MCPCBs for LED Applications

Thermal Management Material Specifications
Purpose of the Webinar

**Defining your needs**
To break down your needs for thermal management materials, specifically metal core printed circuit board (MCPCB), in LED Applications by *technical requirements* in order to make more effective callouts.

**Controlling the process**
The end result should be shorter lead times, lower cost, and more reliable product.

**Non-browning soldermasks**
Introduce new non-browning white LED soldermasks.
Metal Core Boards

Definition
The MCPCB commonly consists of a metal core layer (typically aluminum or copper), a continuous dielectric layer and a copper circuit layer.
Part One
Specifying Materials for LED Applications
Survey Question

How do you specify materials in MCPCB LED applications?

a) Company Name and/or Part Number (e.g. Bergquist, Laird, DuPont, etc.)
b) Thickness of dielectric
c) $T_g$ or $T_d$
d) “Metal Core”
e) Insulation Resistance & Thermal Conductivity Values
Survey Answer

How do you specify materials in metal core LED applications?

a) Company Name and/or Part Number (e.g. Bergquist, Laird, DuPont, etc.)

Comment
Specifying by brand name locks you into a particular product produced by a particular manufacturer.

Risks Include:
- Locked into pricing
- Subject to lead times
- Preventing new materials from being used on your product
Survey Answer

How do you specify materials in metal core LED applications?

b) Thickness of dielectric,
c) Tg,
d) Td

Specifying only these items may not fully address your needs.
• Does not address thermal conductivity
• Does not address electrical insulation resistance
• Does not address type of dielectric
Comment:
Specifying “metal core” does address anything whatsoever.
Answer

How do you specify materials in metal core LED applications?

f) Insulation Resistance & Thermal Conductivity Values

Comment:
You are a rock star! This is the whole point of our webinar.
Consider *your needs* when bringing the bare board into the equation.
Survey Question

What Are Your Needs When Selecting Materials? (Choose all that apply)

a) Transfer heat (Thermal Conductivity)
b) Prevent short circuiting to base metal core (Electrical Insulation Resistance)
c) Thickness of dielectric
d) Brand name of the material?
Cost Drivers For MCPCBs

Dielectric Substrate
The #1 cost component of the MCPCB is the dielectric substrate between the copper traces and the metal heatsink/core.

Definition
An insulating medium which occupies the region between two conductors. In this case, the copper circuits and the metal core heat sink.
Cost Drivers For MCPCBs (cont.)

Introducing competition

The most effective way to reduce cost of dielectric is to introduce competition:
- Laird
- Bergquist
- Dupont
- Uniplus
- Iteq
- Insulectro
- Plus future innovators
Definition and Applications

Thermal Transfer
Product Application
Electrical Insulation
Product Reliability
Purpose #1

Transfer Heat
Common Callouts include Thermal Impedance / Resistance (°C in²/W) and Thermal Conductivity / (°W/m-K).
Why Kapton® / Polyimide?

Heat Resistance
Stability
Flexibility
Dielectric Properties
Density/Weight

CooLam™ MCPCB (metal core PCB) Offers:
- Very Low Thermal Impedance
- Excellent Reliability Performance
- Excellent Durability and Stability at High Temperature
- Uniform Thermal, Mechanical & Electrical Properties Under Environmental Stress
- Lead Free Solder and Wirebond Process Compatibility
- Halogen Free
- Meets UL 94 V-0
- Construction Variations to Meet Thermal Management Needs
- 3D Shapes
Objective:
Measuring thermal performance per ASTM D5470.

Equipment:
1) Steady State “Thermal Interface Material Tester” (TIM) (Analysis Tech. Inc.)

Factors to Consider:
1) Reducing contact resistance between sample and test unit
2) Repeatability of measured values
3) Identify any equipment and/or material limitations
Basic Principles of ASTM D5470

What is Thermal Resistance?

