ECE695: Reliability Physics of Nano-Transistors
Lecture 30: Breakdown in Dielectrics with Defects

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Outline

1) Introduction

2) Theory of pre-existing defects: Thin oxides

3) Theory of pre-existing defects: thick oxides

4) Conclusions
Theory vs. experiment: large bandgap solids


<table>
<thead>
<tr>
<th>Materials</th>
<th>$\mathcal{E}_g$ (eV)</th>
<th>$E_B$ (predicted)</th>
<th>$E_B$ (observed)</th>
<th>Reference</th>
<th>$\hbar\omega_o$ (eV)</th>
<th>$E_B$ (predicted)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CdS</td>
<td>2.5</td>
<td>$1.7 \times 10^7$</td>
<td>$2 \times 10^6$</td>
<td>(1)</td>
<td>0.038</td>
<td>$4.1 \times 10^6$</td>
</tr>
<tr>
<td>ZnSe</td>
<td>2.6</td>
<td>$1.7 \times 10^7$</td>
<td>$2 \times 10^6$</td>
<td>(1)</td>
<td>0.03</td>
<td>$3.6 \times 10^6$</td>
</tr>
<tr>
<td>ZnO</td>
<td>3.3</td>
<td>$2.2 \times 10^7$</td>
<td>$4 \times 10^6$</td>
<td>(1)</td>
<td>0.07</td>
<td>$6.4 \times 10^6$</td>
</tr>
<tr>
<td>SiO$_2$</td>
<td>9.0</td>
<td>$6.1 \times 10^7$</td>
<td>$9 \times 10^6$</td>
<td>(2,3)</td>
<td>0.12</td>
<td>$1.4 \times 10^7$</td>
</tr>
<tr>
<td>NaCl</td>
<td>8.0</td>
<td>$5.5 \times 10^7$</td>
<td>$1.6 \times 10^6$</td>
<td>(1)</td>
<td>0.024</td>
<td>$6.2 \times 10^6$</td>
</tr>
</tbody>
</table>

Poor correspondence between theory and experiments for larger-gap materials ….
Damaged by plasma etching

Damaged by plasma etching

Voltage stresses the oxide and creates the damage
Damage during electrostatic discharge (nonequilibrium pre-existing defects)

Similar to plasma charging damage
Breakdown with preexisting defects

\[
1 - F = (1 - F_{m=0})^{N_0} (1 - F_{m=1})^{N_1} (1 - F_{m=2})^{N_2} \ldots (1 - F_{m=M-1})^{N_{m-1}}
\]

\[
1 - F = (1 - q^M)^{N_0} (1 - q^{M-1})^{N_1} (1 - q^{M-2})^{N_2} \ldots (1 - q^{M-m+1})^{N_{m-1}}
\]

\[
-\ln(1 - F) = N_0 q^M + N_1 q^{M-1} + N_2 q^{M-2} + \ldots = N_0 q^M \left[1 + \frac{N_1}{N_0} \frac{1}{q} + \ldots\right]
\]
Breakdown with preexisting defects

\[
\ln(-\ln(1-F)) = \ln N_0 + M \ln q + \ln\left[1 + \frac{N_1}{N_0} \frac{1}{q} + \ldots\right] \quad q = at^\alpha = \left(\frac{t}{\eta_0}\right)^\alpha
\]

\[
\cong \ln N_0 + \beta \ln\left(\frac{t}{\eta_0}\right) + \frac{N_1}{N_0} \frac{1}{q} = \ln N_0 + \beta \ln\left(\frac{t}{\eta_0}\right) + \frac{N_1}{N_0} \left(\frac{\eta_0}{t}\right)^\alpha
\]

\[
\lambda \equiv \frac{dF_n}{dt} / (1 - F_n) = (N_0 \frac{\beta}{\eta_0^\beta}) t^{\beta-1} \left[1 + \frac{N_1 \eta_0^\alpha}{N_0} \left(\frac{\beta - \alpha}{\beta}\right) \frac{1}{t^\alpha}\right]
\]

Infant mortality, burn-in protocol …
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Background: Analogy to Fracture Mechanics

1. Leonardo Vinci experimenting with strength of wires
2. Two sciences by Galileo: One is the fracture strength of Venetian ships
3. WWII – 4700 liberty ships made by welded parts, 1200 damaged, 200 fractured, 10 split in half.
4. Comet disaster due to rivet joint 

Critical-sized pre-existing defects can lead to dramatic failure in strength of materials
Pre-existing defects, field enhancement, and breakdown in thick insulators (e.g. polymers)

Defects enhance local electric field and reduce breakdown strength
Defects and fields ...

