Thermal and Mechanical Design Considerations, Materials, and Case Studies

Mobile Devices Hardware Thermal Management

QUALCOMM®

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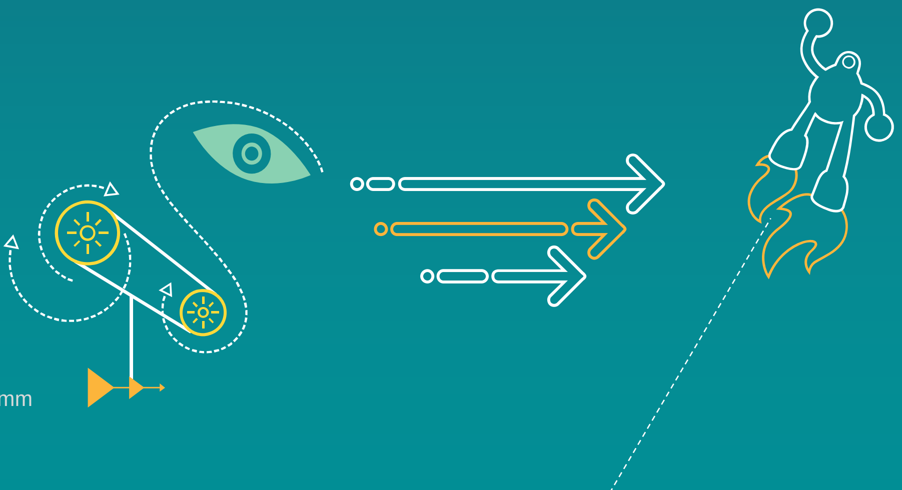

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Revision History

Revision	Date	Description
A	August 2014	Initial release

Contents

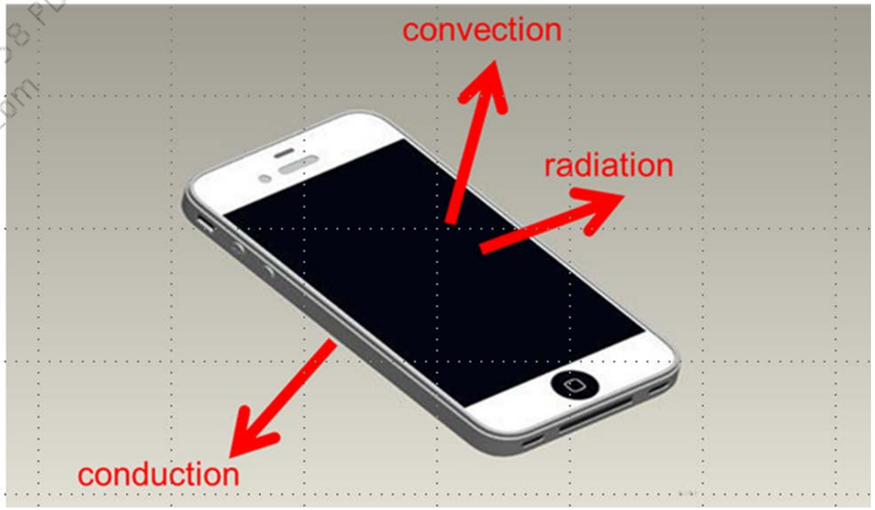
Sec. 1

Thermal Energy in Smartphone

Heat Transfer and Thermal Energy In Mobile Devices

- Heat transfer is a science that studies the thermal energy (heat) movement between two bodies (or mediums) due to their temperature difference. The thermodynamics of the particles in the medium create this thermal energy in the form of heat or increased temperature due to particles collision.
- Heat transfer is the mechanism of thermal energy transfer between physical systems of which there is a potential differences in thermal energy and/or temperature and pressure.
- The amount of heat transferred is Q with unit of Joules (J). 1 Joule is the amount of heat that raises 1 gm of water 1°C. 1 Watt is the rate of energy generation of 1 Joule/second of time (or dQ/dt).

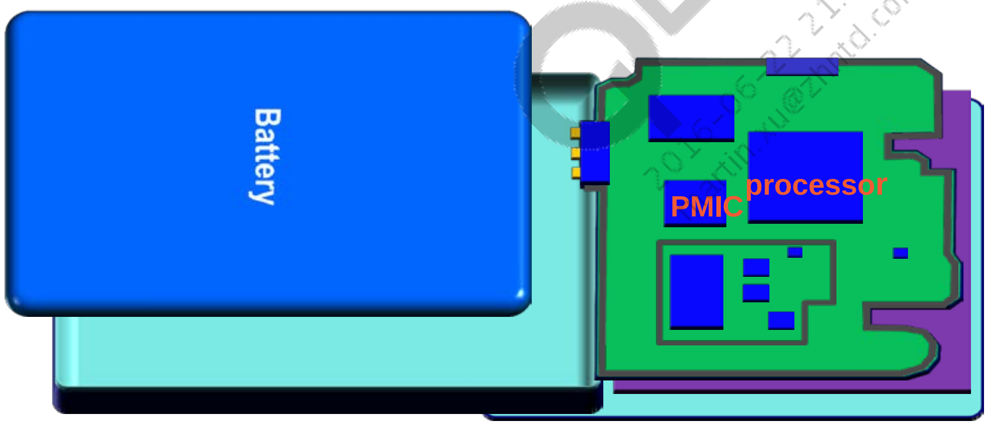
Smartphone major components	Order of power dissipation in SM
LCD	highest
Processors: MSM™, APQ, and MDM	
Power supply modules: PMIC and PMI	
RF: PA's and QCA	
Camera	
Connectivity and codec	
Memory	
Battery	
Other hardware	

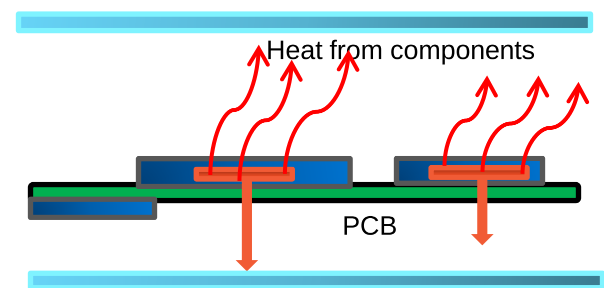


Heat flow out of handset

How Does Heat Get Generated Inside Mobile Devices? – Application Driven Heat

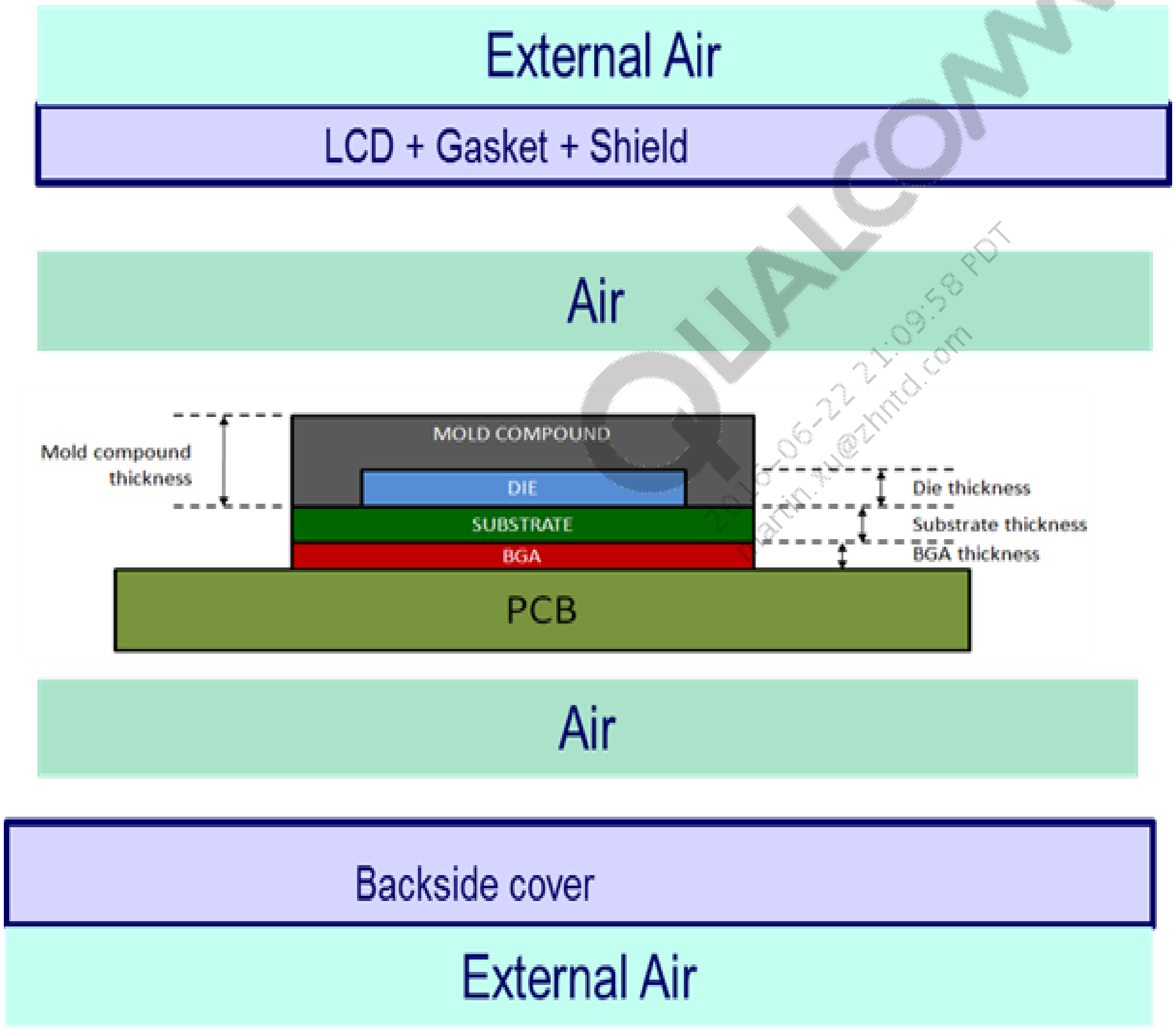
- When a user runs an application such as playing a game or surfing the net, the components inside the mobile device such as the processor and PMIC generate heat.
- Some applications create hot spots inside the components. The hot spots show up as high temperatures on the device skin.
- When the generated heat does not get removed to the outside air or absorbed in the mobile device mechanical structure, the device throttles and shuts down or potentially harm (burns) users.
- To avoid reduction in device throughput, customer complaints, and device returns, it is important to manage the heat generated inside mobile devices.



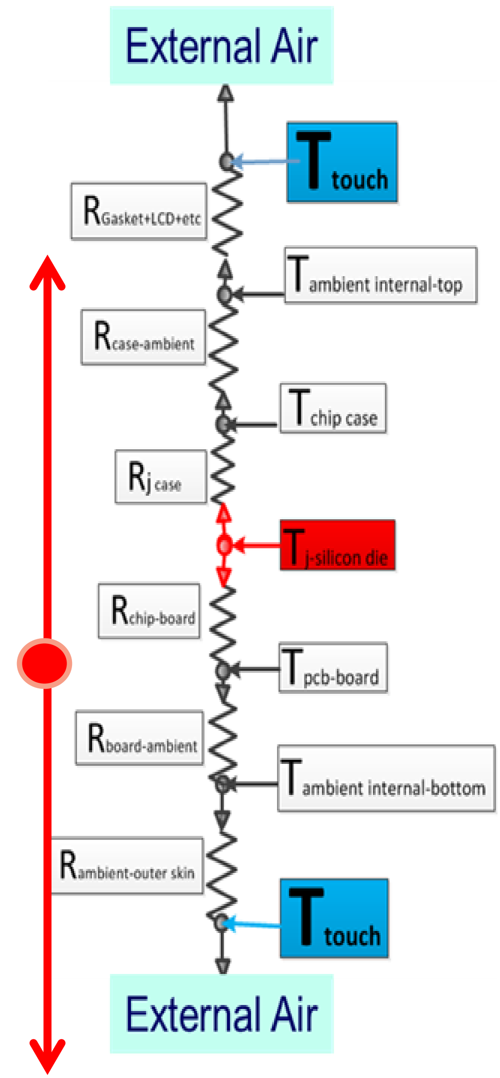


Heat Movement Inside Mobile Devices – The Least Resistance Path

The heat generated by an application in the smartphone components travels through the least resistance path in the system enclosure stack-up.



Possible heat flow path inside device



Sec. 2

Mobile Devices Thermal Management Summary

Key Hardware Factors and Their Effectiveness

Hardware		
Parameters	**Effectiveness**	**Comments/recommendations**
Components packages	- Not as effective - Limited and short duration (~30 s range at full applications)	Component packages for smart telephones are small and have limited thermal capacity and short time constant
PCB	- Limited effectiveness - Dissipates/spreads heat better than components packages (larger surface area and copper content in the layer can help to spread heat) - Higher heat capacity than components	Thermal design recommendations: - Should consider good vias distribution and expanded via surface areas; staggered and array vias pass either through hole or blind - PCB (vias, layout, and increased Cu in layers) - Increased Cu content in power and ground layers - Possible heat saturation if components are too close and excessive number of components on small board - Heat still needs to be dumped out of the device through mechanical structure
▪ **Mobile device mechanical enclosure** ▪ **Heat spreading** ▪ **Heat pipes (HP) and vapor chambers (VC)**	▪ Mechanical enclosure good and effective – if designed properly (this is where hardware thermal management should be implemented) ▪ Heat spreading – very effective; it spreads heat evenly in the lateral direction and shields skin temperature if proper thickness is used. It has limited heat capacity based on surface area. ▪ Heat pipes and vapor chambers – highest impact; HP and VC have the highest heat removal capability and possess excellent latent heat properties. They reduce hot spots and increase the device operation time. Serious considerations should be made to include HP and VC in thermal designs of mobile devices.	Thermal design recommendations: - Include metal structure in the device (system) - Design hidden vents and openings for hot air to leave the system - Implement contacts between PCB and device structure so that heat can scape - Optimize the enclosure design by maximizing surface areas - Battery can be used as an auxiliary heat sinking method in addition to heat spreaders and TIM gap filler materials - Heat spreading material: • Stabilizes and spreads the device's skin temperatures • Increases components time constant before software thermal mitigation is enabled • Can be applied to individual or group of components in the mobile device - Using heat pipes and vapor chambers provides both; to ensure robust mobile device thermal design with chances of obtaining higher benchmark scores and lesser thermal issues, HP and VC should be considered.

Software Thermal Management Parameters and Their Effectiveness

Software		
Parameters	**Effectiveness**	**Comments**
Thermal mitigation algorithms	Limited and short duration	- Does not dissipate or remove heat - Mostly applied when the overall device touch temperature gets above certain thresholds - Used to protect consumer and system - Reduced system performance
Thermal mitigation protocols	Shuts system down	- Used when system exhibits near thermal catastrophes such as throttling or system shutdown - Saves customer investment but no application advantages
- Mitigation algorithms - Mitigation protocols	Software mitigation reduces performance + modem data rate reduction on UE at threshold values - impact applications by reducing clock frequency	- Cannot solve thermal problems and too late for a solution - It is a temporary fix and is for safety protection

Note: Refer to *MSM8994.LA Power Thermal Management Overview* (80-NM328-12).

Sec. 3

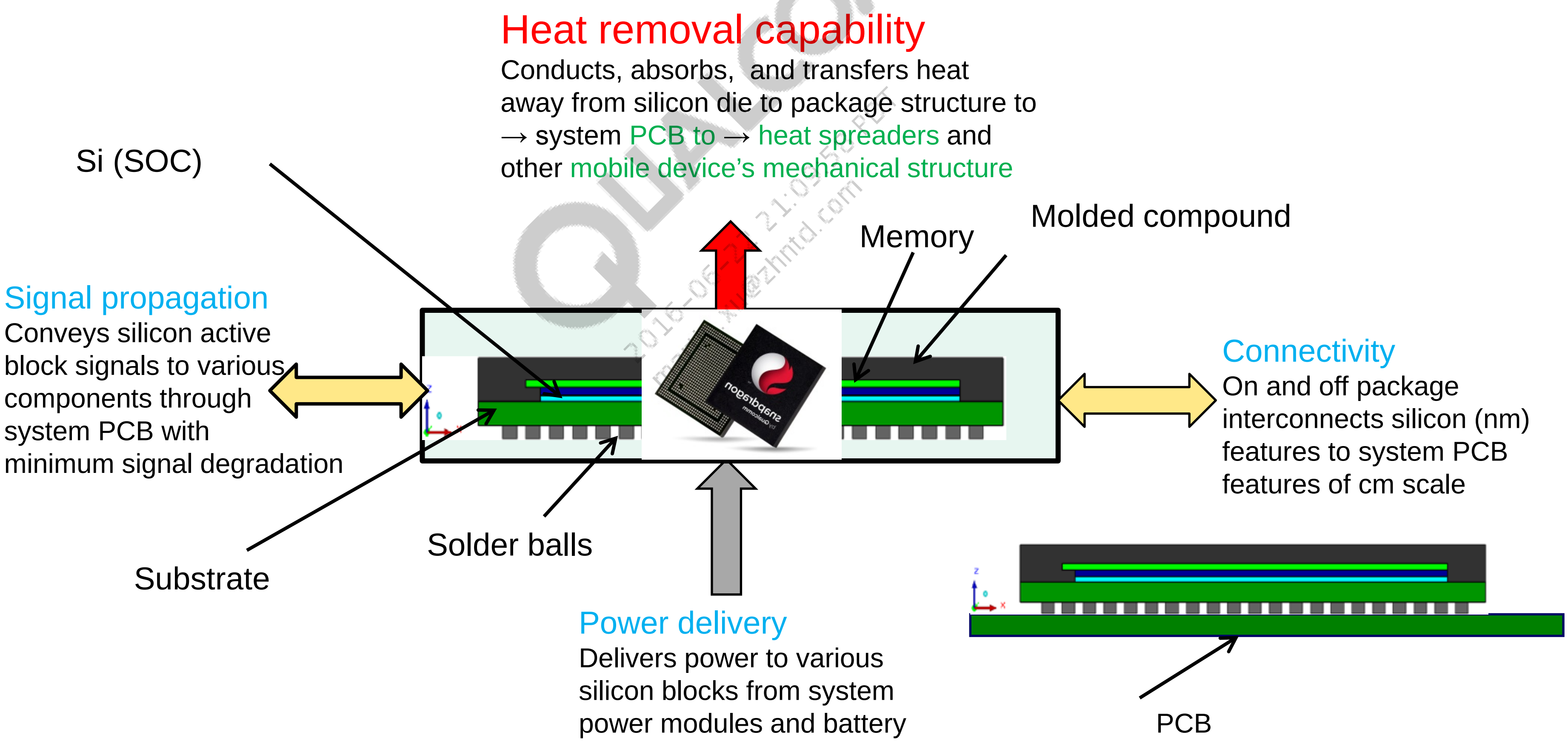
Mobile Devices Mechanical and Thermal Design Considerations

Sec. 3.1

Component Package Influence on Mobile Devices Thermal Design

Thermal Role of Component Package

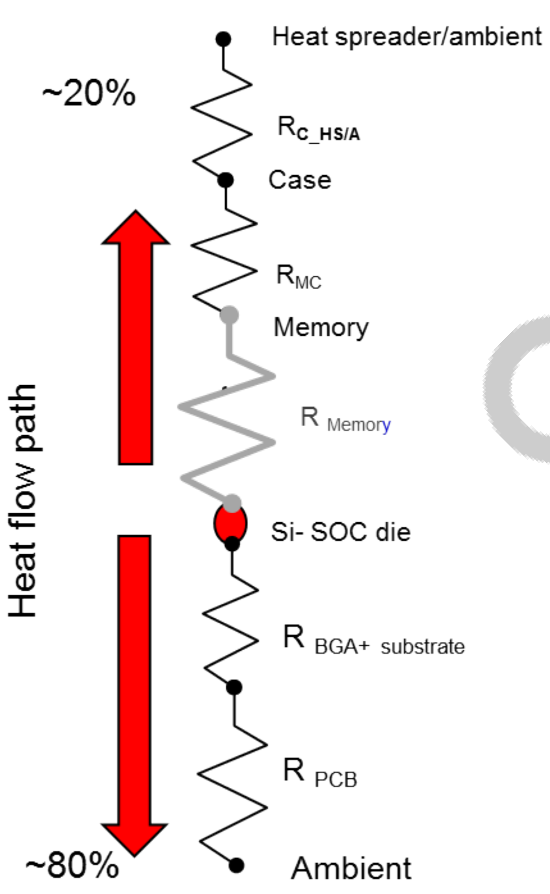
- ASIC devices are encapsulated in complex structure packages with multiple layers of molded compound, FR substrate, and solder balls. The package is placed in mobile device PCB to perform various important tasks.
- One of the important functions of the mobile devices component package is to remove heat from hot silicon devices.



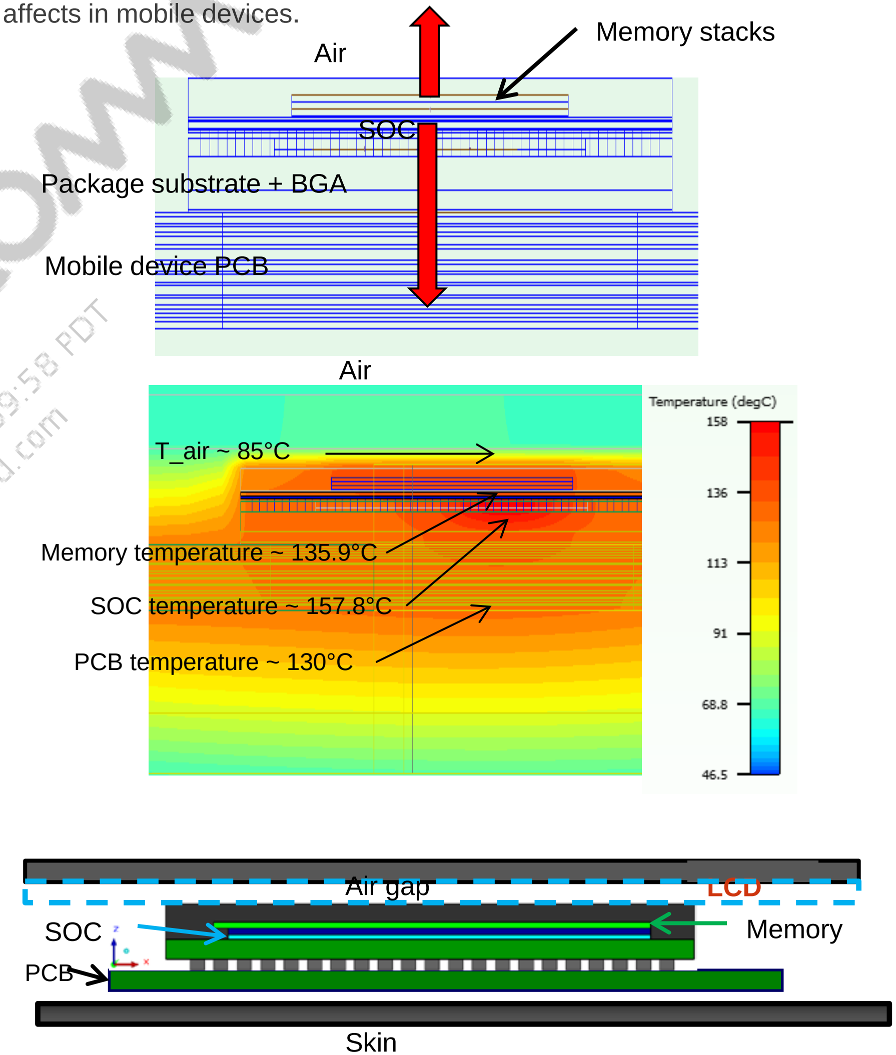
Thermal Design Decision

Note: Simulation example uses high power dissipation to illustrate the quantitative concept of heat flow path in packages and PCB and its thermal affects in mobile devices.

Will heat from PCB affect enclosure skin?
What is the alternative?