Thermal Resistance \( (R_{th}) \) is defined as the difference in temperature between two closed isothermal surfaces divided by the total heat flow between them.

\[
R_{th} = \frac{(T_{(A)} - T_{(B)})}{\text{Power}}
\]

\( \Delta \degree C \)

\( \text{Watt} \ (V^*I) \)

* Present system does a good job of accounting for all heat and monitoring temperature but nothing is perfect.
Power (Watts)

Thermal Resistance ($R_{th}$): \[ \frac{\Delta \, ^\circ\text{C}}{\text{Watt}} \]
\[ = \left( \frac{\Delta \text{ Temp.}}{\text{power}} \right) \]

Thermal Impedance ($R_{thI}$): \[ \frac{\circ\text{C} \cdot \text{in}^2}{\text{Watt}} \]
\[ = (\text{Thermal Resistance}) \times \text{area (of test sample)} \]

and

Thermal Conductivity: \[ \frac{\text{Watt}}{\text{m} \cdot ^\circ\text{C}} \]
\[ = \frac{\text{thickness (material)}}{\text{thermal impedance}} \]
Total Thermal Resistance ($R_{th\ total}$) is the sum of components and its thermal resistance value.
ASTM D5470 Thermal Measurement Technique

Measured Thermal Impedance (C-in²/Watt):

\[ R_{thI}^{\text{grease\_top}} + R_{thI}^{\text{sample}} + R_{thI}^{\text{grease\_bottom}} = \text{Total } R_{thI} \]

\[ R_{thI}^{\text{sample}} = \text{Total } R_{thI} - (R_{thI}^{\text{grease\_top}} + R_{thI}^{\text{grease\_bottom}}) \]
Thermal Impedance

Electronics industry defines thermal impedance as the following:

\[ impedance_{thermal} = \frac{\text{thickness}}{k} \]

This does **not** include an area through which the heat flows!

**Thermal Impedance**

\[ I = \frac{t_{\text{Dielectric}}}{k_{\text{Dielectric}}} \]

Units:

\[ I \rightarrow \frac{m}{W/mK} = \frac{m^2K}{W} \]

**Thermal Resistance**

\[ R = \frac{t_{\text{Dielectric}}}{k_{\text{Dielectric}}A} \]

Units:

\[ R \rightarrow \frac{m}{W/mK m^2} = \frac{K}{W} \]
Thermal Impedance

Calculating the thermal conductivity of a material

Plot Ra vs. thickness from TIM tester

1/k = thermal conductivity  \( k = \text{the slope of the line} \)

Thermal Conductivity LG: 0.25 W/M-K

= 1.0 in / 39.35 K-in2/W
= 0.006394 W/in-K x 39.4 in/M (convert to metric)
= 1.0 W/M-K
Example problems

What is the thermal resistance through the thickness of a 0.3 meter by 0.3 meter piece of stainless steel that is 1.5 cm thick? Assume the thermal conductivity of stainless steel is 15 W/mK.

\[ R = \frac{t}{kA} \]

\[ R = \frac{0.015m}{(15 \text{ W/mK})(0.3m)(0.3m)} \]

\[ R = 0.011 \text{ K/W} \]
Example Problems

This same piece of stainless steel now has a heater attached to one side that generates 100 Watts of heat into the plate.

If the bottom of the plate measures 45°C (318K), what is the temperature of the top side of the plate?

\[
q = \frac{(T_{top} - T_{bottom})}{R_{thermal}} \quad (T_{top} - T_{bottom}) = q \cdot R_{thermal}
\]

\[
T_{top} = q \cdot R_{thermal} + T_{bottom}
\]

\[
T_{top} = 100W \cdot 0.011K/W + 318K
\]

\[
T_{top} = 319.1K = 46.1°C
\]
Basic Question

Room Temp = 30°C

Same LED and power input

MCPCB 1

MCPCB 2

T\text{\textsubscript{junction}} = 65°C

T\text{\textsubscript{junction}} = 70°C

WHY???

Heat Transfer
Thermal Management for LED Applications

What is the role of the PCB?

