26. STATISTICS OF SOFT BREAKDOWN

26.1 Review/background

We know that dielectrics break down especially when they are very thin. We learned that when the first percolation path forms, that is the time when the oxide is broken. This however is too conservative and cannot give you adequate lifetime. In the last lecture we saw that for having a soft break down the power dissipated through the percolation path is less than 20 microwatt. The first break down does not tell us much and so in this lecture we will explain how to measure how much additional degradation we will have in the second, third, and fourth breakdown. This lecture will be divided into two parts. The first part will discuss the time correlation, whether trap generation become faster after the first break down. The second part will discuss space correlation, whether the first breakdown happens at point xy and whether the second breakdown happens close by.

26.2 Part1: Methods of Markov Chains

26.2.1 Spatial vs. Temporal correlation:

Spatial correlation means that things may happen faster or not but they happen closer by. Temporal correlation means things happen random but at an accelerated pace.
Figure 26.1. oxide breakdown phenomenon and associated gate leakage currents

Figure 26.1 shows the oxide breakdown phenomenon in completely correlated, essentially uncorrelated and completely uncorrelated systems, respectively. It can be noted that in a completely correlated systems, gate leakage current increases by orders of magnitude within a short period of time. On the other hand, in essentially correlated and completely uncorrelated systems, gate leakage current increases gradually with respect to time, which is due to soft breakdown. Soft breakdown improves dielectric lifetime.

Figure 26.2. Transistor with M x N cells in the gate oxide

We will analyze the device failure probability (TDDB) based on the assumption that that trap generation has equal probability throughout the device life-time (completely uncorrelated). It is easy to see from Figure 26.2 that the probability a column fails (one percolation path) is
\[ p = q^M \]  \hspace{1cm} 26.1

Where, \( q \) = probability that one trap is being generated in the oxide (~at\( \alpha \)), \( M \) = Minimum number of defects needed to complete the percolation path from gate edge to channel (number of cells in one column). The probability of having 1 and only 1 breakdown is given by

\[ P_1 = Np(1 - p)^{N-1} \]  \hspace{1cm} 26.2

The probability of having 2 and only 2 (not 2 or less) is given by

\[ P_2 = \binom{N}{2} p^2 (1 - p)^{N-2} \]  \hspace{1cm} 26.3

Following the percolation model we can now come up with an expression for large \( n \)

\[ P_n = \left( \frac{x^n}{n!} \right) e^{-x} \]  \hspace{1cm} 26.4

Where \( \chi = \left( \frac{t}{\eta} \right)^\beta \) and \( \beta = \alpha M \)

If we define equation 26.3 as \( 1-F_n \), then compute \( \ln(-\ln(1-F_n)) \) and plot it as a function of time, this plot is known as a weibull distribution. \( \beta \) is the weibull slope. In soft breakdown where the correlation is weak a weibull distribution dependent on “n” will be produced as shown in Figure 26.3 which corresponds to the following weibull equation

\[ W_n = (n\beta) \ln(t) + \text{const} \]  \hspace{1cm} 26.5

For hard breakdown, correlation is strong and the weibull distribution is independent of “n” as shown in Figure 26.4. strong correlation weibull distribution independent of n which corresponds to the following weibull equation

\[ W_n = (\beta) \ln(t) + \text{const} \]  \hspace{1cm} 26.6
Figure 26.3. weak correlation weibull distribution dependent on n
26.2.2 Markov Chain Process for Soft Breakdown:

A different way of doing the statistics of SBD involves using the generalized Markov chain \[4\]. We can bin the transistors according to the number of faulty column formed as shown in Figure 26.5. Markov Chain Process. Initially all the transistors would be in bin \( R_0 \), where there are no shorts present. \( R_1 \) groups all the transistors with 1 short. \( R_2 \) groups transistors with 2 shorts. The term \( \xi \) gives the correlation between the local trap generations (enhancement factor).
At any point in time, the sum of transistors in every bin should be the same as the total number of transistors.

$$\sum_{n=0}^{\infty} N_n(t) = N_0(t = 0) \quad 26.7$$

The difference equation can be written at a bin boundary as:

$$\frac{dP_n}{dx} = k_{n-1}P_{n-1} - k_nP_n \quad 26.8$$
At the first bin boundary

\[
\frac{dP_0}{dx} = -k_0P_0 = e^{-x}
\]

With this Markov Chain approach, we would get the same result as we obtained using the simple probability theory (previous section). Thus, using the rate equation of defect generation we can establish a formula for \(P_n\) which is given as

\[
P_n = f(\xi) \left( \frac{x^n e^{-x}}{n!} \right)
\]

\[
f(\xi) = \prod_{m=0}^{n-1} \left( 1 + m\xi \right) \left( \frac{1 - e^{\xi x}}{\xi x} \right)^n
\]

For the above two special cases, \(f(\xi)\) becomes 1 for \(\xi=0\) (no correlation), and \(f(\xi)\) becomes 0 (for \(n > 0\)) for \(\xi=\infty\) (fully correlated). A significant outcome of this derivation is the ability to predict the life-time for any \(n\), using just the measurement results from using \(n=0\) and \(n=1\). The correlation factor \(\xi\) derived from the above measurement remains constant independent of \(n\). Figure 26.6. correlated distributions for multiple SBD shows the correlated distributions for multiple SBD [3]. The correlation factor is 25%, which was determined by the plots. In the next section we will show how we can use leakage current as a signature of TDDB.
26.2.3 **Post Silicon IDDQ Leakage Current**

We can use the leakage current IDDQ through the device for estimating the soft-breakdown. As explained above using Markov chain process, we can derive normalized values of current flowing to the chip ground as shown in Figure 26.7.
The normalized value of the current flowing to the chip ground is given by

$$\frac{IDDQ}{N_T I_0} = \sum_{n=1}^{\infty} n \times P_n$$  \hspace{1cm} 26.12

where \(N_T\) is the number of transistors in the chip and \(I_0\) is the current with zero defects. Using this model we can estimate the correlation factor.