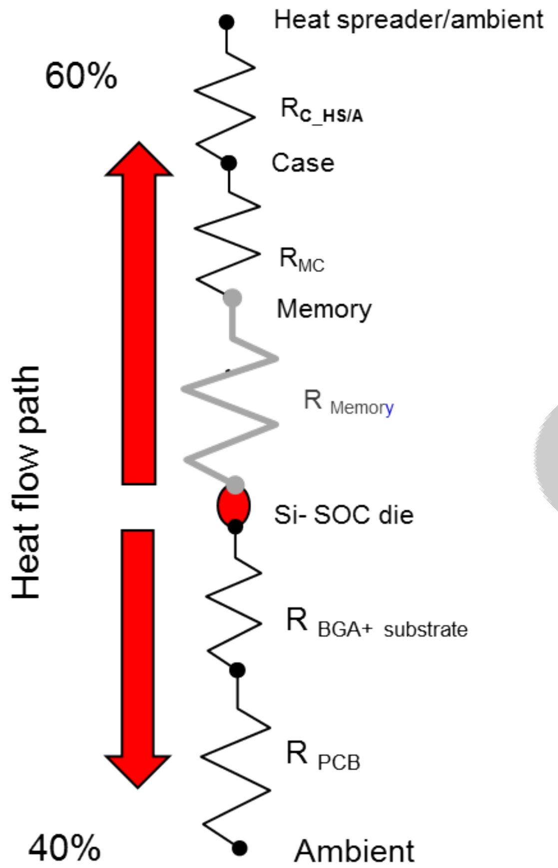
Thermal resistance network



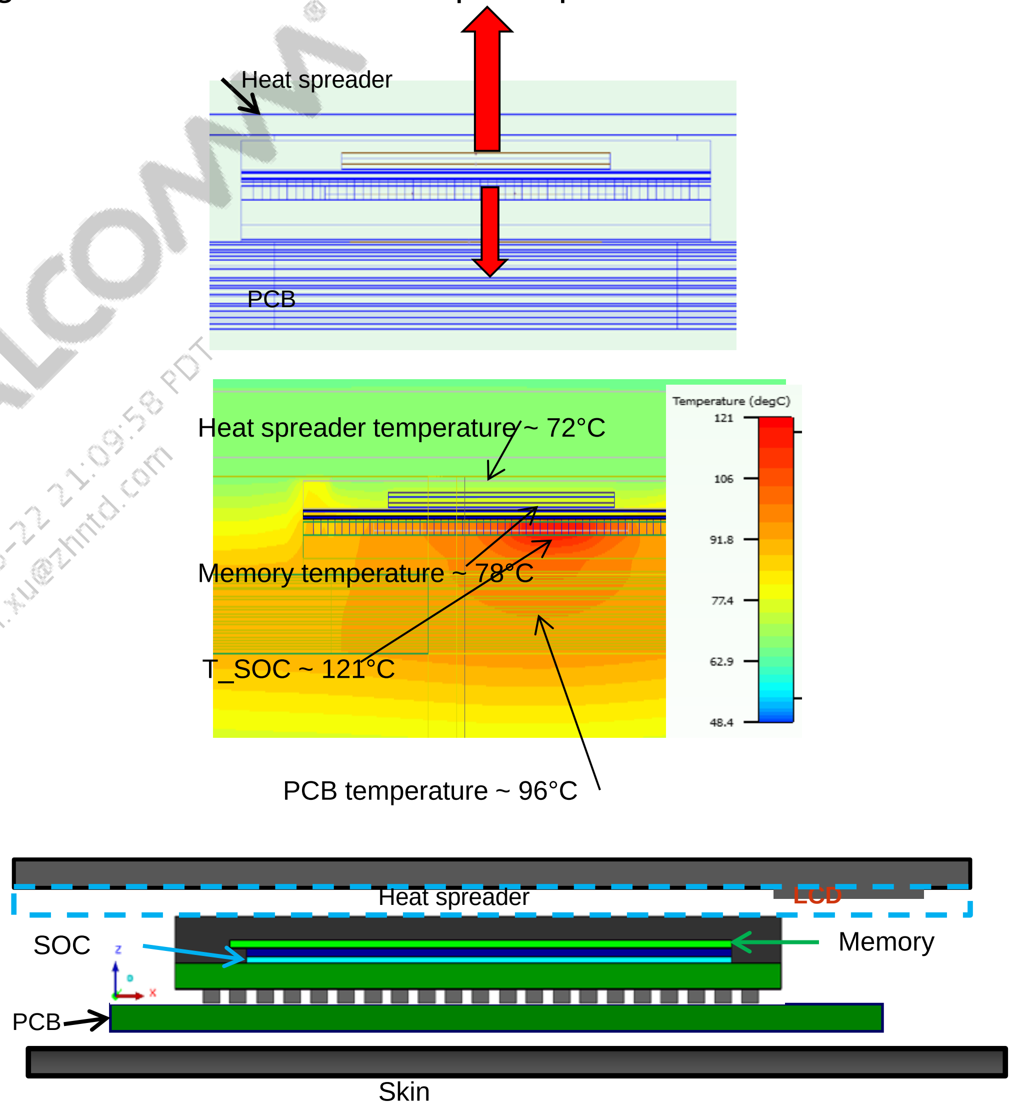
Thermal simulation

Role of Heat Spreader

Adding heat spreader on top of component package surface biases heat flow path upward.



Thermal resistance network



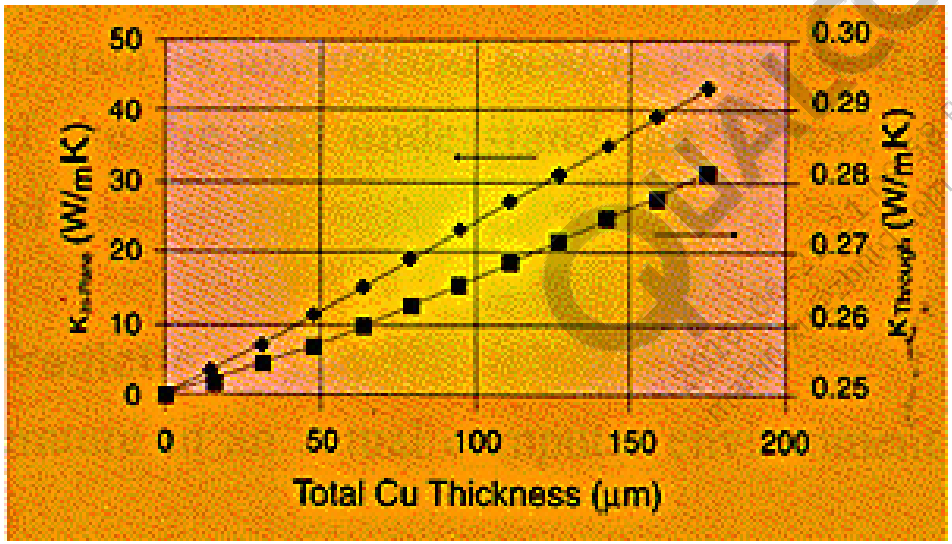
Thermal simulation

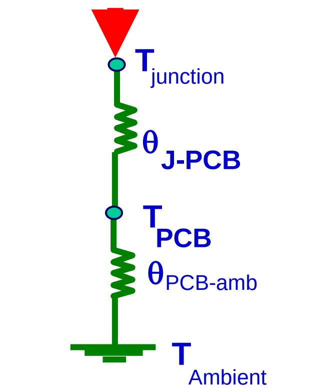
Sec. 3.2

Importance of PCB Thermal Design in Mobile Devices

In mobile devices, PCB is the heat conductor and spreader. So, improving the thermal conductivity of PCB improves PCB spreading capabilities.

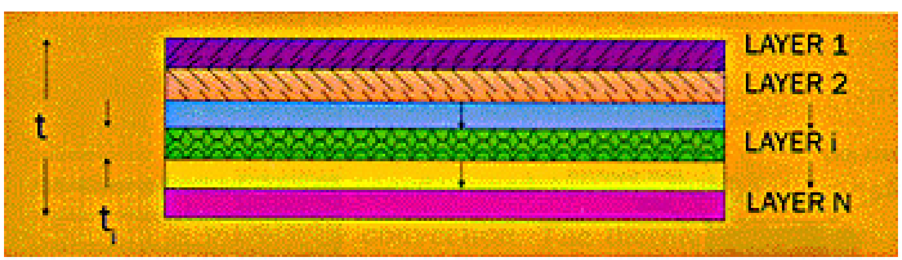
- Thermal conductivity: Total PCB thickness is 0.8 mm
- PCB comprises of only copper and FR4 layers
- k of copper is 390 W/mK; k of FR4 is 0.25 W/mK

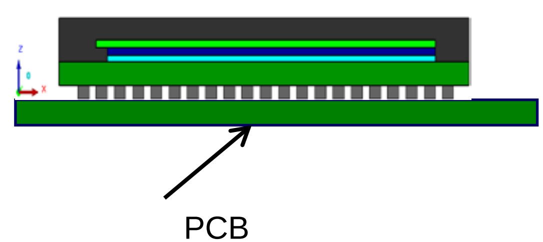




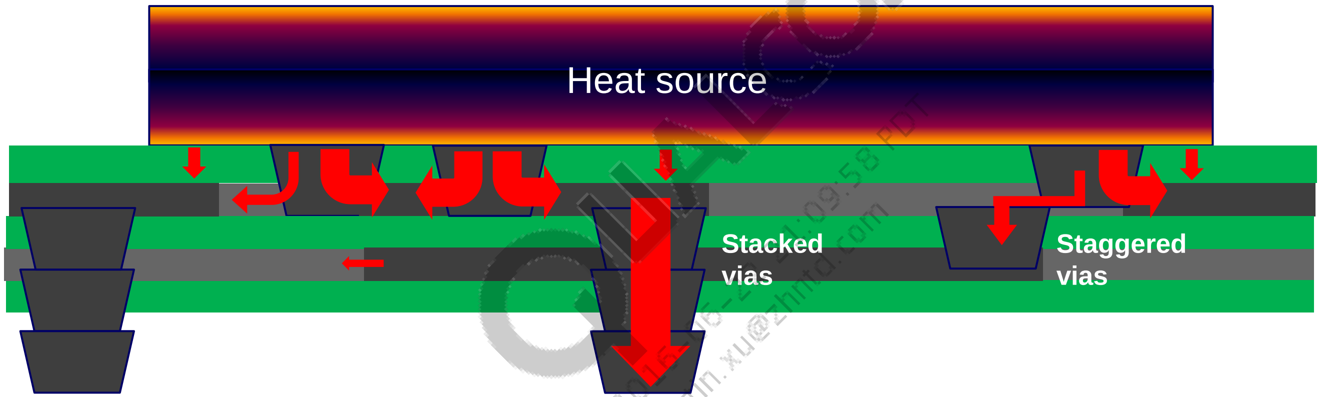
k-copper~390 W/mK;
K-FR4 ~ 0.25 W/mK

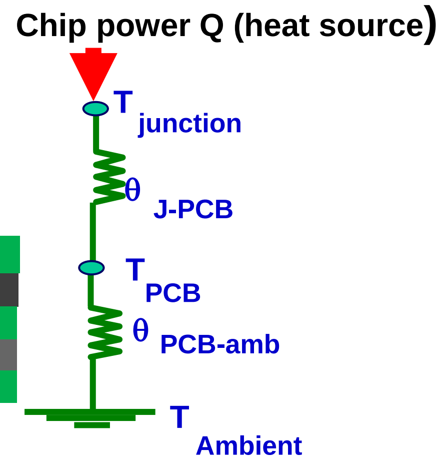
Thermal conductivity: Total PCB thickness is 0.8 mm; PCB comprises of only copper and FR4 layers.





In smartphones, OEMs rely on PCB to remove most of the heat produced by the components in the mobile devices. Therefore, it is mandatory to incorporate high number of vias under the processors and the PMICs and at least 1 oz of Cu in the ground and power planes to improve PCB spreading capabilities.



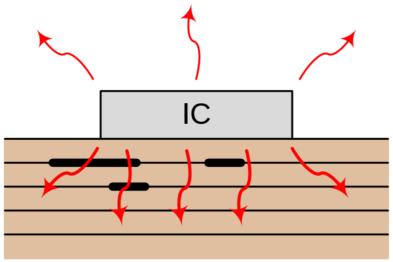


Stacked vias provide good thermal advantages

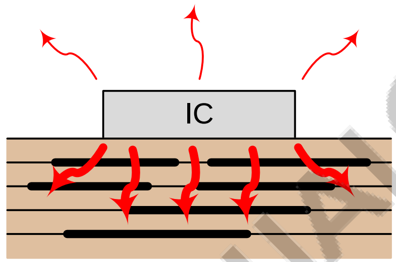
More vias provide less thermal resistance and better heat spreading and conduct more heat.

Thermal conductivity from PCB and below ICs

Poor conductivity



Better conductivity

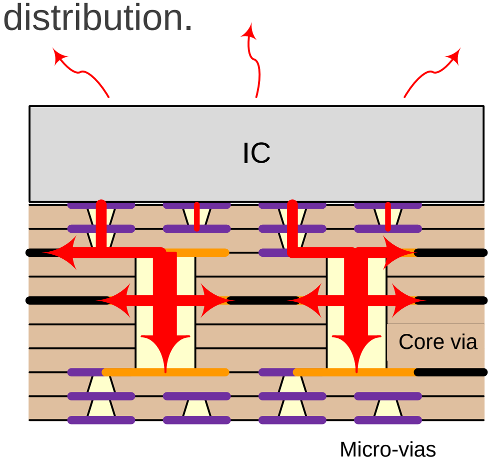


Include several layers with high copper density on each layer to increase thermal conductivity. Higher copper density provides better thermal relief and heat transfer.

- Do not rely on only air dissipation for RF power amplifiers; lots of copper is needed as a heat sink for these thermal loads.
- Fill empty board layers with copper , wherever possible.
- It is important that the mounting side of the heat source is filled with copper.
- Use thick copper as much as possible, especially for high current DC power supply distribution.

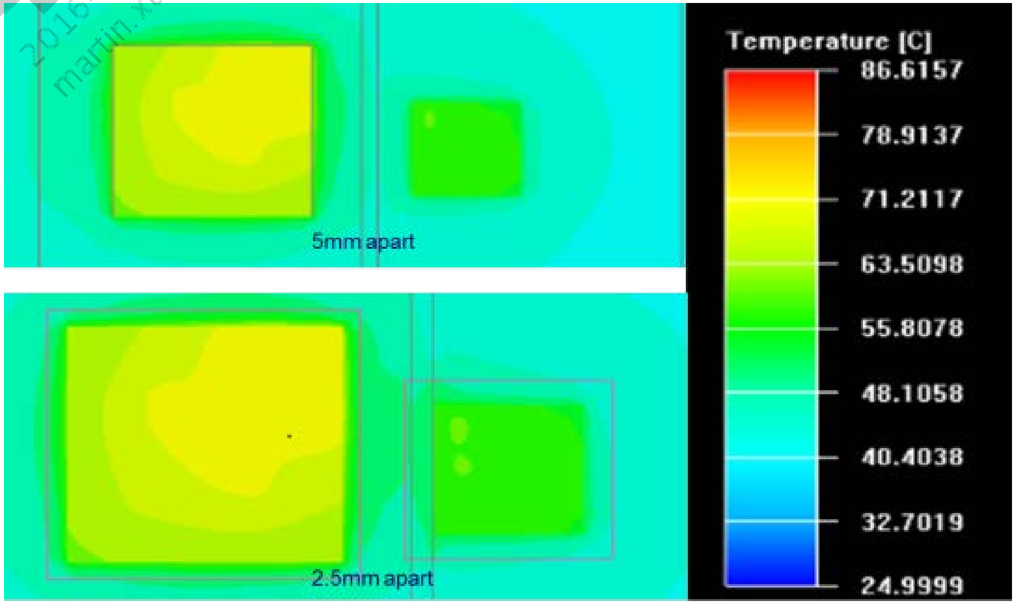
Include several vias under and around hot spots.

- Vias should go to large ground planes for better heat transfer.
- Via material is important – solid copper is better than paste.
- Core vias are better than micro vias; stacked vias are better than staggered.
- Vias in the PA ground pad are important – use as many as possible.

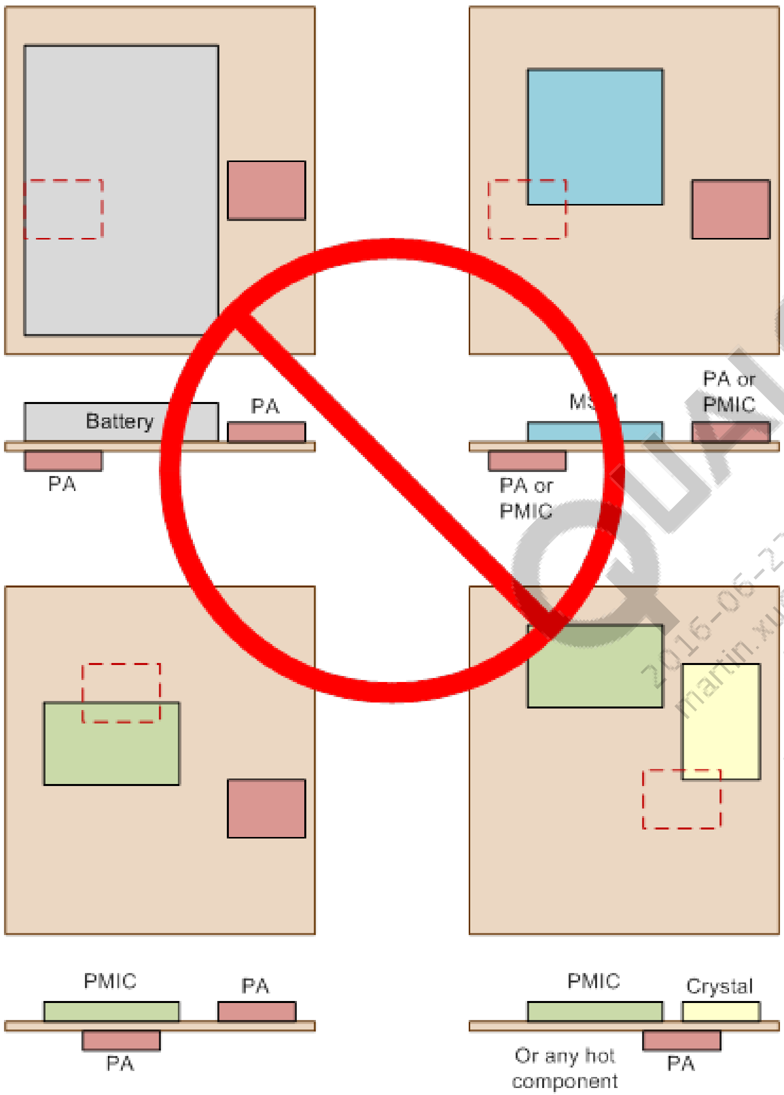


Components Placement Thermal Recommendations

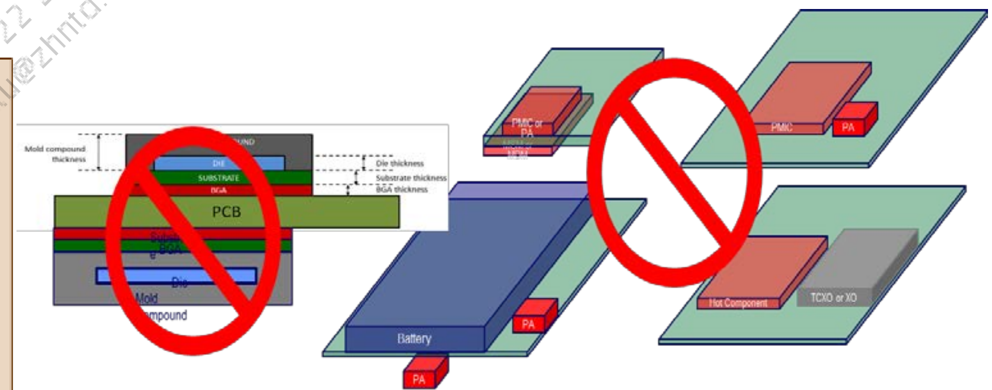
- Improve PCB via structure:
  - Longer and thinner vias create higher electrical and thermal impedances.
  - Electrical current in longer and smaller diameter vias increases electrical impedance which induces Joule heating.
  - Joule heating reduces signal propagation and increases temperature inside PCB.
  - Temperature rise inside the PCB layers reduces heat spreading.
  - Improve via matrix distribution and increase number and size, whenever possible – particularly under MSM, PMIC, and PA footprints; perform thermal simulation to estimate the optimum size, number, and structure.
  - Increase trace thickness and minimize its length, whenever plausible.
- Increase Cu contents in the ground and power planes and provide pathways for heat to spread.
- Components layout guidance:
  - Never mirror high power components such as MSM, PMICs, and PAs.
  - Minimum spacing between hot components should not be less than 5 mm from package adjacent edge-to-edge.
- Maximize PCB size when plausible .



Plan Component Thermal Placement Carefully



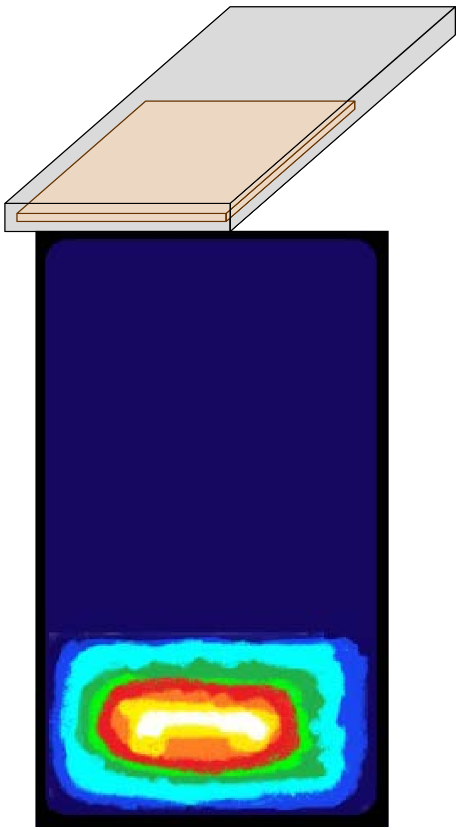
- Components placement planning is important to avoid thermal issues.
- The best ways to ensure proper components placement thermally is through thermal simulation methods.
- Just by looking into a PCB placement by the naked eye will not reveal technical facts about the potential thermal issue that might incur
- Avoid obvious placements such as shown here.



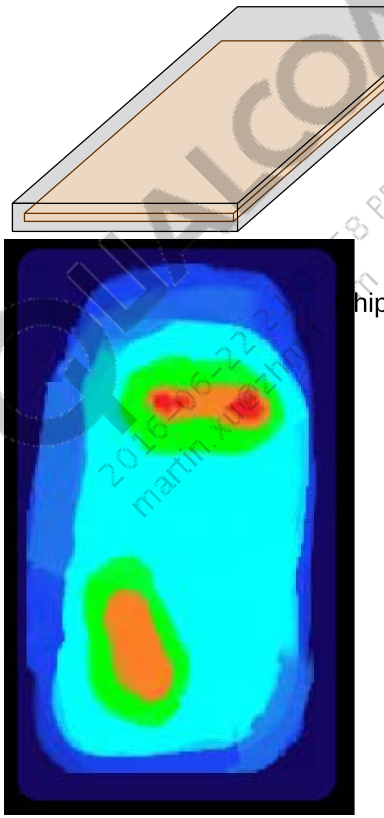
Distribute Heat Sources and Increase PCB Size

PCB Area and Heat Distribution

Spreading the heat across a large PCB surface area helps avoid hot spots within the handset.



Larger PCB area (and proper parts placements) results in better heat distribution.



Conclusion:

- Heat spreading becomes challenging with thinning phones.
- To meet skin temperature limit, thin devices must have more distributed heat sources and larger PCB to compensate for heat removal.

