Thin Gate Oxide Reliability: Past & Present Trends in Characterization, Physical Modeling, and Assessment

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Outline

Part I. Physics, Statistics and Models
  1. Voltage, Electric Field, Current, and Energy
  2. Effects of Stress on Oxides and Devices
  3. Physical Models of Wear-Out and Breakdown
  4. Percolation and Statistics of Breakdown

Part II. Reliability Characterization and Test Methodology
  1. Accelerated Stress Tests
  2. Reliability Extrapolation
  3. Extrinsic Oxide Breakdown
PART I.

Physics, Statistics, and Models
Physics, Statistics and Models

Outline

1. Voltage, Electric Field, Current, and Energy
   a. Voltage and Electric Field
   b. Fowler-Nordheim and Direct Tunneling
   c. Energy Distribution of Tunneling Carriers
   d. Trap-assisted Conduction
   e. Hot Carrier Injection

2. Effects of Stress on Oxides and Devices
   a. Defect Generation and Trapping
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   c. Wear-out and Breakdown
Physics, Statistics and Models

Outline (continued)

3. Physical Models of Wear-Out and Breakdown
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   b. Anode Hole Injection
   c. Trap Creation
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4. Percolation and Statistics of Breakdown
   a. Percolation
   b. Failure Distributions
   c. Bi-Modal and Non-Linear Distributions
   d. Area Dependence
   e. Thickness Dependence
Voltage, Electric Field, Current and Energy

- The physical models for wearout are premised on voltage, electric field, current or carrier energy.

- This section provides a brief description of these topics as they pertain to the reliability of metal-oxide-semiconductor devices.
Voltage and Electric Field

- For a capacitor, the gate voltage ($V_{\text{gate}}$) can be described in terms of the voltage across the polysilicon ($V_p$), the voltage across the oxide ($V_{\text{ox}}$), the voltage across the substrate ($V_q$) and the electrode-semiconductor work-function difference ($\phi_{\text{ms}}$):

$$V_{\text{gate}} = V_p + V_{\text{ox}} + V_q - \phi_{\text{ms}}$$

- The voltage drop across the polysilicon is important mainly for thin oxides (high electric fields) when the polysilicon becomes depleted (PD).

- For thin oxides (high electric fields), the voltage drop across the substrate must include the effects of density of state quantization (QM).
The PD effect and QM effect must also be included when analyzing capacitance-voltage characteristics.

The QM effect results in a shifting of the inversion layer electrons below the surface and a change in the surface potential. The shifting of the carriers from the interface reduces capacitance in both accumulation and inversion.

The PD effect reduces capacitance mainly when the gate electrode is in depletion.
Current and Energy

Quantum-Mechanical Tunneling Current

Fowler-Nordheim Tunneling
Occurs when electrons are injected into the conduction band of the dielectric through the triangular barrier.

Direct Tunneling
Occurs when electrons are injected directly into the conduction band of the anode through the trapezoidal barrier.
Current and Energy

Tunneling Current Calculations

Methodologies used to calculate tunnel currents range from self-consistent solutions of the Schroedinger and Poisson equations to analytical formulations for potentials and transmission probabilities.

Self-consistent solutions are generally more accurate but require extensive numerical computation and are time consuming.

Analytical formulations are known to be less accurate and less physically based but are are many times fit to experimental data by choosing an insulator effective mass and/or barrier height.
The current density is strongly dependent on thickness when plotted as a function of voltage.

- The Fowler-Nordheim current is only dependent on electric field (not thickness).

\[
J_{\text{FN}} = A F_{\text{ox}}^2 \exp\left[-\frac{B}{F_{\text{ox}}}\right] \quad J_D = \frac{AF_{\text{ox}}^2}{1 - \left(\frac{\phi_b - qV_{\text{ox}}}{\phi_b}\right)^{3/2}} \exp\left[-\frac{B \phi_b^{3/2} - (\phi_b - qV_{\text{ox}})^{3/2}}{F_{\text{ox}} \phi_b^{3/2}}\right]
\]

\[
A = \frac{q^3}{16\pi^2 h\phi_s}
\]

\[
B = \frac{4}{3} \frac{(2m_{\text{ox}})^{3/2}}{q\hbar \phi_s^{3/2}}
\]

Current and Energy

Average Energy of Tunneling Carriers

- For thick oxides (~>5.0 nm) and $E_{ox} < ~1.5$ MV/cm, the electrons are scattered by Polar Optical Phonons (POP) resulting in electrons traveling near the SiO$_2$ conduction band with energies < 0.153 eV.

- For thick oxides and $E_{ox} > ~1.5$ MV/cm, the electrons gain more energy than they lose from POPs. When the electrons reach ~2 eV, the distribution is stabilized by Nonpolar Phonon scattering.

- For thin oxides the electrons no longer experience scattering so ballistic transport is observed.

