Lecture Notes

Heat Sinks and Component Temperature Control

Need for Component Temperature Control

- All components, capacitors, inductors and transformers, and semiconductor devices and circuits have maximum operating temperatures specified by manufacturer.
  - Component reliability decreases with increasing temperature.Semiconductor failure rate doubles for every 10 - 15 °C increase in temperature above 50 °C (approx. rule-of-thumb).
- High component operating temperatures have undesirable effects on components.

Capacitors

Electrolyte evaporation rate increases significantly with temperature increases and thus shortens lifetime.

Magnetic Components

- Losses (at constant power input) increase above 100 °C
- Winding insulation (lacquer or varnish) degrades above 100 °C

Semconductors

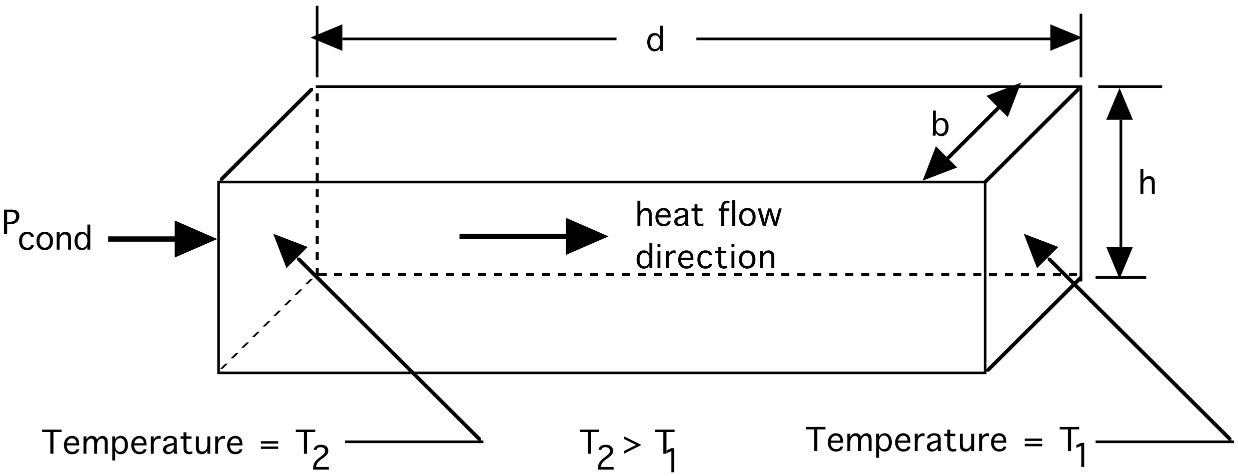
- Unequal power sharing in paralleled or seriesed devices.
- Reduction in breakdown voltage in some devices.
- Increase in leakage currents.
- Increase in switching times.

Temperature Control Methods

- Control voltages across and current through components via good design practices.
  - Snubbers may be required for semiconductor devices.
  - Free-wheeling diodes may be needed with magnetic components.
- Use components designed by manufacturers to maximize heat transfer via convection and radiation from component to ambient.
  - Short heat flow paths from interior to component surface and large component surface area.
- Component user has responsibility to properly mount temperature-critical components on heat sinks.
  - Apply recommended torque on mounting bolts and nuts and use thermal grease between component and heat sink.
  - Properly design system layout and enclosure for adequate air flow so that heat sinks can operate properly to dissipate heat to the ambient.

