ECE650: Reliability Physics of Nano-Transistors
Lecture 25: Theory of Soft and Hard Breakdown

Muhammad Ashraful Alam
alam@purdue.edu
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Outline

1. Oxide breakdowns need not be catastrophic

2. Observations about soft vs. hard breakdown

3. A simple model for soft/hard breakdown

4. Interpretation of experiments

5. Conclusions
PMOS Reliability with SBD

![Graph showing PMOS Reliability with SBD](image)

- Oxide Thickness (nm)
- V_{op}, V_{safe} (volts)
- Multiple SBD
- PMOS
- ITRS
- SBD Threshold
- 1st SBD

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Soft breakdown for PMOS

The poly-Si electrode has melted away over 20mm²


(9.5nm oxide)

The oxide is shorted after breakdown
- Localized increase in current through the gate observed mainly in thinner oxides at lower voltages.
- SBD conduction is non-ohmic — retains insulating property, while post-HBD conduction is ohmic.
Transistors after Soft Breakdown

The transistor characteristics unaffected by soft breakdown.

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Changes in the off-current insignificant

No GIDL (drain to body current) observed

1.7nm. Vg=3.8V (stress), Vd=1.2V (meas)

Changes in the off-current insignificant
For low input-impedance circuits, soft breakdown does not degrade $I_{DS}$ noise.
Threshold Voltage: Small at All Positions

Mean threshold voltage shift small regardless the BD position

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Const. Voltage vs. Const. Current Stress

Constant Voltage Stress

\[ V \]

\[ I_{\text{post}} \]

\[ \ln (I_{\text{gate}}) \]

\[ \ln (\text{time}) \]

Constant Current Stress

\[ I \]

\[ C_{\text{ox}} \]

\[ V_{\text{post}} \]

\[ V_{\text{init}} \]

\[ \ln (\text{time}) \]
Softer Breakdown for Thinner Oxides

Stress at -1mA/cm²

3.5nm  4.0nm  5.0nm  6.5nm

Constant Current Stress

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Softer breakdown for lower stress

4.0 nm oxide

Constant Current Stress

Voltage

Time
Softer with larger area, but less probable
Const V: Softer BD at Reduced Voltage

Expt. Evidence of SBD @ low VG

Performance unaffected by SBD

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Softer Breakdown for Constant Current

- Med. Time to Fail is the same for both meas.

- For Const. Voltage, $V_{postbd}$ is Voltage at 10mA/cm$^2$ after breakdown occurs.

- 4nm oxide structure stressed at -5.3V and -10mA/cm$^2$
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A Simple Model for SBD and HBD

(a) $t < \text{TBD}$, only tunneling

(b) $t = \text{TBD}$, BD current initiates

(c) $t > \text{TBD}$, transient heating

If $P(t)$ exceeds certain threshold, HBD is possible
# Area Independent breakdown Current

Large-area Test capacitor

<table>
<thead>
<tr>
<th>Device Area (cm²)</th>
<th>Current (µA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1E-8</td>
<td></td>
</tr>
<tr>
<td>1E-7</td>
<td></td>
</tr>
<tr>
<td>1E-6</td>
<td></td>
</tr>
</tbody>
</table>

Current scales with area before BD

Post-breakdown Current
Area-independent

Current scales with area before BD

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A Simple Model for SBD and HBD

\[ A \times C_{ox} \left( \frac{dV}{dt} \right) + A \times \alpha e^{-\beta / V} + \{ g_0 \} V^\delta = A \times J_s \]

Alam, ITED 2002, p. 232
Configuration and Conductance

Occurences

Conductivity (Arb. Units)

1 2 3 4

8 4 0

Conductivity (Arb. Units)
Statistical Distribution of Perc. Resistance

- Weakly thickness dependent
- $G_{\text{max}}/G_{\text{min}} = 5 - 10$

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$G_p$ is known, how to Determine $P_{\text{THER}}$?

$P = G_p V^2$

$G_{p,\text{crit}} = P_{\text{THER}}/V^2$

Based on ratio of soft to hard- BDs at $V_1$ and $V_2$, determine $P_{\text{THER}}$.

