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Advanced Thermal Control Enabling Cost Reduction for Automotive Power Electronics

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DOE's Advanced Power Electronics and Electric Machines (APEEM) Research

National Renewable Energy Laboratory (NREL)
Lead: APEEM Thermal Control R&D



Oak Ridge National Laboratory (ORNL)
Lead: Power Electronics & Electric Machines R&D

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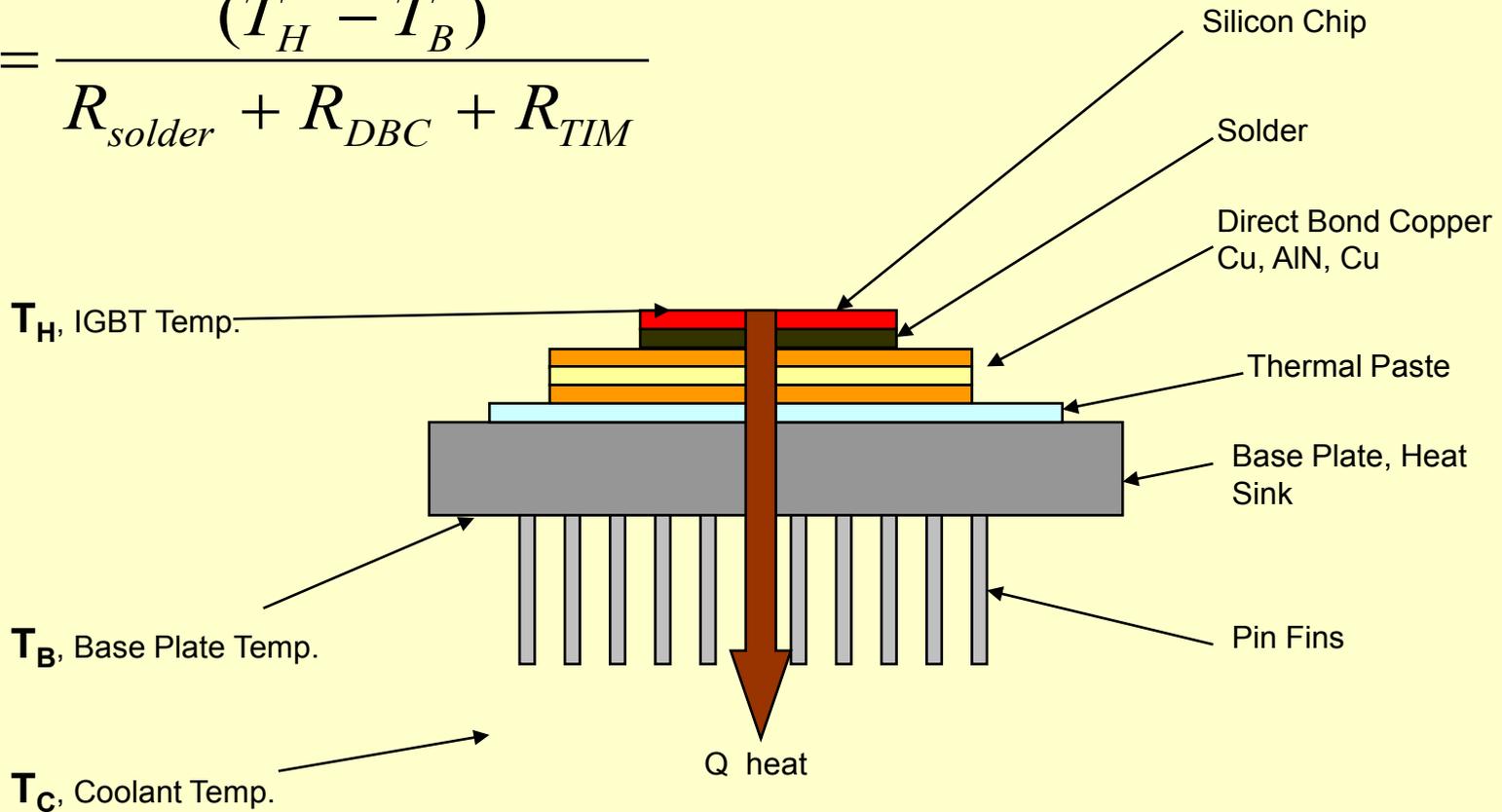
Industry and Academia

Motivation

- Most aggressive target of FreedomCAR program is the cost (2020 target is \$8/kW for a 55 kW traction system).
- Meeting the cost target is critical for greater penetration of the vehicles market .
- NREL's Advanced Power Electronics team is working on next-generation advanced cooling technologies (jets/sprays/micro-channels with single or two-phase) and novel packaging topologies.
- Advanced cooling technologies are used in conjunction with novel packaging topologies for identifying low-cost materials for cost (and weight) reductions while meeting the targets of performance and reliability.

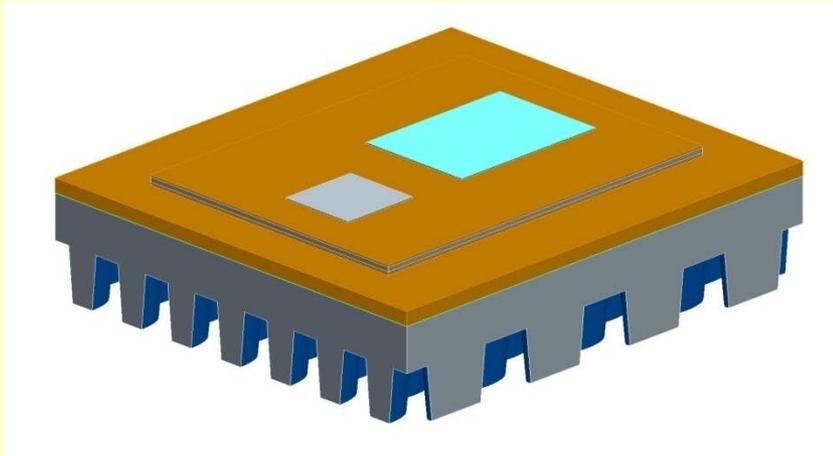
Description of Technology

$$Q = \frac{(T_H - T_B)}{R_{solder} + R_{DBC} + R_{TIM}}$$

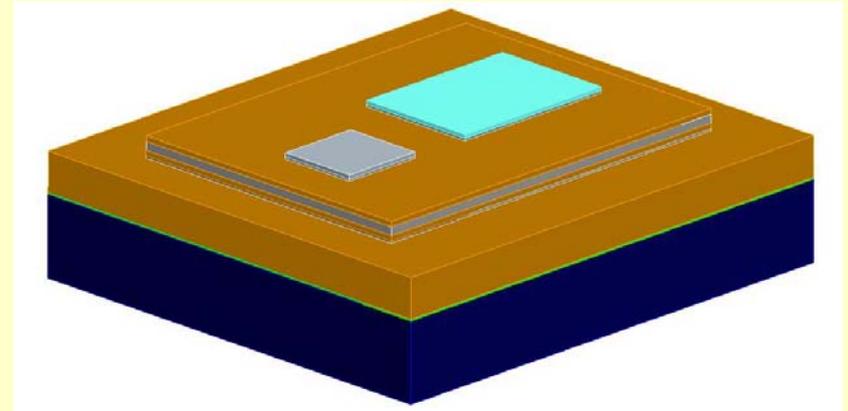


$$Q = h A (T_B - T_C)$$

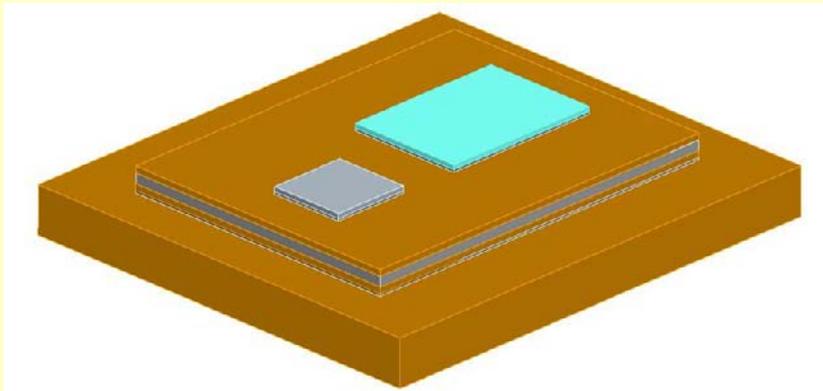
Topologies



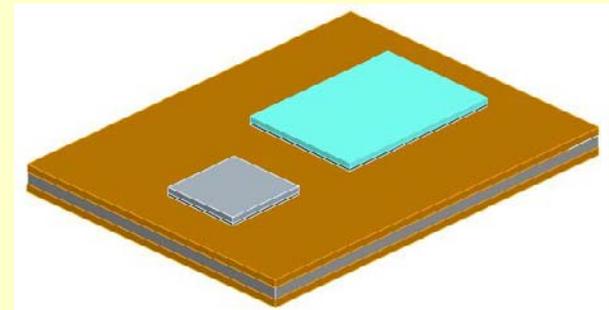
Baseline Topology



Topology 1 (very similar to the baseline topology, which uses Thermal Interface Material)



