Reliability of Embedded Planar Capacitors: A Review

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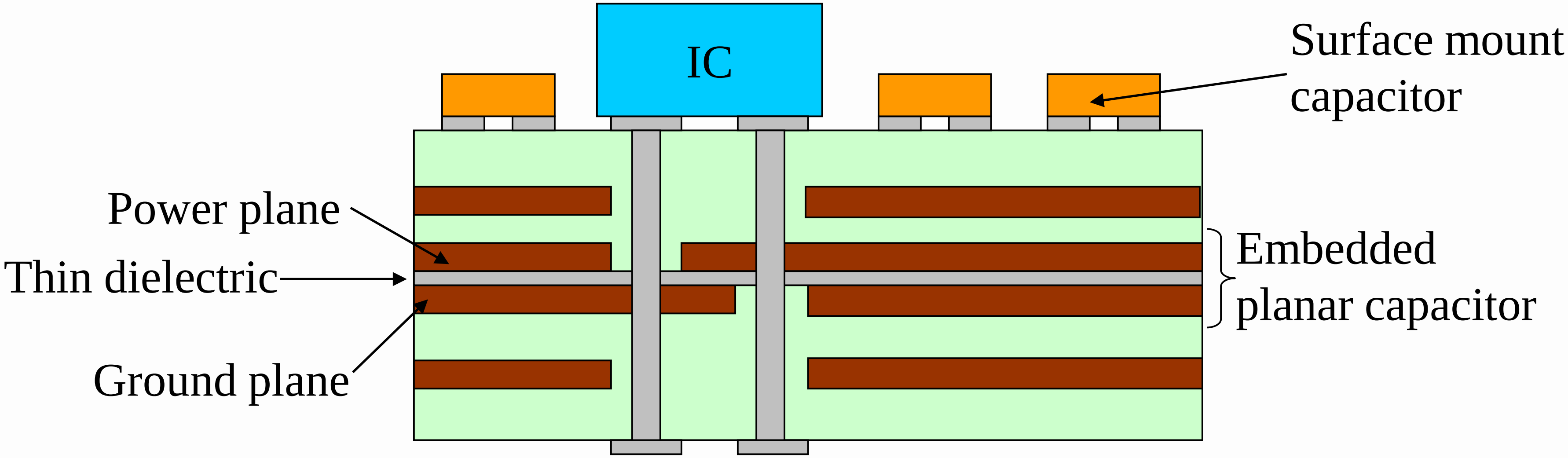
Outline

- **Introduction**
- Overview of Reliability Studies
- Conduction Mechanism
- Conclusions

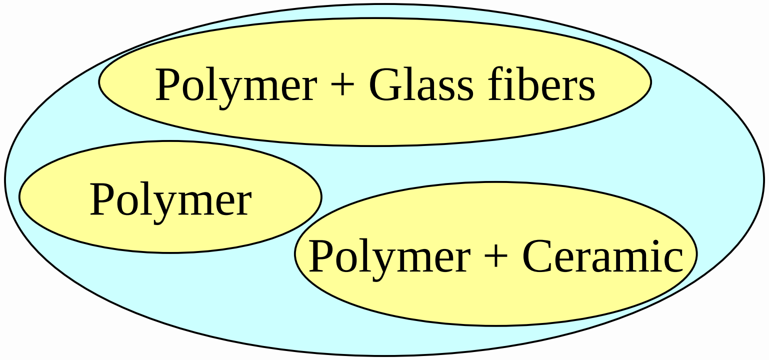
Embedded Planar Capacitors

- Embedded planar capacitors are thin laminates embedded inside a PWB that serve both as a power/ground plane and as a parallel plate capacitor.
- These laminates extend throughout the board and consist of a thin dielectric (8-50 μm), sandwiched between two copper layers.
- Their low parasitic inductance makes them effective replacements for discrete local decoupling capacitors that function at high frequency.



Dielectric Materials

- The dielectric material in a planar embedded capacitor can be:
  - Polymer (such as epoxy or polyimide)
  - Polymer reinforced with glass fibers (to provide mechanical strength).
  - Polymer filled with high dielectric constant ceramic



- The dielectric constant of pure polymer or polymer reinforced with glass fibers is low (typically <5).
- Polymer ceramic composite (polymer filled with ceramic powder) is one of the most promising materials for embedded capacitors due to its higher dielectric constant.

Why Polymer-Ceramic Nanocomposites?

- Pure ceramic dielectrics are brittle and require processing temperatures (~1100°C) that are much higher than the processing temperature of typical PWB manufacturing process (~300°C).

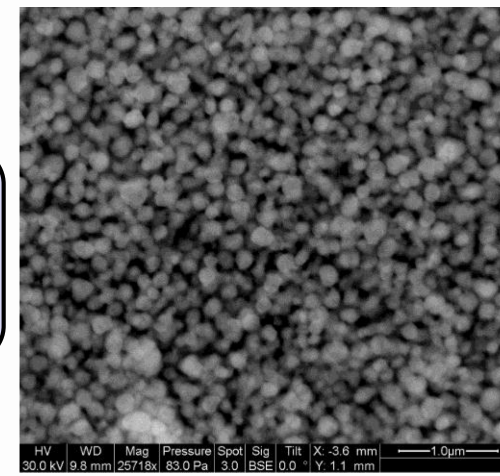
Polymer
Low processing temp. (~200°C)

+

Ceramic
High dielectric constant (~1000)

→

Composite
Low processing temp. (~200°C)
Moderately high dielectric constant (~30)



- The polymer typically used is epoxy.
- The ceramic widely used is Barium Titanate ($BaTiO_3$) whose dielectric constant (ε) can be as high as 15,000 in the crystalline phase.

The effective dielectric constant (ε_c) of the composite can be increased by increasing the ceramic loading (up to 50-60% by Vol.)

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Reliability of Embedded Planar Capacitors

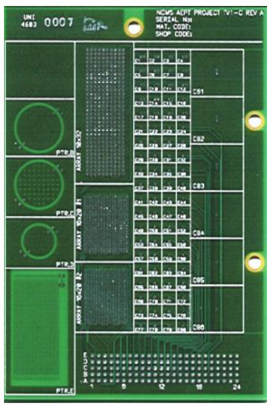
- Failure of an embedded capacitor can lead to board failure since these capacitors are not reworkable.
- Change in electrical parameters of an embedded capacitor, such as:
  - capacitance (*C*),
  - dissipation factor (*DF*), and
  - insulation resistance (*IR*),

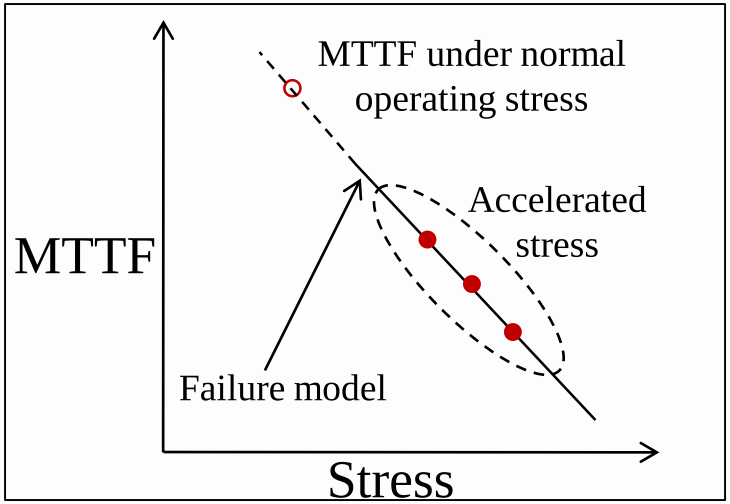
  can affect a circuit connected to these capacitors.

