Reliability of Ultra-Thin Silicon Dioxide under Substrate Hot-Electron, Substrate Hot-Hole, and Tunneling Stress

Eric M. Vogel, Monica Edelstein, and John Suehle

National Institute of Standards and Technology
Semiconductor Electronics Division
Gaithersburg, MD 20899
Motivation #1
Determining physical model for oxide breakdown ($V_g < \sim 7.5 \text{ V}$)

**Energetic Carrier Models**

$$t_{bd} \approx \frac{Q_{bd}}{J_g}$$

- Trap Creation/Hydrogen Release
- Anode Hole Injection

$$Q_{bd} \approx \frac{N_{bd}}{P_g}$$

**Electric Field Models**

$$t_{bd} \approx A \exp\left(\frac{\Delta H_0}{kT}\right) \exp(\gamma(T)E)$$

(Thermochemical-E)

Motivation #2
Comprehensive and self-consistent understanding of MOSFET degradation and breakdown that includes hot-carrier and uniform tunneling stress conditions
Experimental for SHE/CVS

- N-channel MOSFETs
- <100> silicon, $N_a = 2 \times 10^{17}$ cm$^{-3}$
- $t_{ox} = 2.0$ nm to 3.4 nm
- $n^+$ polysilicon

- Constant Voltage Stress (CVS), $V_g > 0$, $V_s = V_d = V_b = 0$

- Substrate Hot Electron (SHE) Stress, $V_g > 0$, $V_s = V_d = 0$, $V_b < 0$, $V_{inj} < V_b$

- Stress Induced Leakage Current (SILC) and sinusoidal Charge Pumping (CP) used to monitor electrically active defects.
The gate current is the sum of the SHE current and the tunnel current. The SHE current has an energy distribution at the interface determined mainly by the substrate bias, and a density that can be controlled using the injector bias. The tunneling carriers have energy in the silicon that corresponds approximately to the bottom of the conduction band and a density that is determined by the gate bias.
Effect of Substrate Bias on Gate Current Density

- The observed independence of gate current on substrate voltage indicates that the oxide voltage drop is independent of the applied substrate bias.

- The gate current density is independent of substrate bias because the inversion layer potential is pinned.
SHE Gate Current Density Characteristics

- For low gate voltages, the SHE current dominates the gate current and is dependent on the injector bias.

- For higher gate voltages, the normal tunneling current dominates the gate current characteristics.
Charge-to-Breakdown ($Q_{bd}$) for CVS

- For CVS, the $Q_{bd}$ is independent of substrate bias.
- For ultra-thin oxides ($<\sim 3.0$ nm), $Q_{bd}$ versus $V_g$ is approximately independent of thickness.
• At a given $V_g$, the $t_{bd}$ increases with increasing thickness due to the smaller current flowing in a thicker oxide at a given gate voltage.
Time-to-Breakdown ($t_{bd}$) versus $E_{ox}$ for CVS

- At a given $E_{ox}$, the $t_{bd}$ decreases with increasing thickness because a larger gate voltage is required for a thinner oxide to obtain a given electric field.
Other Data on CVS

• $Q_{bd}$ (and $P_g$) vs. $V_g$ is universal independent of oxide thickness, cathode or anode type, or anode type.

• $t_{bd}$ vs. $E_{ox}$ depends strongly on oxide thickness which means that either $N_{bd}$ is not dependent on oxide thickness or that the defect generation rate is a strong function of thickness. This is not experimentally observed.

• $t_{bd}$ vs. $E_{ox}$ depends strongly on anode type and cathode type.
The SHE $Q_{bd}$ versus $V_g$ characteristic for low $V_g$ (where hot-electrons are dominating the current) is observed to be independent of both thickness and current density.
- The $t_{bd}$ versus $V_g$ characteristics are inversely proportional to the gate current density.
• For thin oxides (<~ 3.0 nm) the number of defects at breakdown measured using SILC is approximately independent of thickness and stress condition (CVS vs. SHE).
• For thin oxides (<~ 3.0 nm) the number of interface states at breakdown measured using charge-pumping is approximately independent of thickness and stress condition (CVS vs. SHE).
The generation probability for SHE stress at high substrate bias has a weaker gate voltage dependence than for CVS because more low energy electrons reach the anode as the gate voltage increases due to increasing barrier transparency at lower energies*.

