EE-463 STATIC POWER CONVERSION-I

Thermal Design in Power Electronics

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Thermal Design in Power Electronics

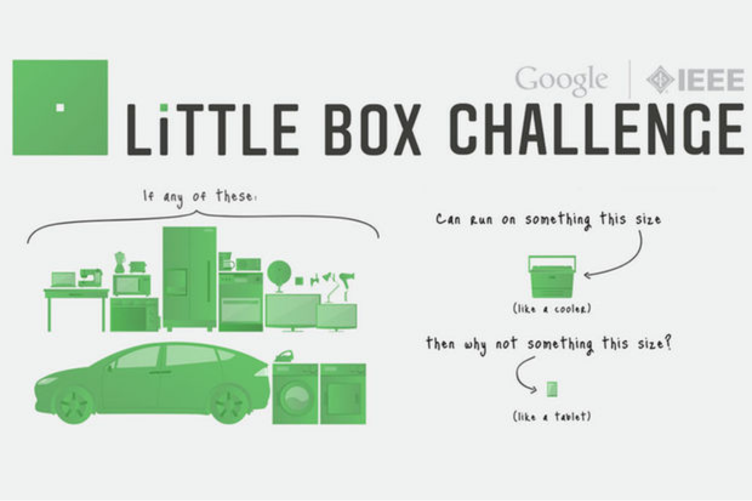
Thermal Design in Power Electronics

Why is it important?

Thermal Design in Power Electronics

Why is it important?

Power Density (kW/l)



Thermal Design in Power Electronics

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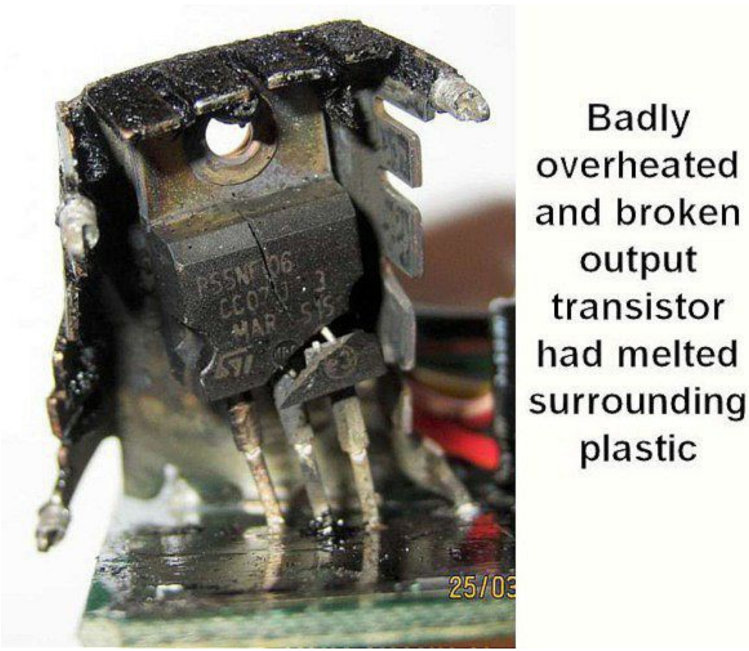
Survivability