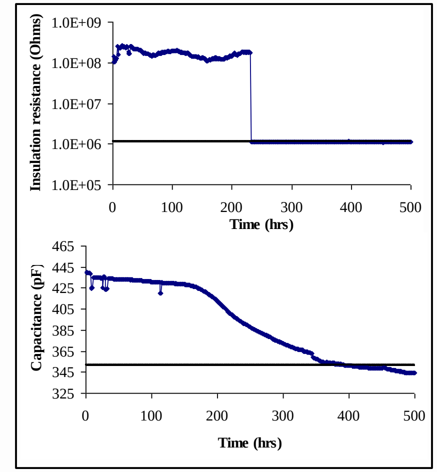
Motivation for CALCE Research on Embedded Planar Capacitors

- Adoption of embedded planar capacitors would be encouraged by availability of
  - failure models;
  - long term reliability data; and
  - insights into failure mechanisms (e.g., the mechanism of leakage current).

CALCE's Reliability Testing of Embedded Capacitors







Test vehicle of embedded capacitor

Accelerated tests:
1) Temperature and voltage
2) Temperature-humidity-bias

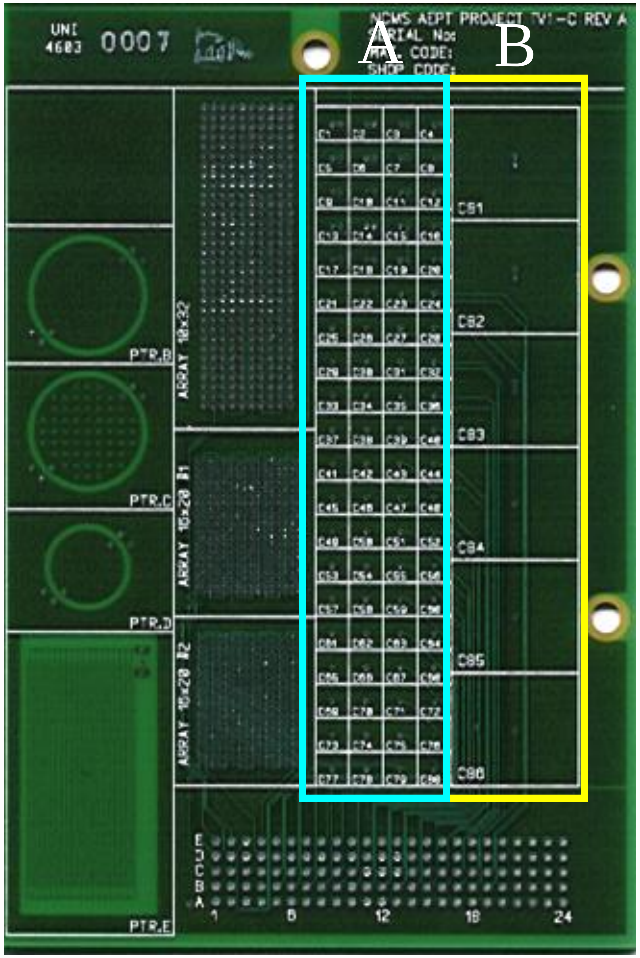
Measure electrical parameters in-situ
1) Capacitance (100 kHz)
2) Dissipation factor (100 kHz)
3) Insulation resistance (10V)

Apply failure criterion and find failure statistics (e.g., MTTF[1])

Failure analysis and design of experiments to identify the failure mechanism

[1]MTTF=Mean time to failure

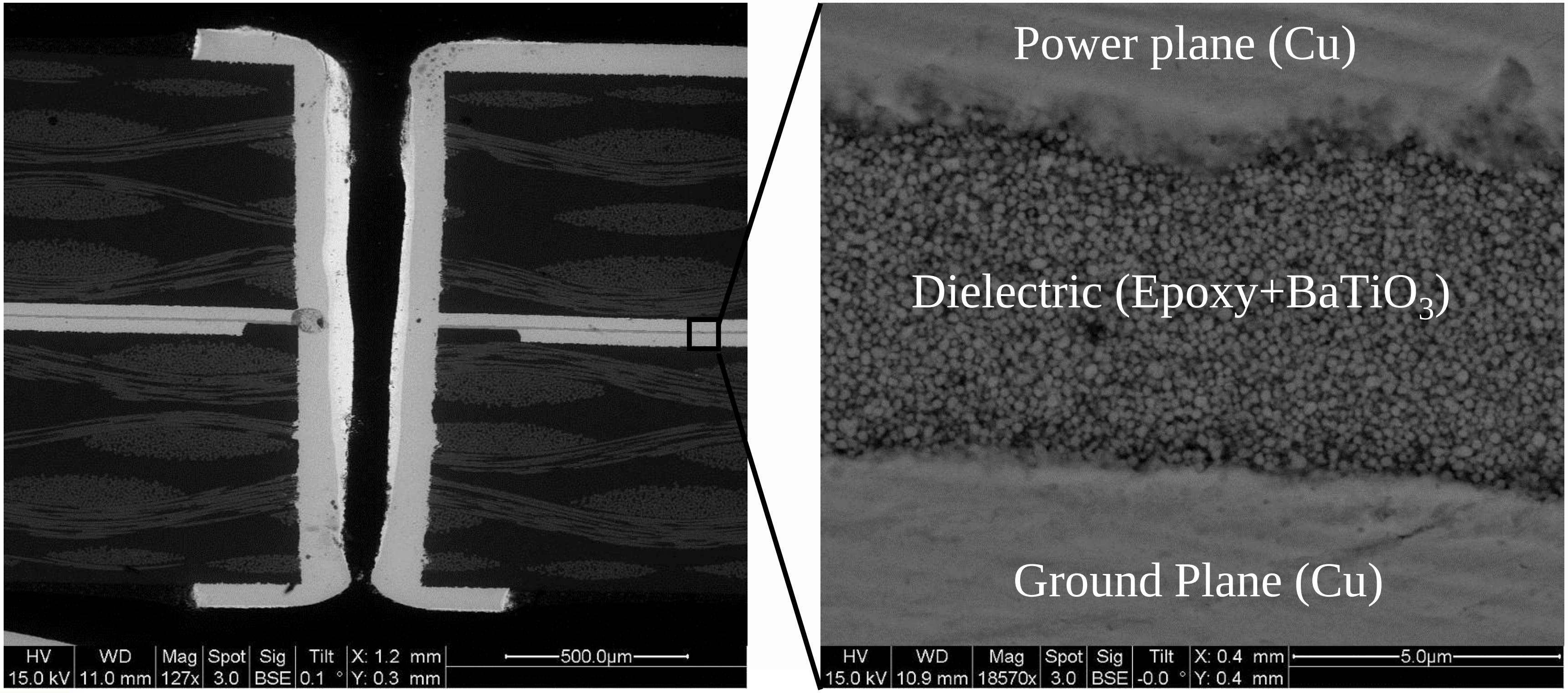
Test Vehicle



- The *test vehicle* was a 4-layered PWB in which a commercially available planar capacitor laminate formed layer 2 and layer 3.
- The *power plane was etched* at various locations to form individual capacitors and the ground plane was continuous.
- *Two sizes* of capacitor were investigated:
  - Group A (small): 0.026 in^2, 400 pF; 80 capacitors/test vehicle
  - Group B (large): 0.19 in^2, 5 nF; 6 capacitors/test vehicle.
- The *failure criteria* used were:
  - 20% decrease in capacitance (C)
  - increase in dissipation factor (DF) by a factor of 2
  - drop in insulation resistance (IR) to approximately 1.1 MOhms.

