Reliability Testing for the Next Generation of Microelectronic Devices

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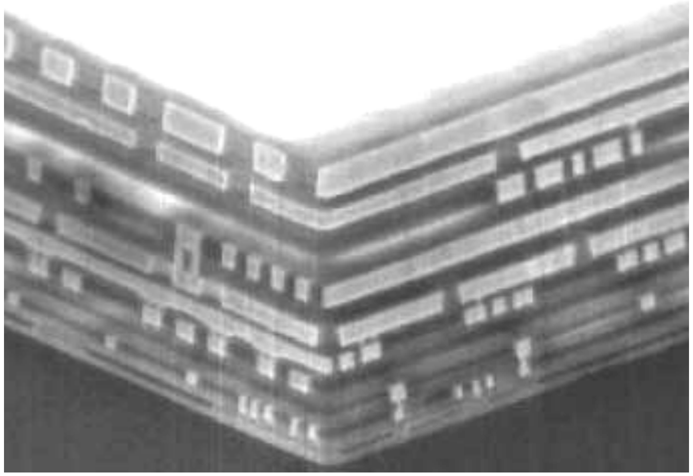
IC Reliability: Dielectric Breakdown

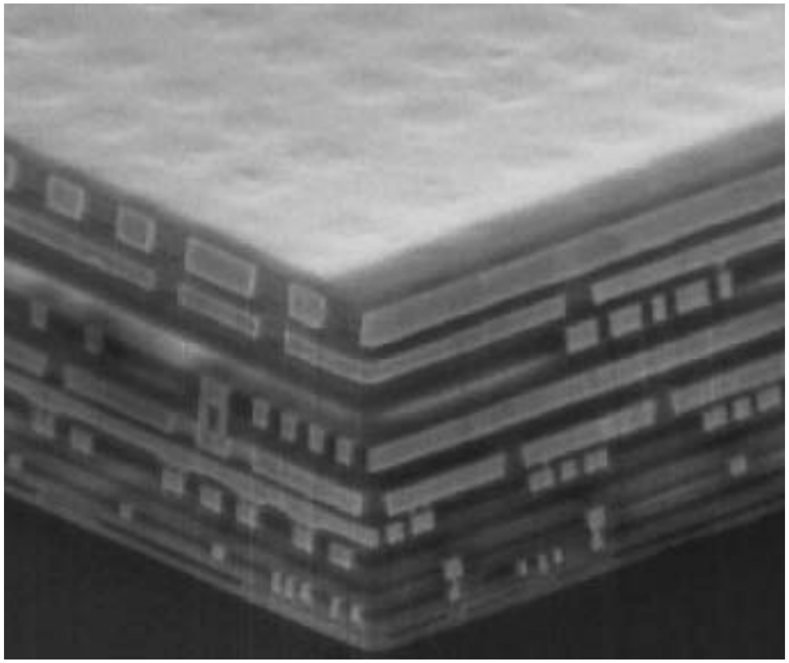
- Dielectric breakdown is a fundamental physical phenomenon that has been studied for over 100 years. No solution yet.
- Reliability of integrated circuits is becoming a problem as we approach the fundamental limits at which we can pattern and conventional materials.
- Dielectrics break down due to exposure to high temperatures, high electric fields and due to metal ion contamination inside them.



Dielectric Breakdown - Interconnects

- SiCOH is a family of organosilicate low-k materials used to separate copper interconnects.

- Interconnect reliability may be comprised as thinner materials operate at higher temperatures and field strengths.



- Copper ion diffusion into the low-k dielectric is suspected to facilitate the breakdown of the material.

- Experimental results will show how the effect of copper diffusion can be quantified and expressed in a model.

