Lecture 19: Heat Sink and its types

Transistor Biasing circuits And Thermal stability

DI02011011: Electronics Circuit and Application (ECA)

Lecture Blueprint: Thermal Management & Heat Sink Types

- Fundamentals of Heat Transfer Modes: Conduction, Convection, and Thermal Radiation.
- Thermal Interface Materials (TIM): Greases, Phase-Change Materials, Elastomeric Pads, and Gap Fillers.
- Analysis of Thermal Contact Resistance θ_{CS} & Mounting Torque Effects.
- Classification & Architecture of Heat Sinks: Stamped, Extruded, Pin-Fin, and Skived-Fin.
- Advanced Cooling Topologies: Two-Phase Vapor Chambers, Heat Pipes, and Liquid Cold Plates.
- Natural Convection vs. Forced Air Convection Volumetric Performance.
- Heat Sink Sizing Equation Methodology (θ_{SA} Calculation) & Worked Examples.

Fundamentals of Heat Transfer Mechanisms in Electronics

- Conduction (Solid Material Transfer): Heat flow through solid silicon, copper flange, and aluminum heat sink body, governed by Fourier's Law.
- Convection (Fluid/Air Interface Transfer): Heat dissipation from heat sink fins to surrounding air, governed by Newton's Law of Cooling.
- Radiation (Electromagnetic Waves): Direct infrared radiative heat loss from heat sink surface to surrounding enclosures, governed by Stefan-Boltzmann Law.
- Dominant Mode in Heat Sinks: Convection across fin surface area accounts for $80\% - 90\%$ of total heat dissipation in forced air systems.

Governing Equations of Thermal Dissipation Modes

- Fourier's Law of Conduction: $Q_{cond} = -kA\frac{dT}{dx} = \frac{kA}{L}(T_1 - T_2) \implies \theta_{cond} = \frac{L}{kA}$ (°C/W), where k is thermal conductivity (W/m · K).
- Newton's Law of Convection: $Q_{conv} = hA_{surface}(T_s - T_\infty) \implies \theta_{conv} = \frac{1}{hA_{surface}}$, where h is heat transfer coefficient (W/m^2 · K).
- Stefan-Boltzmann Law of Radiation: $Q_{rad} = \epsilon\sigma A_{surface}(T_s^4 - T_{surr}^4)$, where ϵ is surface emissivity ($0.85 - 0.95$ for black anodized aluminum) and $\sigma = 5.67 \times 10^{-8}$ W/m^{2}K^4.
- Combined Sink Resistance Equation: $\theta_{SA} = \frac{1}{hA_{fin} + h_{rad}A_{rad}}$.

Thermal Interface Materials (TIM) and Thermal Contact Resistance θ_{CS}

- Microscopic Surface Imperfections: Microscopic air gaps ($k_{air} \approx 0.026\,\mathrm{W/m \cdot K}$) between transistor case and heat sink create high thermal contact resistance.
- Role of Thermal Interface Material: TIM displaces air voids with higher conductivity compounds ($k_{TIM} \approx 1.5 - 8.0\,\mathrm{W/m \cdot K}$).
- Primary Classes of TIM Materials:
- • Thermal Greases / Pastes: Lowest thermal impedance ($0.05 - 0.15°\mathrm{C \cdot in^2/W}$); requires manual application.
- • Phase-Change Materials (PCM): Melts at $45 - 60°\mathrm{C}$ to fill microscopic voids; clean automated application.
- • Elastomeric Silicone Pads: Provides electrical isolation with moderate thermal resistance ($0.5 - 1.5°\mathrm{C/W}$).
- • Graphite / Gap Fillers: Compressible thick pads for bridging large mechanical tolerances.

