

# Thermal Models of Multilayer Ceramic Capacitors for 3D Power Electronics

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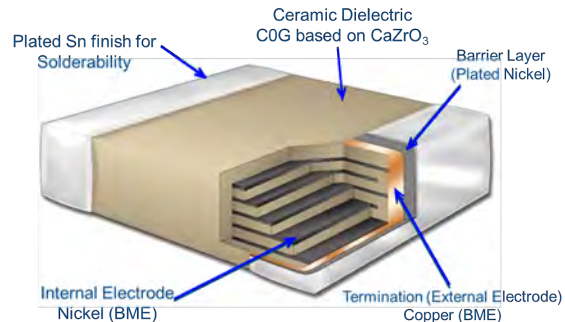


## Presentation Outline

- Introduction
- Thermal Resistance
  - Analytical Model
  - Finite Element Models
  - Experimental Results
- Thermal Capacitance
  - Analytical Model
  - Experimental Results
- Conclusions
- Future Work

## Introduction

- Multi-layer Ceramic Capacitors (MLCC) made with Ni BME COG have been developed for use with WBG semiconductors [1 & 2] with:
  - **Reliable performance even at 150°C**
  - **Stable capacitance with temperature and voltage**
  - **High voltage ratings (no derating required!)**
  - **Very low dissipation factors (low loss)**
  - **High IR (low leakage) & high breakdown voltages**
  - **High ripple current capability**
- Designers need to understand their thermal performance under different conditions to determine the cooling required.
- This presentation describes research into thermal models of large case size 3640 MLCCs to understand the distributed nature of power dissipation in the dielectric.

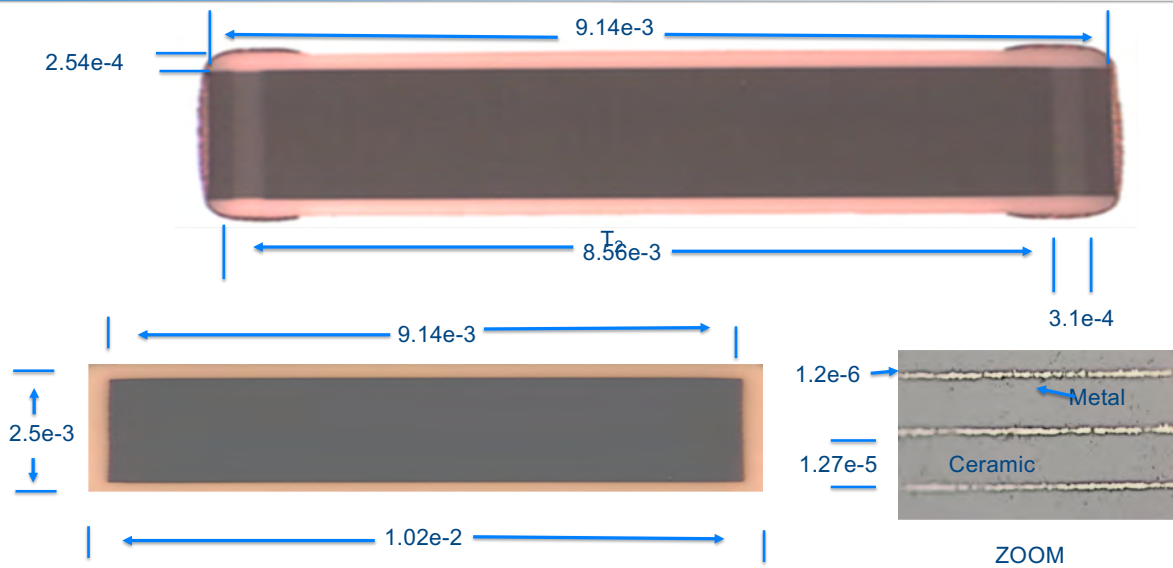


[1] J. Bultitude, 'Development Challenges for DC-Link Capacitors for Wide Band Gap Semiconductor Applications', PSMA Industry Session, APEC 2017, March 26-30, 2017, Tampa, Florida, USA.  
[2] J. Bultitude et al, 'An Evaluation of BME COG Multilayer Ceramic Capacitors as Building Blocks for DC-Link Capacitors in 3-D Power Electronics', Proceedings of the 3D-Power Electronics Integration and Manufacturing Symposium, June 13-15, 2016, Raleigh, NC, USA.

