Thermal PCB Design Guideline

Prepared by
VISHNUPRIYA_D

Thermal PCB

A **Thermal PCB** is a printed circuit board designed specially to **manage heat** generated by electronic components. Its main purpose is to **control, spread, and remove heat** so that the components do not overheat.

High-Heat PCB Components

- Power MOSFETs / Transistors
  • Heat Cause: Conduction losses (I^2R) and high frequency switching losses.
  • Applications: SMPS stages, motor control, inverter and driver circuits.
- Voltage Regulators (Linear & Switching)
  • Heat Cause:
  – *Linear:* Power dissipation due to (Vin – Vout) × I.
  – *Switching:* Switching and conduction losses.
  • Applications: DC power regulation modules.
- Power Resistors
  • Heat Cause: Resistive power dissipation (I^2R) during high current flow.
  • Applications: Current sensing, load banks, power limiting circuits.
- High-Power LEDs
  • Heat Cause: Electrical power not converted into light is released as heat (Vf × I).
  • Applications: Lighting modules, display backlights, indicator clusters.
- Microcontrollers / CPUs / FPGAs
  • Heat Cause: High transistor switching activity → dynamic power dissipation.
  • Applications: High-performance and compute-intensive embedded systems.
- Inductors / Transformers
  • Heat Cause: Copper winding losses and magnetic core losses under high-current switching.
  • Applications: SMPS converters, motor drivers, power electronics.

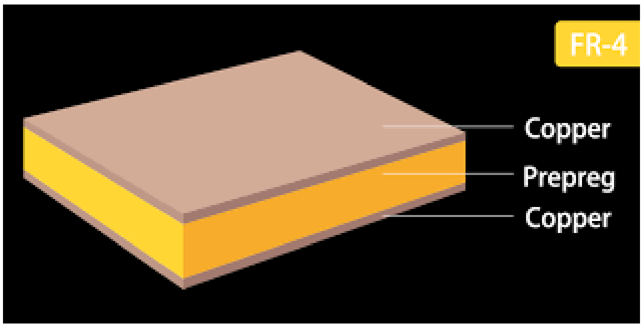
Thermal PCB Design Guide

1.PCB Material

Selecting the appropriate PCB material is critical for thermal stability, mechanical reliability, and overall performance. Consider **Glass Transition Temperature (Tg)**, **thermal conductivity (k-value)**, **Coefficient of Thermal Expansion (CTE)**, and **moisture absorption** when choosing materials.

Standard FR-4 (General Use)

- Tg: 130°C – 140°C
- Suitable for consumer electronics and low-to-medium power circuits
- Advantages: Low cost, widely available
- Limitations: Not suitable for high-thermal or high-frequency designs

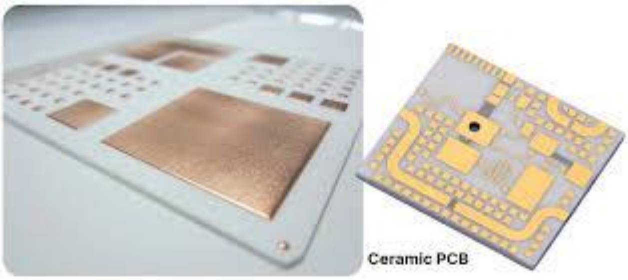


High-Tg FR-4 (High-Temperature Boards)

- Recommended for PCBs exposed to operating temperatures above 100°C
- Common Materials:
    - Shengyi S1000-2 – Tg ~170°C
    - Isola 370HR – Tg ~180°C
    - ITEQ IT-180A – Tg ~180°C
    - Arlon 85N – Tg ~250°C (for harsh environments)
- Benefits:
    - Better thermal stability
    - Reduced Z-axis expansion (minimizes via cracking)
    - Enhanced reliability for power electronics, automotive applications, EV chargers, and inverters

Ceramic PCBs (Al_2O_3, AlN, BeO)

