Benchmark Study of Metal Core Thermal Laminates

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Overview

- Background
- Theory
- Method
- Results
- Discussion
- Conclusion
- Acknowledgements

An Attractive Market

High Brightness Light Emitting Diodes (HB-LEDs), > 1W

- Total Market – About $5 Billion for all applications

- Applications
  - Lamps/Lighting
  - Portable Devices
  - Signs & Displays
  - Automotive

- Details of LED Lighting Market
  - In 2007, global market for HB-LEDs was $337 Million
  - Forecast to grow to $1.647B by 2012, CAGR of 37% (forecast done before global financial crisis)

    Source: Steele; Robert V., “The Market for High-Brightness LEDs in Lighting”; Strategies Unlimited, August, 2008.

Value of LED Lighting

- General Lighting Example – “LED City” Project in Raleigh, NC
  - ❑ Partnership between city of Raleigh, NC and Cree
  - ❑ Purpose is to document advantages of HB-LEDs in general lighting.
  - ❑ Converted 141 high pressure sodium lamps on three levels of a city parking garage with HB-LED lighting fixtures.

- Results (see references below)
  - ❑ Reduced energy consumption by 40%
  - ❑ Improved light quality by nearly 100% as measured in survey of user opinions (also see photos below)
  - ❑ User perception of safety in parking garage increased by 76%

- Significant Value Demonstrated

Raleigh municipal parking garage

References:

http://www.ledcity.org/applications/garage-lighting.html → (Source of photos above)

http://www.ledcity.org/lib/resources/Raleigh-LED-Garage-Report-FINAL.pdf

LED versus Traditional Lighting

- LEDs produce light within a semiconductor…
  - ❑ NOT in a filament (incandescent bulbs)
  - ❑ NOT by ionized gas (like fluorescent bulbs)

- Although LEDs are more efficient than other light sources, there is a different thermal challenge.
  - ❑ As filaments get hotter, they operate MORE efficiently and light produced is of better quality.
  - ❑ As LEDs get hotter, efficiency and reliability are reduced.

- Thermal Transfer
  - ❑ Most existing light sources transfer heat by radiation and convection.
  - ❑ LEDs primarily transfer heat by conduction.
  - ❑ Thermal conductivity of materials generally not a big deal for existing lighting technology.

Light source	Heat lost by radiation, %	Heat lost by convection, %	Heat lost by conduction, %
Incandescent	>90	<5	<5
Fluorescent	40	40	20
High Intensity Discharge	>90	<5	<5
LED	<5	<5	>90

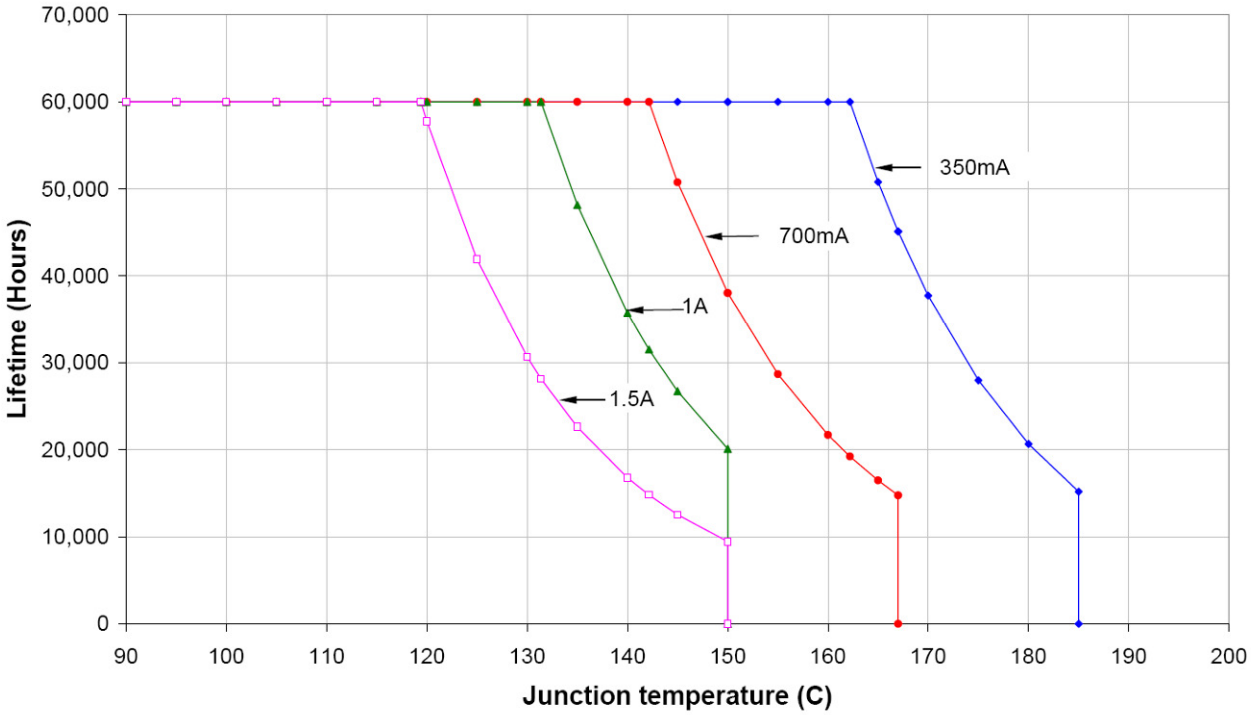
Table 1: Comparison of typical lighting sources with LEDs

From "Spacing of High-brightness LEDs on Metal Substrate PCB's for Proper Thermal Performance"
James Petroski

Importance of Heat Conduction

- Laminate materials must effectively conduct heat away from the LED!
  - ❑ Cooler LEDs are more efficient
  - ❑ Cooler LEDs are more reliable (longer lifetime)