Topology 2 (Base plate cooling; does not involve Thermal Interface Material)



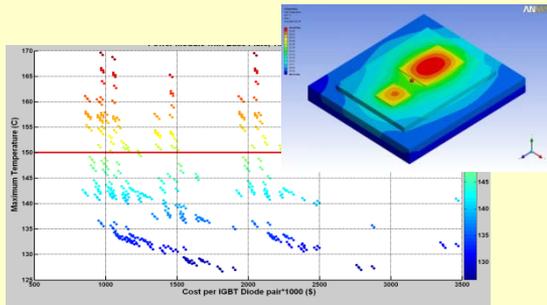
Topology 3 (Direct Cooling of Direct Bonded Copper)

Thermal Materials Exploration Study – Steps

Thermal Materials Exploration Study

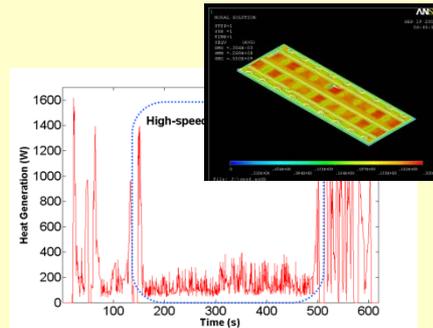
Part 1:

Exploring tradeoffs between thermal performance and cost for several topologies



Part 2:

Evaluation of Thermal Stress and Reliability Aspects



Part 3:

Emerging technologies:
1)LTCC substrates
2)Organic substrates



- Performance: Peak temperatures of the switching devices (IGBTs and diodes) need to be below 150°C.
- Reliability: Power electronics need to meet life-cycle target of 15 years.

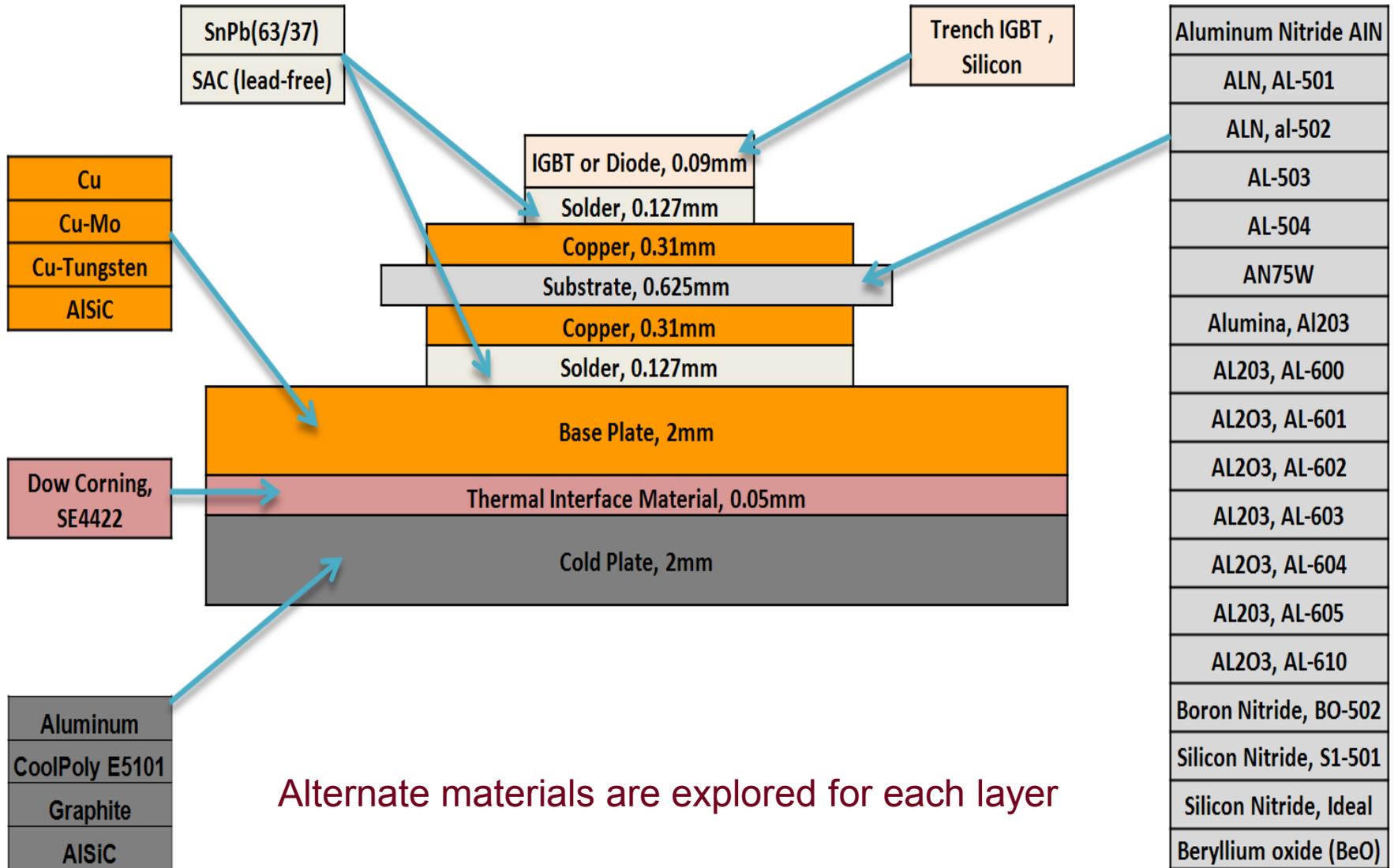
Thermal Materials Exploration Study – Comments

- Two layers that have potential opportunities for cost reduction are the substrate and the cold plate.
- Today's preferred substrate, Aluminum Nitride (AlN) is expensive.
- Low-cost LTCC technology has been well demonstrated in automotive electronics applications. Several issues, notably **thermal disadvantages** have slowed down the spread of this substrate technology [1].
- Silicon nitride (SiN) as a substrate would make economic sense if the cost is reduced to \$5 per pound [2].

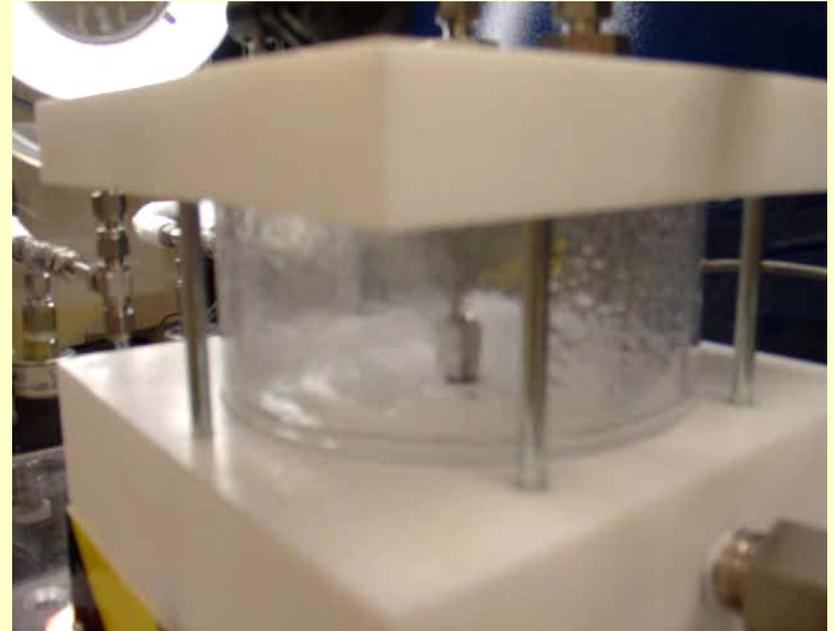
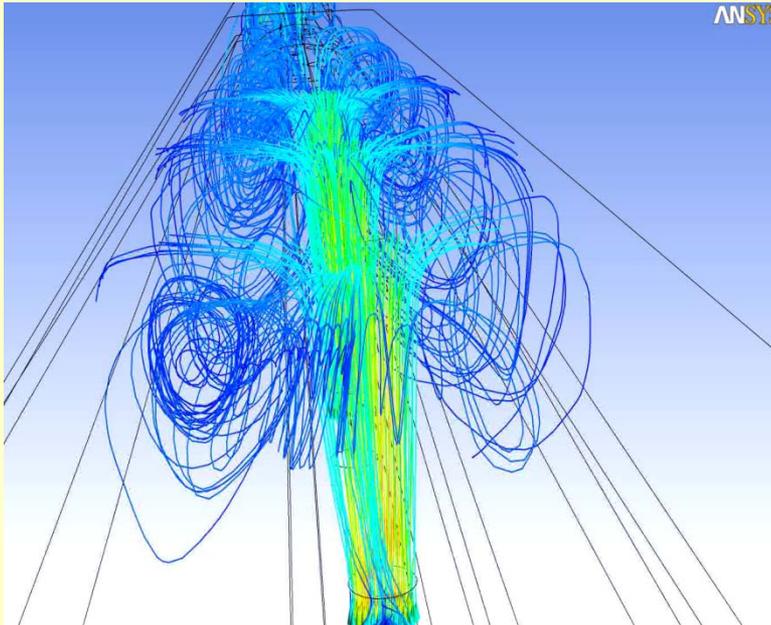
1. Fairchild, M.R., Snyder, R.B., Berlin, C.W., and Sarma, D.H.R., "Emerging Substrate Technologies for Harsh-Environment Automotive Electronics Applications," SAE 2002-01-1052.

