NANOTHERM®

Application Note

Nanotherm NC

Nanoceramic, thermally conductive dielectric-coated substrates

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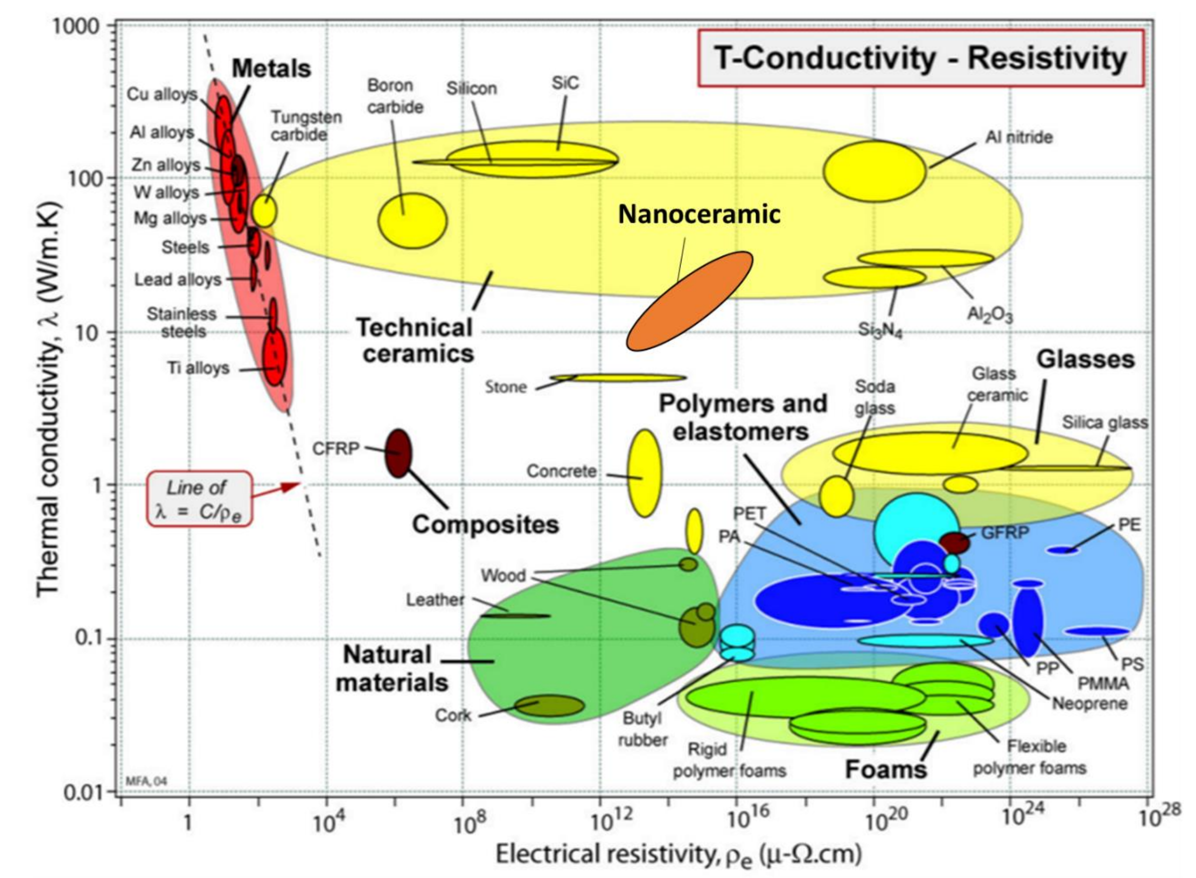
Contents

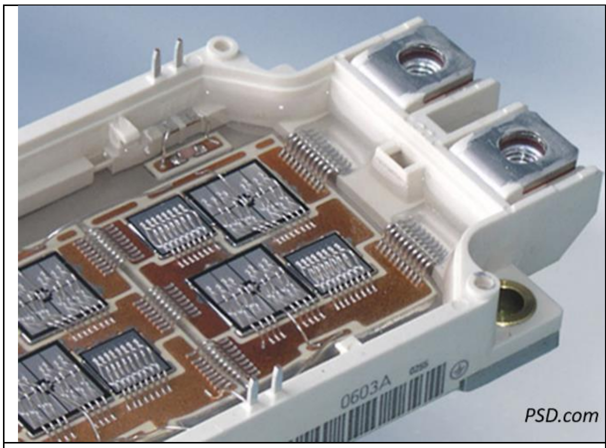
1. Introduction

Materials may be classed as either electrical conductors or insulators and likewise either thermal conductors or insulators. For many materials electrical and thermal properties are due to the same underlying mechanism, so good electricals conductors, like metals, tend also to be good thermal conductors, while good electrical insulators, like polymers and elastomers, have low thermal conductivity.

