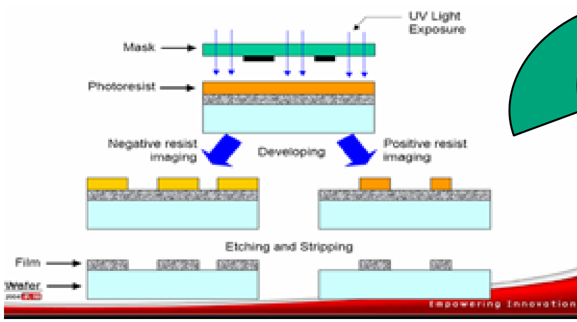
Thermal Analysis of IC Packages

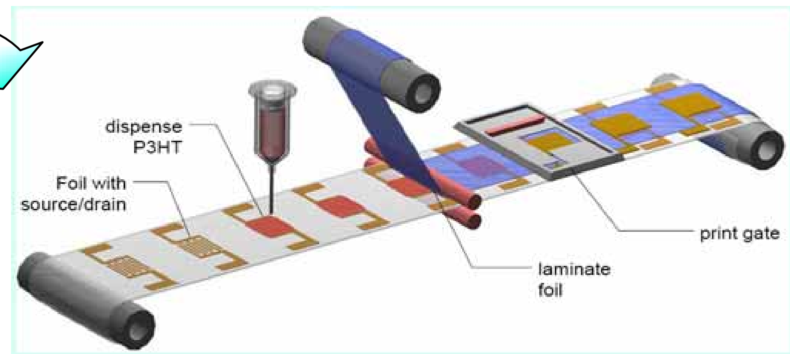
Stanley H. Huang (黃新鉗), Ph.D.
Director
Flexible Electronics Technology Division
ERSO/ITRI
Tel: 03-5917580
E-mail: stanleyhuang@itri.org.tw

Flexible Electronics Technology

- ***Flexible Electronics Technology:* Flexible electronics** is a generic term that represents a range of device and materials technologies built on flexible and conformal substrates such as thin plastic or metal foils. Flexible electronics, using amorphous and low-temperature polysilicon and organic semiconductor materials, is an area that is beginning to show tremendous promise. (Source: Proceeding of the IEEE)

- ***Printed Electronics***, being thin film silicon or inorganic or organic semiconductors, can be used to form Thin Film Transistor Circuits (TFTCs), such as replacing the functionality of simple silicon chips. …Often they will be made by rapid, high-volume reel-to-reel processing even forming a part of regular printing processes for graphics. These circuits will be cheap enough to permit electronics where envisaged silicon chips are always or almost always too expensive, where multiple components are needed, and where silicon is impractical (e.g. not flexible, brittle, thick etc). (Source: Printed Electronics Review, IDTechEx)





Photolithography Process

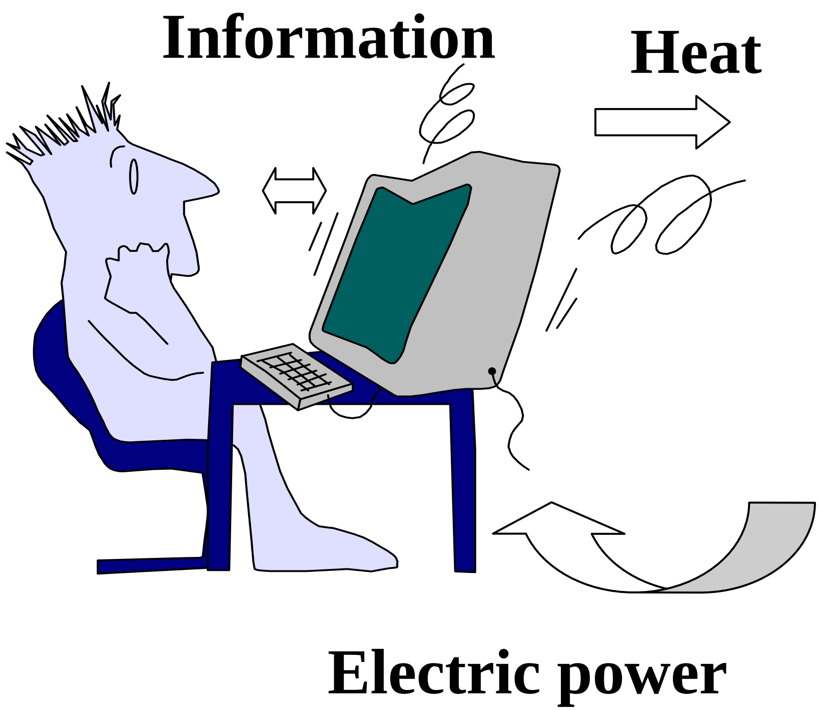
R2R Process (Screen Printing, Inkjet Printing,…)

Outline

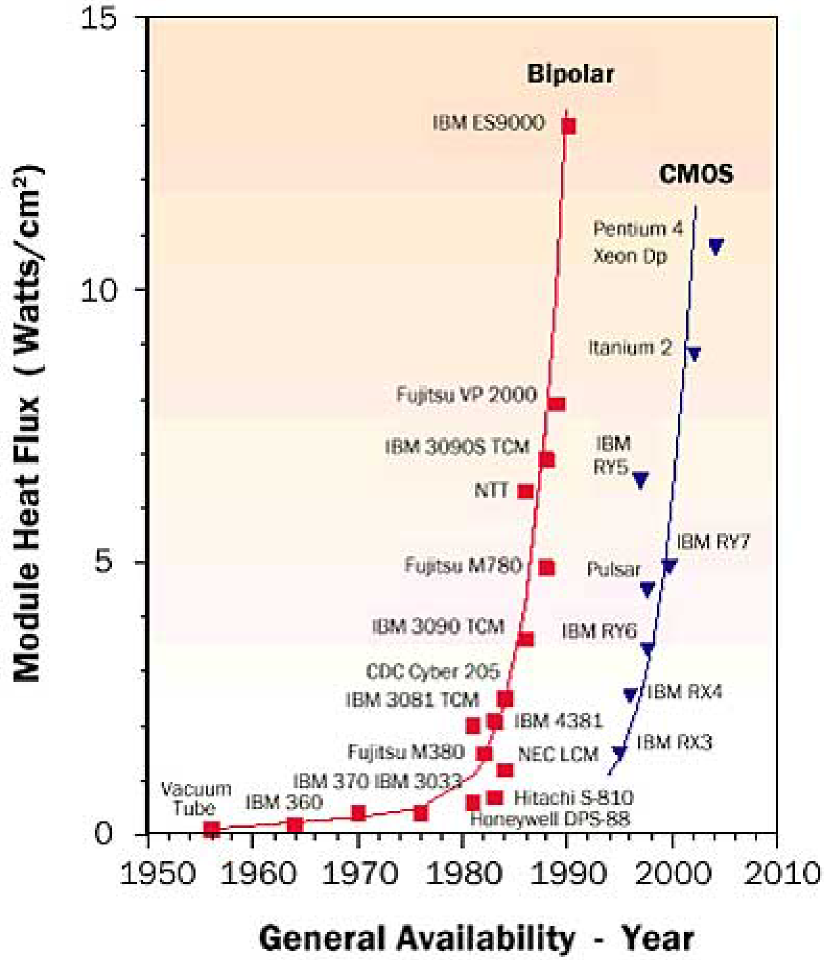
- Issues in electronic cooling
- Overview of heat transfer in electronic cooling
- Numerical analysis of electronic cooling - thermal network method
- Thermal analysis of heat sink

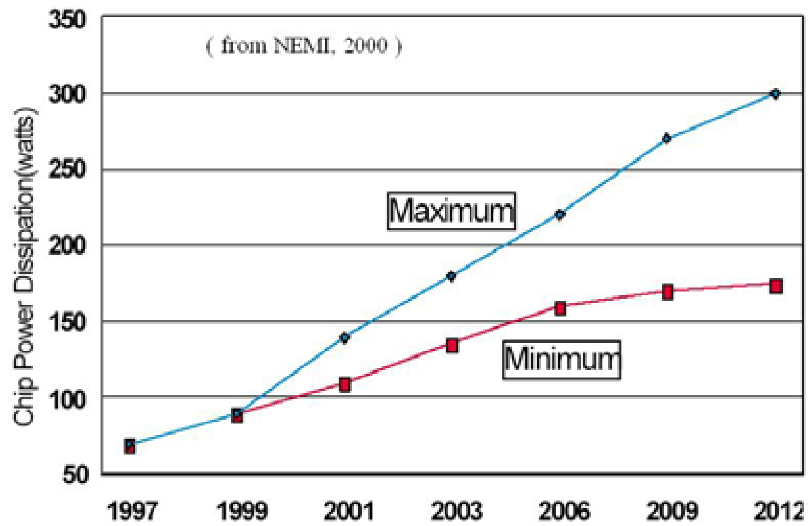
- Measurement of thermal resistance
- Thermal performance of PBGA
- The future
- Conclusions

Issues in Electronic Cooling


Information
Heat
Electric power

Trends of Power Dissipation



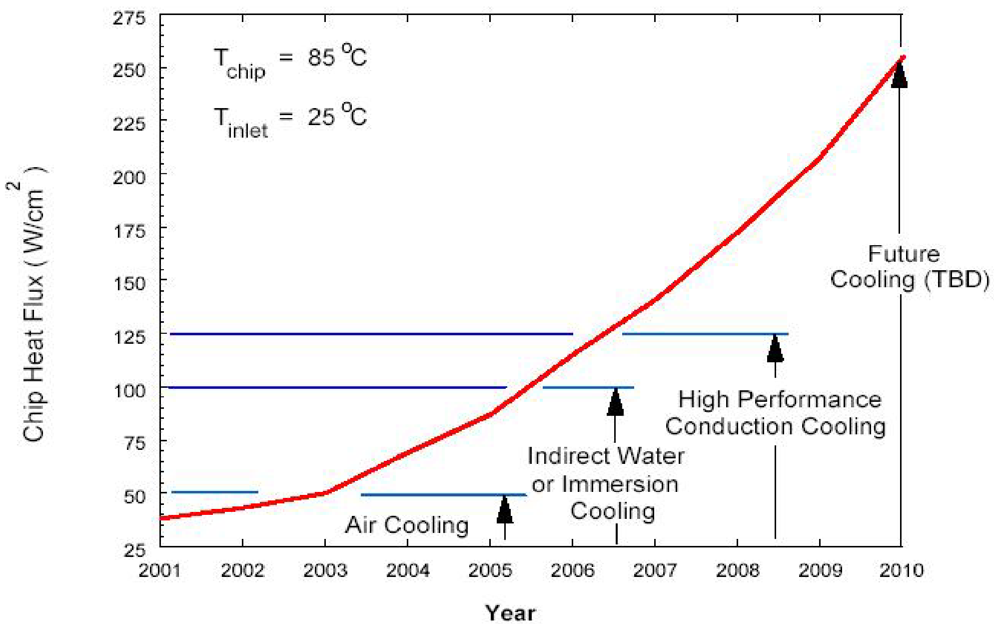


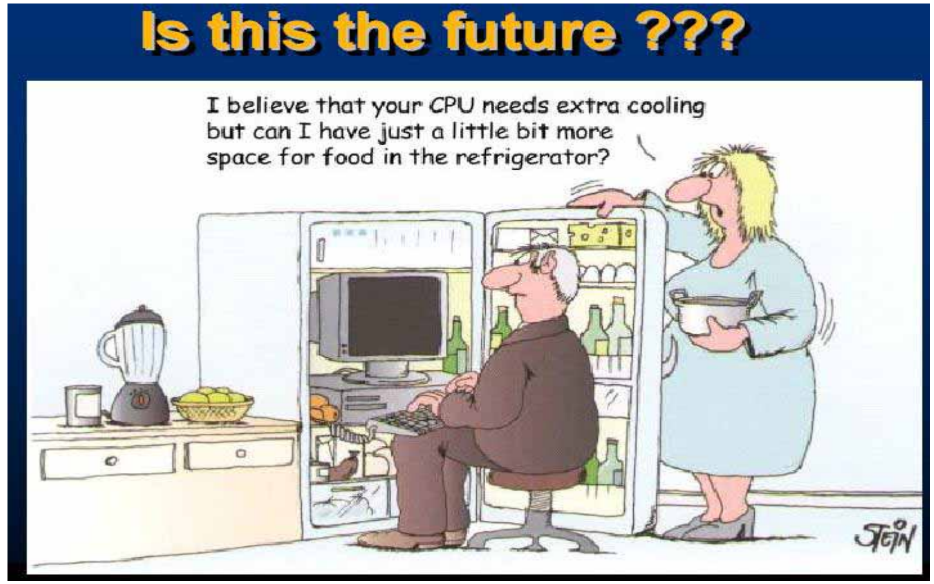
ITRS 2001 Projections from 2001 (0.13 μm) to 2016 (0.022 μ m)[1]

Chip Features	Power[2]	Temperature Limits (°C)		Chip Features	
				Size	Perf.
	W	Junction	Ambient	mm^2	MHz
Commodity products (< $300) (Micro-controllers, disk drives, displays)	n/a	125	55	57-90	415-10,000
Handheld products (< $1,000) (Mobile products, cellular telecommunications)	2.4-3	100	55	57-90	415-10,000
Cost/Performance products (< $3000) (Notebooks, desktops, PCs)	61-158	85	45	170-307	1,700-29,000
High Performance products (> $3000) (High end work stations, servers, avionics)	130-288	85	45	310-310	1,700-29,000
Automotive (Under-the-hood sensors, passenger products)	14-27	150	-40-125	60-150	60-234

1. Excluding memory
2. Single chip packages

New Cooling Technologies Are Needed





Heat Sink w/ Fan

Fan w/ Heat Pipe

Liquid Cooling

Issues Induced by Heat

- Temperature too high: burned-out

–Pentium 4 2.0GHz : lower operating frequency, continuously works

–Pentium 3 1.0GHz : device down when overheat. No damaged

–Athlon 1.4GHz (ThunderBird) : No protection, damaged if temperature exceeds 370 C

–Athlon 1.2GHz (Palomino) : No protection. damaged if temperature exceeds 300 C

- Temperature gradient induces noise between devices

Driver
(40 C)

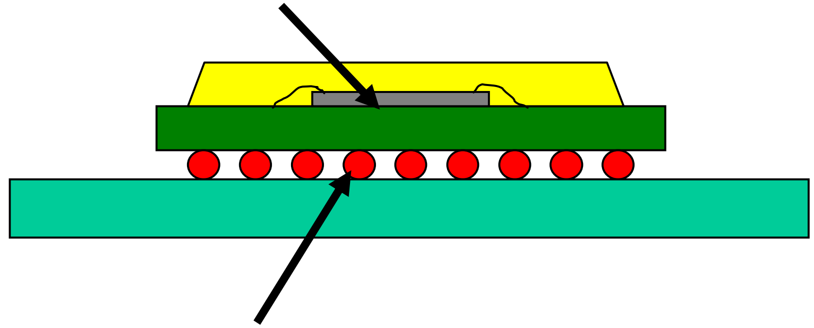
Receiver
(70 C)

Issues Induced by Heat

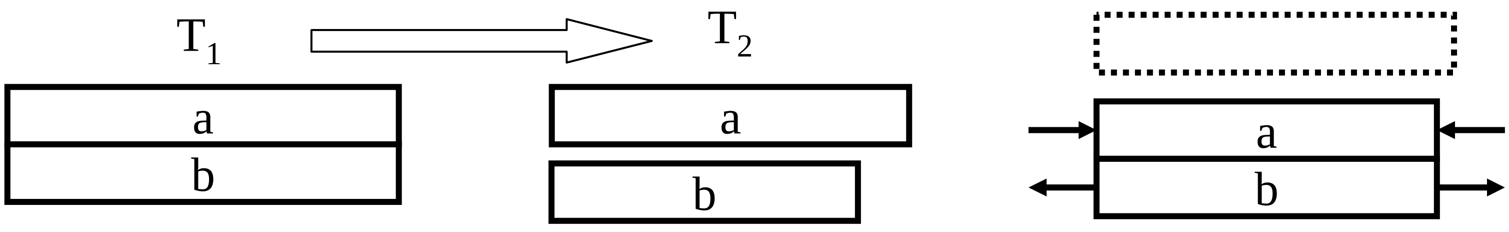
- Mismatch of CTE induces thermal stress

Material	CTE (ppm/C)
Si	4.2
Die Attach	50.0
Copper	17.0
Gold	14.3
Alloy 42	6.4
Molding Compound	17.0
Solder	26.0
BT substrate	14~17
FR-4 PCB	17