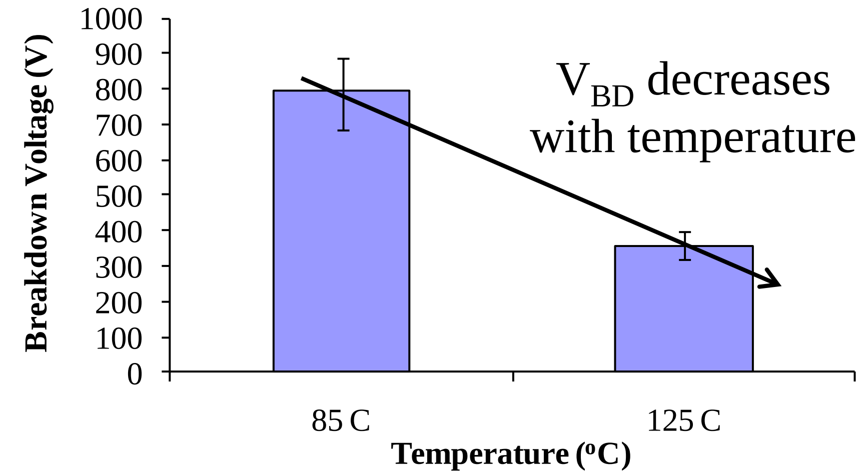
Sectional View of an Embedded Capacitor

- Each capacitor had its power plane connected to a PTH and the ground plane was common for all capacitors.
- The dielectric (8 μm thick) was a composite of $BaTiO_3$ of 250 nm mean diameter loaded to 45% by volume in epoxy.



Stress Levels for Life Testing

- Maximum temperature (T_{max}) and voltage (V_{max}) were selected such that:
  - T_{max} < 130^{o}C (maximum operating temperature of the PWB).
  - V_{max} < V_{BD} (breakdown voltage at that temperature).

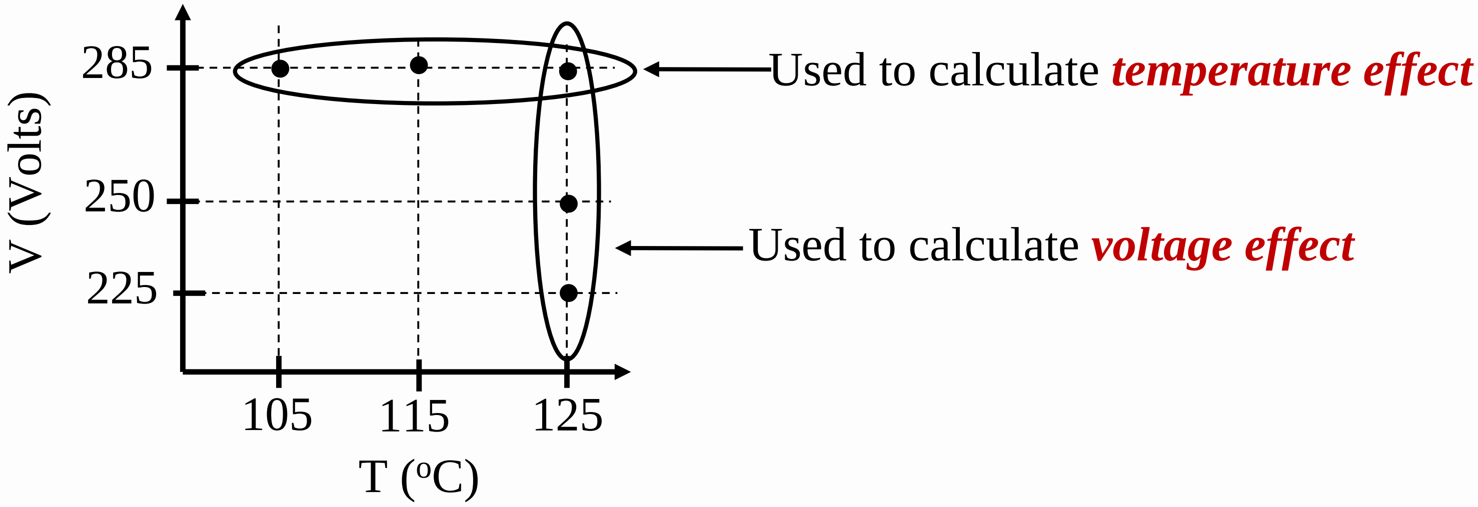


Measurement of breakdown voltage (V_{BD}) on 10 small capacitors

- The reduction in the breakdown voltage with temperature can be explained by an increase in free volume of the polymer matrix.

Design of Experiments for Lifetime Modeling

- Failure terminated highly accelerated life tests (HALT) were conducted at multiple stress levels.

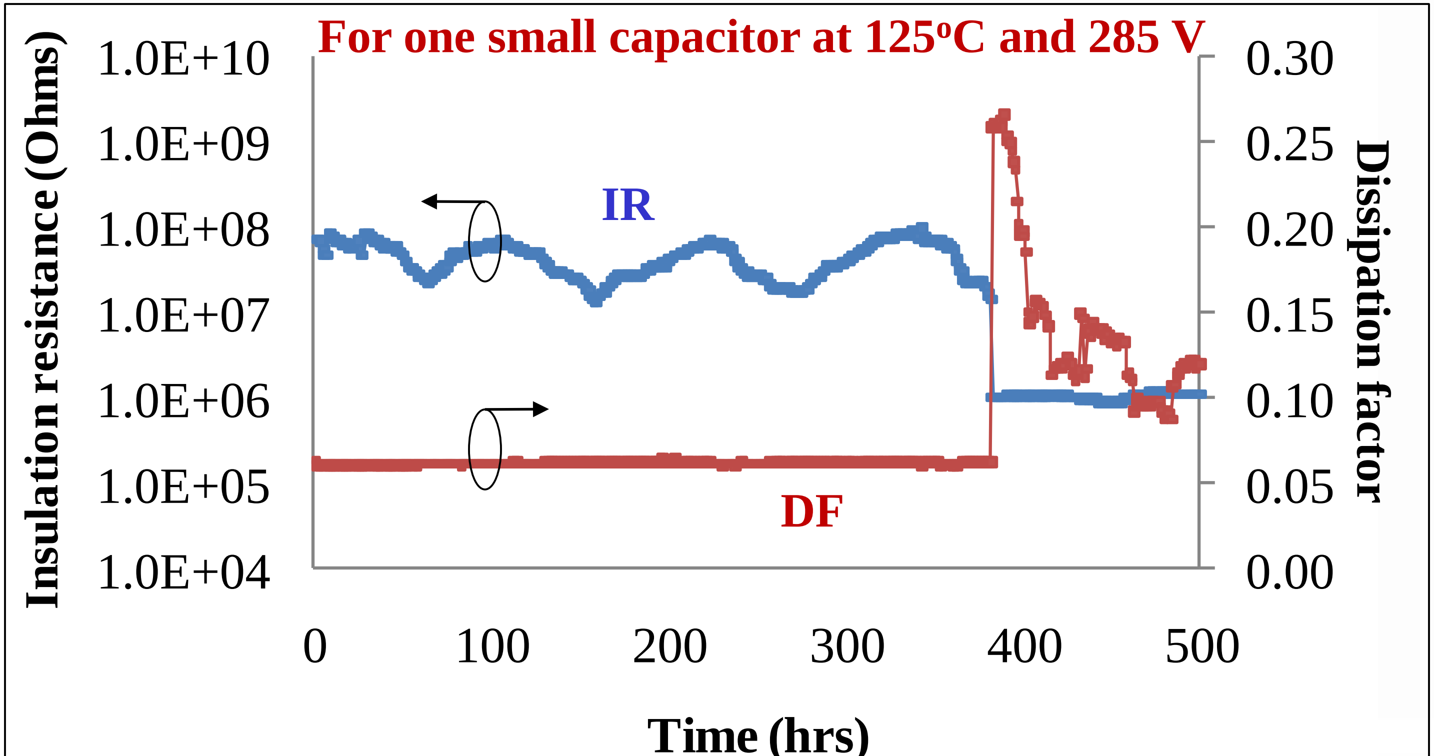


Failure Modes Observed During Lifetime Testing

- The failure modes observed were:
  - Sudden decrease in insulation resistance
  - Sudden increase in dissipation factor
  - Gradual drop in capacitance

→ Avalanche breakdown of the dielectric

- There was no trend in the values of IR or DF before failure.



