ECE695: Reliability Physics of Nano-Transistors
Lecture 13: Introductory Lecture on HCl Degradation

Muhammad Ashraful Alam
alam@purdue.edu
copyright 2013

This material is copyrighted by M. Alam under the following Creative Commons license:

[Image of Creative Commons logo]

Attribution-NonCommercial-ShareAlike 2.5 Generic (CC BY-NC-SA 2.5)

Conditions for using these materials is described at

http://creativecommons.org/licenses/by-nc-sa/2.5/
Outline of Lecture 13

1. Background and features of HCl Degradation
   1. Phenomenological observations
   2. Origin of Hot carriers

2. Theory of Si-H Bond Dissociation

3. Theory of Si-O Bond Dissociation

4. Conclusions
Hot Carrier Degradation: Emerging Issue

- **PMOS NBTI** dominates
- **PMOS NBTI** reduces with NMOS transistors. **HCI** dominates due to high $V_{DD}$
- **TDDB** increases due to $T_{OX}$ scaling, NBTI re-emerge due to increased fields
- **HCI** reduces due to $V_{DD}$ scaling, LDD structures
- **HCI** still remains an issue in spite of reduced $V_{DD}$

Transistor Count

Year


- 4004
- 8080
- 8088
- 286
- 386
- 486
- Pentium
- Dual core Itanium 2
- Quad core Itanium 2
- P4
- PIII
- PII
- Itanium 2
- Itanium 2
- Dual core Itanium 2
- Quad core Itanium 2
Hot carrier degradation

HCl occurs during the on-state \((V_G > V_T)\), at \(V_D > V_G\)
**Classical HCI ... only ON state?!**

True only for logic transistor, at relatively low operating voltage
Impact on Device Performance

- Degradation of $I_{DLIN}$, $V_T$ and $I_{DSAT}$ occur during hot carrier stress
Observation 1: Time exponents and recovery

\[ \Delta I_{CP} \propto N_T = A \times t^n \]

- Time exponent, \( n > 0.3 \)
- \( n \) depends on stress time

No recovery

- Stress
  - 7.0V
  - 6.5V
  - 6.0V

- Relax
  - No recovery
Observation 2: HCl Degradation is Universal

\[
\Delta I_{CP} \propto N_T = f \left( \frac{t}{\tau(V_D)} \right)
\]
ON-State Logic: Universality of various metrics

- **ON-state degradation** ($V_G = 1\text{V \& 2\text{V}}$) in logic transistors ($L_{CH} = 0.16\mu\text{m \& 0.7\mu\text{m}}$) also show universal behavior.
Observation 3: Hydrogen vs. deuterium

**Graphs and Data:**

- **Desorption Yield** (atoms/electron) vs. **Sample Voltage (V)**
  - Hydrogen vs. Deuterium at 11 K and 300 K.
  - Data from Foley, PRL, 80(6), 1336, 1998.

- **Log (time)** vs. **Log (NIT)**
  - Hydrogen and Deuterium with slopes $n \approx 0.3-0.7$ and $x \approx 2-3$.
  - Data from Hess, TED, 45(2), 406, 1998.

---

**Notes:**

- **Log (time)** vs. **Log (NIT)**
  - Hydrogen and Deuterium with slopes $n \approx 0.3-0.7$ and $x \approx 2-3$.
  - Data from Hess, TED, 45(2), 406, 1998.

---

**Additional Information:**

- **Foley, PRL, 80(6), 1336, 1998.**
- **Hess, TED, 45(2), 406, 1998.**
Summary: Empirical Observations

Time exponent

Voltage Scaling

Temp. Scaling

Significant difference between H and D!

Scales with respect to drain voltage!

Negative temp. coefficient!
Outline of Lecture 13

1. Background and features of HCl Degradation
   1. Phenomenological observations
   2. Origin of Hot carriers

1. Theory of Si-H Bond Dissociation

2. Theory of Si-O Bond Dissociation

3. Conclusions
Different types of dangling bonds
Bias condition for hot carriers

Transistors off, very few carriers

Transistors on, Maximum damage

Transistor ON, but relax over channel
Contributions of SiO, SiH, and trapped Charges

Region I
\( V_G \) low

Region II
\( V_G \sim V_D/2 \)

Region III
\( V_G \sim V_D \)

Region IV
\( V_G > V_D \)

- \( I_{e,h} \)
- \( I_{G,Net} \)
- \( N_{TR}, N_{OT} \)

Si-O

Si-H

Electron trapping
1. Background and features of HCl Degradation
   1. Phenomenological observations
   2. Origin of Hot carriers
   1. Theory of Si-H Bond Dissociation
   2. Theory of Si-O Bond Dissociation
   3. Conclusions
Dissociation of SiH and SiO bonds

\[ V_G = \frac{V_D}{2} \]

VS

VD

n^+ \rightarrow I_{SD} \rightarrow n^+

p

\[ \text{Gate Oxide (SiO}_2\text{), amorphous} \]

\[ \text{Si-Channel, crystalline} \]

E'(10.4 Gauss Doublet)