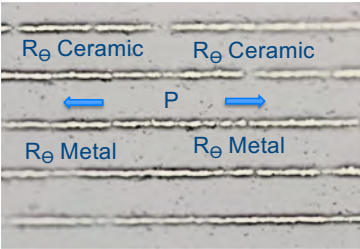
## Thermal Resistance Analytical Models

- F.M. Schabauer and R. Blumkin provide a good analytical model of thermal behavior of small case size MLCCs in 'Thermal Resistance, Power Dissipation and Current Rating for Ceramic and Porcelain Multilayer Capacitors', RF Design Magazine May/June and July/August 1981.
  - Heat generated in the MLCC is removed primarily through conduction out to the end termination through the metal electrodes and ceramic dielectric.
  - The assumptions are the heat is removed from the end termination and both terminations are at the same temperature.
- KEMET MLCC design program uses this model to calculate a  $R_{\theta}$  based on finished dimensions and material properties.

# Part Cross Section Has More Than 100 Electrode /Actives Dimensions in Meters (m)



# Thermal Resistance Path to Each Termination



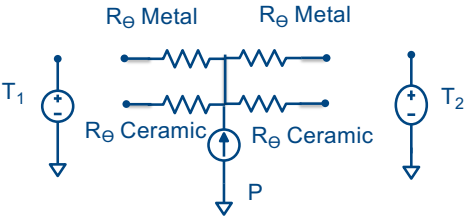
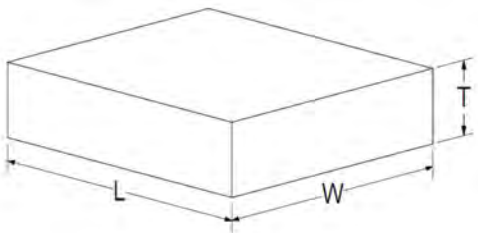
$P$  is Dissipated Power (Heat)

$$R_{\theta} = \frac{L}{K \cdot A}$$

$K$  = thermal conductivity

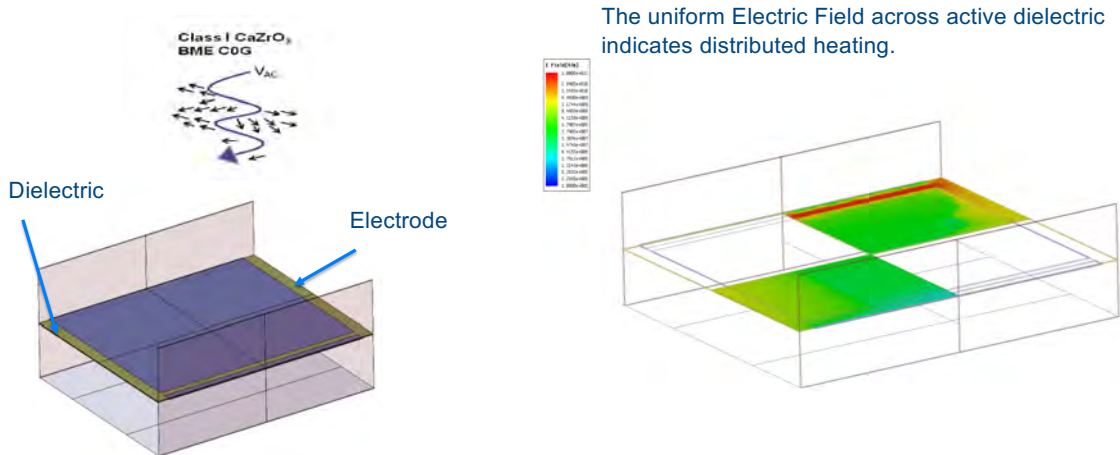
$A$  = cross sectional area  $W \cdot T$

The Low Length to Width Aspect Ratio of 3640 MLCCs helps reduce  $R_{\theta}$ .