Interfaces between internal materials



Interfaces between component and PCB



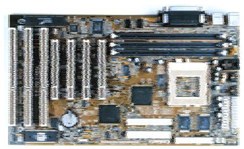
(1) $T_1 > T_2$

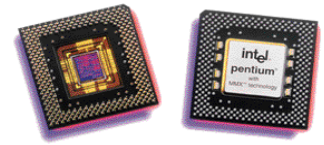
(2) $\alpha_a < \alpha_b$

Material a: Compressive stress

Material b: Tensile stress

Hierarchy of Electronic Cooling

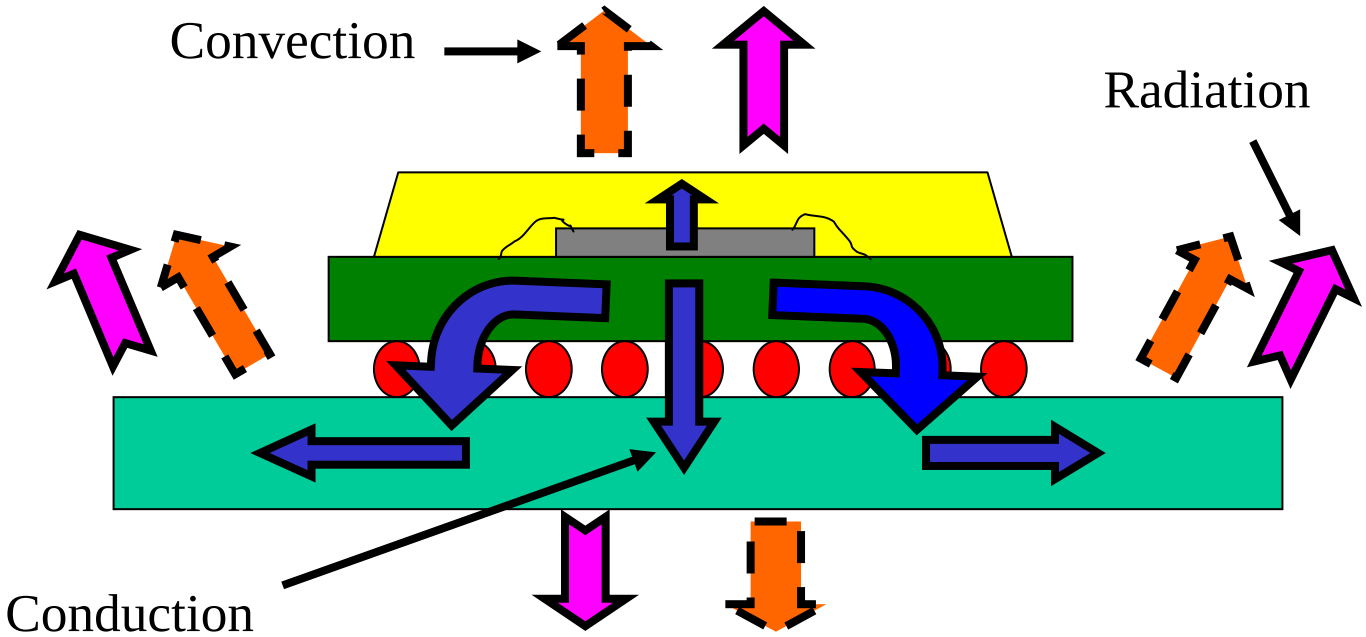




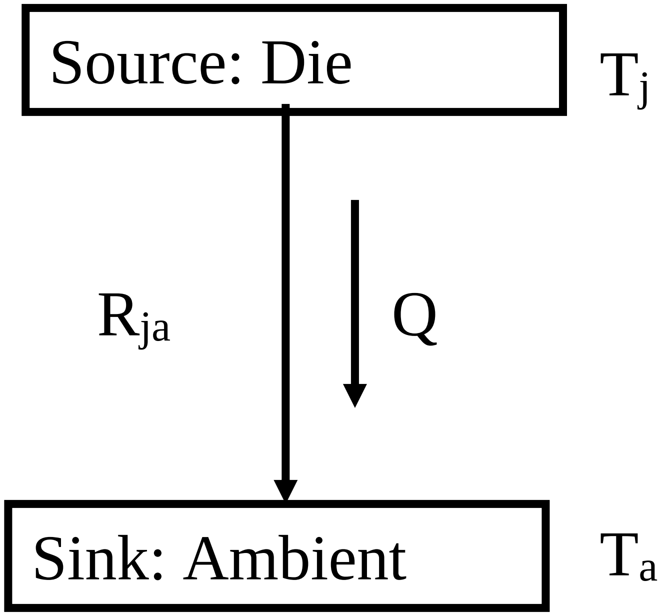
	System Level	Board Level	Component Level
INPUT DATA	–FRAME, SHELF & PCB PHYSICAL/THERMAL PROPERTIES –PCB POWER LEVELS –FAN DATA –FRAME AMBIENT	–CHANNEL, BOARD & COMPONENT PHYSICAL/THERMAL PROPERTIES –COMPONENT POWER LEVELS –CHANNEL THERMAL & FLOW AMBIENT	–COMPONENT/CHIP PHYSICAL/THERMAL PROPERTIES –CHIP POWER LEVELS –BOARD & CHANNEL AMBIENT
OUTPUT DATA	–AVERAGE PCB TEMP –MEAN CHANNEL AIR VELOCITY –MEAN CHANNEL AIR TEMP –FAN SELECTION	–COMPONENT CASE TEMP –BOARD TEMP PROFILE –CHANNEL TEMP PROFILE	–JUNCTION TEMP –THERMAL RESISTANCE

Overview of Heat Transfer in Electronic Cooling

Heat Transfer Path in IC Package



Thermal Resistance



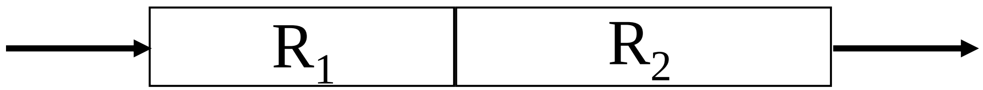
- Thermal resistance
  - An index to identify the ability of thermal design
  - Unit : C/W

$$R_{ja} = \frac{T_j - T_a}{Q}$$

$$= \frac{\Delta T}{Q}$$

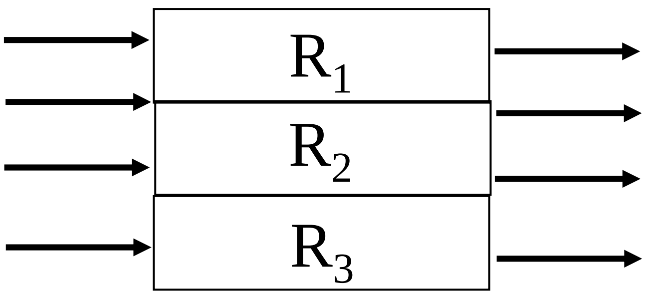
Combination of Thermal Resistances

- Series



$$R_{equ} = R_1 + R_2$$

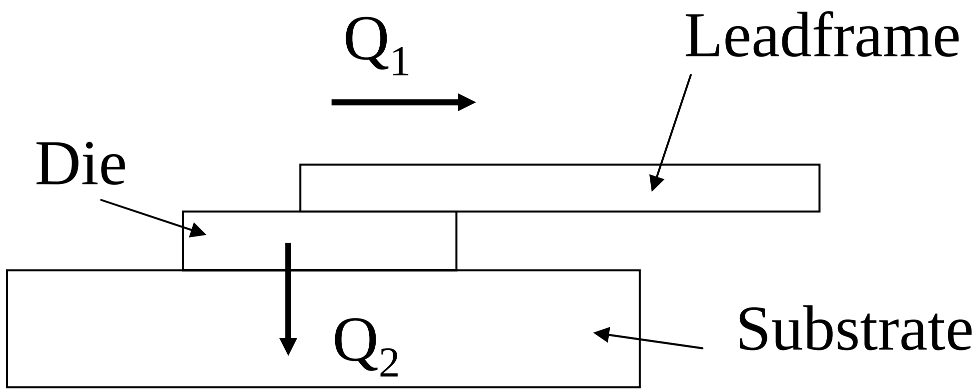
- Parallel



$$\frac{1}{R_{equ}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

Calculation of Thermal Resistance

- Is It Correct?



$$\frac{1}{R_{equ}} = \frac{1}{R_1} + \frac{1}{R_2}$$

?

R_1: thermal resistance of die and substrate

R_2: thermal resistance through the lead frame

Thermal Resistances in Component Level

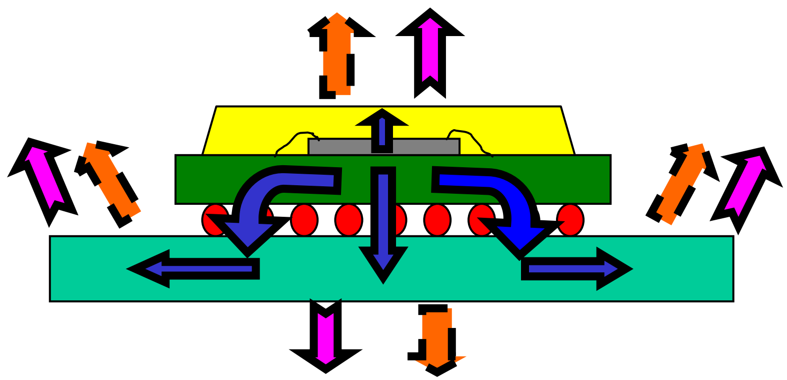
- Total Thermal Resistance R_{ja} : die junction - to - ambient
- Internal Thermal Resistance R_{jc} : die junction - to - case
- External Thermal Resistance R_{ca} : case - to -ambient

$$R_{ja} = R_{jc} + R_{ca}$$

$$R_{ja} = (T_j - T_a)/Q$$

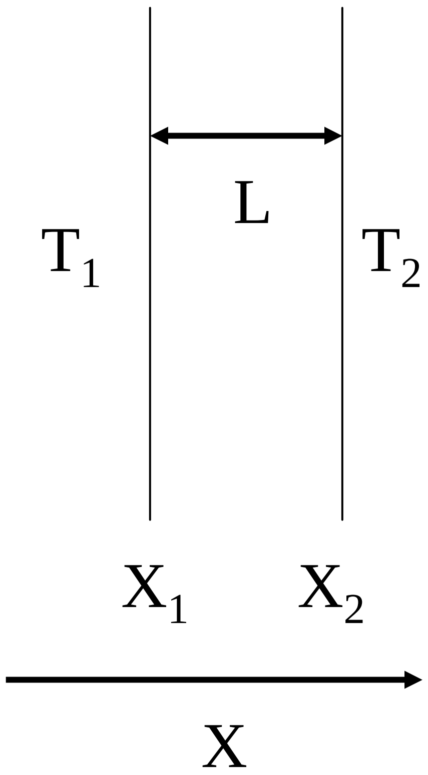
$$R_{jc} = (T_j - T_c)/Q$$

$$R_{ca} = (T_c - T_a)/Q$$



One Dimensional Model

- 1-D steady state without heat generation



$$\frac{d^2T}{dX^2} = 0$$

$$\frac{dT}{dX} = C_1$$

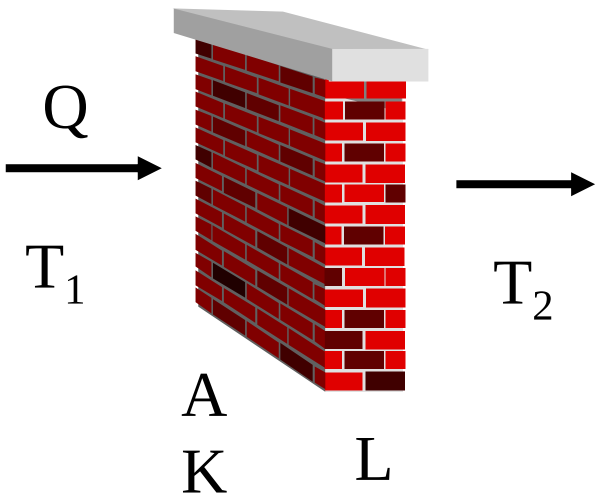
$$T(X) = C_1X + C_2$$

Boundary Condition

$$T(X_1) = T_1, \quad T(X_2) = T_2$$

$$T(X) = (T_2 - T_1)\frac{X}{L} + T_1$$

Conductive Thermal Resistance



Fourier's law

$$Q = -KA\frac{dT}{dX}$$

$$Q = KA\frac{T_1 - T_2}{L}$$

Conductive thermal resistance

$$\Delta T = RQ$$

$$R = \frac{L}{KA}$$

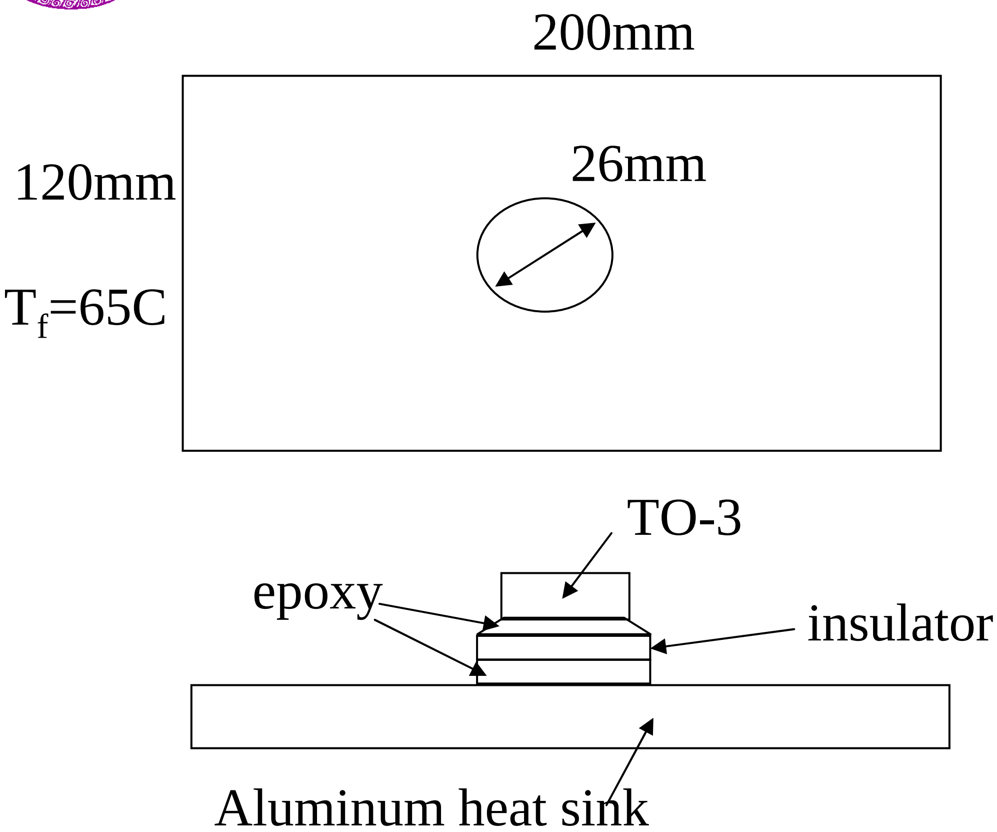
R: Thermal resistance (C/W)
L: Length of heat transfer path (m)
K: Thermal conductivity (W/mC)
A: Cross-sectional area (m^2)

Thermal Conductivity

- Thermal conductivity
  - Unit: W/mC

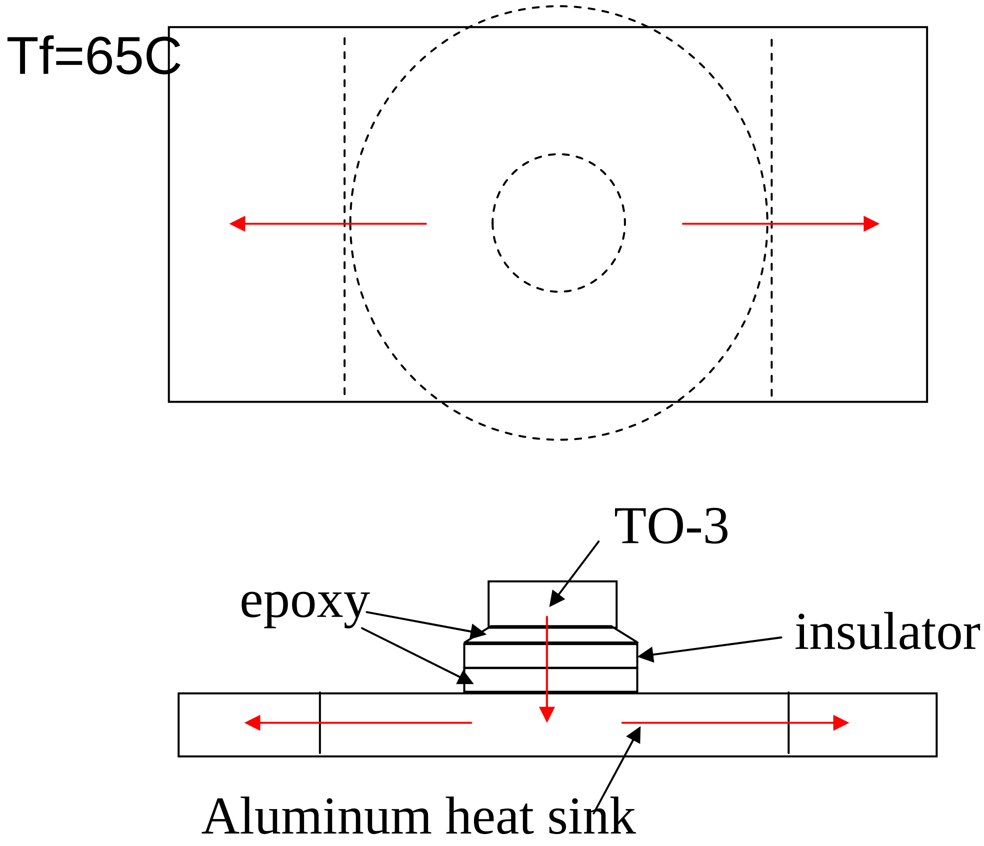
Material	Thermal conductivity (W/mC)
Si	85~147
GaAs	58.0
Air	0.02624
EME-6300H	0.67
Alloy 42	15.9
C7025	170.3
KLF-125	151.2
Al 6061	155.0
63Sn/37Pb	50.0
Cu	386
BT	0.17
Al2O3(96%)	25.9

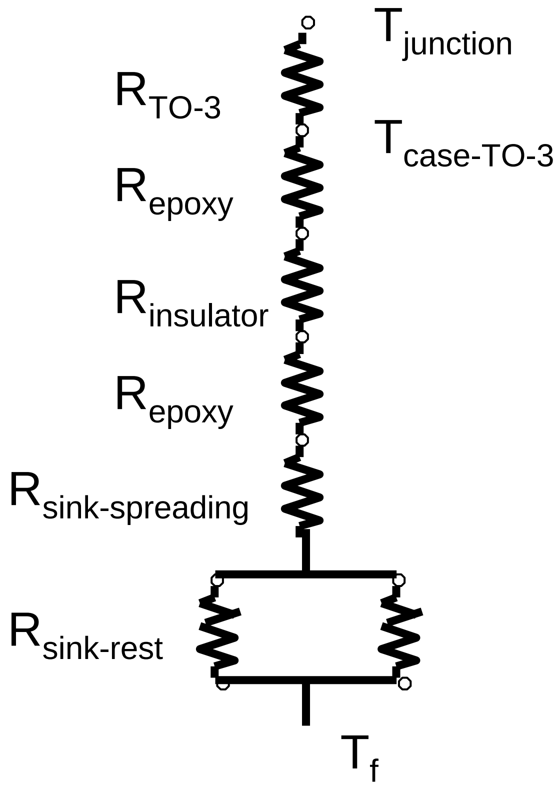
Example: Thermal Analysis of TO-3



- TO-3: Rjc=1.52 C/W
- Epoxy
  - –thickness=0.025mm
  - –K=0.0004 W/mmC
- Insulator
  - –thickness=1.5mm
  - –K=0.0276 W/mm C
- Aluminum heat sink
  - –thickness=10mm
  - –K=0.2165 W/mm C
- Temperature of the farthest edge=65 C
- Tj=? @ Q=55 W

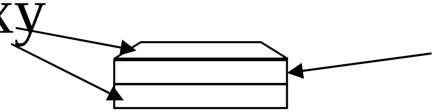
A Simple Thermal Network Model





A Simple Thermal Network Model (cont.)

- Determine the temperature gradient from TO-3 case to the heat sink

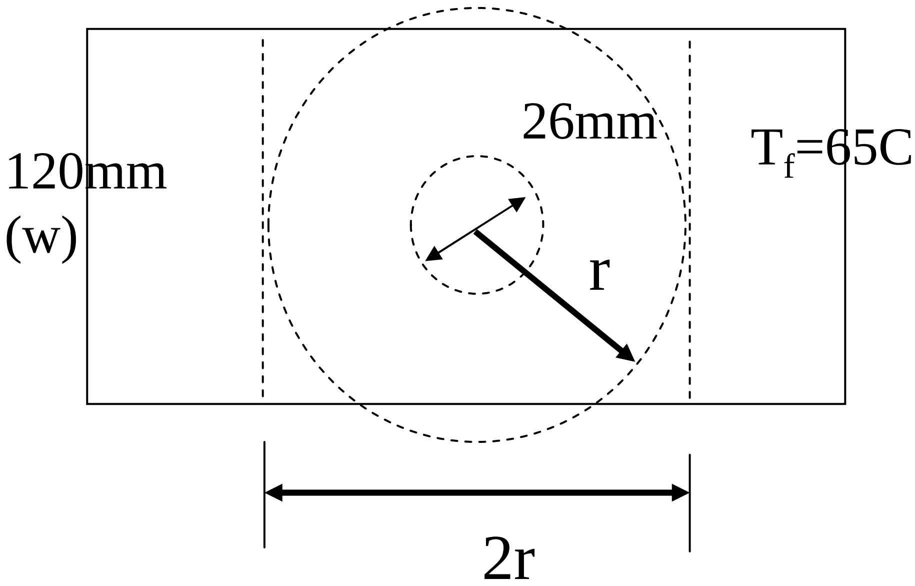


$$\Delta T_m = QxR_m = 55\left(\left(\frac{1.5}{0.0276\pi\left(\frac{26}{2}\right)^2}\right) + \left(\frac{2(0.025)}{0.0004\pi\left(\frac{26}{2}\right)^2}\right)\right) = 18.6C$$

A Simple Thermal Network Model (cont.)

- Determine the temperature gradient from TO-3 mounting area through the heat sink base to the farest edge

120 mm >> 26 mm !

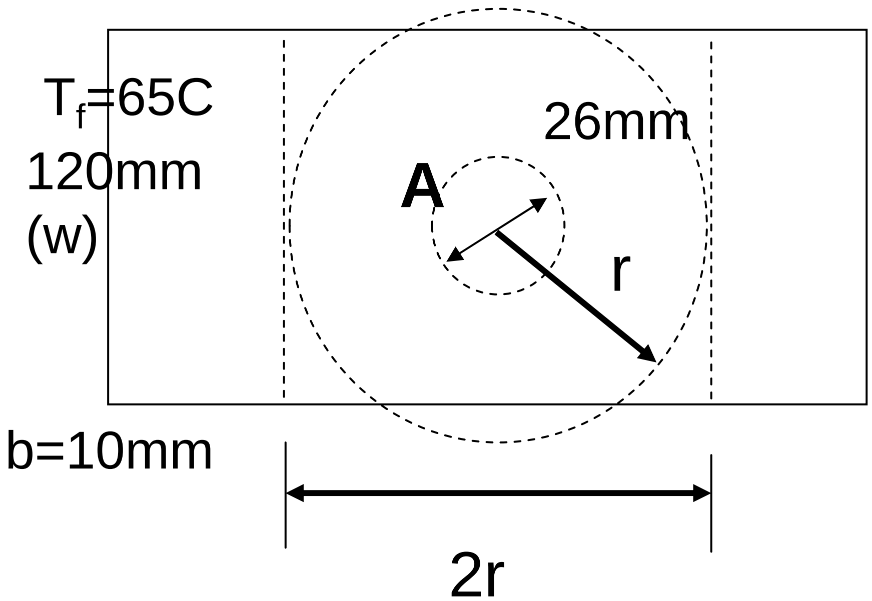


$$2wr = \pi r^2$$

$$r = \frac{2w}{\pi} = \frac{2\text{x}120}{\pi}$$

$$= 76.5\text{mm}$$

A Simple Thermal Network Model (cont.)



$$\Delta T_{AB} = Q\left(\frac{1}{2\pi K_{HS} b}\ln\left(\frac{d_o}{d_i}\right)\right) + \frac{Q}{2}\left(\frac{L}{K_{HS} wb}\right)$$

$$= 55\left(\frac{1}{2\pi X0.2165X10}\ln\left(\frac{76.5X2}{26}\right)\right) +$$

$$\frac{55}{2}\left(\frac{(200-2X76.2)/2}{0.2165X120X10}\right)$$

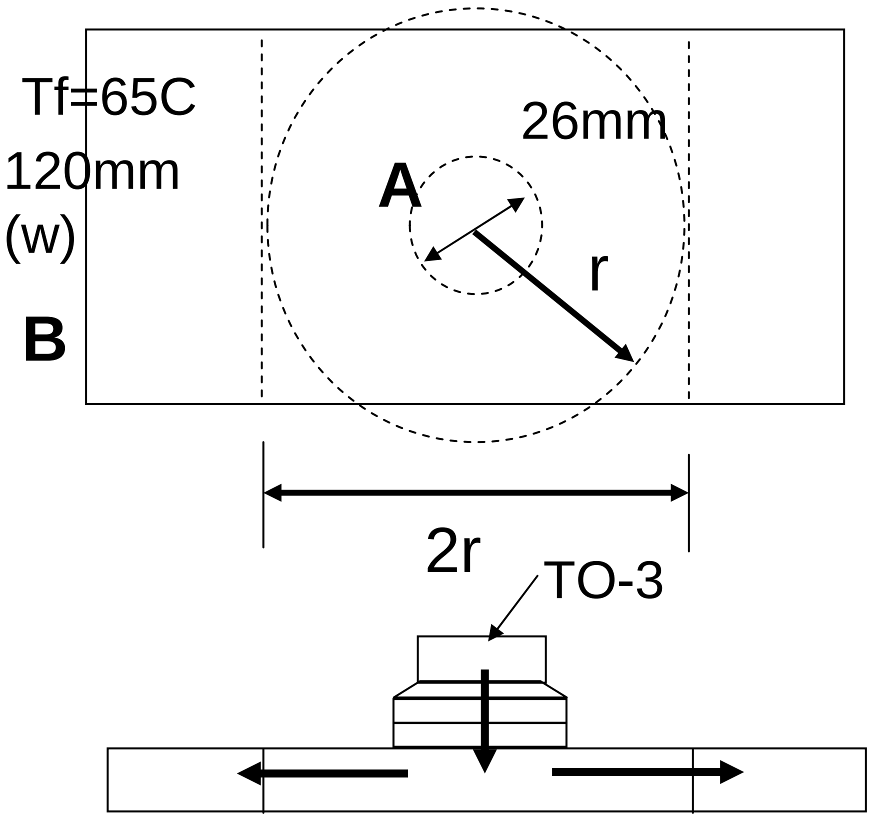
$$= 9.7C$$

r=76.5mm

$$R = \frac{1}{2\pi Kb}\ln\left(\frac{D_o}{D_i}\right)$$

Di : diameter of the inner cylinder
Do : diameter of the outer cylinder
K : thermal conductivity of the cylinder
b: thickness (length) of the cylinder

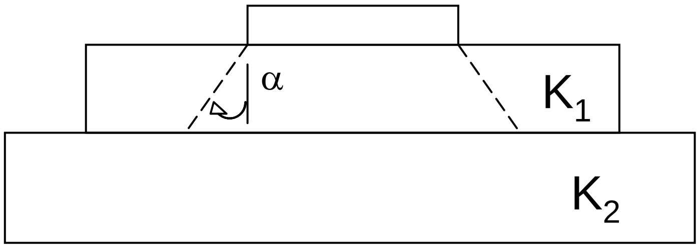
A Simple Thermal Network Model (cont.)

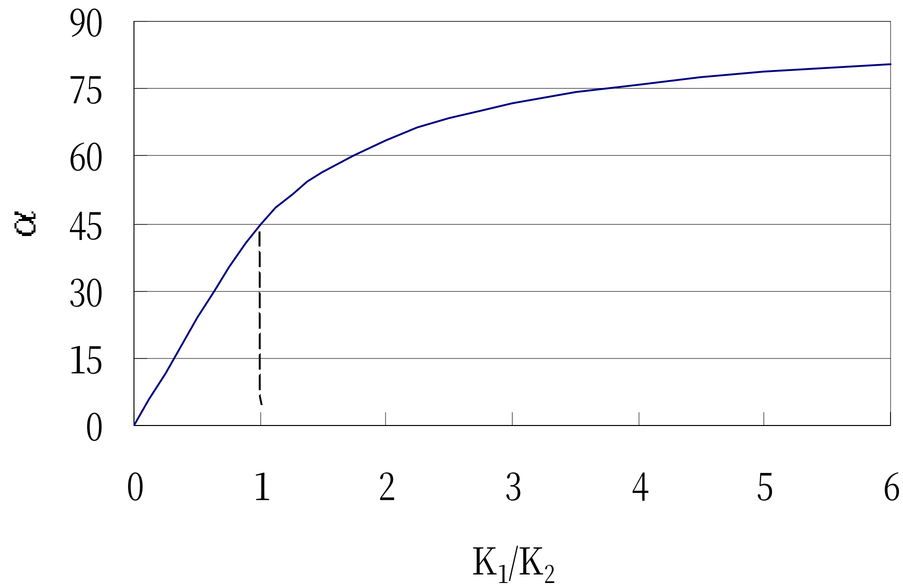


$$T_j = T_f + \Delta T_{AB} + \Delta T_m + \Delta T_{TO}$$
$$= 65 + 9.7 + 18.7 + 55X1.52$$
$$= 177C$$

Heat Spreading

- Model of heat spreading





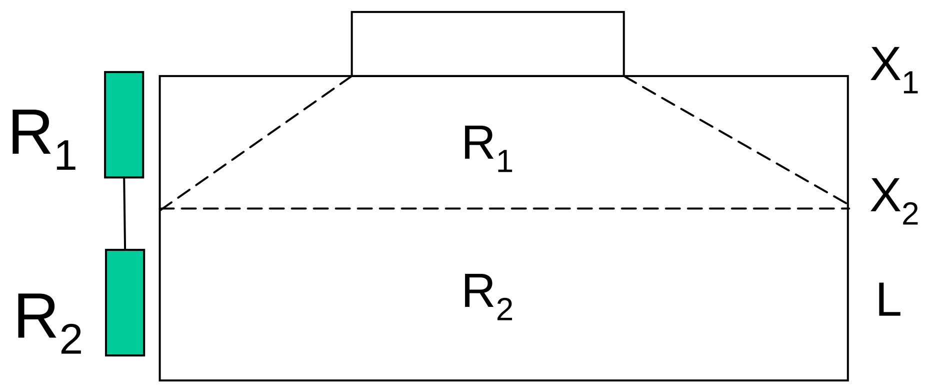
- Model 1

$$\alpha = \tan^{-1}\left(\frac{K_1}{K_2}\right)$$

- Model 2

$$\alpha = 45^{o}$$

Heat Spreading

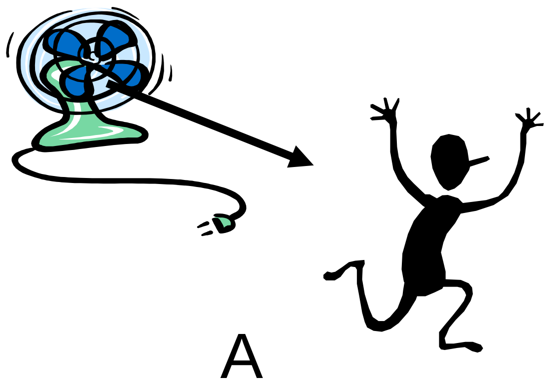


$$R_1 = \int_{X_1}^{X_2} \frac{dX}{kA(x)}$$

$$R_2 = \frac{L}{KA}$$

$$R = R_1 + R_2$$

Convective Thermal Resistance



- Newton's cooling law

$$Q = hA(T_w - T_o)$$

Q Heat flow (W)
A Area (m^2)
T_w Wall temperature
T_o Fluid temperature
h Heat transfer coefficient (W/m^2C)

- Convective thermal resistance

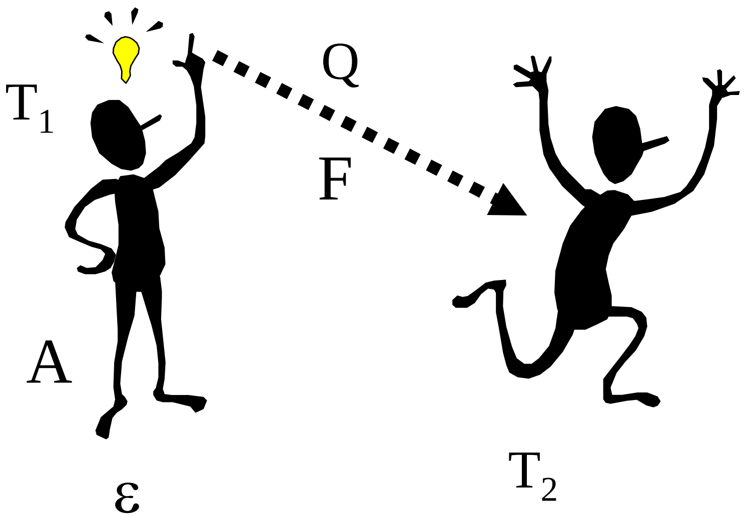
$$R = \frac{1}{hA}$$

Heat Transfer Coefficient

- Heat transfer coefficient is a characteristic of flow field, not a fluid property!
- DO *NOT* COPY ANY EQUATION INTO YOUR MODEL EXCEPT YOU HAD VERIFIED IT BY EXPERIMENTAL WORKS!
- EACH PROBLEM HAS ITS UNIQUE HEAT TRANSFER COEFFICIENT!
- *WHAT SHOULD WE DO?*

Radiation Heat Transfer

- Energy is transferred by electromagnetic wave



$$Q = \varepsilon\sigma F A(T_1^4 - T_2^4)$$

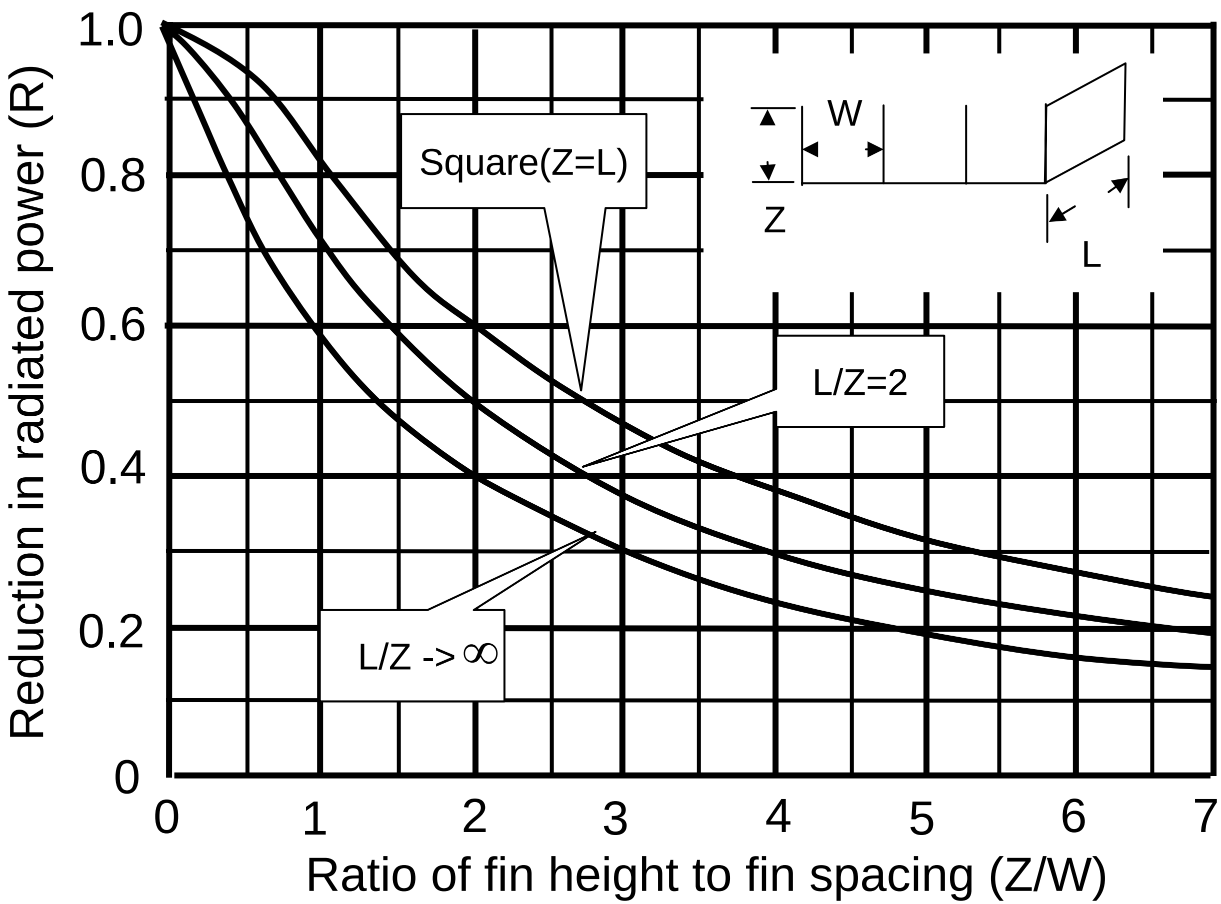
$$R = \frac{1}{hA}$$

$$h = \varepsilon\sigma F(T_1^2 + T_2^2)(T_1 + T_2)$$

Surface	Emmissivity
Commercial Aluminum (polished)	0.05
Anodized Aluminum	0.80
Aluminum	0.27~0.67
Commercial Copper (Polished)	0.07
Oxidized Copper	0.70
Stainless Steel (Polished)	0.17
Stainless Steel (With heavy oxide)	0.85
Oil Paints (Any color)	0.92
Molding Compound	0.8 ~ 0.85

F: View Factor
T: Temperature (K)
ε : Emissivity
σ: Stephan-Boltzman constant
(5.673E-12 W/cm^2K^4)

Reduction of Heat Transfer Area (View Factor)



$$Q = \varepsilon\sigma FA(T_1^4 - T_2^4)$$
$$= \varepsilon\sigma S_r(T_1^4 - T_2^4)$$

- Sr Effective radiating area of the subject surface, taking into account shielding effects

Misunderstanding

- False
  - Radiation is only significant in very high temperature.
- True
  - Co-existing for natural convection and radiation
  - Radiation almost occupies 1/3 !
  - Equivalent heat transfer coefficient

    $h=h_c+h_r$

    h_c: heat transfer coefficient from natural convection

    h_r: heat transfer coefficient from radiation

Analogy of Several Physical Theories

Heat Transfer

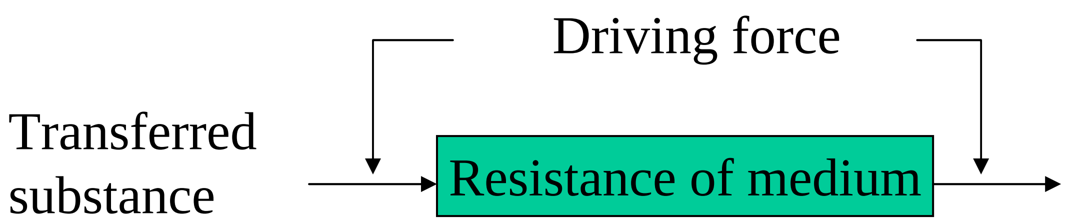
- Heat flow Q (W)
- Temperature difference ΔT (C)
- Thermal resistance R (C/W)
- ΔT=RQ
- Fourier law

Electricity

- Current I (Amp)
- Voltage drop ΔV (Volt)
- Electrical desistance R (Ω)
- ΔV=RI
- Ohm’s law

Force

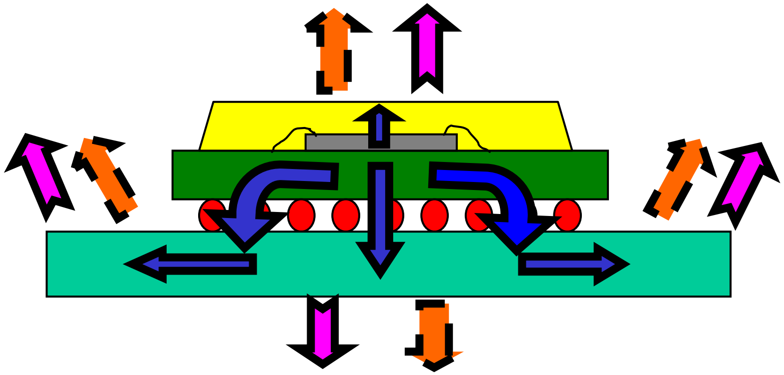
- Displacement X (m)
- Force F (kg)
- Stiffness K (m/kg)
- F=KX
- Hook’s law



Summary

- Conduction $R = \frac{L}{KA}$
- Convection $R = \frac{1}{hA}$
- Radiation $R = \frac{1}{hA}$

$$h = \varepsilon\sigma F(T_1^2 + T_2^2)(T_1 + T_2)$$



Numerical Analysis of Electronic Cooling - Thermal Network Method

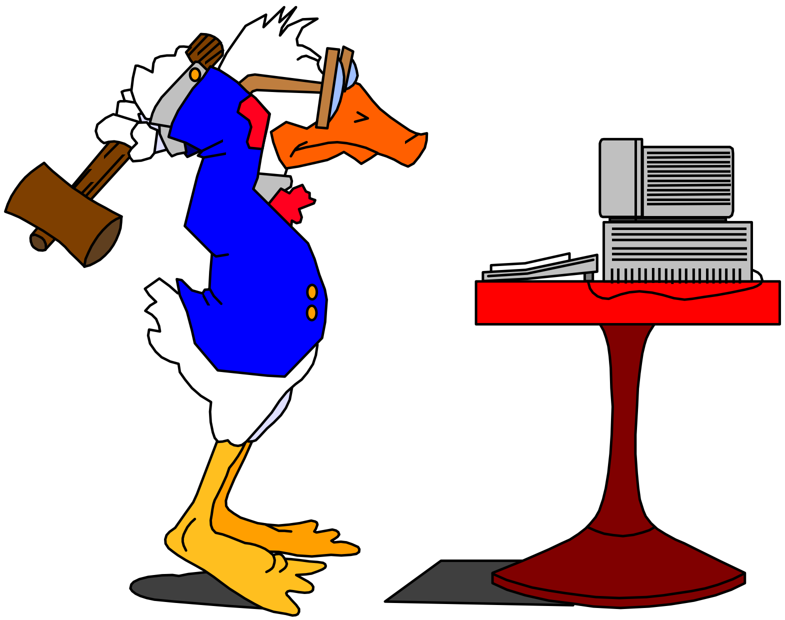
Numerical Simulation of Electronic Cooling

- Objective
  - To understand thermal performance of IC package: thermal resistance
  - To obtain the trends of thermal performance improvement
- What we want to have
  - Temperature distribution
  - Thermal resistance
  - Heat transfer distribution

Numerical Software for Electronic Cooling

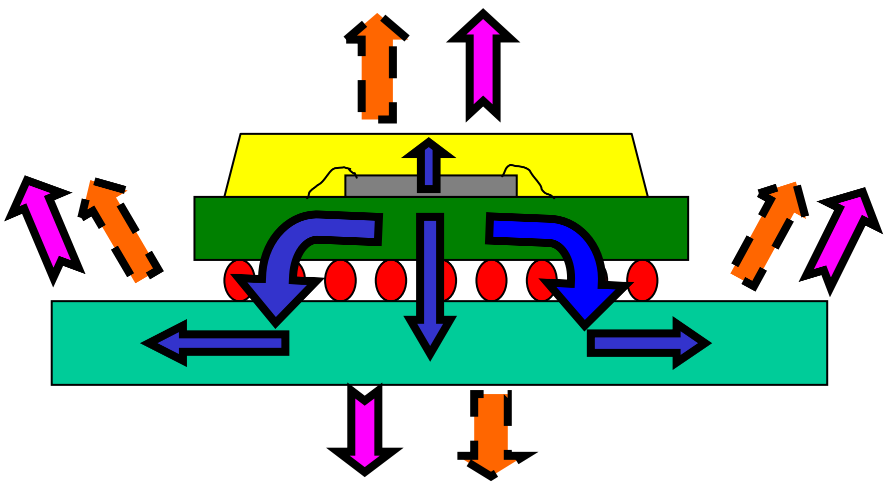
- ANSYS:General Purpose, FEM
- FloTherm :Specific purpose from system to component level), FVM
- ThermoPKG for Windows NT & 95: Specific purpose for component level developed by ERSO/ITRI, FEM
- Others

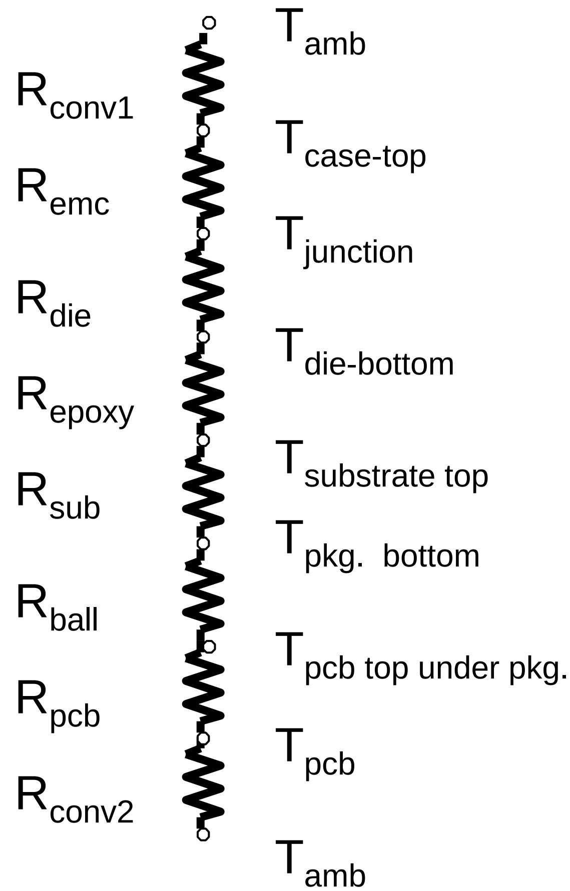
Numerical Simulation Methods



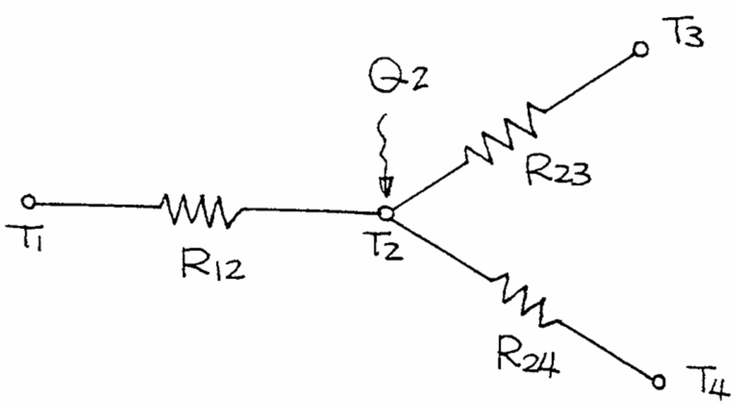
- Thermal network method
  - From thermal-electrical analogy to obtain algebraic equation
- Finite element method
  - From energy integral to obtain algebraic equation
- Finite difference method
  - From difference equation to obtain algebraic equation

Thermal Network Method





Basic Theory of Thermal Network Method



For Point 2

$$Q_{in} = Q_{out}$$

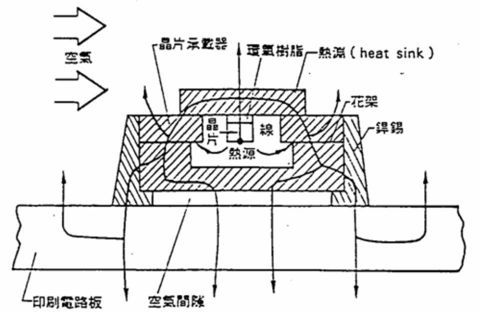
$$\frac{T_1 - T_2}{R_{12}} + Q_2 = \frac{T_2 - T_3}{R_{23}} + \frac{T_2 - T_4}{R_{24}}$$

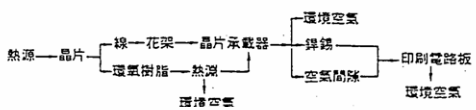
$$\left(\frac{1}{R_{12}} + \frac{1}{R_{23}} + \frac{1}{R_{24}}\right) T_2 = \frac{T_1}{R_{12}} + \frac{T_3}{R_{23}} + \frac{T_4}{R_{24}} + Q_2$$

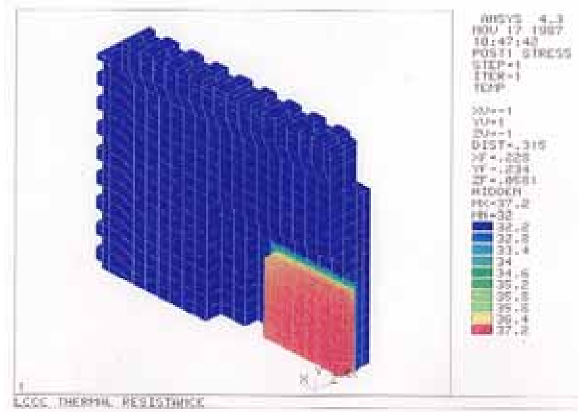
$$T_j = \frac{\sum_{i \neq j} \frac{1}{R_{ij}} T_i + Q_j}{\sum_{i \neq j} \frac{1}{R_{ij}}}$$

Example of Thermal Network Method

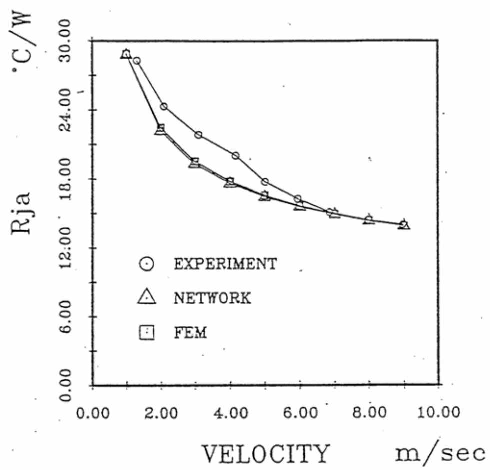
•68 PAD LCCC (Leadless Ceramic Chip Carrier)

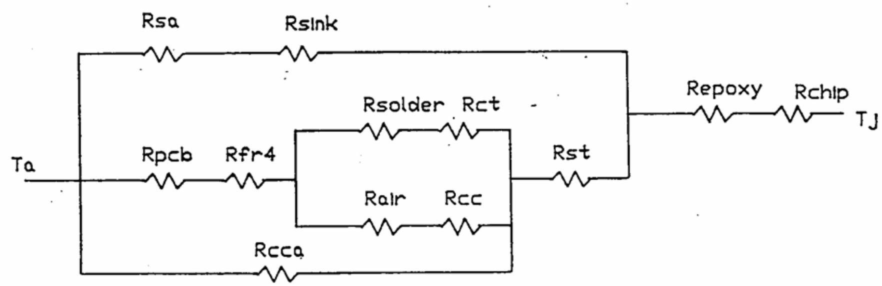






FEM: Nodes:4765; Elements:3453

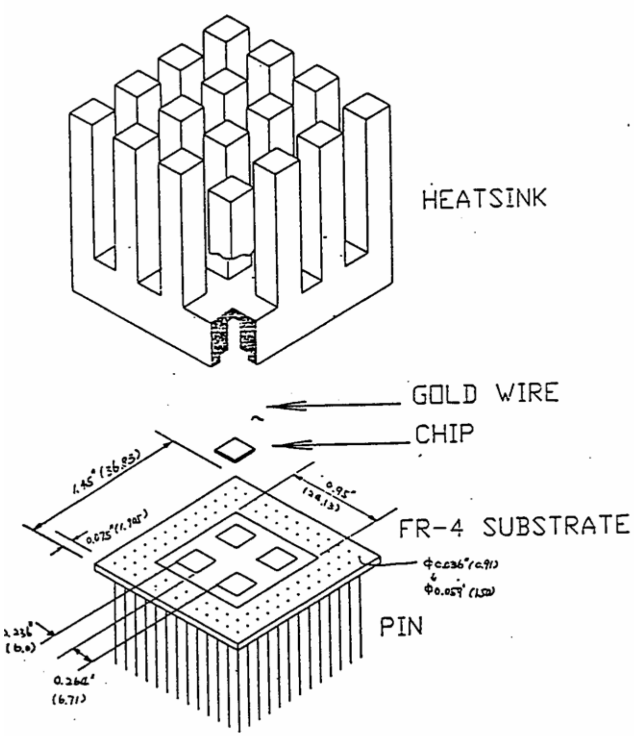


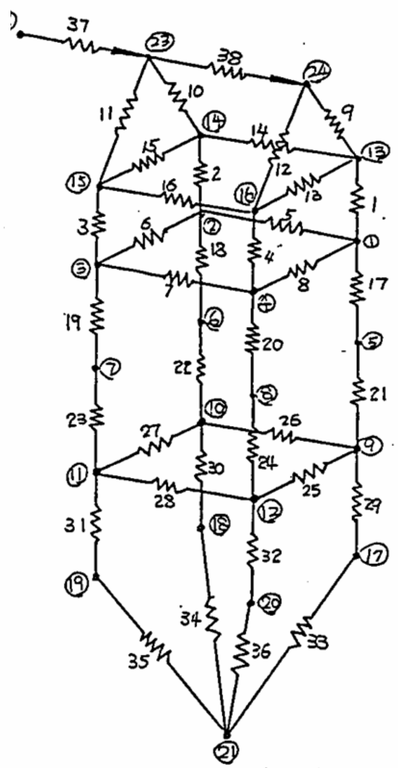


Thermal Network Method
(Nodes: 10; Elements: 12)

Example of Thermal Network Method

- Four Chip Module Chip Module





1~38 : Element number

(1) ~ (24) : Node number

Natural convection case:
connect elements
9,10,11,12 to node 22,
no elements 37,38 and
nodes 23,24

Example of Thermal Network Method

Forced Convection Thermal Resistance Unit：C/W

Velocity (m/sec)	Chip1		Chip 2		Chip 3		Chip 4		Case Temp.	
	Exp.	Net.	Exp.	Net.	Exp.	Net.	Exp.	Net.	Exp.	Net.
3.82	38.77	36.49	20.80	21.98	20.65	21.59	20.86	21.98	20.37	21.37

Note：Chip 1 (0.98W)；Ambient Temperature 18.52C

Forced Convection Thermal Resistance Unit：C/W

Velocity (m/sec)	Chip 1		Chip 2		Chip 3		Chip 4		Case Temp.	
	Exp.	Net.	Exp.	Net.	Exp.	Net.	Exp.	Net.	Exp.	Net.
6.96	41.75	41.89	44.81	40.27	45.88	41.01	47.67	42.44	24.50	23.98

Note：Chip 1 (1.02W)、Chip 2 (0.92W)、Chip 3 (0.97W)、Chip 4 (1.07W)
Ambient Temperature 19.62C

Natural Convection Thermal Resistance Unit：C/W

Chip 1		Chip 2		Chip 3		Chip 4		Case Temp.	
Exp.	Net.	Exp.	Net.	Exp.	Net.	Exp.	Net.	Exp.	Net.
70.0	70.34	67.5	69.01	72.1	69.75	70.7	70.58	55.2	58.45

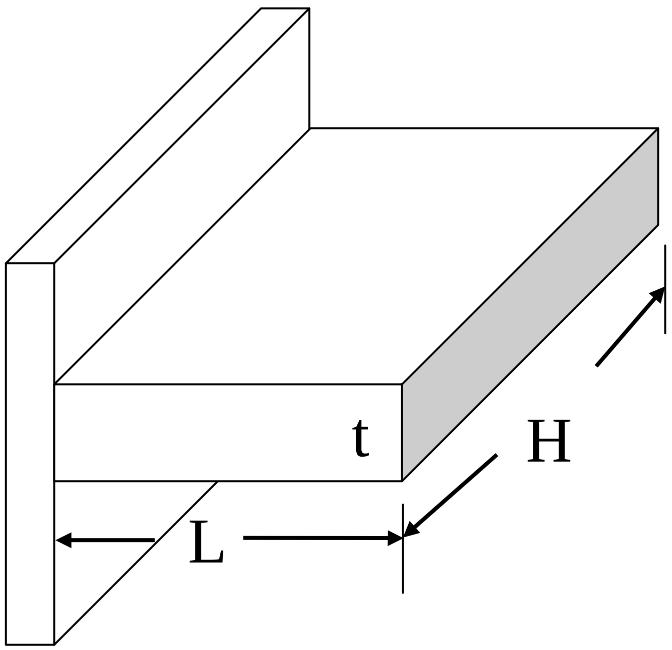
Note：Chip 1 (0.71W)、Chip 2 (0.62W)、Chip 3 (0.67W)、
Chip 4 (0.73W)；Ambient Temperature 18.7C

Summary

- Keys to Success For Thermal Network Method
  - 遠觀其勢，近取其值
  - Identify correctly the major heat transfer paths
  - Identify correctly the major thermal resistances
  - Engineer’s judgment
  - Key: heat spreading effect
  - It’s an art!
  - Again and again

Thermal Analysis of Heat Sink

Fin Efficiency (E)



$$E = \frac{\text{actual heat transfer}}{\text{heat transfer based on base temperature}}$$

$$= \frac{Q_t}{Q} = \frac{h_e A_s (T_s - T_a)}{h A_s (T_s - T_a)}$$

$$= \tanh\sqrt{R_k / R_s} \Big/ \sqrt{R_k / R_s}$$

where

$$R_k = \frac{L}{kA_k} = \frac{L}{kHt} \qquad R_s = \frac{1}{hA_s} = \frac{1}{hHL}$$

h: average heat transfer coefficient

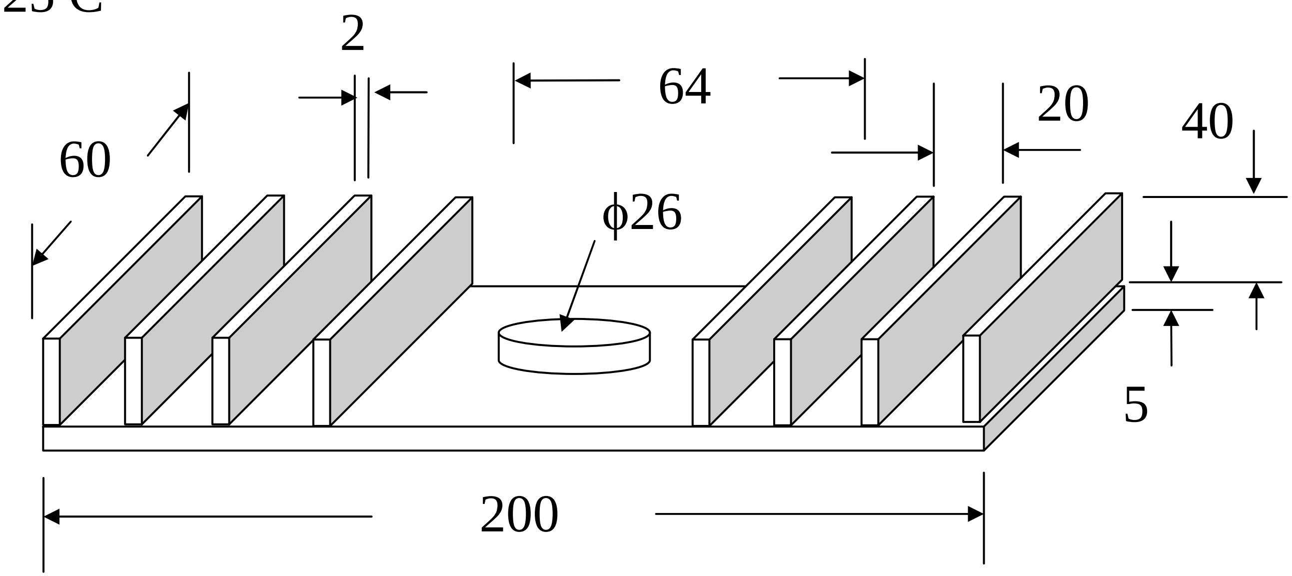
h_e: effective heat transfer coefficient

T_s: fin base temperature

T_a: ambient temperature

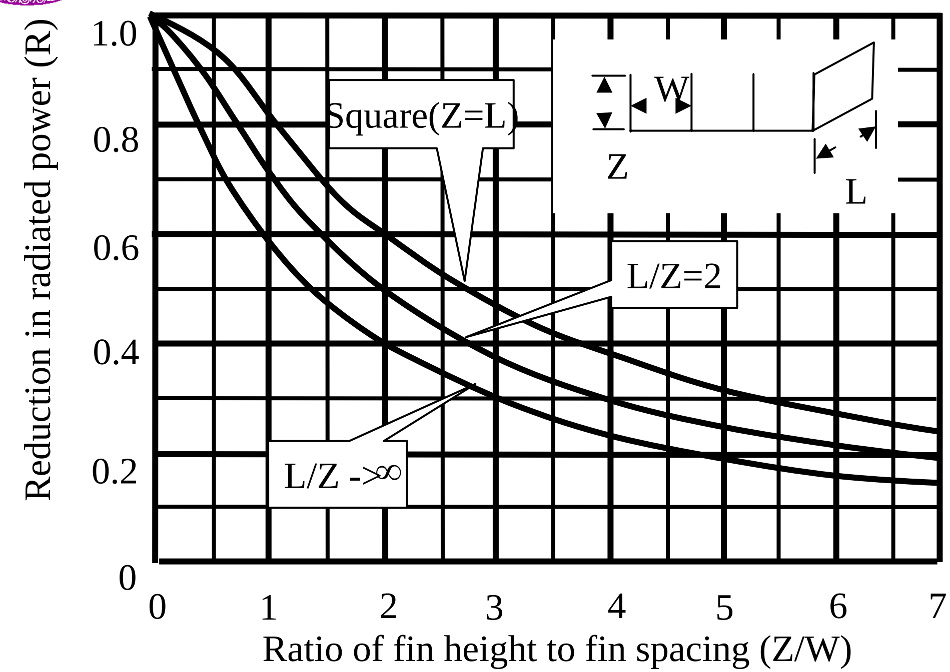
Example

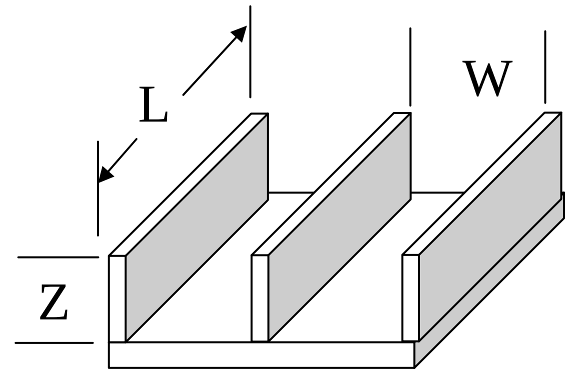
- TO-3: junction - to - heat sink surface temperature difference = 60.3 C
- Power dissipation = 25 W
- Anodized heat sink
- Natural Convection
- Tj = ? C @ Ta=25 C



Unit: mm

Effective Radiation Area

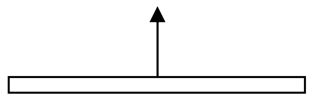




Radiation Area $S_r = 327cm^2$

Number of Surface	L/Z	Z/W	Surface Area (cm^2)	f	Effective Surface (cm^2)
2	-	-	2(4.5*6)=54	-	54
6	1.5	2	6(4+4+2)*6=360	0.55	198
1	1.5	0.63	(6.4+4+4)*6=86.4	0.87	75
			500		327

Calculation of Natural Convection



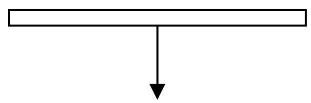
A_1=20*6 = 120 cm^2

$h_1=0.0022(\Delta T/P)^{0.25}$ W/in^2C

P=20*6/2(20+6)=2.308cm=0.91 in

$h_1=2.2533*10^{-3}*\Delta T^{0.25}$ W/in^2C

$=3.493*10^{-4}*\Delta T^{0.25}$ W/cm^2C



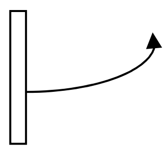
A_2=20*6 = 120 cm^2

$h_2=0.0011(\Delta T/P)^{0.25}$ W/in^2C

P=20*6/2(20+6)=2.308cm=0.91 in

$h_2=1.1262*10^{-3}*\Delta T^{0.25}$ W/in^2C

$=1.7457*10^{-4}*\Delta T^{0.25}$ W/cm^2C



A_3=2*(4.5*6)+14*(4*6)

=390 cm^2

$h_3=0.0024(\Delta T/P)^{0.25}$ W/in^2C

P=4cm=1.575 in

$h_3=2.142*10^{-3}*\Delta T^{0.25}$ W/in^2C

$=3.320*10^{-4}*\Delta T^{0.25}$ W/cm^2C

Power Dissipation Calculation

- Radiation: Anodized: ε=0.8

$$Q_r = \varepsilon\sigma S_r (T_s'^4 - T_a'^4)$$

$$= 5.673\times10^{-12}\times0.8\times327\times\left[(T_s+273)^4-(25+273)^4\right]$$

$$= 1.484\times10^{-9}\times\left[(T_s+273)^4-298^4\right] \qquad \text{(W)}$$

- Natural Convection

$$Q_c = h_1A_1\Delta T + h_2A_2\Delta T + h_3A_3\Delta T$$

$$= 0.0419\Delta T^{1.25} + 0.0209\Delta T^{1.25} + 0.1295\Delta T^{1.25}$$

$$= 0.1923\Delta T^{1.25} = 0.1923(T_s-25)^{1.25} \qquad \text{(W)}$$

- Total Heat Dissipation $Q = Q_c + Q_r$

Power Dissipation Calculation

- Assume 1/2 - 1/2 heat dissipation

$$\frac{25}{2} = 0.1923(T_s - 25)^{1.25} = 0.1923\Delta T^{1.25}$$

$$\Delta T = [(25/2)/0.1923]^{0.8} = 28.21\,C$$

$$T_s = \Delta T + 25 = 53.21\,C$$

Nonlinear Problem!
Iteration!

- Calculate radiation heat dissipation

$$Q_r = 1.489 \times 10^{-9}\left[(T_s + 273)^4 - 298^4\right]$$
$$= 5.1\,W$$

- Calculate residue heat dissipation

$$Q^* = 25 - 25/2 - 5.1 = 7.4\,W$$

Power Dissipation Calculation

- Assume 2/3 - 1/3 heat dissipation

$$Q_c = 25/2 + 7.4 \times 2/3 = 17.4 \text{ W}$$

$$17.4 = 0.1923(T_s - 25)^{1.25} = 0.1923\Delta T^{1.25}$$

$$\Delta T = 36.81 \text{ C}$$

$$T_s = \Delta T + 25 = 61.81 \text{ C}$$

- Calculate radiation heat dissipation

$$Q_r = 1.489 \times 10^{-9}\left[(T_s + 273)^4 - 298^4\right]$$

$$= 6.94 \text{ W}$$

- Calculate residue heat dissipation

$$Q^* = 25 - 17.4 - 6.94 = 0.66 \text{ W}$$

Power Dissipation Calculation

- Assume 2/3 - 1/3 heat dissipation

$$Q_c = 17.4 + 0.66 \times 2/3 = 17.84 \text{ W}$$

$$17.84 = 0.1923(T_s - 25)^{1.25} = 0.1923\Delta T^{1.25}$$

$$\Delta T = 37.49 \text{ C}$$

$$T_s = \Delta T + 25 = 62.49 \text{ C}$$

- Calculate radiation heat dissipation

$$Q_r = 1.489 \times 10^{-9}\left[(T_s + 273)^4 - 298^4\right]$$

$$= 7.1 \text{ W}$$

- Calculate residue heat dissipation

Convergence!

$$Q^* = 25 - 17.84 - 7.1 = 0.06 \text{ W} \Rightarrow Q_t = 25 - 0.06 = 24.94 \text{ W}$$

Temperature Calculation

- Fin Efficiency

$$E = \tanh\sqrt{R_k/R_s}\Big/\sqrt{R_k/R_s}$$

$$R_k = \frac{4}{2.165\times(0.2\times6)} = 1.54\ C/W$$

$$R_s = \Delta T/Q_t = 37.49/24.94 = 1.50\ C/W \qquad \text{for entire surface}$$

$$R_s = 1.5\times8 = 12\ C/W \qquad \text{for entire surface}$$

$$E = \tanh\sqrt{R_k/R_s}\Big/\sqrt{R_k/R_s} = 0.96 = 96\%$$

$$\Delta T_t = \Delta T/E = 37.49/0.96 = 39.05\ C$$

$$T_j = T_a + \Delta T_t + \Delta T_{js} = 25 + 39.05 + 60.3$$

$$= 124.35\ C$$

Summary

- Co-existing for natural convection and radiation
- Radiation almost occupies 1/3 !
- Equivalent heat transfer coefficient $h=h_c+h_r$ should be used in the calculation
- 1/3-2/3 method is introduced to have the equivalent heat transfer coefficient quickly

Measurement of Thermal Resistance

Standards for Thermal Resistance Measurement

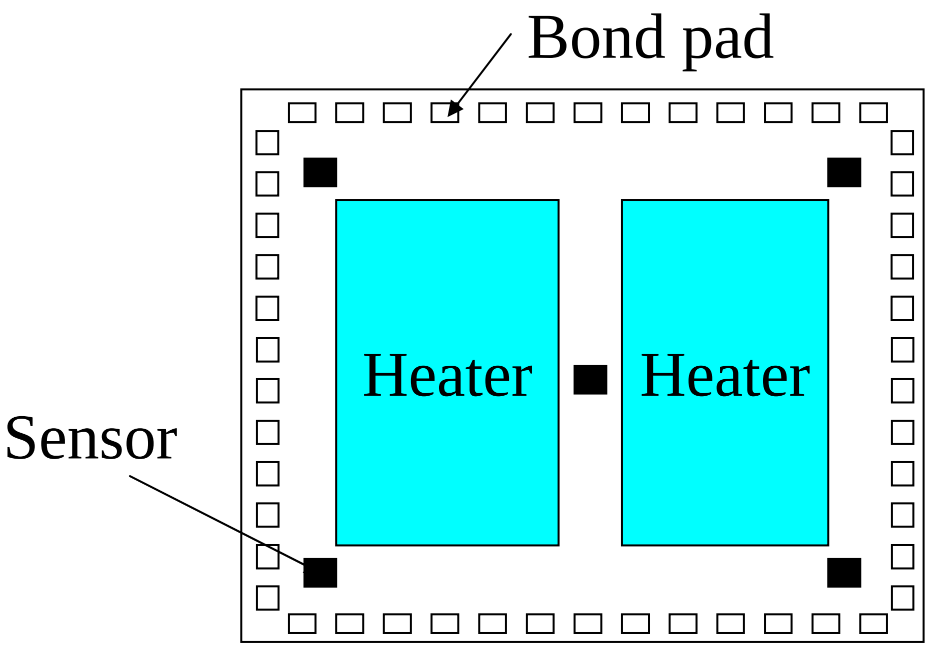
- Major Standards
  - —*MIL-STD-833C-METHOD 1012.1* THERMAL CHARACTERISTICS
  - —*SEMI G38-96* : TEST METHOD FOR STILL- AND FORCED-AIR JUNCTION-TO-AMBIENT THERMAL RESISTANCE MEASUREMENTS OF INTEGRATED CIRCUIT PACKAGES
  - —*SEMI G42-96* : SPECIFICATION FOR THERMAL TEST BOARD STANDARIZATION FOR MEASURING JUNCTION-TO-AMBIENT THERMAL RESISTANCE OF SEMICONDUCTOR PACKAGES
  - —*EIAJ/JEDEC EIA/JESD51-1* : INTEGRATED CIRCUIT THERMAL MEASUREMENT METHOD-ELECTRICAL TEST METHOD (SINGLE SEMICONDUCTOR DEVICE)
  - —*EIAJ/JEDEC EIA/JESD51-2* : INTEGRATED CIRCUIT THERMAL TEST METHOD ENVIRONMENTAL CONDITIONS-NATURAL CONVECTION (STILL AIR)

Equipment Requirements

- Thermocouple: type-T; welded, AWG 30 or above
- Voltage measurement resolution: 0.5 mV
- Temperature measurement system resolution: ±0.5 C
- Volume flow rate: ±10 %
- Wire: AWG 36
- Standard test board: G42-96

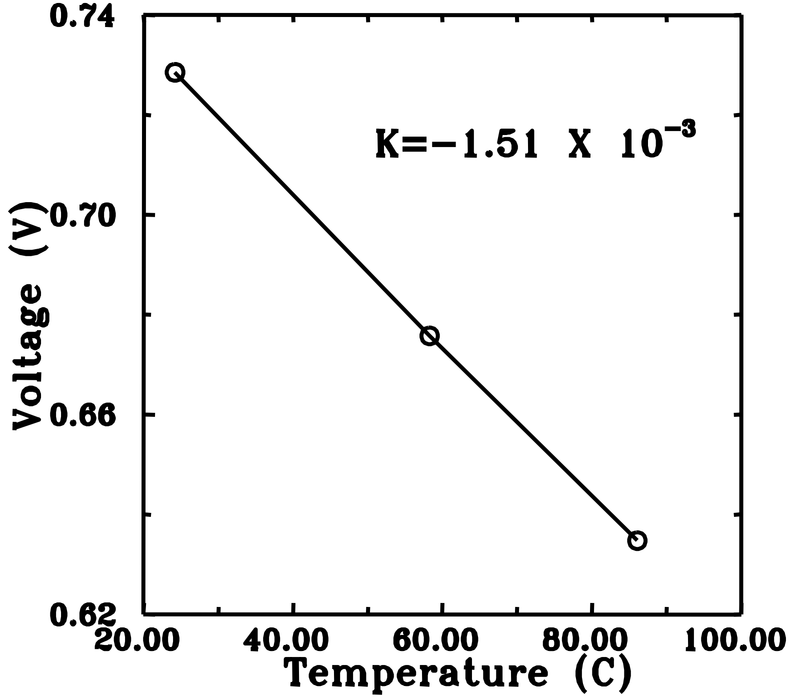
Design of Thermal Chip

- Basic elements:
  - —Diode sensor
  - —Heater



Fundamental Theory

- Temperature sensitive parameter (TSP)

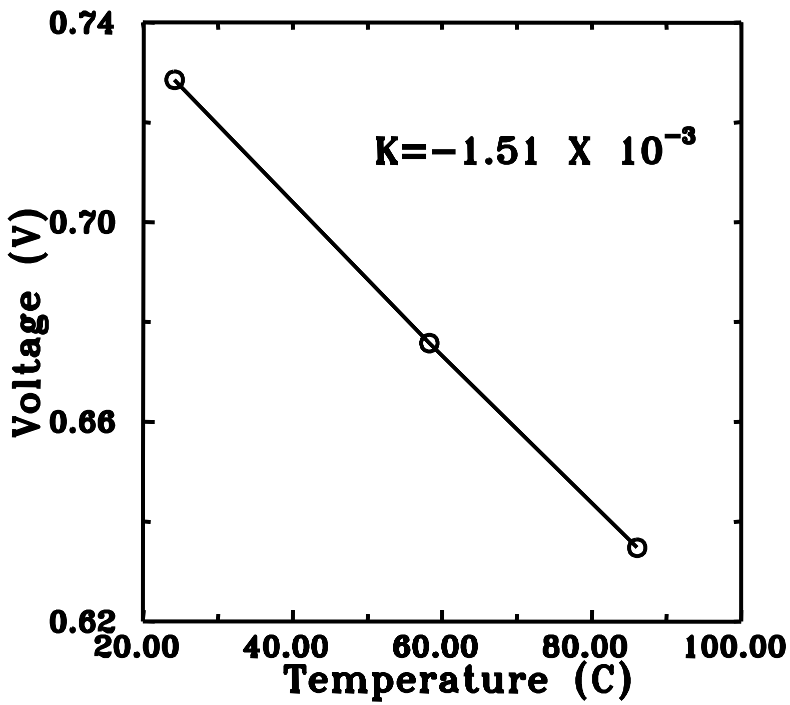


$$K = \frac{\Delta V}{\Delta T}$$

Procedures of Measurement

- Calibration of TSP
  - Objective: To obtain the TSP of sensors
- Measurement under heating
  - Objective: To obtain the packaging thermal resistance
  - Forced convection
  - Natural convection

Calibration of TSP



- TSP calibration
  - HEAT chamber : oven, or fluid bath
  - Measuring current: 0.05~5 mA (1mA)
  - Three points required
  - Calculating TSP

Measurement: Natural Convection

- Objective: to investigate the relationship between thermal resistance and power dissipation
- Enclosure: 1.0 x 1.0 x 1.0 feet
- High reflectance finish: emissivity < 0.1
- $\Delta T > 20$ C
- Room temperature measurement (Ta, Va) 及 heating measurement (Tj, Vj, Pj)

$$T_j = T_a + (V_j - V_a) / K$$

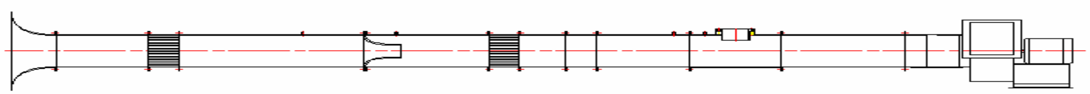
$$R_{ja} = (T_j - T_a) / P_j$$

Measurement: Forced Convection

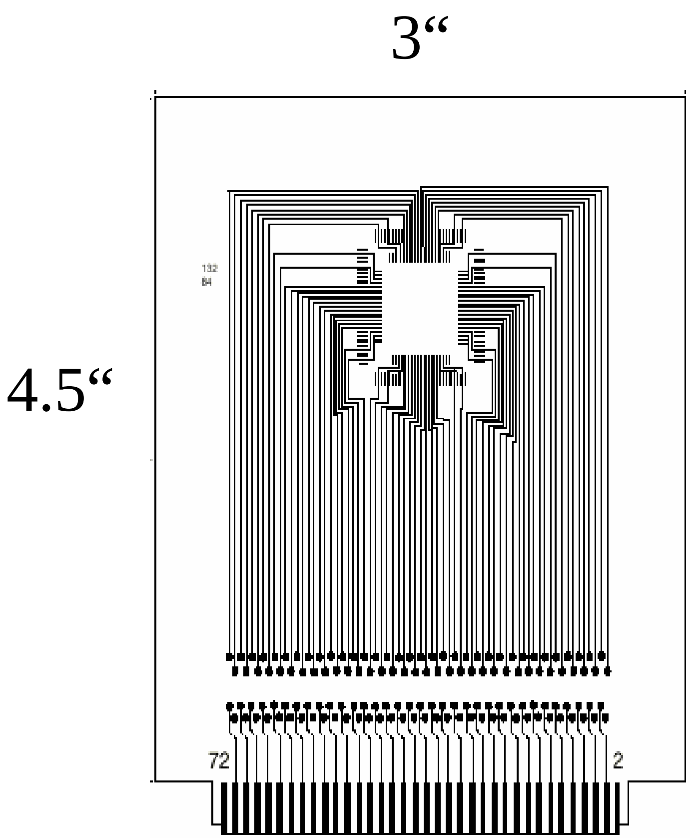
- Objective: To obtain the relationship between thermal resistance and flow velocity
- Wind Tunnel: inner diameter 8 inch
- $\Delta T > 20$ C
- Room temperature measurement (Ta, Va) 及 heating measurement (Tj, Vj, Pj)

$$Tj = Ta + (Vj - Va) / K$$

$$Rja = (Tj - Ta) / Pj$$



SEMI Standard Test Board



- 3 inch x 4.5 inch
- Double / Multi-layer FR-4 board

Summary

- TSP is the most important parameter for thermal resistance measurement of IC packaging
- Standards of thermal characterization are introduced

Thermal Performance of PBGA

Thermal Resistance

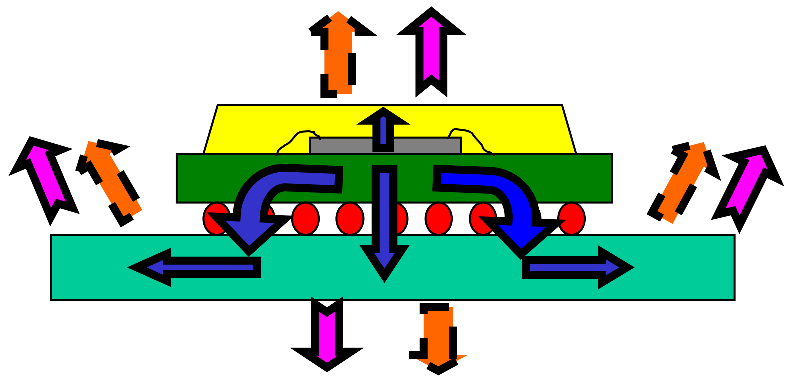
- Total thermal resistance R_{ja} : die junction - to - ambient
- Internal thermal resistance R_{jc} : die junction - to - case
- External thermal resistance R_{ca} : case - to -ambient

$$R_{ja} = R_{jc} + R_{ca}$$

$$R_{ja} = (T_j - T_a)/Q$$

$$R_{jc} = (T_j - T_c)/Q$$

$$R_{ca} = (T_c - T_a)/Q$$



Internal Thermal Resistance

- Major parameters for R_{jc}

—Molding compound

√ Substrate

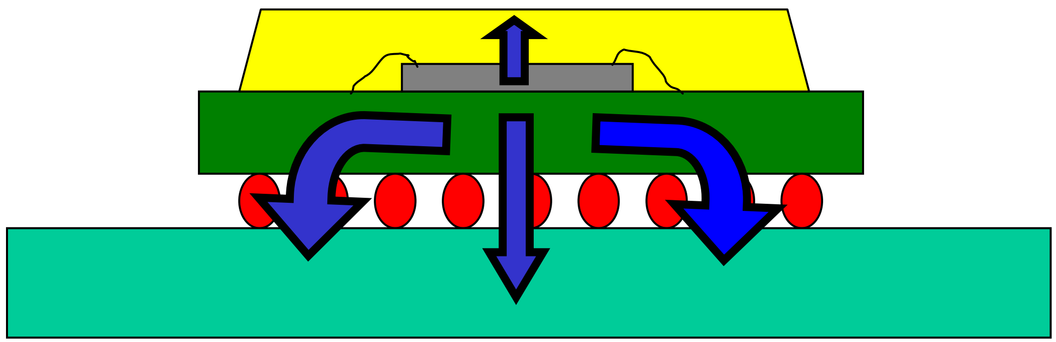
√ Ground plane

—Die size

√ Thermal ball

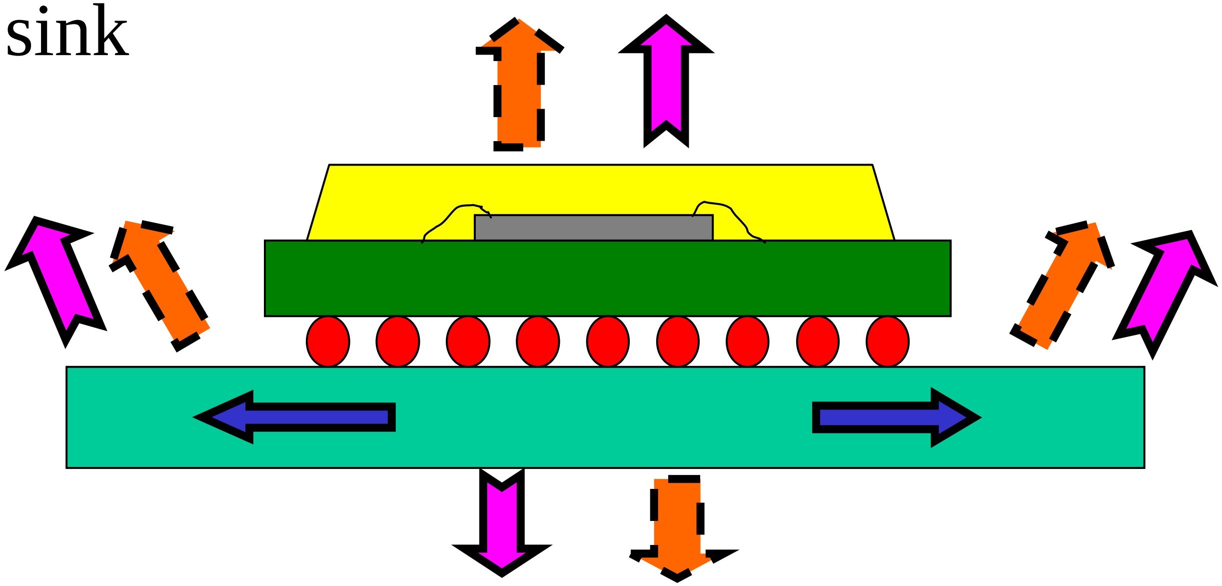
√ Thermal via

√ Heat spreader / heat slug



External Thermal Resistance

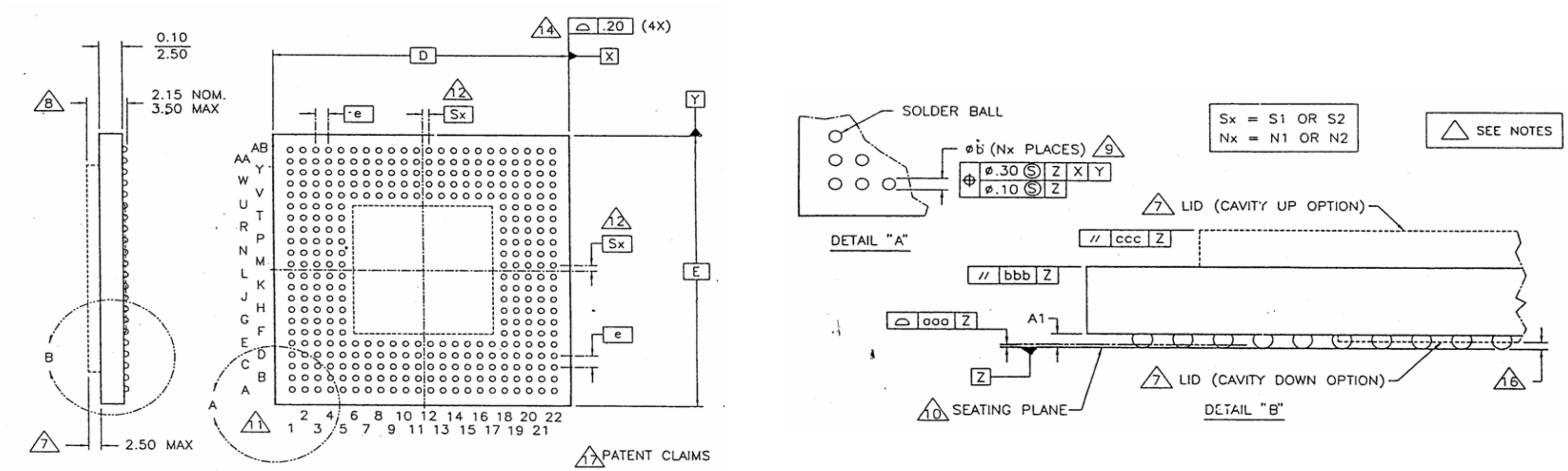
- Major parameters of R_{ca}
  - PCB
  - Air velocity
  - Heat sink



Thermal Analysis of PBGA

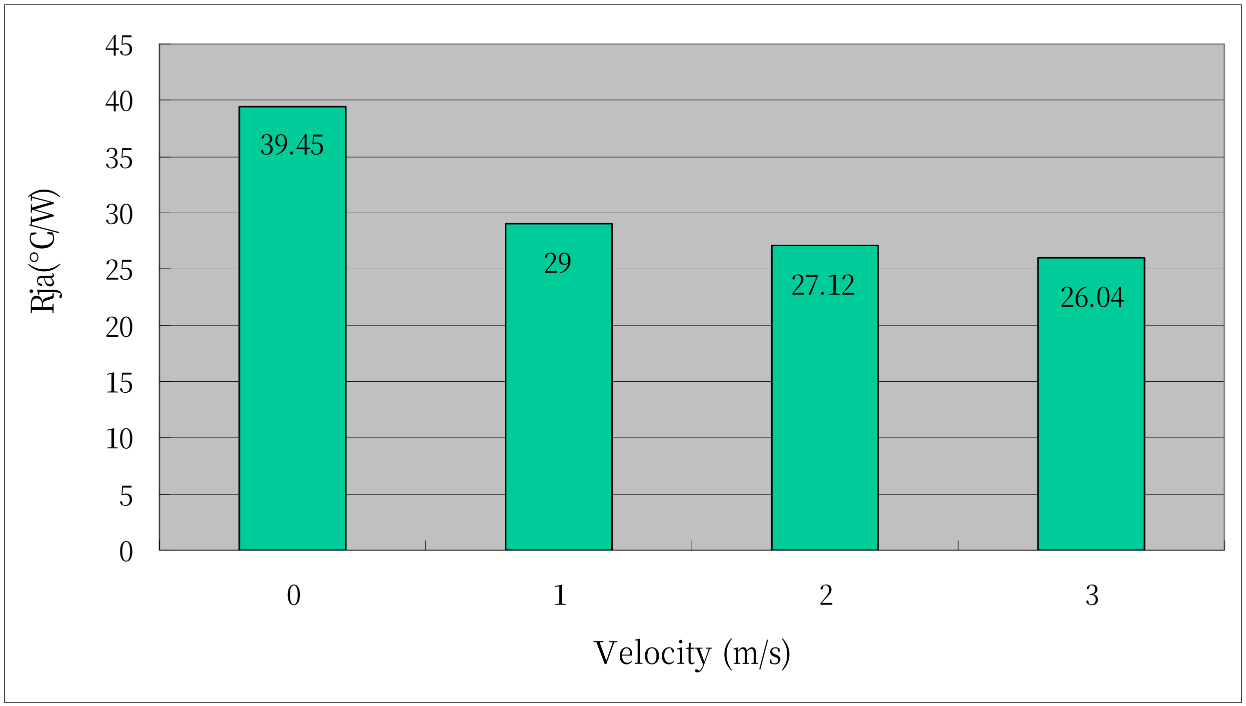
- Example: PBGA352

Base Condition: 2 layers BT substrate, 4 layers PCB, ground plane, 17 thermal vias, no thermal ball, natural convection, 1.5W