- A phenomenological model has been developed which describes the average energy of electrons:

\[
E_{gain} = \phi_b + (E_{ox} \lambda) \left[ 1 - \exp \left( -\frac{1}{\lambda} \left[ t_{ox} - \frac{\phi_b}{E_{ox}} \right] \right) \right], \quad V_{ox} > \phi_b; \quad E_{gain} = V_{ox}, \quad V_{ox} < \phi_b
\]

For thick oxides (>~ 5nm) and moderately high voltages, the average energy of the electrons entering the anode at a given gate voltage is dependent on thickness.

For thin oxides (<~ 5nm), the average energy of the electrons entering the anode at a given gate voltage is independent on thickness.
Current and Energy

Average Energy of Tunneling Carriers

- For thick oxides (>~ 5nm) and moderately high fields, the average energy of the electrons entering the anode at a given electric field is independent of thickness.

- For thin oxides (<~ 5nm), the average energy of the electrons entering the anode at a given electric field is dependent on thickness.
Current and Energy

Energy Distribution of Tunneling Carriers

- As the oxide thickness is reduced, less scattering occurs in the insulator. Therefore, the anode energy distribution of carriers tunneling through a thin oxide is much narrower than that of a thick oxide.

Overlap Tunnel Current

- As the channel length of the MOSFET scales, the tunnel current associated with the source drain extension area to the gate overlap region becomes a significant part of the total current.

- Further work is necessary to understand the implication of this overlap region on reliability.

Valence Band Tunnel Current

- As the oxide thickness is reduced, the current associated with valence band tunneling becomes an increasing contribution of the total gate current.

- Further work is necessary to understand possible implications of this current on device operation and reliability.

Current and Energy

**Trap-Assisted Conduction**

- A number of different mechanisms and models have been used to describe the conduction of electrons through a dielectric that contains traps.

  - **Electronic hopping** is attributed to the jump of thermally excited electrons from between isolated states. (low field)
  - **Field emission** is due to the tunneling of trapped electrons to the conduction band. (mod. field)
  - **Poole-Frenkel conduction** is due to the emission of trapped electrons to the conduction band due to the lowering of the Coulombic potential of the traps under an applied field. (high field)

\[ J_1 = C_1 E \exp \left( -\frac{q \phi_i}{kT} \right) \]
\[ J_2 = C_2 E^2 \exp \left( -\frac{8 \pi \sqrt{2m^* q \phi_i}}{3h} \frac{1}{E} \right) \]
\[ J_3 = C_3 E \exp \left( -\frac{q \phi_i}{kT} \right) \]
\[ \times \exp \left( \frac{1}{kT} \sqrt{\frac{q^3}{\pi \varepsilon_0 K_T E}} \right) \]

Hot Electron Injection

- Hot electrons from the channel or substrate can induce a gate current.
- Degradation of the gate oxide by these hot electrons is usually treated separately from uniform voltage reliability.
- However, many researchers believe that the degradation caused by hot electrons is the same as that in uniform voltage stress [1].

Effects of Stress on Oxides and Devices

- Independent of the physical model assumed for wearout and breakdown of the dielectric, the characteristics of the oxide and device are changed by stressing.

- This section provides a review of some of the effects on both the oxide and the device which are associated with stressing.
Effects of Stress on Oxides and Devices

Defect Generation

• Stressing an oxide can result in the generation or formation of defects (traps) in the dielectric.

• Physical models for creating these defects will be described in the next section.

• These defects can be either Coulombic (positive or negative) or neutral and include traps, interface states and generation-recombination centers.

• In thicker oxides, the charge associated with generating these centers must be separated from the charge associated with trapping.

Effects of Stress on Oxides and Devices

**Trapping**

- Coulombic and neutral centers in the oxide are able to capture free electrons and holes, thus changing the charge state of the defect.

- For defects located within approximately a tunneling distance (~2.5 nm) from an interface, the rate of detrapping is higher than the trapping rate so that the permanent capture of carriers is negligible.

- Trapping can be modeled using first-order kinetics.

- Many times, trap generation is measured by filling these generated traps with carriers (trapping) and measuring the change in charge state.

- When measuring the reliability of thick oxides, it is very important to separate the charge associated with trapping with that associated with trap generation.

Effects of Stress on Oxides and Devices

Degradation of Device Characteristics

- The build-up of defects in the oxide results in the degradation of capacitor and FET device characteristics.

- The device characteristics which degrade due to stressing include threshold voltage, flatband voltage, transconductance, drive current, and interface state density.

- Many times, measurements of these characteristics are used to determine the generation rate of defects in the dielectric as a function of time or charge injected.

Effects of Stress on Oxides and Devices

*Stress Induced Leakage Current (SILC)*

- For thin oxides, as the oxide is stressed, the gate leakage current flowing through the oxide is observed to increase.
- Models have been developed to describe this SILC.
- The stress induced leakage current plotted as, $\Delta J/J_0$, is directly proportional to the increase in bulk oxide defects.
- It has been shown that the defects measured using SILC are related to neutral bulk defects in the oxide.

