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Advanced Thermal Control Enabling Cost Reduction for Automotive Power Electronics

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NREL/PR-540-43819

Presented at the 2008 ANSYS Automotive Conference sponsored by ANSYS held September 4-5, 2008 in Dearborn, Michigan

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

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

U.S. DEPARTMENT OF ENERGY

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

FreedomCAR & Fuel Partnership

USCAR

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Other Industry Partners and Universities

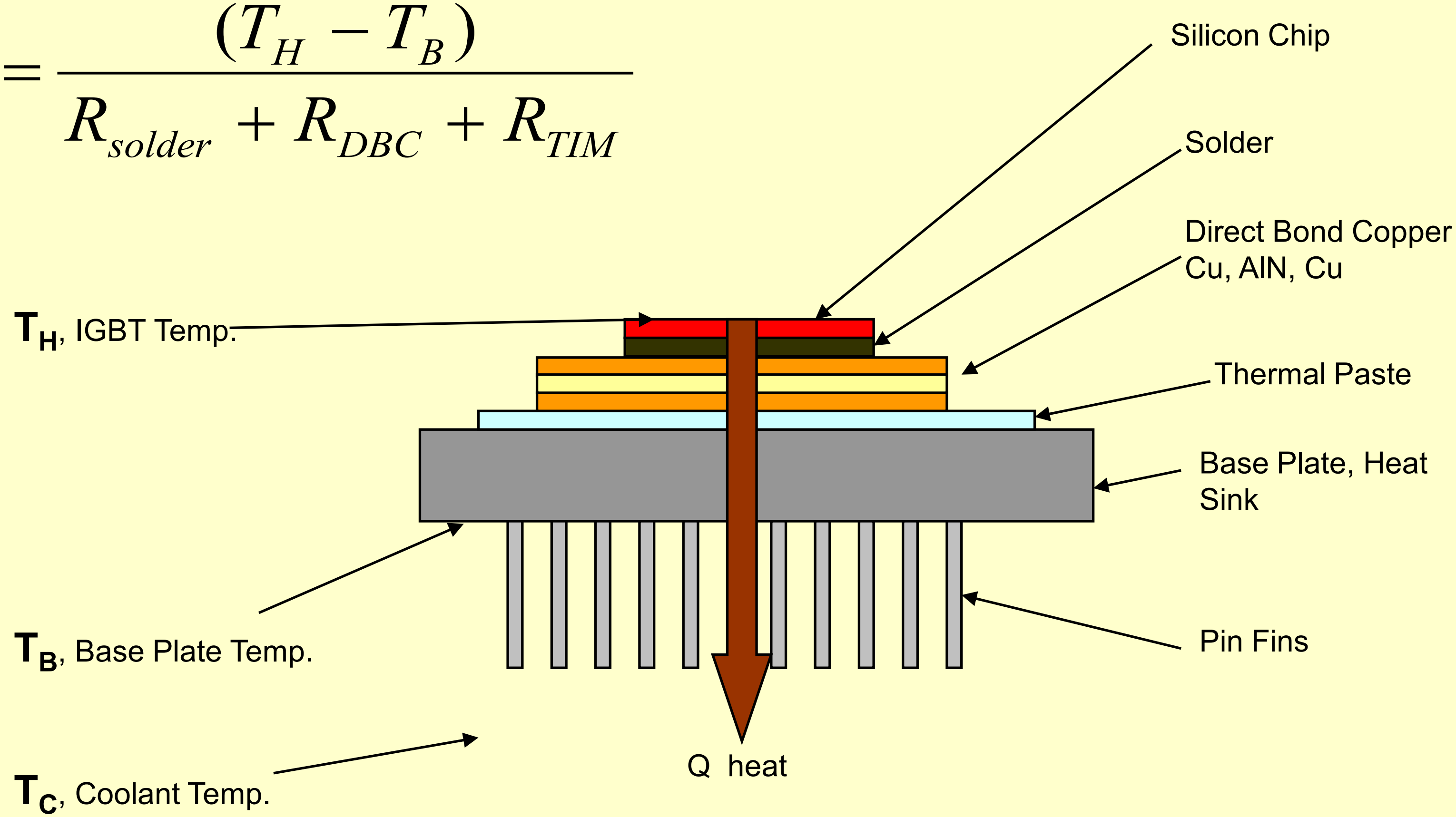
Industry and Academia

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.

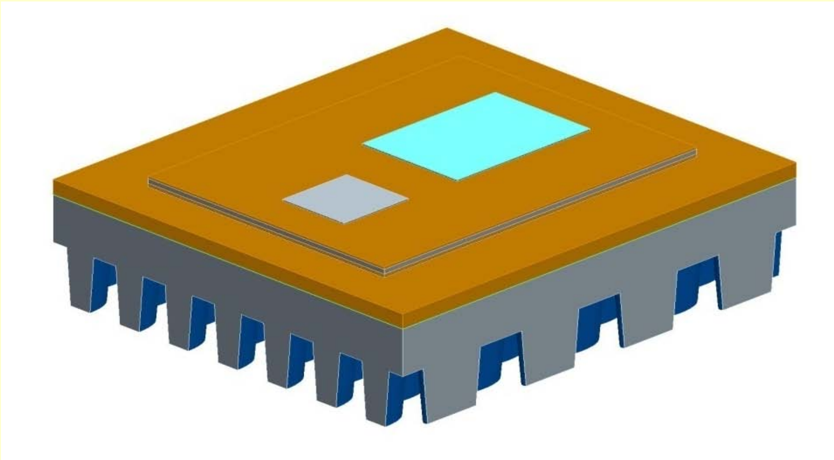
Description of Technology

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

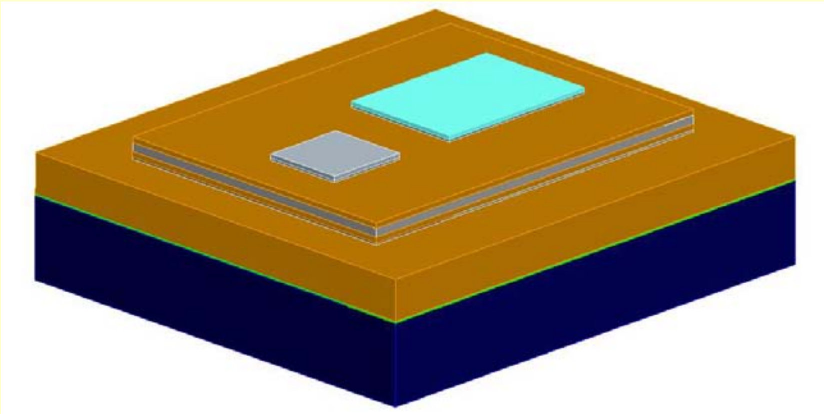


$$Q = h\ A\ (T_B - T_C\ )$$

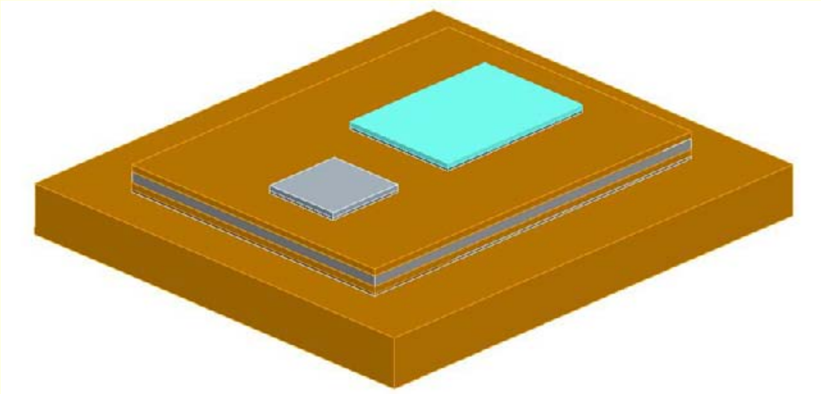
Topologies



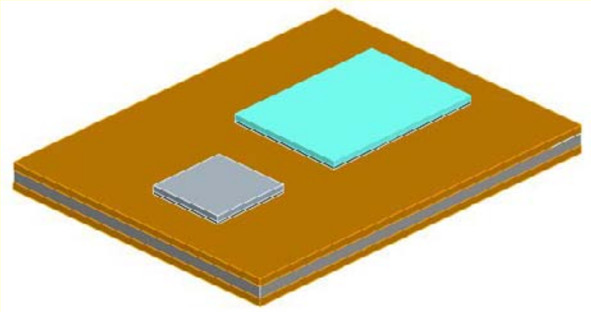
Baseline Topology



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:

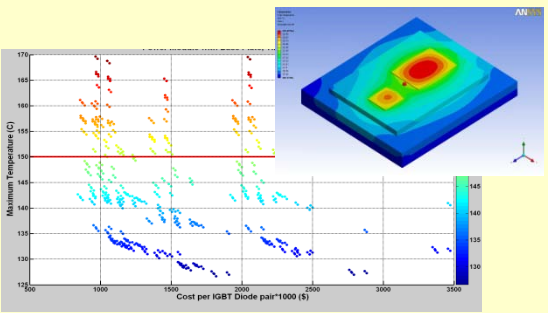
Exploring tradeoffs between thermal performance and cost for several topologies

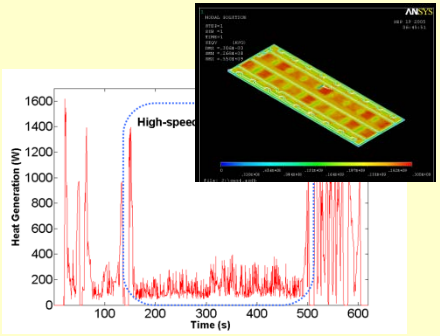
Part 2:

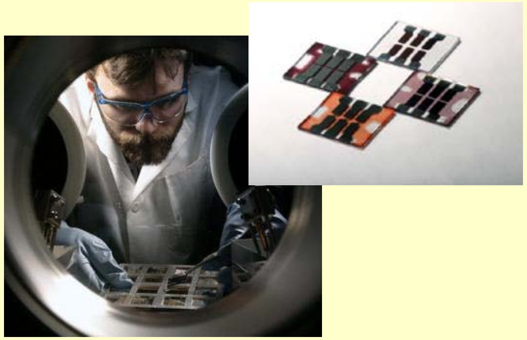
Evaluation of Thermal Stress and Reliability Aspects

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^{o}C.
- Reliability: Power electronics need to meet life-cycle target of 15 years.

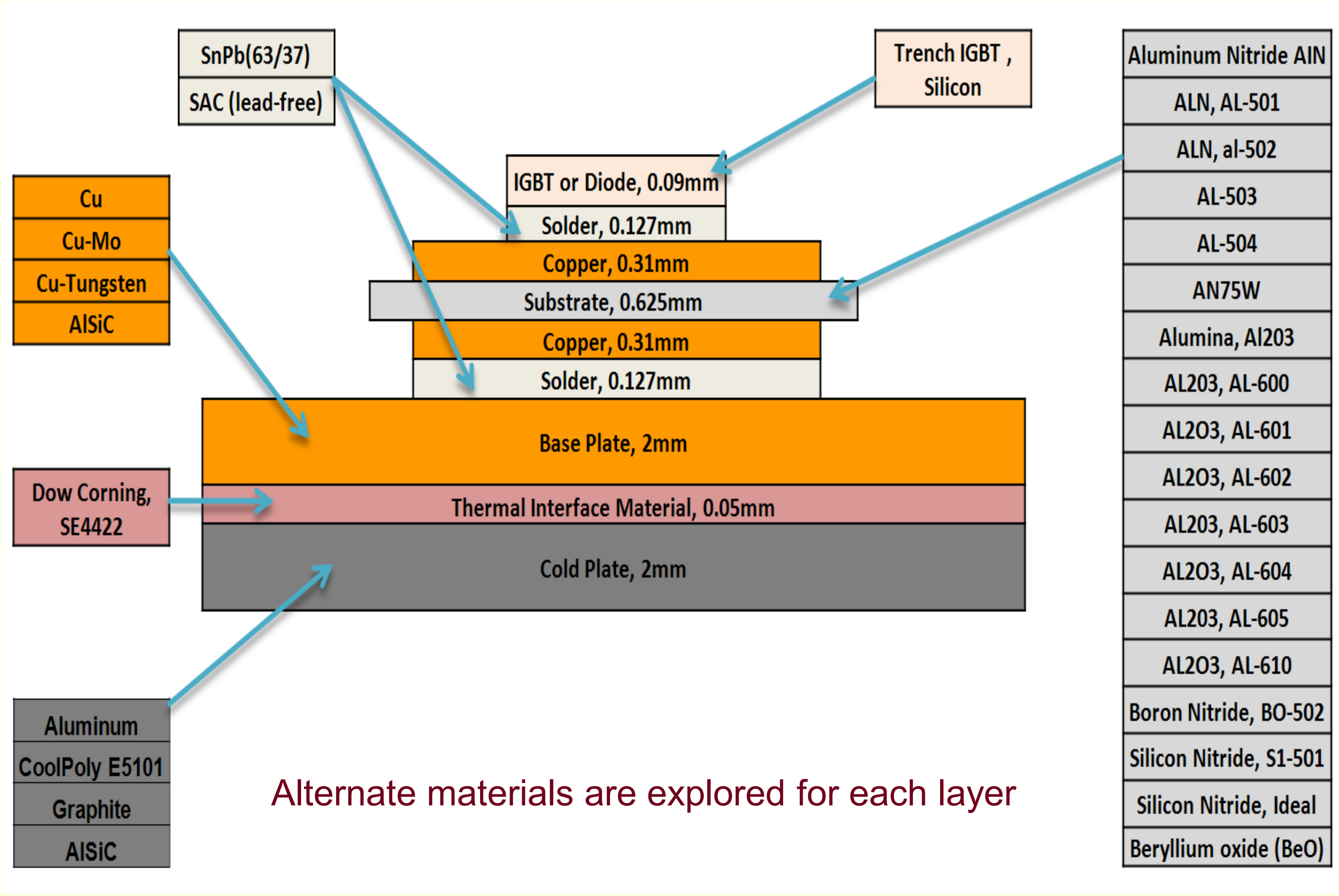
Thermal Materials Exploration Study – Comments

- 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].

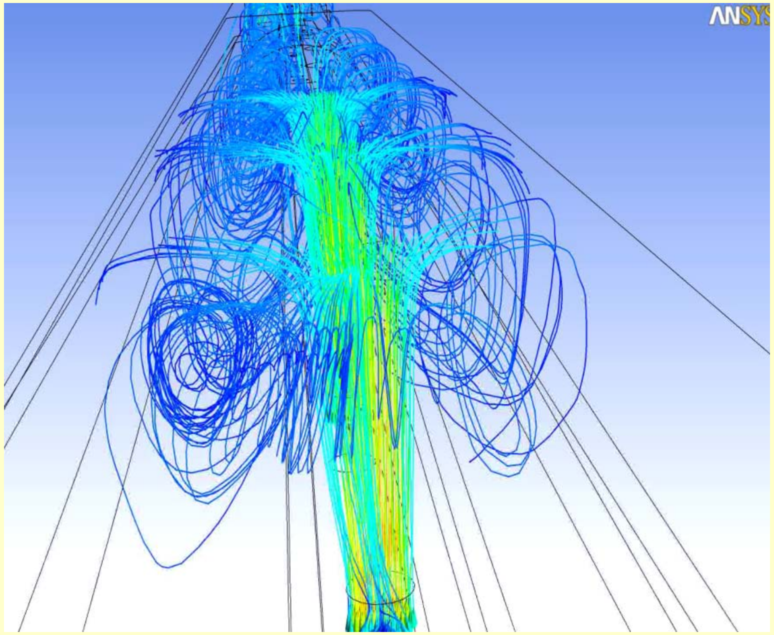
1. Fairchild, M.R., Snyder, R.B., Berlin, C.W., and Sarma, D.H.R., "Emerging Substrate Technologies for Harsh-Environment Automotive Electronics Applications," SAE 2002-01-1052.

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

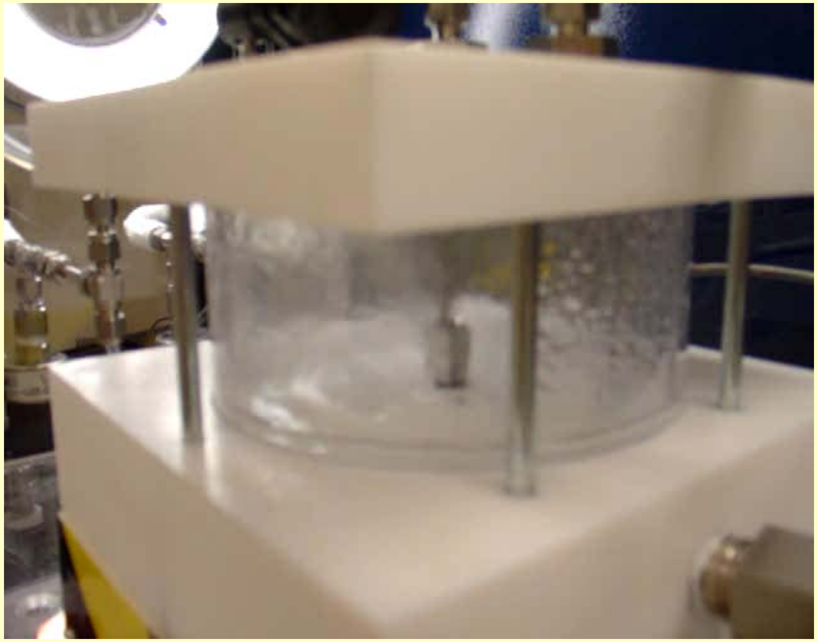
Materials Exploration – Topology 1



Verification of CFD Model with Test



CFD (using Fluent)