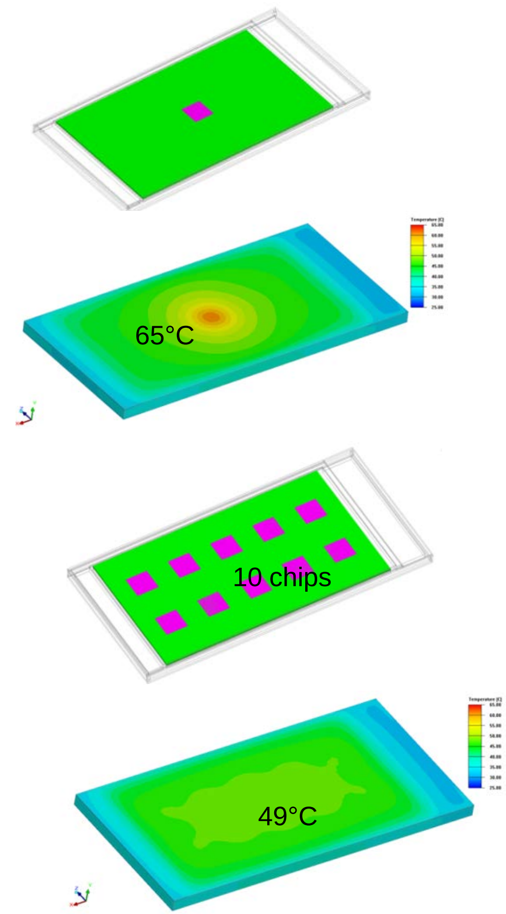
Thin smartphone (5 mm) – skin temperature profile

Two cases:

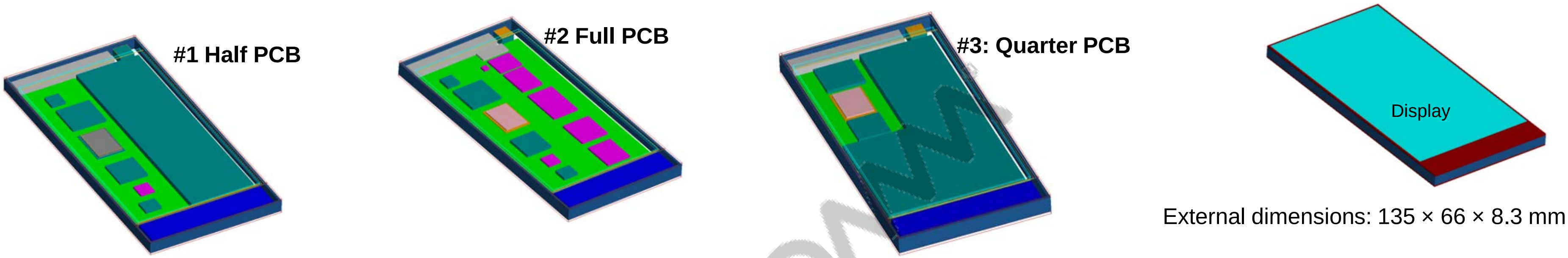
- One chip dissipating 2 W
- 10 chips dissipating 0.2 W each

Result:

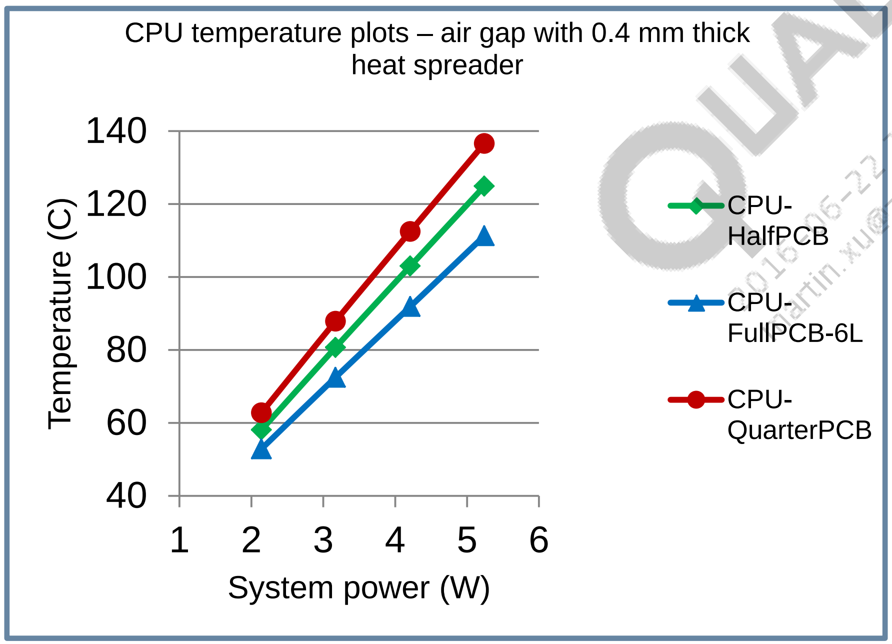
65°C vs. 49°C skin temperature



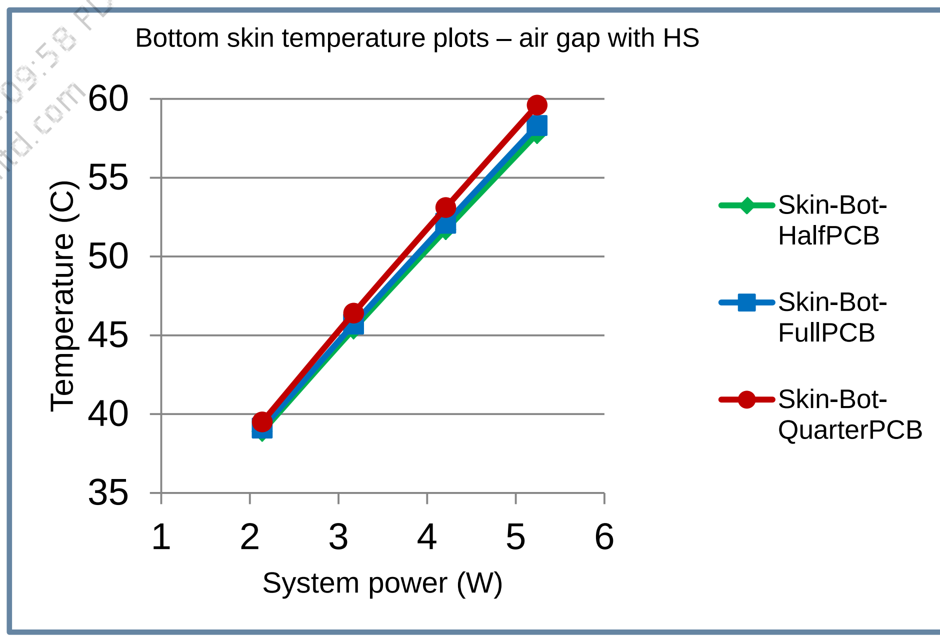
PCB Size Impact on Junction And Skin Temperature



External dimensions: 135 × 66 × 8.3 mm



Junction temperature effect of PCB size



Skin temperature effect of PCB size

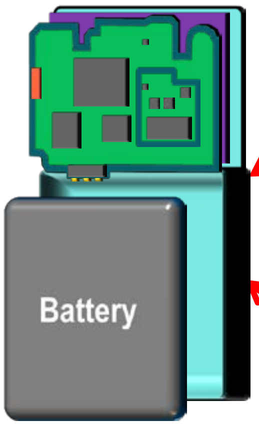
Depending on the stack inside, the smartphone junction and skin temperature can be affected by PCB components layout. Trade-off must be made considering cost and design choices for handset system.

Sec. 3.3

Mechanical Enclosure Thermal Design Considerations

Take Advantage of the Mechanical Structure of the Device

Solid metal frame and high thermal conductivity material foam helps to transfer heat over the UE housing, easing the risk of the hot spots.



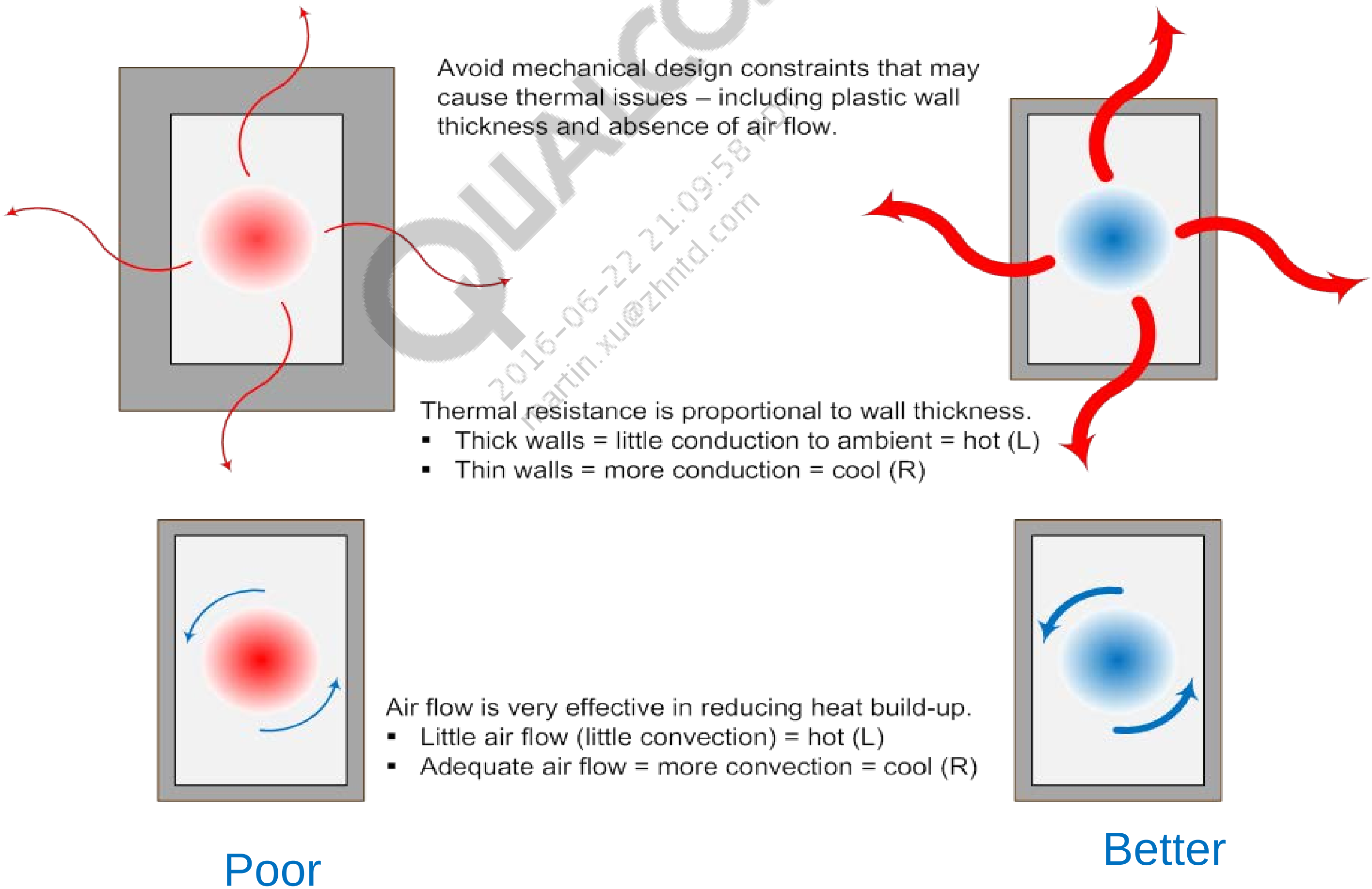
Negative engraving for battery compartment is recommended to maximize heat distribution.

How mobile devices mechanical design can improve thermal:

- Minimize gaps in the stack-up
- Increase board size when possible
- Add hidden louvers to eject heat
- Use metal frame as a heat sink
- Carefully plan system mechanical **stack-up**
- Increase surface area of the device
- Use TIM and heat spreading
- Consider using the battery and LCD as a heat sink and make physical contact between them and the components on the PCB
- Increase mechanical enclosure surface area – by using louvers and grooves with hidden venting
- Use EMI shielding surface area to absorb some of the heat induced by the device

Allow for Heat Movement in the Handset

- Improve heat removal effectiveness – encourage customers to use mechanical protection jackets for mobile devices
- Minimize heat flow path restrictions in the device stack-up – do not incur open circuit.
- Must perform thermal simulation to investigate thermal management options
- Implement heat spreading, thin heat pipes, and vapor chambers when possible – use thermal simulation to size the need.
- Minimize air gaps in the stack-up – evaluate trade-offs between shielding heat vs. conducting and removing it.

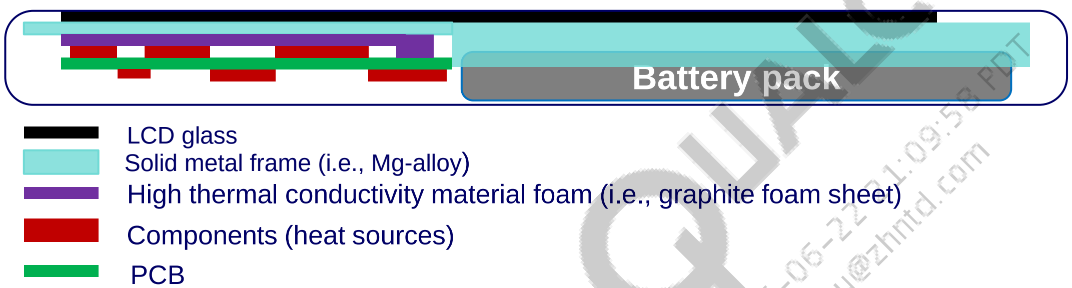


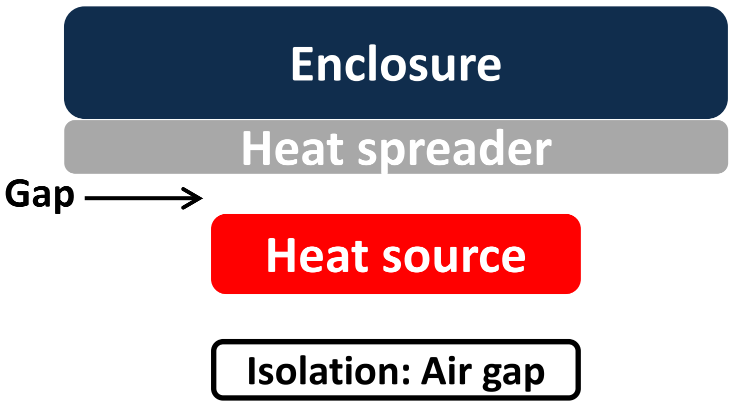
Plan the Mechanical Stack-up Architecture Carefully

Takeaway:
- Analyze system stack-up options
- While working with your mechanical and electrical teams, study design trade-offs to maximize thermal benefits. Consider system design flexibilities.

Takeaway:
Analyze trade-offs between allowing or filling air gaps with TIM.
- Does thermal conditions improve with conduction through air?

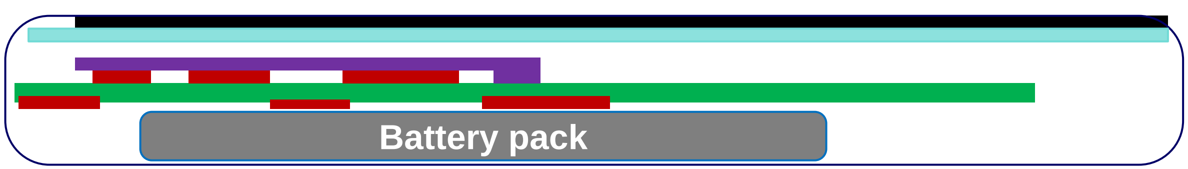
Side view, cross-sectional

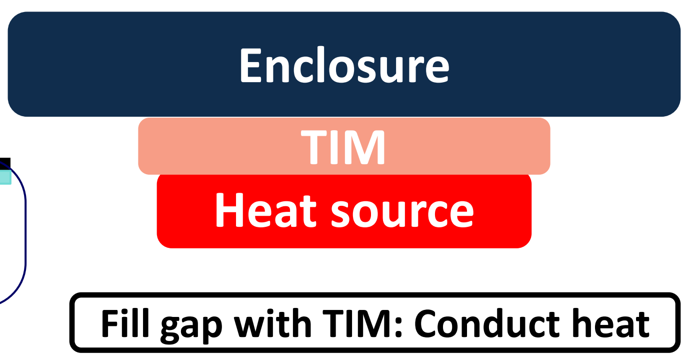




Side view, cross-sectional

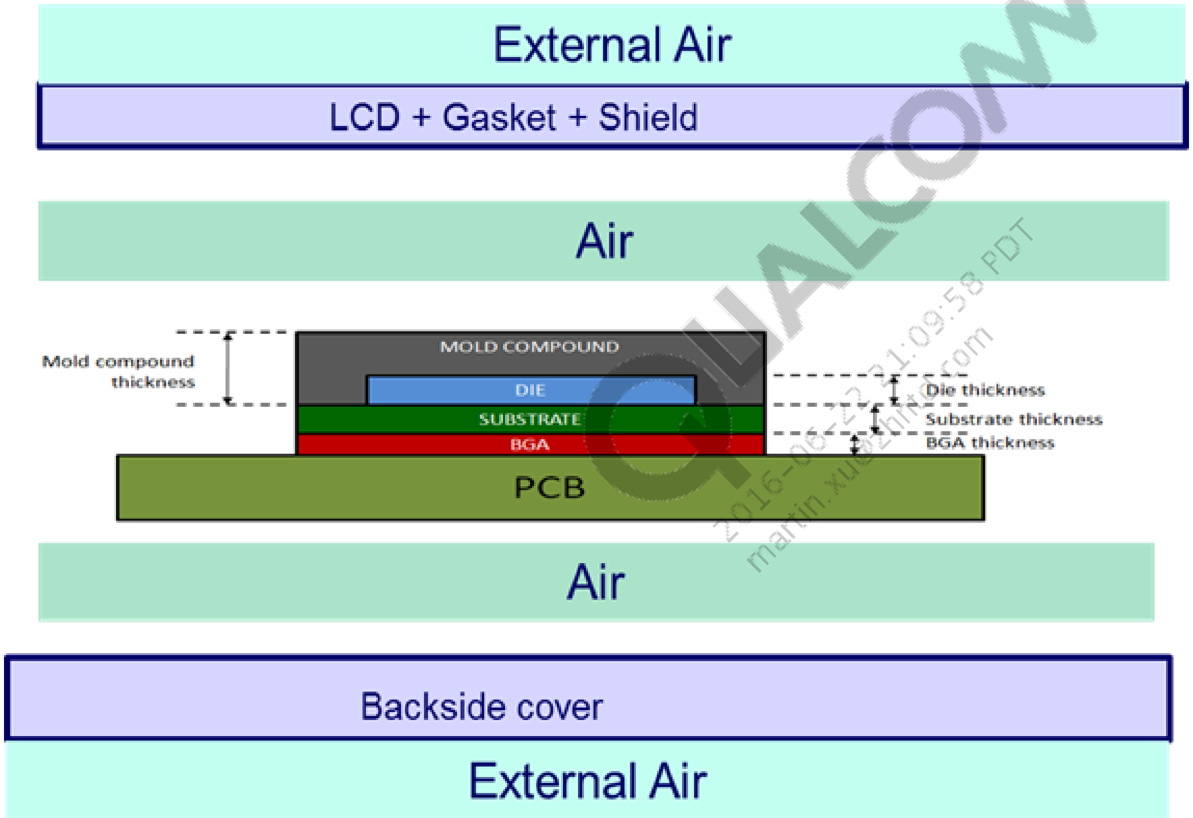
Side view, cross-sectional

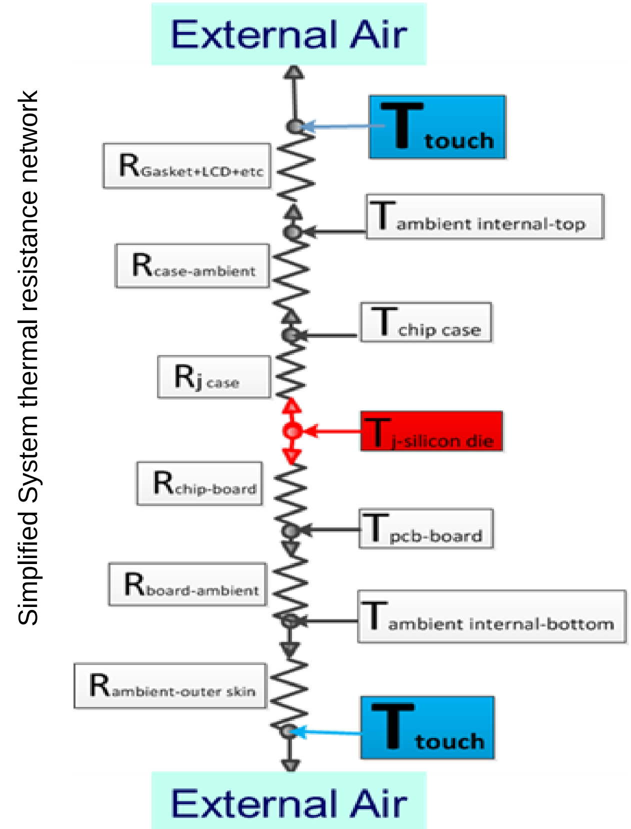




Simple Hand Calculation to Predict Temperature

To assist thermal design using system mechanical stack-up database, it is possible to predict various stack temperature values, including skin and junction temperature values.





Example:

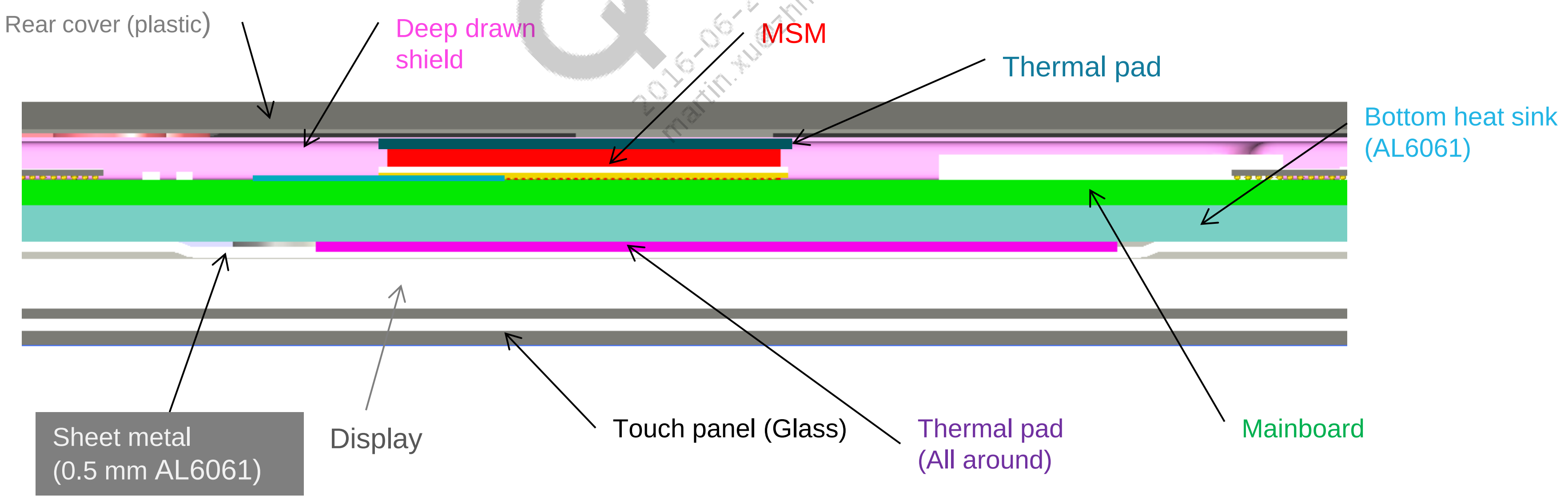
Suppose system stack up has the following thermal parameters

$\sum \boldsymbol{R\_total}$ = 15C/W; P_tdp=3W; T_a=25C ; What is T_j of the component?

$\sum R_{total} = \{T_j - T_a\}/P_{tdp}$ T_j= 70°C

Plan for Thermal Solution Implementation (1 of 2)

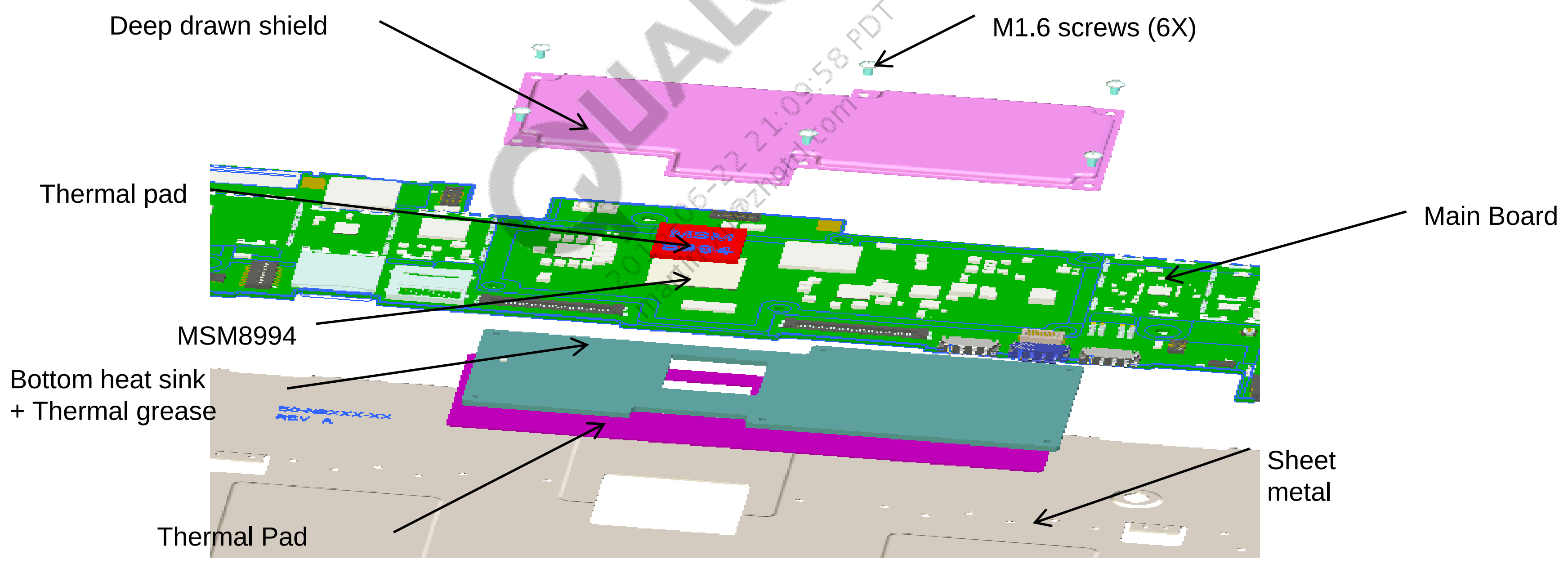
- Allocate space for TIM (thermal pad), heat spreading sheets, heat pipe, etc.
- Ensure complete contact between the MSM chipset, the TIM, or any heat spreading material.
- Thermal simulation will provide valuable information of:
  - Size and type of the TIM (heat spreading) material necessary
  - Thermal design choices and trade-offs such as cost and performance
  - Surface area increases possibilities
  - Placement and stack-up choices for battery, frames, ribs, heat spreading, and TIM materials
- Careful thermal and mechanical design implementation and planning can remove most of the heat generated in an application but when the system runs at high performance level and device skin temperature still exceeds the thermal specification, performance throttling by software mitigation is needed.



In this stack-up, compromises were made between cost and performance to allow for thicker device.

Plan for Thermal Solution Implementation (2 of 2)

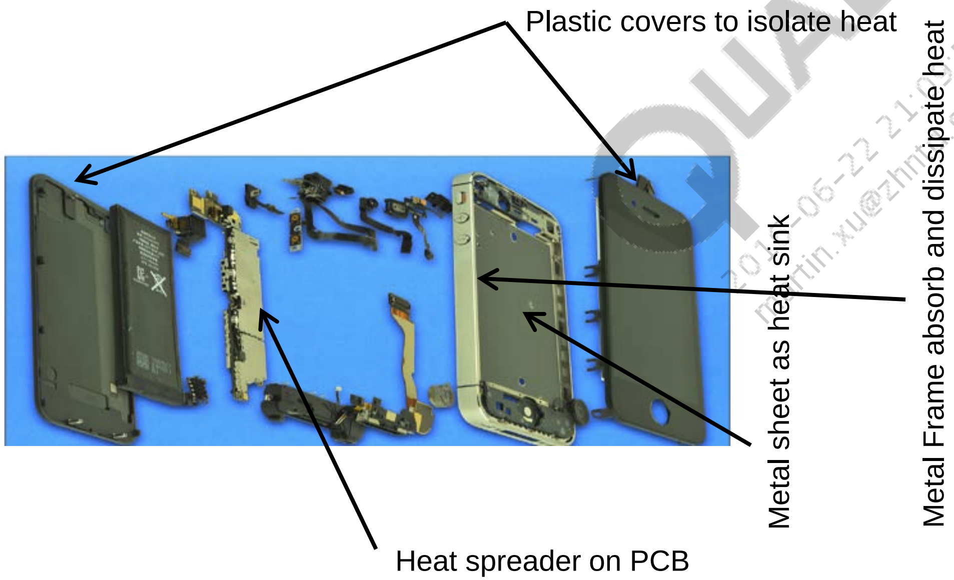
- Use exploded mechanical views to plan the hardware stack-up.
- Perform tolerance analysis to size the thickness of the heat spreading material type and thickness.
- Allow sufficient space for the thermal solution.
- Analyze your manufacturing constraints and limits.
- Couple the thermal strategies with the mechanical design to sync with the design goals and performance.
- Performance, cost, and market segment are trade-off that the design must meet.

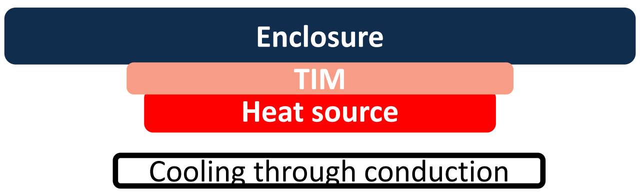


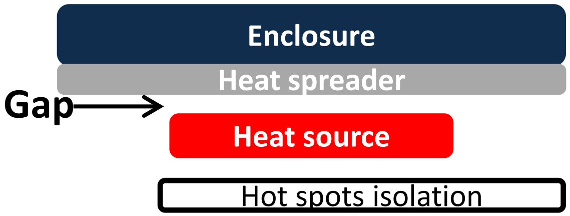
In this stack-up, design compromises were made between cost and performance to allow for thicker device.

Plan Mechanical Enclosure Design in Parallel With Other Hardware

- Mobile device mechanical design is the place to investigate thermal solution options.
- Careful planning must be considered at early stages of the design to couple both thermal and mechanical designs
- Thermal and mechanical design goals
  - Minimize & isolate hotspots from rest of the device's skin
  - Reduce device skin temperature
  - Delay SW thermal mitigation action
- Thermal and mechanical design implementation strategies:
  - Direct (conduction) cooling
  - Hot spot isolation
  - Both methods help ASICs and devices skin at lower temperature than without such methods







Thermal design tip: When the air gap between the internal hot spot and the external enclosure is very small, heat spreader used in "isolation" will significantly cool the internal hot area as there is dominant heat conduction from the inside to the heat spreader through the air.

Sec. 3.4

Estimating Mobile Device Thermal Capacity

Estimating Mobile Devices Thermal Power Dissipation Capacity

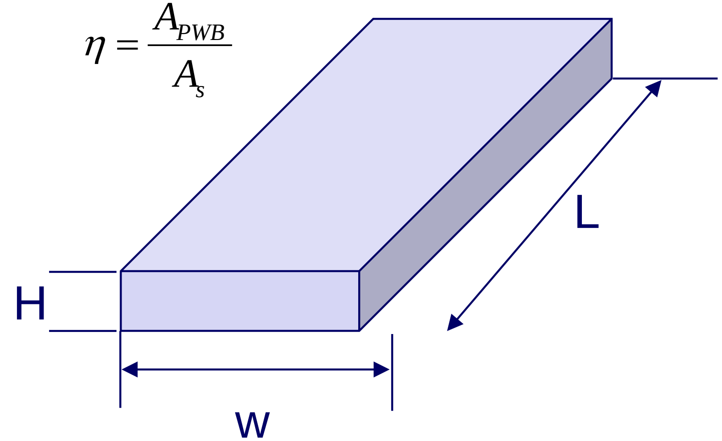
Practicable power dissipation limit, to the 1st order, can be approximated as a ratio of the total PWB and device surface areas.

$$P_1 = \frac{0.25mW}{mm^2} \times A_s \times \eta$$

$$A_{PWB} = \sum_{i=1}^{n} 2L_i W_i$$

$$A_s = 2WL + 2WH + 2LH$$

$$\eta = \frac{A_{PWB}}{A_s}$$



Example -2: Mobile device with the following form factor geometrical dimensions:
PWB: 56 × 58 mm; ε = A_{pwb}/A_s efficiency of the mobile device add by considering PWB
W = 60 mm; L =115 mm; H = 10 mm
We are interested in evaluating its first order power capability limits.

$P_{limit}= \frac{0.25mW}{mm^2}*A_s*ε=\frac{0.25mW}{mm^2}*17{,}300mm^2$= 4,325mW=**4.325W**

Surface area =A_s= 2WL + 2WH + 2LH

A_s= 2*60*115 + 2*60*10 + 2*115*10

A_s= 17,300mm^2

For first order calculations, the device can withstand a total thermal power of 4.33 W.

Power level of greater than 4.5 may cause the device **skin-touch** to exceed required limits**.**

Note: Approximation ignores contributions from the display and the battery assumes the PWB is isothermal .

Only detailed thermal simulation can determine device thermal limits.

Estimating Mobile Devices Temperature Rise

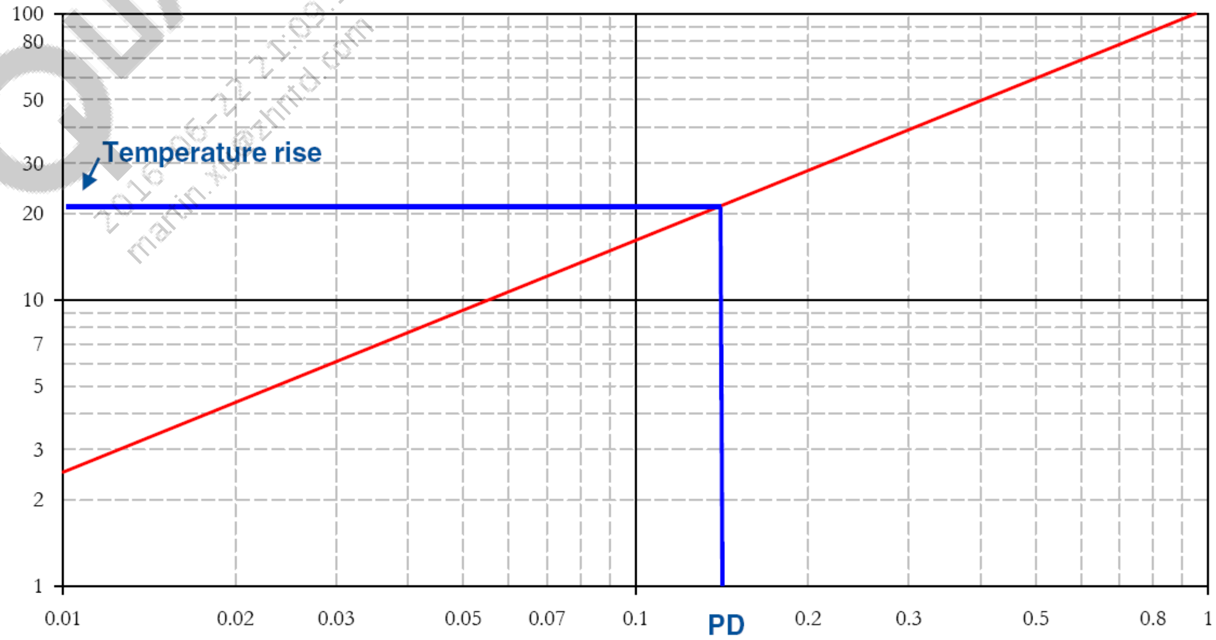
A quick calculation and use of the plot below provides an estimate of a design's external surface (skin) temperature rise.

1. Calculate total surface area: A = 2 (D·W + D·L + W·L)
2. Calculate the total power dissipation (P)
3. Calculate the surface power density: PD = P/A
4. Estimate the temperature rise from the plot

In the example (blue lines):

PD ~ 1.5 W/in2

DT ~ 21°C



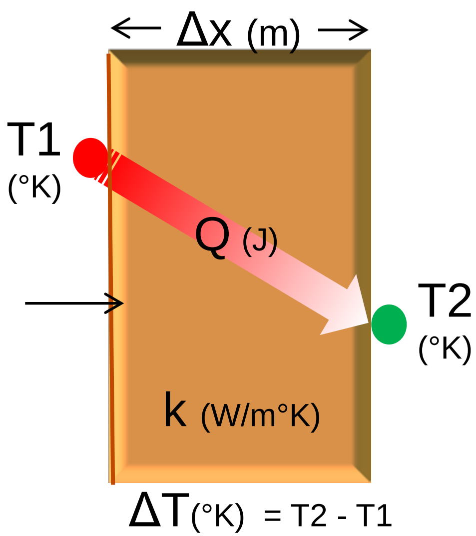
Sec. 4

Material for Mobile Devices Thermal Design and Heat Management

Heat Transfer (Temperature Travel) in Material: Conduction Heat Transfer

Consider current flow in a resistor

Conduction



Q' = heat transfer rate (W)

$$\frac{\Delta Q}{\Delta t} = -kA\frac{\Delta T}{\Delta x}$$

- A larger thermal conductivity (k) material conducts heat better.
  - Metal shields, PCB ground planes, graphite sheets, and device skins made of higher k materials help lower peak temperatures in devices by transferring larger amounts of heat energy away from hot spots (a.k.a heat spreaders).
    - Graphite (in-plane): k > 370 W/m°K
    - Copper: k = 360 W/m°K
    - Aluminum: k = 205 W/m°K
    - Magnesium: k = 156 W/m°K
    - Plastic: k = 0.2 W/m°K
    - Air: k = 0.024 W/m°K (air has 15,000x the thermal resistance of copper)
- A larger heat transfer surface area (A) conducts heat better.
  - Heat spreaders extend heat-transfer surface area of ICs when attached to the IC through a high-k material. (e.g., PCB GND plane connected to IC by solder balls)
  - A PCB ground plane's thickness and width (cross sectional surface area), number of layers and vias is a critical item in reducing IC peak temperatures by spreading heat energy.
- A larger temperature differential (ΔT) across a smaller distance (Δx) conducts heat better.
  - In the device skin, ΔT is constrained by maximum allowed skin touch temperature (T2).

Compliant Gap Filler (1 of 2)

Touch temperature limits for device surface

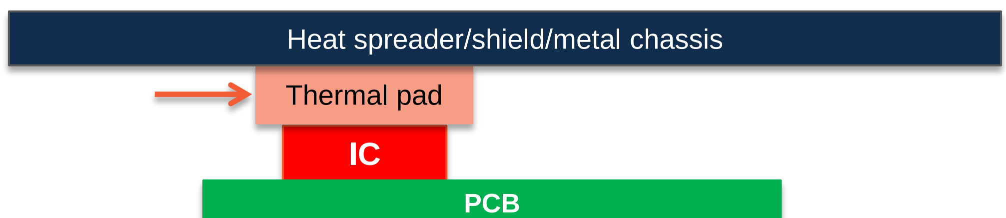
- IEC and Underwriters Lab have similar specifications (see table below).
  - UL 60950-1 in the United States (same as Europe, Canada, Australia, etc.)

- OEMs/carriers typically
  - Have operating temperature specifications of 45°C (25°C ambient case)
  - Limits external rise over ambient to ~20°C
  - Maximum operating temperature of 40°C (ambient) → Total temperature = 60°C < Limit (non metal)

EN60950-1:2005 Max Temperature	External surface of equipment which may be touched	Knobs touched for a short period (10 s)	Handles or grips continuously held in normal use
Metal	70°C	60°C	55°C
Ceramic and glass	80°C	70°C	65°C
Plastic and rubber	95°C	85°C	75°C

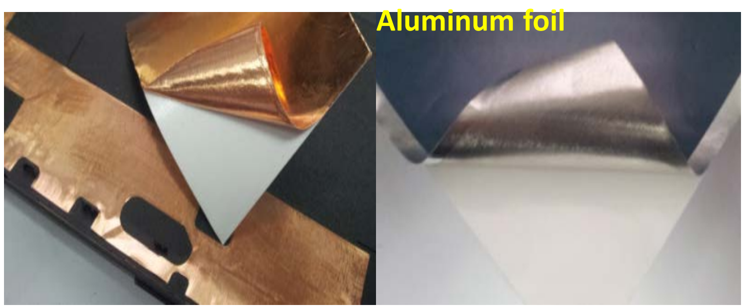
Compliant Gap Filler (2 of 2)

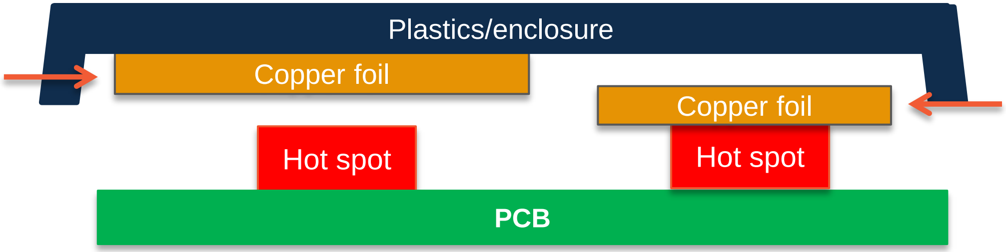
Material type	How and where used in smartphones	Advantage	Disadvantage
Compliant thermal gap filler pads or TIM	Used as a gap filler on the top surface of components or between any two adjacent surfaces. Typical thickness ~0.2–1.0 mm Thermal conductivity	▪ Flexible and compliant – low shore value ▪ Easy to handle and cut to sizes and shapes ▪ Cheaper and widely available ▪ Good heat storage till steady state and then conducts heat later on	• It conducts heat equally in all directions so it is not useful as a thermal shield • Low thermal conductivity



Copper and Aluminum Foils

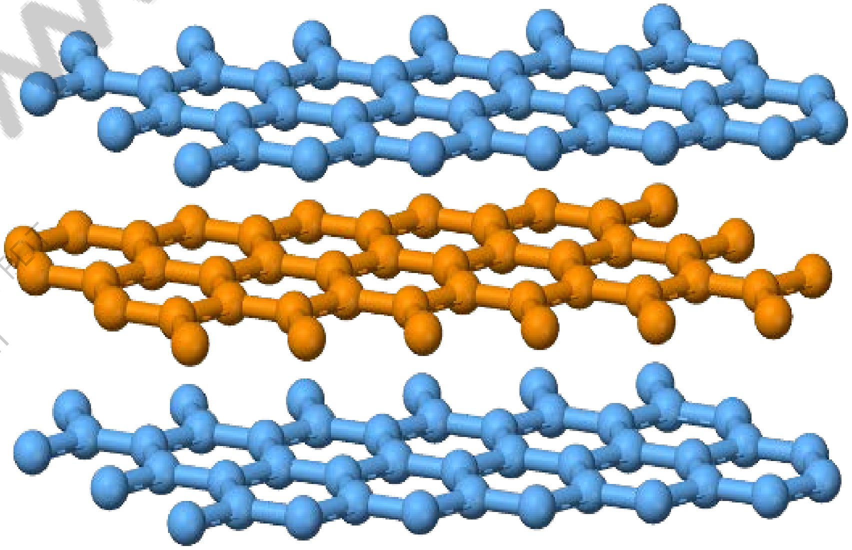
Material type	How and where used in smartphones	Advantage	Disadvantage
Copper and aluminum spreader sheets or foils	Used as heat spreader on the top surface of components or adhered to a hot surface – typically used as a large heat sink sheet of 0.1 mm thick or thicker in smartphones. Commonly used in combination with thermal grease to ensure contact with hot surfaces.	• Good thermal conductivity • Has better heat transfer coefficient to remove heat than PADs • Widely available and cheaper than graphite	• It conducts heat equally in all directions so it is not useful as a thermal shield • Rigid – not compliant; needs thermal grease for complete contact or adhesives • Could create RF interference issues if placed close to the antenna • Copper is heavy – adds weight

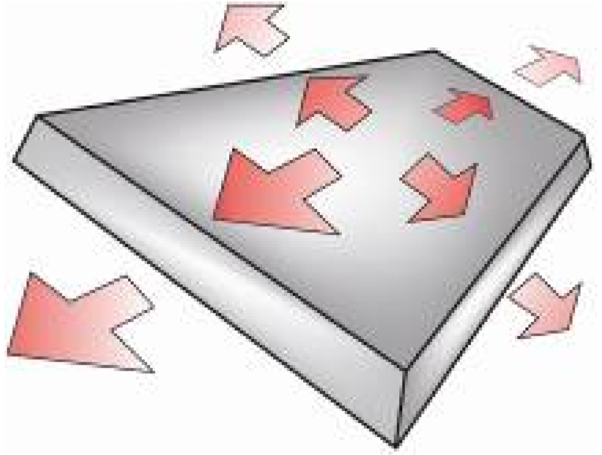




Graphite (1 of 7)

- Graphite is anisotropic:
  - Anisotropy (not isotropic) is the property of being directionally dependent
  - Due to the layered crystal structure, graphite maintains different physical properties in different directions





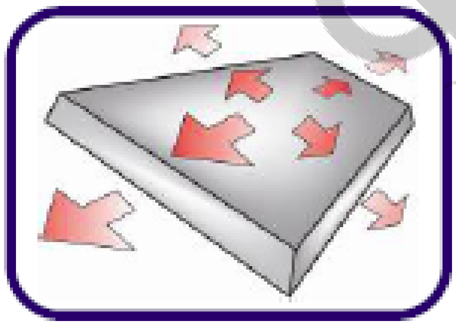
- In finished sheet form:
  - Higher in-plane thermal conductivity
  - Lower through-plane thermal conductivity

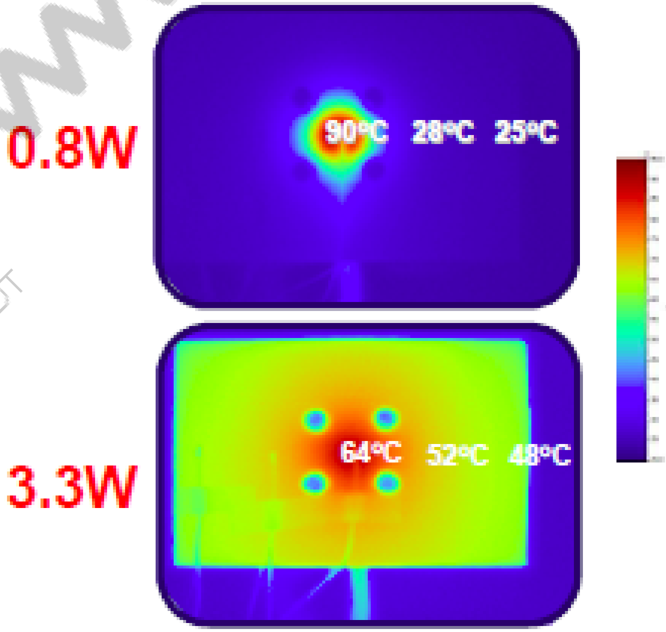
Graphite (2 of 7)

- Typical uses of graphite spreader:
  - Cool heat sources: Power amplifiers, CPU's, and GPU's
  - Spread heat: Evenly over the surface of the OLED or LCD
  - Shield heat: From reaching LCD or OLED display
  - Shield heat: From reaching user through back cover
  - Shield heat: From reaching battery and causing premature cell failure

Why Heat Spreaders?

- A 0.8W heat source (simulating a handset power amp) can generate a 90°C hot-spot
- A 110µ thick die-cut SPREADERSHIELD part can reduce hot-spot temps by 29% while allowing a 400% increase in power (~3.3W)



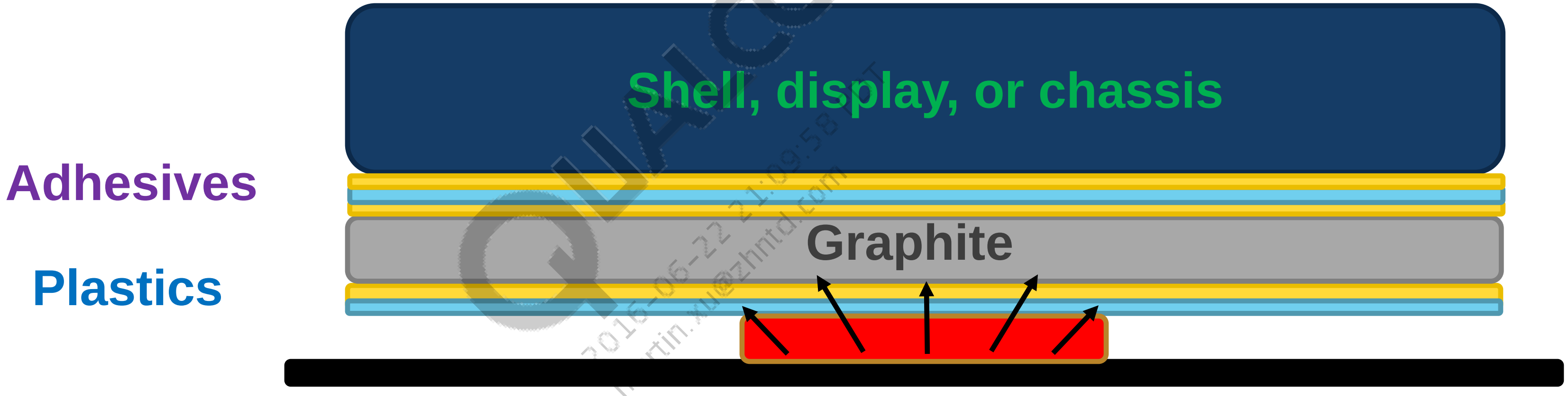


Actual thermal images from a bare 0.8W heat source vs. a 3.3W heat source with SPREADERSHIELD™

SPREADERSHIELD components significantly reduce hot-spots

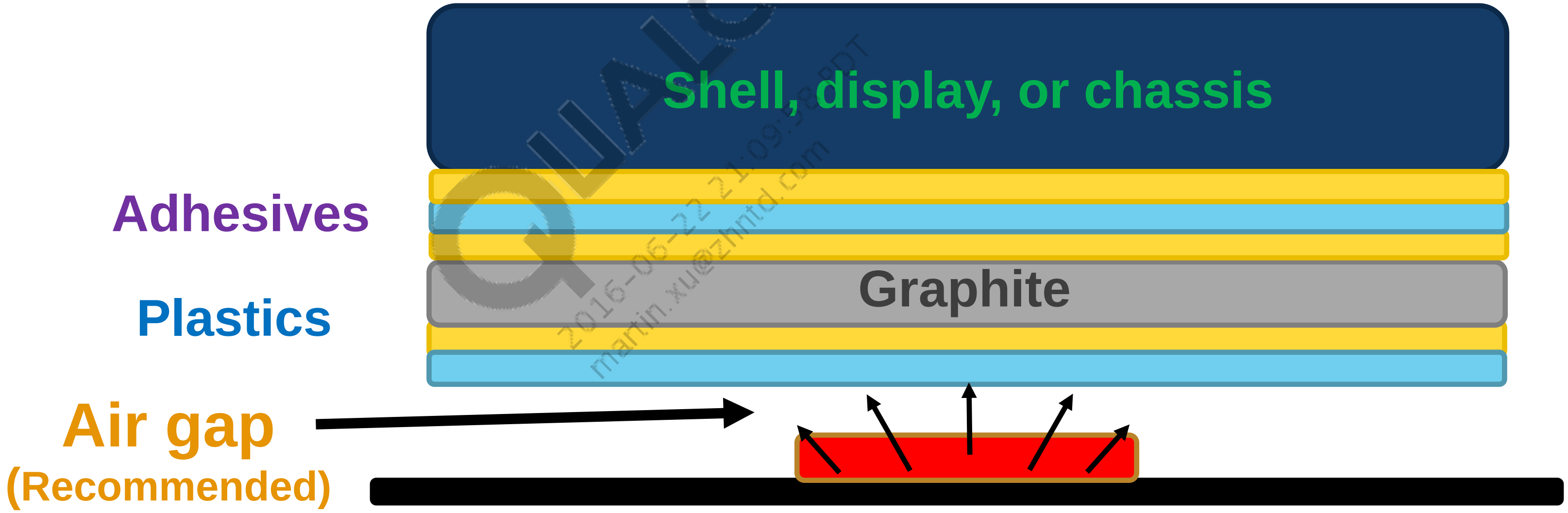
Graphite typically either cools a hot component or shields a temperature sensitive component from hot spots .