2. Das, S., and Curlee, T.R., "The Cost of Silicon Nitride Powder: What Must It Be To Compete?" 1992, ORNL-6694.

Materials Exploration – Topology 1



Verification of CFD Model with Test



CFD (using Fluent)

Test

	CFD	Test
Average Heat Transfer Coefficient (W/m ² .K)	18,350	18,481

”What-If” option of Design Explorer in “ANSYS Workbench Thermal Simulation” is used to automate materials exploration studies

Heat Load per Diode = 35 W

Heat load per IGBT heat load = 85 W

What-If Design Points

Parameter Information

The table below gives information about each parameter in the analysis.

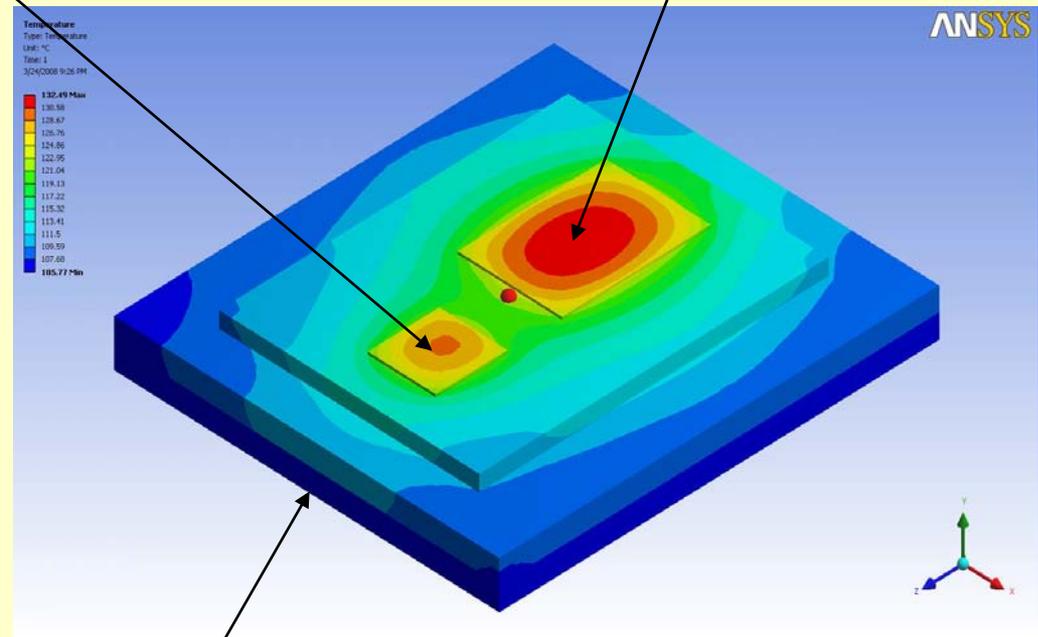
Parameter Name	Source Application	Type	Nature	Initial Value
Load Poles Thermal Conductivity	ID_ECA	Input	Continuous	220
Solders Thermal Conductivity	ID_ECA	Input	Continuous	35
Substrates Thermal Conductivity	ID_ECA	Input	Continuous	170
Base-Plates Thermal Conductivity	ID_ECA	Input	Continuous	175
Temperature Maximum	Analysis	Output	Continuous	155.84

Design Points

The table below represents a list of design points that can be used to examine the relationship between input and output parameters. To modify the table, click on the cell that contains the text "Max" to modify a value, or "Min" to provide the output parameter values.

Run #	Material	$k_{coldplate}$	k_{solder}	$k_{substrate}$	$k_{baseplate}$	Temperature
1	1	10	10	10	10	155.84
2	20	10	10	10	10	138.46
3	20	10	10	10	10	138.46
4	20	10	10	10	10	138.46
5	20	10	10	10	10	138.46
6	20	10	10	10	10	140.39
7	20	10	10	10	10	140.39
8	20	10	10	10	10	140.39
9	20	10	10	10	10	140.39
10	20	10	10	10	10	140.39
11	20	10	10	10	10	140.39
12	20	10	10	10	10	140.39
13	20	10	10	10	10	140.39
14	20	10	10	10	10	140.39
15	20	10	10	10	10	140.39
16	20	10	10	10	10	140.39
17	20	10	10	10	10	140.39
18	20	10	10	10	10	140.39
19	20	10	10	10	10	140.39
20	20	10	10	10	10	140.39
21	20	10	10	10	10	140.39
22	20	10	10	10	10	140.39
23	20	10	10	10	10	140.39
24	20	10	10	10	10	140.39
25	20	10	10	10	10	140.39

Plot the selected design point.
 Delete the selected design points.
 Import new "What-If" design points from Excel.
 Sweep Input Parameters.



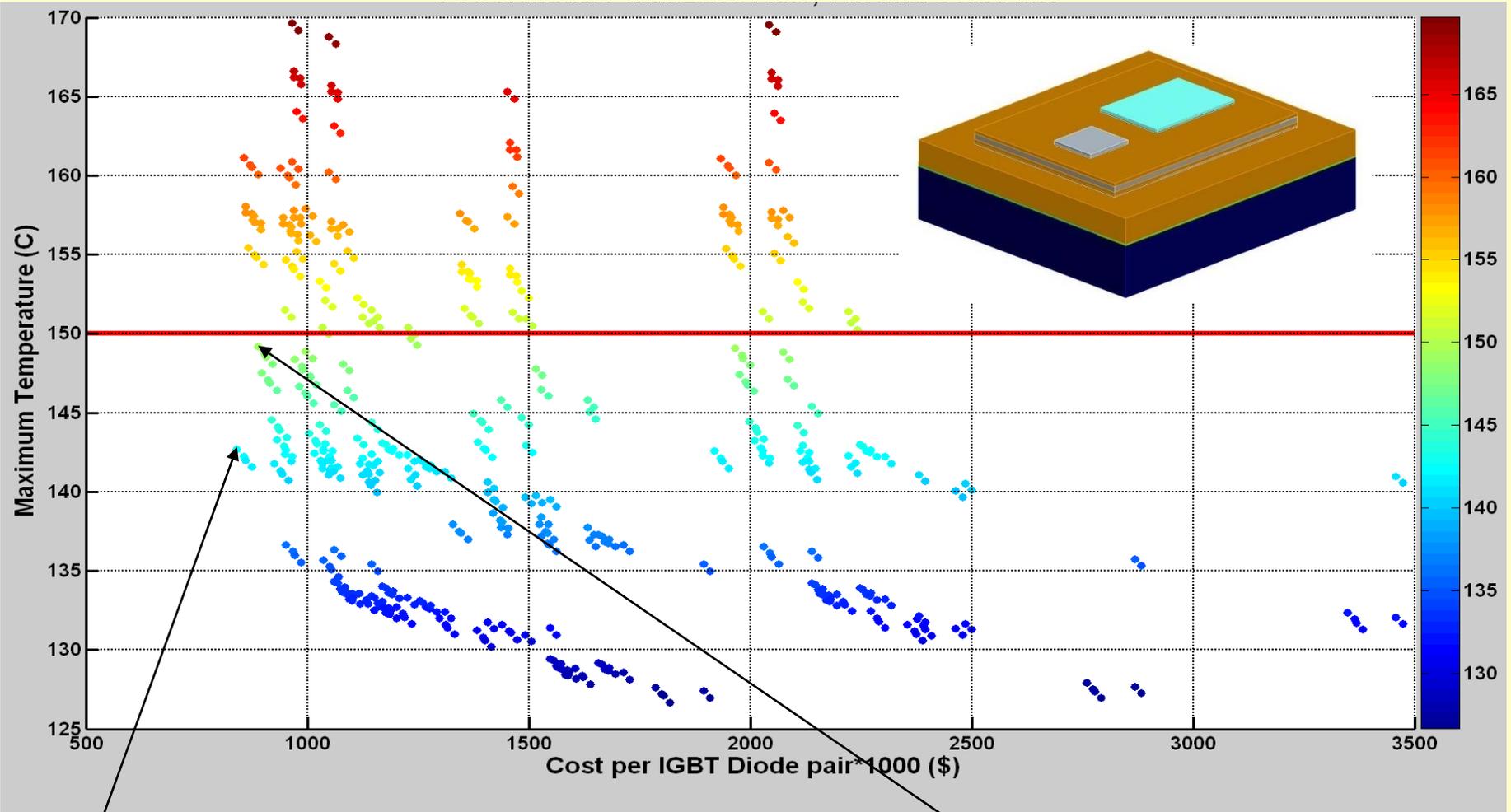
Thermal Conductivity is varied for all the layers according to the material

Bulk material costs are assigned on a volumetric basis

Heat Transfer Coefficient = 18,350 W/(m².K)

Coolant Temperature = 105 °C

Materials combination for cost reduction – Topology 1



Low-cost combination that meets the performance target (Cu-Mo, Graphite, SiN-Ideal)