- Use for extreme heat and high power-density devices
- Thermal Conductivity:
    - Alumina (Al_2O_3): 20–30 W/m·K
    - Aluminum Nitride (AlN): 150–200 W/m·K
    - Beryllium Oxide (BeO): 200–250 W/m·K (toxic, rarely used)

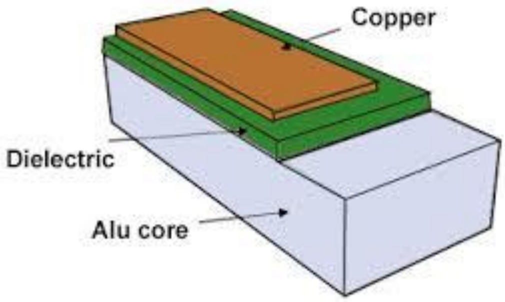


- Applications:
    - Power amplifiers
    - LED headlights
    - RF and microwave modules
    - High-current motor drivers

Metal Core PCBs (MCPCB)

- Recommended for high-power components generating significant heat (LED drivers, battery chargers, BLDC drivers)
- Core Types:
    - Aluminum – cost-effective, common
    - Copper – highest thermal performance

- Steel – mechanical strength with moderate thermal conduction



- Advantages:
    - Efficient heat spreading
    - Reduced need for large heat sinks
    - High reliability under thermal cycling

Material Selection Based on Application

Application	Recommended Material
Consumer Electronics	Standard FR-4
SMPS / Inverters	High-Tg FR-4
Automotive ECU / EV Charger	170°C–180°C High-Tg FR-4 or Metal Core
LED Lighting	Metal Core PCB
RF / Microwave Circuits	Ceramic / PTFE Laminates
High-Power MOSFET Boards	Metal Core / High-Tg FR-4

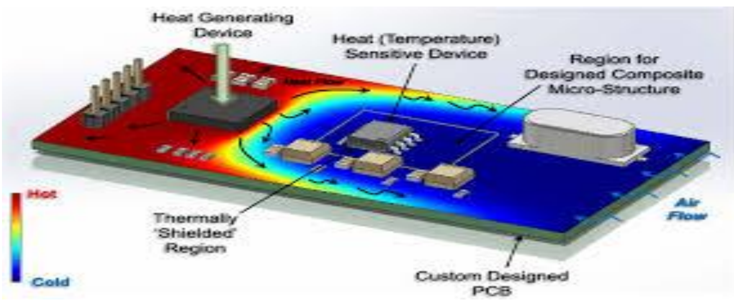
2.Component Placement

Proper component placement reduces hotspots, improves heat spreading, and enhances PCB reliability. Key goals:

- Allow heat sources to dissipate efficiently
- Protect heat-sensitive components
- Maintain even board temperature

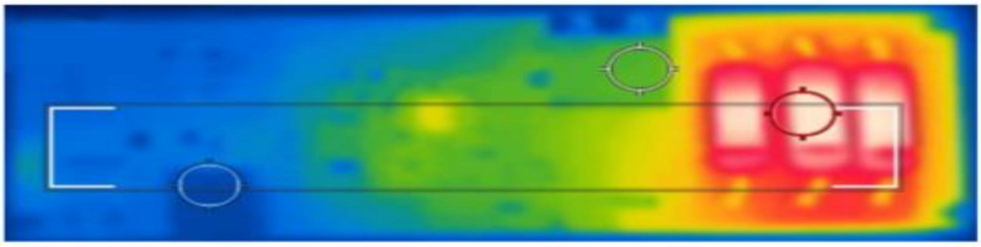
Guidelines for Thermal Component Placement

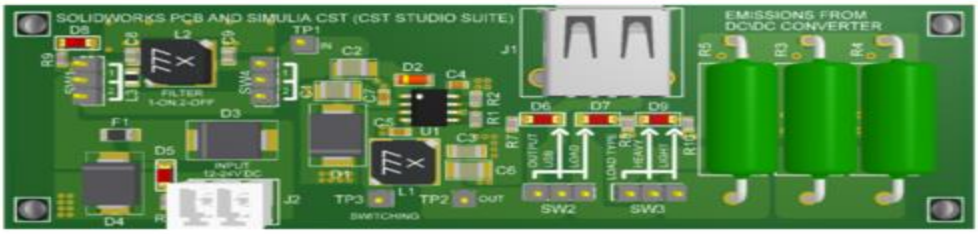
- **Separate Heat-Generating and Heat-Sensitive Components**
    - Place MOSFETs, regulators, power ICs, and LEDs away from sensitive components like sensors, ADCs, crystal oscillators, and op-amps.