	K (Watts/(°C*m))	W (m)	T (m)
Metal	90	$9.14 \times 10^{-3}$	$1.2 \times 10^{-6}$
Ceramic	3	$1.02 \times 10^{-2}$	$1.27 \times 10^{-5}$ Active $2.54 \times 10^{-4}$ Cover

## Ansys HFSS Finite Element(FEM) Electromagnetic Model of a Single Electrode Pair Active Slice



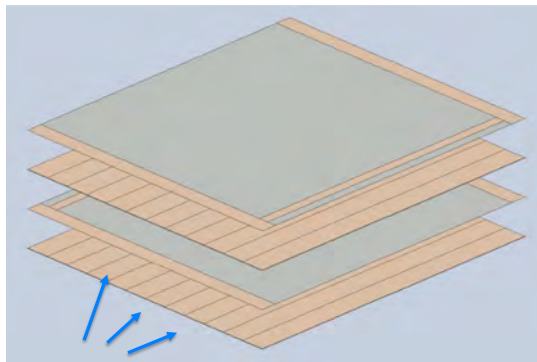
Heat is generated in the dielectric by the change in orientation of the dipoles with an alternating field and by ohmic loss in the metal electrodes.

## Solid Works Finite Element Thermal Model of 3640 MLCC



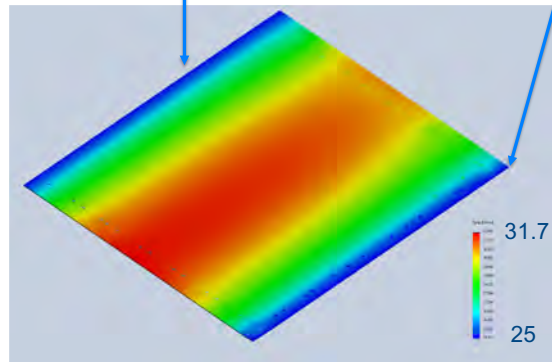
- MLCCs have more than 100 alternating electrode parallel plate active layers
  - First a simple model of a 2 electrode 2 active slice of the MLCC was created.
  - Second 10 actives and a cover were modeled to compare surface to inner electrode temperature.
  - Third convection and radiation at surface of cover were modeled with an ambient air boundary.

## Solid Works Thermal Finite Element Model of Active Slice



10 Equal Heat Sources 7.5e-5 m wide per Active Pair

Termination Heat Sink (Forced Air Convection) Boundary

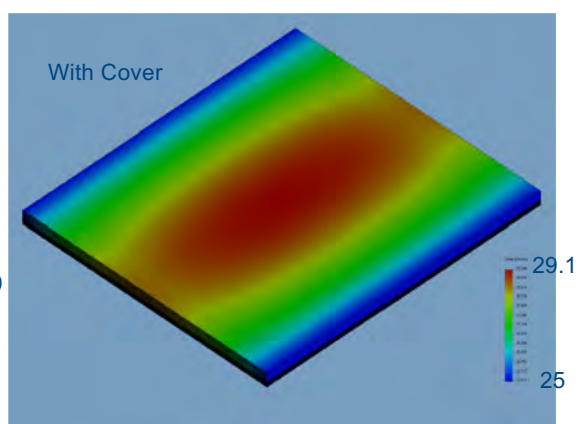
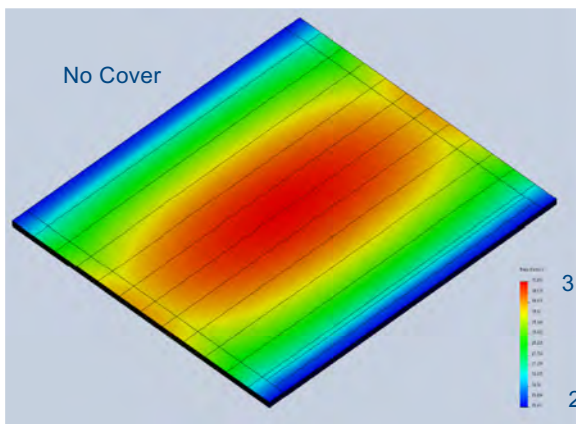