HW: SiH contribution a factor of 3 larger …

Pb0

[100] surface Pb0 along [111]
NBTI & HCl degradation compared

**NBTI (PMOS)**
- Cold holes
- Traps uniform in channel
- SiH bonds

**HCl (NMOS)**
- Hot carriers
- Localized damage
- SiH and SiO bonds

\[
V_G < 0V
\]
\[
V_S = 0V\quad H \quad H \quad H \quad H \quad H \quad V_D = 0V
\]
\[
V_G \sim V_D/2
\]
\[
V_S = 0V\quad H \quad H \quad H \quad H \quad H \quad V_D > 0V
\]
Time Exponent of Si-H dissociation

\[ \frac{dN_{IT}}{dt} = k_f \left[ N_0 - N_{IT} \right] - k_r N_{IT} N_H(0) \quad \Rightarrow k_f N_0 / k_r = N_{IT} N_H(0) \]

\[ N_{IT}(t) \propto \int N_H(r,t) dV \]

\[ N_{IT}^{NBTI}(t) = N_H^{(0)} \times \sqrt{D_H t} \]

\[ N_{IT}(t) = \sqrt{\frac{k_f N_0}{k_r}} (D_H t)^{1/4} \]

\[ N_{IT}^{HCl}(t) = \left( \frac{\pi}{12} \right) N_H^{(0)} \times \left( \sqrt{D_H t} \right)^2 \]

\[ N_{IT}(t) = \sqrt{\frac{k_f N_0}{k_r}} (D_H t)^{1/2} \]

\[ \sqrt{D_H t} = \lambda_D \]

Alam ECE-695
Universal Scaling for SiH Bonds

\[ N_{IT}^{SiH} = \left( \frac{k_F (V_G, V_D) N_0}{k_R} \right)^\alpha \times t^n \]

\[ \equiv \left( \frac{t}{t_0} \right)^n = f_{SiH} \left( \frac{t}{t_0} \right) \]

with \[ t_0 (V_G, V_D) = g(k_F, k_R, N_0) \]

All curves scaled by a factor form a universal curve.
What about Relaxation?

Experiments show very little relaxation!

Normalized $\Delta N_{\text{IT}}$

\begin{align*}
\text{ON} & & \text{OFF} \\
\text{ON} & & \text{OFF} \\
\end{align*}

$\text{NBTI} \quad \text{HCI}$

$\text{Experiments show very little relaxation!}$


Alam  ECE-695
Very Small Relaxation for HCl

With \( n = 1/2 \) for atomic H diffusion …

\[
\frac{N_{IT}^{HCl}(2t_0)}{N_{IT}^{HCl}(t_0)} \bigg|_H = \frac{1}{1 + \frac{1/2 t_0}{(t_0 + t_0)}} = \frac{4}{5}
\]

With \( n = 1/3 \) for H2 diffusion …

\[
\frac{N_{IT}^{HCl}(2t_0)}{N_{IT}^{HCl}(t_0)} = \frac{1}{1 + \frac{1/3 t_0}{(t_0 + t_0)}} = \frac{6}{7}
\]

25% of bonds broken is SiH, so the relaxation <5%.
Origin of Si-H and Si-D bond dissociation

Of Pa, Pb, Pc -- only Pb survives Related to NBTI degradation
1. Background and features of HCl Degradation
   1. Phenomenological observations
   2. Origin of Hot carriers

1. Theory of Si-H Bond Dissociation

2. Theory of Si-O Bond Dissociation

3. Conclusions
Dissociation of SiO Bonds

\[ V_G = \frac{V_D}{2}, \quad V_D \]

Gate Oxide (SiO₂), amorphous

Si-Channel, crystalline

E'(10.4 Gauss Doublet)

E'(74 Gauss Doublet)
Different types of dangling bonds
Dissociation barriers and their distribution

![Energy vs. Distance Diagram]

- Energy
- Distance

Energy distribution graph showing the probability density function $g(E)/N_0$ in eV$^{-1}$ as a function of energy $E$ in eV.
SiO bond dispersion model

\[
\frac{dN_{IT}(t)}{dt} = k_f \left( N_0 - N_{IT}(t) \right)
\]

\[
\frac{dN_{IT}(t)}{dt} = \int_{E_0-n\sigma}^{E_0+n\sigma} k_f(E) \left( g(E) - f(E,t) \right) dE
\]

Universal scaling function for SiO bonds

\[ N_{IT}^{SiO} = \sum_E g(E, E_A) \left[ 1 + e^{-k_F(E, V_G, V_D) t} \right] dE \equiv f_2 \left( \frac{t}{t_0(V_G, V_D)} \right) \]

Will discuss the exact form of \( t_0 \) later …

\[ t_0^{-1}(V_G, V_D) = I_G = k \frac{I_D}{W_{\text{eff}}} \left[ \frac{I_{\text{sub}}}{I_d} \right]^{\Phi_e/\Phi_i} \]

\[ t_0^{-1}(V_G, V_D) = I_G = \frac{r_i m_i I_D}{k_1 W} + \frac{r_i m_I D^2}{k_2 W^2} + \frac{V_d^\gamma}{k_3} \frac{I_D^\alpha}{W^\alpha} \]
Conclusions

- Hot carrier degradation became important soon after NMOS and PMOS technologies were introduced. Insistence on keeping the VD unchanged contributed to the issue.

- Hot carriers break both SiH as well as SiO bonds. And the hot electron/hole trapping also contributes. Taken together there could be a significant shift in voltages.

- One can treat the kinetics of SiH and SiO bond dissociation separately. Both follow universal scaling laws.
Self-Test Questions

1. Both SiH and SiO are involved in HCI degradation. Give two evidences.
2. Why doesn’t HCI occur during NBTI stress condition?
3. I suggested that HCI curve can shifted horizontally to form a universal curve, do you believe that I can do a corresponding vertical shift to form the universal curve.
4. What is the physical origin of distribution of bond-strengths for SiO bonds?
5. Why is it that SiH bonds are easily repassivated, while SiO bond are not. What can you do to repassivate these bonds?
6. HCI is a bigger problem for NMOS compared to PMOS – what could be the reason.
7. Why did people expect HCI to disappear below 1V?