Effects of Stress on Oxides and Devices

Wearout and Breakdown

- The process of oxide breakdown is described in two stages:
  1) The oxide is damaged over time creating defects \( \rightarrow \) Physics
  2) Eventually, enough defects are created to result in a rapid runaway process and the formation of a permanent conductive path through the insulator \( \rightarrow \) Statistics

The issue of soft or hard breakdown will be described in the Characterization and Methodology part.

The breakdown to be described in the following is the first breakdown event (soft or hard).
Effects of Stress on Oxides and Devices

Wearout and Breakdown - Measurement

A fixed gate bias is applied to either a MOS capacitor or FET with other terminals grounded.

The amount of charge flowing through the dielectric is recorded as the gate current density \( J_{g,\text{stress}}(t) \).

Many times the device characteristics or defect densities are tracked as a function of time or charge injected using SILC, CV, etc.

At some point breakdown occurs and the time- and charge-to-breakdown \( (t_{bd}, Q_{bd}) \) is recorded.

\[
Q_{bd} = \int_0^{t_{bd}} J_{g,\text{stress}}(t) \, dt
\]

\[
Q_{bd} \approx J_{g,\text{stress}} \cdot t_{bd} \quad \text{(thin oxides)}
\]
Effects of Stress on Oxides and Devices

*Intrinsic vs. Extrinsic*

- Oxide failures generally fall into three groups:
  
  **A-mode**: Instant device failure usually related to defects not intrinsically associated with the oxide (extrinsic).
  
  **B-mode**: Early device failures usually related to defects not intrinsically associated with the oxide (extrinsic).
  
  **C-mode**: Failure associated with the intrinsic properties of the dielectric (intrinsic).

- Extrinsic failures can result from a variety of effects including metal contamination, plasma damage or implant damage.

- *The majority of this discussion will be on intrinsic reliability (unless otherwise stated).*
Physical Models of Wearout and Breakdown

- A variety of physical models in the literature attempt to describe the physical basis of intrinsic wearout and breakdown.

- Debate still exists as to the exact physical nature of the mechanisms.

- This section provides a review of the main models proposed and examines some of the experimental data associated with intrinsic wearout and breakdown.
Physical Models of Wearout and Breakdown

**Bandgap Ionization**

- When the energy of an electron in the conduction band of the insulator reaches energies close to the bandgap (~9 eV), electron-hole pairs can be generated which can interact and create defects in the oxide.

- This process occurs in films thicker than ~20 nm at fields higher than ~7 MV/cm and is associated with the high-energy tails of the electron distribution.

Physical Models of Wearout and Breakdown

“Classical” Anode Hole Injection

- A fraction of the electrons entering the anode have enough energy to create a “hot” hole which can tunnel back into the oxide.

- These holes create defects and breakdown occurs when a critical hole fluence is reached.

- The “classical” anode hole injection model predicts a $1/E_{ox}$ dependence of breakdown and a dependence on the anode Fermi level.

$$Q_{bd} = \frac{Q_p}{\alpha_p} \exp \left( \frac{B}{E_{ox}} \left[ \phi_p (V_{ox}) \right]^2 \right)$$

$$t_{bd} = \frac{Q_{bd}}{J_n}$$

Physical Models of Wearout and Breakdown

*Probability of Hole Injection*

- Some researchers have suggested based on both theoretical and experimental evidence that significant injection and trapping of anode holes does not occur until the electron obtains an energy of ~7.6 eV in the anode.

- Recent studies on improved models for impact ionization suggest that anode hole injection may be probable at low energies and that the dependence of anode hole induced breakdown on voltage is linear.

- However, there are no known studies conclusively showing that anode injected holes at low voltage are trapped in the oxide and lead to breakdown.
Physical Models of Wearout and Breakdown

*Trap Creation - Hydrogen Release*

- The trap creation model suggests that the energetic electrons create oxide damage by interacting with the oxide lattice itself or with a secondary species such as hydrogen.

- An energy threshold for defect generation of approximately 5 eV in the anode (2 eV in the oxide) has been attributed to H release and diffusion towards the cathode where it interacts with the oxide creating defects.

- The role of H was suggested based on the observation of H release and buildup measured after stress and the impact of plasma generated H on defects in the dielectric.


Physical Models of Wearout and Breakdown

Trap Creation

- The degradation process below 2 eV is assumed to be the subthreshold tail of the trap creation process.
- This model predicts a linear dependence of breakdown on voltage.

Physical Models of Wearout and Breakdown

Thermo-chemical E Model

- Thermodynamic
- Eyring Model

\[ T_{BD} = A \exp\left(\frac{\Delta H_o}{K_BT}\right) \exp[\gamma(T)E] \]

- Based on the observed linear E-field dependence of breakdown, some researchers have suggested that the low field degradation is due to the interaction of electric field with weak bonds in the oxide.

Physical Models of Wearout and Breakdown

**Polarity Dependence of Breakdown**

- A strong dependence of breakdown on anode and cathode type has previously been observed [1].

- The cathode dependence of $t_{bd}$ or $Q_{bd}$ at a given $E_{ox}$ has been explained by the difference in current density for an n-type versus p-type cathode [1].

