Thermal Coupling

Outline

- Physical principles
- Sources of power consumption
- Thermal coupling / Self heating models
- Effects of temperature on circuit performance
- Effects of temperature on circuit reliability
- Cooling strategies
- Temperature monitoring
**Physical Principles: Definitions**

- **Thermal Energy**
  - Kinetic and potential energy of particles. Phonons

- **Heat**
  - Energy transferred between bodies at different Temperature

- **Relation between Energy-Temperature**
  
  \[ E = C \cdot \Delta T = m \cdot c \cdot \Delta T \]

  - Similar to: Capacitance, charge, Voltage.
  - **WARNING:** CHANGES OF PHASE!!
  - 1 cal = 4,184 J

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**Specific Heat: Some examples**

<table>
<thead>
<tr>
<th>Substance</th>
<th>c, KJ/Kg·K</th>
<th>c, Kcal/Kg·K</th>
<th>- Btu/lb·F°</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂O</td>
<td>4,18</td>
<td>1,00</td>
<td></td>
</tr>
<tr>
<td>Ethylic Alcohol</td>
<td>2,4</td>
<td>0,58</td>
<td></td>
</tr>
<tr>
<td>Al</td>
<td>0,900</td>
<td>0,215</td>
<td></td>
</tr>
<tr>
<td>Cu</td>
<td>0,386</td>
<td>0,0923</td>
<td></td>
</tr>
<tr>
<td>Au</td>
<td>0,126</td>
<td>0,0301</td>
<td></td>
</tr>
<tr>
<td>Ag</td>
<td>0,233</td>
<td>0,0558</td>
<td></td>
</tr>
<tr>
<td>Glass</td>
<td>0,840</td>
<td>0,20</td>
<td></td>
</tr>
<tr>
<td>Ice (-10 °C)</td>
<td>2,05</td>
<td>0,49</td>
<td></td>
</tr>
<tr>
<td>Si</td>
<td>0,703</td>
<td>0,168</td>
<td></td>
</tr>
</tbody>
</table>
Heat flow – Power – Heat transfer

- **Energy rates**
  - $J/s = W$
  - Temporal Evolution of Temperature (Adiabatic condition)
    \[
    \frac{dE}{dt} = P(t) = Q(t) = C \cdot \frac{dT}{dt}
    \]

- **Examples of heat generation:**
  - Joule Effect
  - Scattering of carriers in the conductor lattice and phonons

- **Temporal evolution of temperature (non adiabatic):**
  - Conservation of Energy
    \[
    \Delta T = \text{Generated Energy} - \text{transferred energy}
    \]

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Modes of heat transfer: Phoenomenological laws

- **Heat conduction in solids: Fourier law**
  - $q$: W/m²
  - $k$: thermal conductivity
    \[
    W/(K\cdot m)
    \]
  - $Q$: W
    \[
    q = -k \nabla T = \frac{Q}{A}
    \]
    \[
    q = -k \frac{dT}{dx}
    \]

- **Thermal resistance**
  - $\Delta T = R_{th} Q$
    \[
    R_{th} = \int_{x_1}^{x_2} \frac{dx}{A(x) \cdot k(x)} = \frac{1}{k} \cdot \frac{L}{A}
    \]
Thermal conductivity. Examples

- **Si**
  - \( k(T) = \frac{286}{(T-100)} \) W/cm · K
  - \( k = 1.05 \) W/cm·K (\( t = 100^\circ\text{C} \))

- **Cu**
  - \( k = 3.93 \) W/cm·K

- **Alumina (99-99.5 %)**
  - \( k = 0.25 \) W/cm·K

- **Epoxi (conductive)**
  - \( k = 0.016 \) W/cm·K

- **Epoxi (non conductive)**
  - \( k = 0.004 \) W/cm·K

- **Berilia**
  - \( k = 2.05 \) W/cm·K (\( t = 20^\circ\text{C} \))