lifetimes for InGaN Luxeon K2



Source http://www.philipslumileds.com/pdfs/WP12.pdf

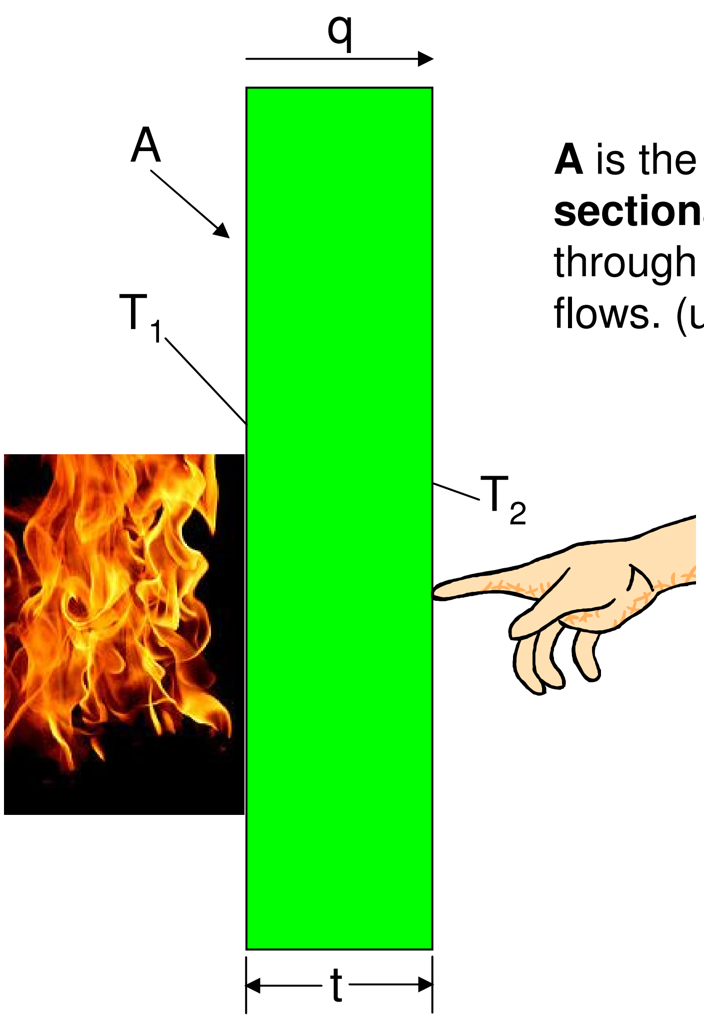
Theory

Assume 1 dimensional, steady state conduction (Constant q)

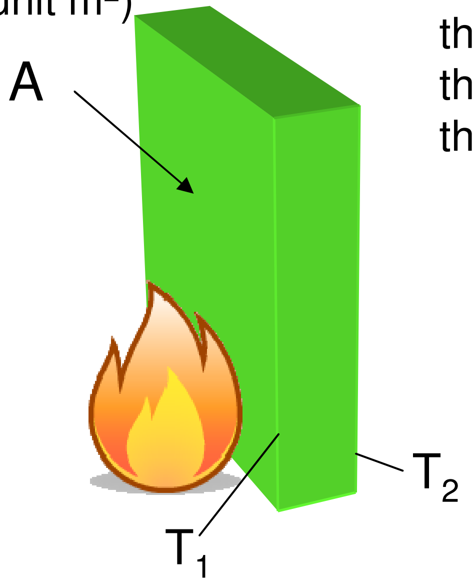
$$\frac{kA}{t}(T_1-T_2) = q$$

⇨ **Heat input** (unit W)

(intensity of the fire in this case, can't change this)



A is the **cross sectional area** through which the heat flows. (unit m^2)

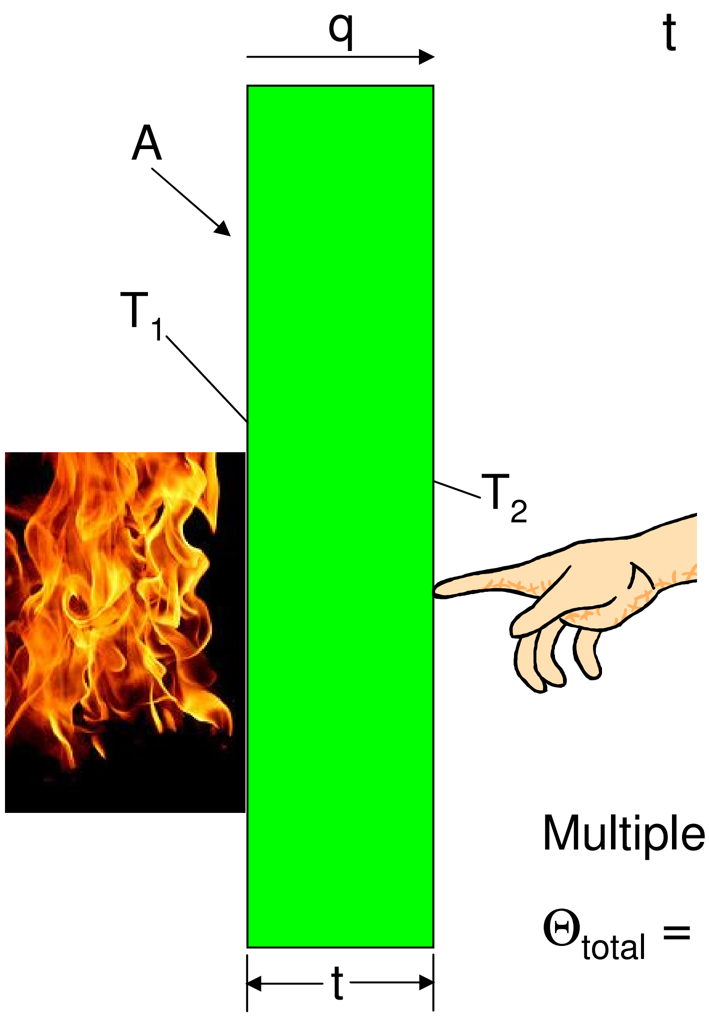


k is the **thermal conductivity** of the material. The larger the k, the more heat is conducted through the material. (unit W/mK)

$\mathbf{T_1}$ and $\mathbf{T_2}$ are the **temperatures** on opposite sides of the material (unit degrees K)

t is the **thickness** of the material. (unit m)

Theory



$$\frac{kA}{t}(T_1-T_2) = q$$

Use simple analogy to conduction of electricity and electrical resistance

$$R_{electrical} = \frac{(E_1-E_2)}{I}$$

$$\Theta = R_{thermal} = \frac{(T_1-T_2)}{q} = \frac{t}{kA}$$

Thermal Resistance (Θ) is a useful figure of merit for determining how well heat is conducted away from HB-LEDs (Unit °C/W)

Multiple layers add like series resistors.

