14.1 Review/Background

In the previous lectures various features of NBTI, such as time, temperature and field dependence were discussed along with their physical models. In this lecture we will focus on the electrical measurement of the interface traps, namely, the generation of broken silicon-hydrogen bonds.

In order to investigate the interface trap density, one can look for the following signatures of the silicon-hydrogen bonds:

1. Silicon-oxide interface charges through Poisson’s equation.
2. The drain-source current flux and fluctuation which are related to the interface traps states and hopping electrons.
3. The electron spin associated with broken Si-H bonds, whose signature can be found in the recombination current (in the presence of magnetic fields).

![Figure 1. Si-SiO2 interface and energy-band diagram of the interface Si-H bonds](image)

The top part of Figure 1 illustrates the silicon-oxide interface under the gate area (top view in real space). The silicon-hydrogen bonds are oriented at different directions across the interface, resulting in multiple trap states in the band diagram (bottom part of Fig. 1). Since the Si-H bonds are also at different locations along the interface, each trap state can be described as a quantity by position average of those with similar bond orientation. The electrons cannot hop from one state to another as one might
expect, due to different physical location of the states.

14.2 Electrostatic Signature of Interface Traps (Poisson Equation)

14.2.1 Sub-threshold Slope Method

The subthreshold source-drain current of a MOSFET can be written as:

\[ I_D = [I_0 \exp(qV_G / mkT)] \cdot [1 - \exp(-qV_D / kT)] \quad (1) \]

Where the first bracket describes the junction forward current at the source and the parameter \( m \) is defined as \( V_G \) over the surface potential \( \phi_s \), namely, \( m = V_G / \phi_s \). The second bracket in this case is very close to unity since \( qV_D \) is several times the magnitude of \( kT \), and the total current \( I_D \) become independent of \( V_D \). In order to find the relation between \( I_D \) and the trap density \( N_I \), we proceed as follows:

Define sub-threshold swing \( S \) as the gate voltage swing required to change the drain current by one decade. Assume we have \( V_{G1} \) and \( V_{G2} \) which satisfy \( I_D = I_0 \exp(qV_{G1} / mkT) \) and \( 10I_D = I_0 \exp(qV_{G2} / mkT) \). Taking log of both sides:

\[ \ln I_D = \ln I_0 + qV_{G1} / mkT \quad \text{and} \quad \ln 10 + \ln I_D = \ln I_0 + qV_{G2} / mkT, \]

so that we have

\[ V_{G2} - V_{G1} = \ln 10(mkT / q) = \delta V_G = S ; \quad S = \ln 10 \cdot dV_G / d(ln I_D) = 2.3 \frac{mkT}{q}. \]

Previously we have defined that \( m = V_G / \phi_s \), which is related to the interface trap density by

\[ m = 1 + \frac{C_B + C_{it}}{C_{ox}} = 1 + \frac{C_B + q \cdot N_I}{C_{ox}}, \]

where \( C_{ox} \) is the oxide capacitance and \( C_B \) the depletion-layer capacitance. \( C_{it} \) stands for the capacitance from interface traps and can be expressed as \( q \cdot N_I \), where \( N_I \) is the interface trap density. The equivalent circuit for the MOS structure described is illustrated in Fig. 2.

Figure 2. MOS equivalent circuit
Now with the above relation, we can rewrite

$$S = 2.3 \frac{mkT}{q} = 2.3 \frac{kT}{q} \left(1 + \frac{C_u + C_{ul}}{C_{ox}}\right).$$

And the change in sub-threshold swing (due to change in interface trap density) is $\delta S = 2.3 \frac{kT}{q} \frac{\delta N_{\text{tr}}}{C_{\text{ox}}}$, assuming the depletion-layer capacitance is constant. From I-V measurement’s perspective, the change in sub-threshold swing can be illustrated below (Fig. 3):

During the $V_g$-$I_d$ measurement, the sub-threshold $S$ is changing with the gate bias when interface traps are present. Each time the Fermi-level on the semiconductor side crosses one trap state, $V_T$ shifts by one quanta, and the accumulated value of this shift is reflected in the subthreshold parameter $S$, as shown in figure 3.

If we monitor the degradation of the interface trap density after certain stress time, we can expect a liner relation between the change in sub-threshold swing $\log(\delta S)$ and the log of stress time $\ln t$. The longer the MOSFET is stressed, the more silicon-hydrogen bonds get broken and results in higher interface trap density, hence increasing $\delta S$.

Although a straightforward physics concept, the phenomenon observed in the measurement of $\delta S$ is actually more complex. Due to the relaxation of NBTI or the recovery of the Si-H bonds during the stress-off period (when low gate voltage
sub-threshold slope is being measured), the device is subject to alternate stress-relax cycles shows less NBTI degradation than the one that’s under constant stress. For the sub-threshold swing $S$ method, the device is alternating between stress and measurement (relax/recovery) phases and the Si-H bonds are allowed to recover under certain part of the measurement period, as illustrated in the following figure (Fig. 4). This results in a higher interface trap degradation rate from the measured $\delta S$.