Effect of Temperature and Voltage on IR

Prokopowicz[1] proposed a model that is used in accelerated life testing of multilayer ceramic capacitors (MLCCs) to describe IR failures.

$$\frac{t_1}{t_2} = \left(\frac{V_2}{V_1}\right)^n \exp\left(\frac{E_a}{k}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)\right)$$

The values of *n* and E_a for $BaTiO_3$ in MLCCs can be found in the literature

The values of *n* and E_a for epoxy-$BaTiO_3$ composite had not been documented

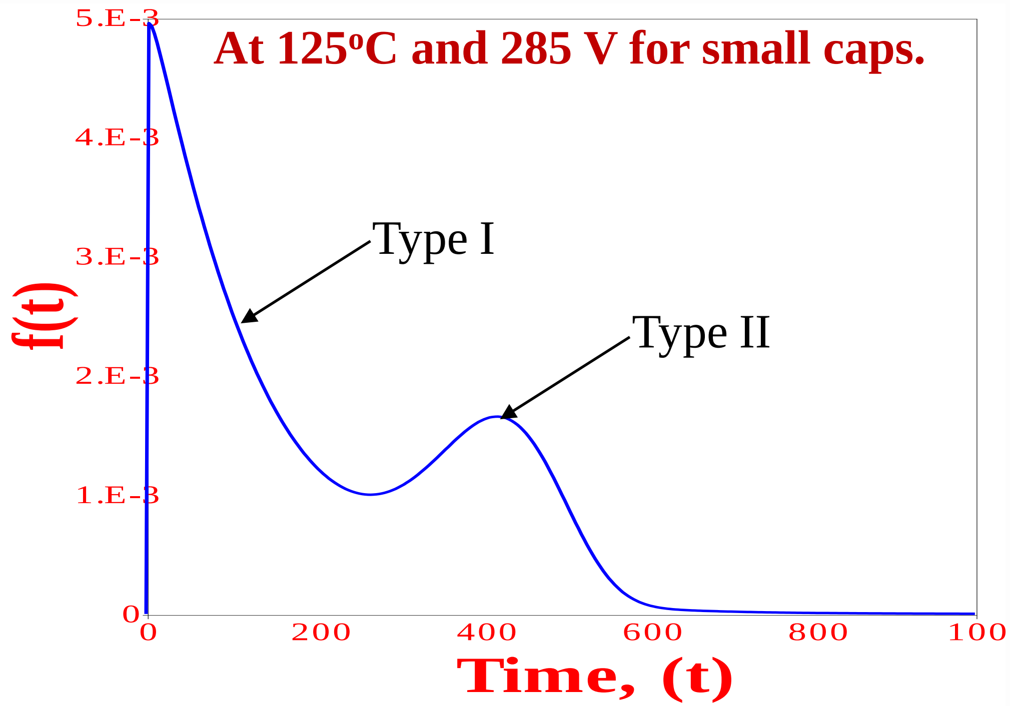
where *t* is the time-to-failure, *V* is the voltage, *n* is the voltage exponent, E_a is the activation energy, *k* is the Boltzmann constant, *T* is the temperature, and the subscripts *1* and *2* refer to the two aging conditions.

The applicability of this model for an epoxy-$BaTiO_3$ composite dielectric had not previously been established.

[1]T. Prokopowicz and A. Vaskas, Final Report, ECOM-90705-F, pp. 175, NTIS AD-864068, 1969.

Lifetime Modeling of Avalanche Breakdown Failures

- At all stress levels, the time-to-failure was observed to follow a **bimodal distribution**:
  - A mixed Weibull with 2 subpopulation was used to calculate the mean time to failure (MTTF).

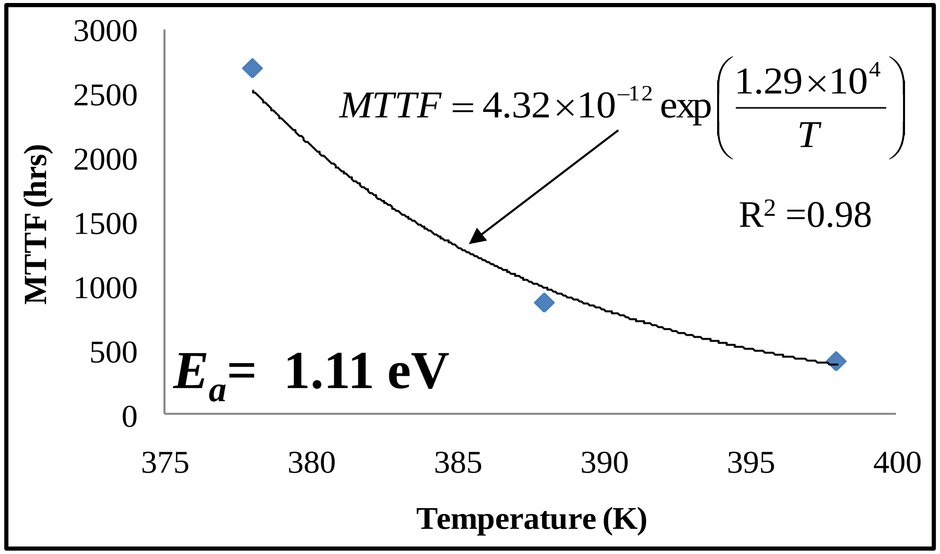


- **A shorter time-to-failure (all Type I) of large capacitors implies that their failures were defect driven, whose probability increases with capacitor area.**
- Statistical analysis was not performed on large capacitors due to small sample size (4).

Activation Energy (E_a) of the Prokopowicz Model

Type I failures seem to be **random** (β~1) and Type II represent a **wear-out** mechanism (β>1) so only Type II failures were modeled.

	Type I (Random failures)			Type II (Wear-out failures)		
	β	η	MTTF (hrs)	β	η	MTTF (hrs)
125ºC and 285V	1.0	130	130	6.0	444	413
115ºC and 285V	1.1	65	63	1.8	979	871
105ºC and 285V	1.6	267	238	4.9	2937	2702

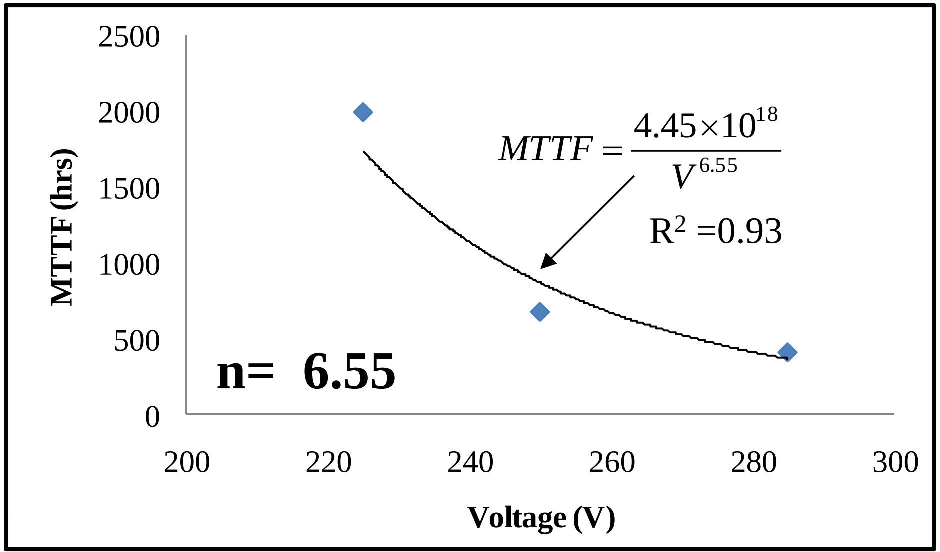


$$MTTF = A\exp\left(\frac{E_a}{kT}\right)$$

Voltage Exponent (*n*) of the Prokopowicz Model

Type I failures seem to be **random** ($\beta \sim 1$) and Type II represent a **wear-out** mechanism ($\beta > 1$) so only Type II failures are modeled.