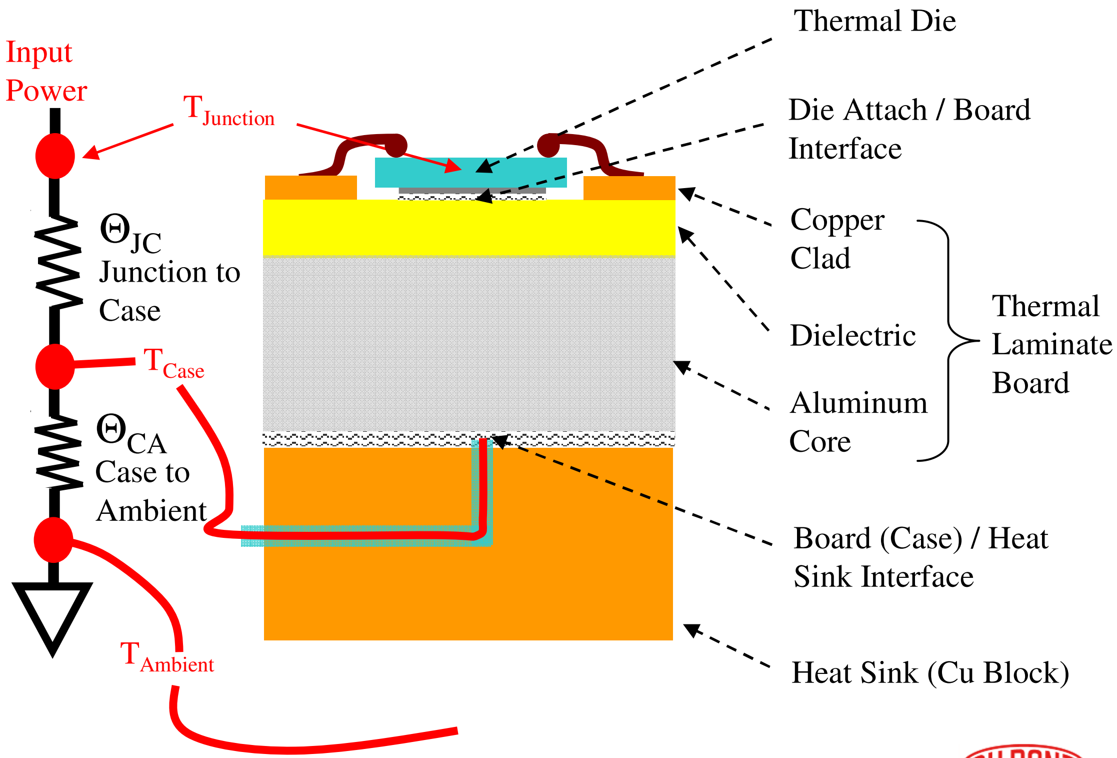
$$\Theta_{total} = \Theta_1+\Theta_2+\ldots+\Theta_n$$

Overview of Benchmark Study

- Method developed and testing conducted by Industrial Technology Research Institute of Taiwan (ITRI).
- DuPont sponsored the study.
- Two DuPont laminates and two competitive laminates compared.
- 10 samples per laminate.
- FR4 tested as a benchmark control.

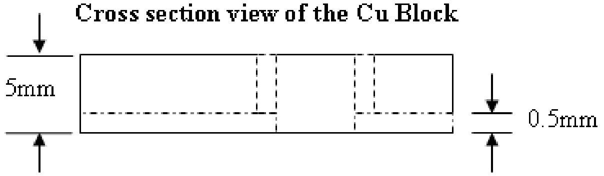
Thermal Model

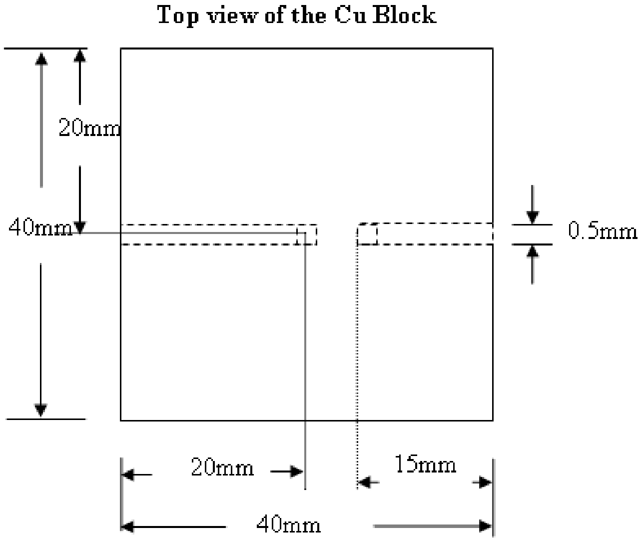
- One dimensional thermal model assumed
- Schematic of thermal model shown below
  - ❑ Thermal die used instead of LED. Die is well characterized so Tj can be accurately determined from forward voltage.
  - ❑ Channel cut into heat sink to allow temperature measurement at bottom of board (T_{Case}) and filled with thermal interface material (*Dow Corning*® SC102).
  - ❑ Thermocouple tips 0.1 x 0.2 mm.
  - ❑ Aluminum Core = 5052 Alloy (k = 138 W/m-K)
  - ❑ Evaluate at input power levels: 0.5 W, 1.0 W, 1.5 W
  - ❑ Measuring thermal resistance from die to bottom of board (includes die attach, dielectric and aluminum).