- **Distribute High-Power Components**
    - Avoid clustering multiple power devices to prevent local hotspots. **do not place all heat-generating components in one small area of the PCB**.Instead, **spread them across the board** so heat is not concentrated in one spot.

- **Edge Placement for Hot Components**
    - Position power devices near board edges to facilitate natural heat escape.





- **Strategic Sensor Placement**
    - Place temperature sensors close to power stages for accurate monitoring but not directly on heat sources.
- **Crystal Oscillators**
    - Place away from heat sources to maintain accuracy

A crystal oscillator vibrates at a fixed frequency (8 MHz, 16 MHz, 32.768 kHz, etc.).But **temperature causes the crystal's frequency to drift**.

3.Component Selection

Choosing the right components helps reduce heat, improve performance, and make your PCB more reliable. Good component selection means:

- Less heat generation
- Better heat spreading
- Components survive higher temperatures

Guidelines for Thermal Component Selection

- **High-Temperature Components**

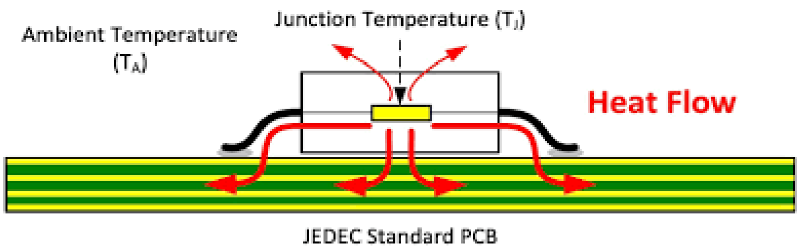
- Use components rated for higher temperatures (105°C, 125°C, 150°C)
- Automotive-grade components (AEC-Q100/Q200) are more reliable in hot environments

Automotive grade means **electronic components that are specially designed, tested, and certified to work reliably in harsh automotive environments**. These components follow **AEC-Q standards**, created by the Automotive Electronics Council.

- **Package Size and Type**
  - Larger packages spread heat better
  - Packages with **exposed thermal pads** (QFN, Power PAD, DPAK) transfer heat efficiently to the PCB

Component Type	Small Package	Large Package	Difference
MOSFET	SOT-23	DPAK / TO-220	Large package handles higher current & stays cooler
Linear Regulator	SOT-223	TO-220	TO-220 can use a heat sink → better cooling
Diode	SOD-123	SMA / SMB / SMC	Large diode survives higher surge current
Resistor	0603	2512	Larger resistor has higher power rating (0.1W → 1W)

- **Thermal Resistance (Rθ)**
  - Thermal resistance shows how easily heat flows from a component to the PCB or air
  - **RθJA (Junction-to-Ambient):** Heat flow from the component to air

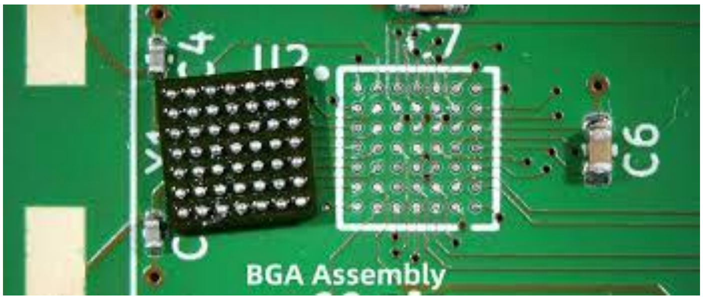


  - **RθJC (Junction-to-Case):** Heat flow from the component to its metal case
  - Lower Rθ = better heat dissipation
- **Low-Loss Power Devices**
  - Choose MOSFETs with low Rds(on) and low switching losses
  - Reduces heat generated during operation