	Mode I (Random failures)			Mode II (Wear-out failures)		
	β	η	MTTF (hrs)	β	η	MTTF (hrs)
125ºC and 285V	1.0	130	130	6.0	444	413
125ºC and 250V	1.4	188	171	5.5	739	680
125ºC and 225V	1.0	935	935	22.3	2058	1996



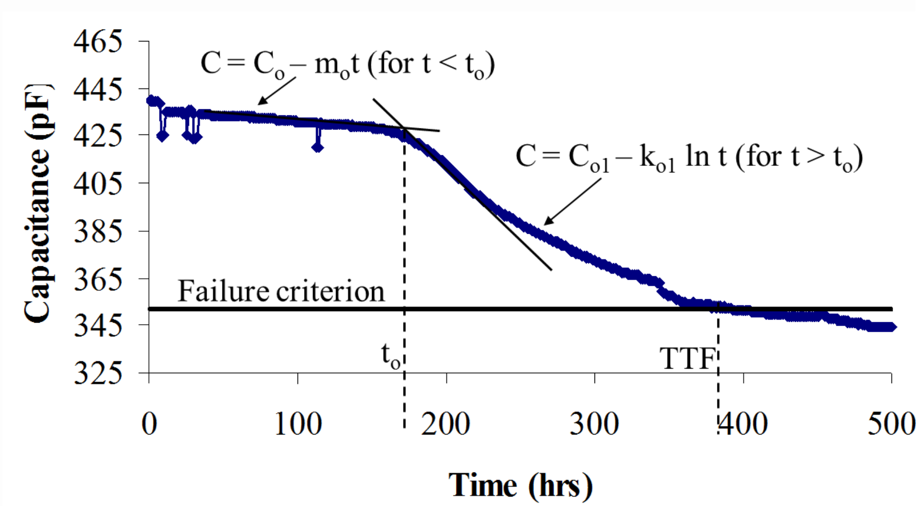
$$MTTF = \frac{B}{V^n}$$

Gradual Decrease in Capacitance

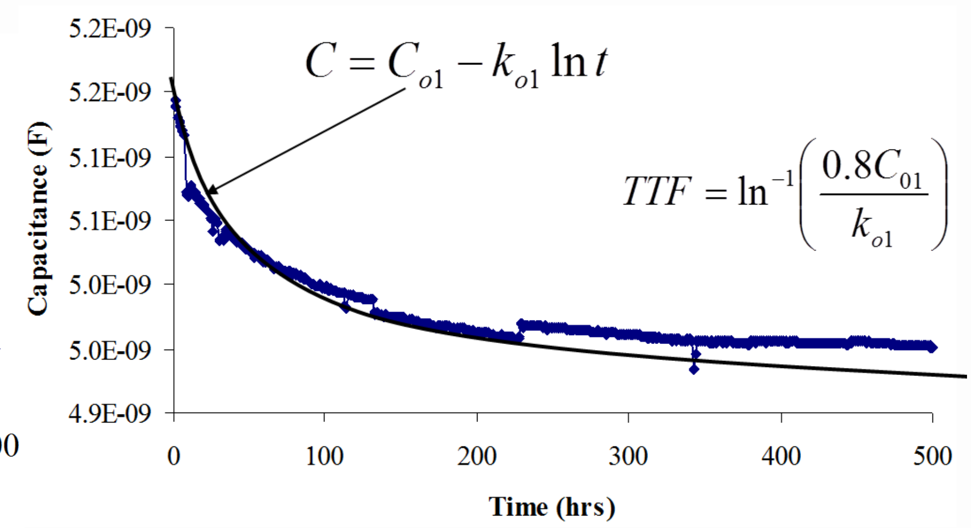
(Plot of Capacitance at 125ºC and 285 V for Group B Capacitor)

- In small capacitors (group A) the onset of logarithmic degradation was delayed by a time which is referred to as t_o.
- The linear degradation region was absent in group B (large) capacitors.

Group A (small)



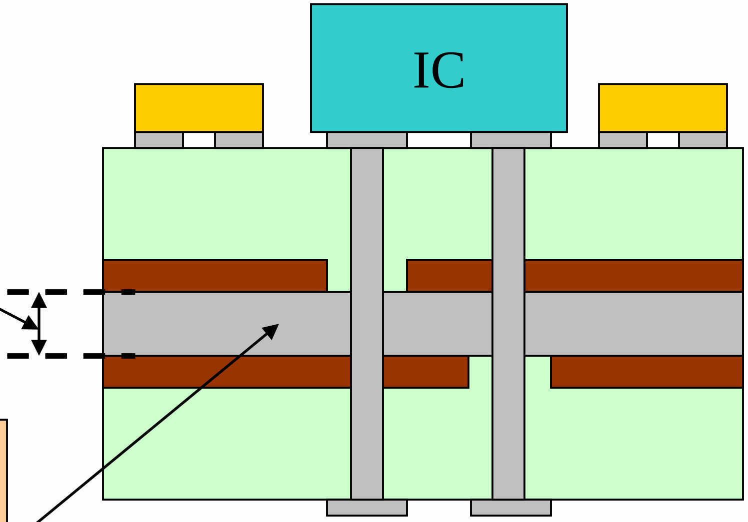
Group B (large)



Failures were not observed in group B (large) capacitors due to a large value of initial capacitance (C_{o1}) as compared to group A.

Effects of Temperature on Capacitance

An increase in plate spacing as a result of thermo-mechanical stress generated due to CTE mismatch



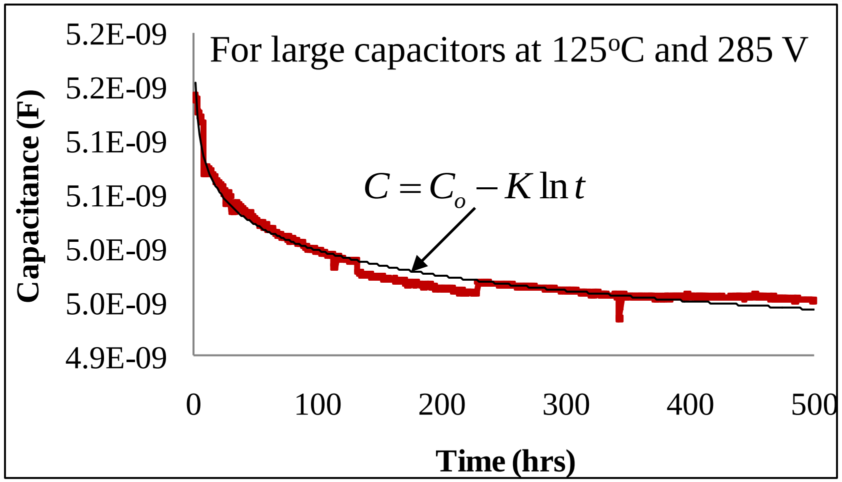
Decrease in the dielectric constant:

- Aging in $BaTiO_3$
- Residual stress relaxation in polymer

$$C = C_o - k \ln t$$ → Aging model

where C is the capacitance at time t, C_o is the initial capacitance, k is the capacitance degradation rate, and t is time.