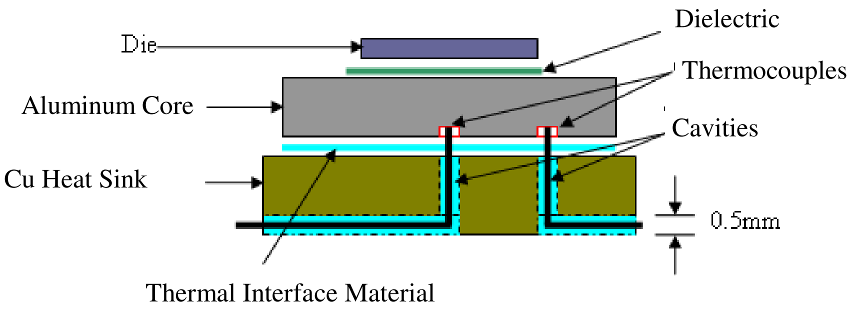


Test Vehicle

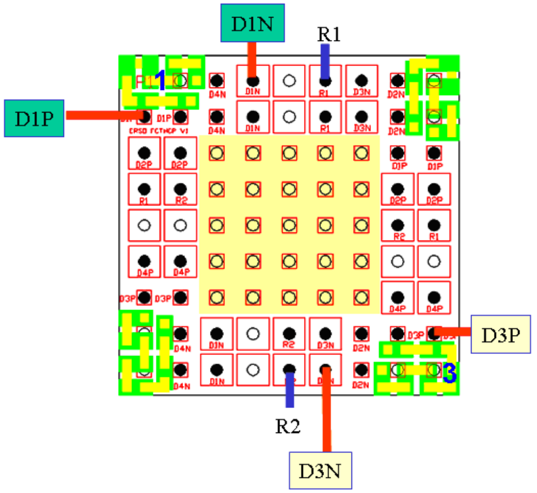
Cu Heat Sink Detail



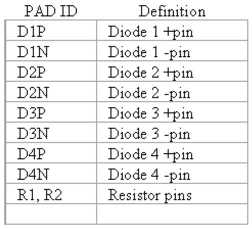




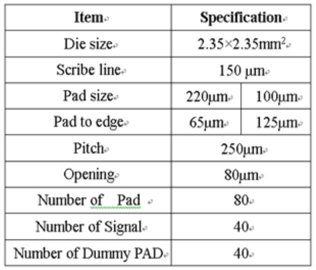
Thermal Die Detail



Die Size：2.35mm X 2.35mm



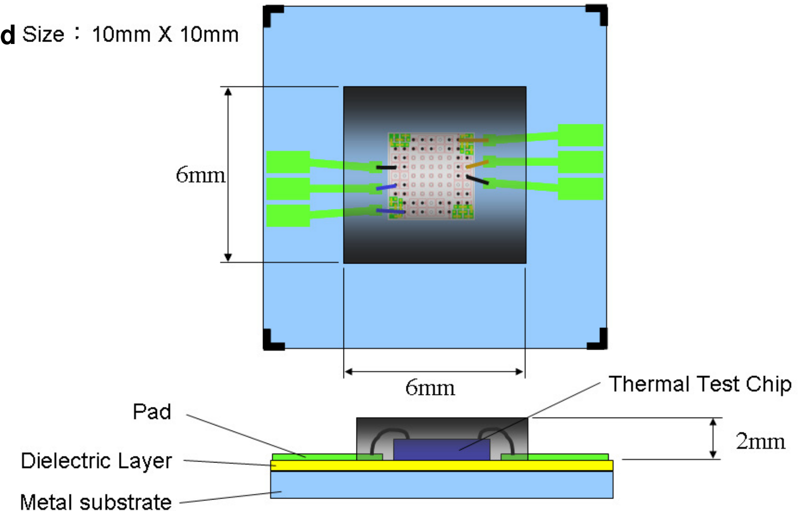
PAD ID	Definition
D1P	Diode 1 +pin
D1N	Diode 1 -pin
D2P	Diode 2 +pin
D2N	Diode 2 -pin
D3P	Diode 3 +pin
D3N	Diode 3 -pin
D4P	Diode 4 +pin
D4N	Diode 4 -pin
R1, R2	Resistor pins



Item	Specification	
Die size	$2.35 \times 2.35 mm^2$	
Scribe line	150 µm	
Pad size	220µm	100µm
Pad to edge	65µm	125µm
Pitch	250µm	
Opening	80µm	
Number of Pad	80	
Number of Signal	40	
Number of Dummy PAD	40	

Laminate Board – Detail

Board Size：10mm X 10mm



Board 10mm X 10mm

Sample Construction Details

- Dielectric Properties
  - ☐ CooLam™ LX – Ceramic Filled Polyimide
    - Thermal Conductivity = 0.8 W/m-K
    - Typical Dielectric Thickness = 17 microns
  - ☐ CooLam™ LC – Ceramic Filled Polyimide
    - Thermal Conductivity = 1.2 W/m-K
    - Typical Dielectric Thickness = 16 microns
  - ☐ Material A – Ceramic Filled Epoxy
    - Thermal Conductivity = 2.2 W/m-K
    - Typical Dielectric Thickness = 75 microns
  - ☐ Material B – Ceramic Filled Epoxy
    - Thermal Conductivity = 1.6 W/m-K
    - Typical Dielectric Thickness = 80 microns
  - ☐ FR4
    - Thermal Conductivity = 0.3 W/m-K
    - Typical Dielectric Thickness = 100 microns

- Metal Properties
  - ☐ Core = 5052 Aluminum Alloy Used for All Samples (Thermal Conductivity = 138 W/m-K)
    - 1 mm thick for CooLam™ Samples
    - 1.5 mm thick for Material A and B Samples
    - Difference due to availability of materials
  - ☐ Clad = 1 oz Copper

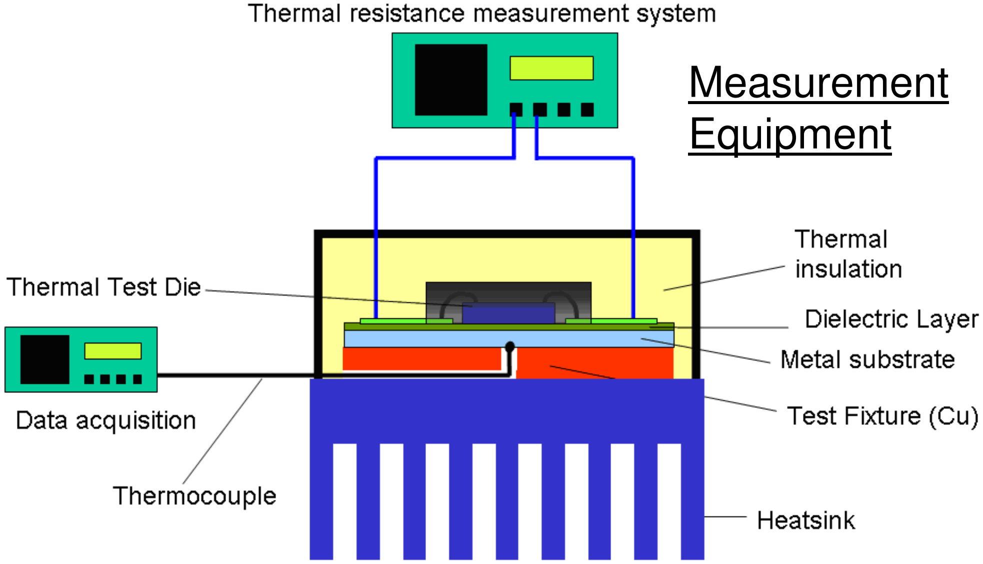
- Die Attach
  - ☐ Thermally Conductive Adhesive
    - Lord Thermoset™MD-140
    - k = 12 W/m-K
  - ☐ Typical thickness 30 microns

Measurement Details

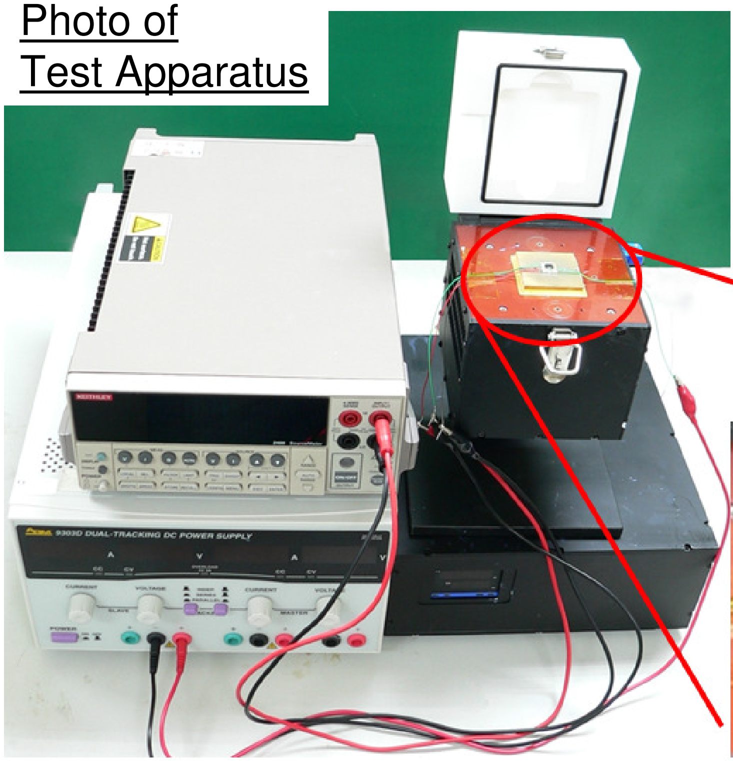
Ten board samples of the following dielectrics:

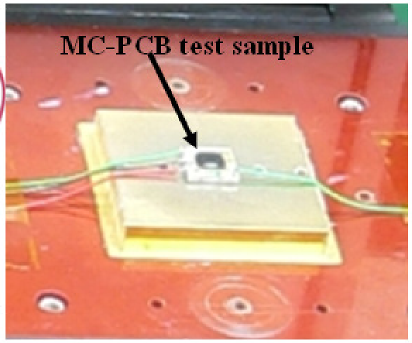
- CooLam™ LX
- CooLam™ LC
- FR4
- Material A
- Material B

<u>Measurement Equipment</u>



<u>Photo of Test Apparatus</u>

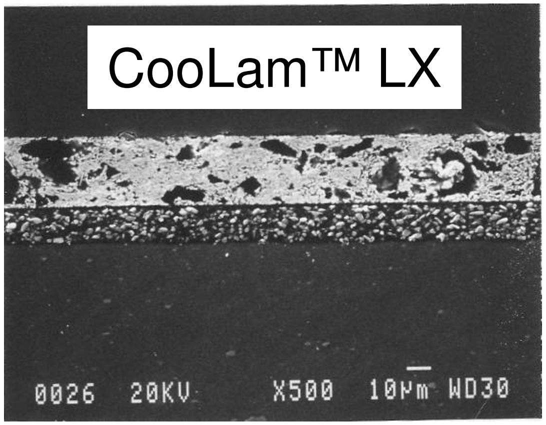


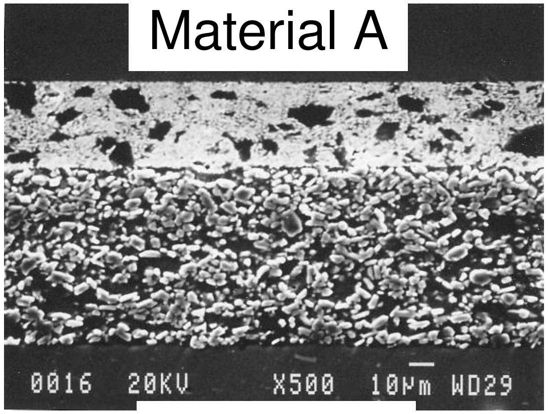


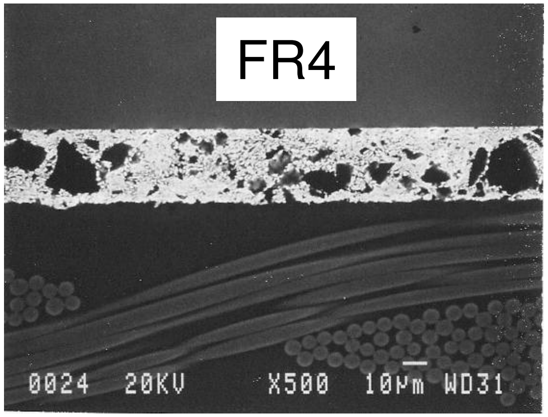
- ❑Two thermocouples used to verify steady state condition (see heat sink detail on previous slide).
- ❑For all samples at all power levels, <0.5C difference between thermocouples after 10 minutes.

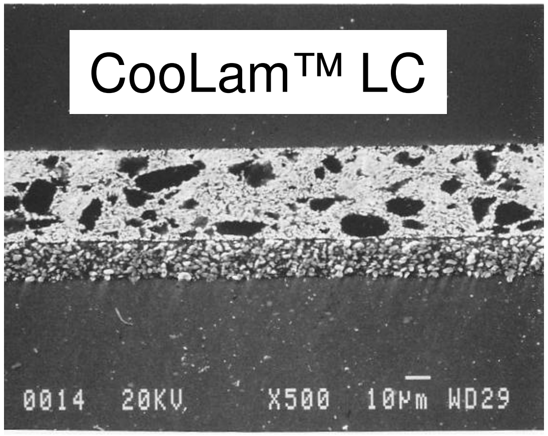
Results – Cross Sections

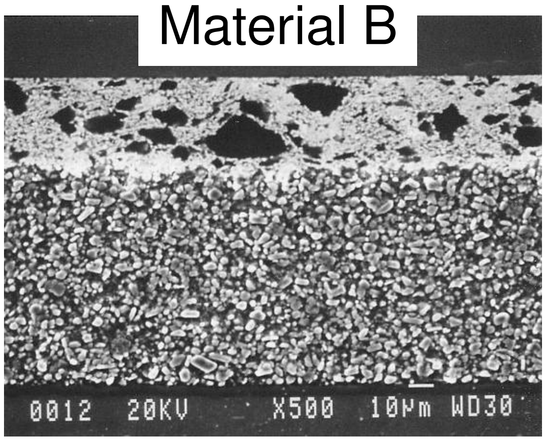
Cross Sections of Each Case (Die Attach, Dielectric, Metal Base)