- To cool a hot component, use thin plastic (1–2 μm) and thin plastic/adhesive (10–12 μm).



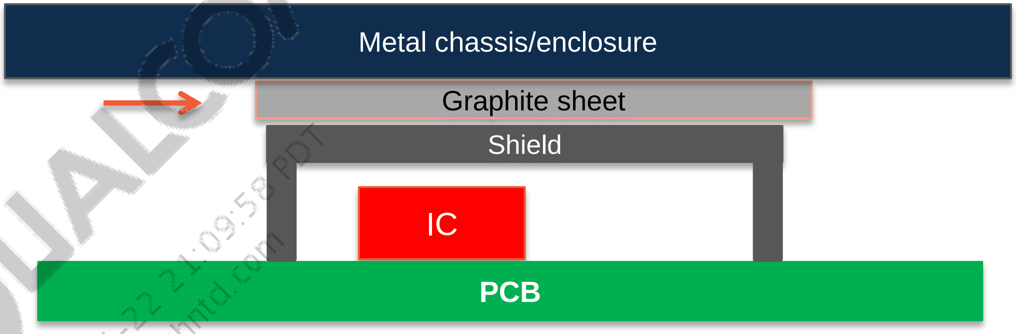
Graphite typically either cools a hot component or shields a temperature sensitive component from hot spots.

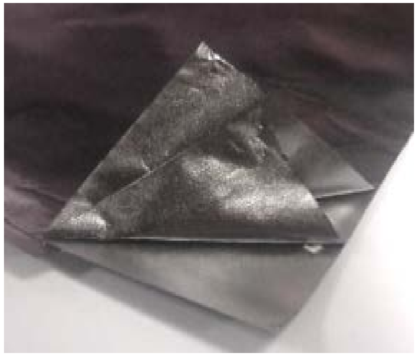
- To shield, use thick plastic (13 µm) and thick plastic/adhesive (30–38µm).

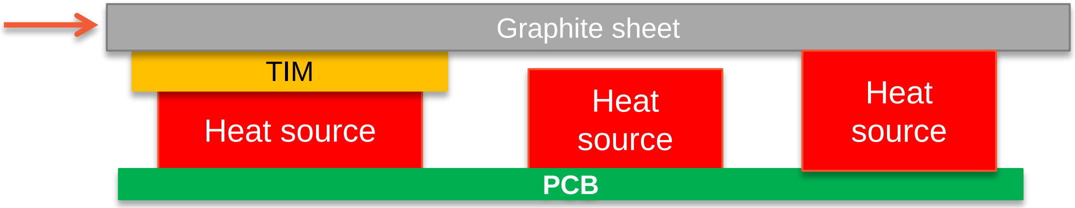


Material type	How and where used in smartphones	Advantage	Disadvantage
Natural and artificial graphite sheets	Used as: • Heat spreader on top surfaces of components or adhered to a hot surface • An isolator or a heat shielding layer • Can be used in conjunction with TIM or metal foils • Come in single and multilayers depending on the thickness available in the handset. Multilayer graphite sheets absorb more heat and have higher heat capacity than single layer but thicker	• Very good thermal conductivity • Due to its anisotropic (nonisotropic) thermal conductivity– makes it excellent method of both heat spreading and shielding for smartphones • Very light weight compared to metal foils • Does not impact RF as metal foils • Widely used and proven to provide thermal advantages • Easy to cut into shapes and sizes • High spreading capability – provides temperature uniformity lower hot spots	• Expensive than metal foils and gap fillers • Limited number of suppliers

Single and multilayer graphite sheets recommended implementation techniques in smartphones.



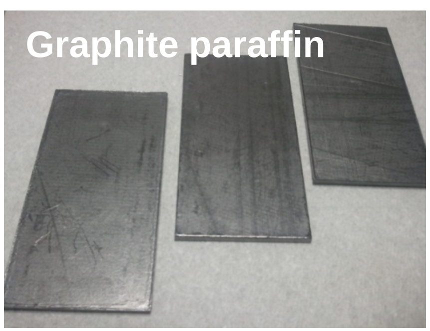


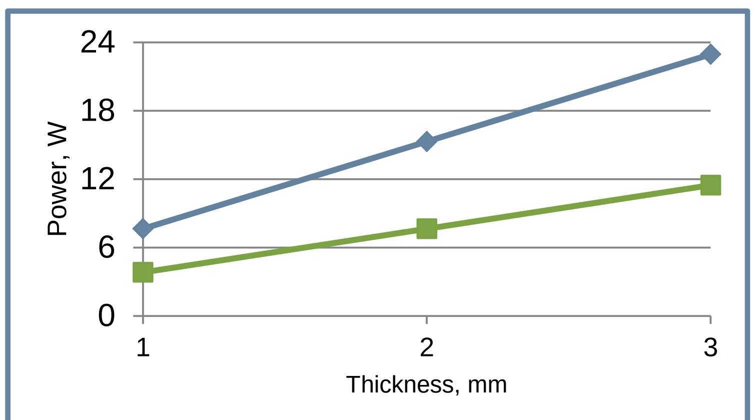


(Same as the application of single-layer graphite sheet)

Other Materials

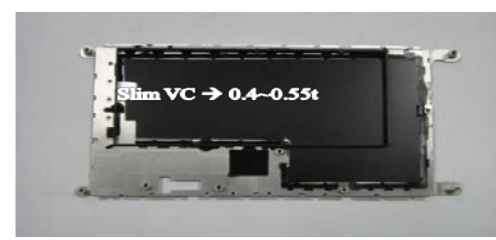
Material type	How and where used in smartphones	Advantage	Disadvantage
PCM: changes state → solid to viscous state when heated to certain temperature. It solidifies when heat is removed	• Used as a heat absorber and in combination with metal foils • PCM is naturally tacky and keeps in solid state for easily assembling. • Can be used as gap filler gap < .15 mm but needs external force for contact	• Fairly cheap • Easy to use and cut into pieces • Higher thermal conductivity than some PAD material • Low thermal resistance	• Difficult to handle • Bad electrical isolation due to phase transition • Bad electrical isolation due to phase transition • The volume requirement may be too high for mobile application, especially smartphones • The thermal conductivity of PCM is usually poor, possibly preventing complete melt
Thermal gel and Paraffin	• Not widely used in smartphones • Used as gap filler due to its softness • Can be used to fill EMI shield to absorb the heat from the heat sources	• Low thermal resistance • Good heat capacity • High latent heat, high density, high thermal conductivity, melting temperature of interest, low toxicity	• Need special handling equipment to implement such as injection equipment in production line • Expensive





HP and VC

Material type	How and where used in smartphones	Advantage	Disadvantage
Heat pipes (HP) and vapor chambers (VC) – Very thin (0.5–0.8 mm) and long tubes filled with fluid. The walls of both VC and HPs are sintered to allow for vapor condensation. The fluid latent heat provides good cooling in a closed loop fluid flow cycle – from hot to cold	Used to : • Remove and conduct heat away from heated location to a cooler one • There are two sides for HP: hot (at the heat source) and cold; the cold side must be attached to a lower temperature location in the handset such as a battery or any location at lower temperature than the heat source	• Has higher capacity of removing more heat than graphite sheets and TIM • Helps reduce hot spots and improve performance and increases application time before system slow down • Widely available	• Not as flexible as metal foils and graphite sheets • Need mechanical design • Higher cost same or higher than graphite • Thin HP and VC are still in early stages of development – yield rate issue



Thermal Material Suppliers

Supplier name	Thermal management type
GrafTech http://www.graftech.com	Manufactures thin (~0.1–0.3 mm thick) graphite heat spreader sheets used in Mobile Devices
Panasonic http://www.panasonic.com/industrial	Provides thin (~10 µm) impregnated and no fill type graphite heat spreader sheets.
Laird Technologies http://www.lairdtech.com	Supplies TIM/gap filler.
Fuji Poly http://www.fujipoly.com	Manufactures thin sheets of silicon with high conductivity and aluminum based thermal interface material.
Parker Hannifin Chomerics http://www.chomerics.com	Thin custom made copper foils that can be bent and shaped to fit any size IC package – widely used in the small form factor electronic systems. Also manufactures TIM/gap fillers
Bergquist Company http://www.bergquistcompany.com	Provides phase change materials, TIM/gap fillers, and other interface material.
AVC http://www.avc.com.cn	Manufactures very thin heat pipes, vapor chambers, and other special purpose heat sinking products.
CoolerMaster http://www.coolermaster.com	Manufactures very thin heat pipes, vapor chambers, and other special purpose heat sinking products.
Suzhou Tianmai Thermal Technology Co., LTD http://www.sz-tianmai.com	Manufactures very thin heat pipes
Shin-Etsu www.shinetsu.co.jp	Used as a paste for making good contact between rough surfaces. Product names: X-23-7868-2D & X-23-7772-4 (Note: not necessary to use if a flexible TIM pad is used).
Dow Corning http://www.dowcorning.com	Manufactures thermal PADs (TIMs), thermally conductive adhesives, etc.
Murata http://www.murata.com	Manufactures thermistors for temperature detection of XO, PA, camera, charger, WLAN, and device kin

Sec. 5

Mobile Devices Thermal Design Case Studies

Smartphones Thermal Design Case Studies

- Examples show:
- Impact/improvement of implementing heat spreading in smartphone devices
- Techniques/methods of implementing heat spreading in smartphones

Note:

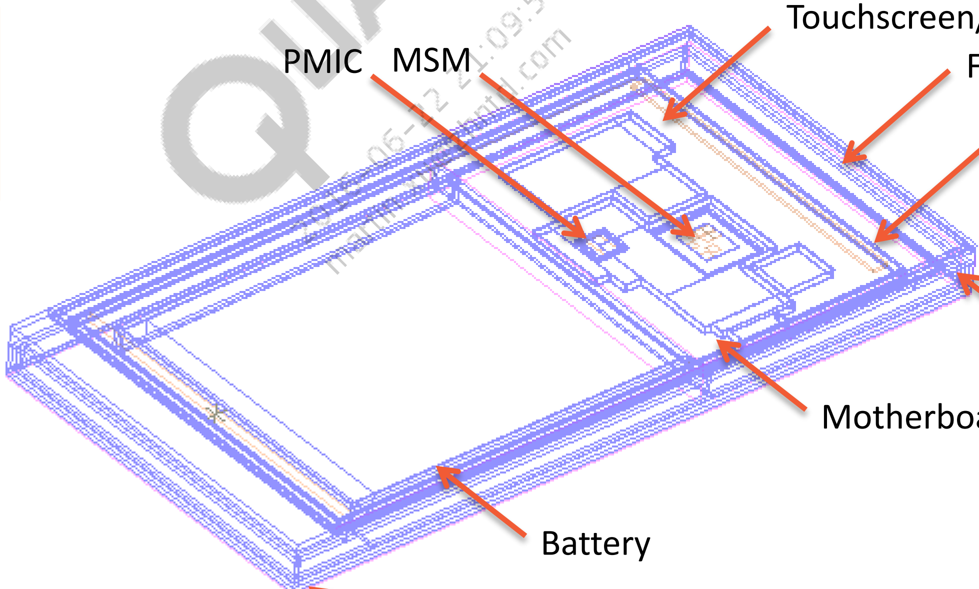
- The slides illustrate how thermal material (graphite sheets, heat pipes, and vapor chambers are being implemented in a design.
- End users are encouraged to use their own imaginations to design their thermal management methods.
- Thermal simulation will help in deriving a proper implementation.

Simulation of TIM/Heat Spreader

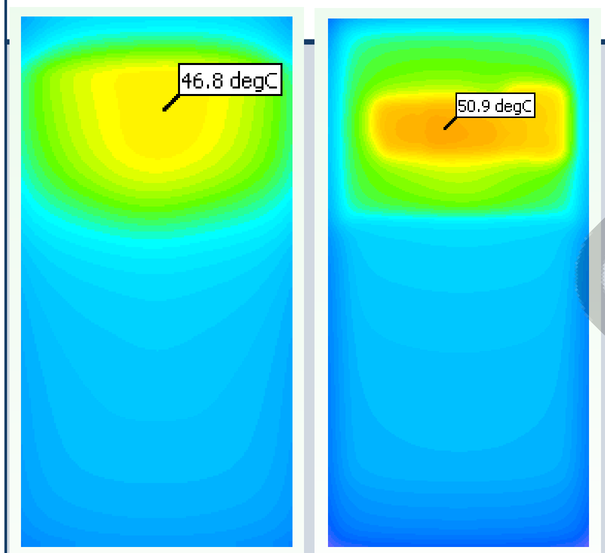
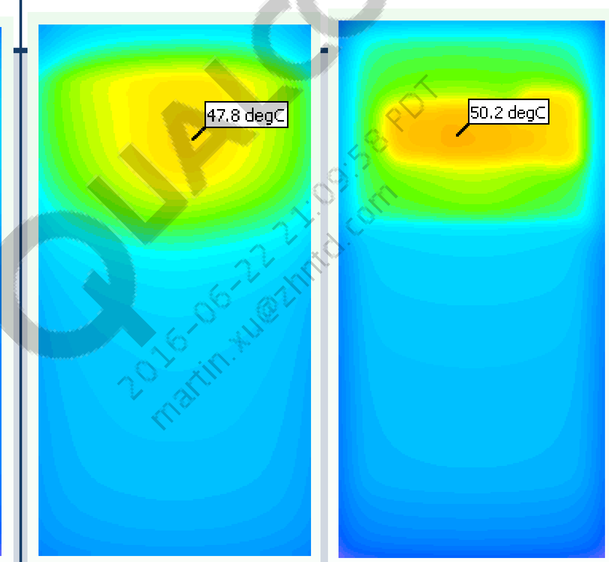
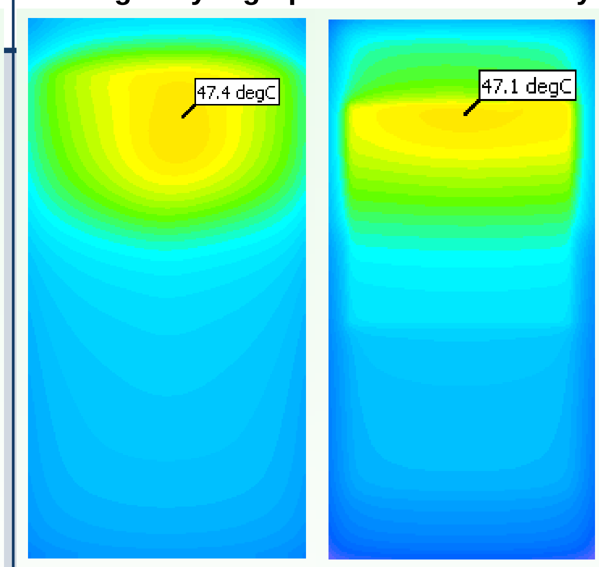
Thermal simulation

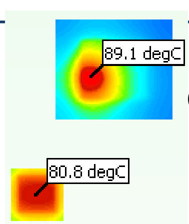
Case studies of TIM, copper foils, and graphite heat spreader implementation in mobile devices .

Ambient
25°C
Main heat sources
Pd on MSM: 1.8 W
Pd on PMIC: 1.1 W
Pd on display: 0.4 W

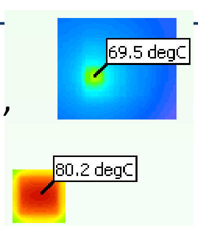


Simulation Studies of Heat Spreader

No TIM and heat spreader	With: o TIM between MSM chip and shield	With: o TIM between the MSM chipset and shield o Single-layer graphite sheet on battery
		
CTS=0.52	**CTS=0.54**	**CTS=0.61**

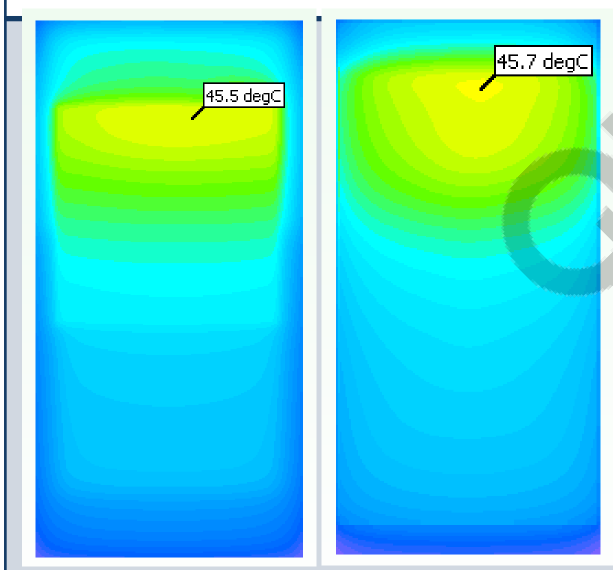
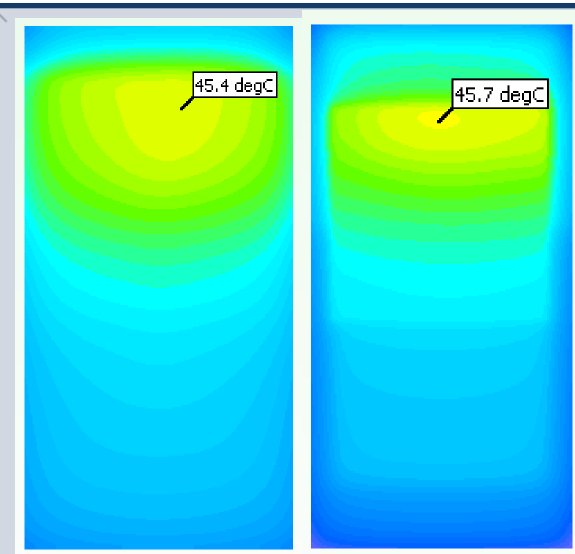


- Prior to the addition of TIM, MSM skin temperature is over 85°C.



Graphite sheet on the battery cover lowers the skin temperature and increases the CTS however the peak skin temperature on the touchscreen still exceeds 46°C.

Simulation of TIM/Heat Spreader

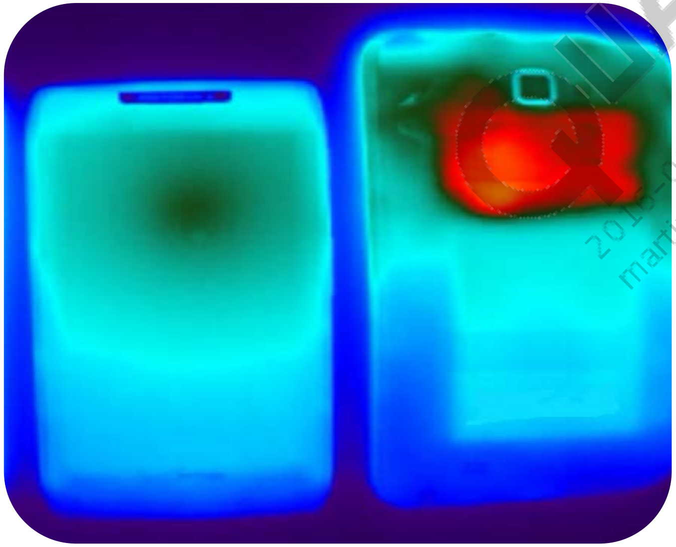
With: o **TIM between MSM chip and shield** o **Single-layer graphite sheet on battery cover (60 mm × 60 mm)** o **Dual-layer graphite sheet between stainless plate and shields (60 mm × 60 mm)**	**With:** o **TIM between MSM chip and shield** o **Copper foil on battery cover (60 mm × 60 mm)** o **Single-layer graphite sheet between stainless plate and shields (60 mm × 60 mm)** o **Copper foil at the back of display to cover backlight LED area (60 mm × 60 mm)**
	
CTS=0.67	**CTS=0.67**

- Using dual-layer graphite sheet lowers the maximum skin temperature on the touchscreen to below 46°C, however it is observed the display backlight LED contributes lot of heat on the surface.

- Copper foil at the back of display better dissipates the heat of backlight LED, and total cost is less than dual-graphite sheet.
- CTS is the same.

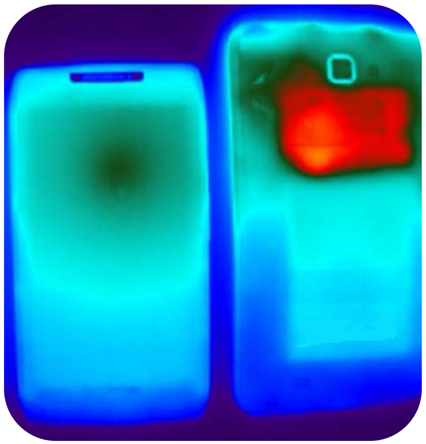
Heat Spreading With Graphite (1 of 9)

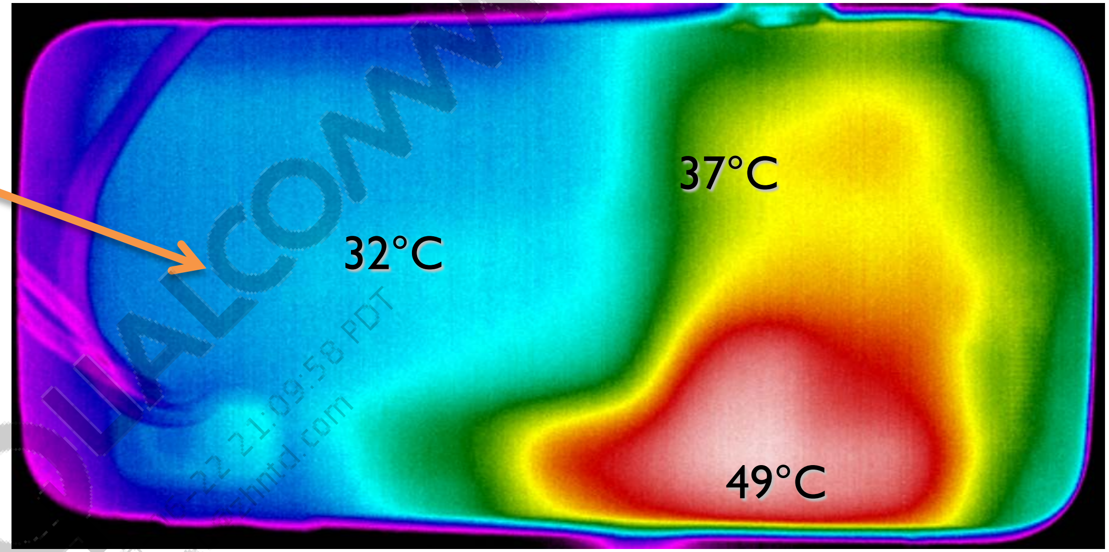
- Heat spreading
  - Balances temperature distribution on device surfaces
  - Reduces hot spots
  - Lowers device skin temperature
  - Increases time before device throttles
  - Improves benchmarks test scores
  - Enhances devices performance



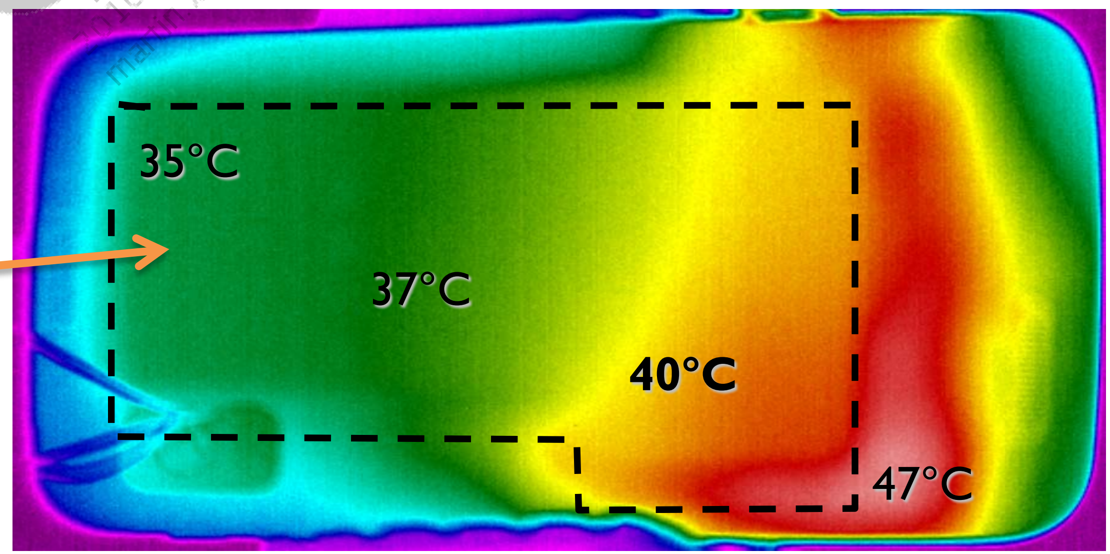
Back cover of phone with and without Graphite heat spreader