Modeling the Decrease in Capacitance During HALT



Dielectric aging rate (K) →

Stress levels	Small (group A)	Large (group B)
105ºC, 285V	12.64×10^{-11}	3.35×10^{-11}
115ºC, 285V	7.94×10^{-11}	3.43×10^{-11}
125ºC, 285V	6.89×10^{-11}	3.98×10^{-11}
125ºC, 250V	4.43×10^{-11}	7.21×10^{-11}
125ºC, 225V	4.13×10^{-11}	4.97×10^{-11}

– Time-to-failure as a result of 20% decrease:

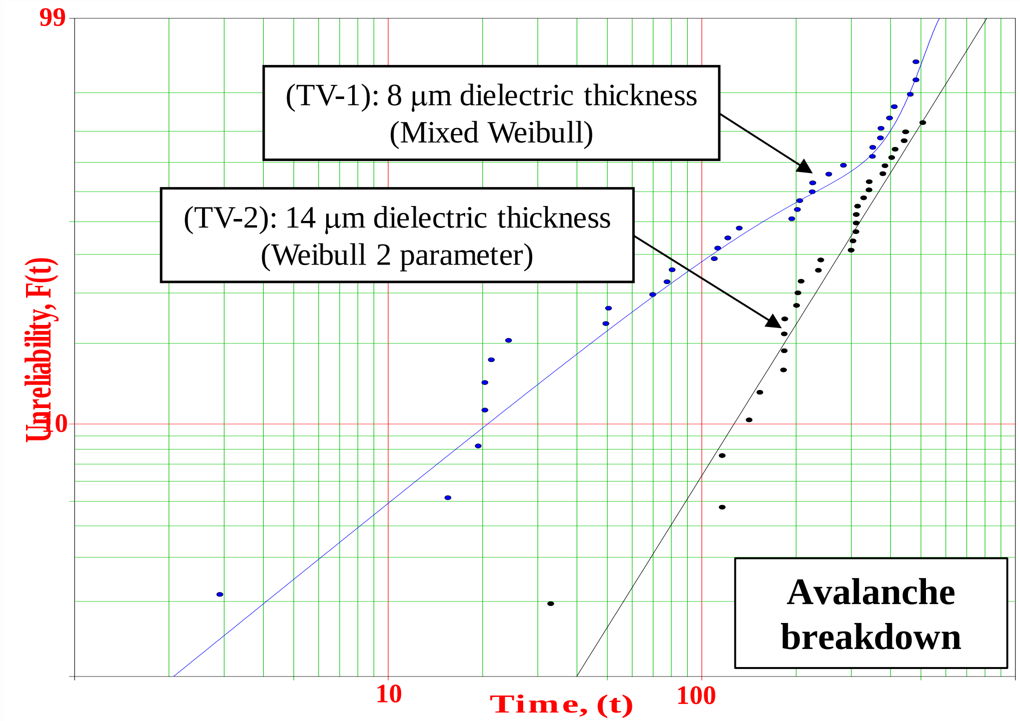
$$TTF = \exp\left(\frac{0.2\,C_o}{K}\right)$$

Initial capacitance (C_o) of large capacitors was an order of magnitude higher

Dielectric aging rate (K) is approximately the same for both capacitors

→ **No failures were observed in large capacitors (group B).**

Thickness Effect: 8 μm versus 14 μm

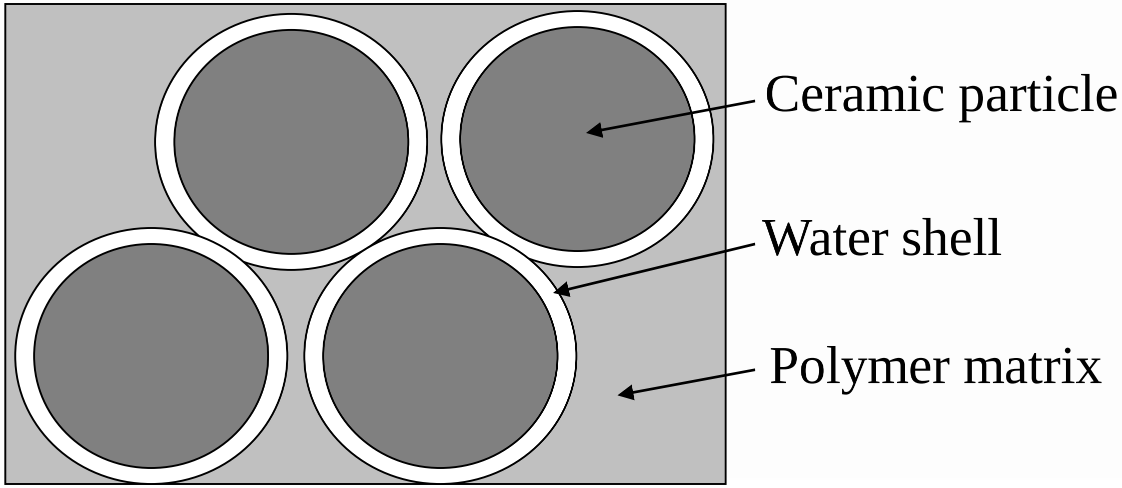


Type I failures were not observed in TV-2 (14 μm)

	Avalanche breakdown at 125°C and 285 V						Decrease in capacitance
	Type I			Type II			
	β	*η*	*MTTF (hrs)*	*β*	*η*	*MTTF (hrs)*	*K*
TV-1 (8 μm)	1.0	130	130	6.0	444	413	6.89×10^{-11}
TV-2 (14 μm)				2.0	383	341	4.52×10^{-11}

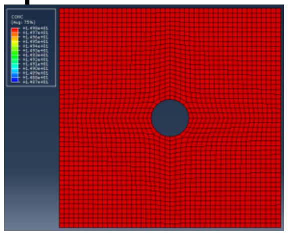
Effect of Humidity

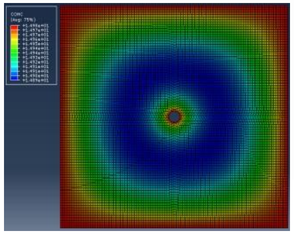
- Under humid conditions, the *capacitance and DF were found to increase* due to moisture absorption in the dielectric (since $\varepsilon_{water} > \varepsilon_{air}$, where ε is the dielectric constant).
- The primary site of absorbed moisture in these composites is the *interface* between the ceramic and the polymer matrix.
- The level of moisture absorbed in these composites increases with a decrease in the ceramic particle size or an increase in the ceramic loading, both of which increase the interfacial area.