Mounting Hardware, Torque Controls, and θ_{CS} Optimization

- Impact of Mounting Pressure: Increasing clamping pressure compresses TIM, reducing bond-line thickness (BLT) and lowering θ_{CS}.
- Optimal Torque Specification: Screw-mounted packages (TO-220, TO-247) require $0.5 - 0.8\,\text{N}\cdot\text{m}$ mounting torque.
- Over-Torquing Hazard: Excessive torque warps the copper header tab, bowing the contact surface away from the heat sink and INCREASING θ_{CS}.
- Spring Clip Mounting: Provides constant uniform clamping pressure across thermal cycles, compensating for thermal expansion stress.

Extruded & Stamped Heat Sinks: Structure & Performance

- Stamped Heat Sinks: Fabricated by stamping thin aluminum or copper sheets ($0.5 - 1.5\,\text{mA}$ thick). Low cost; suited for low-power board-level components ($P_D < 5\,\text{W}$, $\theta_{SA} \approx 10 - 25^\circ\text{C/W}$).
- Extruded Aluminum Heat Sinks (6063-T5): Fabricated by forcing hot aluminum billets through shaped dies. High thermal conductivity ($k \approx 200\,\text{W/m} \cdot \text{K}$).
- Fin Design Profiles: Straight vertical fins optimize natural convection chimney effects. Aspect ratios (fin height to gap width) typically reach $8:1$ to $10:1$.
- Application Window: Standard choice for medium-to-high power amplifiers ($P_D = 10\,\text{W} - 100\,\text{W}$, $\theta_{SA} \approx 0.5 - 5.0^\circ\text{C/W}$).

High-Density Surface Architectures: Pin-Fin & Skived-Fin

- Pin-Fin Heat Sinks: Array of round, square, or elliptical pins. Omnidirectional air flow capability; disrupts boundary layers to increase convective heat transfer coefficient h.
- Skived-Fin Heat Sinks: Produced by shaving thin, continuous fins directly from a solid copper or aluminum block using a precision blade.
- High Aspect Ratio Advantage: Enables extremely dense fin spacing with aspect ratios up to $25:1$ and zero thermal interface resistance between fins and base plate.
- Material Advantage of Copper: Skived copper heat sinks ($k \approx 390\,\text{W/m}\cdot\text{K}$) provide double the thermal conductivity of aluminum, ideal for space-constrained high-flux power density.

Two-Phase Passive Cooling: Heat Pipes & Vapor Chambers

- Phase Change Thermodynamics: Utilizes latent heat of vaporization of working fluid (water/alcohol under vacuum) to transport heat with near-zero temperature drop.
- Operation Cycle: Liquid vaporizes at hot evaporator interface → Vapor travels at high speed to cold condenser section → Vapor condenses releasing latent heat → Liquid returns to evaporator via capillary wick action.
- Effective Thermal Conductivity: Ultra-high equivalent conductivity ($k_{eq} \approx 5,000 - 50,000\,\mathrm{W/m \cdot K}$), $10\times - 100\times$ higher than solid copper.
- Vapor Chamber Application: Planar 2D heat spreader placed directly under high-power density chips to eliminate localized thermal hot spots.

Forced Air Convection vs. Natural Convection Performance Dynamics

- Natural Convection: Driven solely by buoyant forces of heated air ($v_{air} \approx 0.1 - 0.5\,\mathrm{m/s}$). Convective coefficient $h \approx 5 - 15\,\mathrm{W/m^2 \cdot K}$. Requires wide fin spacing ($5 - 10\,\mathrm{mm}$) to prevent boundary layer overlap.
- Forced Air Convection: Driven by fans/blowers ($v_{air} \approx 2.0 - 5.0\,\mathrm{m/s}$). Convective coefficient $h \approx 30 - 150\,\mathrm{W/m^2 \cdot K}$ ($5\times - 10\times$ increase!).
- Thermal Resistance Reduction: Forced airflow reduces θ_{SA} of an extruded heat sink by $60\% - 75\%$ compared to natural convection.
- Pressure Drop Trade-off: Denser fin spacing increases airflow impedance, requiring higher static pressure fans.