Insulator Boundary Top and Bottom

$R_{\theta}$  for 0.22uF Design predicted by parallel combination of 2 layer slice is 13.8 °C/W without cover layer.

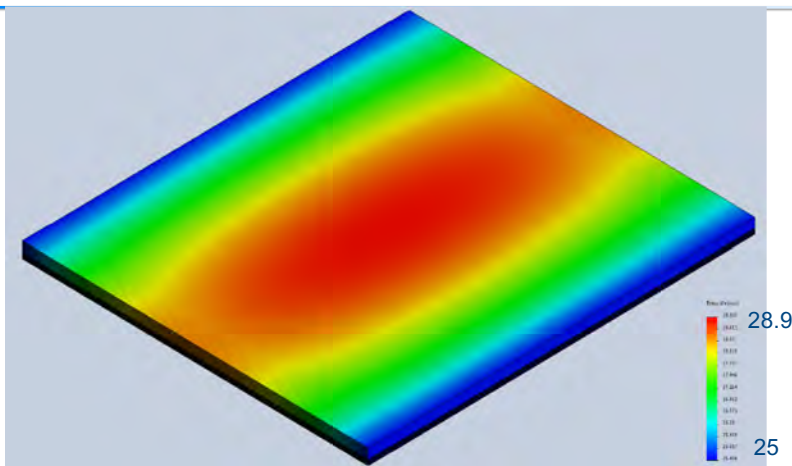
## 10 Actives with and without Cover Modeled with Same Boundaries used as 2 active slice

Steady state temperature of surface is the same as inner electrodes.



Parallel Heat Conduction Path of Cover reduces Temperature by 1.9 °C.

Ambient Air Boundary @ 25 °C with a Nominal Convection Coefficient of 25 W/(m<sup>2</sup>°C ) and a Radiation Emissivity of 0.9



A 3640 MLCC cover has more than 12 X the surface area of a 1210 MLCC.

The effective  $R_{\theta}$  is lowered by natural convection and radiation from the surface of cover by less than 10 %.

## Finite Element Analysis Conclusions

- The effective  $R_{\theta}$  predicted from model of 2 actives is within 15 % of analytical model.
- The parallel heat conduction path of the cover layer reduces  $R_{\theta}$ .
- Surface temperature of MLCC is the same as inner layer temperature.
- Natural Convection and Radiation at the cover layer reduce  $R_{\theta}$ .
- Conduction is still the primary method of heat removal.

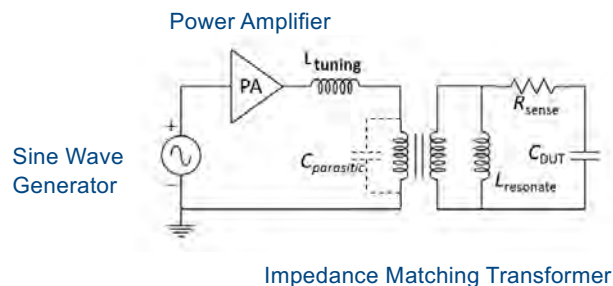
### 0.22 uF Comparison

$R_{\theta}$ Analytical (°C/W)	$R_{\theta}$ of active region without covers (°C/W)	$R_{\theta}$ with covers (°C/W)
14.1	13.8	13.0

## Experimental Validation of MLCC Design Calculations

- How well does KEMET Design Program predict  $R_0$  ?
  - Number of Electrodes/Actives
  - Dimensions
  - Material Properties
- Lab measurements were made on a range of 3640 MLCC Capacitors with an increasing number of electrodes and actives.

