Temperature-Aware and Low-Power Design and Synthesis of Integrated Circuits and Systems

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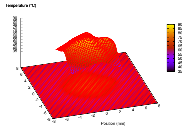
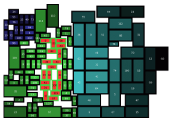
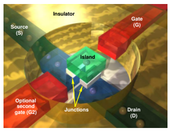


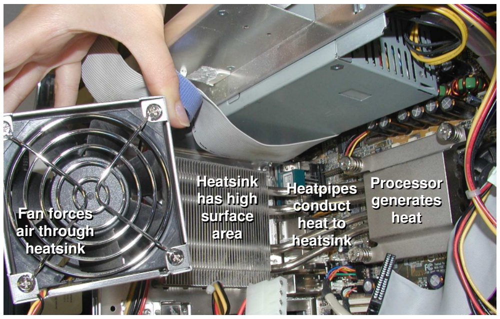




Introduction

- Cooling fundamentals
- Multiple cooling methods
  - Combinations often used in real applications

Multiple modes common in real applications



Conduction

$$P = A\kappa \cdot \Delta T / d$$

- P: Power in W
- A: Area
- κ: Thermal conductivity
- ΔT: Difference in temperature
- d: Depth

Radiative cooling

$$P = Ae\sigma T^4 - Ae\sigma T_A^4$$

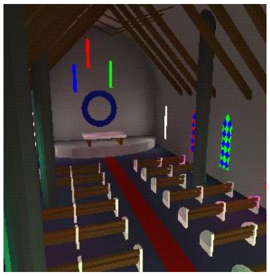
- P: Power in W
- A: Surface area
- e: Emissivity of surface [0:1]
  - 0.3 for Cu, 0 for rough black surface
- σ: Stefan-Boltzmann constant $= 5.67 \times 10^{-8}\,\mathrm{W}/(\mathrm{m}^2\ \mathrm{K})$
- T: Temperature
- T_A: Ambient temperature
- Why does a thermos have mirrored walls?

Radiative interaction

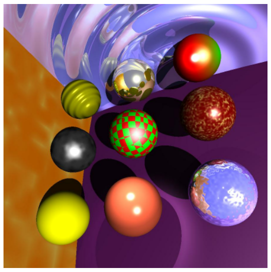
$$k = \frac{A \cos\theta}{4\pi r^2}$$

- k: Patch interaction coefficient
- A: Patch area
- θ: Angle between patches
- r: Distance between patches

Other uses of radiation



Radiosity



Ray tracing

Convection

Convection:

$$P = 2hA(T_S - T_F)$$

$$h \approx k_1 (T_S - T_F)^{1/4}$$

Therefore,

$$I \propto (T_S - T_F)^{5/4}$$

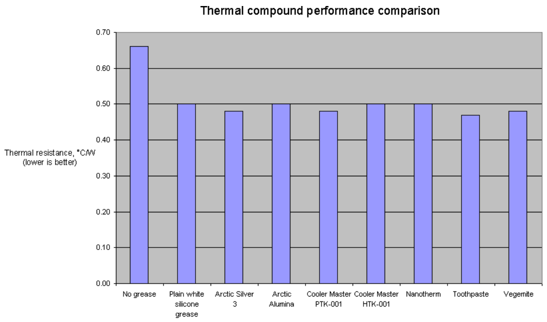
- P: Power in W
- h: Heat transfer coefficient
- k_1: Constant for film coefficient and film conductance ($0.0021\,\mathrm{W}/(\mathrm{m}^2\ \mathrm{K})$)
- A: Area of one side of plate
- T_S and T_F: Solid and fluid temperatures

Forced air heatsink

How to improve?