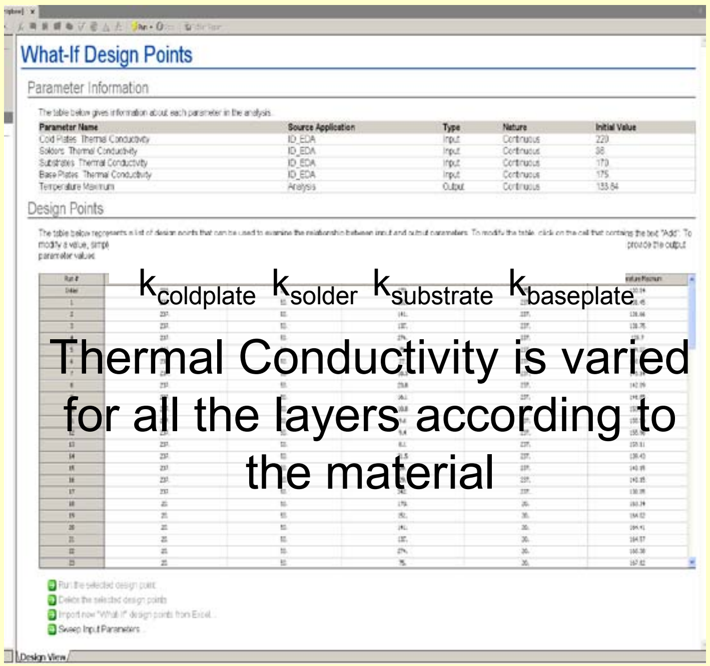
Test

	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

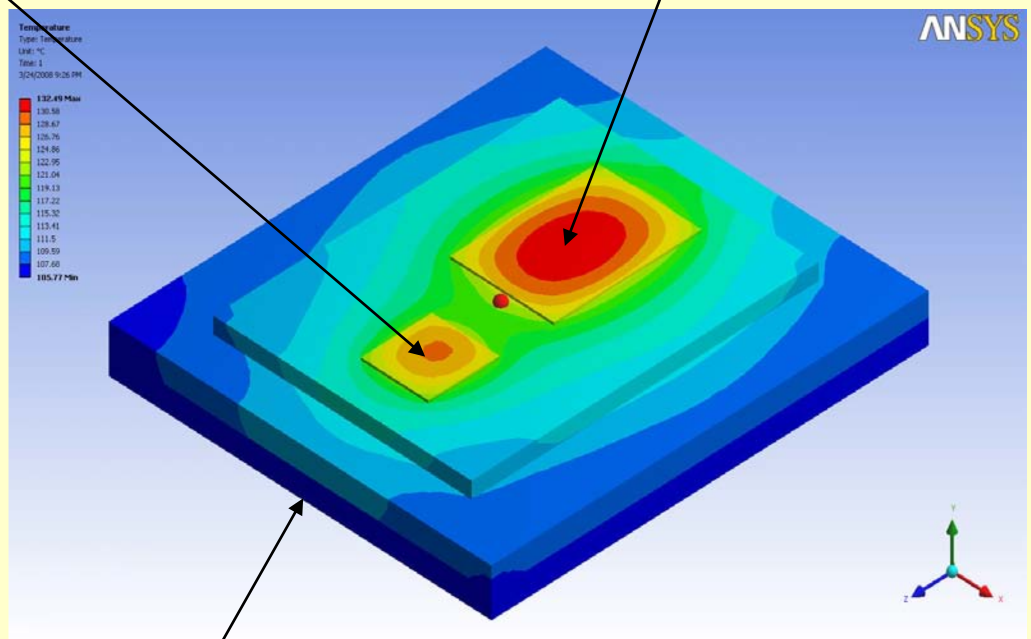
Heat Load per Diode = 35 W

Heat load per IGBT heat load = 85 W



$k_{coldplate}$ k_{solder} $k_{substrate}$ $k_{baseplate}$

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

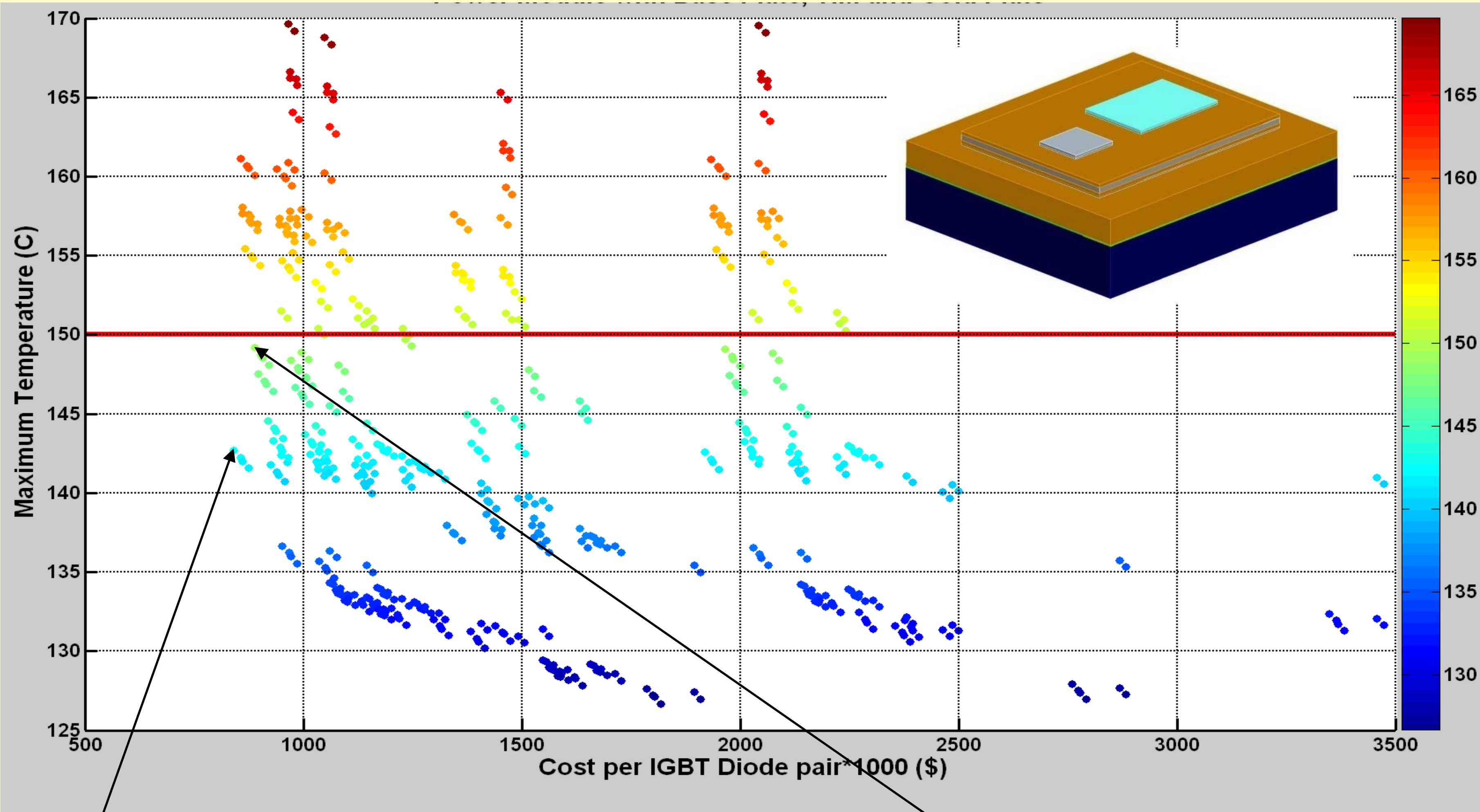


Bulk material costs are assigned on a volumetric basis

Heat Transfer Coefficient = 18,350 W/(m^2.K)