Presented by Clemens Lasance
Clemens is a former Principal Scientist Emeritus with Philips Research, the Netherlands, with a 30 year + focus on thermal management of electronic systems.
He is now a consultant for *Somelikeit Cool*, contact info: [lasance@onsnet.nu](mailto:lasance@onsnet.nu)
Motivation

Providing the right information the first time

The goal is to provide the LED application engineer with the right information to select the most optimal MCPCB from a thermal point of view. Thus, ensuring the best decision is made for a specific application in regards to thermal performance and cost.
Main Goal of Thermal Management

The Calculation of application-specific junction temperatures

Reasons / Key Issues

- Lifetime
- Color point
- Efficiency

All these key issues are significantly dependent on the junction temperature.
Basics of Heat Transfer

Fundamentals of Critical Temperature Calculation

Determining critical temperatures is contingent upon a critical understanding of:

- The electrothermal analogue
- Thermal conductivity $k$
- Heat transfer coefficient $h$
- Thermal resistance $R_{th}$
## Electro-Thermal Analogue

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta T = q * R_{th}$</td>
<td>Temperature drop (°C)</td>
<td>$\Delta V = I * R$</td>
<td>Voltage drop (V)</td>
</tr>
<tr>
<td>$\Delta V = I * R$</td>
<td>Voltage drop (V)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power dissipation (W)</td>
<td>Current (A)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heat flux (W/m²)</td>
<td>Current density (A/m²)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal resistance (K/W)</td>
<td>Resistance (Ohm)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Electro-Thermal Analogue

A heat transfer path can be described by an electrical network

\[ \Delta T = T_{\text{source}} - T_{\text{ambient}} \]

\[ R_{\text{th}} \text{ (K/W)} = \text{thermal resistance} \]
Series Circuit

Example for two resistances in series

\[ \Delta T = T_{\text{source}} - T_{\text{ambient}} = q \times R_{\text{total}} \]

\[ R_{\text{total}} = R_1 + R_2 \]
Consequence of Series Circuit

Often only the largest $R$ is relevant!

Designer’s job: find the largest resistance!
Thermal Conductivity: Fourier’s Experiment (1822)

Result of Fourier’s experiment:
\[ q \sim \Delta T = T_{\text{hot}} - T_{\text{cold}} \]
\[ q \sim A = \text{cross-sectional area} \]
\[ q \sim L^{-1} \]

\[ q = k \cdot \frac{A}{L} \cdot \Delta T \]

The proportionality constant \( k \) is called the ‘thermal conductivity’
Typical Thermal Conductivity Values

Approximate ranges of thermal conductivity for various substances:
(All values are in the neighborhood of room temperature unless noted)
The Heat Transfer Coefficient $h$

The heat transfer from a solid wall into a fluid (air, water) is called convection, and to first order this heat transfer is proportional to the area and the temperature difference between the wall and the fluid:

$$q = h \cdot A \cdot \Delta T$$

The proportionality constant $h$ is called the ‘heat transfer coefficient’

**Typical values:**
- Natural convection: 10 W/m$^2$K
- Forced convection: 50 W/m$^2$K
Practice

Suppose a Designer needs 5W to reach a required light output

What procedure is most optimal?

Information required for first order guess:

• Maximum junction temperature: e.g. 120 °C
• Maximum ambient temperature: e.g. 40 °C
• An estimation of all thermal resistances in the total heat transfer path

\[
q = \frac{\Delta T}{R_{th-total}}
\]
Practice (2)

Next steps

- Check if required power is manageable by suitable heat sinks & convection

- Check which thermal resistances are dominant
  - Then focus on them to reduce the total thermal resistance

- Final step should always be a detailed analysis
  - Recall that often we don’t talk one-dimensional heat transfer but heat spreading, which is a rather complicated issue
  - For more information please see *Heat Spreading, Not a Trivial Problem* in the May 2008 issue of *ElectronicsCooling*
Practical Example

\[ q = k \cdot \frac{A}{L} \cdot \Delta T \]

\[ R_{th} = \frac{L}{k \cdot A} \]

\[ q = h \cdot A \cdot \Delta T \]

\[ R_{th} = \frac{1}{h \cdot A} \]