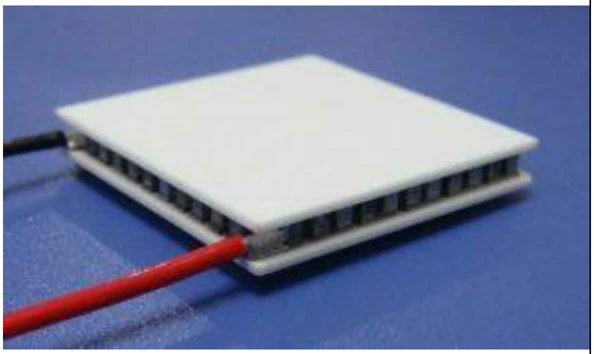


Materials selection chart exploring thermal and electrical conductivities (resistivity is the inverse of conductivity). After Ashby, Granta Design, 2010

From a materials perspective, there are two interesting permutations. They are electrically conductive thermal barriers, used in applications like thermo-electric generators and thermally conductive dielectrics. Electric insulators with high thermal conductivity are in huge demanded in the electronics industry to dissipate ohmic heat from semiconductor components.



Power electronic module with semiconductors mounted on a thermally conductive dielectric substrate



Thermo-electric device where the thermopile is made from electrically conductive elements possessing low thermal conductivity

2. Thermally conductive dielectrics

For applications where there is a need to keep electronic components cool, heat sinks and cold plates are used to capture the heat and dissipate it to either the ambient air or a pumped fluid. For ease of manufacture, robustness, cost and performance, heat sinks and cold plates are mostly made of aluminium. Because aluminium is a metal and therefore an electrical conductor it is necessary to provide a dielectric between it and the electronic components to prevent shorts. As the purpose of the heat sink or cold plate is to keep the electronic components cool, it beholds the dielectric needs to be as thermally conductive as possible.

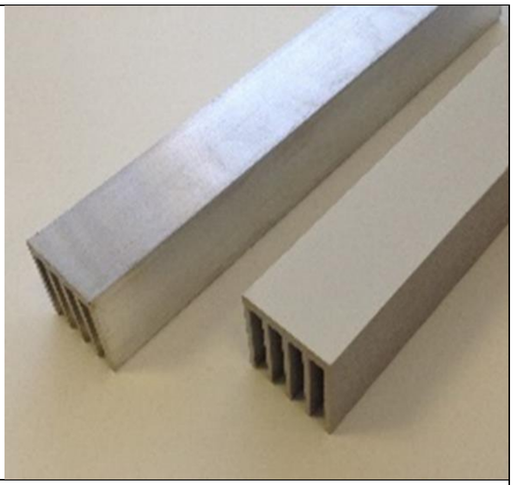
Polymers are electrical insulators, but also possess poor thermal conductivity. This may be rectified to some extent by incorporating thermally conductive particles or fibres. Unfortunately, there is a limit to the loading of second phase material that can be achieved without compromising other properties like adhesive strength in the case of epoxies.

Certain technical ceramics, such as alumina and aluminium nitride are excellent dielectrics and thermal conductors. But they are expensive due to the high energy content associated with manufacture. Available shapes and sizes are also very limited and there is the problem of how to make a low thermal resistance join between the ceramic and heat sink. This is made challenging by the low fracture toughness (brittleness) of such materials and rules out many fastening methods like bolting, while the low thermal expansivity compared with aluminium requires the joint can accommodate differential strain.

Most of the problems of using ceramic dielectrics can be avoided if they are applied directly to the aluminium heat sink or cold plate. Unfortunately, none of the deposition processes available methods results in a mechanically robust layer free of cracks pores and other defects that have a deleterious effect on dielectric properties.

3. Nanoceramic-coated aluminium

Cambridge Nanotherm has developed a process to provide aluminium alloy components with a tough, flexible, electrically insulative and thermally conductive skin of alumina. The layer is ultra-thin (10-35um) because the dielectric strength is 50-75V/um. Keeping the dielectric layer thin confers excellent thermal performance since the thermal impedance of a layer is its thickness divided by the thermal conductivity (7W/mK for alumina in nanograin form). The dielectric is manufactured in an electrochemical cell, where the surface of the aluminium metal core is converted to nanocrystalline alumina. Because the dielectric is created by conversion of the surface of the aluminium component, it is perfectly adhered and presents virtually no thermal impediment to the passage of heat across the interface. The aluminium component can take any shape or form, provided it fits in the electrochemical cell. Even the internal surfaces of blind holes can be converted to dielectric, provided they are wetted by the cell electrolyte.