Thermal Design in Power Electronics

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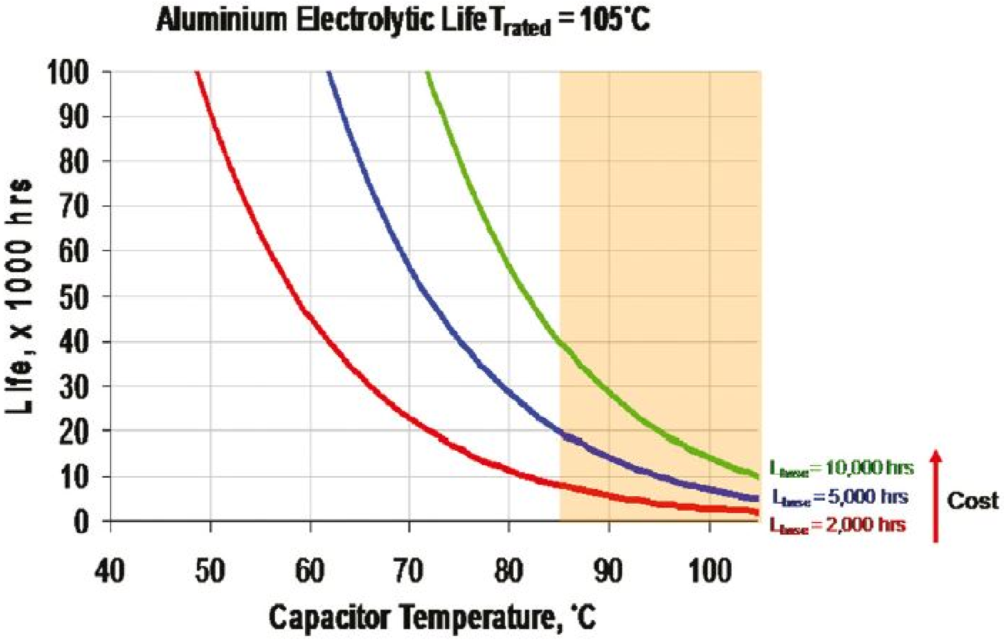
Expected Life



On the Machine (Load) Side

Losses are dependent on temperature and temperature on losses

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Losses are dependent on temperature and temperature on losses

Copper Losses $\propto$ Resistance

$$R(T) = R(T_0)(1 + \alpha \Delta T)$$

For copper (at 20 C)

$$\alpha = 0.003862 \ K^{-1}$$

Methods for Thermal Analysis

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From difficult to easy

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- Experimental

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- CFD (Computational Fluid Dynamics)

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- CFD (Computational Fluid Dynamics)
- FEA (Finite Element Analysis)

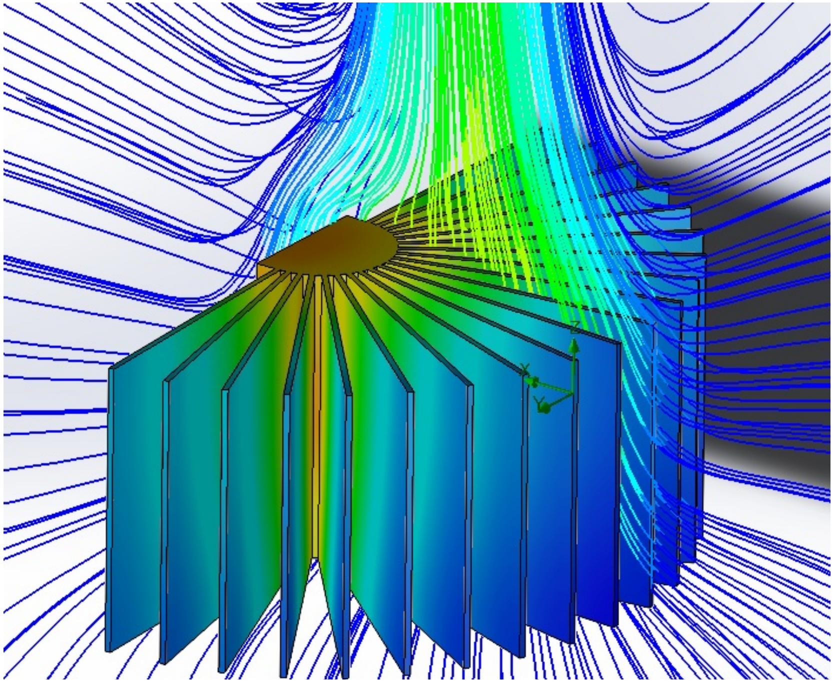
Methods for Thermal Analysis

From difficult to easy

- Experimental
- CFD (Computational Fluid Dynamics)
- FEA (Finite Element Analysis)
- Lumped Parameter Model