CooLam™ LX


Material A


FR4

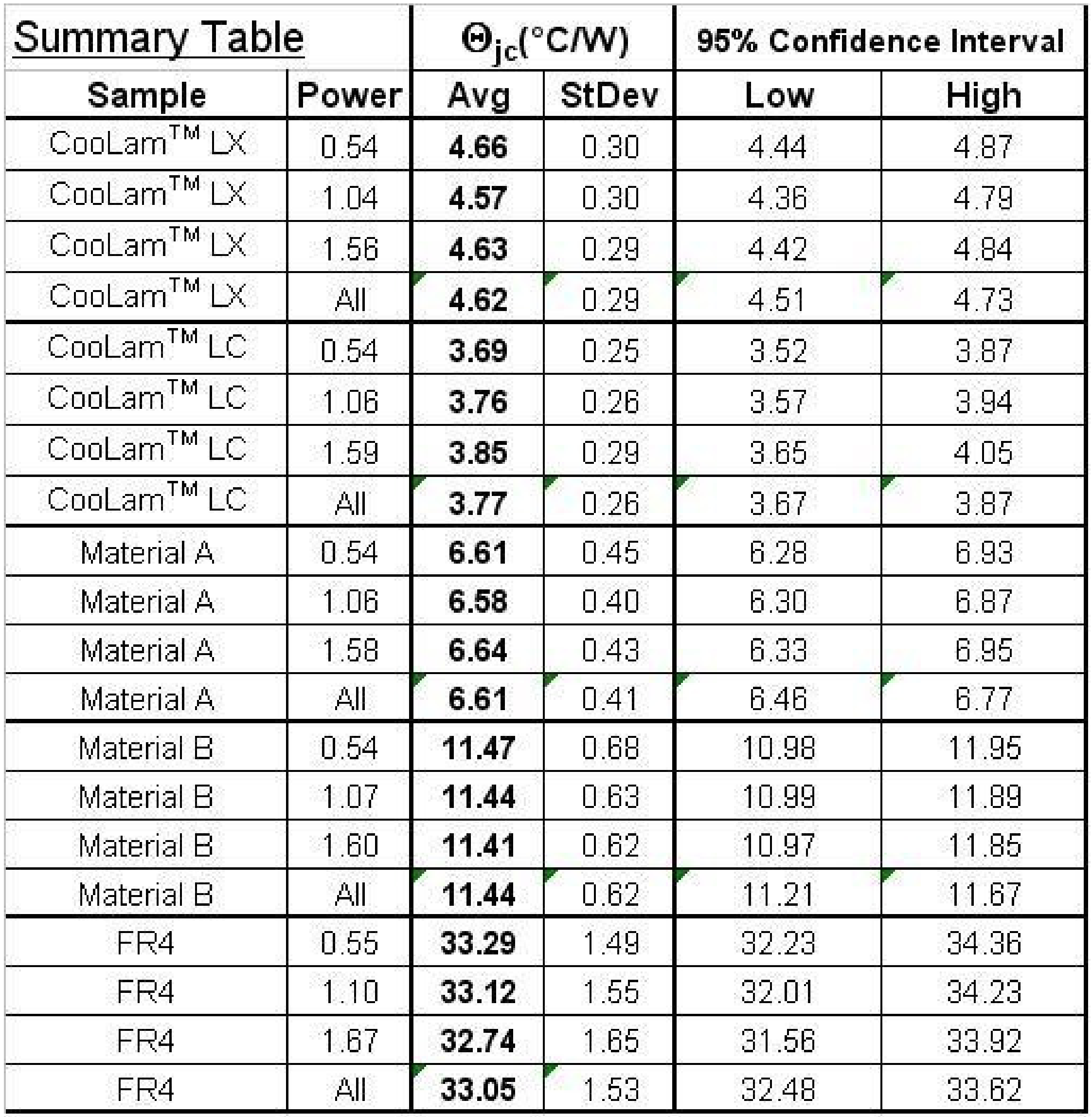

CooLam™ LC


Material B

All Photos have the same scale. Note the dielectric thickness differences.

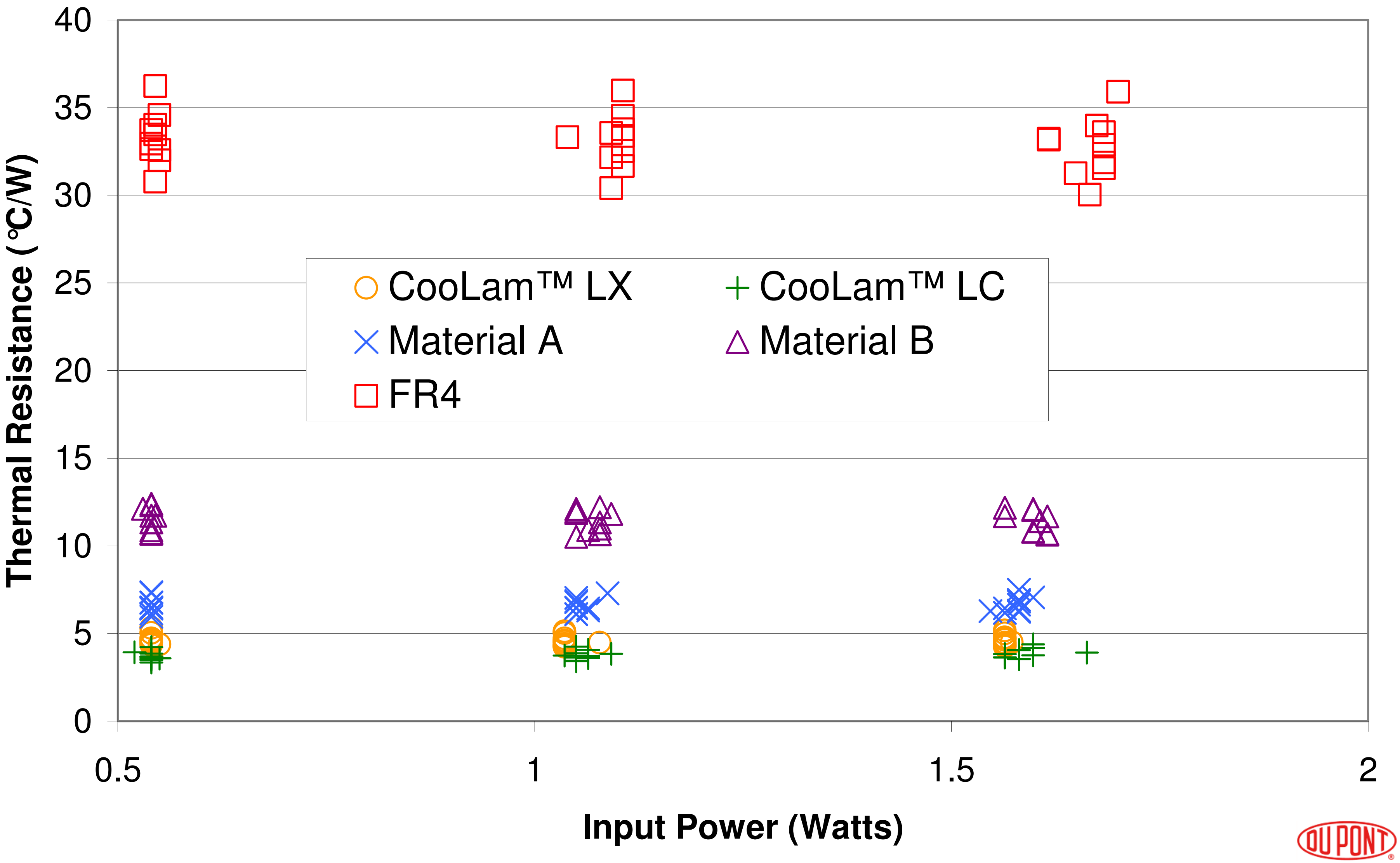
	Measured Thickness (microns)		
Material	**die attach**	**dielectric**	**substrate**
CooLam™ LX	27	17	1040
CooLam™ LC	37	16	1020
Material A	33	75	1470
Material B	36	80	1520
FR-4	30	100	37

Thermal Resistance Measurements



Summary Table		Θ_{jc}(°C/W)		95% Confidence Interval	
Sample	**Power**	**Avg**	**StDev**	**Low**	**High**
CooLam™ LX	0.54	**4.66**	0.30	4.44	4.87
CooLam™ LX	1.04	**4.57**	0.30	4.36	4.79
CooLam™ LX	1.56	**4.63**	0.29	4.42	4.84
CooLam™ LX	All	**4.62**	0.29	4.51	4.73
CooLam™ LC	0.54	**3.69**	0.25	3.52	3.87
CooLam™ LC	1.06	**3.76**	0.26	3.57	3.94
CooLam™ LC	1.59	**3.85**	0.29	3.65	4.05
CooLam™ LC	All	**3.77**	0.26	3.67	3.87
Material A	0.54	**6.61**	0.45	6.28	6.93
Material A	1.06	**6.58**	0.40	6.30	6.87
Material A	1.58	**6.64**	0.43	6.33	6.95
Material A	All	**6.61**	0.41	6.46	6.77
Material B	0.54	**11.47**	0.68	10.98	11.95
Material B	1.07	**11.44**	0.63	10.99	11.89
Material B	1.60	**11.41**	0.62	10.97	11.85
Material B	All	**11.44**	0.62	11.21	11.67
FR4	0.55	**33.29**	1.49	32.23	34.36
FR4	1.10	**33.12**	1.55	32.01	34.23
FR4	1.67	**32.74**	1.65	31.56	33.92
FR4	All	**33.05**	1.53	32.48	33.62