	
Plates of alumina, Nanoceramic-coated aluminium and aluminium nitride	Bare metal and Nano-ceramic-coated aluminium heat sinks

The thermal resistance of a nanoceramic dielectric of typical thickness will be less than 0.027°C.cm^2/W. It must be stressed that thermal engineering is a relatively complex subject and there are many good reasons why thermal conductivity (units W/mK) is an inappropriate thermal metric to use when comparing the thermal performance. The correct units are thermal resistance (°C.cm^2/W) for a product and thermal impedance (°C/W) for each unique design of substrate.

Nanoceramic has remarkable flexibility. This is demonstrated by replacing the aluminium heat sink with a thin foil. Then, the nanoceramic-coated foil can be bent around an 8mm diameter former without fracture.

4. Nanotherm NC design guidelines

Manufacture of aluminium heat sinks, cold plates and other components having a thermally conductive dielectric skin is subject to design rules. Owing to the interdependencies between the components and the manufacturing processes the complete design rule documentation is substantial and complex. To aid customers, a simplified version is set out below. If the proposed design meets all guidelines, generally there will not be a problem with manufacture. The guidelines are specifically called guidelines rather than rules because infringement does not necessarily mean the design is not manufacturable. The table below is very conservative. In instance that a proposed design does not meet the guidelines, Cambridge Nanotherm can review and can comment on aspects like selection of manufacturing partner, product volume, lead time, cost, yield risk etc. that may permit production without undue changes.

Property / Material	Parameter	Guidelines
Aluminium alloy	Alloy type	1XXX, 3XXX, 5XXX and 6XXX series e.g. 1050, 6061, 6082
Component dimension	Length / width	900 mm x 500 mm
	Depth	500 mm
	Weight	8 Kg
Coated area	Area	15 dm^2
	Coverage	100% (electrical connection to component required, typically 1cm^2)
Coating thickness	Planar exterior surfaces	10-50um (will be thinner on convoluted and internal surfaces)
Holes / slots	Minimum diameter	50 um in 0.5 mm thickness
	Aspect ratio	10:1
Masked areas	Uncoated	Requires jig with water-tight mechanical seals
Surface sealing (optional)	Epoxy, polyimide	Enhances electric insulation and decouples properties from influence of ambient humidity

5. Nanoceramic properties

The key properties of Nanoceramic, in the form of a thin layer on an aluminium alloy substrate are given in the table below.

Property	Value
Composition	Al2O3 plus oxides from base alloy
Colour	Ivory-black (varies with process, thickness and base alloy)
Reflectivity	50% at 390 nm
	80% at 1600 nm
Dielectric strength	50-75 V/um
Dielectric constant	7.5-8
Loss tangent	0.004
Volume resistivity	4 GΩ-m

Surface ionic contamination	<<0.2 ug/cm2 equivalent NaCl (below measurement limit)
Thermal conductivity	7.3 W/mK
Adhesion to substrate	300 MPa
Density	3.87 g/cm3
Hardness	1000-1800 Hv (substrate dependent)
Elastic modulus	210 +/-60 GPa (20-25% elastic recovery)
Surface roughness	Ra 0.7 um, Rz 3-4um (varies with base alloy, thickness and process)
Bend radius	8 mm (on foil substrate)
Resistance to chemical attack	4-9 pH
Resistance to corrosion	1000 Hr salt spray (substrate dependent)
Degradation temperature	≈ 600 °C (base alloy melts first)
Transient degradation temperature	2040 °C
Flammability	None – wholly inorganic construction

6. Outgoing quality control

Subject to agreement with the customer, Nanoceramic parts can be evaluated against several criteria for quality purposes. These include,

Live components:

- Visual – uniformity of hue, using x5 ring light magnifier
- Visual – coverage using x10 binocular
- Thickness – eddy current surface contact probe
- Resistance – DC voltage for 1uA leakage using 50mm diameter soft contact

Destructive/witness samples:

- Breakdown – DC voltage for avalanche using point probe
- Thermal conductivity – laser flash by National Physical Laboratory (additional fee & lead time applies)
- Surface characteristics - Ra, Rz using SEM at x1000 magnification

7. Conclusions

Nanotherm NC is a mechanically and chemically robust, thermally conductive dielectric skin for aluminium components. The favourable combination of properties arises from the unique nature of the nanoceramic material and its method of formation by conversion of the underlying aluminium. Nanoceramic-coated aluminium heat sinks and cold plates make excellent components for thermal management of power devices, LEDs, EV batteries and the alike.