Relevant thermal resistances, assume 1 cm² PCB

<table>
<thead>
<tr>
<th>Component</th>
<th>K/W</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_{th})-LED</td>
<td>16</td>
<td>Luxeon Rebel</td>
</tr>
<tr>
<td>( R_{th})-MCPCB</td>
<td>0.5</td>
<td>t = 100 µm, k = 2 W/mK</td>
</tr>
<tr>
<td>( R_{th})-TIM</td>
<td>1</td>
<td>t = 100 µm, k = 1 W/mK</td>
</tr>
<tr>
<td>( R_{th})-heatsink</td>
<td>50</td>
<td>A = 20 cm², h = 10 W/m²K</td>
</tr>
<tr>
<td>( R_{th})-heatsink</td>
<td>2</td>
<td>A = 100 cm², h = 50 W/m²K</td>
</tr>
<tr>
<td>( R_{th})-heatsink</td>
<td>1</td>
<td>A = 1 cm², h = 10000 W/m²K</td>
</tr>
</tbody>
</table>
Practical Example

We need 5W for our light output
Can we find a suitable heat sink?

We have:

\[ T_{\text{junction}} = 120 \, ^\circ \text{C} \]
\[ T_{\text{ambient}} = 40 \, ^\circ \text{C} \]
\[ R_{\text{th-LED}} + R_{\text{th-MCPCB}} + R_{\text{th-TIM}} = 17.5 \, \text{K/W}; \ R_{\text{th-heatsink}} = ? \]

Can we dissipate 5W? No way:
\[ q = \frac{\Delta T}{17.5 + R_{\text{th-heatsink}}} \]

Conclusion:
Even with an ideal heat sink \((R_{\text{th-heatsink}} = 0)\) we cannot dissipate the required 5W. In this case we need an LED with less thermal resistance.
Practical Example

We need 1W for our light output

We have again:

\[ T_{\text{junction}} = 120 \, ^\circ\text{C} \]
\[ T_{\text{ambient}} = 40 \, ^\circ\text{C} \]
\[ R_{\text{th-LED}} + R_{\text{th-MCPCB}} + R_{\text{th-TIM}} = 17.5 \, \text{K/W} \]
\[ R_{\text{th-heatsink}} = ? \]

Which heat sink is OK?

\[ q = \frac{80}{17.5 + R_{\text{th-heatsink}}} \]
\[ R_{\text{th-heatsink}} = 62.5 \, \text{K/W} \]

We found earlier:

\[ A = 20 \, \text{cm}^2, h = 10 \, \text{W/m}^2\text{K} \rightarrow R_{\text{th-heatsink}} = 50 \, \text{K/W} \]

Conclusion:

We can use a simple heat sink with natural convection.
Thermal resistance of the MCPCB does not play any role

- In our first case, the LED thermal resistance was dominant; while in the last case, the convective resistance was dominant.

- Hence, *from a thermal point only*, you can choose MCPCBs with a much lower thermal performance and, hence, lower cost.

- The thermal performance of the PCB is relevant only for very high heat flux cases (e.g. liquid cooling) and for top-of-the-bill LEDs.
Nomenclature

The confusing situation regarding ‘thermal impedance’

Fact:
‘Electrical impedance’ is historically reserved to describe time-dependent electrical resistance. In the limit of steady state, thermal impedance equals thermal resistance → hence, units should be the same!

Hence,
‘Thermal impedance’, as used by U.S. vendors, violates the electro-thermal analogy, because:
- Unit does not correspond (K/W vs. m²K/W)
- Definition does not correspond (time-dependent vs. steady state)

Is this a problem?
Yes, because time-dependent (dynamic) test methods will be increasingly used, one output of which is the ‘correct’ thermal impedance.