Percentage Increase in Capacitance

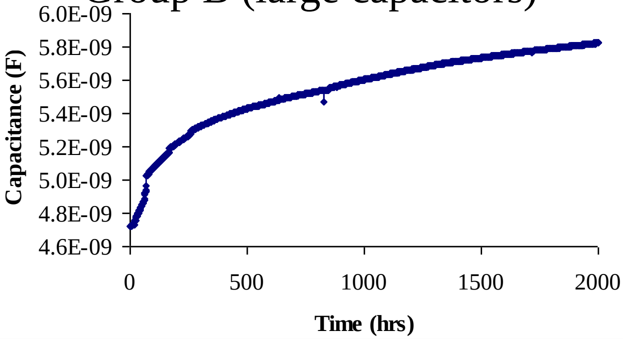
- The increase in capacitance at 85°C, 85% RH and 0 V after 2000 hrs was
  - 19.6% ± 1.3 for group A (small) capacitors
  - 22.6% ± 0.2 for group B (large) capacitors

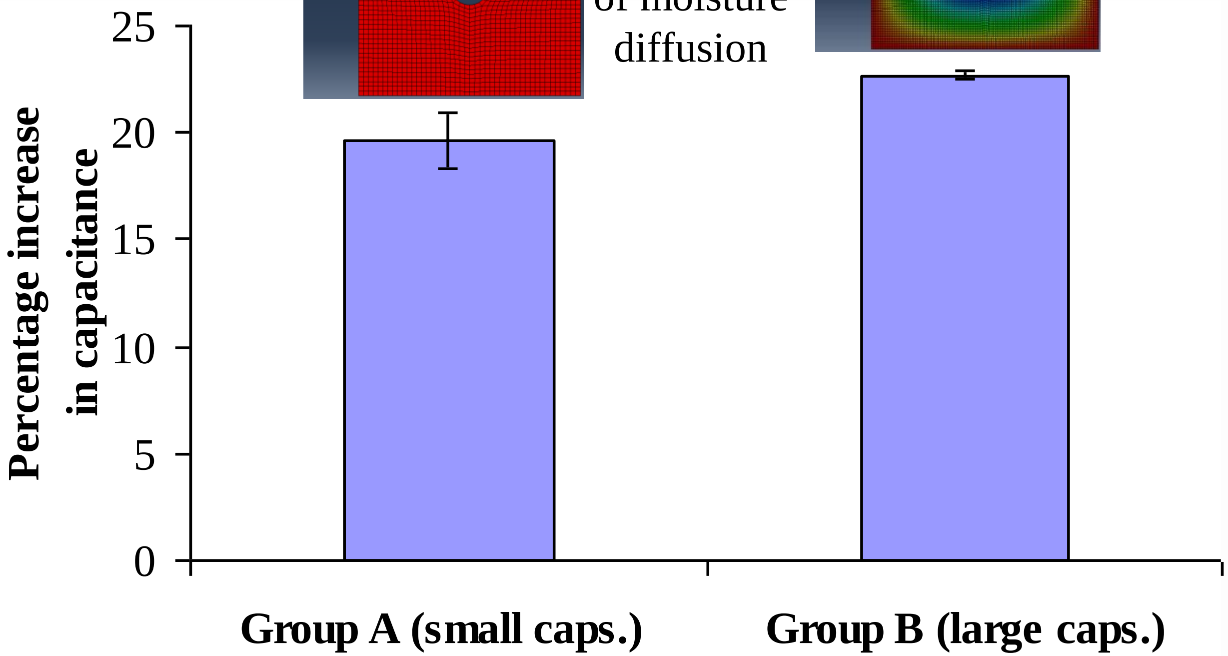




FEM simulation of moisture diffusion

Group B (large capacitors)





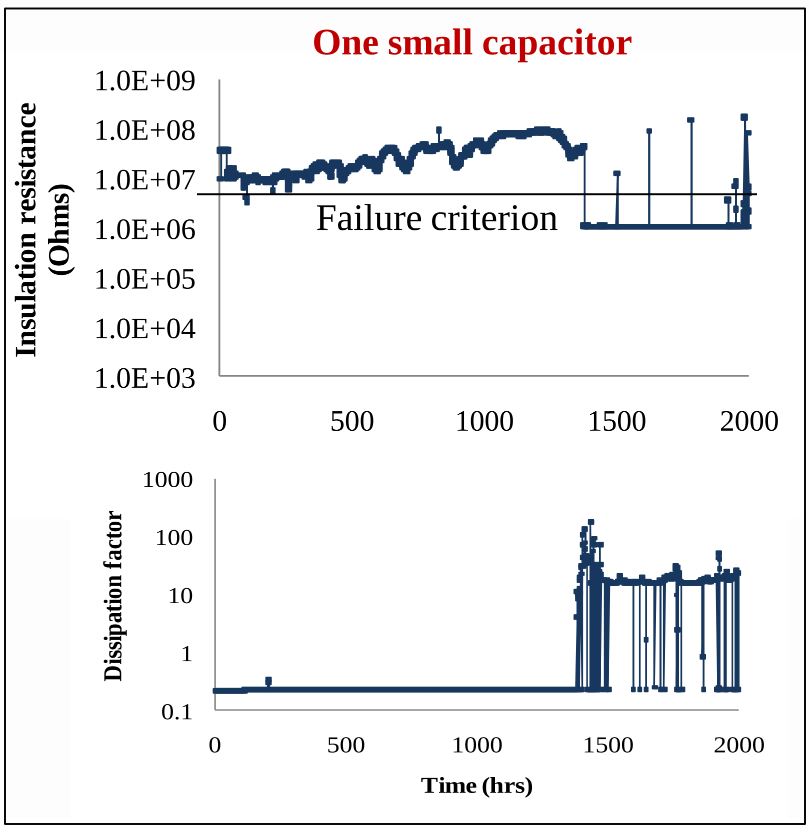
- The capacitance returned to its pre-THB value during a bake at 125°C in about 20 hrs.

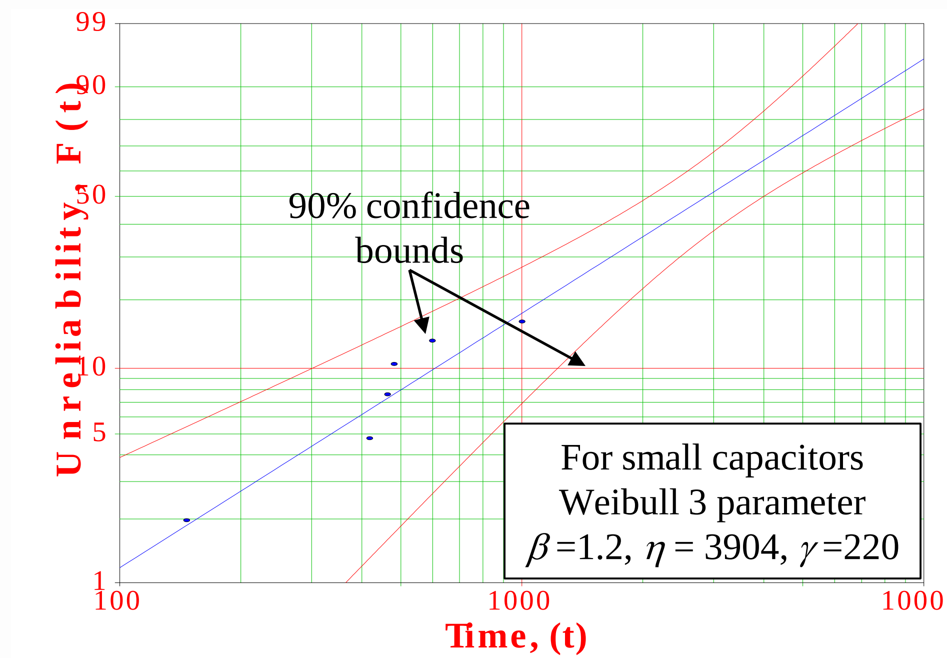
Results of Temperature-Humidity-Bias (THB) Tests

(85ºC, 85% RH, and 5 V)

IR failures as a result of formation of a conduction path were observed :

– **6/36** small capacitors and **2/4** large capacitors failed by this mode.





All failures as a result of formation of a conduction path disappeared after baking at 125ºC for several days.