The derivative of the leakage current with respect to \(\chi\) is given by

$$\frac{dL}{d\chi} = 1$$  \hspace{1cm} 26.13

Therefore

$$L = \chi = t/\eta$$  \hspace{1cm} 26.14

Hence

$$\ln(L) = \beta \ln(t) - \beta \ln(\eta)$$  \hspace{1cm} 26.15

We can now come up with a plot that shows the relationship between the gate current and time as demonstrated in Figure 26.8

![Figure 26.8. using IDDQ measurements to create a gate current vs. time plot and ultimately finding \(\beta\)](image-url)
As can be seen in the plot above, there are quantum jumps in the current at very small time. When the time increases, since it is a log plot, a straight line is produced and the slope of this line is $\beta$. An important by product of this analysis is that, we can use this measured leakage data to estimate the impact of voltage acceleration and thus can predict the life time, without performing extensive measurements. The expression for leakage current under voltage acceleration is given as

$$\ln(I_{\text{leak}}) = \beta \left[ \ln(t) + \gamma_V (V - V_0) + \ln(\eta_0) + \text{const.} \right]$$  \hspace{1cm} 26.16

Figure 26.9 shows the weibull slope and voltage acceleration using the leakage current.

![Figure 26.9. Plot showing the weibull slope and voltage acceleration using leakage current.](image)

### 26.3 Part 2: Breakdown Position Correlation:

For estimating the correlation factor ($\xi$) it is important to obtain the exact location during the first and subsequent breakdowns. $\xi$ is related to time correlation of the defect formation. In order to determine the location during breakdown, we will be using a current ratio method [1]. Based on the location of the defect in the oxide, current flowing through the gate and drain would change. If the defect is very close to the source, this will result in a situation where the entire source current is coming from gate and not from
the drain. On the other hand, if the defect is near the drain, the gate current will contribute less to the source current. Hence, the simple equation of location of defect can be derived as a ratio of the source current and drain current as shown below

$$D \frac{d^2 n}{dx^2} = 0$$

$$n = Ax + B$$

$$I_s = qWD \frac{n_0}{x_{BD}}$$

$$\frac{x_{BD}}{L_C} = \frac{I_d}{I_d + I_s}$$

Where $x_{BD}$ is the location of defect from the source as shown in Figure 26.10.

![Figure 26.10. Current ratio technique for estimating the location of the defect](image-url)
Similar technique can be employed to find the location of second defect where we can find the relative distance between first and second defect. Figure 26.11 shows the measured data of the location of defects in a transistor. To begin we assume that the formation of defects are independent and therefore the derived formulae for two defects is given as

\[
P_2(x_1 - x_2 < x) = 2x - x^2
\]

where \(x_1\) and \(x_2\) are the position of the first and second defects respectively. If the \(x\) value is zero, then the defects are close together. When the \(x\) value is equal to 1 the distance is maximum.

![Diagram of two defects in a transistor](image)

Figure 26.11. Distribution of two defects in a set of devices

The breakdown position randomly distributed over the channel is expected to be a straight line, however it flattens out close to the source and drain as shown in Figure 26.12. This is because the drift component cannot be neglected in these areas, hence the “s” shape of the plot.
The cumulative PDF of defects estimated from measurement are given in Figure 26.13 and the results predicted uncorrelated assumption. The close matching of data indicates that, trap generation is spatially uncorrelated. Such information about special correlation would have been difficult without the leakage current signature of TDDB.

![Cumulative distribution of single defect and two defects assuming defect generation probabilities are independent](image)

Figure 26.13. Cumulative distribution of single defect and two defects assuming defect generation probabilities are independent
We can also use voltage-ratio method to locate the defects. As shown in Figure 26.14, we can measure the floating drain voltage or source voltage to determine where the location of the defect is. If we are using the drain voltage method, if the defect is close to the source then the drain voltage will be very small. If we are using the source voltage method, the same scenario applies. The voltage-ratio can simply be determined by the following equation

\[
\frac{x}{L} = \frac{V_D I_D}{V_S I_S + V_D I_D}
\]

Figure 26.14. voltage ratio technique for estimating the location of the defect

26.4 **Weak Localization:**

The main reason behind this uncorrelated nature is the structural relaxation of oxide defects. This phenomenon can be estimated using quantum yield measurement. The electron component of the gate current is always larger than the hole component and this difference decreases for large gate voltages. A model with no hole ionization can explain the quantum yield at low values of gate voltage. At low gate voltage the electron current is a lot higher than the hole current as can be seen in Figure 26.15. The jump in electron current after breakdown is huge however in hole current it is miniscule. It is important to
mention such energy relaxation can occur only in thin oxides and in thick oxides the defects are correlated.

26.5 Conclusion

In this lecture we discussed the statistics of multiple breakdown events related to TDDB. We saw that for thin oxides at low operating voltages, oxide defect formations are spatially uncorrelated and hence the device lifetime is many orders of magnitude more than that associated hard breakdown. We have modeled the soft breakdown using Markov chain and final distribution of time dependent oxide defects follows Weibull distribution. Using this observation we have derived a simple experimental procedure based on leakage current (IDDQ) for estimating the soft-breakdown. This led to efficient estimation of circuit life time using voltage acceleration measurement of leakage current. From this analysis it is clear that soft breakdown cannot paralyze the operation of the chip, however a harder break down can. Energy relaxation in thin oxides is an important phenomenon which makes the dielectric breakdown uncorrelated.
Reference:


