6.334 Power Electronics
Spring 2007

Power Electronics Notes - D. Perreault

★★ Thermal Modeling and Heat Sinking

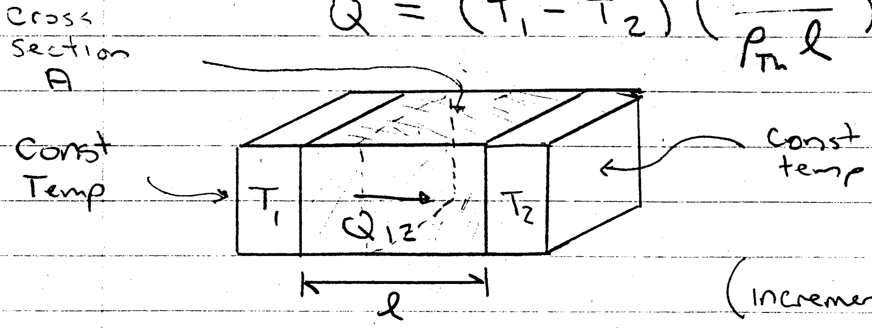
3 Methods of heat removal:

1. Convection: Transfer of heat to a moving fluid which takes it away
2. Conduction: Flow of heat through thermal conductor away from source
3. Radiation: Flow of heat by long-wave electromagnetic radiation.

Radiation of heat depends nonlinearly on temperature difference of source and environment (proportional to $[T_{source}^4 - T_{env}^4]$) and can be neglected in most applications.

Conduction: One dimensional heat conduction through a material can be expressed as:

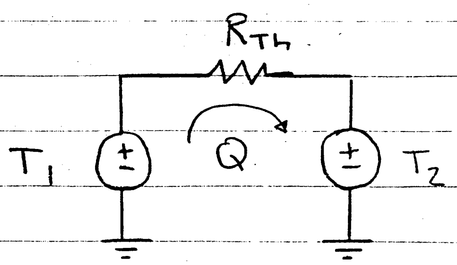
$$Q = (T_1 - T_2)\left(\frac{A}{\rho_{Th}\, l}\right)$$



q is heat flow (W)
ρ_{Th} is thermal resistivity $\left(\frac{W\text{-}m}{K}\right)$
A is cross sectional area (m^2)
l is length (m)

(incrementally, $q = -\frac{A}{\rho_{Th}}\frac{\partial T}{\partial x}$)

This relationship suggests an electrical circuit analog:



Q is heat flow in W
T is temperature in °C
R_{Th} is thermal resistance in °C/W

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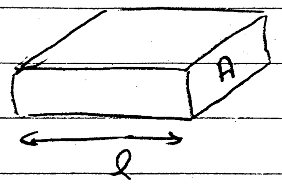
Thermal resistance is very like regular resistance

$$R_{Th} = \frac{\rho_{Th}\, l}{A}$$



l - length of material
A - cross sectional area
ρ_{Th} - thermal resistance $\frac{{}^{o}C \cdot m}{W}$

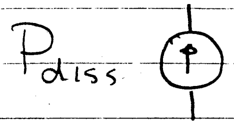
Because of this, we can connect thermal resistances and calculate temperatures & heat flows in various series and parallel paths using simple circuit model.

Convection: convective heat transfer from a surface to a fluid in motion can be modeled as:

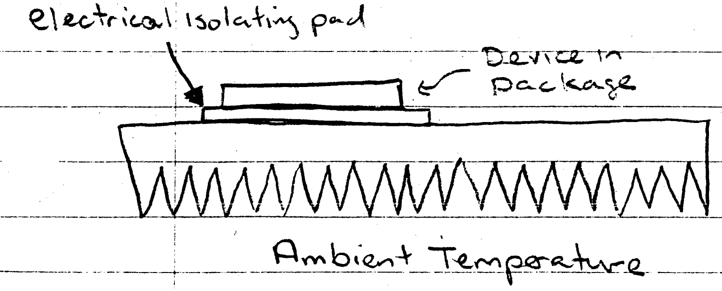
$q = hA(T_{surf} - T_{fluid})$ where h = heat transfer coefficient
A = "wetted area"

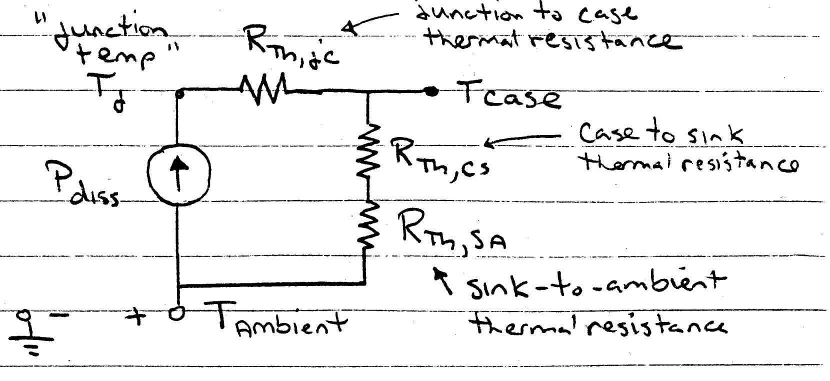
Thus we can also model convective heat transfer with a thermal resistance $R_{Th} = (hA)^{-1}$

Usual Case: heat power is generated and must be removed



Heat source looks like a current source in our electrical analog





Example:

IRF 620 Mosfet in TO-220 package $R_{TH,jc} \simeq 2.5\,°C/W$

$R_{TH,cs} \simeq 0.5\,°C/W$

Redpoint Thermalloy KM50-1 Heat sink $R_{TH,SA} \approx 4.8\,°C/W$

So if $T_A = 40°C$, P_{diss} (device) = 10W

$$T_j = T_{amb} + P_{diss}(R_{Th,jc} + R_{Th,cs} + R_{Th,SA})$$

$$= 40 + 10(2.5 + 0.5 + 4.8)$$

$$= 118°C$$

Typ limits for $T_j \sim 125°C - 175°C$ depending on device.

Note: The data sheet "current rating" or "power rating" of many devices are specified by temperature rise limits. They usually assume the case can be held at 25°C (difficult in real life) and compute allowable current + power diss. for $T_{j,max}$ to be reached. Hence, the IR620 is theoretically a 50W device, but this is usually impractical to achieve.

The typical design problem is: given P_{diss}, $R_{Th,jc}$, $R_{TH,cs}$, find $R_{Th,SA}$ to limit T_j or Tcase to acceptable value.

Ex: $P_{diss} = 10W$, $R_{THjc} + R_{TH,cs} = 3.0\,°C/W$

$T_A = 100°C$ what R_{TH} for $T_j < 150°C$?

$$T_A + P_{diss}(R_{TH,jc} + R_{TH,cs} + R_{TH,sA}) \le T_{j,max}$$

$$\Delta T = T_{j,max} - T_A = 50^\circ C = 10(3 + R_{TH,sA})$$

$$\Rightarrow R_{TH,sA} \le 2^\circ C/W$$ → buy such a heat sink

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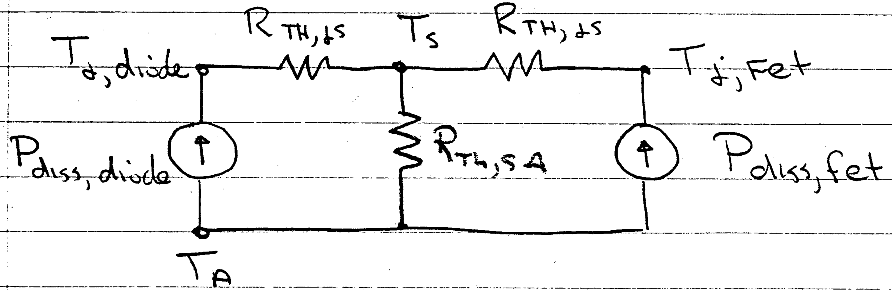
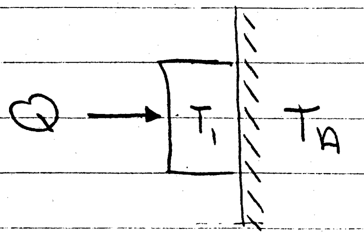
Things get more complicated with multiple heat sources, such as a diode and a MOSFET on the same heat sink

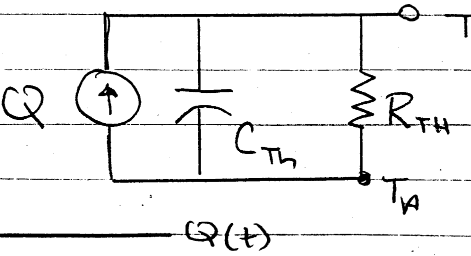


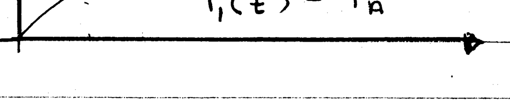
Dynamic case: If we have pulsed power:
(e.g. a UPS that runs for only a short time or
a pulse discharge circuit that operates only once)

- The mass of an element can store heat energy

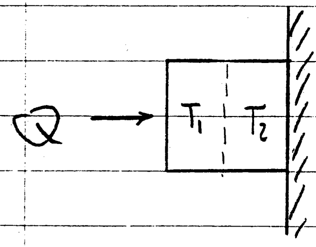
∴ Thermal Capacitance C in J/°C $\left\{\text{heat capacitance in } \frac{J}{^\circ C \cdot kg} \times \text{mass}\right\}$

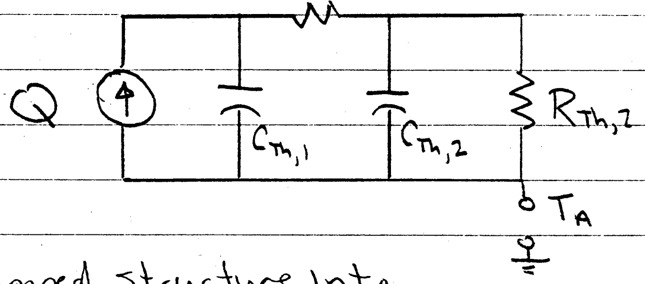




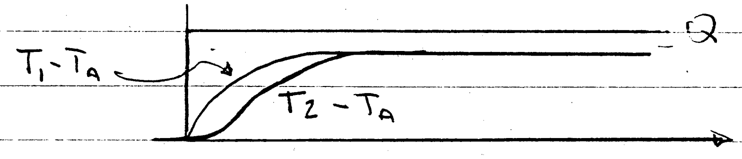


Note: This is a lumped parameter model for a distributed system. The temperature calculated is the average temperature across the block. If we want to look over short intervals of time (e.g. << $R_{Th}C_{Th}$), at high frequency, or across small spaces, we need to use more "lumps"





(e.g. break previously lumped structure into 2 equal lumps $R_1C_1 = R_2C_2 = \frac{1}{4}RC$ → shorter timescales)



We can break the system down into as many lumps as needed. In limit, we can go to partial differential equation (distributed) representation.

PDE description ⇒ R. Haberman, "Elementary Applied Partial Differential Equations, 2nd Ed." Prentice-Hall

Transient Thermal Impedance

To express the temp rise of a subsystem under transient conditions, sometimes a "transient thermal impedance" is used

$$Z_{Th}(t) = \frac{\Delta T(t)}{Q} \begin{array}{l} \leftarrow \text{Temp rise across element} \\ \leftarrow \text{magnitude of power step} \end{array}$$

So use to get $\Delta T(t)$ for steps or pulses of power.
this is a reflection of the "RC" type behavior shown above

Note: Sometimes temp rise is expressed as a function of duty ratio and pulse repetition rate (of power input). This is based on similar models.

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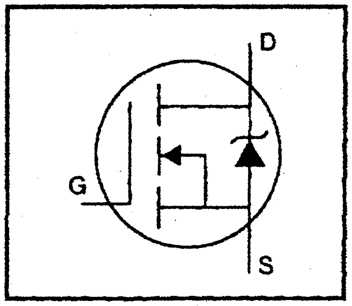
International
IOR Rectifier

PD-9.317H

IRF620

HEXFET® Power MOSFET

- Dynamic dv/dt Rating
- Repetitive Avalanche Rated
- Fast Switching
- Ease of Paralleling
- Simple Drive Requirements



$V_{DSS} = 200V$

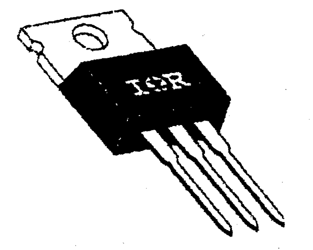
$R_{DS(on)} = 0.80\Omega$

$I_D = 5.2A$

Description

Third Generation HEXFETs from International Rectifier provide the designer with the best combination of fast switching, ruggedized device design, low on-resistance and cost-effectiveness.

The TO-220 package is universally preferred for all commercial-industrial applications at power dissipation levels to approximately 50 watts. The low thermal resistance and low package cost of the TO-220 contribute to its wide acceptance throughout the industry.



TO-220AB

Absolute Maximum Ratings

	Parameter	Max.	Units
I_D @ $T_C = 25°C$	Continuous Drain Current, V_{GS} @ 10 V	5.2	A
I_D @ $T_C = 100°C$	Continuous Drain Current, V_{GS} @ 10 V	3.3	
I_{DM}	Pulsed Drain Current ①	18	
P_D @ $T_C = 25°C$	Power Dissipation	50	W
	Linear Derating Factor	0.40	W/°C
V_{GS}	Gate-to-Source Voltage	±20	V
E_{AS}	Single Pulse Avalanche Energy ②	110	mJ
I_{AR}	Avalanche Current ①	5.2	A
E_{AR}	Repetitive Avalanche Energy ①	5.0	mJ
dv/dt	Peak Diode Recovery dv/dt ③	5.0	V/ns
T_J T_{STG}	Operating Junction and Storage Temperature Range	-55 to +150	°C
	Soldering Temperature, for 10 seconds	300 (1.6mm from case)	
	Mounting Torque, 6-32 or M3 screw	10 lbf•in (1.1 N•m)	

