ECE606: Solid State Devices
Lecture 39: Reliability of MOSFET

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Outline

1. Introduction
2. Negative Bias Temp. Instability
3. Gate Dielectric Breakdown
4. Radiation Induced Damage
5. Conclusion
In this course, you are learning to analyze/design MOSFETs that go in an IC ...

... because the ICs operate in incredibly harsh conditions, turning on and off trillions of time during its lifetime ....

... therefore the properties of the MOSFET keep changing. Eventually, S/D can be shorted, the gate oxide can break, etc ....
SiO and SiH Bonds

*Broken Si-H bonds*
- Negative Bias Temperature Instability (NBTI)
- Hot carrier degradation (HCl)

*Broken Si-O bonds*
- Gate dielectric Breakdown (TDDDB)
- Electrostatic Discharge (ESD)
- Radiation induced Gate Rupture (RBD)
Negative Bias Temperature Instability Defined

![Image of a circuit diagram showing the relationship between V_D (volts) and I_D (mA) before and after stress. The graph shows a decrease in I_D after stress.]

![Image of a graph plotting stress time (sec) against % degradation. The graph indicates a linear increase in degradation over time.]

**Presentations:****

- **Warranty**
- **Spec.**

**Graphs:**

1. A graph showing the relationship between V_D (volts) and I_D (mA) before and after stress. The graph indicates a decrease in I_D after stress.
2. A graph plotting stress time (sec) against % degradation. The graph shows a linear increase in degradation over time.

**Equations:**

- V_D = 0
- V_DD

**Legend:**

- **before stress**
- **after stress**

**Notations:**

- V_D (volts)
- I_D (mA)
- % degradation
- Stress Time (sec)

**References:**

- Alam ECE-606 S09
NBTI defined ...

\[ \Delta V_T = A e^{-E_a / k_B T} t^n \]

- \( n \approx 0.25 \)
- \( E_a \approx 0.5 \text{ eV} \)
- \( A \) depends on \( \text{Eox} \)

- 25°C (0.23)
- 90°C (0.25)
- 150°C (0.27)

\[ T_{\text{PHY}} = 36 A, \ V_G = 4.5 \text{V} \]
Diffusion Distance

$t_1 < t_2 < t_3$

$x \sim (Dt)^{0.5}$
NIT with H diffusion

\[
\frac{dN_{IT}}{dt} = k_F (N_0 - N_{IT}) - k_R N_H(0) N_{IT}
\]

\[
\left( \frac{k_F N_0}{k_R} \right) \approx N_H(0) N_{IT}
\]

\[
N_{IT}(t) = \frac{1}{2} N_H(0) \sqrt{D_H t}
\]

Combining these two, we get

\[
N_{IT}(t) = \sqrt{\frac{k_F N_0}{2k_R}} (D_H t)^{1/4}
\]

\[
x(t) = \sqrt{D_H t}
\]
SiO Bonds

**Broken Si-H bonds**
- Negative Bias Temperature Instability (NBTI)
- Hot carrier degradation (HCl)

**Broken Si-O bonds**
- Gate dielectric Breakdown (TDDB)
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1. Introduction

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Time-dependent Bulk Trap

\[ V_{th} = V_{th^*} - \frac{x_1}{x_0} \frac{Q_{ox}(x_1, t)}{C_{ox}} \]
Dielectric Breakdown

- Gate Current vs. ln (time)
- Breakdown
- ln(-ln(1-F)) vs. log(TBD)
- $V_{G1} > V_{G2} > V_{G3}$ vs. VDD
Anode Hole Injection for Dielectric Breakdown

\[ T_B = D \left( \frac{N_{BD}}{k} \right)^n \frac{1}{J_e a T_p} \]

- \( J_e \) - Electron current density
- \( a \) - Impact Ionization Rate (probability that a hole will be created by an incoming electron)
- \( T_p \) - Transmission Rate (probability that the hole will travel through the oxide layer)
- \( k \) - Trap Generation Efficiency (probability that the hole will create a percolation defect)
- \( N_{BD} \) - Density of percolation defects at breakdown
Anode Hole Injection Theory of TDDB

\[ J_h = J_e \alpha T_p \]

\[ J_e = A \exp(-B/E) \]
\[ \alpha = 1 - 2 \]
\[ T_p \sim \text{const} \]
\[ \ln(T_{BD}) \sim 1/R \sim 1/E \]

\[ J_e \sim f(E) \]
\[ \langle \alpha T_p \rangle \sim M \exp(DV) \]
\[ \ln(T_{BD}) \sim 1/R \sim V \]
**Percolation Model for Dielectric Breakdown**

**Prob. of exactly 1 BD**

\[ P_1 = \binom{N}{1} p \left(1-p\right)^{N-1} \]

\[ P_1 = (\chi) \exp(-\chi) \]

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

\[ F_1 (\chi) = 1 - P_o (\chi) \]

\[ \ln \left[ -\ln \left(1-F_1\right) \right] \sim \beta \ln t \]

**Prob. of a filled column:** \( p = q^M \)

**Prob. of filled cell:** \( q = (at^a/NM) \)

![Graph showing the relationship between log(TBD) and ln(-ln(1-F)) with V_{G1}, V_{G2}, V_{G3}, and VDD marked.](image)
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Radiation Induced Damage

Geant4 – high energy particle physics based toolkit

Used for the ionization and energy relaxation (\( \sim \)10eV – keVs)
Radiation Induced Charge Buildup

\[ V_{th} = V_{th}^* - \frac{x_1}{x_0} \frac{Q_{ox}(x_1, t)}{C_{ox}} \]

**Equation:**

- \( V_{th} \): Threshold voltage after radiation.
- \( V_{th}^* \): Threshold voltage before radiation.
- \( x_1 \): Oxide thickness after radiation.
- \( x_0 \): Oxide thickness before radiation.
- \( Q_{ox} \): Charge density in the oxide.
- \( t \): Time after radiation.
- \( C_{ox} \): Oxide capacitance.

**Diagram:**

- (1) Electron-hole pairs generated by ionizing radiation.
- (2) Hopping transport of holes through localized states in SiO\(_2\) bulk.
- (3) Deep hole trapping near Si-SiO\(_2\) interface.
- (4) Radiation-induced interface traps within Si bandgap.

**Graph:**

- \( C/C_{ox} \) vs. \( V_G \).
- Ideal \( V_T \) vs. \( V_G \).
- Actual \( V_T \) vs. \( V_G \).
Summary

1) Reliability is a serious concern for scaling of MOSFETs.

2) There are many different types of degradation mechanisms that needs careful modeling to predict the lifetime of a MOSFETs.

3) At present, NBTI in PMOS transistors is the most difficult reliability problem, followed by HCI, TDDB, and Radiation effects.