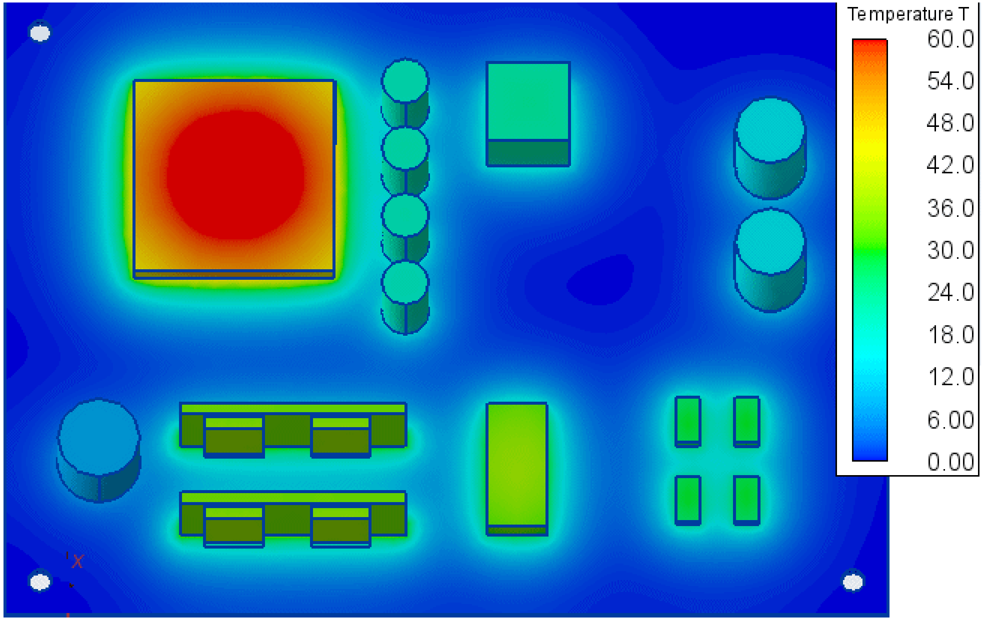
Thermal CFD

Requires intense computation

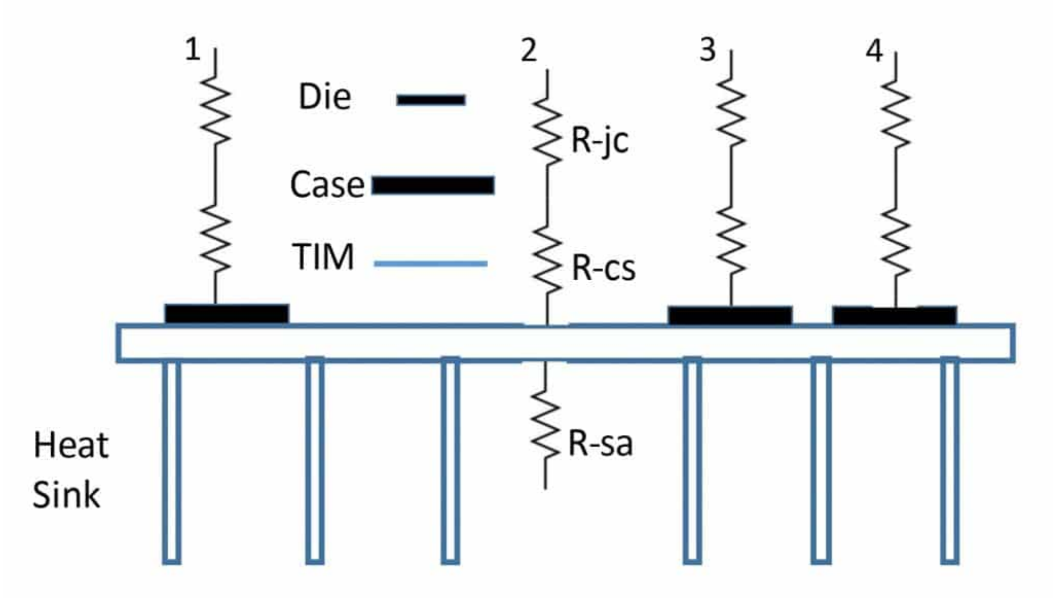


Thermal FEA

No air-flow

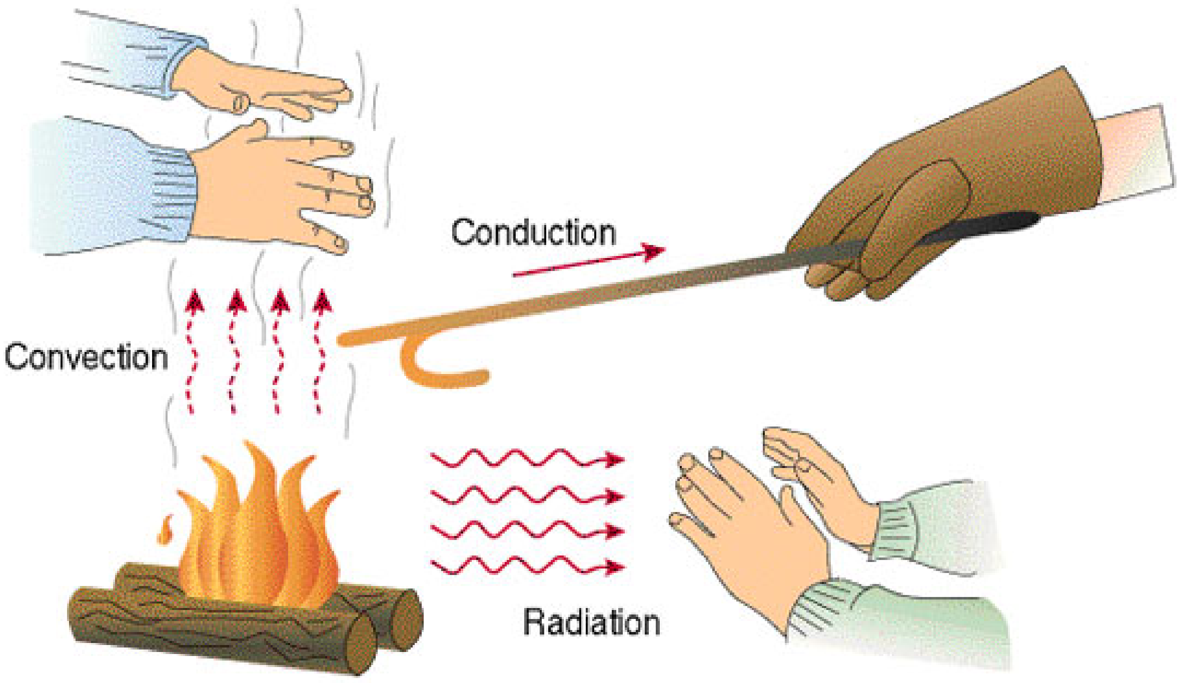


Thermal Lumped Parameter Network



Basics of Heat Transfer

Basics of Heat Transfer



Lumped Thermal Network

Thermal systems can be represented as electric circuits

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Temperature = Voltage

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Heat Input = Current Source

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Thermal Conductivity = Electrical Conductivity