Coolant Temperature = 105 ^{o}C

Materials combination for cost reduction – Topology 1



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

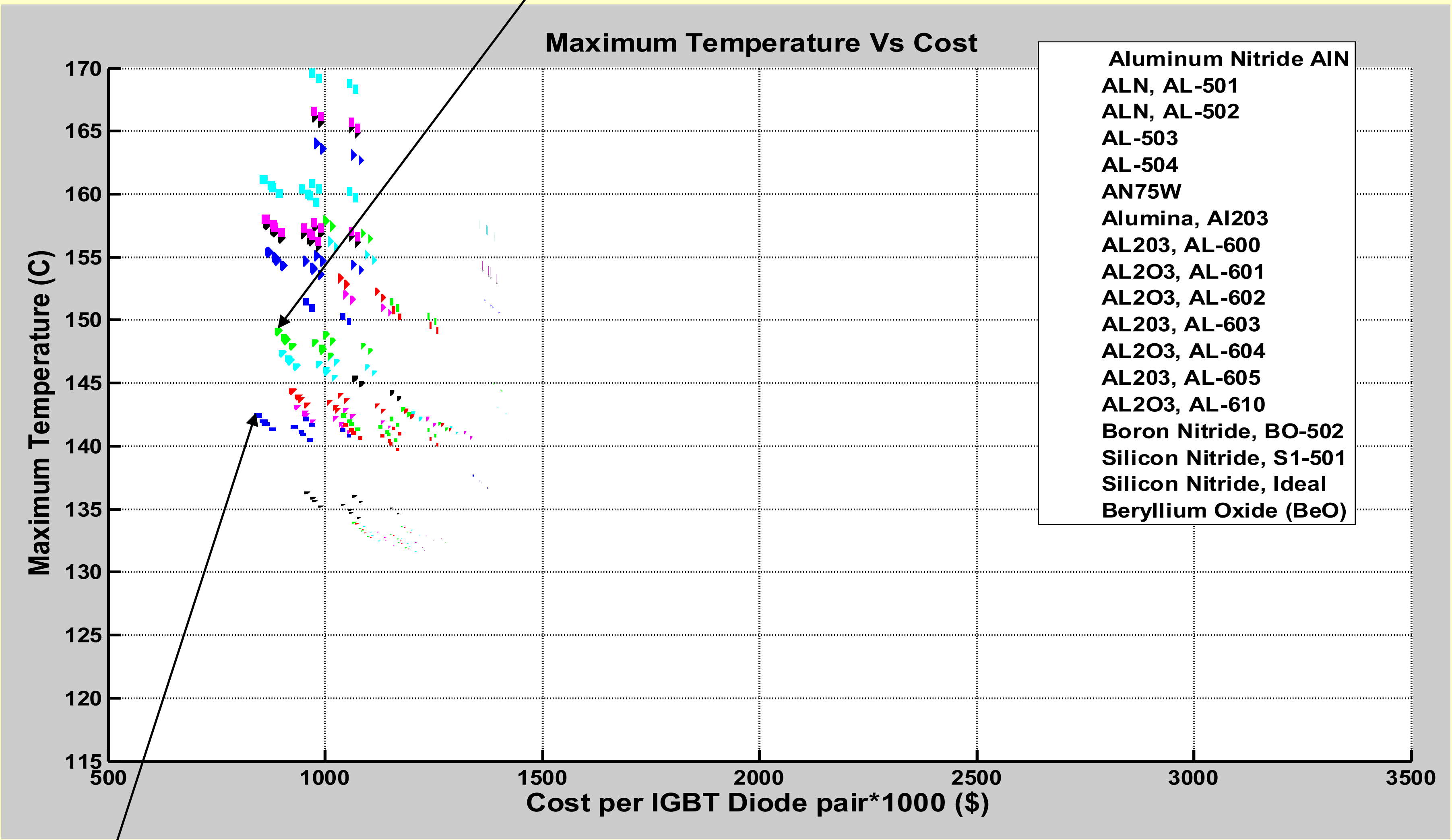
Cost -> 842   Peak Temp -> 142 °C

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

Cost -> 889   Peak Temp -> 149 °C

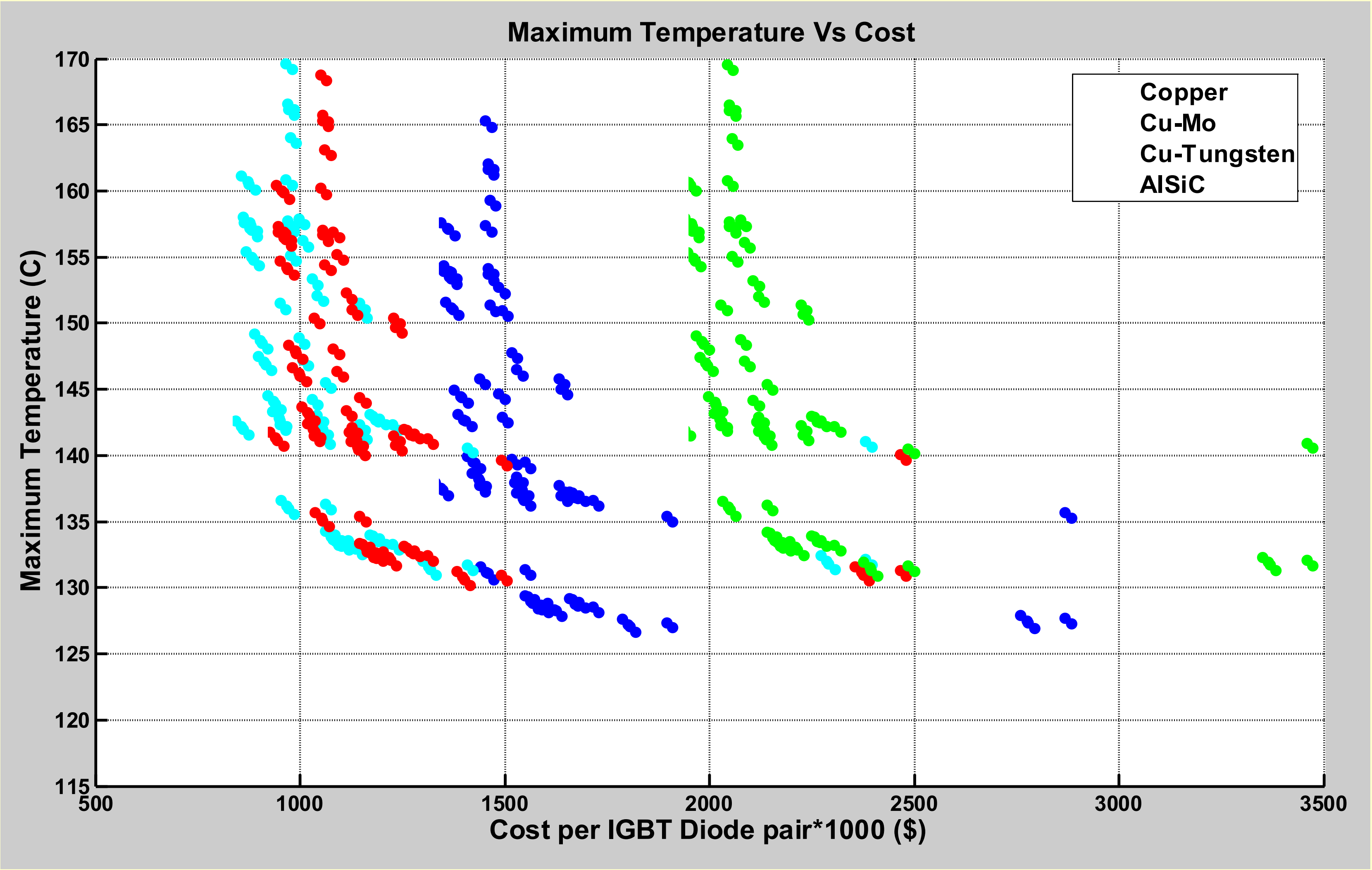
Substrate Materials for Cost Reduction – Topology 1

Alumina, an LTCC substrate



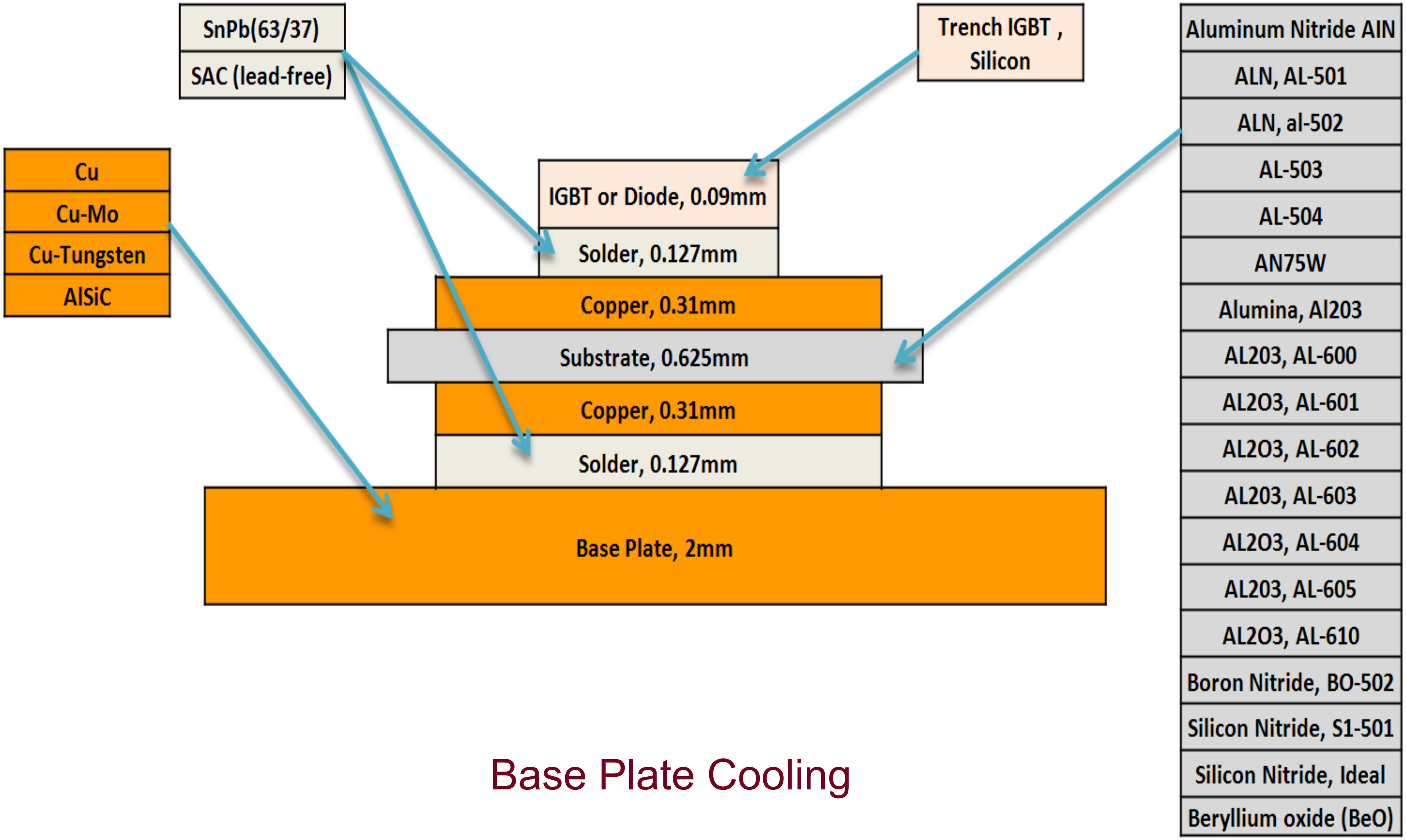
Silicon nitride, ideal

Base Plate Materials for Cost Reduction – Topology 1



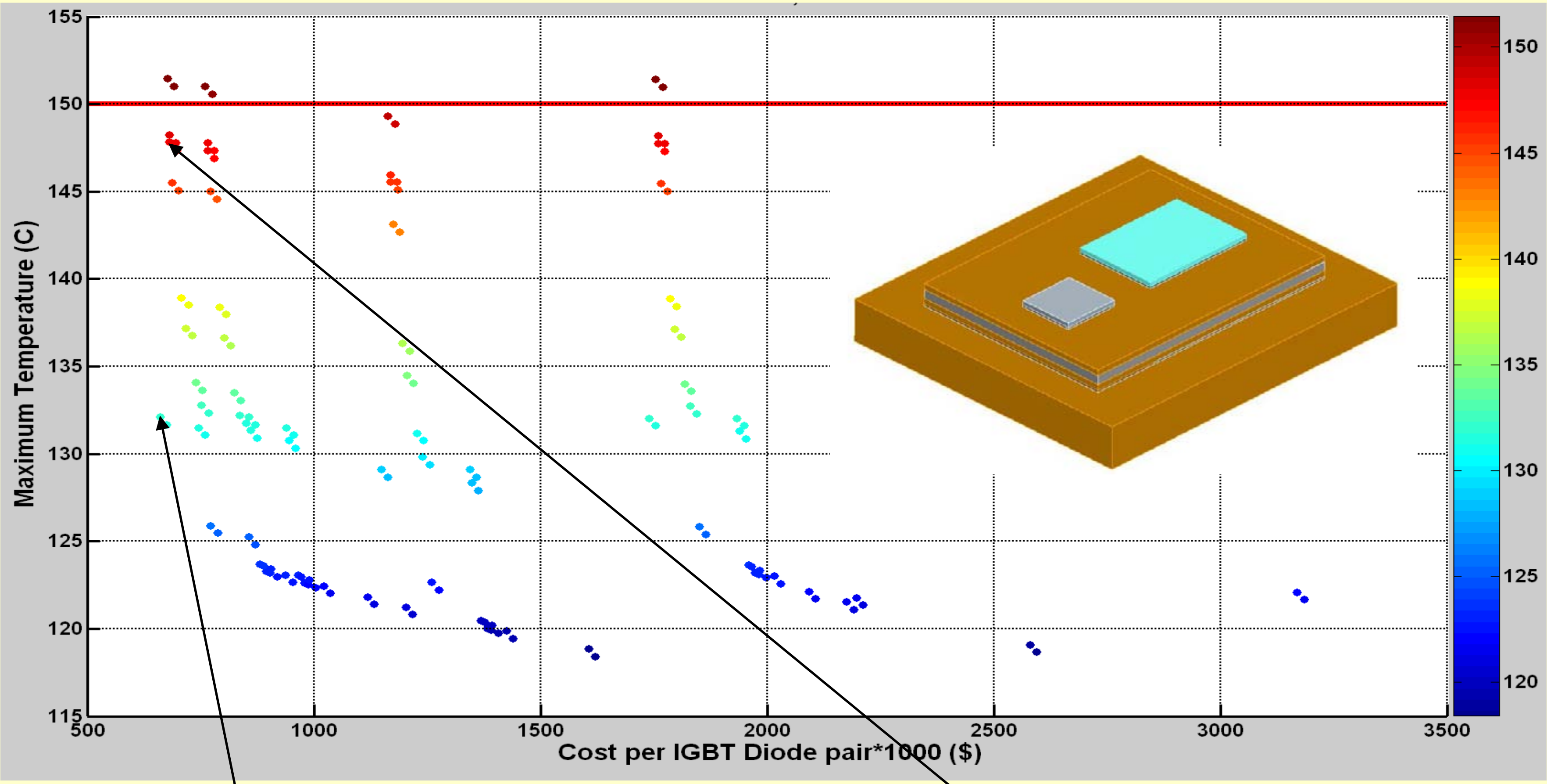
Cu-Mo is a candidate base plate material (used in Prius)

Materials Exploration – Topology 2



Base Plate Cooling

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

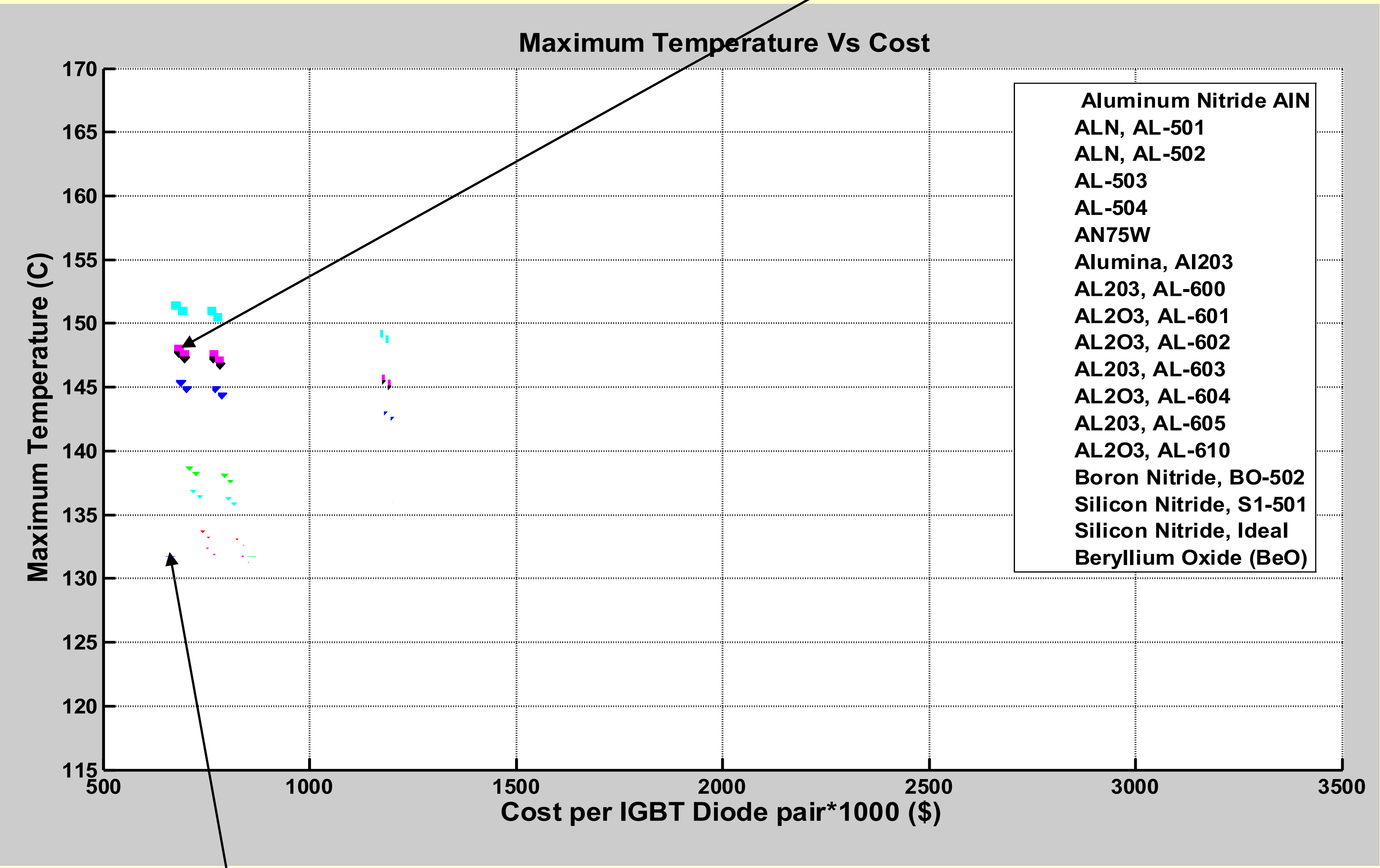
Low-cost combination that meets the performance target (Cu-Mo, Alumina, an LTCC substrate)

Cost -> 682   Peak Temp -> 148 °C

Cost with Topology 1 -> 889

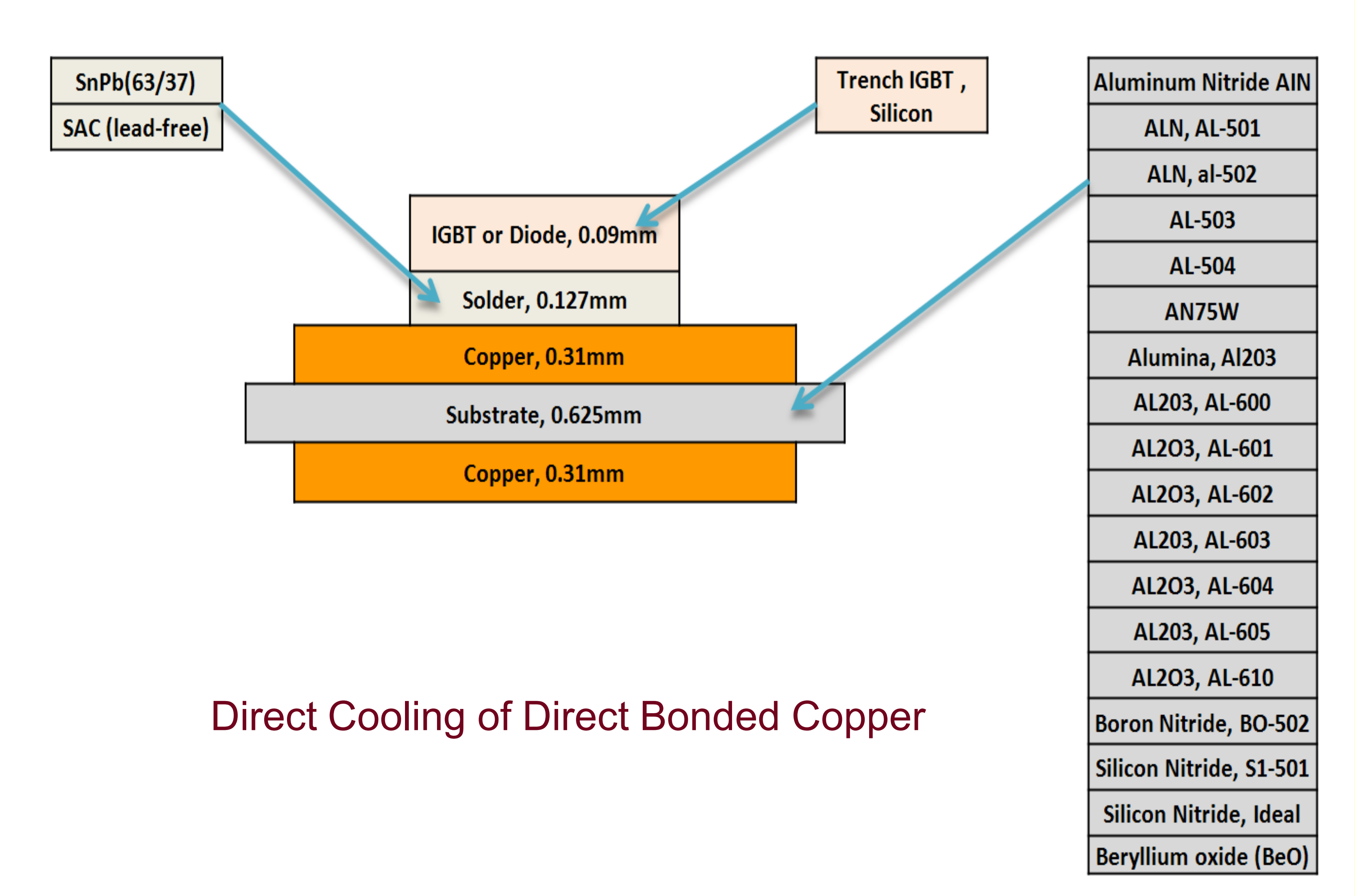
Substrate Materials for Cost Reduction – Topology 2