Extension of Trap-creation Model for Combined SHE and CVS

\[
N_{bd} = P_{g,\text{shei}} Q_{bd,\text{shei}} + P_{g,\text{cv}} Q_{bd,\text{cv}}
\]

\[
t_{bd} = \frac{N_{bd}}{P_{g,\text{shei}} \cdot J_{g,\text{shei}} + P_{g,\text{cv}} \cdot J_{g,\text{cv}}}
\]

\[
N_{bd} \approx \frac{\Delta J}{J_0}_{bd}
\]

\[
P_{g,\text{cv}} \approx \Delta J / \left( J_0 \times Q_{g,\text{cv}} \right)
\]

\[
P_{g,\text{shei}} \approx \Delta J / \left( J_0 \times Q_{g,\text{shei}} \right)
\]

The gate voltage dependence of combined SHEI and CVS can be explained:

- For low gate voltages the SHE terms dominate the CVS terms so that SHEI degradation is dominating.
- The weaker gate bias dependence of SHE stress is due to a weaker gate bias dependence of the SHE generation probability.
- For very high gate voltages, the tunneling carriers dominate both the current density and the reliability characteristics.
- For moderate gate voltages, the tunneling carriers dominate the current density but the generation rate of the SHE carriers is very high.
Summary SHE and CVS Reliability

- The results confirm that energetic electrons are responsible for degradation and breakdown of ultra-thin silicon dioxide.

**Energetic Carrier Models**

\[ t_{bd} \approx \frac{Q_{bd}}{J_g} \]

**Trap Creation/Hydrogen Release**

\[ Q_{bd} \approx \frac{N_{bd}}{P_g} \]

**Anode Hole Injection**

\[ Q_{bd} \approx \frac{Q_{p, crit}}{\alpha} \]
Experimental for SHH/CVS

- P-channel MOSFETs
- <100> silicon, \( N_d = 2 \times 10^{17} \text{ cm}^{-3} \)
- \( t_{ox} = 2.0 \text{ nm and 3.0 nm} \)
- p+ polysilicon

- Constant Voltage Stress (CVS),
  \( V_g \leftrightarrow 0, V_s = V_d = V_b = 0 \)

- Substrate Hot Hole (SHH) Stress,
  \( V_g < 0, V_s = V_d = 0, V_b > 0, V_{inj} > V_b \)

- Stress Induced Leakage Current (SILC) and sinusoidal Charge Pumping (CP) used to monitor electrically active defects.
Substrate Hot Hole (SHH) Injection vs. Anode Hole Injection (AHI)

**SHHI on a p-channel MOSFET**

\( V_g < 0, \ V_b > 0, \ V_{inj} > V_b \)

**Proposed AHI on a n-channel MOSFET**

\( V_g > 0, \ V_b = 0 \)
Current Voltage Characteristics for P-channel FETs

- SHH injection causes an increase in the gate current due to hot holes.

- The amount of increase is related to: (1) The injector bias which controls the density of carriers reaching the interface (2) The substrate and gate bias which controls the fraction of carriers which are injected into the oxide
Gate Voltage Dependence of CP Defects Produced by SHH Stress

- For SHH stress, the number of defects produced per hole injected is independent of gate voltage (oxide field).

- The $N_{bd}$ for SHH stress is much greater than the $N_{bd}$ for CVS.

- SILC and CP show similar results.

Breakdown occurred after the final defect measurement shown.
Gate Voltage Dependence of SILC Defects Produced by SHH Stress

- For SHH stress, the number of defects produced per hole injected is independent of gate voltage (oxide field).

- The $N_{bd}$ for SHH stress is much greater than the $N_{bd}$ for CVS.

- SILC and CP show similar results.

Breakdown occurred after the final defect measurement shown.
Previous Studies on Hot Hole Defect Generation

• Weak oxide field dependence of $D_{it}$ generation due to hot hole injection.


• Weak oxide field dependence of bulk trap generation due to hot hole injection.