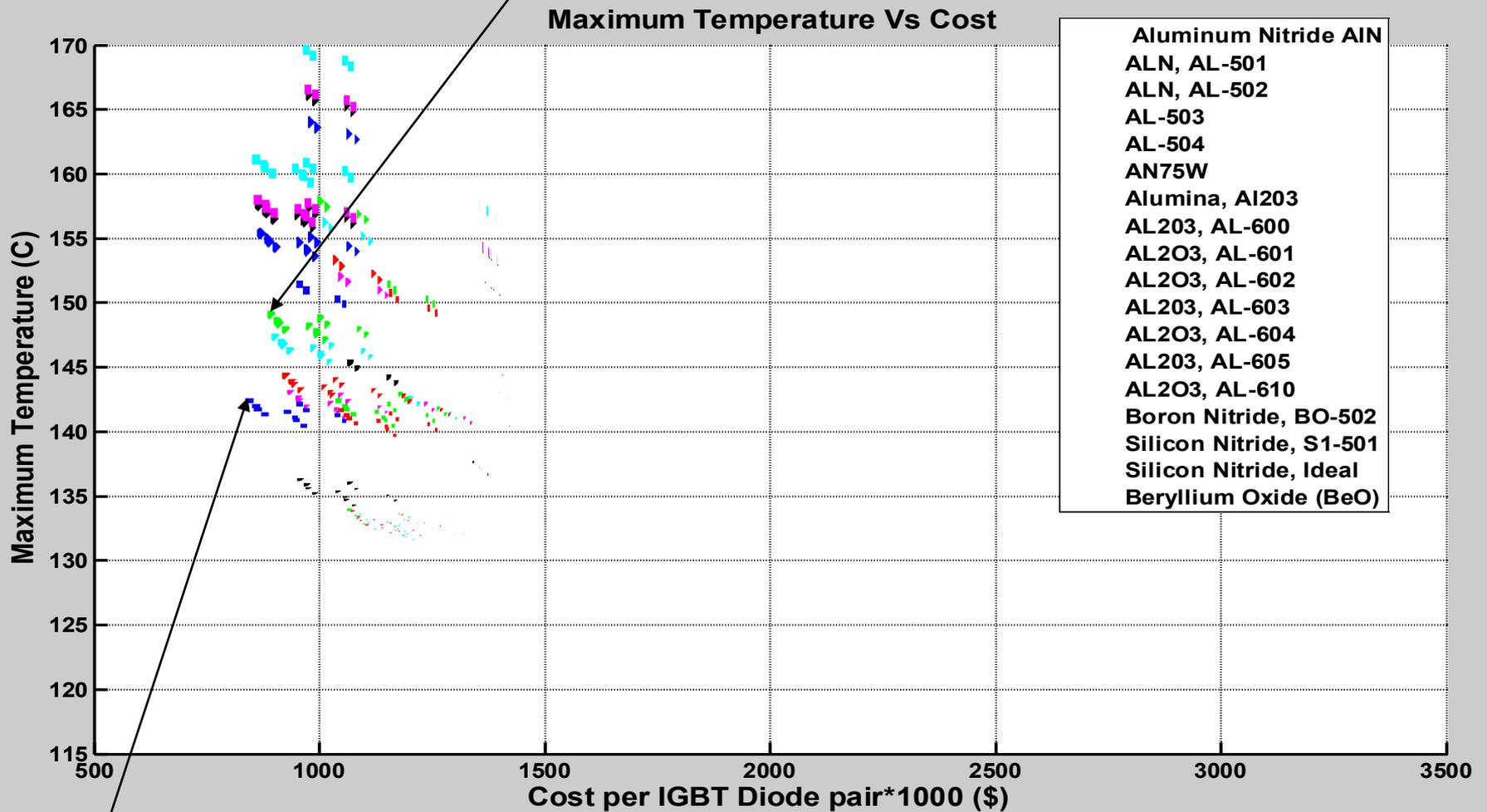
Cost -> 842 Peak Temp -> 142 °C

Low-cost combination that meets the performance target (Cu-Mo, Graphite, Alumina, an LTCC substrate)

Cost -> 889 Peak Temp -> 149 °C

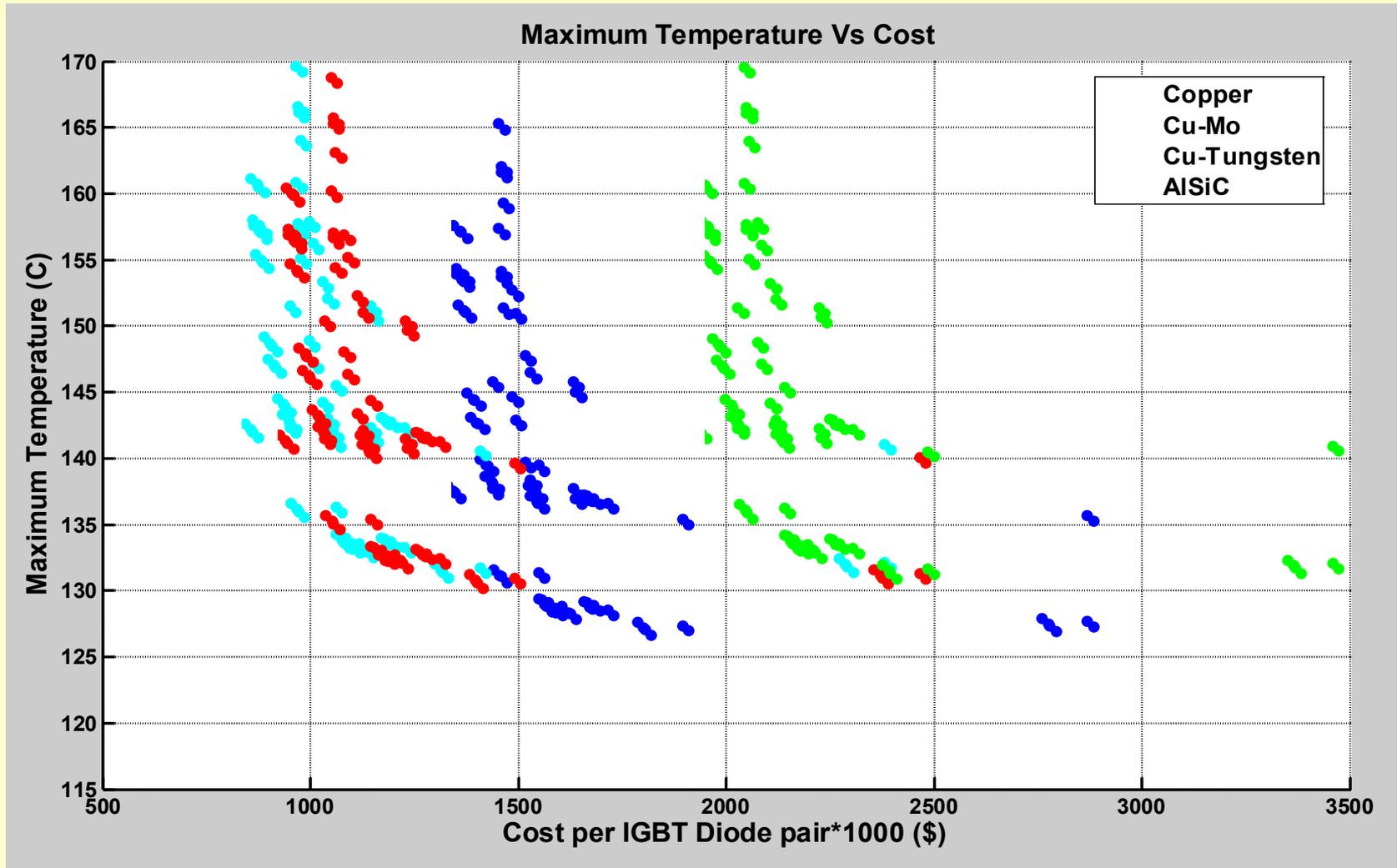
Substrate Materials for Cost Reduction – Topology 1