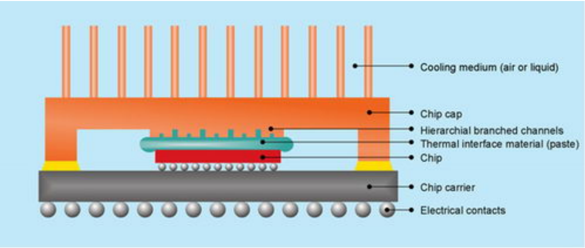
- Increase fluid flow rate, decreasing surface film thickness
- Or increase film conductance
    - Increases k_1
- Increase surface area
- Increase temperature difference (?)
- Increase conductance to heatsink

Thermal compounds



Credit to Dan's Data and Vegemite.

Heatsink attachment



- IBM proposes cutting tree-structure trenches in chip cap
- Thinner interface material, less pressure, few details

Heatsink attachment

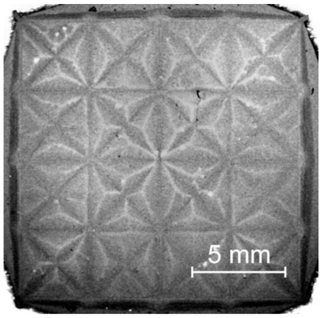


Image credit to IBM.

Ion pump cooling

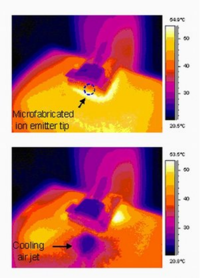


Image credit to N. Jewell-Larsen.

Ion pump operation

- High-voltage positive electrode ionizes air
- Ions travel to negative electrode (chip)
- Air pulled along
- Cooled a few mm^2 by 25 °C this way
- Claiming 180 W/(mm^2 K) at 4.5 kV, 2 mm^2

Liquid cooling

- Specific heat capacity of water 4× air
- Thermal conductivity 25× air
- Passive: Vat of oil
- Active: Recirculating pump
    - Where does heat go?
- Microchannel

Microchannel

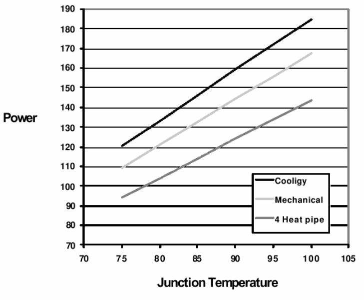
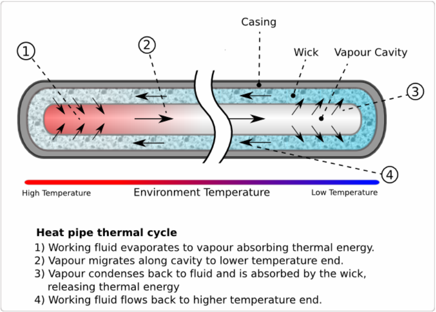


Image credit to Cooligy.

Phase change

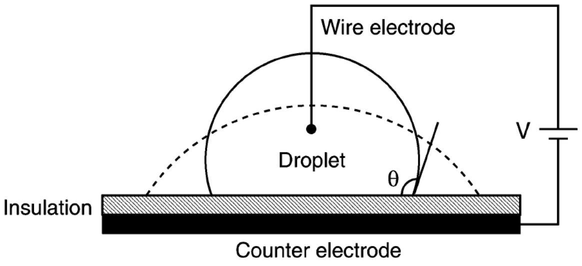
- Abrupt change in heat capacity
- Result in transfer in large amount of energy
  - Rate bound results in mixed state
- Latent heat: Amount of energy released or absorbed during evaporation
- 855 J/g for ethyl alcohol at 78 °C
- 1086 J/g for methyl alcohol at 65 °C
- 2258 J/g for water at 100 °C

Heat pipe



Heat pipe thermal cycle
1) Working fluid evaporates to vapour absorbing thermal energy.
2) Vapour migrates along cavity to lower temperature end.
3) Vapour condenses back to fluid and is absorbed by the wick, releasing thermal energy
4) Working fluid flows back to higher temperature end.