Alumina, an LTCC substrate

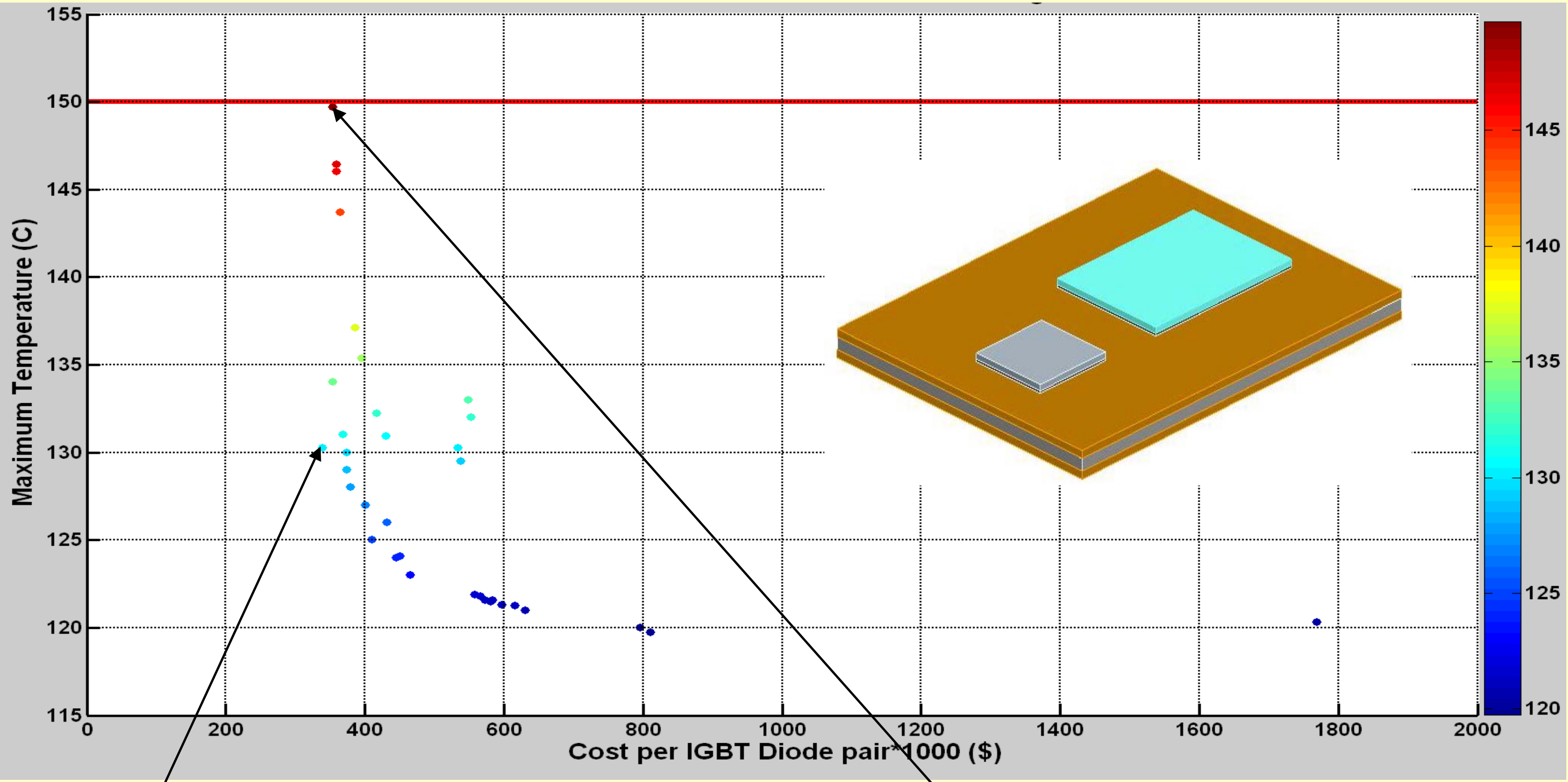


Silicon nitride, ideal

Materials Exploration – Topology 3



Materials Combination for Cost Reduction – Topology 3



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

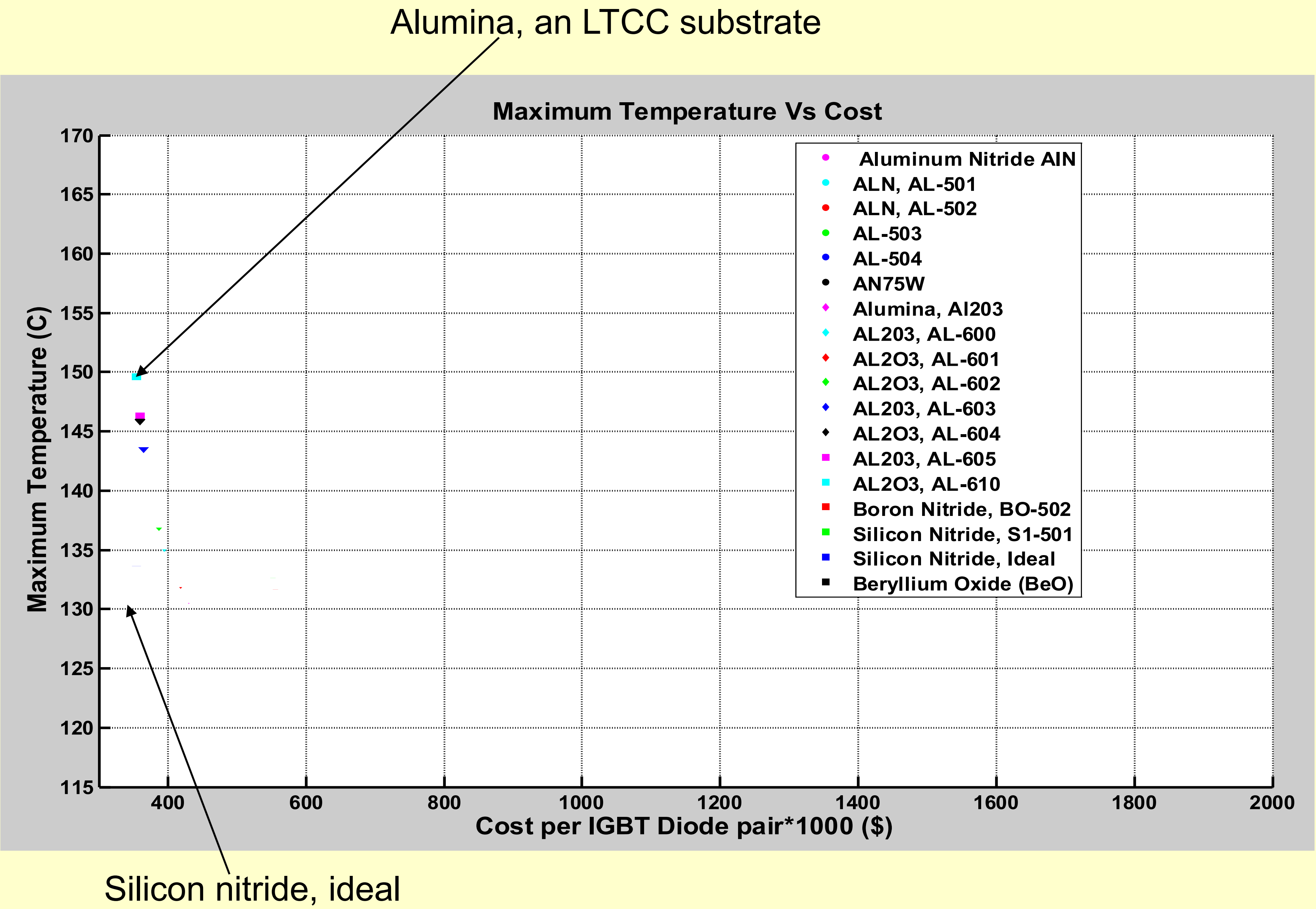
Cost -> 339   Peak Temp -> 130 °C

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

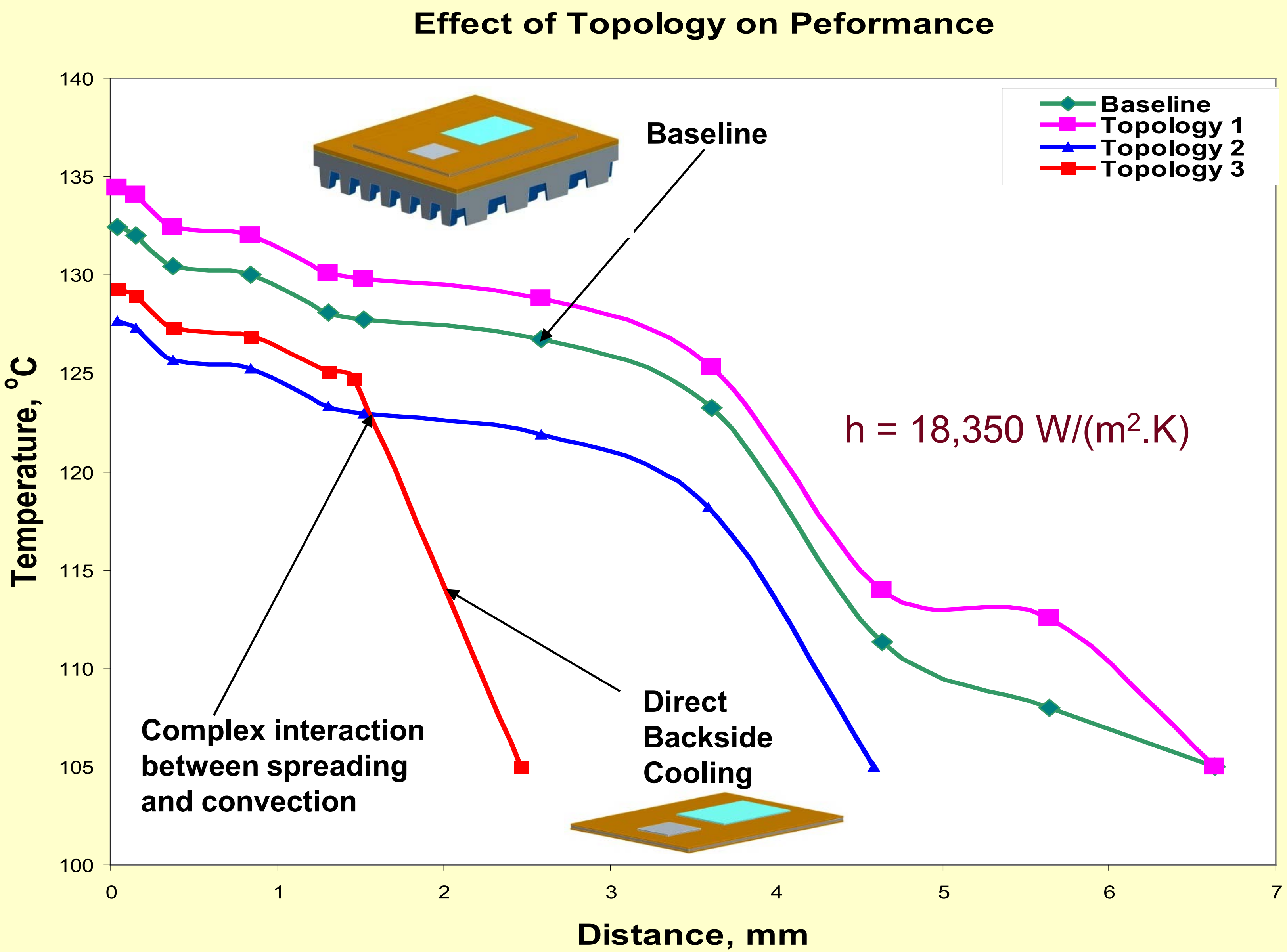
Cost -> 354   Peak Temp -> 149 °C

Topology 1 -> 889, Topology 2 -> 682

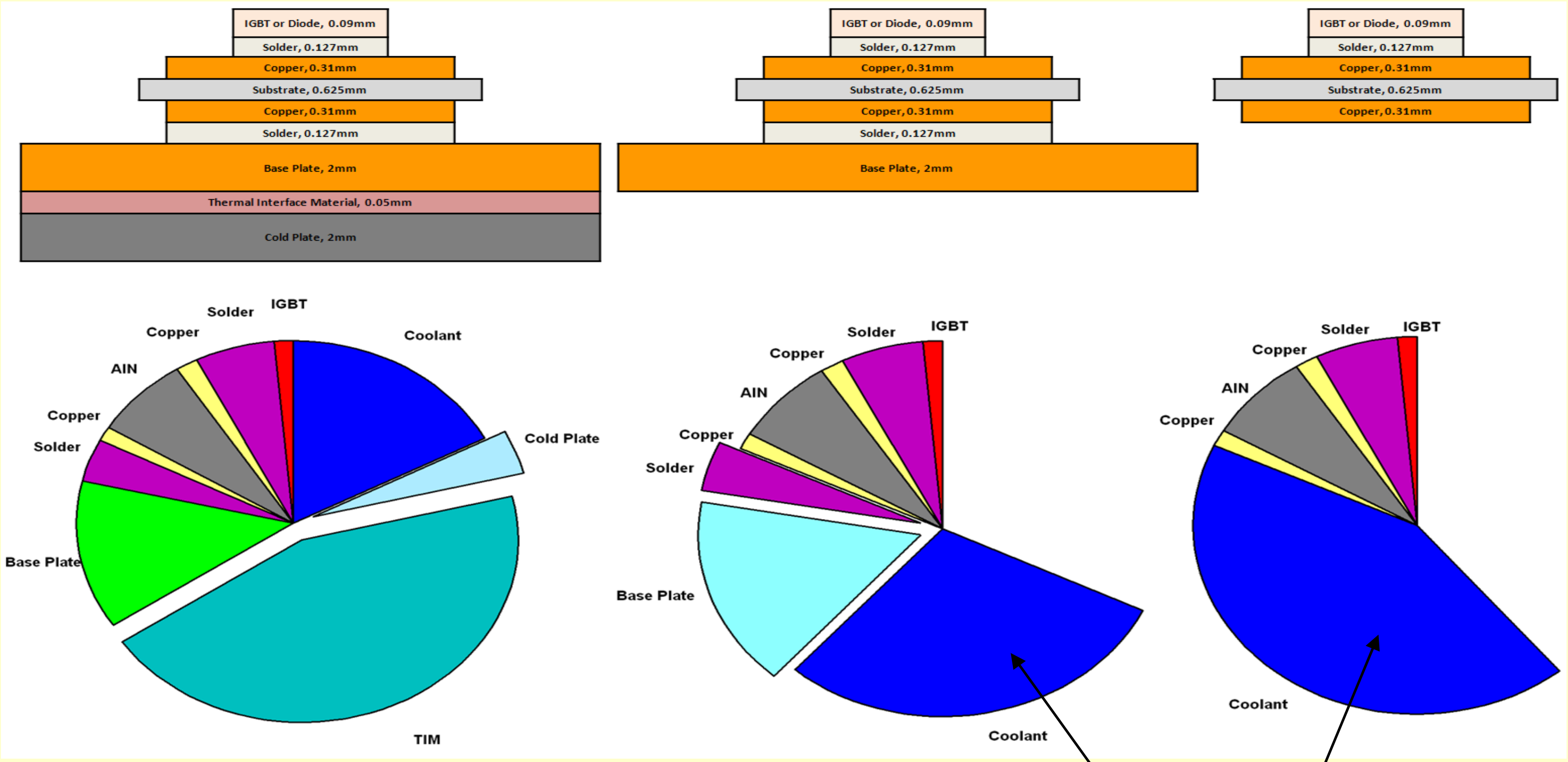
Substrate Materials for Cost Reduction – Topology 3



Topology Effect on Junction Temperature



Thermal Resistances – Contributions



