19.1 Review

In the last class we discussed the characteristics of Time Dependent Dielectric Breakdown (TDDB). We saw that at initial times, the gate-current characteristic is dominated by the impact ionization of carriers (constant current) which is then followed by the log-time dependence. This log(t) dependence arises due to the kinetics of charge trapping in the oxide and is the topic of today’s discussion. The models we discuss here are (1) Ning’s Capture dispersion model, (2) Inhibition model, and (3) Traveling Front model.

19.2 Defects in SiO\(_2\)

In order to discuss the trapping kinetics, we need to know the types of traps in oxides that are likely to capture electrons/holes. Consider, for example, the SiO\(_2\) gate oxide: SiO\(_2\) molecule within the dielectric is tetrahedral in shape and in a crystal where every Si atom is surrounded by four Oxygen atoms and every O atom is linked to two Si atoms, shown schematically as

![SiO2 molecule](image)

The defects in SiO\(_2\) are classified as

1. **Over/Under co-ordination**: This occurs when the total number of O atoms surrounding a Si atom is different from 4. When an O atom is missing from its
lattice position, the corresponding Si atoms form a ‘bridge’ between themselves creating enormous strain (termed as O vacancy). Another example is the undercoordinated bond Si\(_{(3)}\)-O\(_{(3)}\).

(2) Broken bond between Si atoms results in a situation Si-Si\(^+\) (known as Oxygen vacancy).

These defects act as charge trapping sites and can result in threshold voltage variations over device lifetime. Most of these trap levels are distinguished by Electron Spin resonance. We now discuss the kinetics of charge trapping in these defect states.

### 19.3 Inhibition model

The trapping kinetics is described by a first order reaction

\[
\frac{dn}{dt} = k(N_0 - n)\frac{J}{q}\sigma
\]

where \( n \) is the number of occupied traps, \( N_0 \) is the total number of available traps\((\sim 10^{11}/\text{cm}^3)\), \( J \) is the carrier flux and \( \sigma \) is the capture cross-section. This model arises from the fact that traps are independent from each other and capture of a single carrier will inactivate only the corresponding trap and the rest are unaffected. But due to electrostatic considerations, a carrier which has been trapped inhibits other traps in the vicinity (proximity effect). Let \( h \) denote the characteristic radius (\( \sim \) few nanometers) of this exclusion volume and \( V \) the total volume of SiO\(_2\) material. Then a single capture reduces the available traps by a factor \((1-h/V)\). Assuming the trapping events are uncorrelated from each other, the rate of reaction for charge trapping can be modified as

\[
\frac{dn}{dt} = k(N_0 - n)\frac{J}{q}\sigma\left(1 - \frac{h}{V}\right)^n
\]

For small \( n \), the equation can be re-written as

\[
\left(1 - \frac{h}{V}\right)^n = 1 - \frac{nh}{V} \quad \text{and} \quad 1 - \frac{nh}{V} = e^{-nh/V}
\]
If we assume that the number of trapped charges are far fewer than the number of available sites (i.e. $N_0 \gg n$), the solution of equation (3) is

$$\frac{dn}{dt} = k(N_0 - n)\frac{J}{q}0^{\sigma}e^{-\frac{nh}{V}}$$

(3)

where

$$e^{\frac{nh}{V}} = k^* t + c$$

(4)

and hence

$$n = \frac{V}{h} \ln(\left(k^*(t + t_0)\right))$$

(5)

Thus traps generated vary logarithmically on time after the initial transient ($t \gg t_0$). As a result of this time-dependent trapping kinetics, the threshold voltage variation due to charge trapping would also show a logarithmic dependence on time, i.e.,

$$\Delta V(t) = \int x n(x,t) dx$$

(6)

where $x$ denotes the position co-ordinate.

The inhibition model anticipates the log dependence of threshold voltage accurately. It is instructive to note that this model is widely used to study the kinetics of protein adsorption and in CVD processes where the sheer size of one species prevents the occupation of nearby sites by other species. Although it was successful, the fact that traps in SiO$_2$ are rather sparsely distributed made the argument of one trapping event inhibiting the neighboring traps less convincing. We will now see how the traveling front model describes the trapping kinetics.