Heat Conduction Thermal Resistance

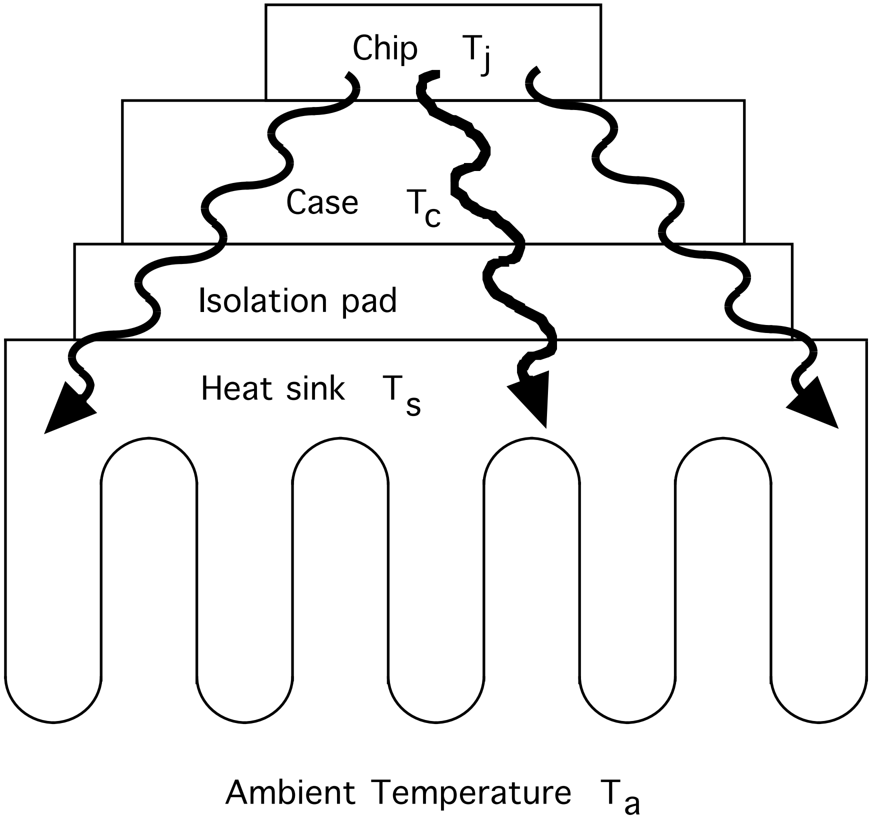
- Generic geometry of heat flow via conduction



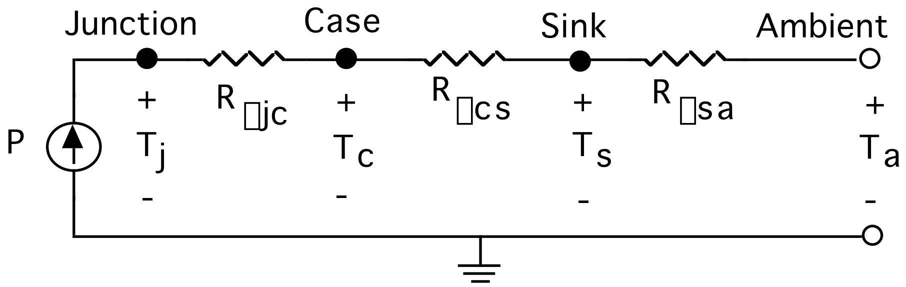
- Heat flow P_{cond} [W/m²] = $\lambda A (T_2 - T_1) / d \quad = \quad (T_2 - T_1) / R_{\theta cond}$
- Thermal resistance $R_{\theta cond} = d / [\lambda A]$
  - Cross-sectional area $A = hb$
  - λ = Thermal conductivity has units of W-m^{-1}-°C^{-1} (λ_{Al} = 220 W-m^{-1}-°C^{-1}).
  - Units of thermal resistance are °C/W

Thermal Equivalent Circuits

- Heat flow through a structure composed of layers of different materials.



- Thermal equivalent circuit simplifies calculation of temperatures in various parts of structure.

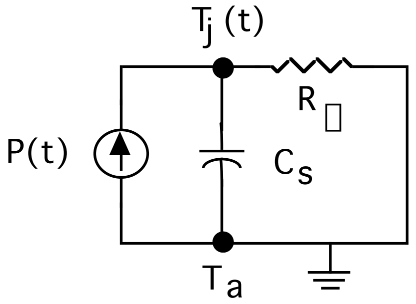


- $T_i = P_d (R_{\theta jc} + R_{\theta cs} + R_{\theta sa}) + T_a$
- If there parallel heat flow paths, then thermal resistances of the parallel paths combine as do electrical resistors in parallel.