100% 68% 61%

Opportunity for further reduction in thermal resistance through surface enhancement

Surface Enhancement

$$U = h \, . \, A$$

Targeted surface area enhancement is about 3

$$U = h \, . \, 3\,A$$

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

$$U = h \, . \, (2.2\,A)$$ (in the test)

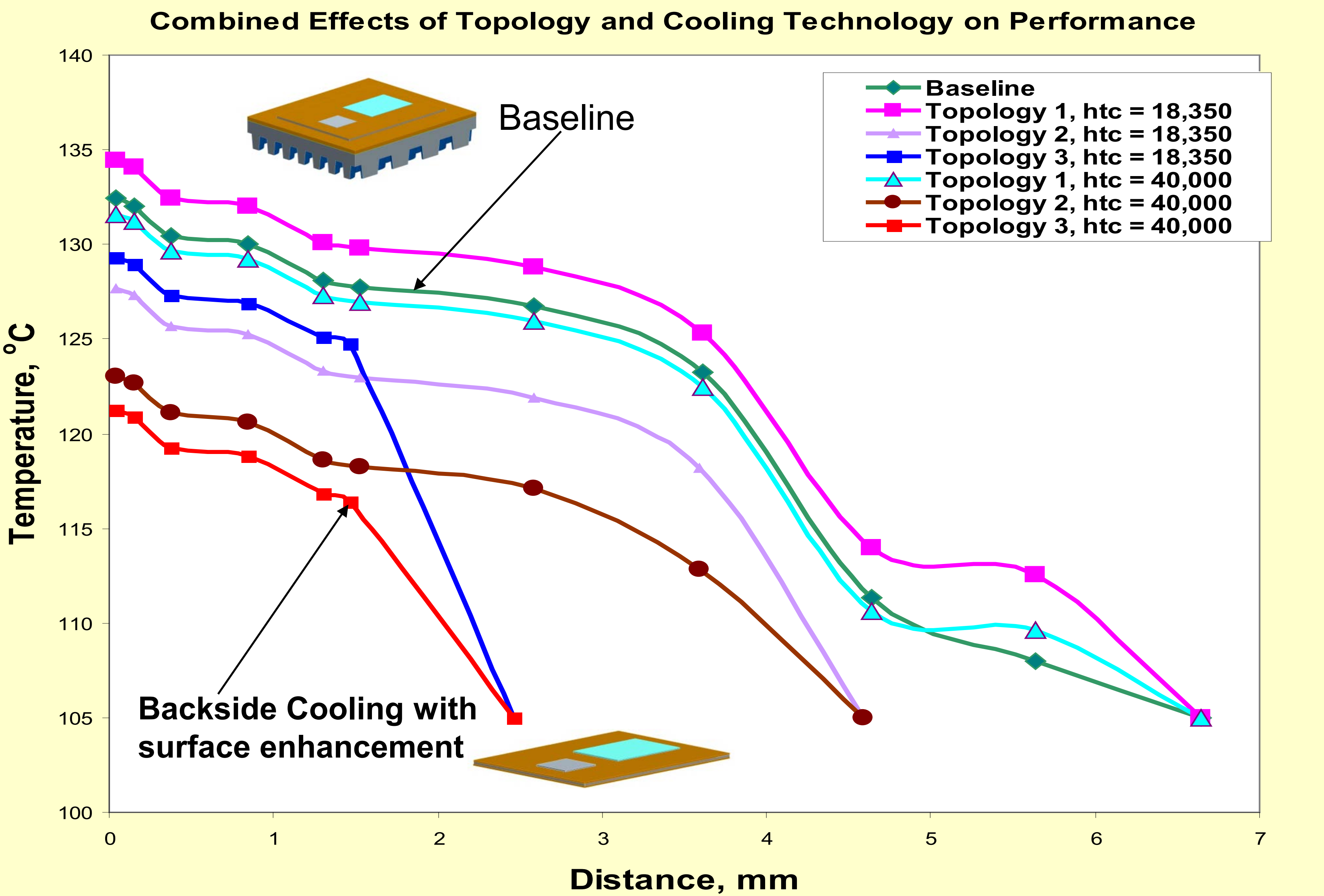
$$U = (2.2\,h) \, . \, A$$ (for modeling purposes)

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

Baseline, h = 18, 350 W/(m^2.K)

Enhanced, h = 2.2 * h = 2.2 * 18, 350 = 40,000 W/(m^2.K)

Combined Effects of Topology and Cooling Technology on Junction Temperature



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.