Without Graphite spreader





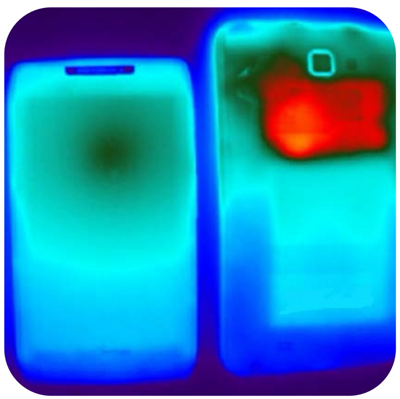
With Graphite spreader

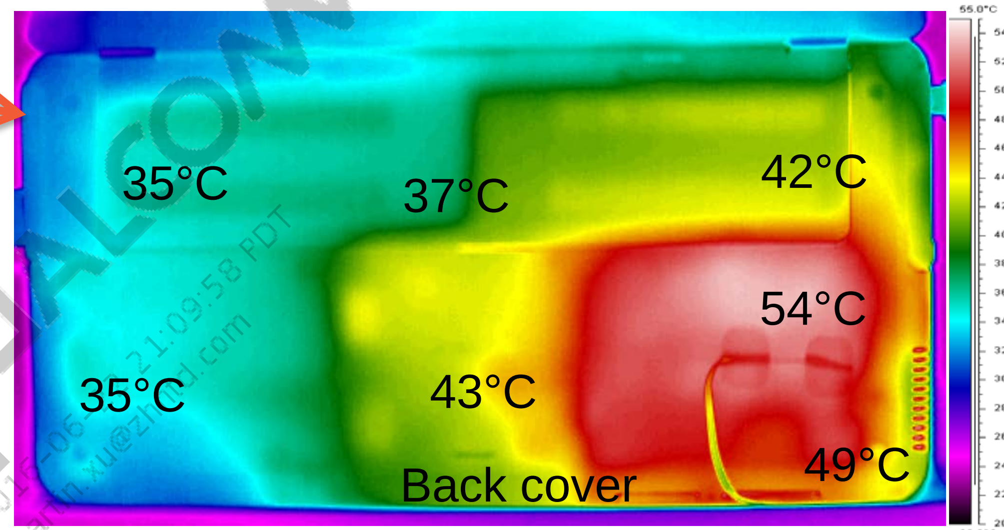


Graphite sheets shields heat from reaching user through back cover

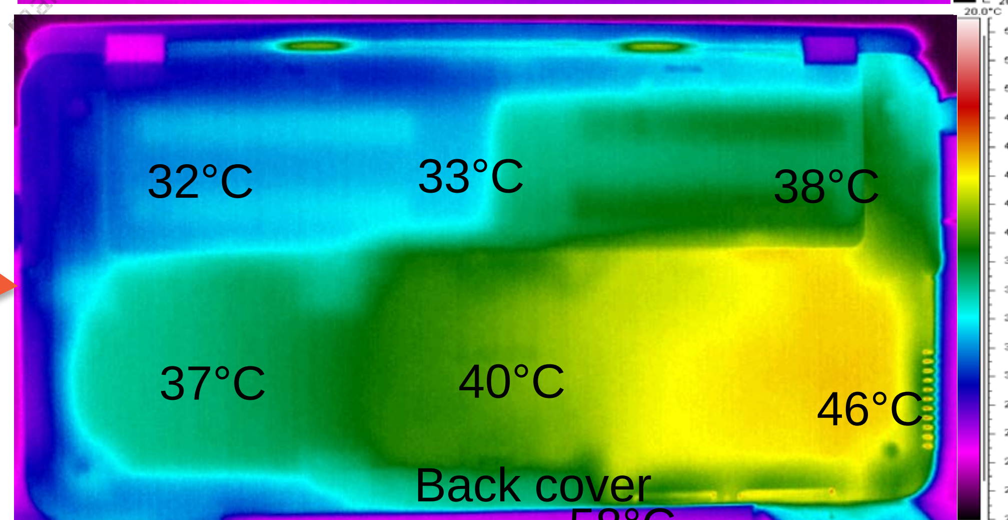
Used to shield back cover for touch temperature reduction.

Without Graphite spreader





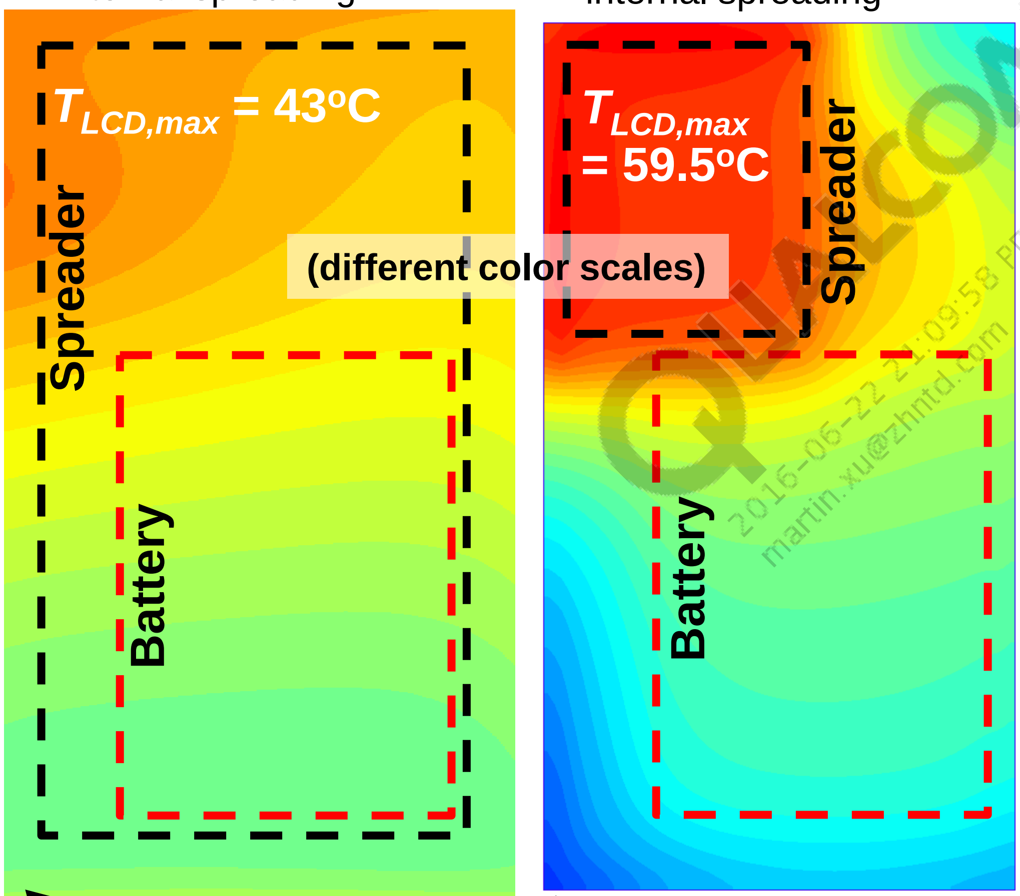
With Graphite spreader



Heat Spreading With Graphite (4 of 9)

Phone LCD with good internal spreading

Phone LCD with poor internal spreading

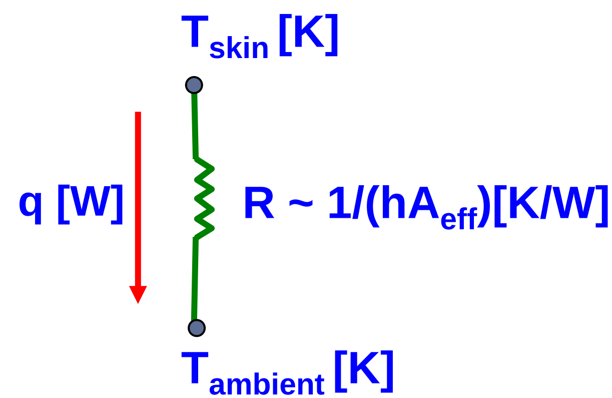


$T_{LCD,min}$ = 38.3°C

$T_{LCD,min}$ = 28.4°C

Qualcomm® FloTHERM simulations

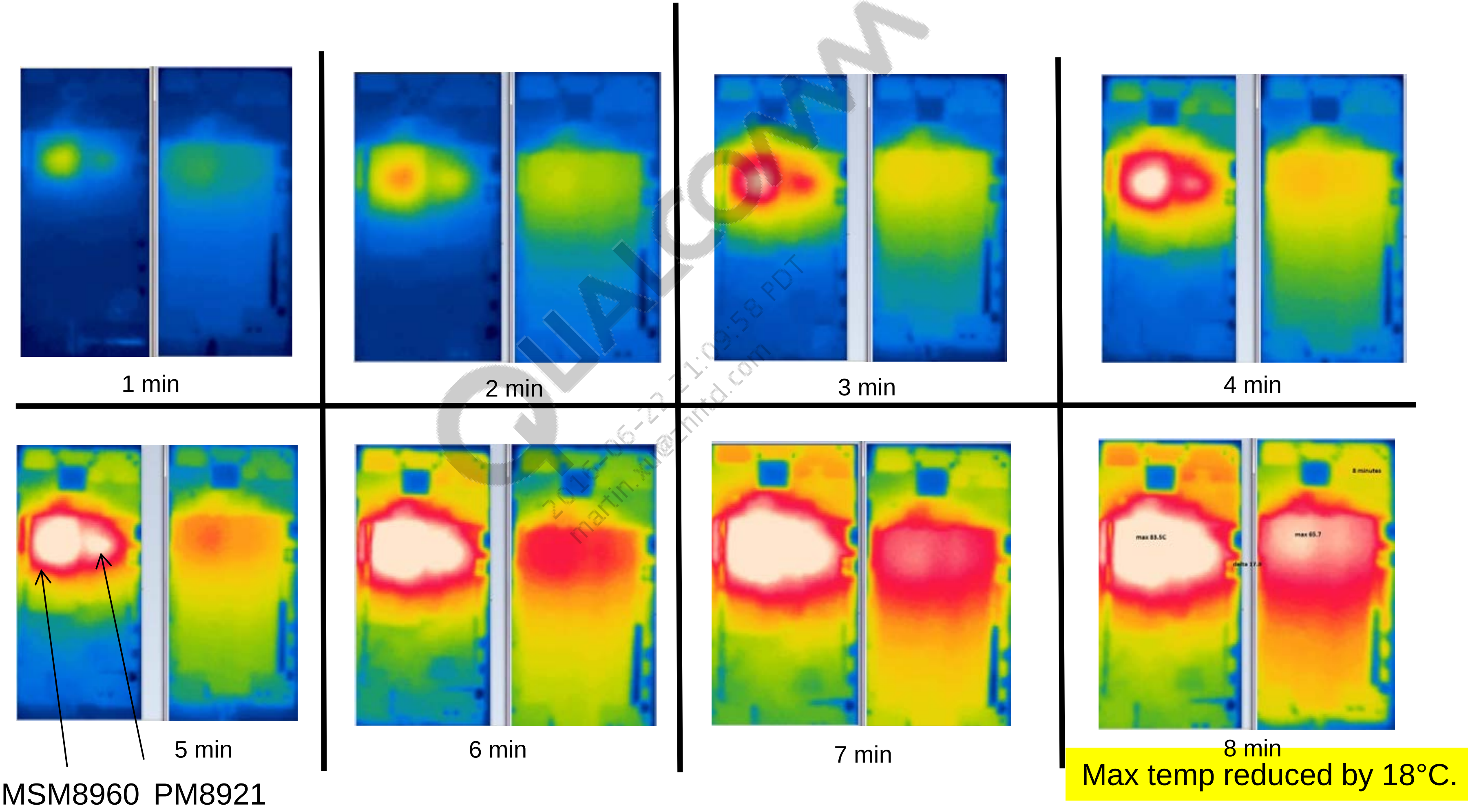
Thermal design quality improves with the uniformity of the surface temperature.



For the same power, the phone with the bigger spreader has:

- lower junction temperature (54°C vs. 74°C)
- lower maximum LCD temperature (43°C vs. 60°C)
- higher minimum LCD temperature (38°C vs. 28°C)

Spreading (thermal sheets)



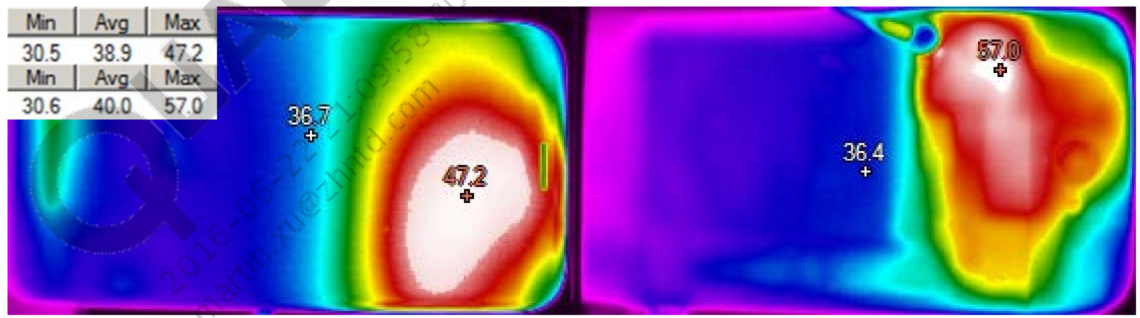
Left picture of each frame is the base design with no spreading (just separation). Right picture is gel on the MSM chipset and PMIC under shields, plus spreader on front and back of board. Frames show heat map every minute for dual Dhrystone at 1.35 GHz . Hot spot still exists and will need to be dealt with before it goes to the surface.

Heat Spreading With Graphite (6 of 9)

Use case: UMTS band1 maximum power + charging + display 50% brightness

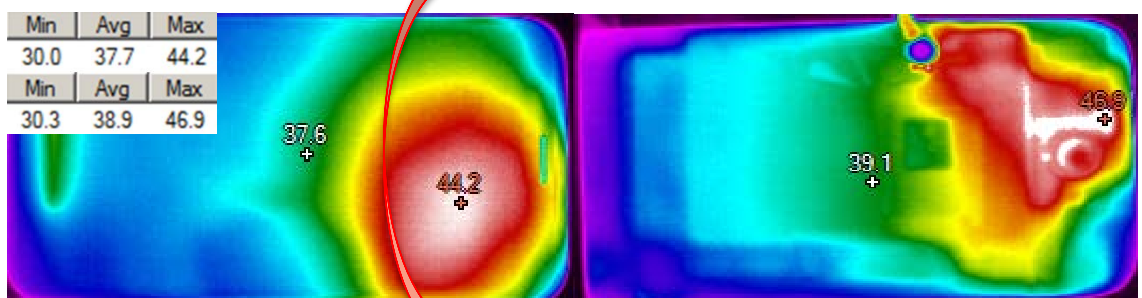
Front side | **Back side**

Without heat spreader ambient temperature: 29.5°C



CTS=0.36

With heat spreader ambient temperature: 28.3°C

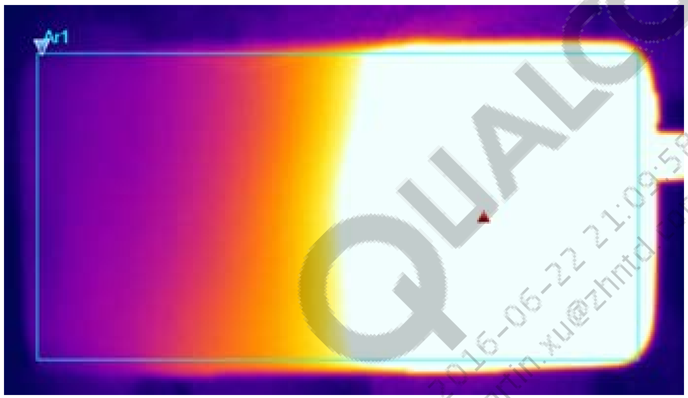


CTS=0.54

Graphite sheets implemented on QRD handset (MSM8x26 chipset).

Use case: Quad-core Dhrystone + charging + display off

Front side

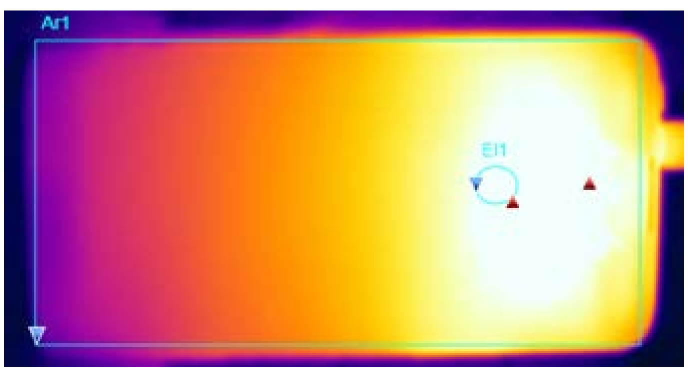


Without heat spreader ambient temperature: 24.9°C

Maximum	52.7°C
Minimum	26.4°C
Average	39.5°C

Front side CTS = 0.53*

Front side



With heat spreader ambient temperature: 25.0 °C

Maximum	44.9°C
Minimum	27.2°C
Average	37.9°C

Front side CTS = 0.65*

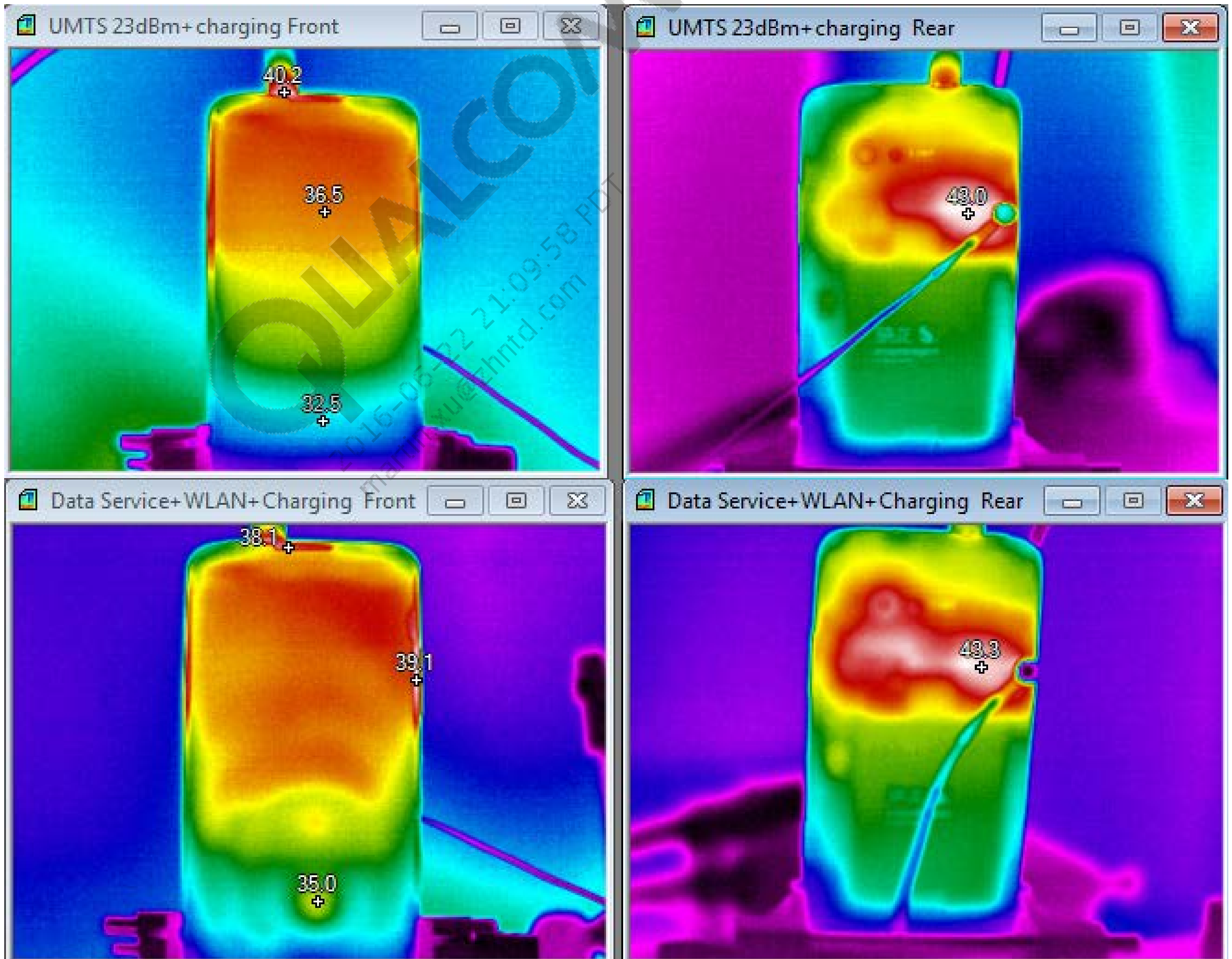
***Note**: Front side CTS for quantifying the heat dissipation capability on front side. Overall device CTS may be smaller.

Heat Spreading With Graphite (8 of 9)

Graphite sheets implemented on QRD handset (MSM8x26 chipset).

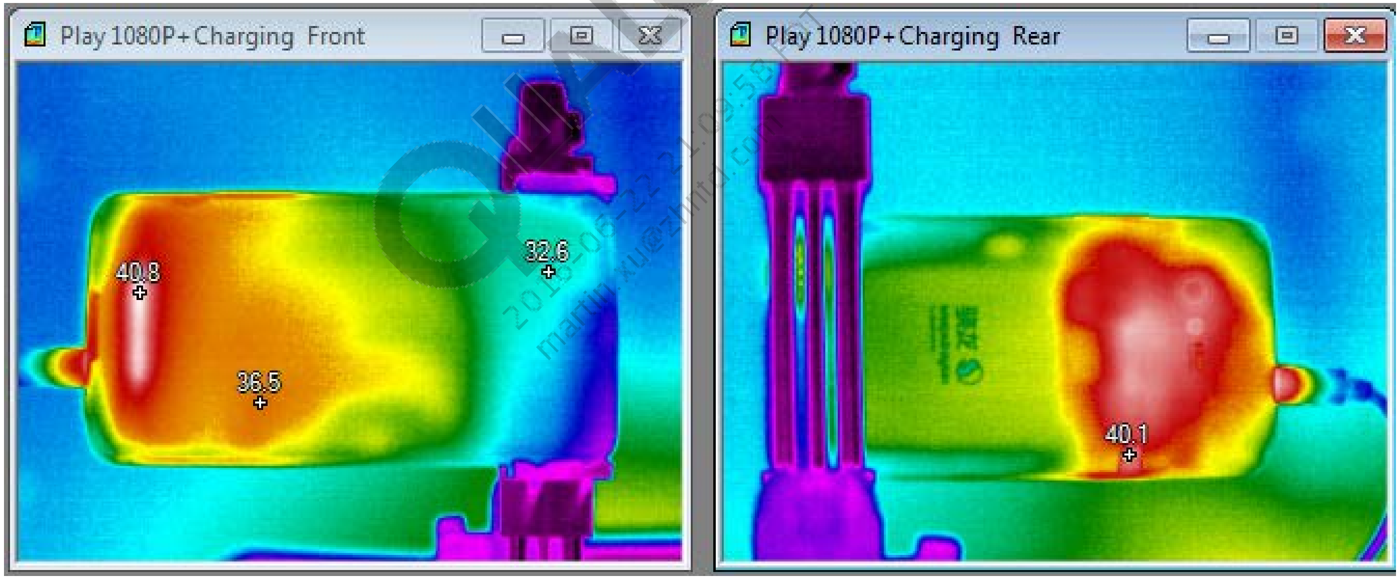
UMTS 23 dbm/AMR+ charging

Data service + WLAN + charging



Graphite sheets implemented on QRD handset (MSM8x26 chipset).