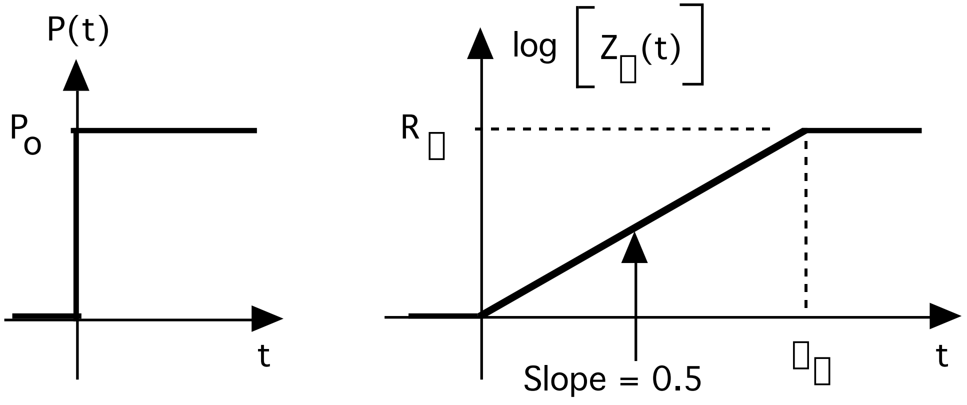
Transient Thermal Impedance

- Heat capacity per unit volume $C_v = dQ/dT$ [Joules /°C] prevents short duration high power dissipation surges from raising component temperature beyond operating limits.

  - Transient thermal equivalent circuit. $C_s = C_v V$ where V is the volume of the component.



  - Transient thermal impedance $Z_\theta(t) = [T_j(t) - T_a]/P(t)$



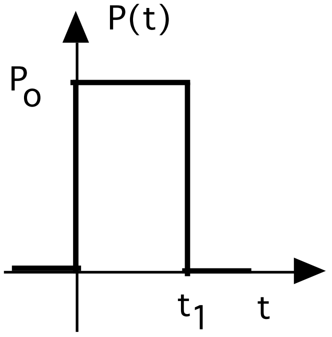
  - $\tau_\theta = \pi R_\theta C_s / 4$ = thermal time constant

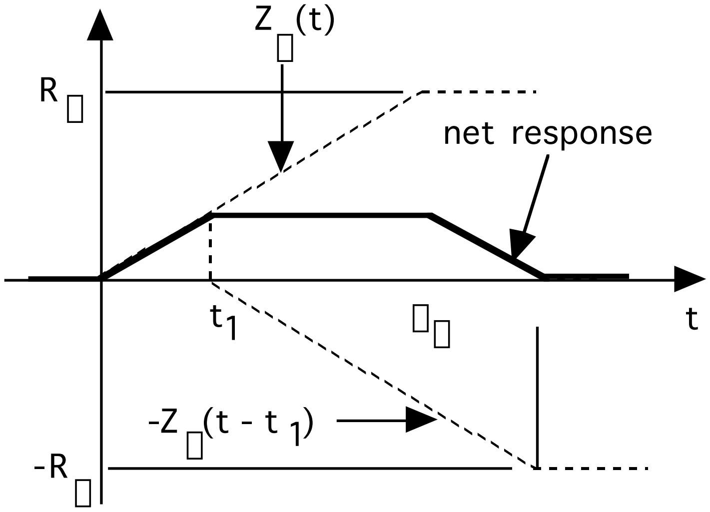
  - $T_j(t = \tau_\theta) = 0.833\, P_o R_\theta$

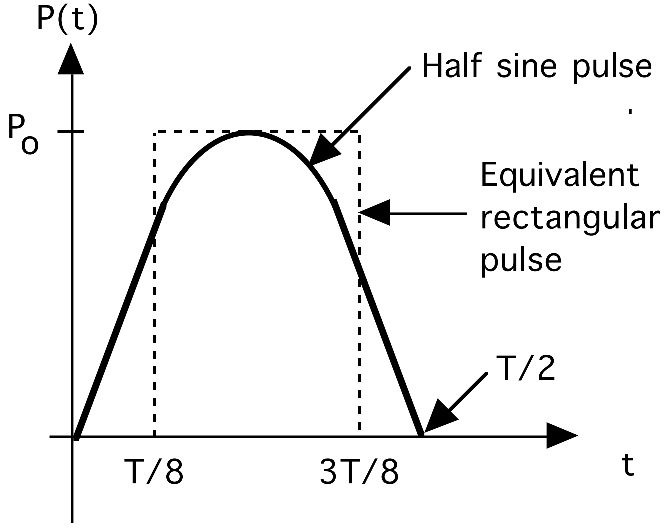
Application of Transient Thermal Impedance

- Symbolic response for a rectangular power dissipation pulse $P(t) = Po \{u(t) - u(t - t_1)\}$.