Lumped Thermal Network

Thermal systems can be represented as electric circuits

Temperature = Voltage

Heat Input = Current Source

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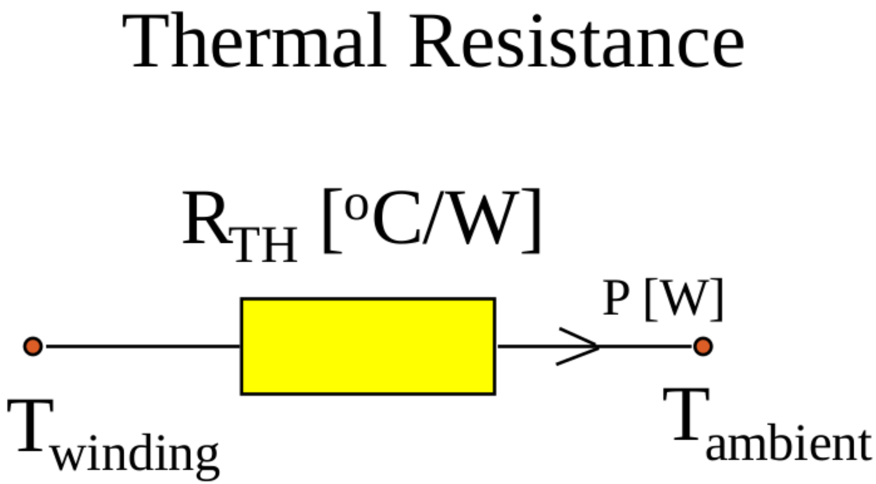
Heat Capacity = Capacitance

Thermal Conductivity

Thermal Conductivity

Thermal Conductivity

Thermal Resistance



Thermal Resistance

Similar to electrical resistance

$$R = \frac{l}{kA}$$

Thermal Resistance

Similar to electrical resistance

$$R = \frac{l}{kA}$$

- k: thermal conductivity

Thermal Conductivity of Some Materials

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- Water:

Thermal Conductivity of Some Materials

- Water: 0.58 W/(mK)

Thermal Conductivity of Some Materials

- Water: 0.58 W/(mK)
- Ice:

Thermal Conductivity of Some Materials

- Water: 0.58 W/(mK)
- Ice: 2.2 W/(mK)

Thermal Conductivity of Some Materials

- Water: 0.58 W/(mK)
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- Concrete:

Thermal Conductivity of Some Materials

- Water: 0.58 W/(mK)
- Ice: 2.2 W/(mK)
- Concrete: 1-1.5 W/(mK)

Thermal Conductivity of Some Materials

- Water: 0.58 W/(mK)
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- Wood:

Thermal Conductivity of Some Materials

- Water: 0.58 W/(mK)
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- Wood:0.12 W/(mK)

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- Water: 0.58 W/(mK)
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- Asbestos:

Thermal Conductivity of Some Materials

- Water: 0.58 W/(mK)
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Thermal Conductivity of Metals

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- Aluminum:

Thermal Conductivity of Metals

- Aluminum: 205 W/(mK)

Thermal Conductivity of Metals

- Aluminum: 205 W/(mK)
- Iron:

Thermal Conductivity of Metals

- Aluminum: 205 W/(mK)
- Iron: 80 W/(mK)

Thermal Conductivity of Metals

- Aluminum: 205 W/(mK)
- Iron: 80 W/(mK)
- Copper:

Thermal Conductivity of Metals

- Aluminum: 205 W/(mK)
- Iron: 80 W/(mK)
- Copper: 400 W/(mK)

Thermal Conductivity of Metals

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- Gold:

Thermal Conductivity of Metals

- Aluminum: 205 W/(mK)
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- Gold: 310 W/(mK)

Thermal Conductivity of Metals

- Aluminum: 205 W/(mK)
- Iron: 80 W/(mK)
- Copper: 400 W/(mK)
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- Epoxy: 0.35 W/(mK)

Thermal Conductivity of Metals

- Aluminum: 205 W/(mK)
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Ref

Conduction Heat Loss

$$P = \frac{\Delta T}{R}$$

$$P = \frac{T_2 - T_1}{R}$$

Convection

Heat transfer on the surface between solids and liquids (or gaseous)