Play h.264 (max resolution) video + charging



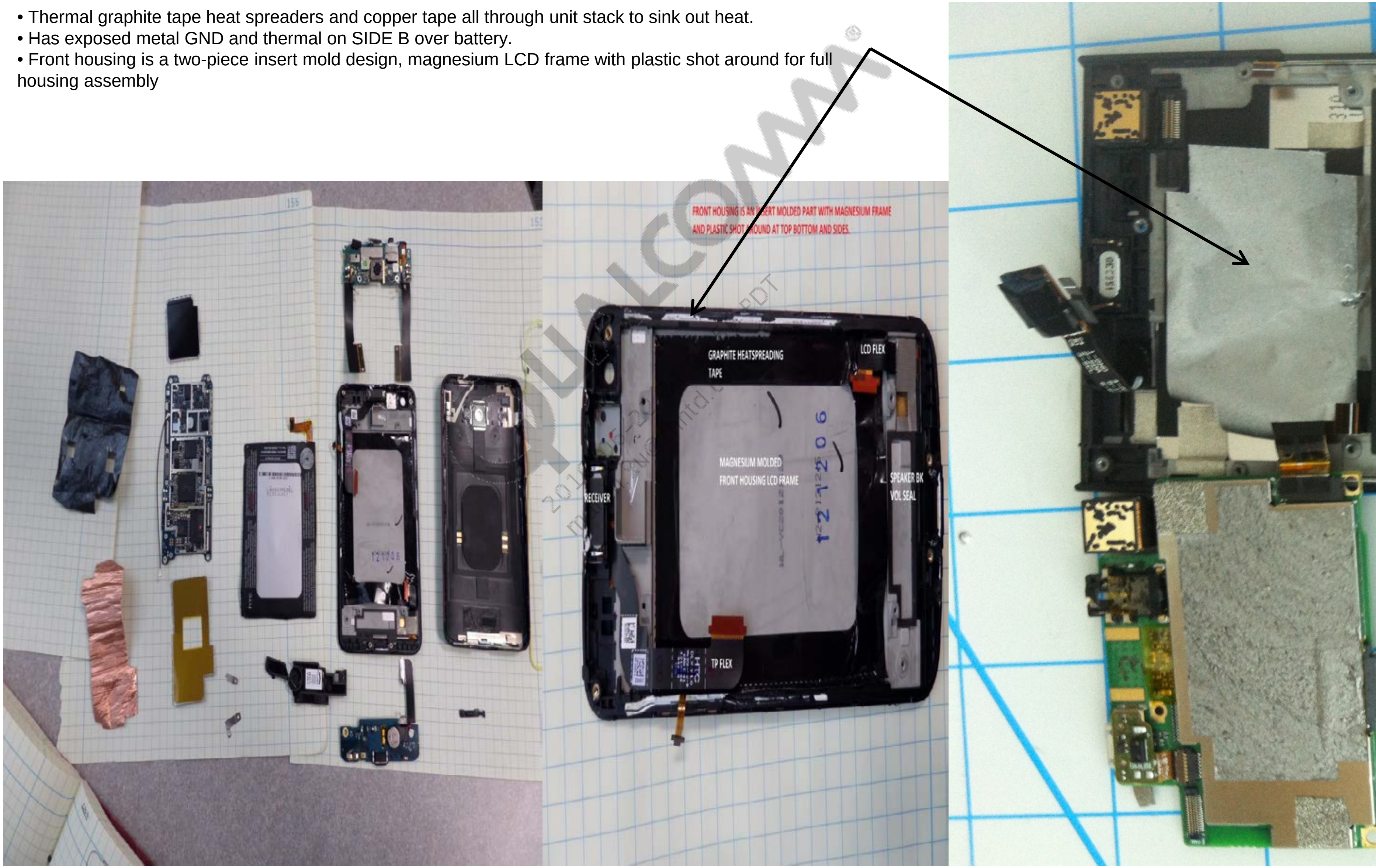
Heat Spreading Implementation Techniques (1 of 7)

Where should we implement heat spreading?

Graphite sheet reduced hot spots on device skin

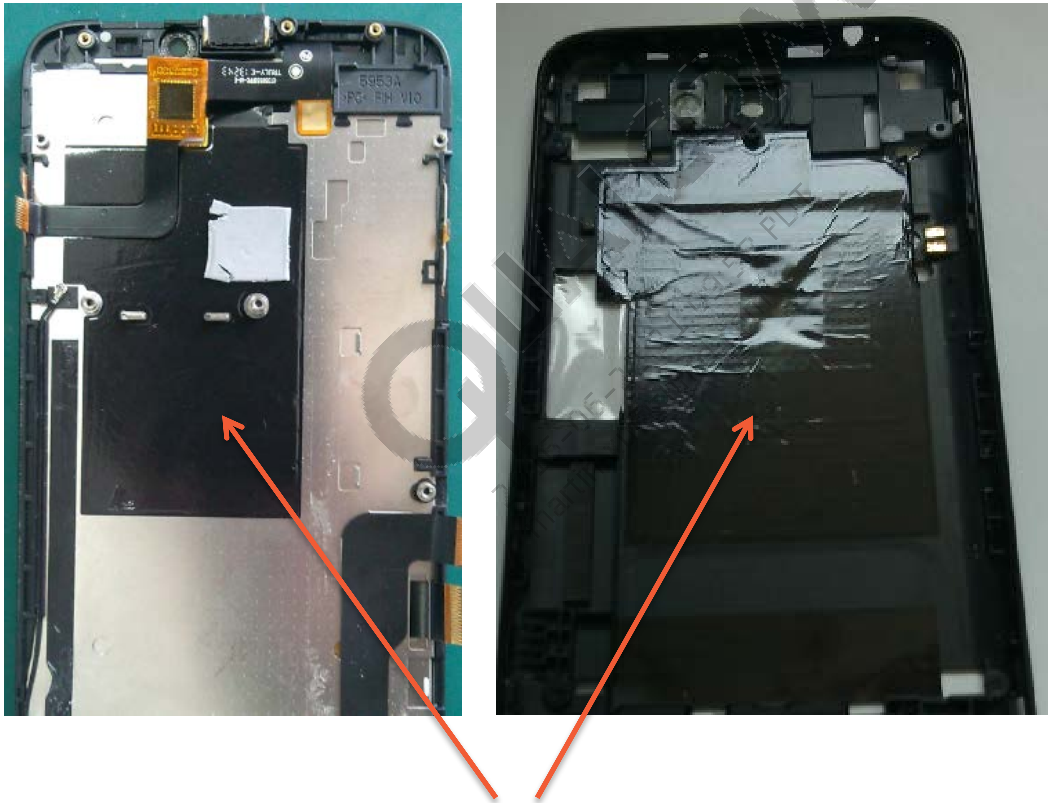
Heat Spreading Implementation Techniques (2 of 7)

- Thermal graphite tape heat spreaders and copper tape all through unit stack to sink out heat.
- Has exposed metal GND and thermal on SIDE B over battery.
- Front housing is a two-piece insert mold design, magnesium LCD frame with plastic shot around for full housing assembly



Heat Spreading Implementation Techniques (3 of 7)

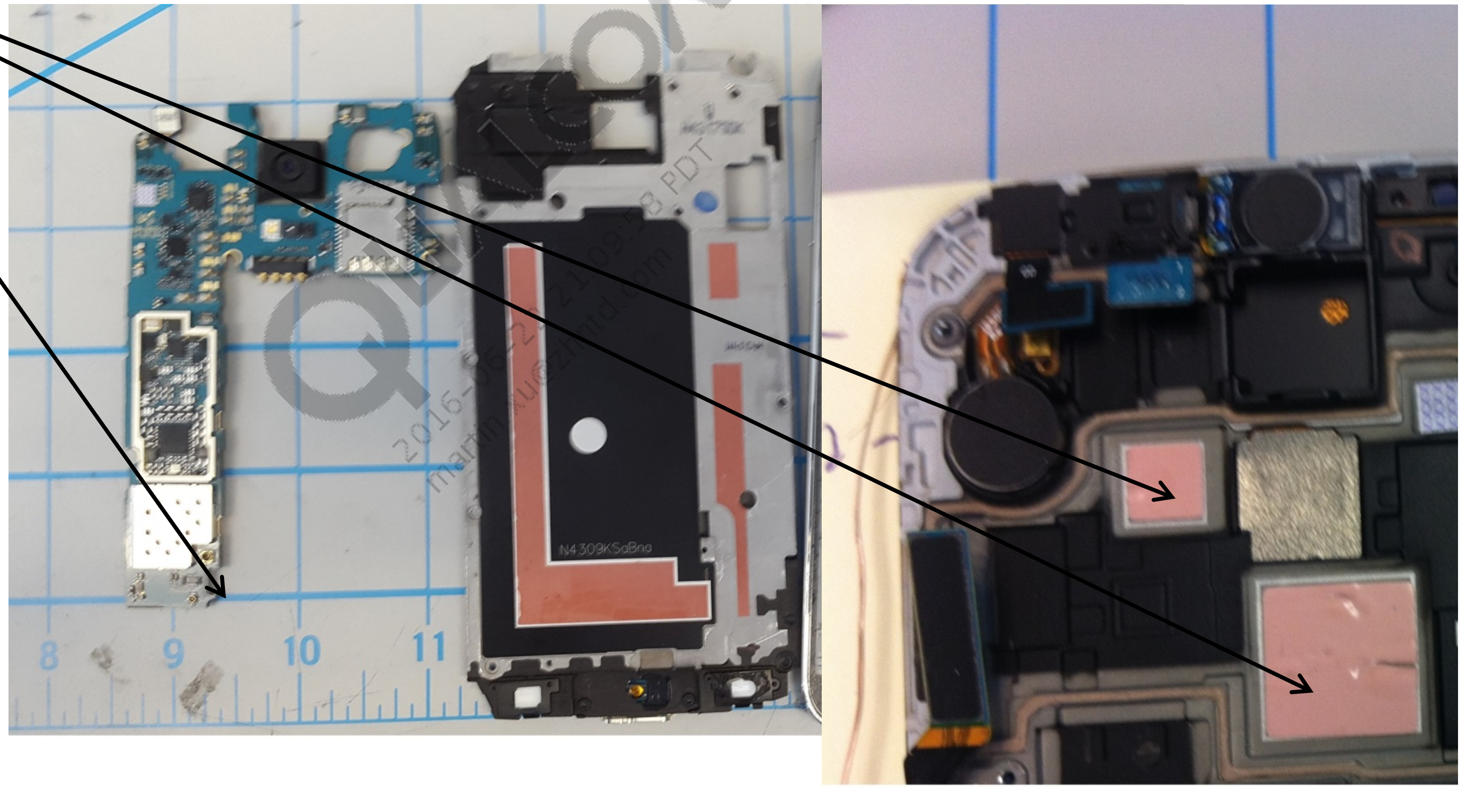
TIM/graphite sheet on QRD (MSM8930)



Graphite sheet

Heat Spreading Implementation Techniques (4 of 7)

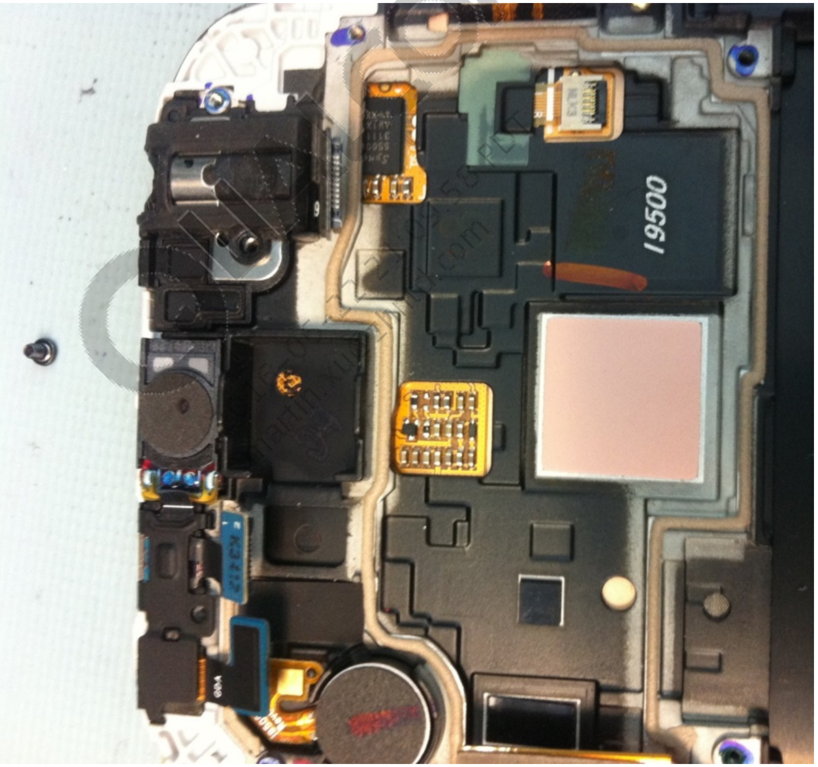
- Thin TIM sheets can be used to cool hot chipsets as heat spreader.
- TIM material absorbs heat beside conducting it; its thermal conductivity 3–15 W/m.K.
- TIM is compliant and can conform to any shape and can be compressed to 40–50 % of its thickness.



- Thin TIM sheets can be cut to sizes and can be attached on a single or multicomponent device.
- TIM can be used in combination with graphite heat spreaders sheets.

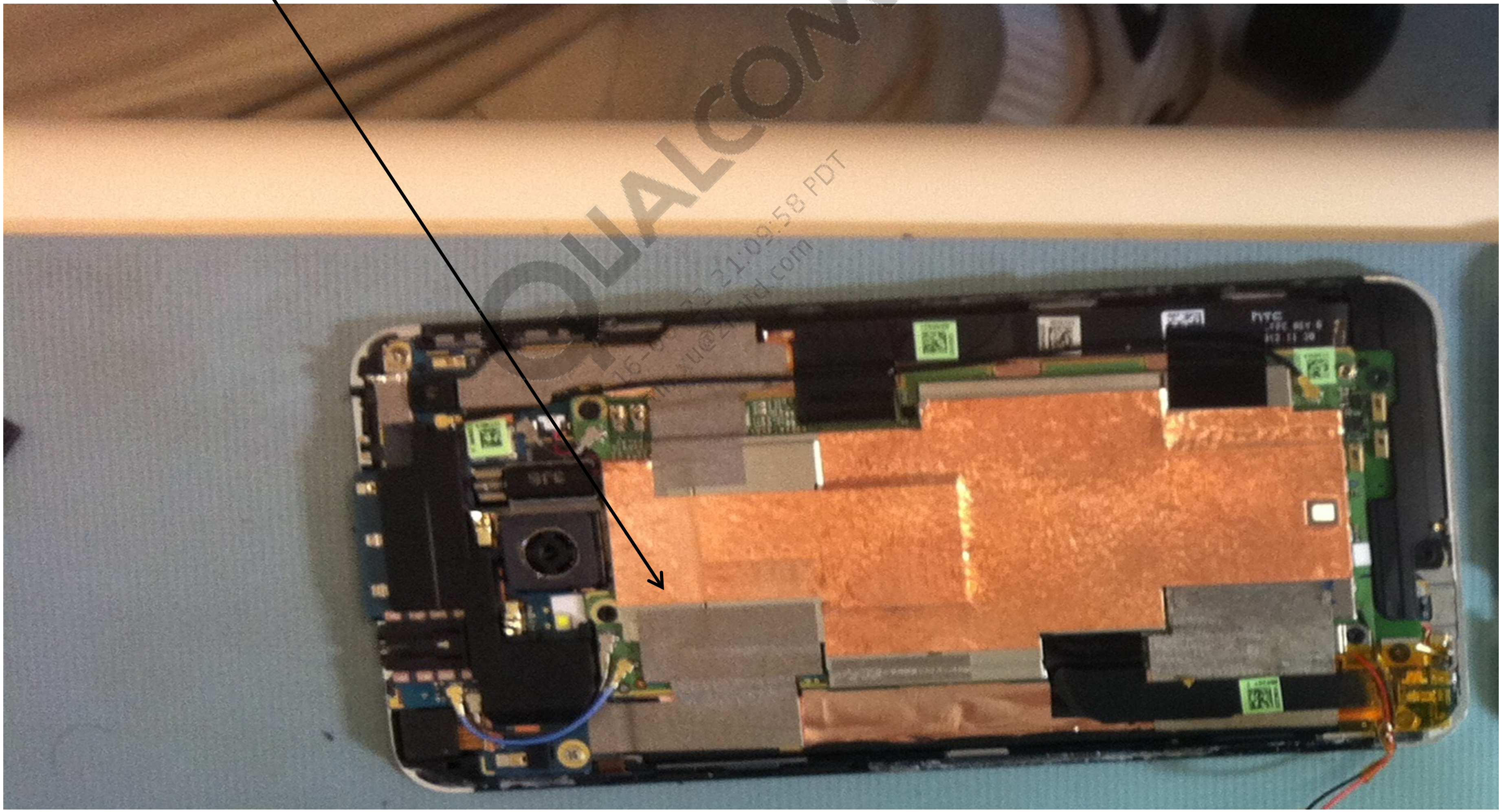
Heat Spreading Implementation Techniques (5 of 7)

- Very thin copper sheets being used to cool hot chipsets.
- Copper sheets are also used as a heat spreader to cool hot spots
- Copper has very high thermal conductivity (400 w/m.k) vs. FR4 has 0.2 W/m.K



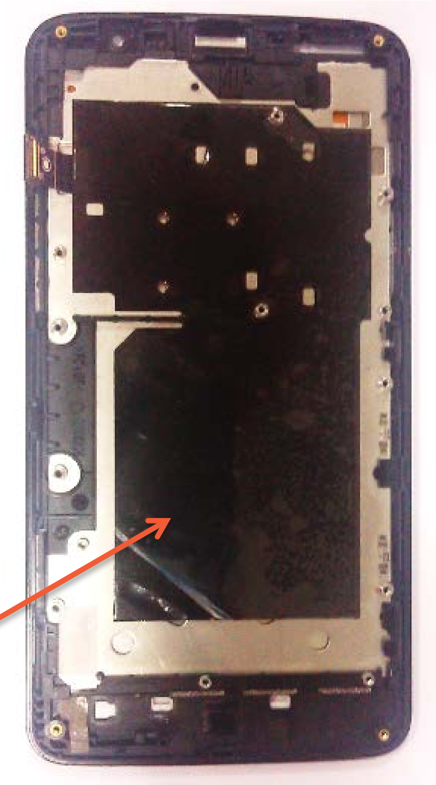
Heat Spreading Implementation Techniques (6 of 7)

- Thin copper sheets used to cool hot chipsets and conduct heat.
- Copper sheets used as a heat spreader to cool hot spots.
- Note that copper is used to both conduct and spread the heat in the smartphone.



Heat Spreading Implementation Techniques (7 of 7)

Graphite sheets implemented on QRD handset (MSM8x26 chipset)

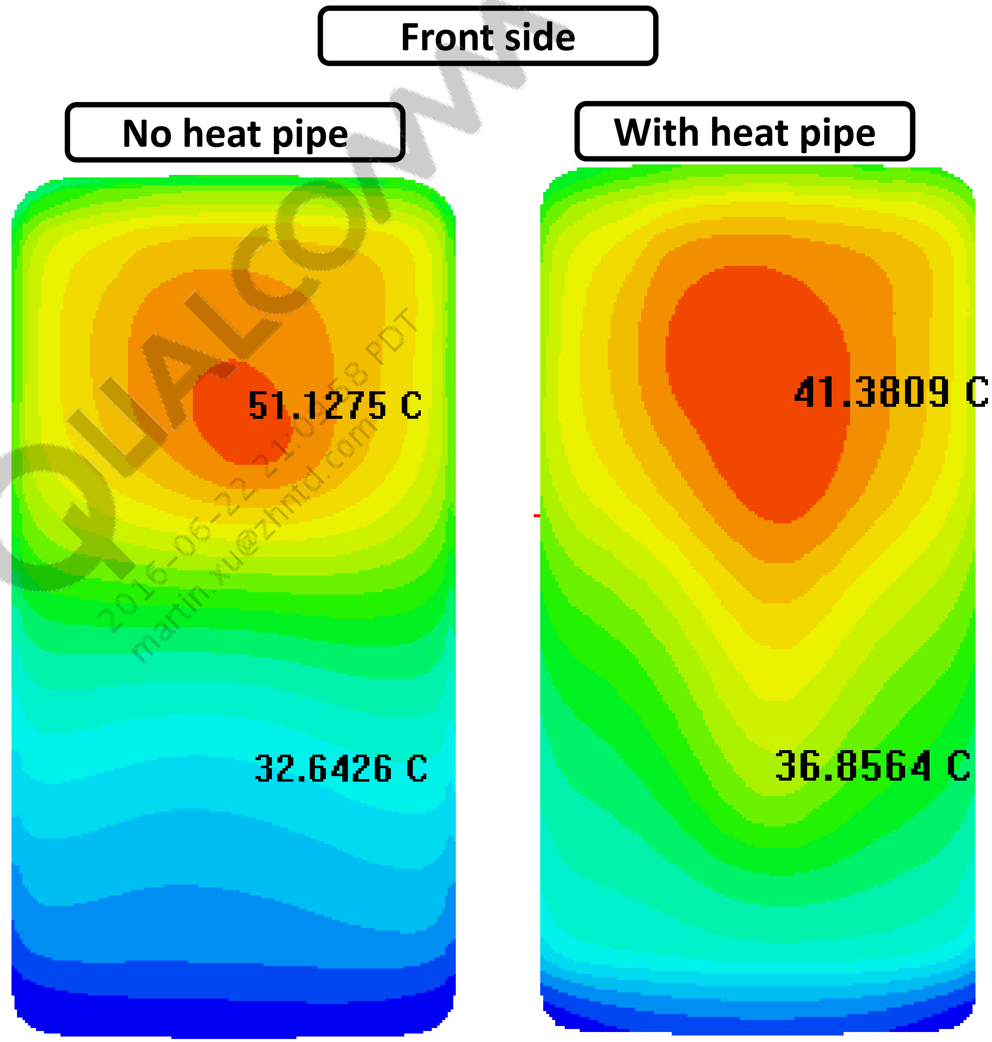


Dual-layer graphite sheet

Heat Pipes

Designing with heat pipes – QRD

Ambient
25°C
Use case
Quad-core Dhry
charging
display off



How to Implement Heat Pipes in Handset Designs?

- Very thin and long heat pipe used to cool hot chipsets.
- Note the curvature and flexibility of the heat pipe.
- Heat pipe conducts, spreads and dissipates heat away from the heat sources to a cooler area.
- Another heat pipe implementation in smartphones.
- Note the heat pipe contacts the frame for the cool side of the heat pipe .
- For the heat pipe to work properly, it must have a cool side and a hot side with sufficient temperature potential difference so that it can perform the closed-loop cycle of operation.
- When implementing heat pipes in a smartphone design, make sure to allow for the heat pipe to have a hot side and a cold side.

Qualcomm Reference Design With Heat Pipe Implementation (1 of 2)

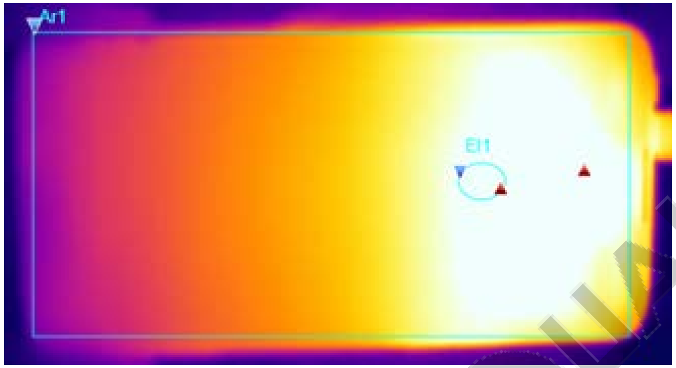
For MSM8x26 chipset based devices

Ultra thin heat pipe module

Note: This is a QRD lab experiment and the data is for reference only.

Observed improvement with heat pipe implementation

Use case: Mem-fidget + charging + display off



Maximum	50.9°C
Minimum	28.3°C
Average	41.7°C

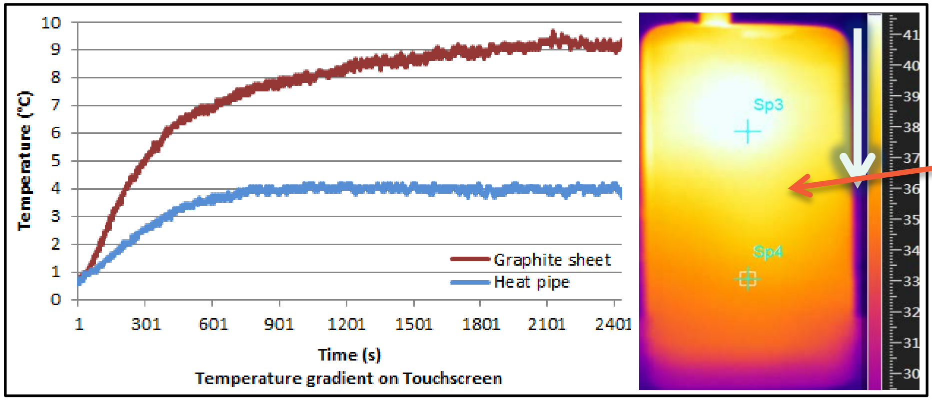
With graphite sheet
Ambient temperature: 25.3°C

Front side CTS = 0.64*

Maximum	42.1°C
Minimum	28.8°C
Average	38.5°C

With heat pipe
Ambient temperature: 25.2°C

Front side CTS = 0.78*



- The skin temperature gradient over the monitor-points reduces to approximately 4°C while it is 9°C by using graphite sheet, then the highest CTS.

* **Note**: Front side CTS for quantifying the heat dissipation capability on the front side. The overall device CTS may be smaller.