Proposal:
Use thermal resistance per unit area, or unit $R_{th}$. 
Electrical Properties

Presented by Michael Gay (Isola) and Norm Berry (Insulectro)
Common Tests

- **Insulation Resistance (IR)**
  - This test is used to provide a quantifiable resistance value for all of a product's insulation.

- **Dielectric Breakdown Strength Test**
  - The test voltage is increased until the dielectric fails, or breaks down, allowing too much current to flow.

- **Dielectric Withstand Voltage Test (DWS) or High Potential Test (HiPot)**
  - A standard test voltage is applied (below the established Breakdown Voltage) and the resulting leakage current is monitored.

- **Conductive Anodic Filament Test (CAF)**
  - This test is used to determine the capability of the material for various design feature spacing under high humidity conditions with applied voltage.
Typical Proof Test (VDC)

Proof Test or High Potential Test (HiPot)
A standard non-destructive test voltage is applied (below the established Breakdown voltage) and the resulting leakage current is monitored. The test is done to evaluate the integrity of the dielectric material.
High Potential Dielectric Testing (HiPot)
This non-destructive testing methodology is used to characterize the laminate material insulation capability under a specified potential. Leakage current is measured and compared to predetermined limits.

**Typical Test Conditions:**
500-2500 Volts DC (VDC)
700-1200 Volts AC @50-60 Hz (VAC)
Up to 30 seconds
10 MΩ – 500 MΩ
10 μA – 100 μA
Breakdown voltage is the stress at failure when AC at power frequency is applied using a rate of rise is 500 Volts/second. Breakdown voltage testing does not relate to proof stress “Proof Testing”. Breakdown voltage is the potential difference at which dielectric failure occurs under prescribed conditions in an electrical insulating material located between two electrodes.
Breakdown (kV AC)

Dielectric Breakdown Voltage

This testing methodology is used to characterize the laminate material insulation capability to failure.

**Typical Test Conditions:**
Ramp Volts AC @50-60 Hz (VAC) until failure

**Example:**
Determine the electric strength in volts per mil for each specimen by dividing the breakdown voltage expressed in kilovolts by the thickness express in inches.

\[
ES = \left(\frac{6.8 \text{ KV}}{.005 \text{ inch}}\right) \times (1000 \text{ V/KV}) \times \left(\frac{1 \text{ inch}}{1000 \text{ mils}}\right) = 1360 \text{ v/mil}
\]
Permittivity (Dk)

Typical thermal management materials are modified to have higher thermal conductivity. The modifications of the dielectric material raise the Dk of the material to the range of 6 or higher.
Product Reliability

Presented by Richard A. Wessel of DuPont
Big concern: what is $T_{\text{junction}}$?

Why?
Lower $T_{\text{junction}}$ Better

Increased relative luminous flux for lower junction or thermal pad temperature
Increased Lifetimes

Lower Junction Temperature

Increased lifetimes for lower junction temperature

Luxeon® Rebel

![Graphs showing lifetime vs. junction temperature for Luxeon Rebel LEDs.](image-url)
Suggested Fabrication Notes

Taking Control of Your Design!
Suggested Fabrication Notes

Purpose of Fab Notes

Take *your* requirements for each characteristic that *you* deem most important and specify (values for thermal conductivity and electrical insulation resistance).

We also suggest including a list of pre-approved materials.
Suggested Fabrication Notes (cont.)

Example of a Fab Note

Copper Weight:  2 oz.
Metal Core:  0.060” Al 5051

Dielectric:

  Thermal Conductivity:  Must meet or exceed 1.3 (°W/m-K)
  Thermal Resistance:  Maximum 0.9 (°C in²/W)
  Electrical Insulation:  Must meet or exceed 2,000 VDC

*Any other characteristic you feel is important:  XYZ*

Currently Approved Materials:

- Bergquist HT-07006
- Bergquist LTI-06005
- Laird T-lam SS 1KA06
- DuPont CooLam
Suggested Fabrication Notes (cont.)

Benefits of Fab Notes

 Allows supplier to quote *multiple vendors*.

