. Black’s formula in Electro-migration: Arrhenius theory predicts an extra $T^2$ pre-factor in the lifetime formula which is not observed in experiments).

### 32.3 General Controversies in Reliability Engineering

In any reliability conference or literature, you might find a somewhat different reasoning and explanation for existing phenomena as discussed in the class. In order to better appreciate the difference mechanism and underlying physics knowledge of alternative camps are essential. Broadly speaking, there are only two such controversies.

#### 31.3.1. $N_{IT}$, $N_{OT}$, vs. trapped charge in MOSFET in HCI and NBTI

Threshold voltage shift during device operation can be attributed to interface traps and trapped charges:

$$\Delta V_{th} = \frac{qN_{IT}}{C_{ox}} + \frac{Q_I}{C_{ox}}$$  \hspace{1cm} (6)

where, first term is based on Reaction-Diffusion (R-D) theory of interface traps. The second term is due to presence of trapped holes in the surface region of the channel.

For HCI, there was a debate about which term dominates the overall degradation effect until 1994 or so. The literature from that time is sometime confusing because film qualities in all the studies could not be assured and with poor Si film quality, 2nd term may dominate the overall $V_{th}$ deterioration. Till 1994, many people in industry believed that trapped holes are the dominant source of degradation, not the interface-traps. Discovery of SiH and SiD bond settles this debate in favor of hot-carrier induced interface traps. A trapped hole can’t distinguish between a H$_2$ or D$_2$ should produce same degradation. But in practice D$_2$ gives a better life time with less degradation effect as discussed in previous lecture (lecture 30).

A similar debate exists in NBTI: It’s almost settled to what we more or less discussed in the class. People still argue that trapped hole component should be added to $V_{th}$ deterioration model. Though hole trapping could be dominant for (very high) nitrogen-rich films, at higher voltages, and lower temperature, in general however interface trap seems to dictate NBTI degradation. We expect to reach a conclusion of this debate in years to come.
32.4.2 On TDDB: Battle of ‘big H’ (Hydrogen atom) versus ‘small h’ (Hole)

This is also known as Anode hole injection vs. Anode Hydrogen release debate. Fig. 32.3 shows the two alternative mechanisms for TDDB physics.

![Diagram of Anode hole injection vs. Anode hole release](image)

Both the process undoubtedly occurs but people are not sure about which mechanism dominates at smaller voltages at about 1V. You have electron current ($J_e$) common in both cases. Then you have impact ionization followed by hole injection breaking the SiO bonds in one path. Hydrogen excitation and Hydrogen diffusion based SiO bond breaking is predicted in the other mechanism. The minute amount of hydrogen/hole generation at such low voltage makes the Monte-Carlo based predictions extremely difficult. So absence of a proof keeps this debate still alive. In practice, however, none of the predictions of AHI has ever been proven wrong and the oxides continue to be reliable as predicted by the AHI theory – therefore the debate is somewhat pedagogical and academic.

32.5 General Comments

Role of mathematical model in reliability physics

In this course, I have relied heavily on mathematical models to quantify the physics of reliability of semiconductor devices. If you ever go to a reliability conference, you will see an emphasis on empirical models, rather than systematic mathematical model as discussed in this course. (although the situation is gradually changing) I believe that mathematical models provide a level of consistency in the analysis and prediction based on observed phenomena and limited experimental data. It provides a framework to think about the consequences of any theoretical hypothesis. Table 32.2 presents a few example of such if-then logical extension of a number of hypothesis discussed in the class.

<table>
<thead>
<tr>
<th>If</th>
<th>Then</th>
</tr>
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<tbody>
<tr>
<td>NBTI: $t^{1/6}$</td>
<td>HCl: $t^{1/3} - t^{1/2}$</td>
</tr>
<tr>
<td>TDDB: Polarity Asymmetry</td>
<td>$T_{BD,PMOS} &lt; T_{BD,NMOS}$ (degradation over a fixed time interval)</td>
</tr>
<tr>
<td>NBTI: Relaxation</td>
<td>Frequency independence</td>
</tr>
</tbody>
</table>

Why does theory works at all?

Although the question may sound a little odd at the beginning, a little thought shows that the answer is not so obvious. The reliability phenomena are often catastrophic in nature.
At current technology a MOSFET undergoes about 10 MV/cm stress in the gate oxide (1 V across 1nm gate oxide), probably a 1000 times larger than the electric-field induced in the high-voltage power-lines. They, even after billion of operations per second, survive over years to provide correct functionality. How can one provide a theory of such a complex and highly nonlinear phenomena? Shouldn’t we be surprised that our theory predicts anything remotely resembling reality?

I believe that the reason our theories are so successful is because there is a remarkable difference between the 0- and 0+ time w.r.t. the breakdown event. Figure 32.4 shows the nature of gate current for a MOSFET over a long period of time. The current suddenly increase due to some catastrophic phenomenon in the gate oxide. Just before this event (time 0-) however, we still can apply the convention current-voltage relationship device physics concepts. But immediately after the breakdown (time 0+) all this law ceases to hold, since the material has dramatically changed during the breakdown. Since, at 0-instance we are approaching the problem from a quasi-equilibrium point where physical laws still hold general.

**Contacts vs. reliability**

From a pedagogical point of view, the role of contacts and the role of reliability in semiconductor devices have many parallels. In physics experiments, contact are always unwanted entities and hence, there effects are carefully avoided. However, electrical engineers can not approximate contacts away without losing device function and performance. Similarly for reliability, physicist can get away without dealing with hot carrier etc. effects by applying a small voltage stress. An electrical engineer, however, must study these phenomena as is in details to predict the life time of the designed product. So, both contacts and reliability are practical engineering aspects which an engineer can’t avoid. It really does not matter if reliability theories are elegant or not (it
often is as you have seen in last few weeks), the important issue is that the theory is practical, useful, and predictive.

32.6 Conclusion
In this course, we have discussed some of the major reliability concerns (like NBTI, TDDB, HCI) in Semiconductor devices. We have discussed the physics behind some of the device breakdown mechanism leading to permanent failures. As we mentioned in the first class, that reliability is a very broad inter-disciplinary area of study. If understood properly, this knowledge can be effectively applied to analyze reliability concerns in areas other than semiconductors.