Electrowetting



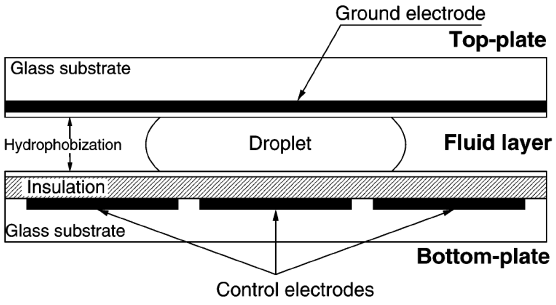
Credit to M. G. Pollack for image.

Electrowetting

$$\gamma_{SL} = \gamma_{SL}^{0} - \frac{\epsilon V^2}{2 \cdot d}$$

- γ_{SL}: Solid-liquid interfacial tension
- V applied voltage
- γ_{SL}^{0}: Solid-liquid interfacial tension at $V = 0$
- ϵ: Dielectric constant for insulating film
- d: thickness of insulating film

Electrowetting microactuator



Credit to M. G. Pollack for image.

Electrical and thermal fields

$$\vec{J}_Q =^{+} \kappa \vec{G}$$
$$\vec{J}_e = \delta \vec{E}$$

- $\vec{J}_Q$: Heat flow
- κ: Thermal conductivity
- $\vec{G}$: Temperature gradient
- $\vec{J}_e$: Electrical current
- δ: Electrical conductivity
- $\vec{E}$: Electric potential gradient

Credit to Prof. Grayson for his notes on this topic.

Thermoelectric interdependence

In the same electric field, hot electrons travel faster than cold electrons inducing heat flow

$$\vec{J}_Q = D\vec{E}$$

Charge flows faster from hot regions to cold regions

$$\vec{J}_e = C\vec{G}$$

Themroelectric effects

$$\vec{J}_e = \delta \vec{E} + C\vec{G}$$
$$\vec{J}_Q = \kappa \vec{G} + D\vec{E}$$
$$D = CT$$

where T is temperature.

Themroelectric devices

Solve for $\vec{E}$ and $\vec{J}_Q$

$$\vec{E} = \vec{J}_e/\delta - S\vec{G}$$

$$\vec{J}_Q = \pi\vec{J}_e + (\kappa - \delta S\pi)\vec{G}$$

$$\pi = ST$$

Peltier effect

$$\vec{J}_Q = \pi\vec{J}_e \Rightarrow I_Q = \pi I_e$$

where I_q is the total heat current and I_e is the total electrical current. Within a piece of metal

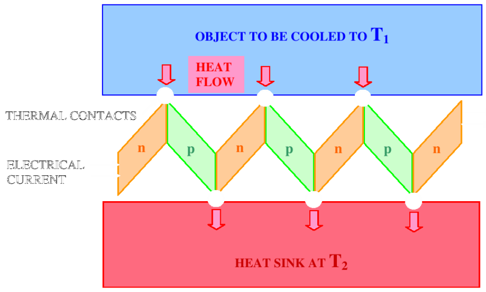
$$I_Q^{in} = I_Q^{out} = \pi I_e$$

However, at junction

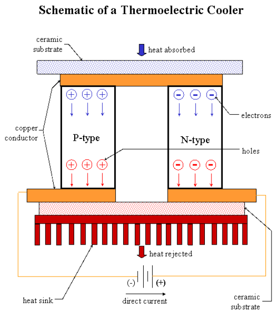
$$I_Q^{in} - I_Q^{out} = (\pi_A - \pi_B) I_e$$

Thus heat can be transported from one junction to another via charge carriers.

Peltier heat pumps



Peltier heat pumps



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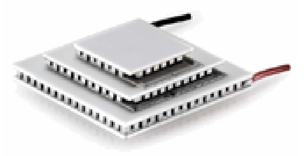
Stacked Peltier



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