Use it can determine $V_{\text{safe}}$. 
Evidence that there exists a threshold for soft-breakdown!
PTHER from Stress Current Dependence

$J_s A$

$C_{ox}$ $R_t$ $G_P$

$V(t)$

Power

$V_{postBD}$

time

$V(t)$

$V_{postBD}$

Power vs $I_{Stress}$

$P_{THER} \sim 20 \mu W$

Alam, IEDM99, p. 449
Sune, IEDM01, p. 117
Breakdown always soft at 1.0V

\[ P_{\text{crit}} = 20 \ \mu W \]
\[ G_{\text{crit}} = \frac{P_{\text{crit}}}{V^2} = 20 \ \mu S \ \ ( @ V=1.0 \ \text{volt} ) \]

\( G_p \) can be experimentally determined

\[ \Rightarrow \text{Prob(} G_p > G_{\text{crit}} \text{) } << 1e-12 \]
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Soft Breakdown at Reduced Voltage

\[ P = G_p V_G^2 \]

Expt. Evidence of SBD @ low VG

Performance unaffected by SBD

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The theory interpreted for stress current is as follows:

- **BD softer with weaker stress**
- **BD is bimodal at intermediate stress**
- **More power is dissipated at larger stress**, HBD is more probable
- **Breakdown becomes softer with higher stress current**

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Conclusions

Soft and hard breakdown is distinguished by a thermal threshold related to power-dissipated during breakdown.

The statistical spread in soft-breakdown reflects the statistical distribution of the percolation resistance.

The breakdown characteristics under constant current stress vs. constant voltage stress are dramatically different, indicating difference in power dissipation in the two structures.

Remember that it is always power, not energy that dictates breakdown – otherwise adding a capacitor would have dramatically changed the breakdown distribution.
References


1) Explain why percolation resistance is area independent?

2) Why is the physical origin of the distribution of percolation resistance?

3) How would the ratio of hard and soft breakdown change with an auxiliary parallel capacitor in constant voltage stress? Explain.

4) What is the evidence from HBD that a thermal process may be involved?

5) In constant voltage stress, do you expect that BD would be harder for thicker oxide? Or does it not matter?

6) How might people have missed SBD even for thin oxides where BD in operating condition is expected?

7) Do you find a limitation of the SPICE like model used in the analysis?
Appendices

1. Few additional slides for SBD and HBD
2. Theory of nonlinear conduction through percolation resistance
3. Interpretation of SBD and HBD experiments.
4. Origin of soft-breakdown in series connected capacitors
(1) PMOS Reliability with SBD

![Graph showing PMOS Reliability with SBD](image)

- **PMOS**
- **Multiple SBD**
- **ITRS**
- **SBD Threshold**

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(1) Off-Current Increase Small at All Positions

Weir, INFQS01
(1) Compliance and Severity of Breakdown

KL Pey et al., IEDM 2002, p. 163.

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(1) Breakdown softer for larger capacitor


Largest Area -- smallest voltage drop

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(2) Nonlinear voltage dependence for Iperc

1. Quantum point-contact (Sune, IRPS01)
   - focuses on voltage dependence
   - voltage dependence from Fermi-functions

[Diagram showing trap configuration and potential]

2. Coulomb blockade (Nigam, IRPS03)
   - focuses on temp. dependence
   - voltage dependence from charging of small area capacitors

[Diagram showing hopping through the defect chain]
(3) Gp Distribution, Power Threshold

\[ P = V_{\text{stress}} I_{\text{perc}} \]

- Increasing number of HBD with stress voltage
- Sharp transition: 0.2-0.3 V increase converts all BD from soft to hard
(3) Interpretation of Area Dependence

Explains both post voltage distribution and bimodal breakdown.
• Breakdown is softer for thinner oxide.
• Bimodal BD at intermediate thickness.
• More power is dissipated in thicker oxides; makes HBD more probable.
Interpretation of Thickness Dependence

- Breakdown is softer for thinner oxide.
- Bimodal BD at intermediate thickness.
- More power is dissipated in thicker oxides; makes HBD more probable.
Interpretation of thickness dependence

Expects $V_{\text{post}}$ distribution and bimodal soft/hard breakdown.
Energy = \frac{1}{2} (C + C_{aux}) V^2

Power = \frac{1}{2} (C + C_{aux}) V^2 / R (C + C_{aux})

= \frac{1}{2} V^2 / R

Series Inductor: Keep Energy the same, change power (Satake, VLSI00)
(4) Lifetime of Series connected capacitors