Thermal Resistance Versus Input Power



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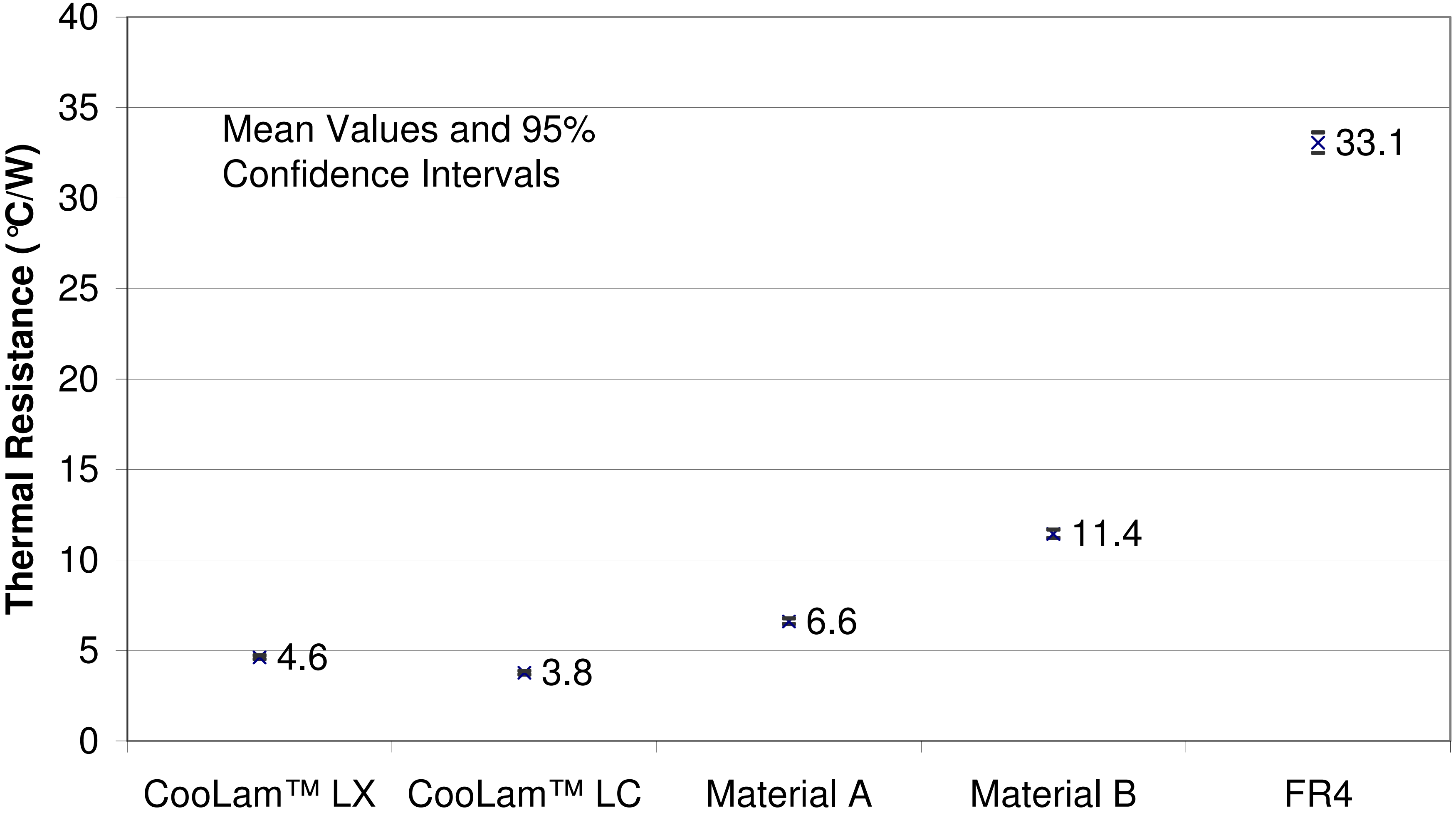
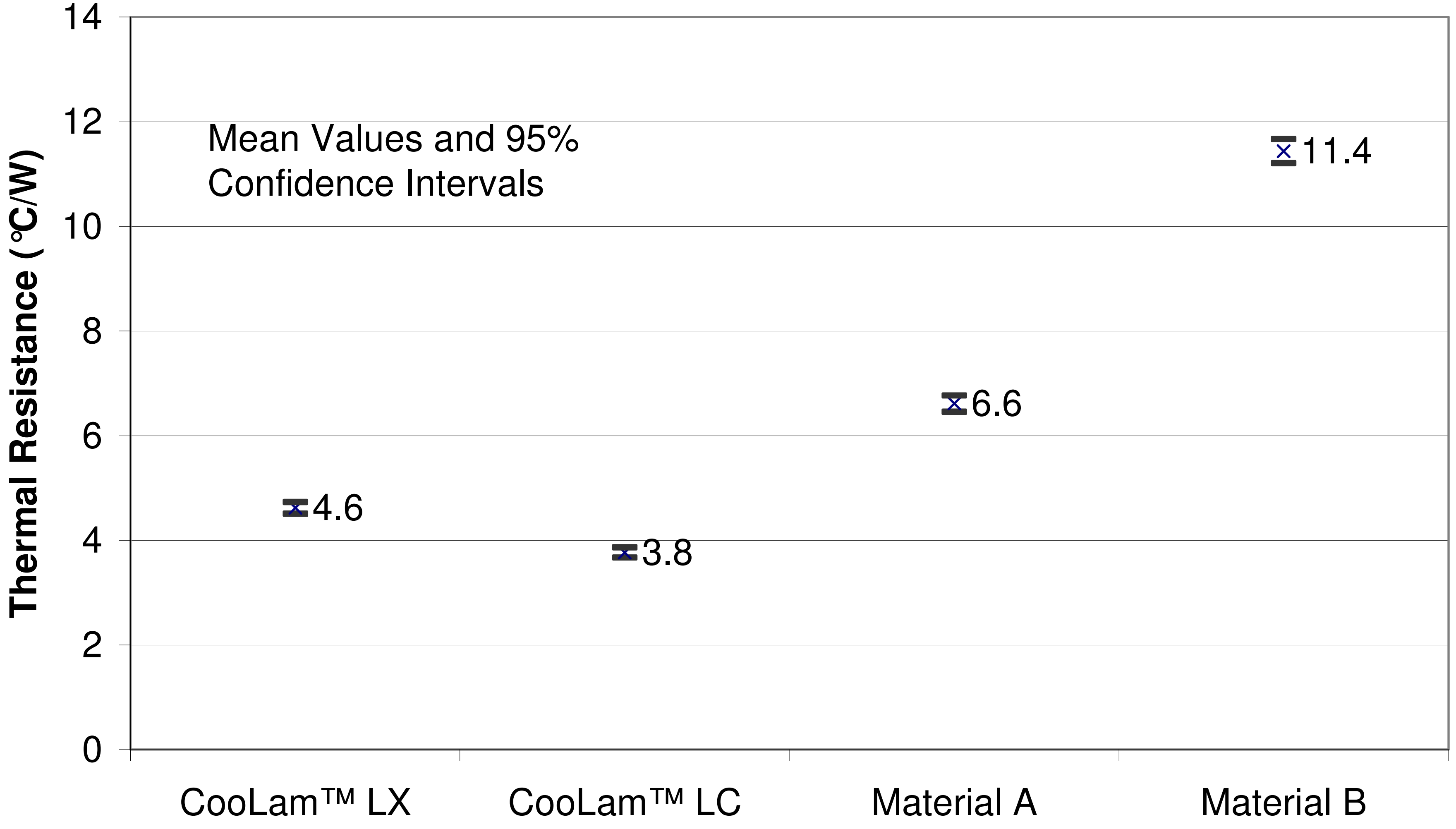
Comparison of Average Thermal Resistance: All Laminates