Rds(on) = Resistance between Drain and Source when MOSFET is ON

If Rds(on) is high → more heat
If Rds(on) is low → less heat

- **Short Leads and Metal Pads**
  - Packages like QFN, DFN, and BGA transfer heat directly to PCB copper
  - Through-hole parts like TO-220 conduct heat to heatsinks or chassis



The heat flows **straight from the chip → metal pad → PCB copper**.

This allows:

- Faster heat transfer
- Lower thermal resistance
- Better cooling through copper planes & thermal via

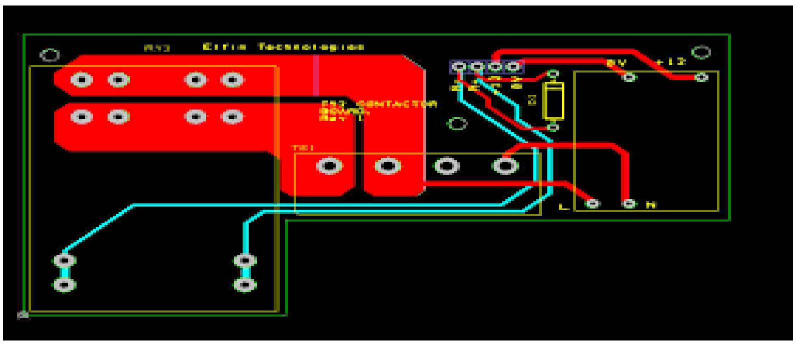
- **High-Stability Passives**
  - Capacitors: MLCC X7R or C0G; electrolytics rated 105°C–125°C
  - Inductors: Low DCR, high-temp ferrite cores

  Some passive components (capacitors, inductors, resistors) change their value when temperature increases.
  High-stability passives are parts designed to **work correctly even at high temperatures** without drifting or failing.

- **Derating Components**
  - Always operate below maximum ratings (current, voltage, temperature)
  - Keeps components safe under heat

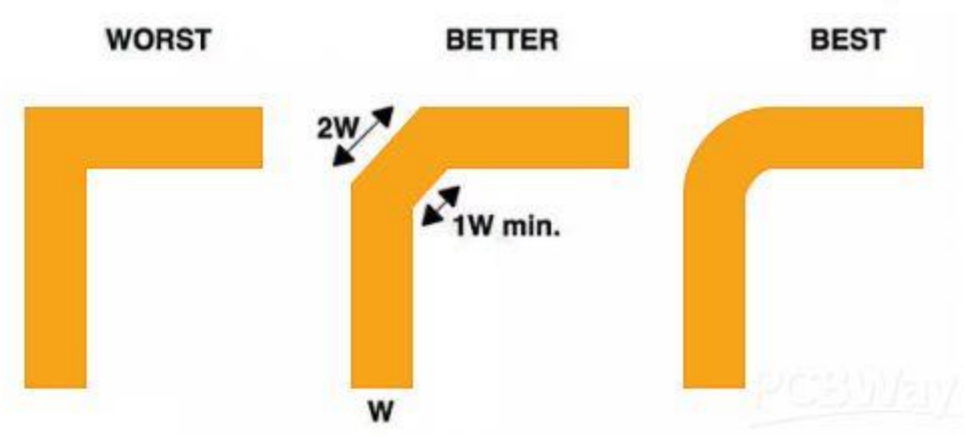
4.Thermal Trace Design

- **Use Wider Traces for High Current**
  - Lower resistance reduces heating and allows safe current flow.