Alumina, an LTCC substrate



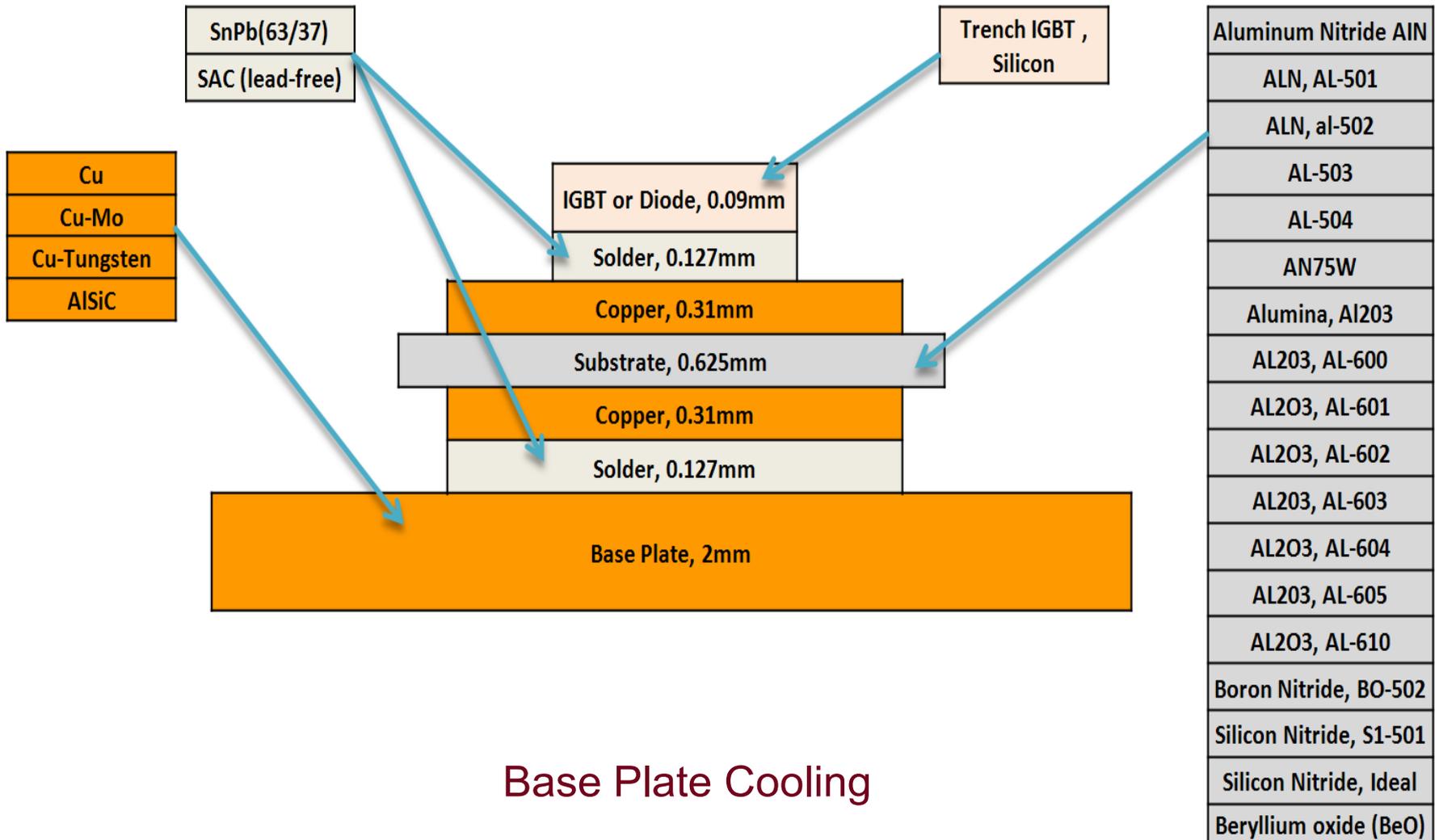
Silicon nitride, ideal

Base Plate Materials for Cost Reduction – Topology 1

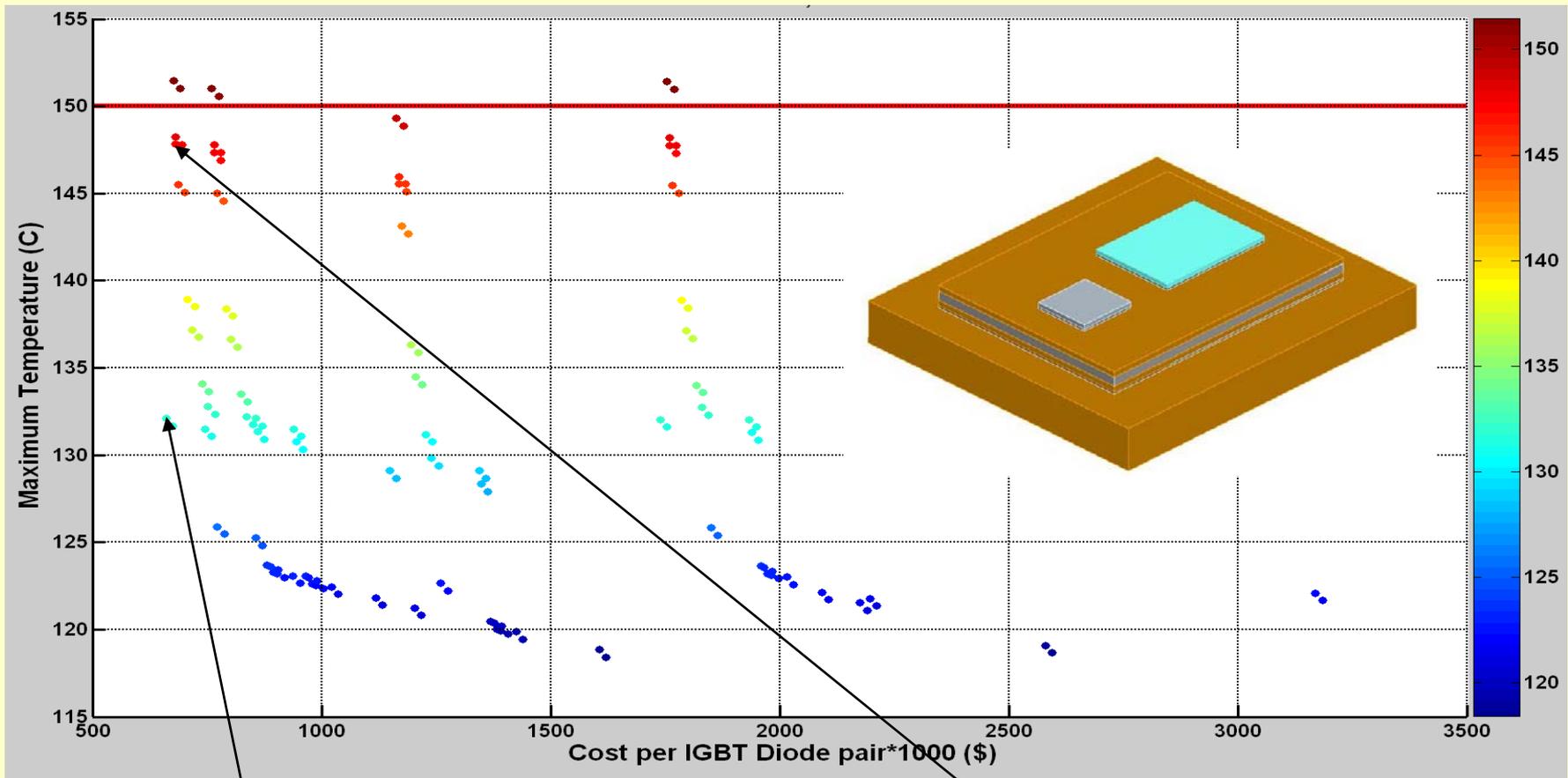


Cu-Mo is a candidate base plate material (used in Prius)

Materials Exploration – Topology 2



Materials Combination for Cost Reduction – Topology 2



Low-cost combination that meets the performance target (Cu-Mo, SiN-Ideal)

Cost -> 662 Peak Temp -> 132 °C

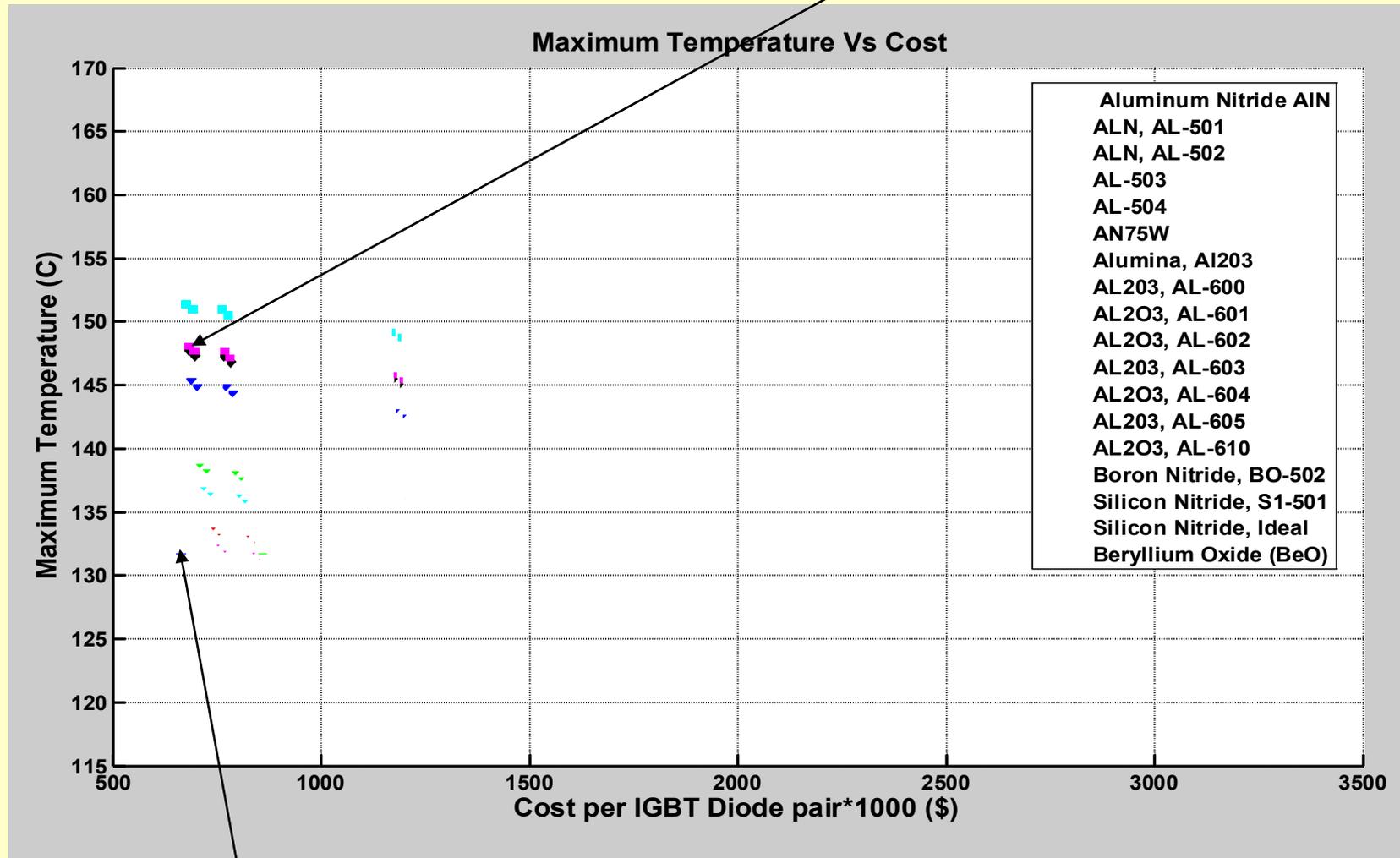
Low-cost combination that meets the performance target (Cu-Mo, Alumina, an LTCC substrate)