- The anode dependence has been explained by the difference in maximum electron energy obtained for an n-type versus p-type anode [2].

Physical Models of Wearout and Breakdown

Trap Creation-General Form

\[
Q_{bd} \approx \frac{N_{bd}}{P_g} \\
T_{bd} \approx \frac{Q_{bd}}{J_g} \\
N_{bd} \approx \frac{\Delta J}{J_0 |_{bd}} \\
P_g \approx \frac{\Delta J}{(J_0 \times Q_{inj})}
\]

- The above is a general form of the trap creation model based on electrons creating damage at some generation rate \(P_g\) which depends on voltage.

- The number of defects required to initiate breakdown \(N_{bd}\) is assumed independent of voltage. \(N_{bd}\) contains the statistical nature of breakdown and is described in the next section.

- The defect density used to determine \(P_g\) and \(N_{bd}\) is many times measured using stress induced leakage current \(\frac{\Delta J}{J_0}\), interface state density, or fixed charge density.

Percolation and Statistics of Breakdown

- Percolation theory has been successfully used to describe the number of defects required to initiate breakdown.

- The statistics of breakdown has been linked to the number of defects required to initiate breakdown.

- In this section, percolation theory and the statistics associated with breakdown is reviewed.
Percolation and Statistics of Breakdown

Percolation (Spheres) Model

- In the percolation model, traps (spheres) are generated randomly through the volume of the dielectric.

- If the spheres of two neighboring traps overlap, conduction is possible.

- Breakdown occurs when a conducting path is created from one interface to another.

- The parameters used to fit experimental data is the trap radius and the fraction of defects effective in initiating breakdown.

Percolation and Statistics of Breakdown

Cumulative Distribution Functions (CDF) for Breakdown

- The two CDF’s most commonly used to describe breakdown is the log-normal and the Weibul (time or charge is interchangeable in the following):

\[
F(t) = \frac{1}{\sigma \sqrt{2\pi}} \int_0^t \frac{d\tau}{\tau} \exp\left[-\frac{1}{2}\left(\frac{\ln \tau - \mu}{\sigma}\right)^2\right]
\]

Log-Normal:

\[t_{50} = e^\mu \text{ and } \sigma = \ln\left(t_{50}/t_{16}\right)\]

Weibul:

\[
F(Q) = 1 - e^{-\left(\frac{Q_{bd}}{\eta}\right)^\beta}
\]

- Weibul is a straight line if plotted as ln(-ln(1-F)) versus log (Q_{bd}) with a slope of \(\beta\) and modal value, \(\eta = Q_{bd}\) (F~63%).
Percolation and Statistics of Breakdown

Comparison of Log-Normal and Weibul

- The experimental data was fit at high cumulative failure rates using both Weibul and Log-Normal.

- The Weibul function provides a much better fit at low cumulative failure rates.

Experimental data from:
Percolation and Statistics of Breakdown

*Weibul Distribution Function*

- The most commonly used CDF for describing reliability is the Weibul.
- This is because it better fits experimental data and because breakdown is believed to be a “weakest-link” type of problem which Weibul statistics describes.

- The Weibul function can be described in terms of percolation theory:

\[
\ln[-\ln(1-F)] = \ln \frac{A}{a} + \ln \left\{a_{ox}p - \ln \sum_{n=0}^{N_{bd}-1} \frac{(a_{ox}p)^n}{n!}\right\}
\]

where, \(A=\) oxide area, \(a=\) cell size, \(p=\) probability for any one unit failing.
Percolation and Statistics of Breakdown

Bi-Modal Weibul Distributions

- Sample sets with extrinsic failures will show Weibul distributions with two distinct slopes.

- The extrinsic portion of the distribution will generally result in smaller breakdown values with a smaller Weibul slope.

- For thin oxides, separating extrinsic and intrinsic distributions becomes more difficult because the intrinsic Weibul slope also becomes smaller.

Percolation and Statistics of Breakdown

Non-Linear Weibul Distributions

For thin oxides, the Weibul $t_{bd}$ distributions show non-linear behavior with a change of slope from high to low percentiles.

The Weibul $Q_{bd}$ distributions do not show this non-linear behavior.

The percolation model predicts a thickness dependence of the Weibul slope which is observed experimentally.

The smaller Weibul slope for thinner oxides is explained as follows: in the thinnest oxides, the conductive path consists of only a few traps and therefore has a larger statistical spread.

Percolation and Statistics of Breakdown

Critical Defect Density Required for Breakdown

- Percolation theory is able to predict the experimentally observed thickness dependence of $N_{bd}$.

- For thin oxides (~2.7 nm), $N_{bd}$ is independent of thickness and voltage.

- The thickness independence below 2.7 nm has been explained by the “effective” net defect size (trap or sphere radius) required to trigger breakdown.

Percolation and Statistics of Breakdown

*Area Dependence of the Modal Value*

- The modal value of breakdown is known to increase with decreasing area.