## Experimental Setup



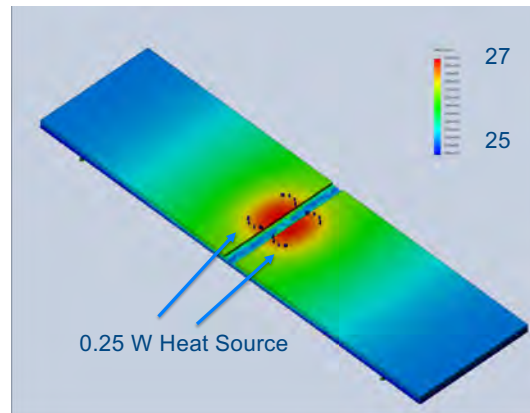
- The circuit consists of three main function blocks: signal source (signal generator + RF power amplifier), a toroidal transformer based impedance matching network (transformer +  $L_{\text{resonate}}$  +  $C_{\text{DUT}}$  to match load impedance to  $50\Omega$ ), a  $10\text{m}\Omega$  current sensing resistor monitored with a DMM.
- Temperature was measured two ways by type T thermocouple and infrared imaging.



Capacitor Under Test Mounted on Dual Sided 5 oz Copper 60 mil Thick FR4 Substrate and Attached to a low  $R_{\theta}$  Heat Sink( Minimize Substrate Heating)

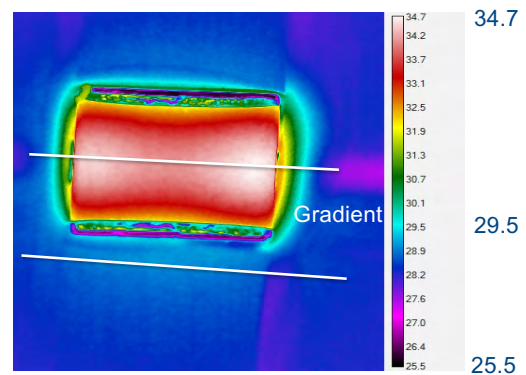
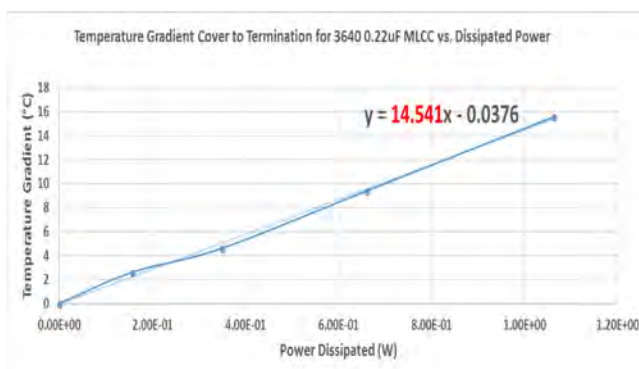


Substrate on Large Heat Sink with  $R_{\theta}$  of less than 0.25 C / W



FEM Model of MLCC terminations as heat sources predicts an  $R_{\theta}$  of 8 °C/W from termination to heat sink. High Ripple Currents heat Copper Substrate as well.

Experimental Measurements for 3640 0.22uF MLCC Design



The temperature gradient from center of cover to copper substrate at termination was plotted against power dissipated ( $I^2 \cdot ESR$ ) in MLCC. The trendline slope 14.54 is the  $R_{\theta}$  in °C/Watt.



## Experimental Results for Range of MLCCs



Capacitance (uF)	R <sub>θ</sub> Analytical (°C/W)	R <sub>θ</sub> Experimental (°C/W)
0.082	17.6	17.2
0.22	14.1	14.5
0.47	11.4	11.5

Experimental results validate KEMET MLCC design program analytical values.

R<sub>θ</sub> decreases with increasing number of active layers and electrodes which increases MLCC thickness.