Cost -> 682 Peak Temp -> 148 °C

Cost with Topology 1 -> 889

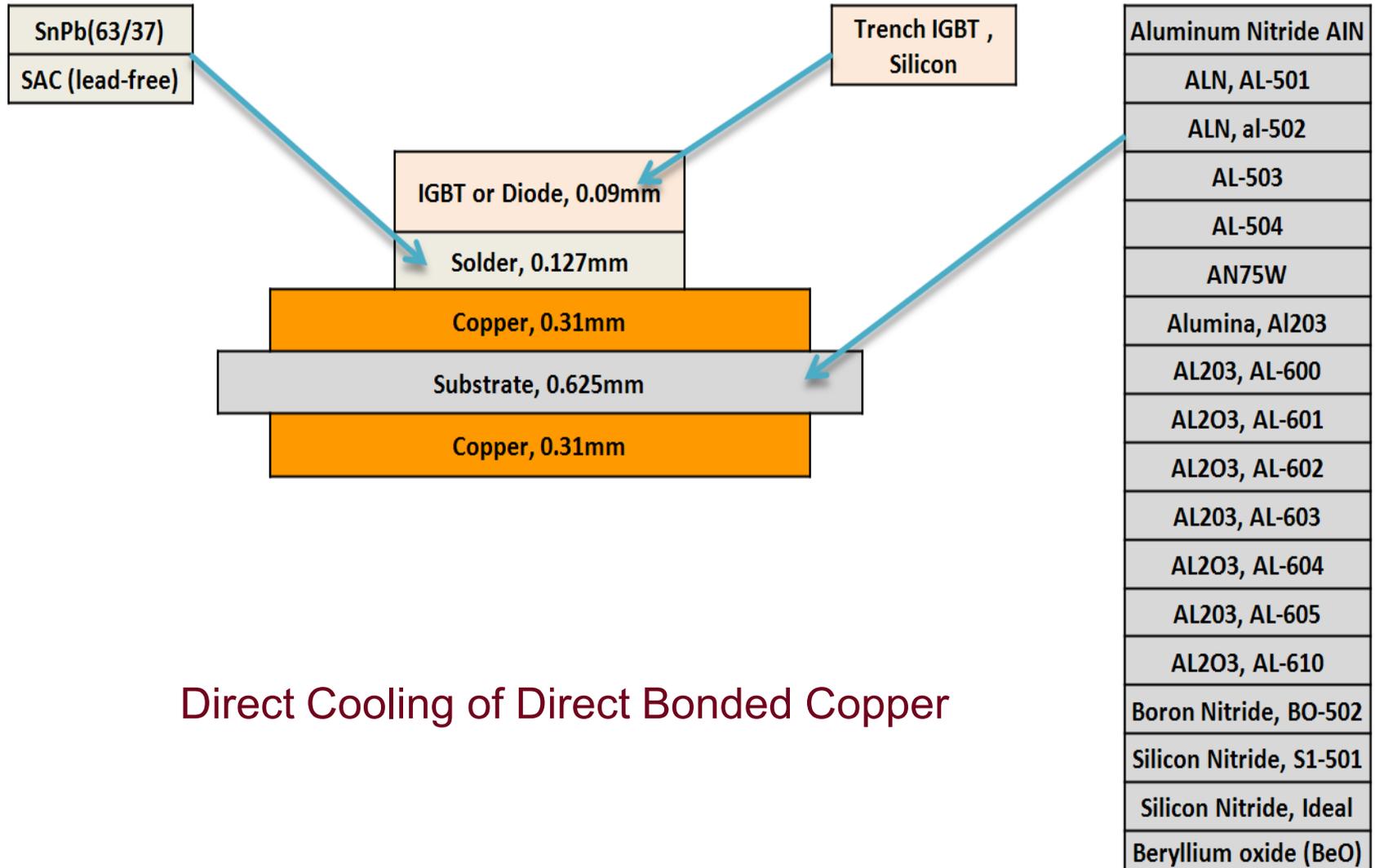
Substrate Materials for Cost Reduction – Topology 2

Alumina, an LTCC substrate



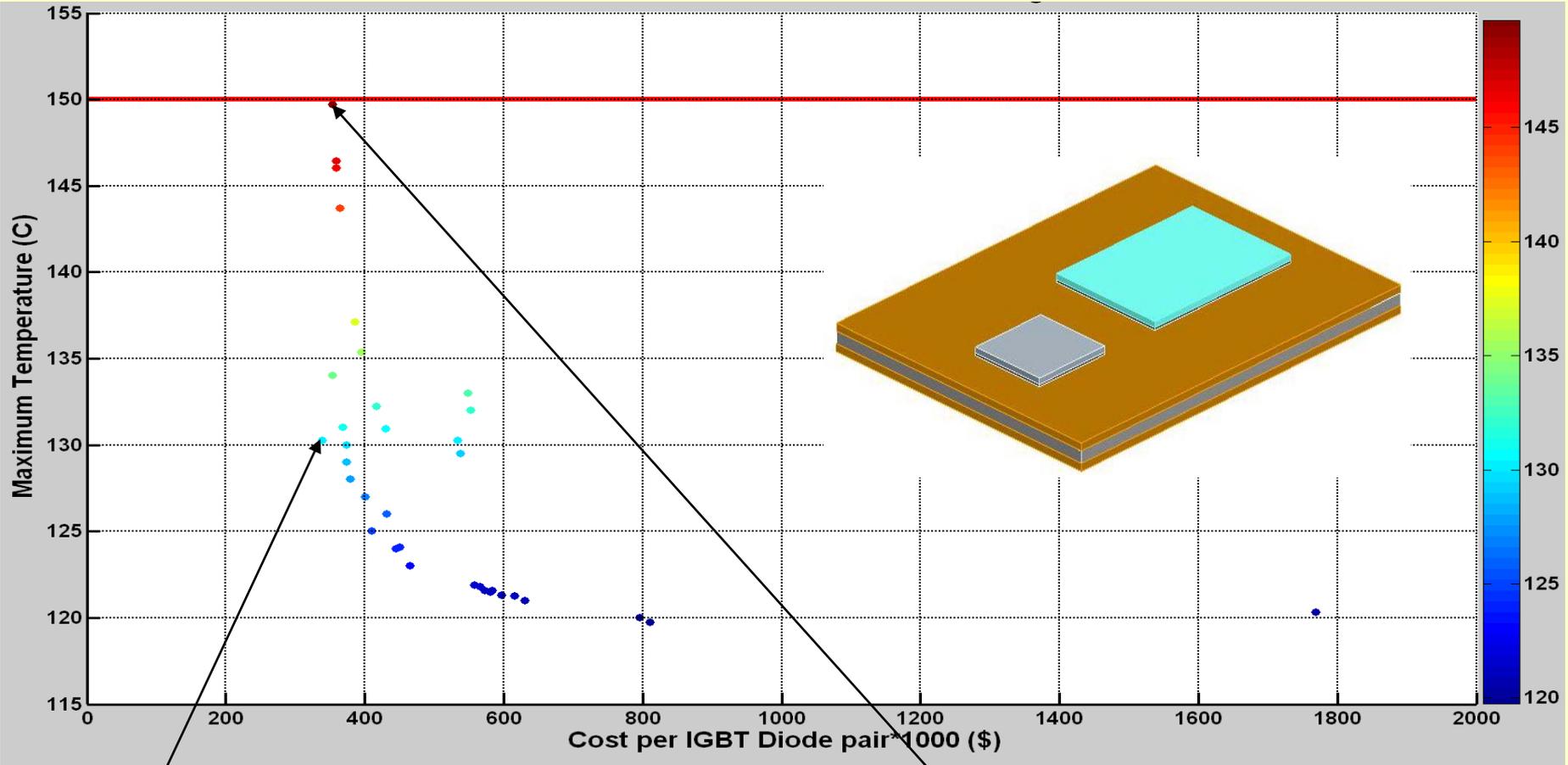
Silicon nitride, ideal

Materials Exploration – Topology 3



Direct Cooling of Direct Bonded Copper

Materials Combination for Cost Reduction – Topology 3



Low-cost combination that meets the performance target (SnPb(63/37), SiN-Ideal)