- Based on Weibul statistics it can be shown that

$$\eta_1 = \left( \frac{A_2}{A_1} \right)^{(1/\beta)}$$

- Since $\beta$ decreases with thickness, the area dependence becomes larger for thinner oxides.

Physical Models of Wearout and Breakdown

Experimental Observations of E-Field Dependence

- Several researchers have shown experimentally that at low fields the breakdown time is linear with $E_{ox}$.


For ultra-thin oxides (< ~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 inverse dependence of $t_{bd}$ on current density.

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.

Physical Models of Wearout and Breakdown

**Time-to-Breakdown Under Hot Electron Injection**

- The $t_{bd}$ under substrate hot electron injection is inversely proportional to the current density.

\[ V_b = -8.25 \, \text{V} \]
\[ A = 2.2 \times 10^{-7} \, \text{cm}^2 \]

**Physical Models of Wearout and Breakdown**

**Polarity Dependence of Breakdown**

- This polarity dependence essentially shifts the trap creation threshold relative to the Si anode Fermi level (not the SiO$_2$ conduction band).

- It has been shown that the polarity dependence can be approximately normalized by plotting $Q_{bd}$ versus $V_g$ [1].

The Trap Creation Model Describes the Thickness Dependence of $T_{bd}$

The Trap Creation Model Describes the Thickness Dependence of $T_{bd}$

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

$$
Q_{bd} \approx \frac{N_{bd}}{P_g}
$$
Physics, Statistics and Models

Summary

- A detailed review of the physics, statistics and models associated with the reliability of MOS devices was given.

- This provides the fundamental background information necessary for the second part of this tutorial on Reliability Characterization and Test Methodology.
PART II.

Reliability Characterization and Test methodology
PART II.

OUTLINE

1) Accelerated Stress Tests:
   a. Description of Tests
   b. Post-breakdown characteristics and modeling

II) Reliability Extrapolation
   a. Statistical Scaling
   b. Voltage and Temperature Acceleration

III) Extrinsic Oxide Breakdown
   a. Oxide thinning model
   b. Separation of Distributions
   c. Competing Distributions
Part II. Reliability Characterization and Test Methodology

1. Accelerated Stress Tests
Accelerated Stress Tests

- Constant Voltage
- Constant Current
- Voltage Ramp
- Current Ramp
- Stepped Voltage
- Stepped Current

\[ Q_{BD} = \int_{0}^{t_{BD}} i(t) \, dt \]
Constant Current $Q_{bd}$ for Ultra-Thin Oxides Exhibits a Current Density Dependence

Constant Current $Q_{bd}$ and $T_{bd}$ Independent of Thickness for Thick Oxides

E. Wu et al., IEDM, 1998
Use Constant Current Stress for Thick Oxides (Tox >~ 5 nm)

- Stressing occurs in Fowler-Nordheim regime ($V_g > ~4 \text{ V}$) where $J$ is dependent only on $E_{ox}$, independent of thickness.
- Due to scattering, the energy gained by the electron depends only on $E_{ox}$ (not on $V_g$), independent of thickness.
- The $N_{bd}$ and the Weibull slope are large and approximately independent of thickness.

- Therefore, for thick oxides the CCS $Q_{bd}$ and $T_{bd}$ depends only on current density and is independent of thickness.
- This is why CCS $Q_{bd}$ was used as a standard metric independent of thickness.
Use Constant Voltage Stress for Thin Oxides (Tox $<\sim 4$ nm)

- Stressing occurs in Direct-Tunneling regime ($V_g \lessapprox 4$ V) where $J$ is dependent on $V_g$ and thickness.
- The electron tunnels ballistically so the energy gained by the electron is simply the gate voltage independent of thickness.
- The $N_{bd}$ and the Weibull slope are small and depend on thickness.

- Therefore, for thin oxides the CVS $Q_{bd}$ and $T_{bd}$ depends on gate voltage and and is dependent on thickness.
- Therefore, CVS $Q_{bd}$ as a function of gate voltage is required to compare dielectrics. $Q_{bd}$ is also less sensitive than $T_{bd}$ on thickness.
Constant Voltage Stress for Thin Oxides

T. Nigam, IRPS, 1998

Constant Current

Constant Voltage

J=.5 A/cm²

J=.1A/cm²
Ramp Tests and Analysis JEDEC
V-Ramp Test (used mainly for extrinsics)
Post-Breakdown Characteristics

Devices observed to fail as:

- opens
- shorts
- high resistive paths
- diodes (polysilicon gate diffused into substrate)
- quantum point contacts (ultra-thin films)
Post-Breakdown Models of n-channel FET

$V_g > 0$

$V_g < 0$

Gate to Channel BD

Gate to Source/Drain BD

Failure Criteria in Standard GOI Tests Must be Modified

Ramped Voltage

Constant Current

Constant Voltage

Eric M. Vogel, Oxide Reliability Tutorial, IRW 2001
Breakdown Detection Becoming Difficult for ultra-thin films

Types of Breakdown:

• “Hard” ($I_{\text{post BD}} \sim V_{\text{post BD}}/R_s$)
  - thermal effects dominate
  - electrode melts/diffuses into oxide

• “Soft/Quasi” ($I_{\text{post BD}} \sim G_0 V^\delta$)
  - percolation conduction path
  - small power dissipation
  - limited thermal damage

• “Noisy” ($I_{\text{post BD}} \sim G_0 V^\delta$)
  - observed in large area devices
  - $I_{\text{stress}} \sim I_{\text{post BD}}$
Are “Soft” and “Hard” Breakdown The Same Mechanism?