- **Alumina**
  - \( k = 0.17 \) W/cm·K (\( t = 20^\circ\text{C} \))

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Exercise: Thermal resistance calculation

- **Different shapes**
  - Area Sphere: \( 4\pi r^2 \)
  - Area cylinder: \( 2\pi rh \)

<table>
<thead>
<tr>
<th>Case 1</th>
<th>Case 2,3: Concentric cylinder (H), sphere</th>
</tr>
</thead>
</table>

\[ \Lambda = L^2 \]

**Angle:** \( 45^\circ \)
Convection heat transfer

- **Definition**
  - Energy transferred to a moving fluid

- **Convection classification**
  - Natural: Difference of densities
  - Forced: Fan or pump

- **Different classification of fluids**
  - Laminar, turbulent...

Convection heat transfer: Newton cooling law

- Phenomenological relationship
  \[ q = h_c \cdot \left( T_s - T_f \right) \]

- \( h_c \): Convective coefficient of heat transfer
  - Units: \([W/m^2\cdot K]\)
  - Depends on: fluid and convection types, viscosity, orientation, temperature differences...
  - Air. Natural convection: 3-25
  - Water. Natural convection: 15-100
  - Air. Forced convection: 10-200
  - Water. Forced convection: 50-10,000

- Thermal resistance due to convection
  \[ R_{Conv} = \frac{1}{h_c \cdot A} \]
  \[ Q \cdot R_{Conv} = T_s - T_f \]
Convection Heat Transfer

Radiation heat transfer: Black body and real surfaces

Each surface has its own emissivity $\varepsilon$

Gray body: emissivity constant

Plank law

$$q_{bl} = \frac{C_1 \lambda^{-5}}{e^{C_2/\lambda T} - 1}$$

$C_1 = 3,742 \cdot 10^8 \text{ W} \cdot \text{µm}^4/\text{m}^2$

$C_2 = 1,4389 \cdot 10^4 \text{ µm K}$

$\lambda : \text{µm}$

Wien law

$$\lambda_{max} \cdot T = 2897,6 \mu \text{mK}$$

Stefan-Bolzmann law

$$q_b = \sigma T^4$$

$\sigma = 5.6697 \cdot 10^{-8} \text{ W/m}^2 \text{ K}^4$
Heat transfer equation in an IC

Stored energy (DT) = Generated Energy – transferred energy

Expression per unit of volume:

\[ c_p \frac{\partial T}{\partial t}(t,r) = q_{\text{GENERATED}}(t,r) - \nabla q_{\text{CONDUCTED}}(r,t) \]

\[ c_p \frac{\partial T}{\partial t}(t,r) = q_{\text{GENERATED}}(t,r) + \nabla k \nabla T(r,t) \]

Boundary conditions:
- Convective (Realistic)
- Isotermal
- Adiabatic
- Power dissipated as boundary condition
Sources of power consumption

- **Digital CMOS circuits**
  - Static power dissipation
    - Reverse-biased junction leakage current
    - Gate direct tunneling leakage
    - Subthreshold leakage ($I_{SUB}$)
  - Dynamic power dissipation
    - Short circuit current
    - Charging capacitances
      - MOS transistor
      - Routing capacitances
      - $P_c = 0.5C_{Load}V_{DD}^2 f\alpha$

- **MOS transistors**
  - Dissipation beneath the gate

- **Routing interconnect**
  - Joule Effect
  - Surrounded by insulator
  - Important heating as technology scales

- **Analogue Circuits**
  - Bias
  - Signal processing
Sources of Power Consumption: Evolution, density and distribution