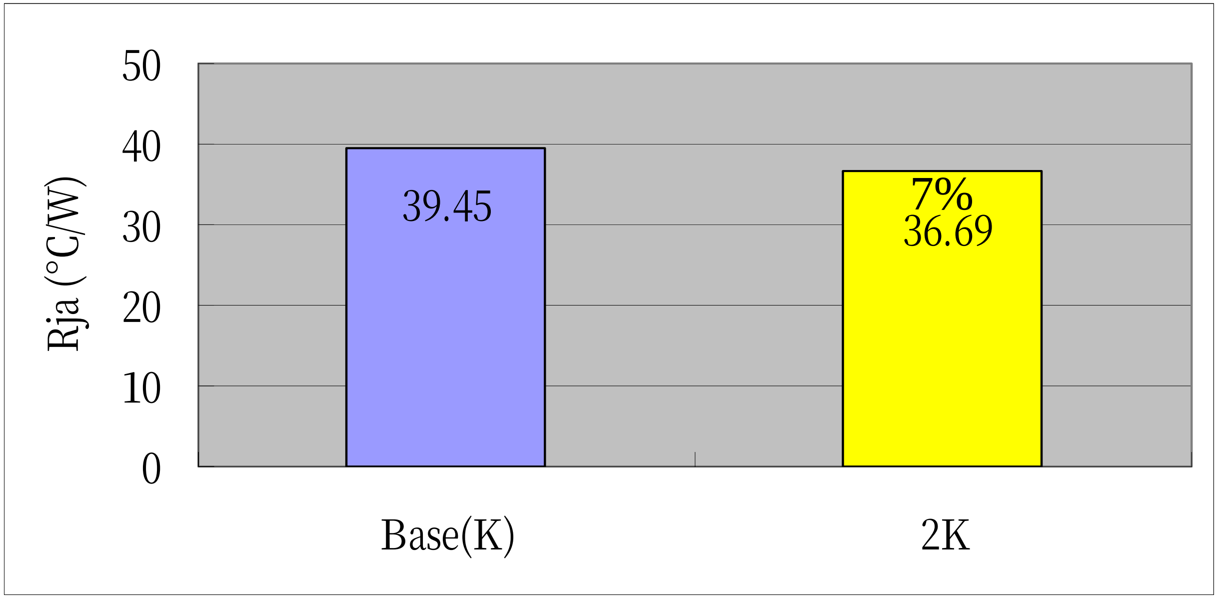
Simulation Tool

- Tool:ThermoPKG for Windows NT & 95 Version 3.0B (developed by ERSO/ITRI)



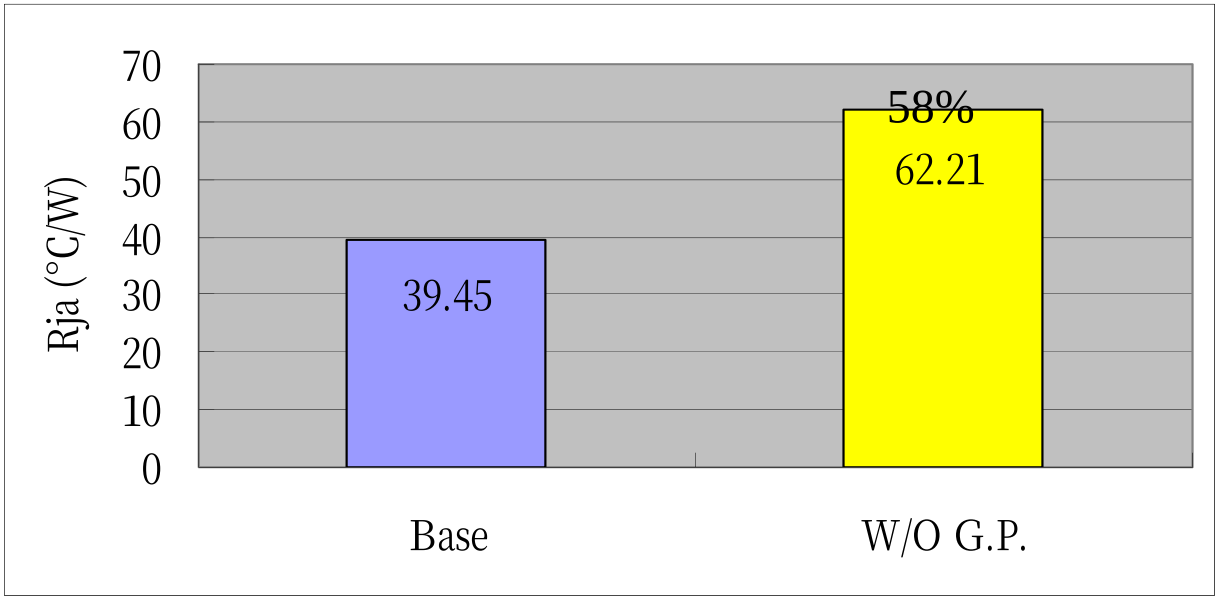
The Effects of Substrate

- Substrate



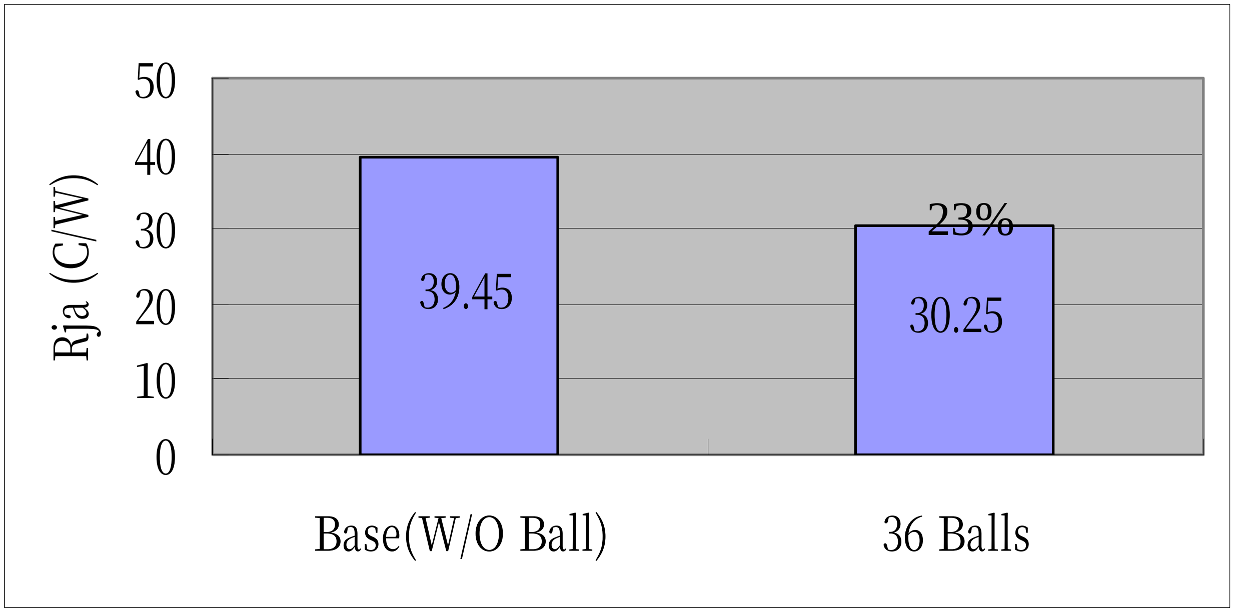
The Effects of Ground Plane

- Ground plane



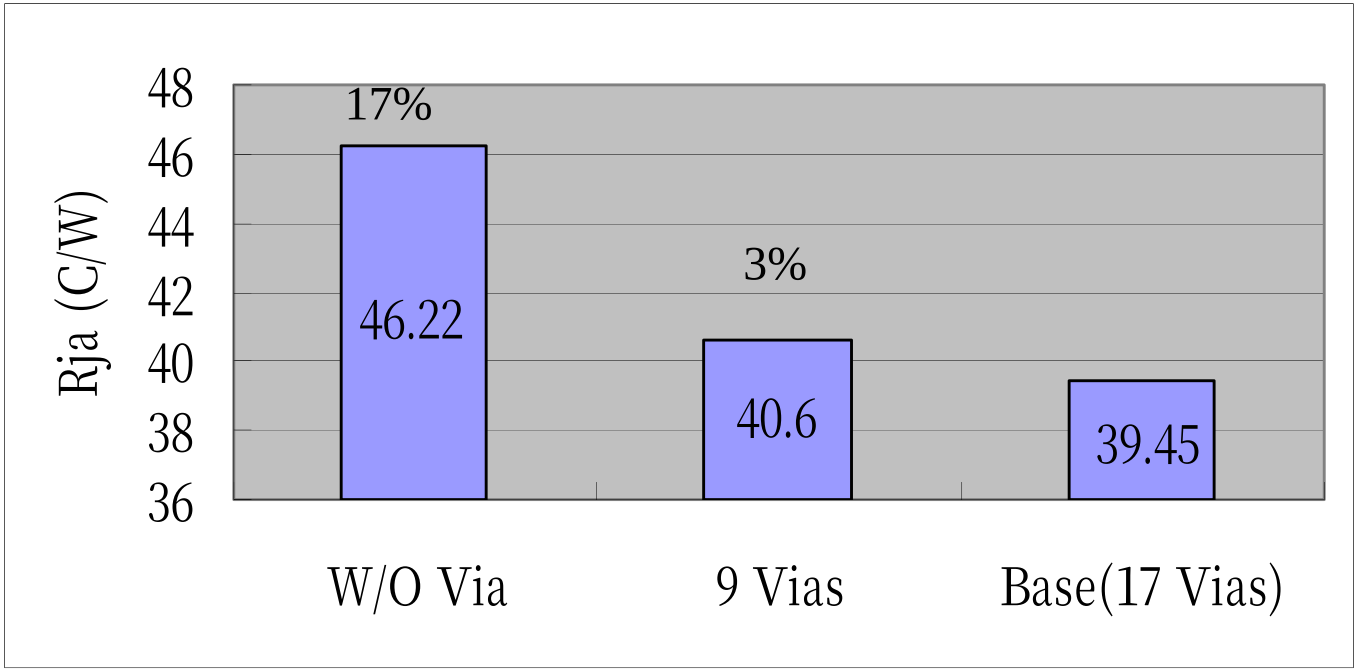
The Effects of Thermal Ball

- Thermal ball



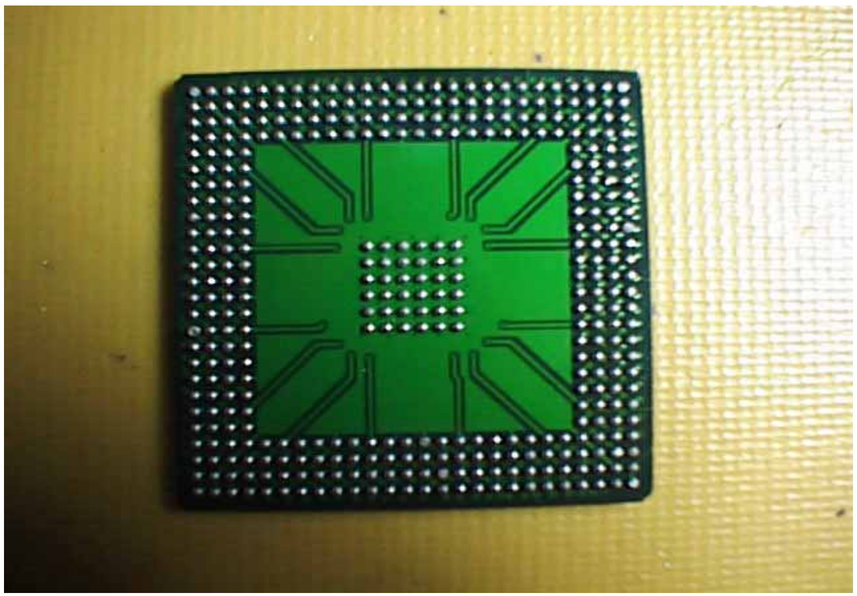
The Effects of Thermal Via

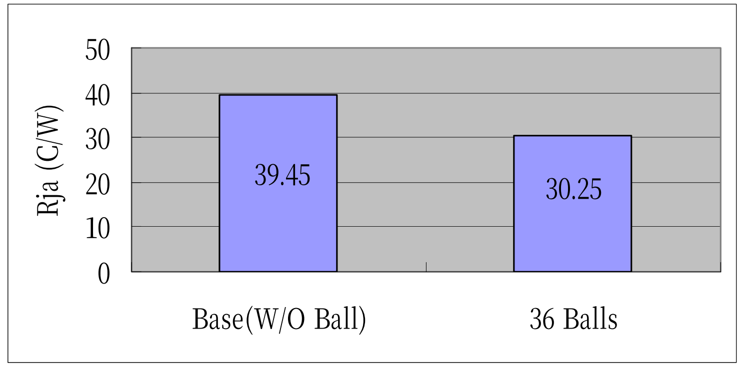
- Thermal via

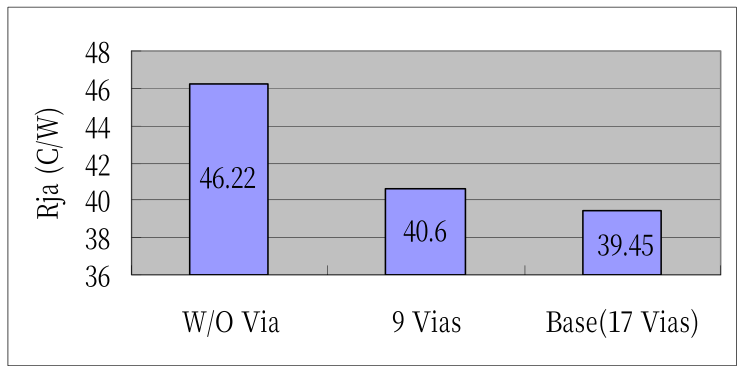


Enhancement of Thermal Performance

- Method 1 : Thermal Ball / Thermal Via
  - Reduce R_{ja} about 35%及15%

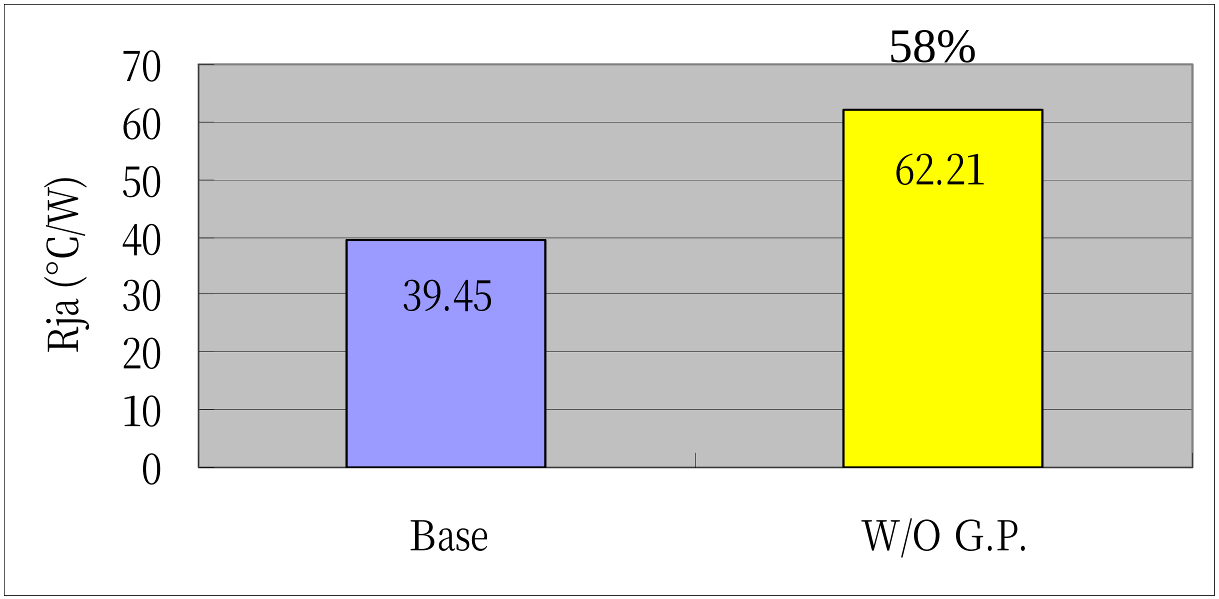






Enhancement of Thermal Performance

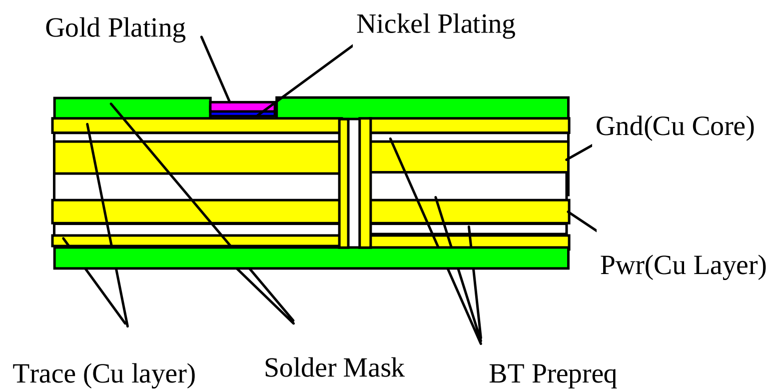
- Method 2: Ground Plane



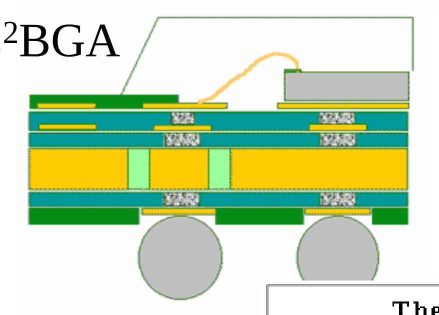
Base Condition: PBGA352, 2 layers BT substrate, 4 layers PCB, ground plane, 17 thermal vias, no thermal ball, natural convection, 1.5W