⇒ “Soft”, “Quasi”, “Noisy” refer to event where limited thermal damage does not allow surge in current or compliance.

- Noise Explained as Trap-Trap transport. (K. Farmer et al., APL 1989)
- Multiple Tunneling Via Electron Traps, Occurs after critical # of SILC Traps (Depas et al., IEEE, TED 1996)
- Localized Damage Region, Noise is Dynamic Trapping/Detrapping (Lee et al., IEDM 1994)
- Insufficient Energy Transfer of Tunneling Electrons to Anode Holes (J. Bude et al., IEDM 1998)
Breakdown Becomes Softer for Larger Areas
Future Test Standards Will Use Noise As Failure Criteria

$\text{Ramped Current}$  $\text{Ramped Voltage}$  $\text{Current Noise}$

$\text{Voltage (V)}$ $\text{Time (s)}$ $\text{Voltage (V)}$ $\text{Time (s)}$ $\text{Voltage (V)}$ $\text{Time (s)}$

$t_{\text{ox}} = 3.0 \text{ nm}$  $t_{\text{ox}} = 3.0 \text{ nm}$  $t_{\text{ox}} = 3.0 \text{ nm}$

$A = 0.0005 \text{ cm}^2$  $A = 0.0005 \text{ cm}^2$  $A = 0.01 \text{ cm}^2$

$Slope \text{ Ratio}=16.64$  $Slope \text{ Ratio}=1.23$

$\text{Current (A)}$  $\text{Slope Ratio}$  $\text{Current Noise}$

$1 \times 10^{-12}$  $1 \times 10^{-11}$  $1 \times 10^{-10}$

$1 \times 10^{-9}$  $1 \times 10^{-8}$  $1 \times 10^{-7}$  $1 \times 10^{-6}$

$1 \times 10^{-5}$  $1 \times 10^{-4}$  $1 \times 10^{-3}$  $1 \times 10^{-2}$

$1 \times 10^{-1}$  $1 \times 10^{0}$  $1 \times 10^{1}$  $1 \times 10^{2}$
Soft Breakdown

“Soft”/”Noisy” Breakdown

\[ I_{bd} \ll I_{tunnel} + I_{SILC} \]
Device Consequences of Soft Breakdown

T. Pompl et al, 1999 IRPS

E. Wu et al, 1998 IEDM

- $G_m$ and $V_t$ Change Small
Device Consequences of Soft Breakdown

Gate-Source/Drain Breakdown More Serious

G-S/D BD More Probable as L is Decreased

Soft Breakdown

Summary

- Thermal Damage limited by Power Dissipation, \( P(t) = V(t)I(t) \) †
- Occurrence increases as:
  - \( t_{ox} \) decreases.
  - Area increases. (\( I_{\text{stress}} \sim I_{\text{post BD}} \))
  - \( V_{\text{stress}} \) decreases.
  - Constant current stress. (Stored energy decays with time)
- \( I_{\text{post BD}} \) limited by percolation path resistance. (\( I_{\text{post BD}} \sim G_o V^\delta \))
- Must assess effect on circuit performance
  - Gate-source/drain breakdown more serious.

Accelerated Stress Tests

Summary

• CVS should be used for thin oxides whereas CCS should be used for thick oxides.
• “Soft” and “Quasi” breakdown in ultra-thin films make detection difficult. (new detection techniques required)
Part II. Reliability Characterization and Test Methodology

2. Reliability Extrapolation
Intrinsic Reliability Extrapolation

\[
\frac{T_{bd,1}}{T_{bd,2}} = \left( \frac{A_2}{A_1} \right)^{\frac{1}{\beta}} \\
F(T_{bd}) = 1 - e^{-\left( \frac{T_{bd}}{\eta} \right)^{\beta}}
\]

There are three main extrapolations required to evaluate reliability:

1) Voltage and Temperature - the reliability of the dielectric needs to be known at the operating voltage and temperature

2) Area - the reliability of the dielectric needs to be known at the product area (typically 0.1 cm\(^2\))

3) Low cumulative failure - the reliability of the dielectric needs to be known at the appropriate cumulative failure rate (typically 100 ppm)
Intrinsic Reliability Extrapolation - Statistics

- The ratio of projected (A=0.1 cm², F=100 ppm) breakdown characteristic \( t_{bd} \) or \( Q_{bd} \) to measured (F=63%) breakdown characteristic for various test areas as a function of \( \beta \) is shown.