### 19.4 Traveling Front Model

Unlike the Inhibition model, here we consider spatial dependence the trapping process in a dielectric explicitly. At initial time, traps which are close to the interface gets filled first
and the subsequent hopping transport or tunneling results in carrier capture at far away traps. So the entire process is equivalent to a traveling wave front of carriers moving across SiO$_2$ dielectric and getting trapped (Fig.1 and 2).

![Carrier flux and Oxide](image1)

![Space Time Traps](image2)

**Fig 1.** The first figure shows the energy band diagram with carrier injection from the left. The figure on the right shows the spatial occupation of traps as a function of time. Traps close to interface are filled first followed by the distant ones. It is like a fixed charge moving away from Gate-oxide interface.

**Fig.2.** Number of filled traps as a function of space and time. The kinetics is similar to a wave front moving in time across the dielectric.
The first order reaction dictating the trapping kinetics can be modified as (see Eq. 3)

\[
\frac{dn}{dt} = k\sigma_0 \frac{J_0}{q} \left( N_0 - n \right) e^{-\frac{x}{x_0}}
\]

(7)

where \( x \) is the distance from the Gate-oxide interface and \( x_0 \) signifies the characteristic distance due to tunneling, \( J_0 \) = Current at \( x=0 \). The rate of trapping should equal the current into the traps at \( x = 0 \). i.e.,

\[
\frac{dn}{dt} = a(x)(N_0 - n)
\]

(8)

\[ n = N_0 \left( 1 - e^{-at} \right) \]

(9)

Re-arranging to find the first characteristic time

\[ 1 - \frac{n}{N_0} = e^{-at} = \frac{1}{e} \]

\[ 1 = a(x^*) t^* \]

(10)

(11)

Substituting for \( a(x) \), we get

\[ 1 = k\sigma_0 \frac{J}{q} e^{\frac{-x}{x_0}} t^* \]

(12)

\[ x = \ln(t) \]

(13)

\[ x^* = x_0 \ln \left( k\sigma_0 \frac{J_0}{q} t^* \right) \]

Inserting the above equation in (6) shows that threshold voltage degradation has log time dependence.

This completes are discussion of three stages of breakdown (i.e., initial constant current phase, log-time dependent phase, and thermal runaway phase) in thick oxides. Now we consider the physics of thin oxides, which has very similar phases of degradation, but
very different physical principles governing them. We will get started today, but really discuss the details of the theory in next two classes.

19.5 Anode Hole Injection Theory

The inhibition and traveling front models successfully explained the log time dependence of device degradation of the thick oxide devices. As scaling progressed, along with the reduction of supply voltage to 5V, it became increasingly difficult to justify impact ionization within the oxide itself (E_g ~ 8-9 eV) and subsequent creation of traps by these energetic carriers. Anode Hole Injection model, proposed by Prof. Chenming Hu, explained the dielectric breakdown in thin oxide devices. According to this model, carriers injected from the gate undergo negligible energy loss as they travel through oxide and on reaching the substrate these high energy electrons cause impact ionization producing hot holes. The hot holes, which move into the gate, create defects in the oxide. It is interesting to note that researchers were aware of loss less transport (ballistic) through materials even before nanoscale devices started appearing. The term Anode Hole Injection (AHI) arises from old cathode tube terminology. Cathode emits the particles and anode collects them. In this case gate emits electrons and substrate collects them and the degradation (defect generation in the oxide) is due to the holes created at the anode (substrate). The schematic shown below illustrates the model.
The amount of defects created depends on the hot hole flux and is given by

\[ J_h = J_e \alpha T_h \]

where \( J_h \) denotes the hole flux, \( J_e \) denotes the electron flux (from gate), \( \alpha \) denotes the impact ionization factor (~1-2) and \( T_h \) denotes the hole transmission probability. We will discuss each of these factors in detail in the next few lectures.

### 19.6 Summary

In this lecture we discussed the origin of log time dependence of dielectric break down in thick oxides. Both the inhibition model and the traveling front model explain this behavior, although the latter is more acceptable in terms physical arguments regarding the trap density in SiO₂. We then started the discussion on Anode Hole Injection theory and will continue with the same topic in the next lecture.