Subsequent Results

- Lower Cost
- Quicker Lead Times
- Adaptability to take advantage of new technologies down the road
- Introduce competition from the raw materials and finished PCB suppliers
# Materials Chart

## Thermal Dielectric Material Selection Chart

<table>
<thead>
<tr>
<th>Brand</th>
<th>Material Type</th>
<th>Resistance (°C in²/W)</th>
<th>Conductivity (°C/W-m-K)</th>
<th>Typical Proof Test (VDC)</th>
<th>Breakdown (kVAC)</th>
<th>Permittivity (Dk)</th>
<th>Glass Trans (°C)</th>
<th>UL Index (°C)</th>
<th>Peel Strength (lb/in)</th>
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<tr>
<td>Bergquist</td>
<td>HT-04503</td>
<td>0.05</td>
<td>2.2</td>
<td>1500</td>
<td>6.0</td>
<td>7</td>
<td>150</td>
<td>140 / 140</td>
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<td>7</td>
<td>150</td>
<td>140 / 140</td>
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<td>2.2</td>
<td>1500</td>
<td>6.5</td>
<td>7</td>
<td>90</td>
<td>130 / 130</td>
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<td>7</td>
<td>90</td>
<td>130 / 130</td>
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<td>1.3</td>
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<td>6</td>
<td>90</td>
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<td>110</td>
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<td>150</td>
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<td>&gt; 300°</td>
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<td>140 / 110</td>
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<tr>
<td>Iteq</td>
<td>IT-858T (80 um)</td>
<td>0.128</td>
<td>2.2</td>
<td>&gt; 6000</td>
<td>&gt;4.0</td>
<td>159</td>
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<tr>
<td>Iteq</td>
<td>IT-858T (100 um)</td>
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<td>159</td>
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<tr>
<td>Iteq</td>
<td>IT-859GT (80 um)</td>
<td>0.126</td>
<td>2.2</td>
<td>&gt; 6000</td>
<td>&gt;4.0</td>
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<td>0.4</td>
<td>&gt; 3000</td>
<td>&gt;3.0</td>
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<td>&gt;3.0</td>
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Part Two

Non-browning White Soldermask
White Soldermask

Current Resin Systems

- Focus on initial thermal shock, not constant heat
- Tend to Brown over time
- Not developed to be a Reflecting Surface for LEDs
White Soldermask (cont.)

Desired Resin Systems

- Remain white through Assembly and Lifespan of LED final product
- Have high reflectivity to enhance LED performance
  - Some believe high reflection soldermask results in lower power consumption for same light output
What are the Solutions?

New White High Temperature Liquid Photo-Imageable Soldermasks

- Past two years a number of “LED” white soldermasks have been introduced
  - Unfortunately we have not seen improvements in all of them

- Through numerous studies we have so far found two offerings that show significant improvement:
  - Peters *(SD2491SM TSW)*
  - Sun Chemicals *(CAWN 2589/2591)*
If *Bright* white soldermask is the objective, these solutions may not suffice

- Suggest base coat of LPI White then topcoat of High-Temp thermal white soldermask
- After numerous thermal whites, one does not brown after multiple cycles (*Peters SD2496TSW*)
- This is the formula behind “proprietary” white soldermasks offered by other PCB vendors

**New White High Temperature Thermal Soldermasks**

What are the Solutions? (cont.)
Cost Expanders

New White High Temperature Liquid Photo-Imageable Soldermasks

- To date, we’ve seen cost increases over standard soldermask price of 30% - 100%
  - Approximately .20 to .30 cents per panel (18” x 24”)

New White High Temperature Thermal Soldermasks

- To date, we’ve seen cost increases over standard soldermask price of > 100%
  - Approximately $1 per panel (18” x 24”)
  - Includes labor and set up for secondary application process
Thermal Webinar Conclusion

**Specify** your needs for thermal performance of the dielectric

**Specify** your needs for the electrical performance of the dielectric

**Specify** your needs in context of entire product, not just PCB (when applicable)

**Know** that you have white soldermask choices

but keep your fab notes open to take advantage of future developments