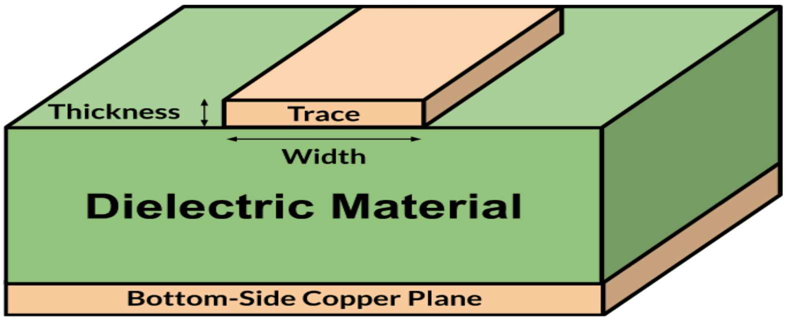


  - Example:
    Narrow trace = high resistance → gets hot
    Wide trace = low resistance → stays cool

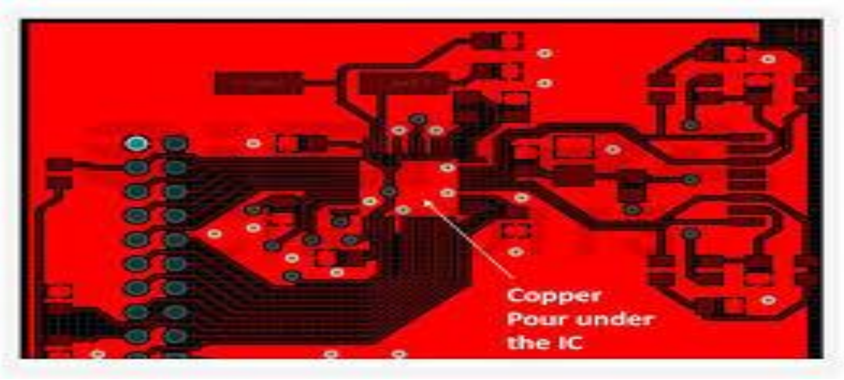
- **Keep Trace Length Short**
    - Minimizes resistance, heat generation, and noise.
- **Avoid 90° Corners**
    - Use 45° angles or rounded bends to prevent hotspots and improve current flow.



- **Increase Copper Thickness**
    - Thicker copper spreads heat better and support higher current.



- Standard: 1 oz (35µm), Moderate: 2 oz (70µm), High-power: 3–4 oz
- **Use Copper Pours for Power Traces**
    - Large copper areas spread heat and reduce trace resistance.



- **Gradual Trace Width Transitions**
    - Tapering or curved expansions prevent hotspots caused by sudden narrowing.

- **External Layer Placement**
    - High-current traces on top/bottom layers dissipate heat more effectively.
- **Maintain Proper Spacing**
    - Prevents heat coupling, insulation stress, and thermal issues.
- **High-Frequency Considerations**
    - Wider or parallel traces reduce skin-effect heating and signal loss.

5.Ground & Power Planes

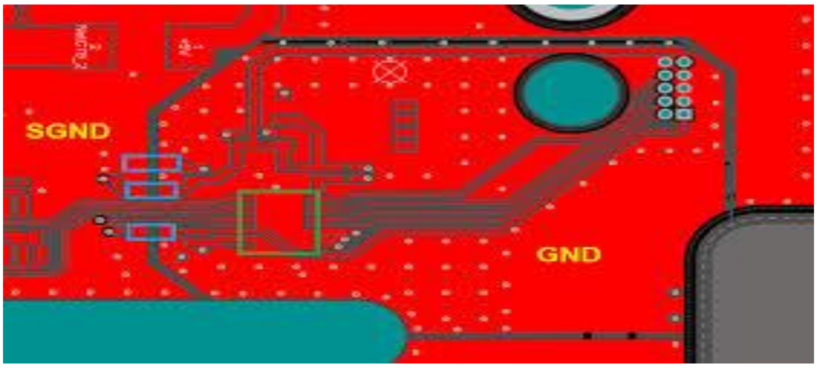
Ground (GND) and Power (VCC, 5V, 12V, etc.) planes are large copper areas that serve **both electrical and thermal functions**, helping with heat spreading, current handling, and signal integrity.