\[ E \equiv E_0 \sqrt{\frac{l_x(p)}{p}} \]

\[ E = E_0 \left(1 + \frac{l_x}{l_y}\right) = E_0 \left(1 + \sqrt{\frac{l_x}{\rho}}\right) \]

\[ \rho \equiv l_y^2 / l_x \]
Analogy to resistor network

Defects reduce breakdown current ....
Small-cluster size distribution

\[ n_1(p) = 1 \times p \times (1 - p)^4 \]

\[ n_2(p) = 2 \times p^2 \times (1 - p)^6 \]

\[ n_3(p) = 2 \times p^3 \times (1 - p)^8 + 4 \times p^3 \times (1 - p)^7 \]

\[ n_s(p) = \sum_{t} g_{st} \times p^s \times (1 - p)^t \]
Size distribution and critical defect size

At a defect level $p$, most probable size of defect is $l_c(p)$

\[ n_1(p) = L^2 p^{l_x} (1 - p)^{2l_x + 2} \]
\[ \sim L^2 p^{l_x} \quad (p \to 0) \]
\[ p^{\langle l_x \rangle} L^2 \sim 1 \Rightarrow \]
\[ \langle l_x(p) \rangle = \frac{-2 \ln L}{\ln p} \]
Breakdown field for islands of size $L_c$

$$E_0^{\text{crit}} \sqrt{\langle l_x(p) \rangle} / \rho = E_{BD}$$

$$\langle l_x(p) \rangle = \frac{-2 \ln L}{\ln p} = \rho \left( \frac{E_{BD}}{E_0} \right)^2 = \rho \left( \frac{LE_{BD}}{V_{\text{app}}} \right)^2$$

$$\frac{V_{\text{app}}}{LE_{BD}} = \sqrt{\frac{\rho \ln p}{-2 \ln L}}$$

$V_{BD}$ reduces to zero at sample size $L$ goes to infinity, because large defects is present with probability 1.

Smaller $\rho$, larger $V_{BD}$
$V_{BD}$ distribution close to percolation threshold

$$1 - F(E_0) = \prod_{i=1}^{n} [1 - f_i(E_0)]$$

$$\approx 1 - \sum_{i=1}^{n} f_i(E_0) - \sum_{i=1}^{n} f_i(E_0)$$

$$\equiv e^{-Ag_1(E_0)}$$

Defect density that breaks at $E_0 = \frac{V_{app}}{L}$

$$\ln(-\ln(1 - F(E))) = \ln A + \ln g_1(E)$$
Size distribution at percolation threshold

\[ g_1(p) \equiv L^{-2} n_1(p) \]

\[ = p^{l_x} \times (1 - p)^{2l_x + 2} \]

\[ \sim l_x^{-\tau} \quad @ \quad p = p_c \]

\[ \langle l_x \rangle = \rho \left( \frac{E}{E_0} \right)^2 \]

\[ g_1(E) \sim \rho^{-\tau} \left( \frac{E}{E_0} \right)^{-2\tau} \]
Distributed failure probabilities

\[ W \equiv \ln(-\ln(1 - F(E))) \]
\[ = \ln A + \ln g_1(E) \]
\[ = \ln(A \rho^{-\tau}) + 2\tau \ln\left(\frac{E_0}{E_{BD}}\right) \]
\[ = \ln(A \rho^{-\tau}) + 2\tau \ln\left(\frac{1}{E_{BD}} \frac{V_{\text{app}}}{L}\right) \]

HW: Show that larger area oxides fail at smaller voltages.
What does it all mean (ramp voltage tests)?

$n_s(p_c) \sim s^{-2}$
Conclusions

The basic steps of breakdown processes are essentially the same for thin and thick oxides; the key differences are

1) Breakdown in thick oxides is extrinsic, dominated by defects, while that of thin oxide is intrinsic, dominated by contacts.

2) Breakdown in thick oxides is correlated (Lichtenberg figures), while the BD in thin films is uncorrelated.

3) The breakdown strength of thick oxides is often dramatically reduced due to pre-existing defects. In this sense, the physics of fracture and the physics of dielectric breakdown are closely related.
The percolation theory is discussed in detail in 2009 Summer School Lectures on “Nanostructured Electronic Devices: Percolation and Reliability” [http://nanohub.org/resources/7168]


Plasma charging figure taken from [http://www.timedomaincvd.com/CVD_Fundamentals/plasmas/plasma_damage.html]
Review questions

1. What is the difference between extrinsic vs. intrinsic breakdown?
2. Does gas dielectric have extrinsic breakdown? Why or why not?
3. What does ESD damage and the plasma damage to thin oxides?
4. Can you explain the physical meaning of infant mortality? How does it relate to yield of semiconductor manufacturing?
5. Can you reinterpret the Apgar tests in terms of infant mortality?
6. What is the difference between the Weibull for thick vs. thin oxides?