Experiment – Dielectric Stack

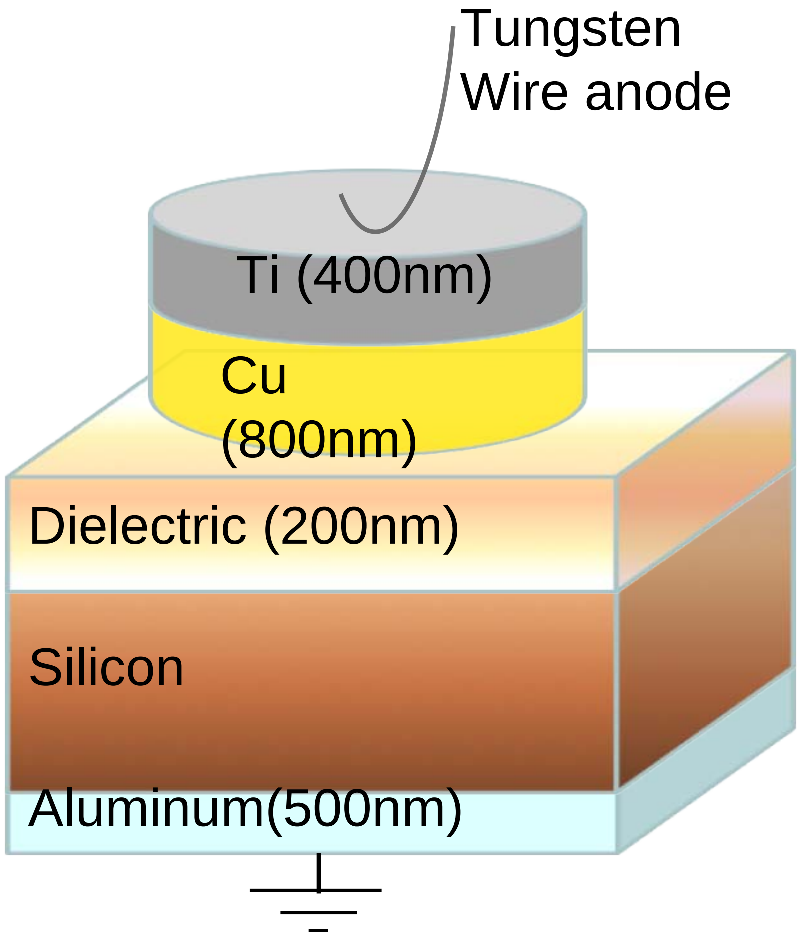


Figure 1: The Dielectric Stack used for I-t and I-V testing.

- 2 mm diameter dots were deposited directly on low-k, forming a pseudo 1-d system.
- A titanium cap on the copper was used to prevent copper oxidation during elevated temperature testing.
- An aluminum blanket on cathode was used for the backside electrical contact.

Experiments - I-t Testing

- Time dependent dielectric breakdown (TDDB), or I-t testing is used to determine breakdown due to wear-out of the interconnect.

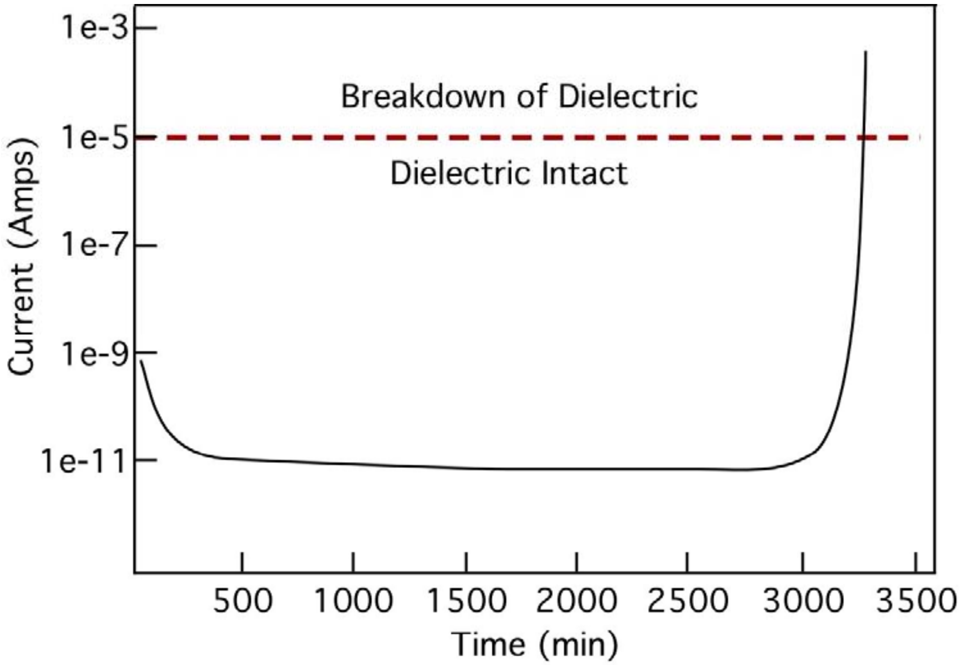


Figure 4: A current vs time (I-t) profile. Sample stressed at 200ºC and 3.2 MV/cm.