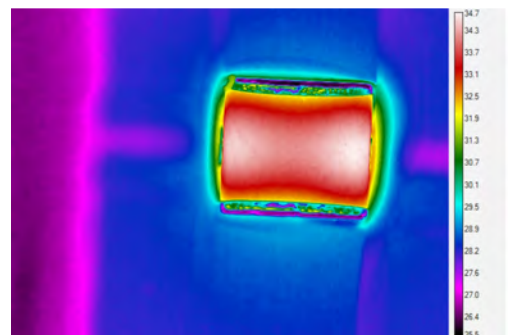
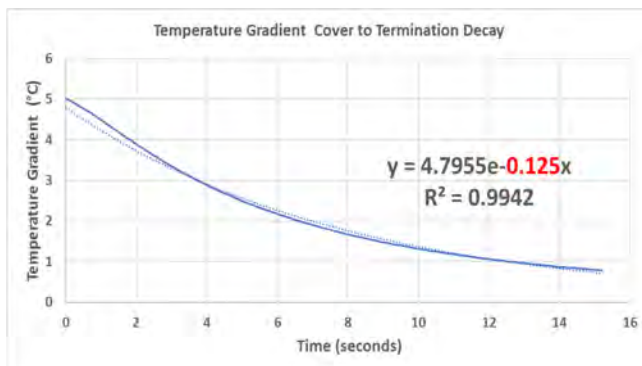
**Thermal Capacitance C<sub>θ</sub> of the MLCC is a Measure of How Much Energy Must be Dissipated in Device to Raise Temperature 1 degree**



Material	L	W	T	V	Layers	Total Volume	Density	Mass	Specific Heat	C <sub>θ</sub>
	(m)	(m)	(m)	(m <sup>3</sup> )		(m <sup>3</sup> )	kg/(m <sup>3</sup> )	kg	J/kg°C	J/°C
Metal	0.00886	0.00914	1.20E-06	9.72E-11	138	1.34E-08	8908	1.20E-04	440	5.26E-02
Ceramic Active	0.00914	0.01016	1.3E-05	1.18E-09	138	1.63E-07	4780	7.78E-04	558	4.34E-01
Ceramic Cover	0.00914	0.01016	0.00025	2.35974E-08	2	4.72E-08	4780	2.26E-04	558	1.26E-01
									Total	6.13E-01

$$C_{\theta} = \text{mass} * \text{specific heat}$$

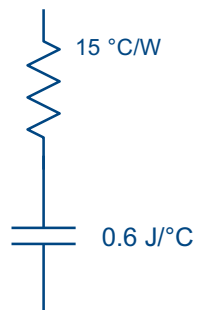
## Exponential Temperature Decay of MLCC after Current Removed ( Video of Decay)



(Scale Changes)

$T = T_{diff} * e^{-t/Tau}$  where Tau is thermal time constant  $R_{\theta} \times C_{\theta}$ ,  $1/Tau = 0.125$   
**Tau = 8 seconds** using experimental  $R_{\theta}$  of 14.5 °C/W  $C_{\theta}$  is computed to be 0.55 J/°C with in 10 % of predicted value based on the properties of the composite material of the MLCC.

## Equivalent Thermal Model for 3640 0.22uF MLCC



## Conclusions

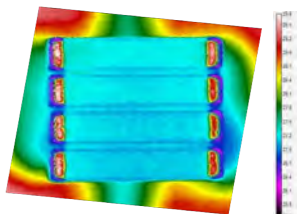
- The  $R_{\theta}$  values predicted by KEMET MLCC design program are in good agreement with experimental results.
- Experimental  $C_{\theta}$  data agrees with analytical calculation for composite material.

## Future Work

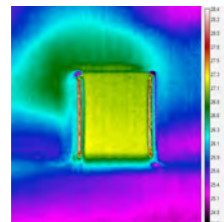
- Validate thermal models for large case size Leadless Stack components.



Low Loss Orientation



Top View



Side View