<table>
<thead>
<tr>
<th>Year of Production</th>
<th>Near-term Maximum junction temperature (°C)</th>
<th>Long-term Maximum junction temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost performance</td>
<td>45</td>
<td>45</td>
</tr>
<tr>
<td>High performance</td>
<td>45</td>
<td>45</td>
</tr>
<tr>
<td>Cost performance</td>
<td>85</td>
<td>85</td>
</tr>
<tr>
<td>High performance</td>
<td>85</td>
<td>85</td>
</tr>
<tr>
<td>Ambient temperature (°C)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost performance</td>
<td>45</td>
<td>45</td>
</tr>
<tr>
<td>High performance</td>
<td>45</td>
<td>45</td>
</tr>
<tr>
<td>Power (W)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost performance</td>
<td>150</td>
<td>150</td>
</tr>
<tr>
<td>High performance</td>
<td>150</td>
<td>150</td>
</tr>
</tbody>
</table>

Thermal coupling models

Problem definition

Procedure:
- Resolution of the heat transfer equation in the IC structure
- Initial and Boundary conditions

Techniques
- Analytical (Closed form or Fourier Decomposition)
- Circuitual Model (Finite difference method)
- Numerical Solution
Thermal coupling: Circuit model

\[ q \Delta V + \Delta q_e + \Delta q_j - \Delta q_{e+1} - \Delta q_{j+1} = \frac{\Delta E}{\Delta t} \quad (4-51) \]

(a) Representative subvolume.  
(b) Equivalent thermal network; \( R_L = 1/(a\beta) \) and \( C_L = \rho \Delta V \sigma_v \)

Thermal coupling: characteristics at silicon level

- Low pass filter behavior
  - Cut off: 10 kHz – 1 MHz
- Diffusion process
  - Variable penetration depth (frequency dependent)
  - Attenuation increasing with distance
Thermal coupling: System level model

Thermal coupling examples:

Cross Section

Power Pulse

Dynamic ΔT

Distance = 4 µm
Distance = 24 µm
Distance = 44 µm
Distance = 64 µm

Magnitude = 13 mW

ΔT = 2°C
ΔT = 0.2°C
ΔT = 0.1°C
ΔT = 0.05°C

Time (µs)
Effects of temperature on circuit performance

- MOS transistor.
  Temperature affects:
  - Carrier mobility (MTE: 1.5-2)
  - Threshold voltage (K: .5-4 mV/K)
  - Velocity saturation
  - Depletion layer depth
  - Subthreshold current
- Wires
  - Resistivity ($\rho \propto T$)

\[
\mu_n(T) = \mu_n(T_r) \left( \frac{T}{T_r} \right)^{MTE}
\]
\[
V_t(T) = V_t(T_r) - K(T - T_r)
\]

Effects of temperature on circuit performance

- Effects on digital circuits
  - Signal Integrity
    - Clock skew
    - Delay
    - Power distribution
  - Delay
  - Static power consumption

Ring oscillator as temperature sensor
Effects of temperature on circuit performance: Electrothermal simulation

Effects on circuit reliability

\[ R(t) = \frac{\text{Number of survivals at } t}{\text{Number at } t = 0} \]

\[ \lambda(t) = \frac{\text{Casualty rate at } t}{\text{Survivals at } t} \]

\[ MTBF = \frac{1}{\lambda} \]

Reliability of a component

Failure velocity

\[ \lambda \]

Util life

Infantil mortality

Old mortality

Time
Effects on circuit reliability

- Temperature affects:
  - Static working temperature
  - Temperature gradients
  - Temperature cycling
  - Temperature evolution

- Arrhenius model
  \[ \lambda = \lambda_{\text{ref}} \cdot e\left(-\frac{E_{\text{dev}}}{K T}\right) \]

Cooling strategies

- Dissipators
  - Passive
  - Active
- Liquid cooling
- Thermoelectric coolers
  - Peltier effect

\[ q = \prod_{AB} J_e \]
Temperature monitoring

- Built-in temperature sensors
  - Absolute
  - Differential
- Off chip techniques
  - Contact techniques
    - Mechanical (AFM)
    - Contrast materials: Phosphors, liquid crystal
  - Optical techniques
    - Infra-red emission
    - Laser based techniques

References