- TDDB data was collected over the last year and indicated a common mechanism for failure between SiCOH and SiO2.

- A key parameter, the intrinsic breakdown strength of the dielectric, was needed to model TDDB, which is difficult to get from an I-t test.

Experiment – I-V Testing

- Testing Conditions:
  - N_2 purged e-tester
  - 150ºC to 250ºC
  - 30 minutes of anneal

- I-V testing was used to compare with standard industry practice.

- At the high ramp rates (0.5V/s) normally used, breakdown is not affected by metal ion diffusion.

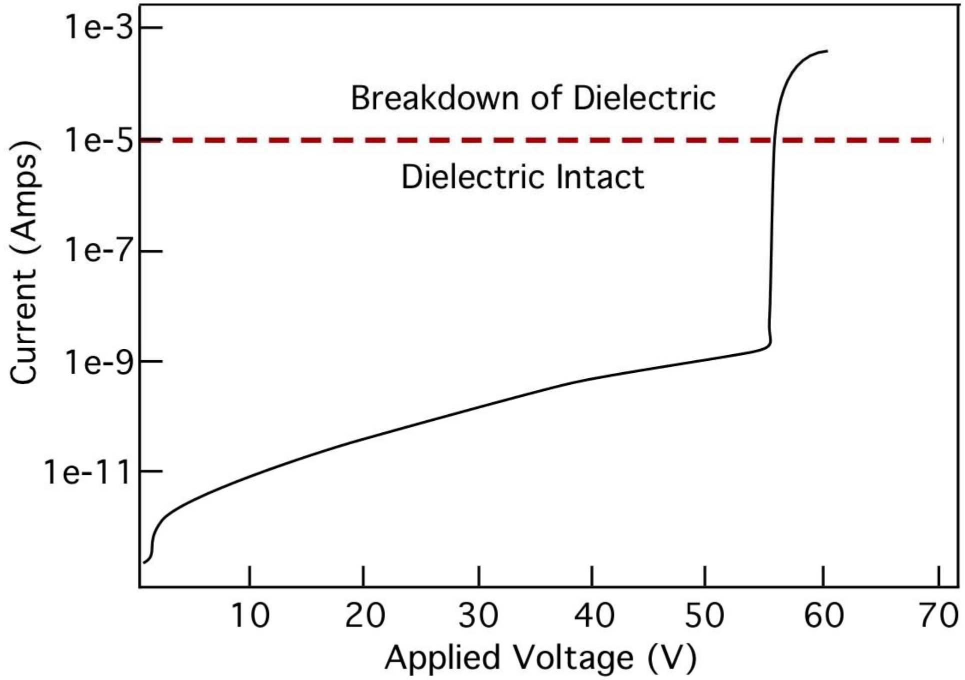


Figure 2: A typical Current/Voltage profile – Cu dot, 250ºC, voltage ramp rate of 0.5V/s.

- We define intrinsic breakdown as the breakdown field required to cause failure in the absence of metal ion diffusion.

Proposed Failure Mechanism

- Cu interacts with the interfacial oxygen and moisture to form a non-stoichiometric oxide (Cu_xO_y).
- The combination of moderate temperatures (<300 C) and an external electric field during operation may induce the breakdown of the copper oxide to ions.
- The Cu oxide, acts as the source of the Cu ions that are available for diffusion.
- Cu ions, driven by the applied field, drift through the dielectric and pile up at the cathode.
- Local field at the cathode rises allowing electrons to tunnel into dielectric conduction band leading to failure.