- The plot can be used to assess the effect of area and failure rate projection on measured reliability data.

\[
\frac{T_{bd,1}}{T_{bd,2}} = \left( \frac{A_2}{A_1} \right)^{\frac{1}{\beta}} \quad \quad F(T_{bd}) = 1 - e^{-\left( \frac{T_{bd}}{\eta} \right)^\beta}
\]
HISTORICALLY, $E$ vs. $1/E$ was the Debate
**TDDB models used in historical thick oxide studies**

<table>
<thead>
<tr>
<th>Authors &amp; year</th>
<th>Model used</th>
<th>thickness (nm)</th>
<th>E-range (MV/cm)</th>
<th>temperature (°C)</th>
<th>Gamma (decades/MV/cm)</th>
<th>Intrinsic/extrinsic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anolick &amp; Nelson 1979</td>
<td>E</td>
<td>&gt; 70</td>
<td>2-4</td>
<td>150</td>
<td>6</td>
<td>extrinsics</td>
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<tr>
<td>Crook 1979</td>
<td>E</td>
<td>30-110</td>
<td>2-5</td>
<td>25 - 160</td>
<td>7</td>
<td>extrinsics</td>
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<td>McPherson &amp; Baglee 1985</td>
<td>E</td>
<td>10</td>
<td>5-8</td>
<td>25-150</td>
<td>varies with Temp.</td>
<td>mixed</td>
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<tr>
<td>Chen, Hu et. al 1985</td>
<td>1/E</td>
<td>7.9</td>
<td>9-18</td>
<td>room</td>
<td>varies with Temp.</td>
<td>intrinsic</td>
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<tr>
<td>Hokari 1985</td>
<td>E</td>
<td>6.1 - 9.6</td>
<td>6 - 8.5</td>
<td>170-250</td>
<td>1.7 - 1.9</td>
<td>intrinsics</td>
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<tr>
<td>Hokari 1985</td>
<td>1/E</td>
<td>5.7 - 19</td>
<td>6 - 9.0</td>
<td>170-250</td>
<td>1.7 - 1.9</td>
<td>intrinsics</td>
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<tr>
<td>Yambe &amp; Taniguchi 1985</td>
<td>E-model</td>
<td>20</td>
<td>6 - 7.5</td>
<td>room</td>
<td>2.5</td>
<td>extrinsics</td>
</tr>
<tr>
<td>Boyko &amp; Gerlach 1989</td>
<td>1/E at 150C E at 60C</td>
<td>21</td>
<td>3 - 8</td>
<td>60 - 150</td>
<td>varies with E and T</td>
<td>extrinsics</td>
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<tr>
<td>Shiono &amp; Itsumi 1993</td>
<td>MTF*E² vs 1/E</td>
<td>11</td>
<td>6.5 - 11</td>
<td>125 - 200</td>
<td>1.1</td>
<td>intrinsics</td>
</tr>
</tbody>
</table>
Acceleration Parameters for Thick Oxides

E vs. 1/E Lifetime Extrapolation - Neither are Valid for Thin Oxides

\[ t_{50} = t_0 \exp \left[ \beta \left( \frac{1}{E_{ox}} - \frac{1}{E_s} \right) \right] \]

\[ \beta = 320 \frac{cm}{MV} \]

\[ t_{50} = t_0 10^{\gamma (E_s - E_{ox})} \]

\[ \gamma = 1 \text{ dec/MV/cm} \]

\[ \gamma = 2 \text{ dec/MV/cm} \]

\[ \gamma = 3 \text{ dec/MV/cm} \]
E and 1/E No Longer Considered Strictly Valid!
E and 1/E No Longer Strictly Valid! Why?

• The thermochemical-E model has been experimentally shown to be invalid.

• The anode hole injection model predicts 1/E only for thick oxides at high fields. For thin oxides at lower fields, the predicted dependence is neither E nor 1/E.

• The trap creation/hydrogen release model is not strictly E field dependent. An increasing $N_{bd}$ and sigmodal $P_g$ has been observed for low voltages.

• E vs. 1/E does not describe the physical defect generation process.
There are now two main debates:

1) Debate over the physical process of defect generation and breakdown (anode hole injection vs. hydrogen release).

2) Debate over the correct voltage dependence of breakdown.
Further long term studies required to determine correct voltage acceleration.

It is generally agreed that breakdown is gate voltage and current (electron energy and fluence) driven.
$N_{bd}$ has been observed to increase with decreasing $V_g$

- It is generally assumed that the voltage dependence of BD is due to defect generation and not $N_{bd}$.

- However, recent experiments have suggested an increasing $N_{bd}$ with decreasing $V_g$ which further challenges voltage acceleration.

Temperature Acceleration

- Temperature acceleration is observed to be non-Arrhenius.

- Different effective activation energies observed as a function of voltage.

Reliability Extrapolation

Summary

- Statistics is critical for extrapolation of area and F.
- Choice of voltage and temperature acceleration is critical.
- More work is required to determine and fundamentally understand correct acceleration parameters.
Part II. Reliability Characterization and Test Methodology

3. Extrinsic Oxide Breakdown
Extrinsic Oxide Breakdown

Origins of Extrinsic Breakdown
- Process Dependent.
- Particles/Contamination.
- Roughness at Interfaces.
- Atomic/Structural non-uniformity.