Ground Plane (GND)

- Large continuous copper layer for GND reference
- Provides stable return path and reduces noise
- Acts as an internal heat sink, spreading heat from high-power components
- Reduces PCB thermal resistance when connected via thermal vias

Power Plane (VCC / VIN)

- Copper layer for distributing supply voltages
- Carries high current with low voltage drop
- Provides heat spreading for power devices and high-current traces
- Acts as a thermal buffer for MOSFETs, regulators, and DC-DC converters



Thermal Benefits of Planes

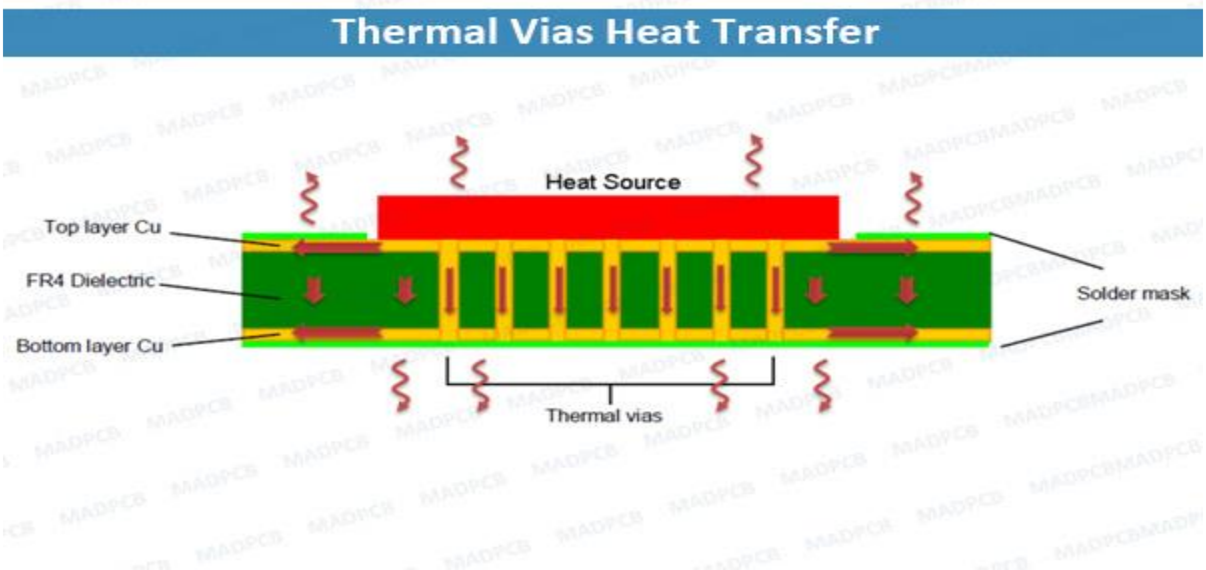
- Large copper area lowers thermal resistance and junction temperature
- Heat spreads efficiently from components to inner/outer layers
- Reduces overheating of traces carrying high current

Best Practices

- Use solid, continuous planes without gaps or slots
- Place multiple **thermal vias** under exposed pads (MOSFETs, regulators)
  - Typical: 0.3–0.4 mm vias, 6–12 per pad
- Use thicker copper for high-current planes
  - 1 oz: standard, 2 oz: high current, 3 oz: power boards/motor drivers
- Connect top pads to inner planes using vias for better heat spreading
- Separate high-current and signal grounds; join at a single point to reduce noise

6.Thermal Vias

Thermal vias are copper-plated holes that transfer heat vertically through the PCB, helping reduce component temperature, prevent hotspots, and improve reliability.



What Are Thermal Vias?