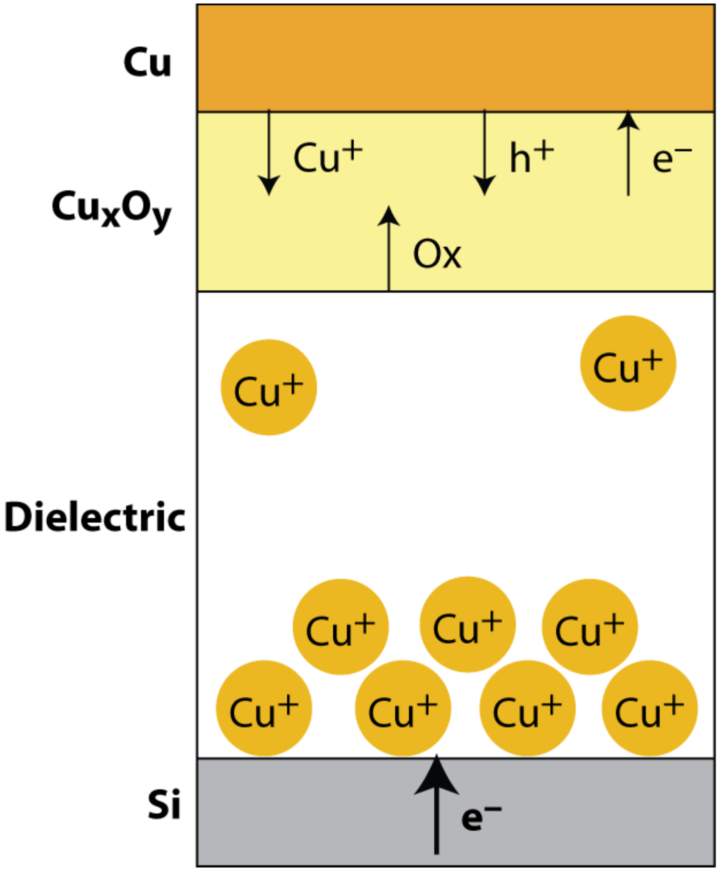


Figure 5: Mechanism of copper drift through low-k

Model- Equations

- Continuity Equation for Cu Concentration

$$\frac{\partial C_{Cu}}{\partial t} = -\nabla \cdot \left\{ \underbrace{-D_{Cu}\left[1+\left(\frac{\alpha}{k_B T}\right)C_{Cu}\right]}_{\text{Diffusion}} \nabla C_{Cu} - \underbrace{\mu_{Cu}\nabla V C_{Cu}}_{\text{Convection}} \right\}$$

- Poisson’s Equation

$$-\nabla \cdot (\varepsilon\varepsilon_0 \nabla V) = qC_{Cu}$$

C_{cu} = Cu ion concentration
D_{cu} = Cu diffusivity
α = Cu elastic stress constant
μ_{Cu}= Electrical mobility

Model- Boundary Conditions

- Initial and Boundary Conditions

$$\mathrm{t} = 0 \qquad C_{Cu}(x,0) = 0 \quad E\left(x,0\right) = 0$$

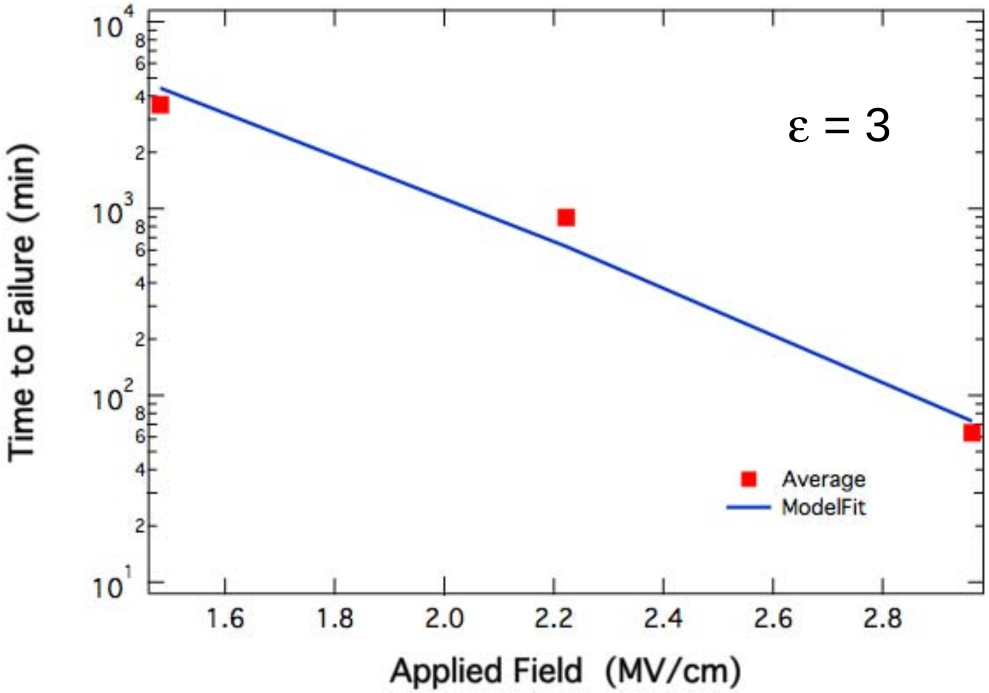
$$\mathrm{x} = 0 \qquad C_{Cu} = C_e$$

$$\underbrace{V = V_0}_{\text{I-t Testing}} \qquad \underbrace{V = a * t + b}_{\text{I-V Testing}}$$

$$\mathrm{x} = \mathrm{L} \qquad \mathrm{J} = -D_{Cu}\frac{\partial C_{Cu}}{\partial x} - \mu_{Cu} C_{Cu}\frac{\partial V}{\partial x} = 0 \qquad V = 0$$