Thickness Dependence of Defect Generation

- Defect generation by SHHs decreases with decreasing thickness but is independent of oxide field (gate voltage).

- Defect generation for CVS depends on gate voltage but is independent of thickness.
Previous Studies on Hot Hole Defect Generation

- Strong thickness dependence of $D_{it}$ generation due to hot hole injection for $T_{ox} < \sim 7.0$ nm.


- Strong thickness dependence of bulk trap generation due to hot hole injection for $T_{ox} < \sim 7.0$ nm.

L. Lipkin et al., J. Appl. Phys. 68, 4620 (1990)
Temperature Dependence of Breakdown by SHHs

- Breakdown by SHHs is observed to have a very weak dependence on temperature as compared to breakdown by CVS.

- This is because defect generation by the trapping of holes has a very weak temperature dependence.
Temperature Dependence of Breakdown by SHHs

- Breakdown by SHHs is observed to have a very weak dependence on temperature as compared to breakdown by CVS.

- This is because defect generation by the trapping of holes has a very weak temperature dependence.

\[ \text{SHH Stress: } V_g = -1.0 \text{ V}, V_b = 8.5 \text{ V}, V_{\text{inj}} = 11.0 \text{ V} \]

\[ T_{\text{ox}} = 3.0 \text{ nm} \]

\[ A = 2.5 \times 10^{-7} \text{ C/cm}^2 \]
Temperature Dependence of Defect Generation by SHHs

- Defect generation by **SHHs** is *decreased* at higher temperatures.
- Defect generation by **CVS** is *increased* at higher temperatures.
Previous Studies on Hot Hole Defect Generation

- Increased bulk trap and $D_{it}$ generation with decreasing temperature for thicker oxides subjected to hot hole injection.

Effect of Lower Substrate Bias (Higher Electron-to-Hole Ratio) on Defects Produced by SHH

- A lower substrate bias was used so that no increase in SHH current over the tunneling current was observable.

- A low gate bias was used so that the defect generation was still dominated by the hot holes.

- The defect generation and $N_{bd}$ due to SHHs is not affected by the electron-to-hole ratio.
Effect of Trapped Holes on Defect Generation

- These results show that prior injection of holes does not result in additional defect generation during electron injection.

\[ \frac{\Delta J}{J_0} \text{ or } \frac{\Delta I_{cp,max}}{I_{cp,max0}} \]

\begin{align*}
\text{SHH Injection} & \quad V_g = -2 \text{ V}, \quad V_s = V_d = 0 \text{ V} \\
& \quad V_b = 11 \text{ V}, \quad V_{ij} = 12.25 \text{ V} \\
\text{Electron Injection} & \quad V_g = -3.0 \text{ V}, \\
& \quad V_b = V_s = V_d = 0 \text{ V} \\
& \quad t_{ox} = 2.0 \text{ nm} \\
& \quad A = 2.5 \times 10^5 \text{ cm}^2
\end{align*}
Effect of Trapped Holes on CVS Breakdown

- These results show that prior injection of holes does not result in a reduction of subsequent CVS $Q_{bd}$.
- This again illustrates the ineffectiveness of defects generated by holes to cause breakdown.
- This suggests that the recently theorized $^1$ “hole-catalyzed thermochemical electric field model” is incorrect.

Summary of SHH Injection

- Defect generation in ultra-thin oxide due to SHH injection has experimental dependencies consistent with previous studies on hole trapping in thicker oxides:
  1) High defect generation rate of holes
  2) Defect generation independent of oxide electric field
  3) Defect generation decreases with decreasing thickness
  4) Defect generation decreases with increasing temperature

- These results do not necessarily preclude the interaction of trapped holes with concurrently injected electrons as a degradation mechanism.
Conclusions

• Energetic electrons are responsible for the degradation and breakdown of ultra-thin silicon dioxide under constant voltage tunneling stress.

• Hole trapping alone can not explain the breakdown of ultra-thin silicon dioxide under tunneling stress conditions.

• Further experimental and theoretical work is required to fundamentally understand the physical nature of the critical defect or precursor which results in the observed $N_{bd}$. 