Liquid Cooling Cold Plates & Direct Substrate Management

- Liquid Cold Plate Architecture: Internal microchannels machined into copper/aluminum blocks connected to a closed-loop liquid pump, radiator, and reservoir.
- Coolant Properties: Water/glycol mixtures possess $4\times$ higher specific heat capacity ($c_p \approx 4184\,\mathrm{J/kg \cdot K}$) and $25\times$ higher thermal conductivity than air.
- Performance Metric: Achieves extremely low thermal resistances ($\theta_{SA} < 0.05^{\circ}\mathrm{C/W}$).
- Application Scope: Essential for high-power electronics ($> 500\,\mathrm{W}$ to several kW) such as EV inverters, motor drives, server racks, and high-power RF transmitters.

Numerical Example: Step-by-Step Heat Sink Sizing Calculation (θ_{SA})

- Given Requirements: Transistor TO-247 package dissipating $P_D = 45\,\text{W}$. Maximum junction temperature $T_{J,\max} = 150°\text{C}$. Maximum ambient temperature $T_A = 50°\text{C}$. Transistor datasheet specifies $\theta_{JC} = 0.8°\text{C/W}$. Mounted with thermal grease and mica washer $\theta_{CS} = 0.4°\text{C/W}$.
- Step 1: Calculate Maximum Allowable Total Thermal Resistance $\theta_{JA,\max}$:
- $\theta_{JA,\max} = \frac{T_{J,\max} - T_A}{P_D} = \frac{150°\text{C} - 50°\text{C}}{45\,\text{W}} = \frac{100°\text{C}}{45\,\text{W}} = 2.22°\text{C/W}$.
- Step 2: Solve for Maximum Allowable Heat Sink Thermal Resistance θ_{SA}:
- $\theta_{SA,\max} = \theta_{JA,\max} - \theta_{JC} - \theta_{CS} = 2.22 - 0.8 - 0.4 = 1.02°\text{C/W}$.
- Step 3: Heat Sink Selection: Select a commercial catalog heat sink rating $\theta_{SA} \leq 1.0°\text{C/W}$ under natural convection or $\leq 0.4°\text{C/W}$ under forced air.

Numerical Example: Evaluating TIM Impact on Junction Temperature

- Comparison Scenario: Same 45 W transistor setup with $\theta_{SA} = 1.0°C/W$, $\theta_{JC} = 0.8°C/W$, $T_A = 50°C$.
- Option A — High-Grade Thermal Grease: $\theta_{CS} = 0.2°C/W$.
- • Total $\theta_{JA} = 0.8 + 0.2 + 1.0 = 2.0°C/W$.
- • Junction Temp $T_J = 50°C + (45\,W \times 2.0°C/W) = 50 + 90 = 140°C$ (SAFE!).
- Option B — Dry Joint without TIM: Microscopic air gaps yield $\theta_{CS} = 1.8°C/W$.
- • Total $\theta_{JA} = 0.8 + 1.8 + 1.0 = 3.6°C/W$.
- • Junction Temp $T_J = 50°C + (45\,W \times 3.6°C/W) = 50 + 162 = 212°C$ (DESTRUCTIVE FAILURE!).
- Conclusion: Omitting thermal interface grease increases T_J by 72°C, causing catastrophic thermal destruction.

Summary & Heat Sink Selection Matrix

- Sizing Formula: $\theta_{SA} = \frac{T_{J,\max} - T_A}{P_D} - \theta_{JC} - \theta_{CS}$.
- Low Power ($< 5\,\mathrm{W}$): Stamped sheet metal heat sinks or direct PCB copper pour plane.
- Medium Power ($5\,\mathrm{W} - 100\,\mathrm{W}$): Extruded aluminum heat sinks with natural or forced convection.
- High Power Density ($100\,\mathrm{W} - 300\,\mathrm{W}$): Skived copper pin-fin heat sinks with heat pipe vapor chambers.
- Ultra Power ($> 300\,\mathrm{W}$): Closed-loop liquid cooling cold plates.
- Golden Rule: Always specify high-grade TIM ($k_{TIM} > 2.0\,\mathrm{W/m \cdot K}$) and apply proper mounting torque to minimize θ_{CS}.