- Breakdown occurs when field at x = L exceeds 4.5 MV/cm

Failure without a Barrier – SiCOH



- γ values are very close to SiO_2 hinting at a common mechanism.
- A values are very different reflecting differences in copper diffusivity and solubility in the two materials.

$$TTF(s) = A\exp\left(\frac{E_a - \gamma E_{app}^2}{k_B T}\right) f(C_e, T, E_{app})$$

Model Parameters [experiments @ 250 ˚C]

Material	A	γ (C^2m^2/J)
SiO2 (k = 4)	9.56×10^{-13}	2.62×10^{-37}
SiCOH (k = 3)	1.16×10^{-10}	2.87×10^{-37}

Results- Dot Material Effects

- The intrinsic breakdown of the dielectric is determined using aluminum contacts. Aluminum ions do not enter the dielectric.

- The copper samples show the effect of ion diffusion, especially at low ramp rates.

- Experiments using very slow ramp rates are essentially equivalent to a standard I-t test.

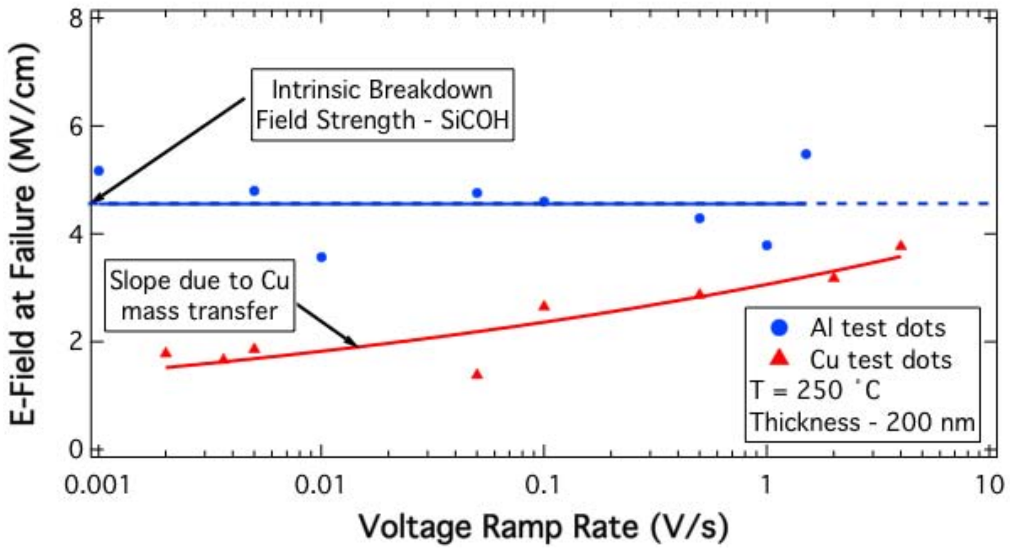
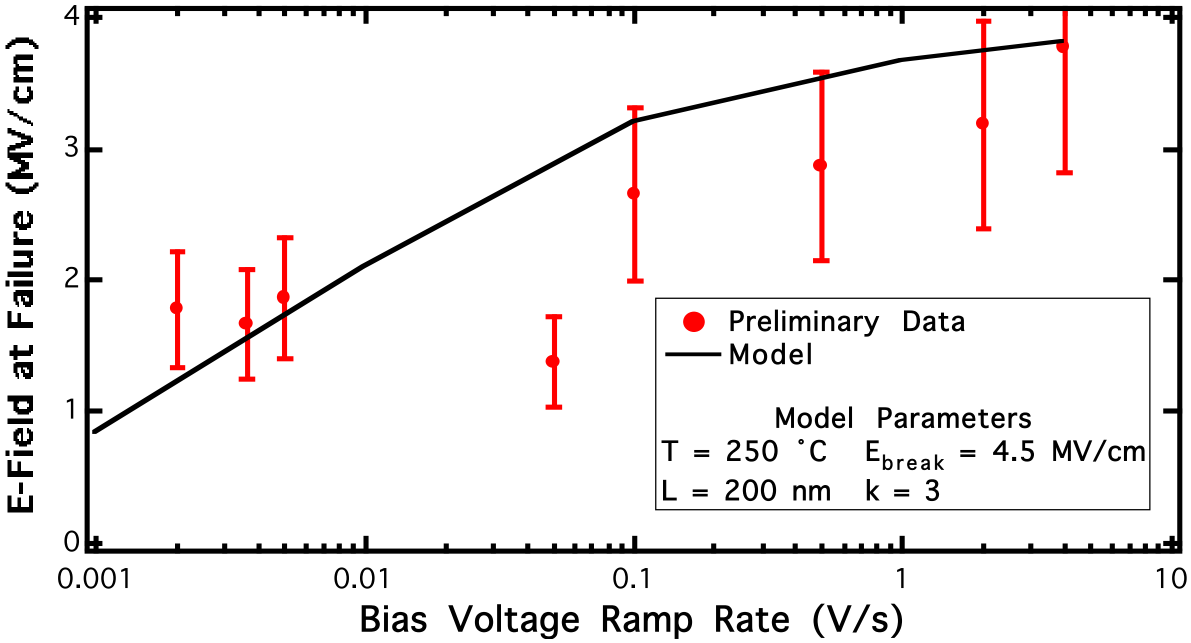