Convection

Difficult to analyze accurately

Convection

Difficult to analyze accurately

Two types of Convection:

Convection

Difficult to analyze accurately

Two types of Convection:

- Natural Convection

Convection

Difficult to analyze accurately

Two types of Convection:

- Natural Convection
- Forced Convection

Types of Flow

Types of Flow

- Laminar FLow

Types of Flow

- Laminar FLow
- Turbulent Flow

Enhanced heat transfer

Turbulance

Heisenberg:

Heisenberg:

Not Walter White

Heisenberg

Werner Heisenberg: Key creator of quantum mechanics, uncertainity principle

Heisenberg: "I would ask God two questions;

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Why quantum mechanics, and why turbulence ?"

Heisenberg: "I would ask God two questions;

Why quantum mechanics, and why turbulence ?"

I think he will have answer for the first one.

Convection Thermal Resistance

Convection Thermal Resistance

$$R_c = \frac{1}{Ah}$$

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A: Area

Convection Thermal Resistance

$$R_c = \frac{1}{Ah}$$

A: Area

h: Convection heat transfer coefficient (W/m2/C)

h: Convection Heat Transfer Coefficient

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Depends on the surface properties

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Depends on the surface properties

Flow Rate, density

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Depends on the surface properties

Flow Rate, density

Reynolds Number

h: Convection Heat Transfer Coefficient

Depends on the surface properties

Flow Rate, density

Reynolds Number

And others (Nusselt number, prandtl number)

Rule of Thumbs

Not very accurate but useful for initial calculations

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Heat Transfer Coefficient

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Heat Transfer Coefficient

- Air-Natural Convection: 5-10 W/(m2.C)

Rule of Thumbs

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Heat Transfer Coefficient

- Air-Natural Convection: 5-10 W/(m2.C)
- Air-Forced Convection: 10-300 W/(m2.C)

Rule of Thumbs

Not very accurate but useful for initial calculations

Heat Transfer Coefficient

- Air-Natural Convection: 5-10 W/(m2.C)
- Air-Forced Convection: 10-300 W/(m2.C)
- Liquid-Forced Convection: 50-20.000 W/(m2.C)

More info: Estimating Parallel Plate-Fin Heat Sink Thermal Resistance, Iterative calculation of the heat transfer coeffici

Radiation

Radiation

Radiant Heaters

Radiant Heaters

Reflective Blankets

Radiation Heat Loss (Black body radiation)

q_R: radiation heat flow (W/m2)

$$q_R = \rho \epsilon F (T_1^4 - T_2^4)$$

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T_1, T_2 absolute temperature of radiant and ambient (K)

Radiation Heat Transfer

h_R: heat transfer coefficient for radiation (for lumped parameter network)

$$h_R = \frac{\rho \epsilon F (T_1^4 - T_2^4)}{T_1 - T_2}$$

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Emissivity of Materials

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Have you ever wondered why most heat sinks are black?

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Emissivity of Materials

Aluminum:

- Black anodized: 0.86
- Polished: 0.04-0.1

Emissivity of Materials

Aluminum:

- Black anodized: 0.86
- Polished: 0.04-0.1

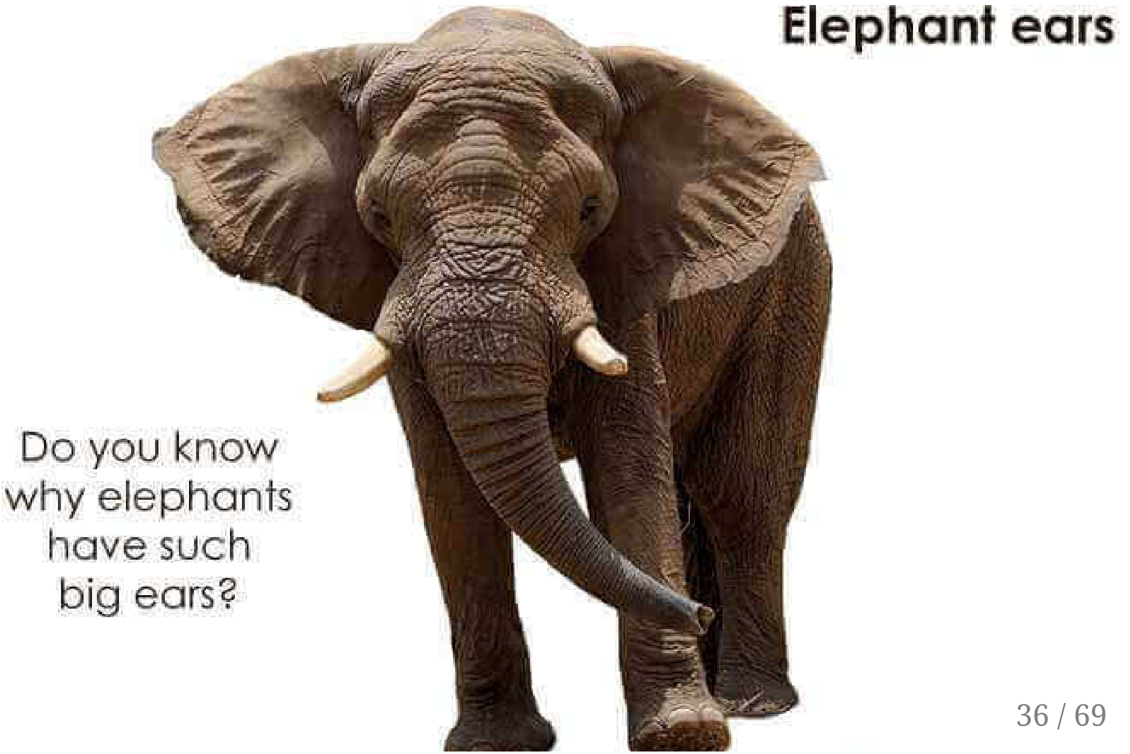
Radiation is more dominant with naturally cooled heatsinks, than the ones with forced cooling

More info:

- **Anodized Aluminum Heatsinks: What You Need to Know**
- **How Heat Sink Anodization Improves Thermal Performance**

Size vs Thermal Performance

Size vs Thermal Performance



Who'll Freeze First? A Puzzle About Size and Staying Warm

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[Who'll Freeze First? A Puzzle About Size and Staying Warm]

[Size and Metobolism]

(Heat $\propto$ Volume, but Heat Dissipation $\propto$ Area)

Square-Cube Law by Prof. Walter Lewin

Square-cube law, small is mighty

(Heat $\propto$ Volume, but Heat Dissipation $\propto$ Area)

Small is mighty

Thermal Design in Power Electronics

Thermal Design in Power Electronics

- Determine your components

Thermal Design in Power Electronics

- Determine your components
- Calculate the losses

Thermal Design in Power Electronics

- Determine your components
- Calculate the losses
- Get the thermal resistances fron datasheet

Thermal Design in Power Electronics

- Determine your components
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- Determine the max. heatsink thermal resistance

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- Find a heatsink, decide on cooling type (natural, forced)

Thermal Design in Power Electronics

- Determine your components
- Calculate the losses
- Get the thermal resistances fron datasheet
- Determine the max. heatsink thermal resistance
- Find a heatsink, decide on cooling type (natural, forced)
- Iterate until you get a reasonable operating temp.

Typical Thermal Circuit

Typical Thermal Circuit

Typical Thermal Circuit

Typical Thermal Circuit

Capacitances can be neglected for steady state analysis.