Comparison of Average Thermal Resistance: Thermal Laminates

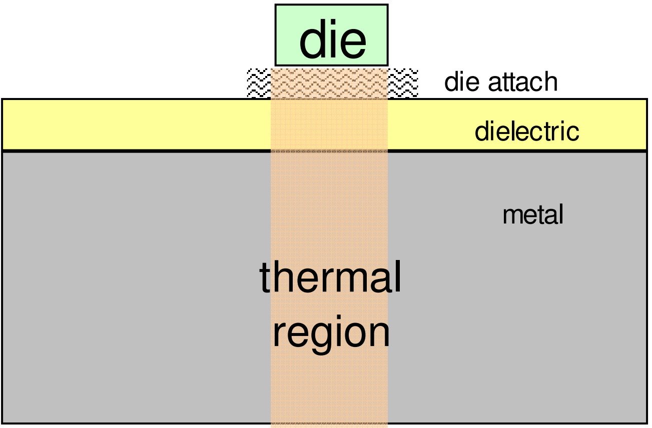


Discussion – Thermal Model

Simplest Analysis – One Dimensional Model

$$\Theta = \frac{(T_1 - T_2)}{q} = \frac{t}{kA}$$

$$\Theta_{total} = \Theta_1 + \Theta_2 + \ldots + \Theta_n$$



Model Not Realistic

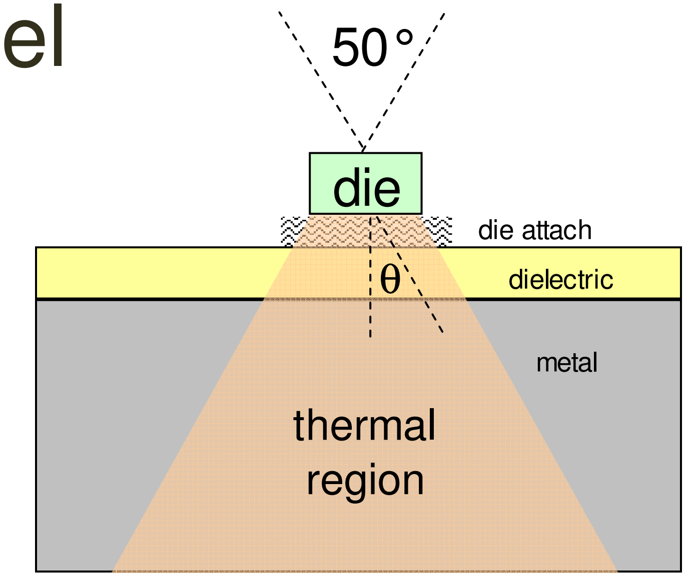
Product	Meas. Thermal Resistance C/W	Thermal Resistance (C/W) Substrate	Die Attach	Dielectric	Calculated Dielectric Thermal Cond. W/(mK)
CooLam™ LX	4.6	1.4	0.4	2.8	1.0
CooLam™ LC	3.8	1.3	0.6	1.9	1.5
Material A	6.6	1.9	0.5	4.2	3.1
Material B	11.4	2.0	0.5	8.9	1.7

Published values are 0.8 and 2.2 respectively

Given known k's for Die Attach and Substrate, calculating k for dielectric yields higher values, however heat does not conduct strictly in a one dimensional way.

$$k = \frac{t}{\Theta A}$$

More Realistic Thermal Model



- Modified Model – Assuming Heat Spreading
- Same math, except the area changes. (Use trigonometry to determine area for each layer thickness.)
- Empirically determined that 2θ = 50° is the most reasonable value. Produces agreement with published thermal conductivity values.
- Heat spreading of θ = 25° is more realistic than the common assumption of θ = 45°.

	Meas. Thermal Resistance C/W	Thermal Resistance (C/W)			Calculated Dielectric Thermal Cond. W/(mK)
Product		Substrate	Die Attach	Dielectric	
CooLam™ LX	4.6	0.7	0.4	3.5	0.8
CooLam™ LC	3.8	0.7	0.5	2.6	1.1
Material A	6.6	0.7	0.5	5.4	2.2
Material B	11.4	0.7	0.5	10.1	1.4

Agreement with published values

- Using this realistic model, the contribution of thermal resistance from the metal is approximately the same for the 1.5 mil thick Aluminum as for the 1.0 mil thick Aluminum core. (Logical since thermal conductivity is so large for Aluminum.)

Conclusions

- A One Dimensional Thermal Model is not Sufficient
    - ☐ One dimensional model could not be reconciled with known thermal conductivity of dielectrics and metals measured
    - ☐ Heat spreading of θ = 25° makes more physical sense
        - Even though Aluminum core is thick (50 x thickness of dielectric), impact on thermal resistance not large
        - Thickness of Aluminum core not a large factor
- DuPont CooLam™ laminates demonstrate improved thermal performance
    - ☐ 40% improvement over Material A – a “high end” thermal laminate
    - ☐ 70% improvement over Material B – a “medium grade” thermal laminate
- CooLam™ is an excellent option for HB-LED applications
    - ☐ Short Thermal Path – Thin dielectric
    - ☐ Polyimide dielectric provides reliability and desirable mechanical and electrical properties

Acknowledgements

- Industrial Technology Research Institute
  - ❑ ***Electronics and Optoelectronics Research Laboratories*** ***http://www.itri.org.tw/***
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