Cost -> 339 Peak Temp -> 130 °C

Low-cost combination that meets the performance target (SnPb(63/37), Alumina, an LTCC substrate)

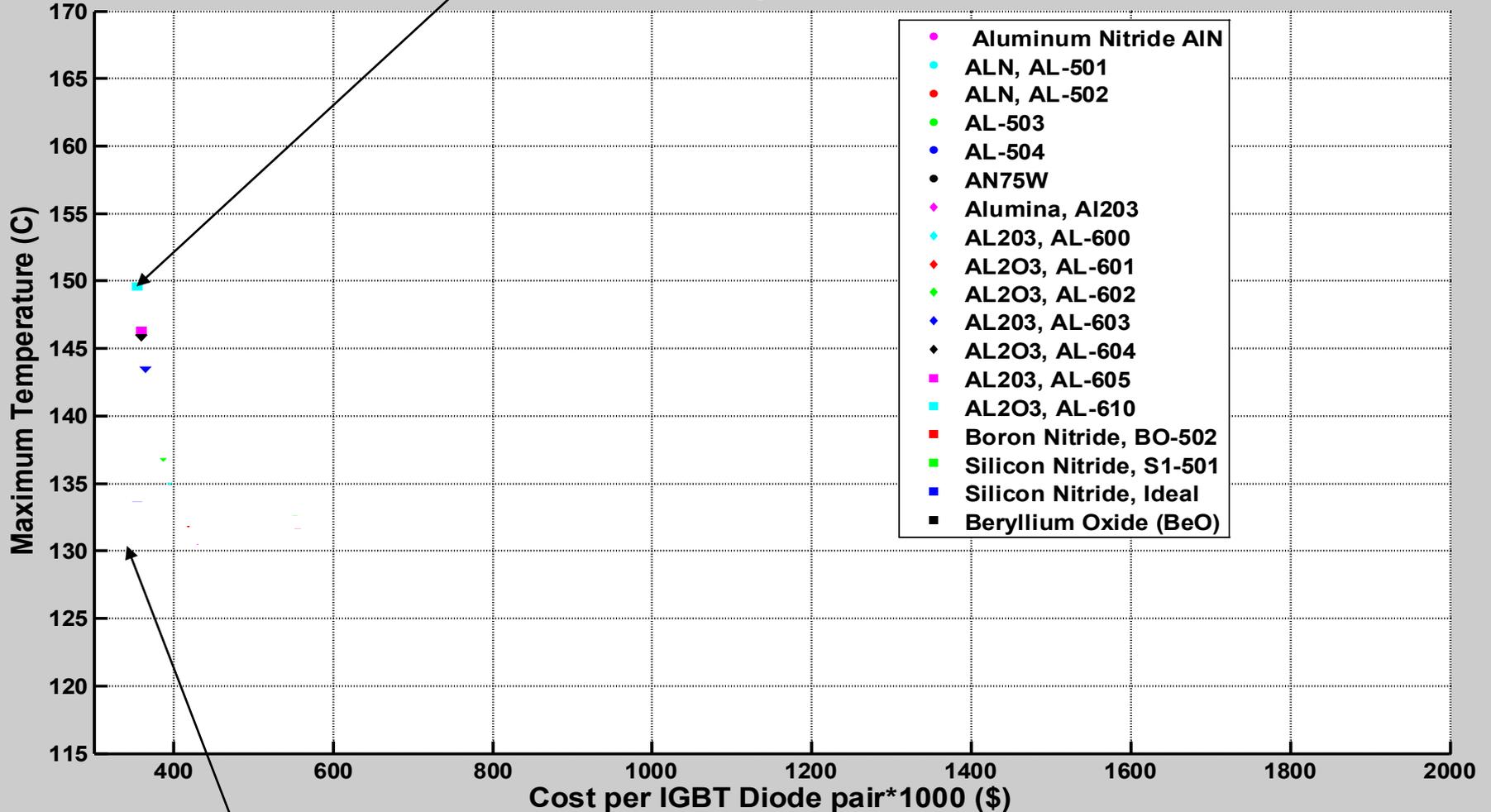
Cost -> 354 Peak Temp -> 149 °C

Topology 1 -> 889, Topology 2 -> 682

Substrate Materials for Cost Reduction – Topology 3

Alumina, an LTCC substrate

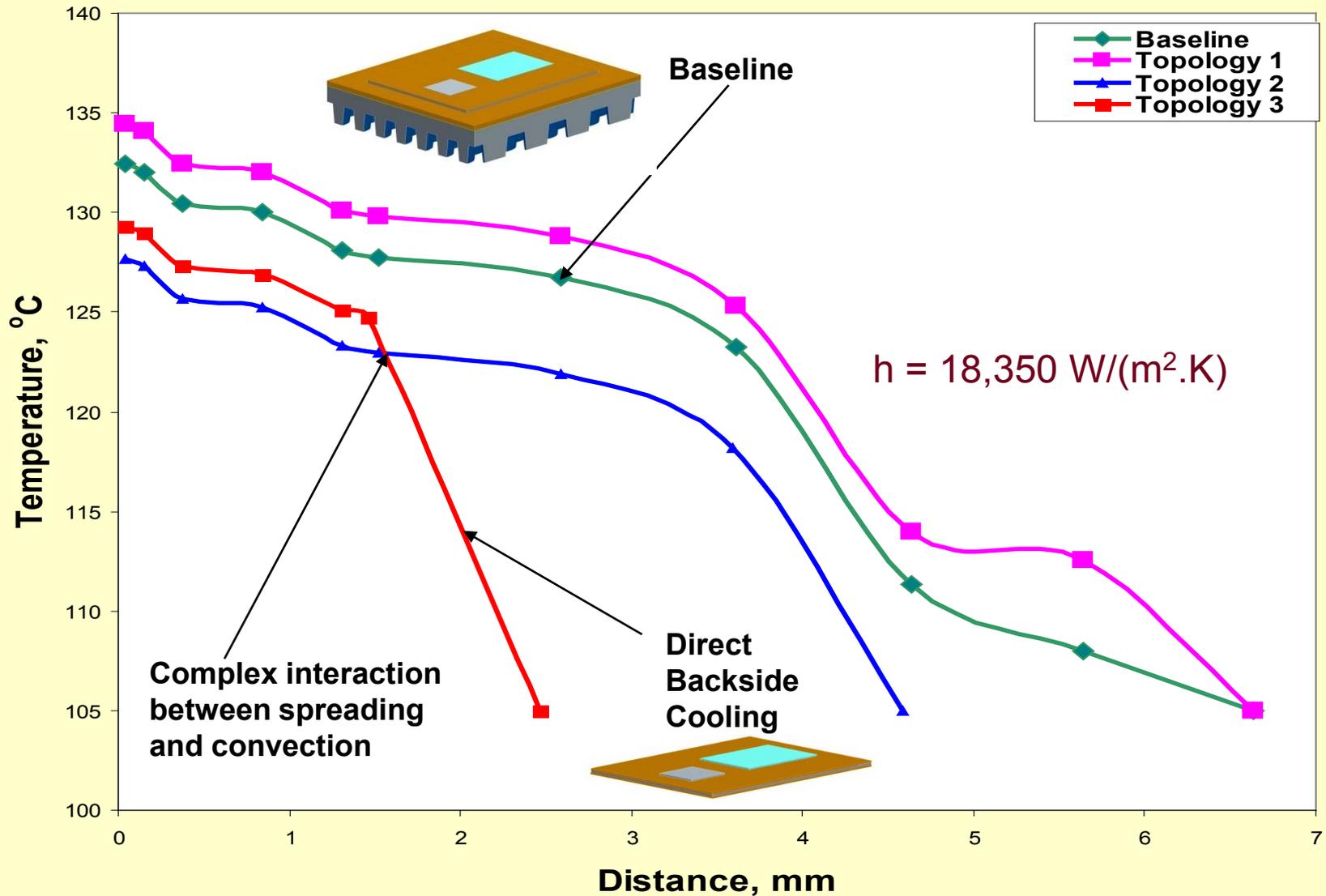
Maximum Temperature Vs Cost



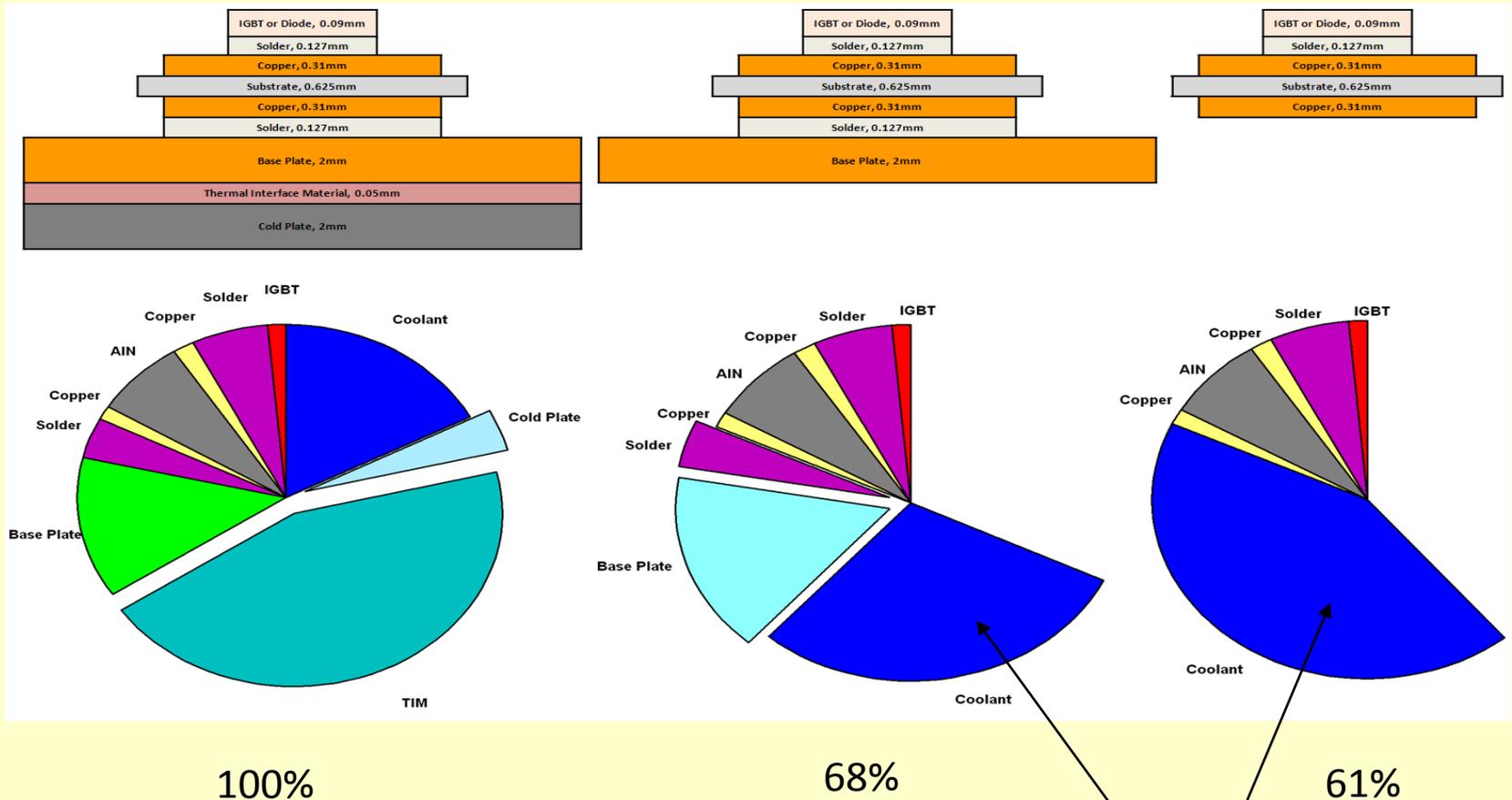
Silicon nitride, ideal

Topology Effect on Junction Temperature

Effect of Topology on Performance



Thermal Resistances – Contributions



Opportunity for further reduction in thermal resistance through surface enhancement

Surface Enhancement

$$U = h \cdot A$$

Targeted surface area enhancement is about 3

$$U = h \cdot 3 A$$

Effective area would be less than 3. Let's assume it's about 2.2:

$$U = h \cdot (2.2 A) \quad (\text{in the test})$$

$$U = (2.2 h) \cdot A \quad (\text{for modeling purposes})$$

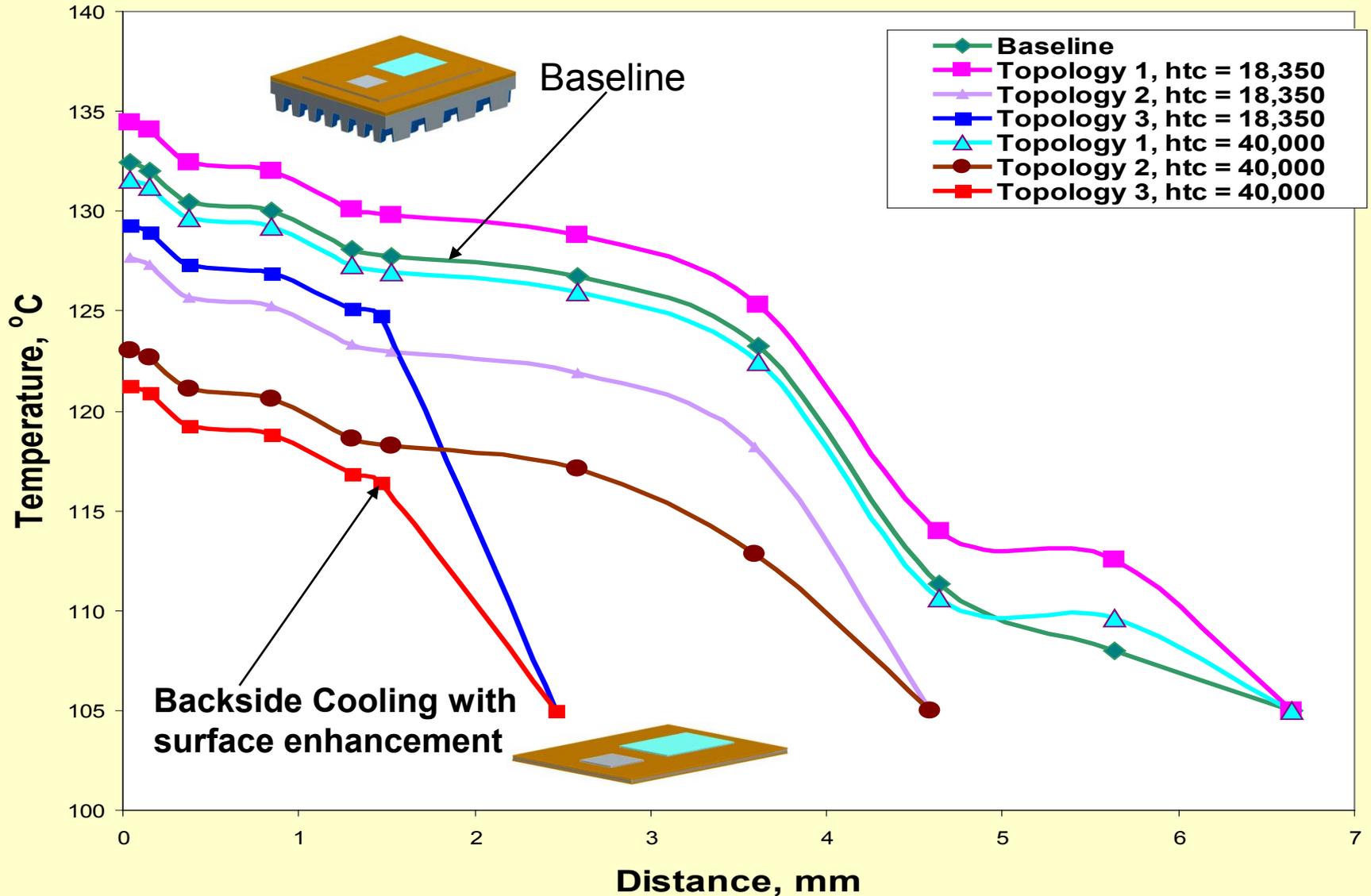
The assumption above might be all right for a first order approximation:

Baseline, $h = 18,350 \text{ W}/(\text{m}^2 \cdot \text{K})$

Enhanced, $h = 2.2 \cdot h = 2.2 \cdot 18,350 = 40,000 \text{ W}/(\text{m}^2 \cdot \text{K})$

Combined Effects of Topology and Cooling Technology on Junction Temperature

Combined Effects of Topology and Cooling Technology on Performance



Conclusions and Future Studies

- Advanced thermal control (advanced cooling technologies and novel packaging topologies) helps to **meet FreedomCAR program's key target of cost.**
- **Direct Backside Cooling (Topology 3) has the greatest potential for cost reduction.**
- Using Advanced Thermal Control, low-cost LTCC substrate (alumina) has the potential to replace the traditional, more expensive HTCC substrate, AlN.
- Surface enhancement provides further opportunity for performance enhancement .
- Future studies would involve reliability aspects and emerging substrate technologies (LTCC and Organic).

Acknowledgements

- First author acknowledges the inputs from Andrew A. Wereszczak, Govindarajan Muralidharan (Oak Ridge National Laboratory), Rajen Chanchani (Sandia National Laboratory), Dr. Liangyu Chen (NASA Glenn Research Center) and Prof. Jean-Paul Issi.