Figure 3: Breakdown field of copper and aluminum test dots as a function of ramp rate.

Comparison with Experiment – SiCOH

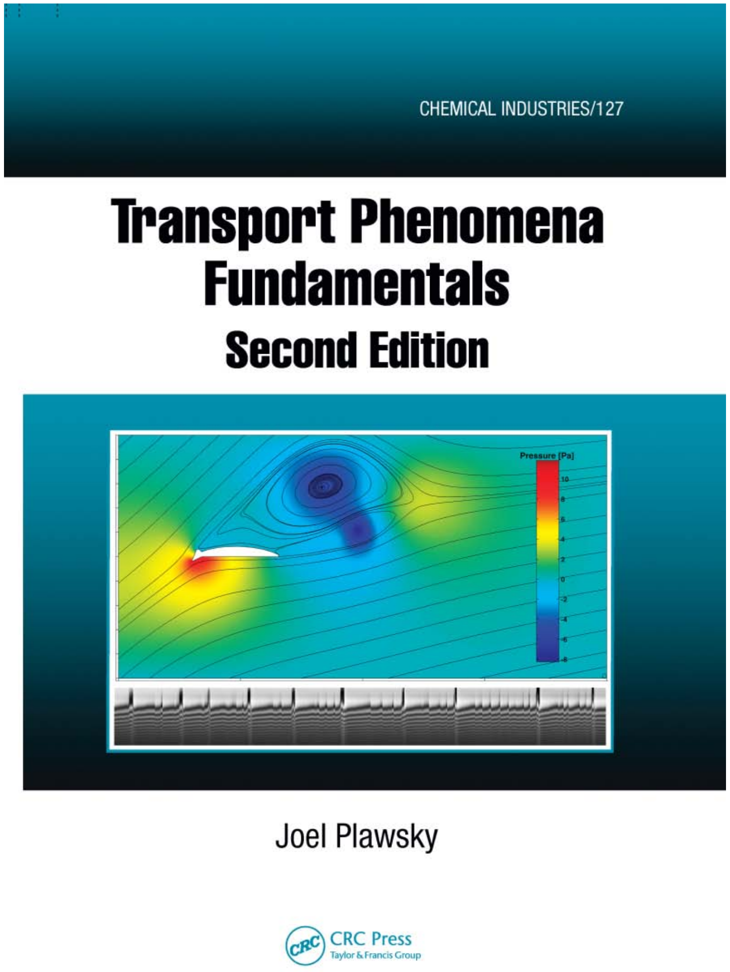


- Experimental data confirms theoretical prediction.
- Model is able of reproducing the trends in breakdown field.
  - Further improvements will occur once we have better physical property data for SiCOH.

Conclusions

- The ramp rate of an I-V test may be used to determine the failure mechanism of the dielectric breakdown in dielectric materials.
  - The use of inert metal contact defines the ‘intrinsic’ breakdown strength.
- The field strength at breakdown decreases with ramp rate when metal contacts that can be ionized and injected into the dielectric are used.
- The model was adapted to include a time-dependent voltage and a preliminary comparison of the model to our experimental data shows good agreement.

Textbook Incorporating Comsol



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