- $T_j(t) = Po \{ Z_{\square}(t) - Z_{\square}(t - t_1) \}$



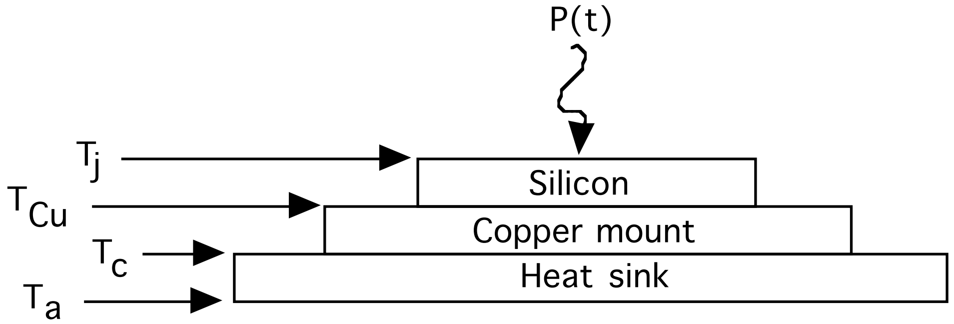




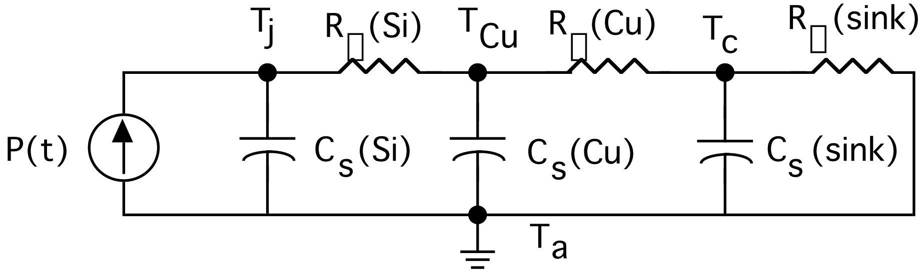
- Symbolic solution for half sine power dissipation pulse.
  - $P(t) = P_o \{u(t - T/8) - u(t - 3T/8)\}$; area under two curves identical.
  - $T_j(t) = Po \{ Z_{\square}(t - T/8) - Z_{\square}(t - 3T/8) \}$

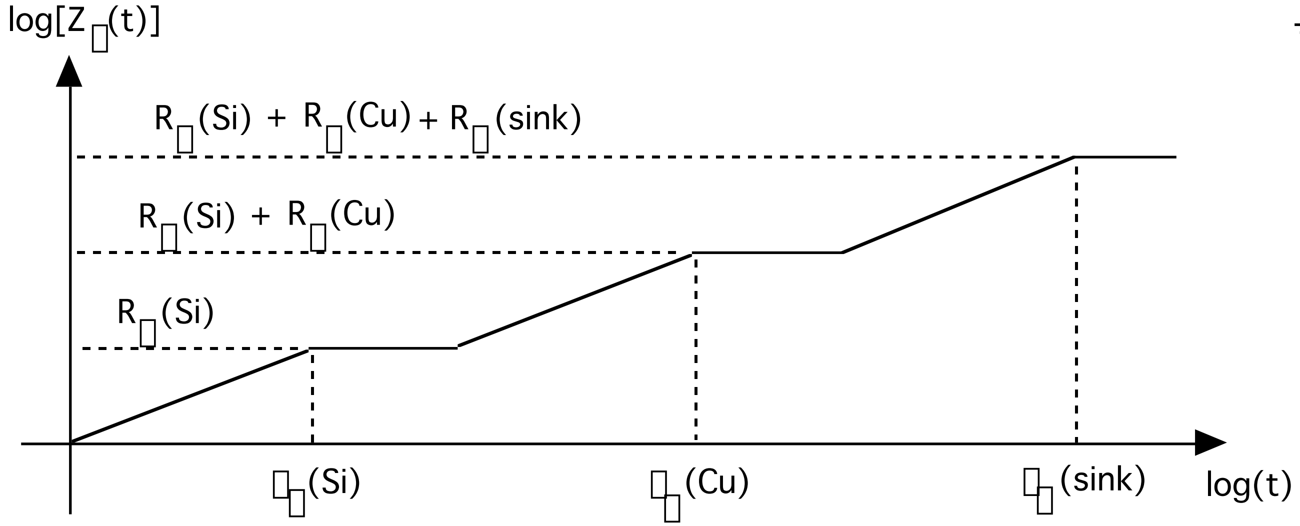
Z_{θ} for Multilayer Structures

- Multilayer geometry



- Transient thermal equivalent circuit





- Transient thermal impedance (asymptotic) of multilayer structure assuming widely separated thermal time constants.