Thermal Resistance

	Parameter	Min.	Typ.	Max.	Units
$R_{\theta JC}$	Junction-to-Case	—	—	2.5	°C/W
$R_{\theta CS}$	Case-to-Sink, Flat, Greased Surface	—	0.50	—	
$R_{\theta JA}$	Junction-to-Ambient	—	—	62	

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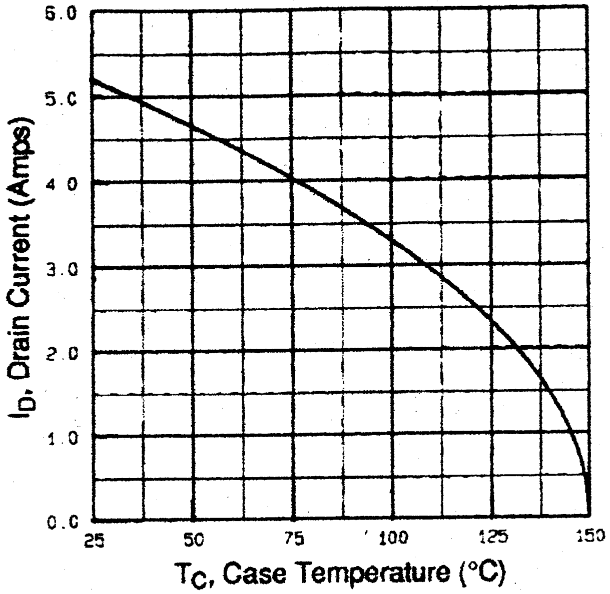

Fig 9. Maximum Drain Current Vs. Case Temperature

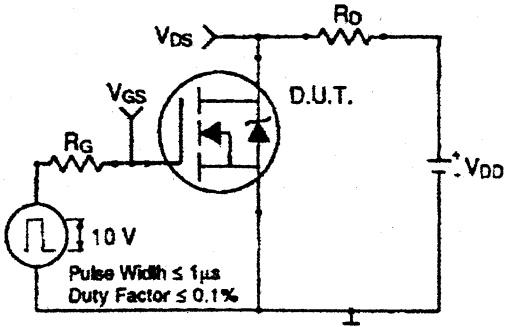

Fig 10a. Switching Time Test Circuit

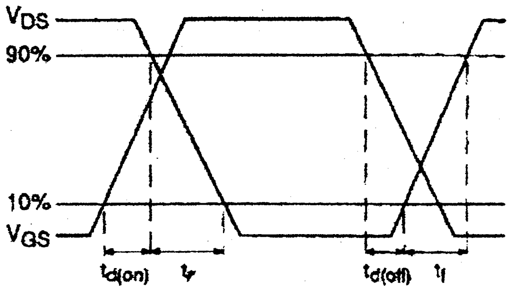

Fig 10b. Switching Time Waveforms

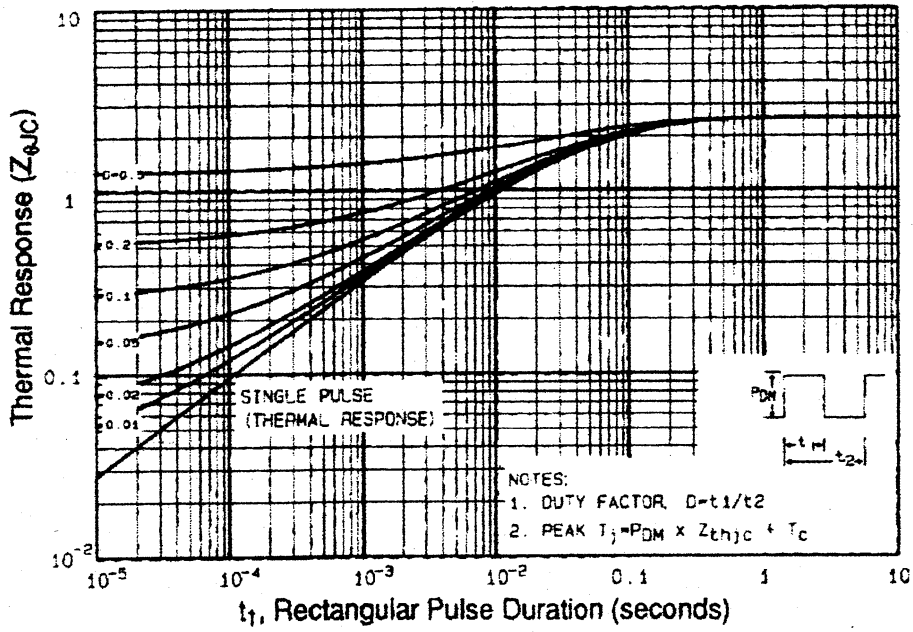

Fig 11. Maximum Effective Transient Thermal Impedance, Junction-to-Case