![Figure 4. NBTI Relaxation in Sub-threshold method.](image)

### 14.2.2 Linear Drain-Current ($I_D,\text{LIN}$) Method

In order to avoid the relaxation inherent in Subthreshold Slope method, one can measure the device in the linear $I_D$ region with constant $V_G$. Since

$$I_{D,\text{linear}} = \frac{C_{ox} W}{L} \mu (V_G - V_T) V_D,$$

taking log gives

$$\ln(I_{D,\text{linear}}) = \ln\left(\frac{C_{ox} W}{L}\right) + \ln \mu + \ln(V_G - V_T) + \ln V_D$$

and again by taking derivative on both sides, we have

$$\frac{\delta I_{D,\text{linear}}}{I_{D,\text{linear}}} = \frac{\delta \mu}{\mu} \frac{\delta V_T}{V_G - V_T}.$$

The term $\frac{\delta \mu}{\mu}$ is the mobility degradation due to charge scattering by interface traps.

The mobility fluctuation can be determined by the following relation:

$$\frac{\delta \mu}{\mu_0} = \sqrt{Gm_0 - 1},$$
where $Gm$ is the trans-conductance of the transistor, i.e., $Gm = \frac{dI_D}{dV_G}$.

The expression $\mu_0 = \sqrt{\frac{Gm}{Gm_0}} - 1$ can be derived as follows: Under high E-field, the electron mobility can be expressed as

$$\mu = \frac{\mu_0}{1 + \theta(V_G - V_T)} ,$$

where $\theta$ is proportionality constant. One can replace the mobility term in the $I_{D,linear}$ $V_G$ equation and compute the trans-conductance $Gm$:

$$Gm = \frac{dI_{D,linear}}{dV_G}$$

$$= \frac{d}{dV_G} \left[ \frac{C_{ox} W}{L} \mu(V_G - V_T) \cdot V_D \right]$$

$$= \frac{d}{dV_G} \left[ \frac{C_{ox} W}{L} \frac{\mu_0}{1 + \theta(V_G - V_T)} \cdot V_D \right]$$

$$\propto \frac{\mu^2}{\mu_0}$$

Therefore, $\mu \propto \sqrt{Gm}$ and one concludes $\frac{\delta \mu}{\mu_0} = \frac{\mu - \mu_0}{\mu_0} = \frac{\mu}{\mu_0} - 1 = \frac{Gm}{Gm_0} - 1$.

By measuring both the mobility fluctuation (via trans-conductance) and $\delta I_D$, one can obtain the shift in threshold voltage $\delta V_T$ and deduce the interface trap density. The following figure illustrates this process through linear $V_g$-Id measurement. (Fig. 5)

![Fig. 5: NIT measurement by Idlin method. Discrete pulses are imposed on gate bias during stress to measure the trans-conductance $Gm = \frac{dI_D}{dV_G}$ and the mobility fluctuation $\delta \mu$. The negative slope of $I_D$ versus time is due to rising $V_T$ caused by the increase of interface trap density.](image)
As a result, the linear Vg-Id measurement with discrete pulses yields more reliable data on interface traps regarding the NBTI phenomenon. The sub-threshold method results in $t^{1/4}$ for the power law, while the linear Vg-Id method provides a better estimate of $t^{1/6}$. Notice in the following figure (Fig. 6) that the slope from the sub-threshold method ($1/4$) will approach asymptotically to that of the linear Vg-Id method ($1/6$) as time goes to infinity.

![Figure 6. Comparison of two NBTI measurements](image)

**14.3 Conclusion:**

We have discussed two methods of measurement of broken Si-H bonds. Although both methods provide estimates of interface traps, there are important limitations: The Subthreshold method detects donor traps, but the technique can not distinguish between SiH and SiO bonds (at the interface). And they suffer from ‘relaxation artifacts’ during measurements, as discussed in Sec. 14.2.1. On the other hand, while the Idlin method is not contaminated by ‘Relaxation artifacts’, the method is incapable of distinguishing between interface traps and bulk traps (both affect $V_T$). In the next two classes, we will talk about three other methods. Only in combination, they provide an accurate picture of the mechanics of interface trap generation during NBTI degradation.

**Supplemental Information (Units of CIT)**

In the literature, you will find expressions like $C_{IT}=qN_{IT}$, $qD_{IT}$, and $q^2D_{IT}$. They are
confusing, but when used correctly with proper dimensions, all of them give the same numerical result!

We begin by noting that \(N_{IT}\) has a dimension of \(\text{states/cm}^2\), while \(D_{IT}\) has a dimension of \(\text{states/cm}^2\cdot\text{eV}\). Since the Si bandgap is approximately 1eV and \(D_{IT}\) is quoted as an average value over the bangap, therefore \(D_{IT}\) and \(N_{IT}\) have the same numerical value. So only thing we have to worry about is which of the two formula, \(qD_{IT}\) or \(q^2D_{IT}\) is actually correct.

Note that \(C_{IT}=q^2D_{IT}\) is ‘dimensionally’ correct only if \(D_{IT}\) is expressed as \(\text{states/cm}^2\cdot\text{J}\): \(q^2D_{IT}=\text{Coul}^2/\text{cm}^2\cdot\text{J}=\text{Coul}^2/\text{cm}^2\cdot(\text{Coul-Volt}) = (\text{Coul/volt})/\text{cm}^2=\text{F/cm}^2\) which is the correct unit for \(C_{IT}\). Only trouble is that \(D_{IT}\) is generally expressed per eV, not per Joule. Since for \(E(\text{eV})=qV\), \(q\) is 1, not \(1.6\times10^{-19}\), the formula that gives numerically right results is \(C_{IT}=qD_{IT}=1\times1.6\times10^{-19}D_{IT}\) – most textbooks have this definition of \(C_{IT}\). Bottom line, \(C_{IT}=qN_{IT} \) or \(qD_{IT}\) are good working formula, given the way \(D_{IT}\) is typically specified in the literature.