Heat Sinks

- Aluminum heat sinks of various shapes and sizes widely available for cooling components.
  - Often anodized with black oxide coating to reduce thermal resistance by up to 25%.
  - Sinks cooled by natural convection have thermal time constants of 4 - 15 minutes.
  - Forced-air cooled sinks have substantially smaller thermal time constants, typically less than one minute.
- Choice of heat sink depends on required thermal resistance, $R_{\theta sa}$, which is determined by several factors.
  - Maximum power, P_{diss}, dissipated in the component mounted on the heat sink.
  - Component's maximum internal temperature, $T_{j,max}$
  - Component's junction-to-case thermal resistance, $R_{\theta jc}$.
  - Maximum ambient temperature, $T_{a,max}$.
- $R_{\theta sa} = \{T_{j,max} - T_{a,max}\}P_{diss} - R_{\theta jc}$
  - P_{diss} and $T_{a,max}$ determined by particular application.
  - $T_{j,max}$ and $R_{\theta jc}$ set by component manufacturer.

Radiative Thermal Resistance

- Stefan-Boltzmann law describes radiative heat transfer.
  - $P_{rad} = 5.7\times10^{-8}\,EA\,[(T_s)^4 - (T_a)^4]$; $[P_{rad}] = [\text{watts}]$
  - E = emissivity; black anodized aluminum E = 0.9 ; polished aluminum E = 0.05
  - A = surface area [m^2]through which heat radiation emerges.
  - T_s = surface temperature [°K] of component. T_a = ambient temperature [°K].

- $(T_s - T_a)/P_{rad} = R_{\theta,rad} = [T_s - T_a][5.7EA\,\{(T_s/100)^4 - (T_a/100)^4\}]^{-1}$

- Example - black anodized cube of aluminum 10 cm on a side. $T_s = 120$ °C and $T_a = 20$ °C
  - $R_{\theta,rad} = [393 - 293][(5.7)(0.9)(6\text{x}10\text{-}2)\{(393/100)^4 - (293/100)^4\}]^{-1}$
  - $R_{\theta,rad} = 2.2$ °C/W

Convective Thermal Resistance

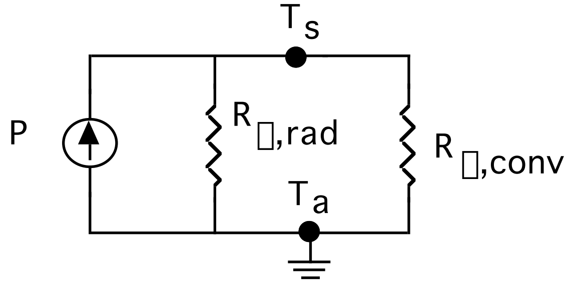
- P_{conv} = convective heat loss to surrounding air from a vertical surface at sea level having a height d_{vert} [in meters] less than one meter.
  - $P_{conv} = 1.34\ A\ [Ts - Ta]^{1.25}\ d_{vert}^{-0.25}$
  - A = total surface area in [m^2]
  - T_s = surface temperature [°K] of component. T_a = ambient temperature [°K].

- $[T_s - T_a]/P_{conv} = R_{\theta,conv} = [T_s - T_a]\ [d_{vert}]^{0.25}[1.34\ A\ (T_s - T_a)^{1.25}]^{-1}$
  - $R_{\theta,conv} = [d_{vert}]^{0.25}\ \{1.34\ A\ [T_s - T_a]^{0.25}\}^{-1}$

- Example - black anodized cube of aluminum 10 cm on a side. T_s = 120 °C and T_a = 20 °C.
  - $R_{\theta,conv} = [10^{-1}]0.25([1.34]\ [6x10^{-2}]\ [120 - 20]^{0.25})^{-1}$
  - $R_{\theta,conv} = 2.2$ °C/W

Combined Effects of Convection and Radiation

- Heat loss via convection and radiation occur in parallel.
  - Steady-state thermal equivalent circuit



  - $R_{\square,\text{sink}} = R_{\square,\text{rad}} R_{\square,\text{conv}} / [R_{\square,\text{rad}} + R_{\square,\text{conv}}]$

- Example - black anodized aluminum cube 10 cm per side
  - $R_{\square,\text{rad}} = 2.2$ °C/W and $R_{\square,\text{conv}} = 2.2$ °C/W
  - $R_{\square,\text{sink}} = (2.2)(2.2)/(2.2 + 2.2) = 1.1$ °C/W