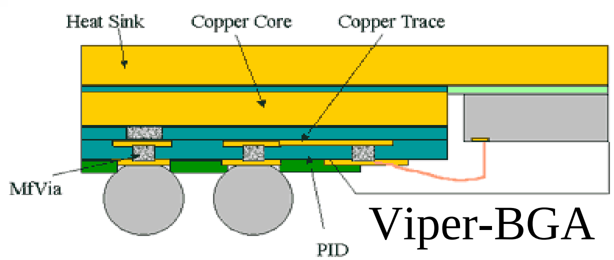
Enhancement of Thermal Performance

- Method 3 : Multilayer Substrate
  - Substrate with metal planes / copper core
  - Reduce Rja about 35%~40%

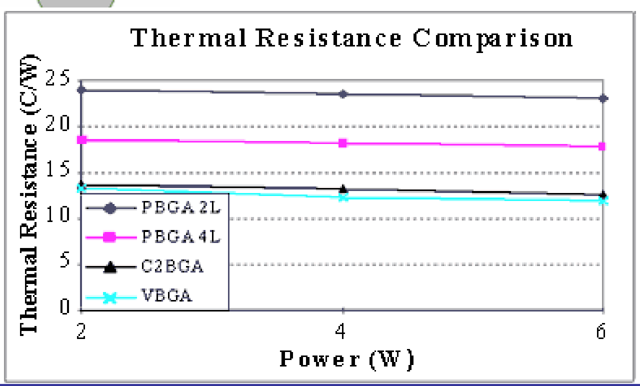


C^2BGA

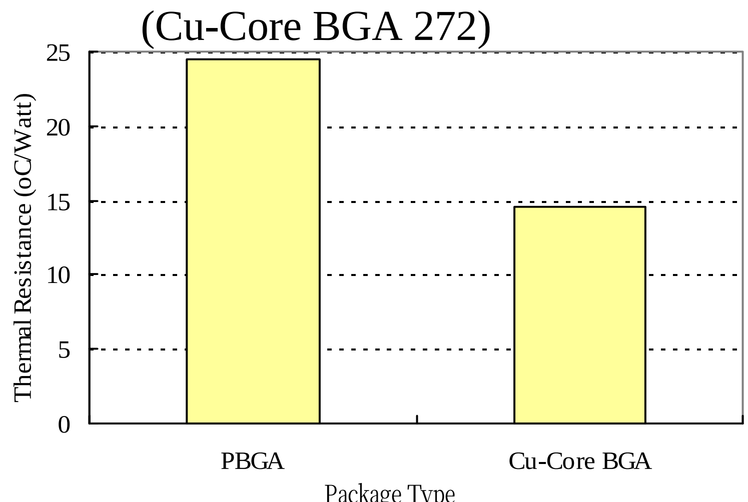




Viper-BGA



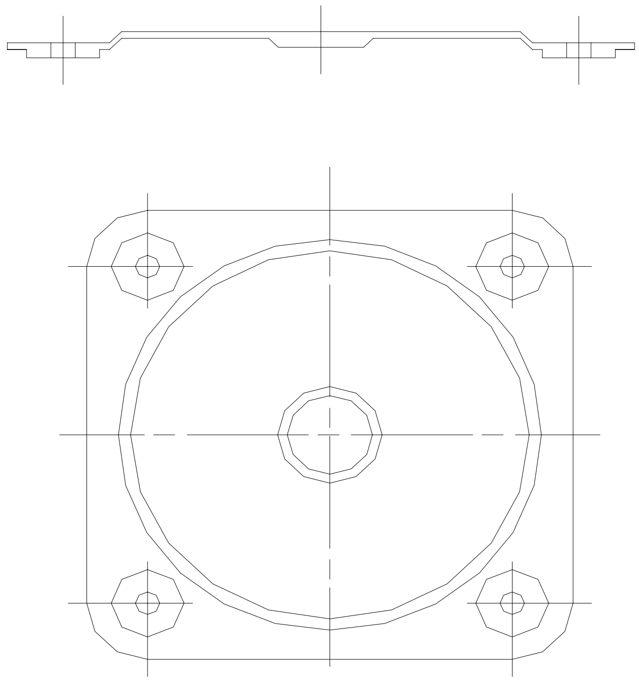
Source:
Prolinx Labs

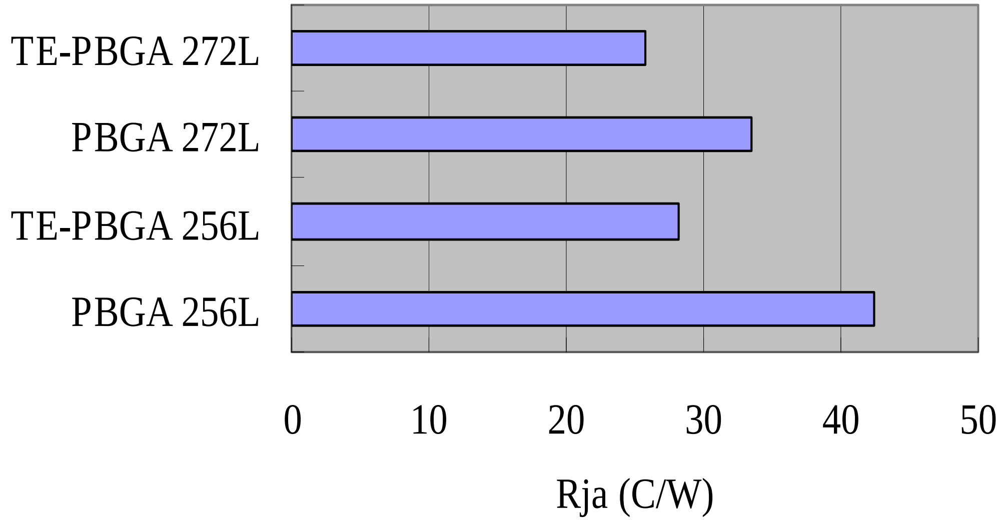


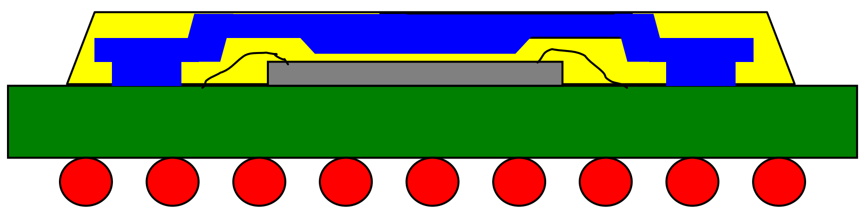
Source: T. Tang, Advanced IC Packaging, 1998

Enhancement of Thermal Performance

- Method 4 : Heat Spreader/Heat Slug





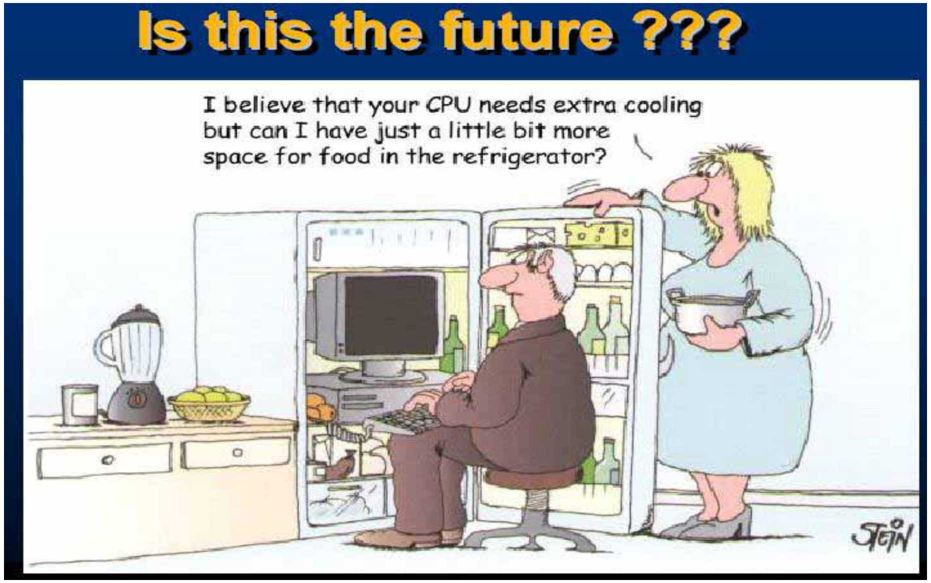


TE-PBGA

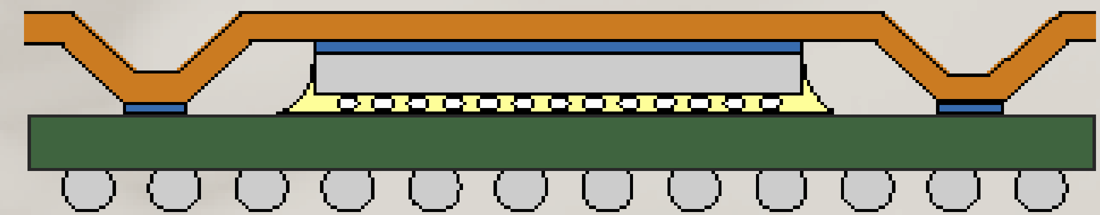
Summary

- Major parameters of internal thermal resistance are introduced
- Four methods of thermal enhancement for PBGA are introduced

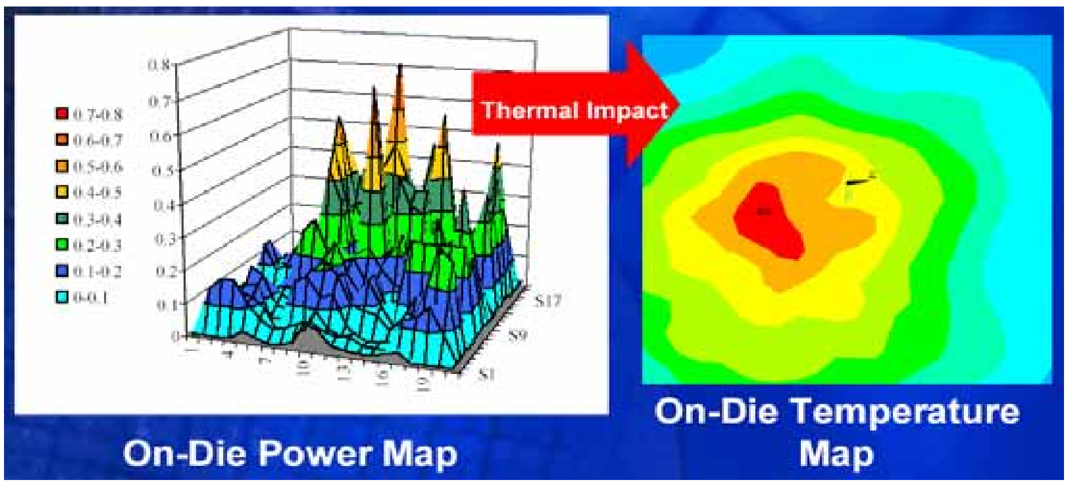
The Future


Is this the future ???
I believe that your CPU needs extra cooling but can I have just a little bit more space for food in the refrigerator?
STEIN

Integrated Heat Spreader



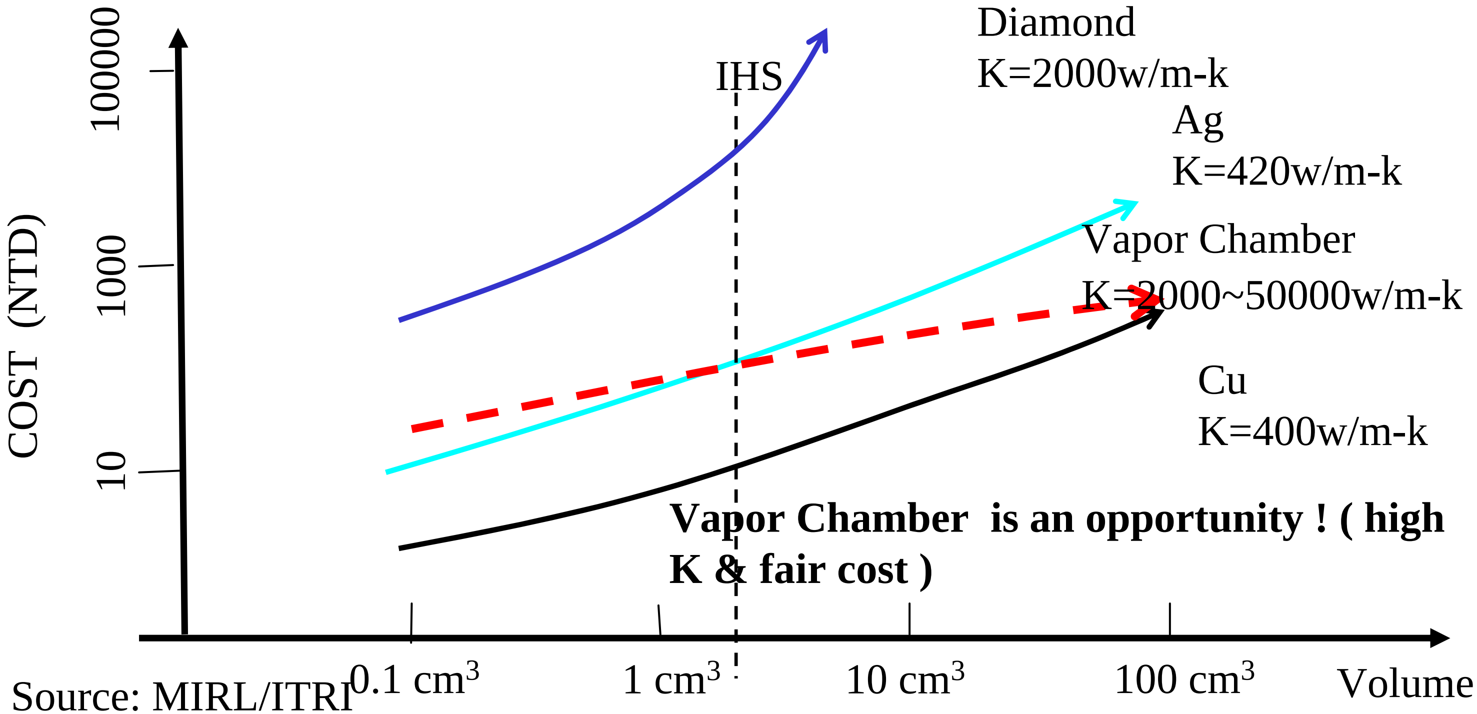
Flip chip BGA with heat spreader



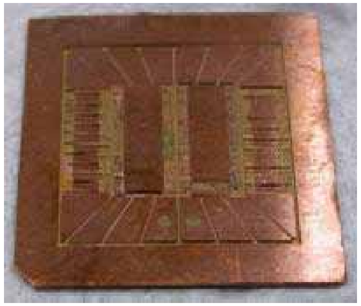
P4 with Integrated Heat Spreader (IHS)

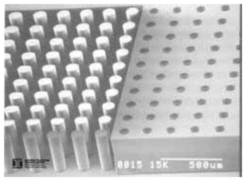
Source: MIRL/ITRI

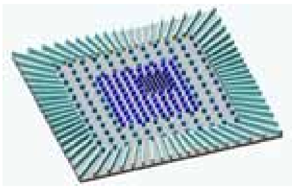
Candidates of Future IHS

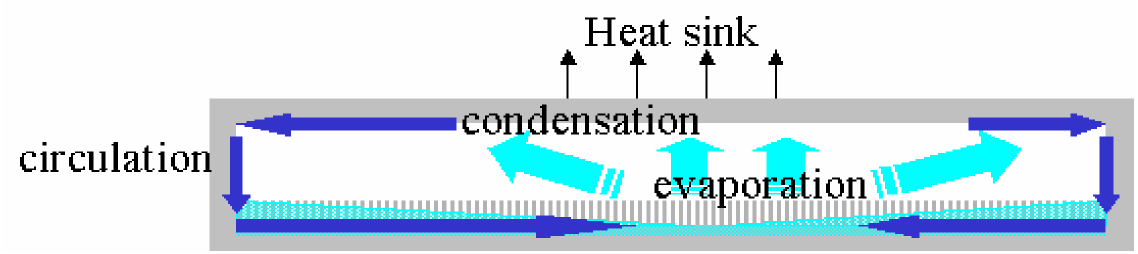


Source: MIRL/ITRI

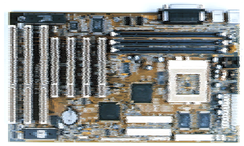


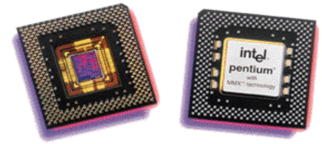






Conclusions





	System Level	Board Level	Component Level
INPUT DATA	–FRAME, SHELF & PCB PHYSICAL/THERMAL PROPERTIES –PCB POWER LEVELS –FAN DATA –FRAME AMBIENT	–CHANNEL, BOARD & COMPONENT PHYSICAL/THERMAL PROPERTIES –COMPONENT POWER LEVELS –CHANNEL THERMAL & FLOW AMBIENT	–COMPONENT/CHIP PHYSICAL/THERMAL PROPERTIES –CHIP POWER LEVELS –BOARD & CHANNEL AMBIENT
OUTPUT DATA	–AVERAGE PCB TEMP –MEAN CHANNEL AIR VELOCITY –MEAN CHANNEL AIR TEMP –FAN SELECTION	–COMPONENT CASE TEMP –BOARD TEMP PROFILE –CHANNEL TEMP PROFILE	–JUNCTION TEMP –THERMAL RESISTANCE

Conclusion

- No one believes an analysis, except the one who made it
- Everyone believes an experiment, except the one who made it
- How about you?