- Placed under or near heat-generating components
- Provide vertical heat paths: Top Layer → Inner Planes → Bottom Layer
- Reduce junction temperature, surface temperature, and material stress

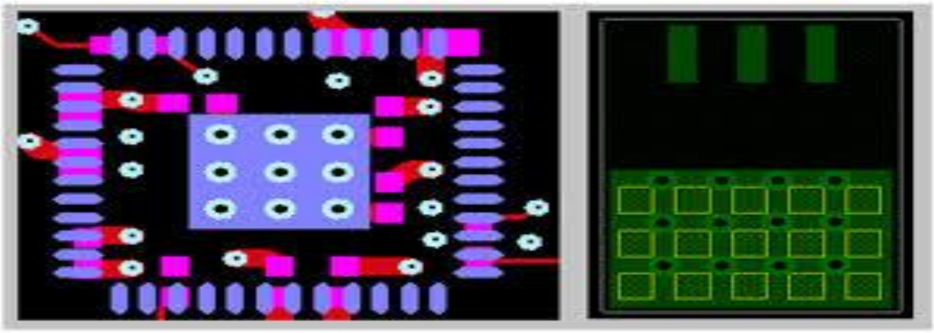
Where to Use Thermal Vias

- **Power Components:** MOSFETs, LDO/DC-DC regulators, motor drivers, power amplifiers, diodes
- **ICs with Thermal Pads:** QFN, DFN, Power PAD, MCUs with exposed pads
- **High-Power LEDs & RF Boards:** LEDs, RF power amplifiers, ceramic PCBs

Best Practices for Thermal Vias

- **Place Multiple Vias Under Pads**
  - Use 6–12 vias for standard ICs; large pads may need 16 or more
  - Ensures heat is distributed evenly and reduces hotspot formation
- **Optimize Via Size and Pitch**
  - Drill: 0.2–0.3 mm; Finished: 0.3–0.4 mm; Pitch ~1 mm

- Proper sizing balances manufacturability and thermal efficiency
- **Use Copper-Filled or Plugged Vias for QFN Pads**
  - Prevents solder from flowing into the vias during reflow
  - Maintains good mechanical and thermal connection
- **Connect Vias to Large Copper Areas**
  - Connect to GND plane, power plane, or bottom copper pads
  - Larger copper area improves heat spreading across the board
- **Use Thicker Copper for High-Power Designs**
  - 1 oz: standard designs
  - 2 oz: medium-power devices
  - 3 oz or more: high-power boards or motor drivers
  - Thick copper reduces resistance and improves thermal dissipation
- **Use Via Arrays for Large Pads**
  - Arrange vias in a grid under thermal pads (e.g., MOSFET drain/source pads)
  - Each via carries a portion of heat; combined they form an efficient thermal path



- **Thermal Via Placement**
  - Place vias evenly under the component's exposed pad
  - Avoid placing vias at the edge of the pad to prevent solder wicking
  - Ensure vias connect to inner and bottom copper layers for vertical heat flow

7.Thermal Standards Compliance

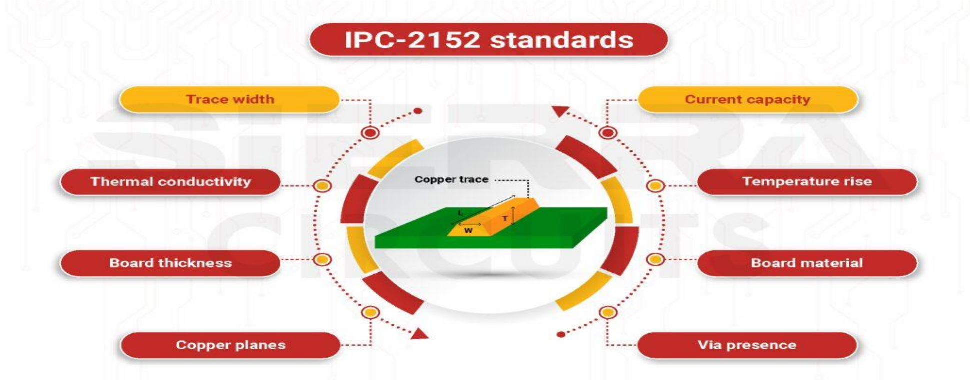
Thermal design must follow industry standards to ensure safety, reliability, and certification readiness. Standards define trace widths, temperature limits, materials, spacing, current capacity, and testing requirements.