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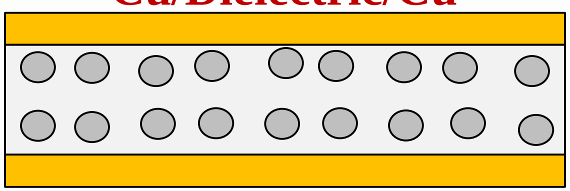
Approach

Fabricated **Cu/Dielectric/Cu** structures with epoxy-$BaTiO_3$ nanocomposite dielectric with different **loading conditions**

Cu/Dielectric/Cu



Area: 40 x 40 mm^2
Dielectric thickness: 125 μm
Number of samples/loading condition: 3

Loading conditions*

		$BaTiO_3$ particle diameter (nm)		
		100	300	500
$BaTiO_3$ loading (Vol.%)	20			x
	40	x	x	x
	60			x

Measured the following parameters:

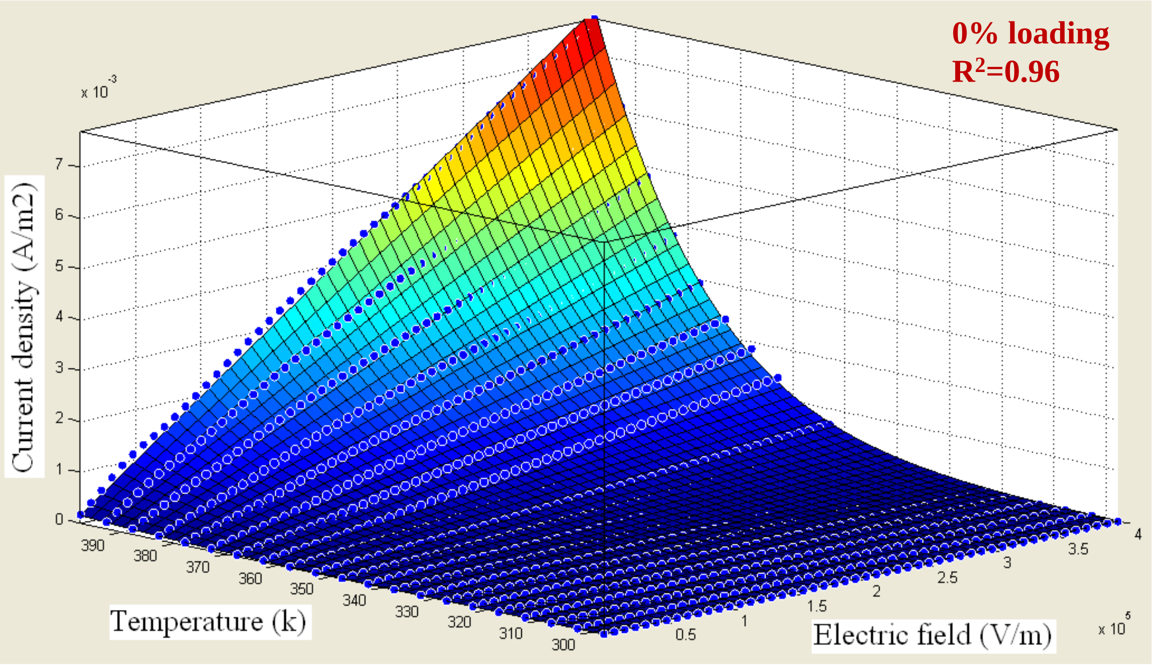
1. Capacitance and dissipation factor (as a function of Temperature)
2. Leakage current (as a function of Temperature and Voltage)

*Three control samples were also fabricated with 0% loading

3D Regression of the Leakage Current Data

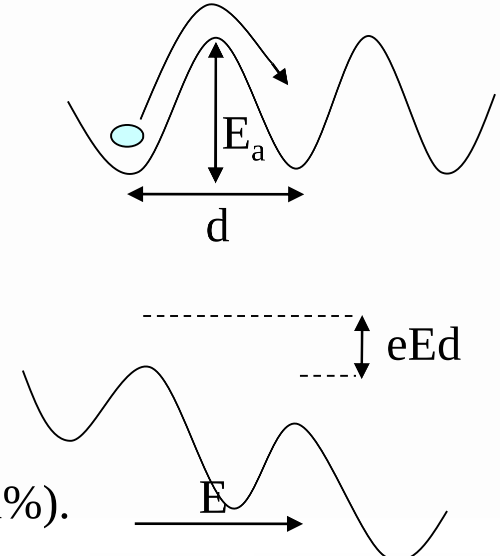
(To Calculate the Activation Energy of Ionic Hopping)

- 3D regression was performed on the leakage current data.
- The goodness of fit (R^2) for ionic hopping conduction was greater than 0.90 for all loading conditions, which indicated that hopping was the dominant conduction mechanism (as opposed to Schottky or Poole-Frenkel).



$$J \approx A\left(\frac{E}{T}\right)\exp\left(-\frac{E_a}{kT}\right)$$

Low field approximation



E_a is a function of particle diameter and loading (~0.9 eV, < 40 vol%).

Effects of Particle Loading and Diameter

- The effective dielectric constant was found to increase with the ceramic loading:
  - The maximum dielectric constant was close to 25 at 60% loading (for 500nm particles).
- The effective dielectric constant was found to decrease when the particle diameter was reduced to 100 nm:
  - this may be due to an increase in the agglomeration of ceramic particles.
- Leakage current was found to increase
  - with an increase in the ceramic loading;
  - with an increase in the particle diameter.
- Leakage current was found to increase with temperature at all voltages (between 1 and 50 V) and loading conditions.

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Conclusions: Temperature and Voltage Aging

- Two failure modes observed:
  1. Sharp drop in insulation resistance (*IR*): bimodal
     - **Mechanism**: avalanche breakdown
     - Type I (infant mortality): **TTF decreased with capacitor area** (defect driven)
     - Type I (infant mortality): risk of failures increased for thinner capacitor
     - Type II (wear-out): determined failure statistics (Weibull parameters, MTTF)
     - Type II (wear-out): Prokopowicz model is applicable
       - Values of constants $n = 6.5$, $E_a = 1.1$ eV; material, not size, dependent
  2. Gradual decrease in capacitance (*C*)
     - **Mechanism**: dielectric aging, plus stress relaxation and electrode separation
     - **TTF increased with capacitor area** (governed by relative changes)
     - Logarithmic aging model is applicable for large area capacitors
     - Smaller capacitors have an initial linear aging trend
       - Aging constant $K = 5 \times 10^{-11}$; material, not size, dependent

Conclusions: Temperature-Humidity (and Bias)

- Temperature-Humidity (no bias):
  - Capacitance and DF both increased with time
  - **Mechanism:** moisture diffusion/adsorption, leading to increase in dielectric constant
  - Diffusion constant was calculated for moisture in epoxy-$BaTiO_3$ nano-composite film: $D \approx 1 \times 10^{-11}$ m^2/s
  - Reversible after bake-out
- Temperature-Humidity-Bias:
  - The failure mode observed was a sharp drop in *IR*
  - DF also increased suddenly at the same time
  - **Mechanism:** moisture diffusion/adsorption followed by conductive path formation (defect-mediated)
  - Reversible after bake-out

Conclusions: Leakage Current Mechanism

- The leakage current was found to be governed by the **ionic hopping mechanism**
- The activation energy for ionic hopping was determined
  - E_a is a function of particle diameter and loading
  - $E_a \approx 0.9$ eV, for loadings less than or equal to about 40 vol%
- The leakage current in the dielectric was found to increase
  - with an increase in the ceramic loading
  - with an increase in the particle diameter

Recommended Future Work:

- Further investigate effects of area, thickness, particle loading, and particle diameter
- Assess alternative film constructions and materials
- Investigate the path of leakage current and identify the charge carriers

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Questions?

Thank You

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