Be careful with low heat capacity (tiny) components

Design Exercise

Design Exercise

- [IGBT: STGW40H120DF2]

Design Exercise

- IGBT: STGW40H120DF2

  Find relevant parameters:

Design Exercise

- [IGBT: STGW40H120DF2]

  Find relevant parameters:

Package Type

Junction to Case Thermal Resistance

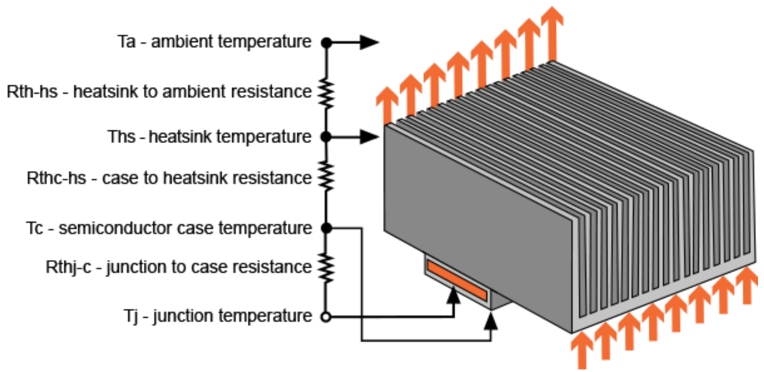
Junction to Ambient (if used without a heatsink)

Design Exercise

- [IGBT: STGW40H120DF2]

Don't forget the freewheeling diode

Choose a Heatsink



How to mount heatsinks?

Useful links: **Online Heat Sink Calculator**, **Heat Sink Calculator**, **Characteristics of common packages**

Choose a Heatsink

Suitable for TO-247 Package

Choose a Heatsink

Suitable for TO-247 Package

Choose a Heatsink

Suitable for TO-247 Package

- R2A-CT4-38E - Heat Sink

Choose a Heatsink

Suitable for TO-247 Package

Check:

- Heatsink to ambient thermal resistance

Choose a Heatsink

Suitable for TO-247 Package

Check:

- Heatsink to ambient thermal resistance
- Thermal resistance vs. air flow

How to

How to

- Calculate losses?

How to

- Calculate losses?
- Junction temperature

How to

- Calculate losses?
- Junction temperature
- Maximum operating limit

Tips & Things to consider

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Beware of hot spot and other heat sources!

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Tips & Things to consider

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Transients operating conditions!

Can be dominant for small (low heat capacity) components

Tips & Things to consider

Consider air flow (both for forced and natural cooling)

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Ambient Temperature

Not always at 25 C. Check the standards

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Ambient Temperature

Not always at 25 C. Check the standards

- Commercial: 0 ° to 70 °C
- Industrial: -40 ° to 85 °C
- Military: -55 ° to 125 °C

Tips & Things to consider

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Non idealities in contact surface

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Imperfections of the contact surface

Tips & Things to consider

Imperfections of the contact surface

That's why we use TIM (Thermal Interface Material)

Tips & Things to consider

Thermal Interface Materials

- Greases, Putties
- (Adhesive) Thermal Pads
- Epoxy, Potting compounds
- and others

Tips & Things to consider

Too much paste does more harm than good

Insufficient thermal paste

Tips & Things to consider

Too much paste does more harm than good

Ideal thickness

Tips & Things to consider

Too much paste does more harm than good

Excessive thermal paste

Tips & Things to consider

Avoid excessive mounting torque

Tips & Things to consider

Tips & Things to consider

Non-uniform cooling

Especially on stacked components on single heatsink

Useful Readings:

Application notes are your friends

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Application notes are your friends

- Thermal Resistance Theory and Practice
- Thermal resistance of IGBT Modules, Semikron
- Thermal effects and junction temperature evaluation of Power MOSFETs
- Heatsink Characteristics, IR
- Thermal Design of Power Electronic Circuits

Useful Readings (cont.):

- How to mount heatsinks?
- A thermal management example
- A Thermal Management Example Part 2:
- Thermal Interface Materials
- How to select a heatsink

You can download this presentation from:
keysan.me/ee463