Importance of Thermal Standards

- Prevent PCB overheating and component failure
- Ensure safe operation under full load
- Reduce fire hazards and delamination
- Maintain long-term reliability
- Simplify manufacturing consistency and product certification (UL, CE, FCC, IEC)

Major Thermal Standards

- **IPC-2152 – Current Carrying Capacity**
  - Provides trace width vs current guidelines, considering layer type, PCB thickness, and copper weight



- **IPC-2221 – Generic PCB Design**
  - Defines minimum conductor spacing, thermal reliefs, material selection, and maximum temperature rise
- **UL 94 – Flammability**
  - Flame rating of PCB materials; V-0 is preferred for safety
- **UL 746E – Polymeric Materials**
  - Max operating temperature, dielectric performance, and creepage under heat
- **IEC 60068 – Environmental Testing**
  - Thermal shock, heat cycling, and high-temperature stress tests for real-world reliability

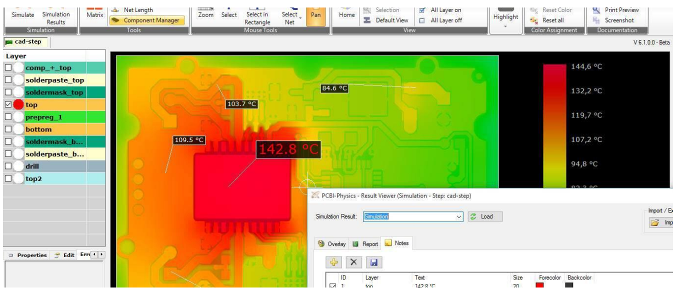
Key Compliance Practices

- **Component Derating:** Operate below max temperature (10–20% margin)
- **PCB Temperature Rise:** 10°C = excellent, 20–30°C = acceptable, >40°C = not recommended
- **Trace Width:** Size traces per IPC-2152 based on current and layer type
- **Component Spacing:** Avoid heat coupling between power ICs, resistors, diodes, and regulators
- **Thermal Reliefs:** Use 4-spoke connections to planes for soldering and heat balance

8.Thermal Analysis

Overview: Detects and resolves potential heat issues before production.

- Simulation tools identify hotspots and guide adjustments in component placement, copper planes, or thermal vias.



- Optimizes airflow and heat sink design, reducing redesign costs and improving reliability.
- Example tool: **Cadence Celsius Thermal Solver** integrates with PCB CAD software.

9. Protective Coatings and Encapsulation

Overview: Enhances heat dissipation and protects the PCB.

- Thermal interface materials, pads, or adhesives improve heat transfer from components to PCB or heat sinks.
- Protective coatings shield components and boards from moisture, dust, and environmental damage.
- Encapsulation compounds can spread heat effectively but must have high thermal conductivity to avoid trapping heat.

10.Cooling Mechanisms

Overview: Active or passive methods to lower component temperatures.

- Heat sinks, fans, or forced airflow reduce temperatures of high-power components.
- Thermal pads or gap fillers help transfer heat across air gaps to heat-dissipating surfaces.
- Cooling solutions should not interfere with other components or cause electromagnetic interference (EMI).

Summary:

- Select PCB material suitable for operating temperature and power density.
- Separate heat-generating and heat-sensitive components; avoid clustering.
- Place high-power components near board edges for better heat dissipation.
- Use wide, short traces and thicker copper for high-current paths.
- Employ copper pours and planes to spread heat efficiently.
- Implement thermal vias under heat-generating components for vertical heat flow.
- Choose components with low losses, high-temperature ratings, and exposed thermal pads.
- Follow industry standards (IPC-2152, IPC-2221, UL) for thermal and safety compliance.
- Use simulation tools to identify hotspots and optimize thermal design.
- Apply protective coatings, thermal pads, or heat sinks to enhance cooling.