Main Problem
- Physics not known.
- Can not model breakdown.
Extrinsic Oxide Breakdown

A Few Studies of Extrinsic Breakdown

Extrinsic Oxide Breakdown

Effective Thinning Model

J.C. Lee, et al., TED 1988

\[ E_{bd} = \frac{V_{bd} - \Delta V}{t_{eff}} \]

Assuming a statistical distribution:

\[ D = -\ln(1-F) \]

\[ \Delta X_{ox} \]

\[ t_{eff} = t_{ox} - t_{def} \]
Extrinsic Oxide Breakdown

Separation of Distributions

Total Data Set

T=225 °C

Extrinsic

Intrinsic

Prendergast et al., IRPS 1995.
T_{ox} = 20 nm

Temperature E - Field MV/cm
175 C 8,9,10,11
195 C 8,9,10,11
205 C 7,8,9,10,11
225 C 6,7,8,9,10,11
245 C 6
300 C 9,10,11
350 C 8,9,10
400 C 7,9
Extrinsic Oxide Breakdown

Separation of Distributions

Intrinsic Analysis: Temperature Acceleration
Extrinsic Oxide Breakdown

Separation of Distributions

Intrinsic Analysis: Field Acceleration

- $E$ Field (MV/cm): 0.001, 0.01, 0.1, 1, 10, 100, 1000, 10000
- Temperature (°C): 195, 205, 225, 300, 350, 400, 450

Graph 1: T50% (Hrs.) vs. E Field (MV/cm)
Graph 2: Gamma (dec/MV/cm) vs. Temp (°C)
Extrinsic Oxide Breakdown

Separation of Distributions

Extrinsic Analysis: Temperature Acceleration

\[ \frac{1}{\text{Temp (1/K)}} \]

<table>
<thead>
<tr>
<th>T50% (Hrs.)</th>
<th>0.01</th>
<th>0.1</th>
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<th>100</th>
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<td>9 M V</td>
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<td>10 M V</td>
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<th>E Field (MV/cm)</th>
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</tbody>
</table>

Eric M. Vogel, Oxide Reliability Tutorial, IRW 2001
Extrinsic Oxide Breakdown

Separation of Distributions

**Extrinsic Analysis: Field Acceleration**

- **Graph 1:**
  - X-axis: Inverse of E Field (E Field (MV/cm))
  - Y-axis: T50% (Hrs.)
  - Data points are fit to different lines for different E Field values.
  - The graph shows a trend where T50% increases with decreasing E Field.

- **Graph 2:**
  - X-axis: Temp C
  - Y-axis: Field Acc Factor
  - Data points are shown for different temperatures, with the field acceleration factor decreasing as temperature increases.

- **Graph 3:**
  - X-axis: E Field (MV/cm)
  - Y-axis: Sigma
  - Data points are shown for different E Field values, with sigma values indicating an increase at lower E Field and a decrease at higher E Field.

**Actual Data Points:**
- Markers indicating measured data points.
- Lines are drawn to fit these points for analysis.

**Best Fit To High E Fields:**
- Lines drawn to represent the best fit for data points in high E Field regions.
Extrinsic Oxide Breakdown

Results from Boyko and Gelach’s Work:
(21 nm, 2.7-8 MV/cm, 60 - 150 °C, 14,000 devices)

- $E_a = f(E)$, $E_a = 1$ eV (5 MV/cm), $E_a = .2$ eV (8 MV/cm),
- $1/E$ model for $T= 150$ °C
- $E$ model for $T= 60$ °C
- $\sigma = f(E)$, $\sigma = 25$ (4 MV/CM), $\sigma = 10$(8 MV/CM)
- $\gamma = 1.7 - 5.4$ decades/MV/cm
Extrinsic Oxide Breakdown

**Competing Distributions**


t_{ox} = 11 \text{ nm},
A = 1 \times 10^{-6} \text{ cm}^2 - 2.45 \times 10^{-2} \text{ cm}^2

\[ f(t) = p_e f_e + (1-p_e) f_i \]

Extrinsics failing after intrinsics??
**Extrinsic Oxide Breakdown**

*Competing Distributions*

- $p$: fraction of population that can fail either extrinsically or intrinsically.

- $R_i(t), R_e(t)$: reliability functions of extrinsics and intrinsics.

\[ f(t) = p(f_e R_i + f_e R_e) + (1-p)f_i \]

intrinsics: $1/E$ model

extrinsics: $E$ model

\[ \beta_e = f(E) \]

\[ \beta_i \neq f(E) \]
Extrinsic Oxide Breakdown

Summary

• The causes for extrinsic breakdown are many and are process related. (Not all extrinsics are created equal !)
• Usually observed as early fails in a bimodal failure distribution.
• Variable field and temperature dependencies observed in experimental studies.
• Very difficult to model. (Don’t spend time to model spend time and effort to eliminate !)