Designing With Vapor Chambers

Skin temperature with vapor chamber test in smartphone

Original Al frame → MP

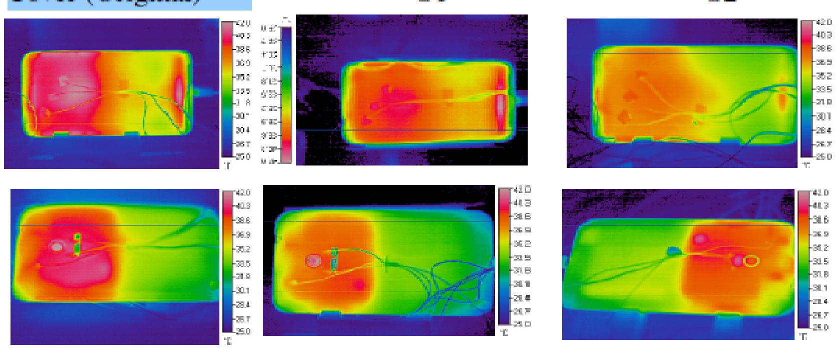
Original Al frame + Graphite + copper sheet) → S1

Slim heat pipe thermal solution (without graphite and copper sheet) → S2

	Top Skin		MP	S1	S2
1	Top 1	38/42	40.5	39.2	38.4
2	Top 2		42.6	39.4	38.8
3	Top 3		42.5	39.6	37.9
4	Top 4		41.5	39.5	38.7
	Bottom Skin				
5	BTM1	38/42	40.6	40.0	38.1
6	BTM2		43.1	42.8	38.2
7	BTM3		42.0	41.4	38.1

IR Photo

Cover (Original) | S1 | S2



Slim heat pipe thermal solution

→ Improve skin temperature from > 40˚C to 38˚C

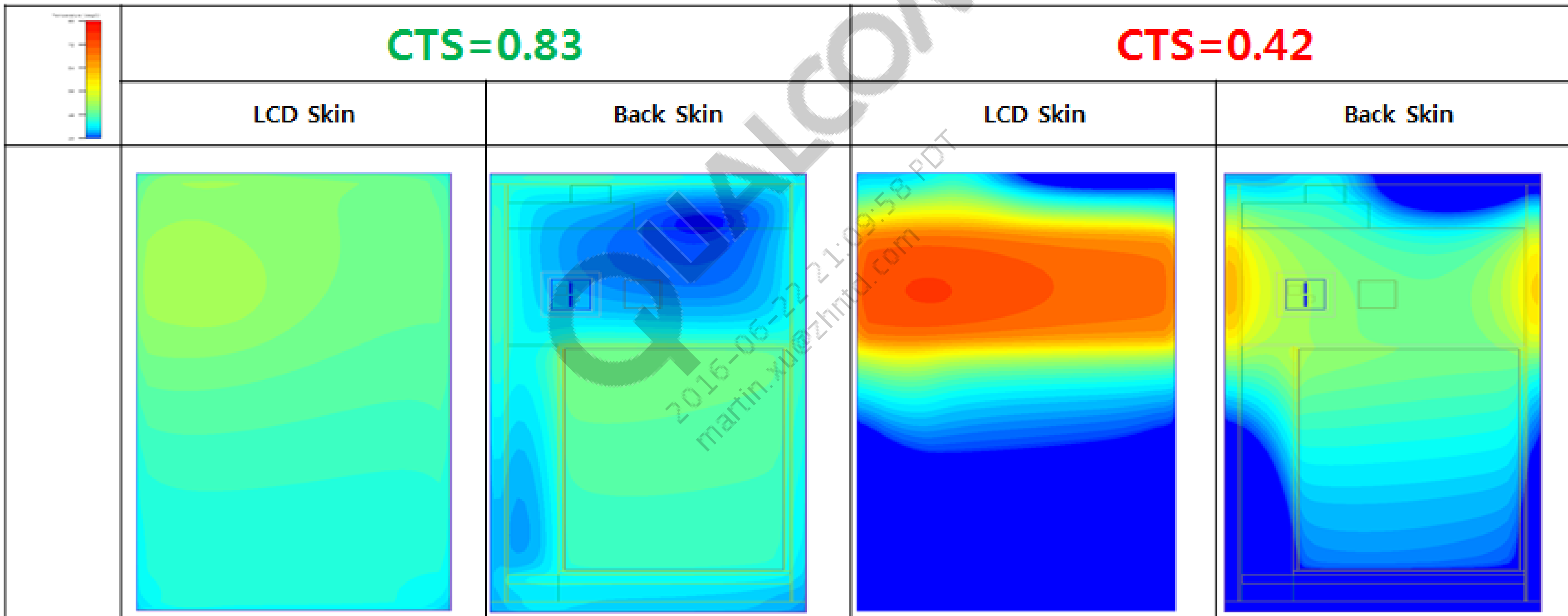
Sec. 6

CTS

What is CTS? – Figure of merit measuring **thermal spreading goodness** of various devices.

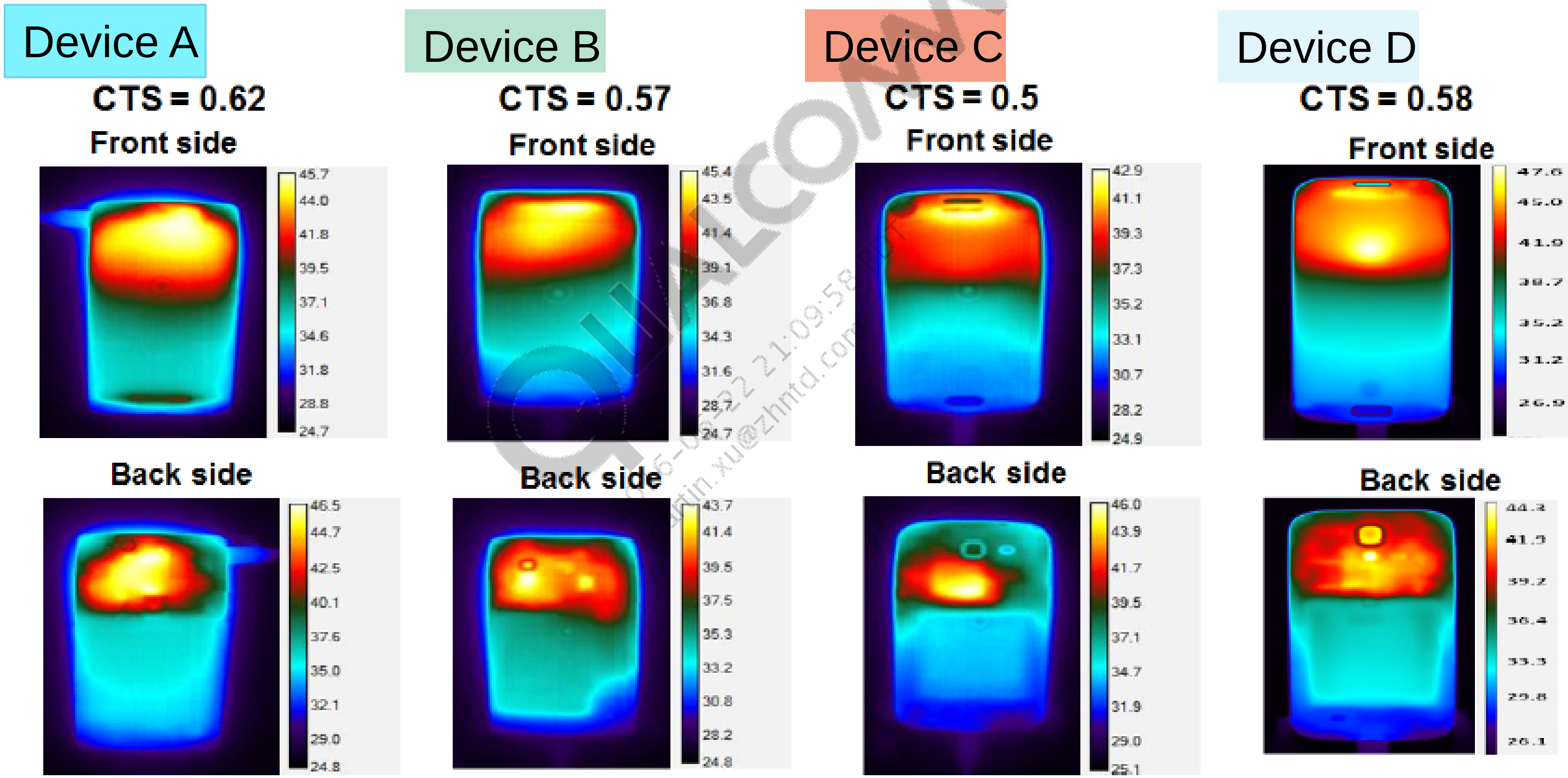
- Impacted by heat spreader size and material, air gap size (from sources to device skin), and battery/brackets
- It is a measure of the smartphone thermal design improvements in the PCB, increased surface area, and utilization of TIM, graphite sheets, and heat pipes during the design of the handset
- Why CTS is important?
  - Refer to *Coefficient Of Thermal Spreading (CTS) - Figure Of Merit For Mobile Thermal Management* (80-VU794-14).

The higher the CTS score the better- Why?



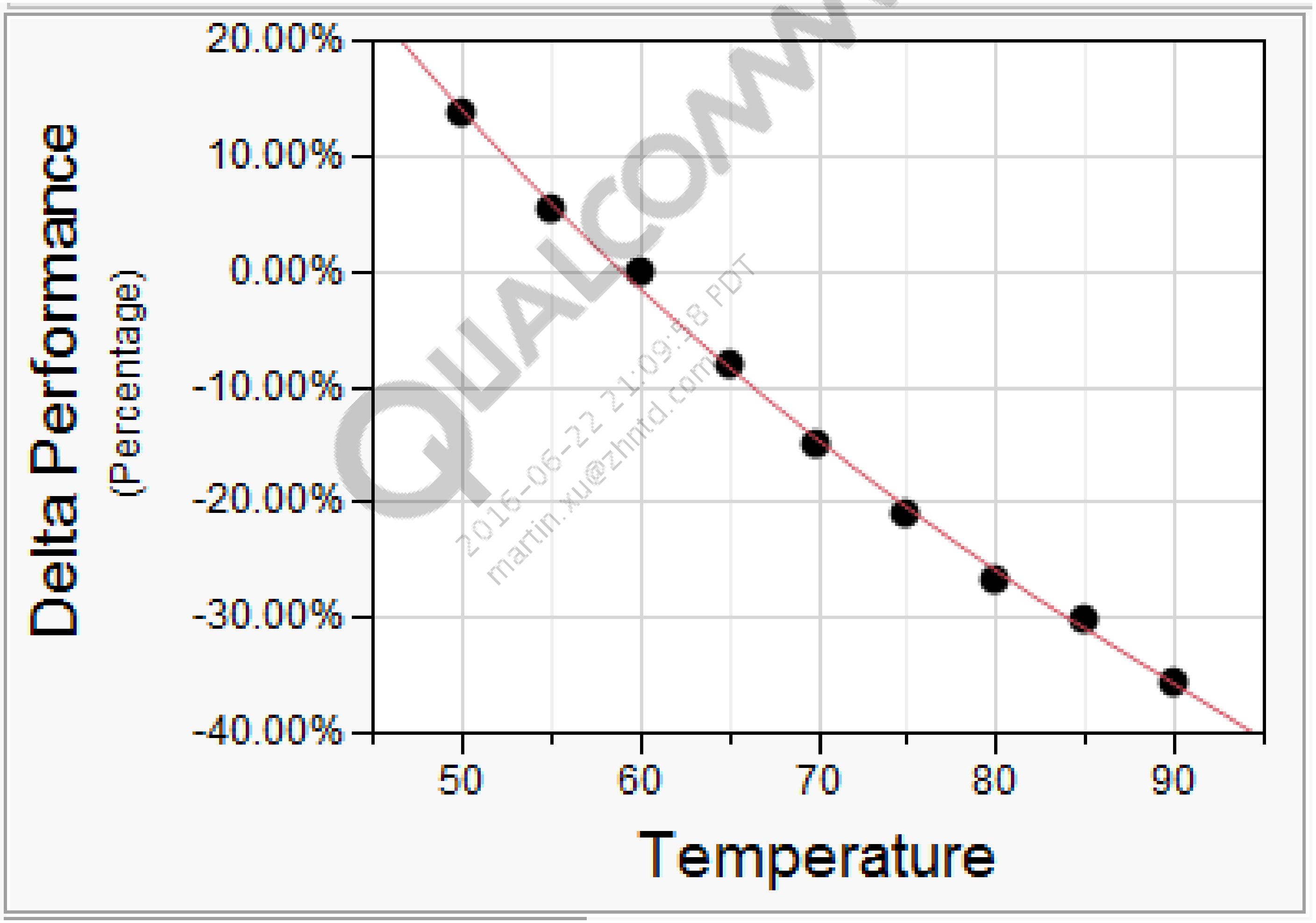
HIGH CTS Device ← **LOW CTS Device**

Higher CTS allows higher power to be dissipated in the same phone form factor.



Measured phones have CTS values between 0.5–0.6. Well balanced phones could be designed to reach a CTS value between 0.8 and 0.9.

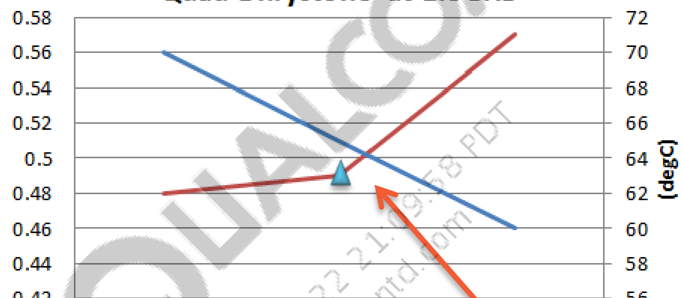
Impact of higher CTS on performance



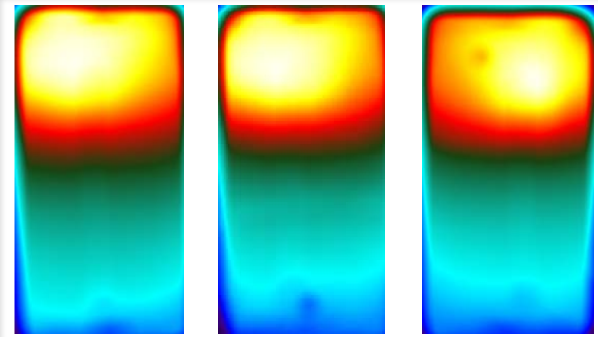
Performance increase of 8–12% for each 10°C drop in temperature in the 60–90°C range.

TIM/heat spreader on MSM8974 chipset based devices

Quad-Dhrystone at 1.3GHz

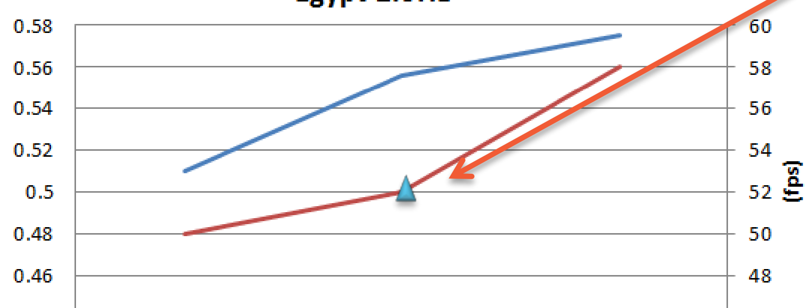


	Without TIM/HS	Without TIM	With TIM/HS
CTS	0.48	0.49	0.57
Max TSENS temp	70	65	60



Without TIM/HS — Without TIM — With TIM/HS

Egypt 2.5HD



	Without TIM/HS	Without TIM	With TIM/HS
CTS	0.48	0.5	0.56
FPS	53	57.6	59.5

Once TIM is adopted with magnesium plate, CTS increases significantly; then TSENS temperature drops and graphic performance improves.

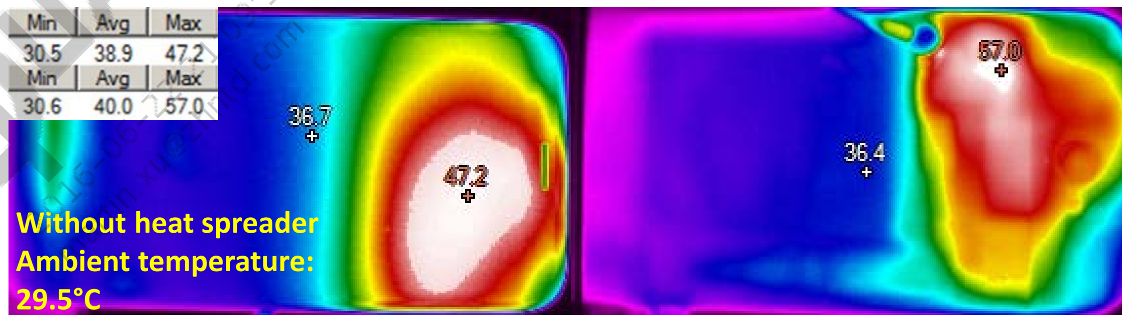
Single-layer graphite sheet on MSM8930 chipset based devices

Single-layer graphite sheet

The peak temperature on plastic rear housing decreases by addition of large pieces of graphite sheets on the front and back. Hence, even in the absence of a magnesium plate inside, thermal distribution is good.

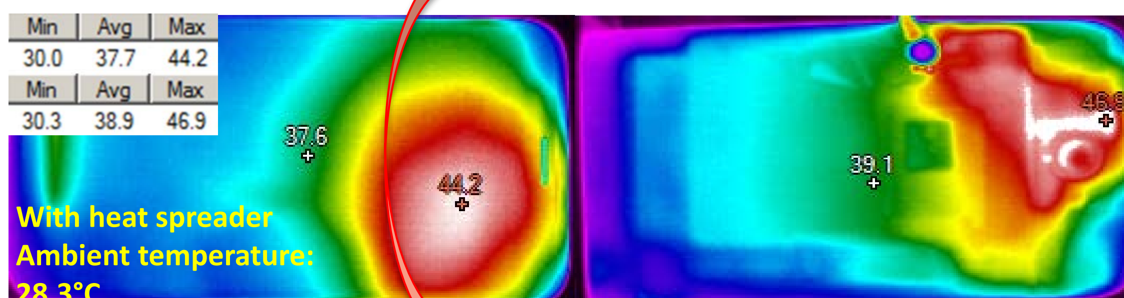
Use case: UMTS band1 maximum power + 1A charging + display 50% brightness

Front side **Back side**



Min	Avg	Max
30.5	38.9	47.2
Min	Avg	Max
30.6	40.0	57.0

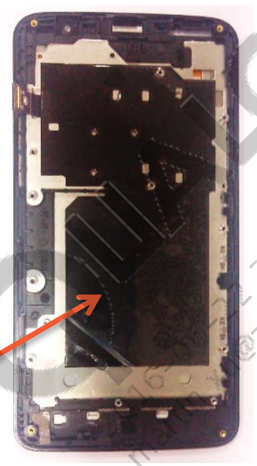
CTS=0.36



Min	Avg	Max
30.0	37.7	44.2
Min	Avg	Max
30.3	38.9	46.9

CTS=0.54

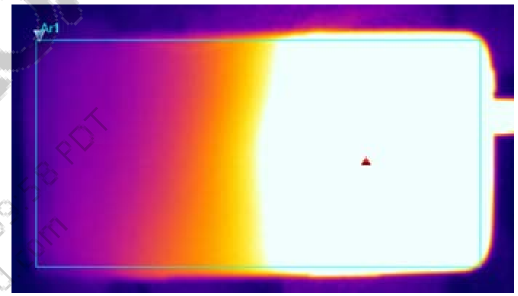
Dual-layer graphite sheet on MSM8x26chipset based devices



Dual-layer graphite sheet

Dual-layer graphite sheet lowers the IC temperature as well as the device skin. Under same use case, the skin peak temperature reduction is up to 14.8% (almost 8°C).

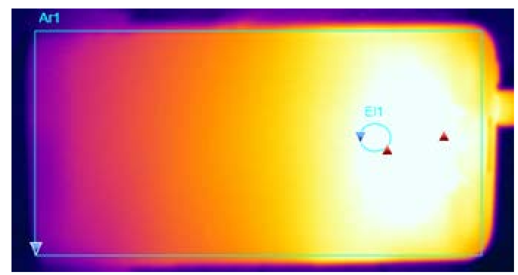
***Note**: Front side CTS for quantifying the heat dissipation capability on front side. Overall device CTS may be smaller.



Front side CTS = 0.53*

Quad-Dhrystone
Without heat spreader
Ambient temperature: 24.9°C

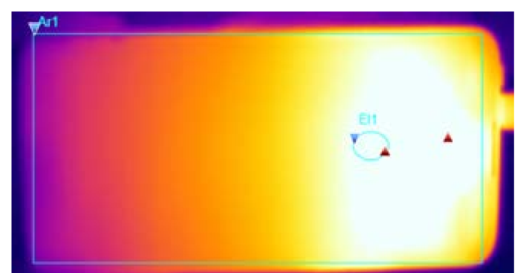
Maximum	52.7°C
Minimum	26.4°C
Average	39.5°C



Front side CTS = 0.65*

Quad-Dhrystone
With heat spreader
Ambient temperature: 25.0°C

Maximum	44.9°C
Minimum	27.2°C
Average	37.9°C



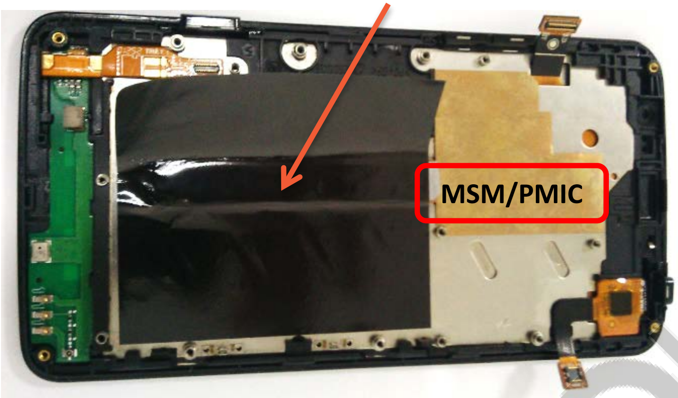
Front side CTS = 0.64*

Mem-fidget (higher system load)
With heat spreader
Ambient temperature: 25.3°C

Maximum	50.9°C
Minimum	28.3°C
Average	41.7°C

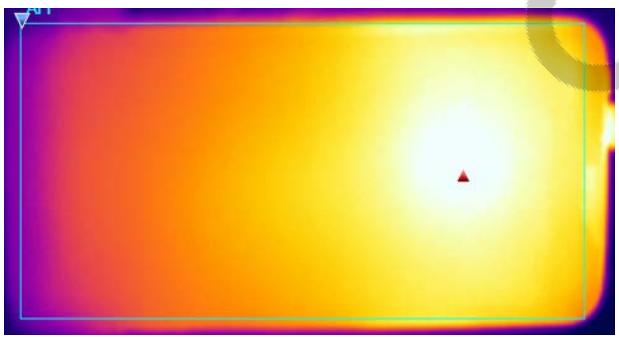
Ultra thin heat pipe experiment on QRD8x26 chipset based devices

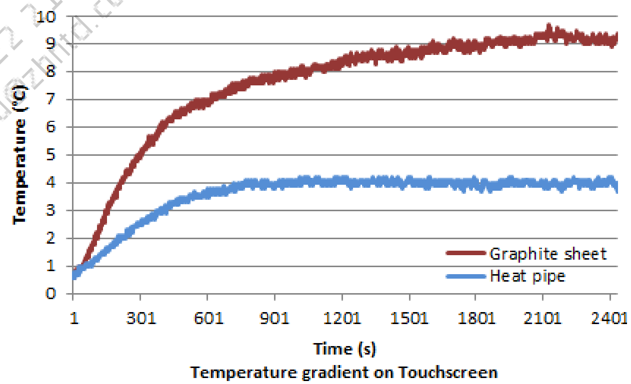
Ultra thin heat pipe module

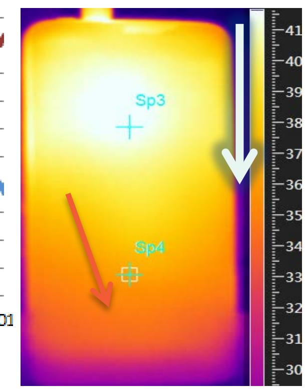


Note: This is an experiment in Qualcomm lab. Data is for reference only.

- By implementation of heat pipe, heat is promptly transferred to the other side (under the battery) and dissipated by heat spreader.
- The skin temperature gradient over the monitor-points reduces to approximately 4°C, while it is 9°C by using dual-layer graphite sheet than the highest CTS.







Maximum	42.1°C
Minimum	28.8°C
Average	38.5°C

Mem-fidget
With heat pipe
Amb temp: 25.2C

Front side CTS = 0.78*

***Note**: Front side CTS for quantifying the heat dissipation capability on front side. Overall device CTS may be smaller.

Questions?

You may also submit questions to:
https://support.cdmatech.com