Considerations for System Power Management and Thermal Options Using **i.MX 6 Series Processors**

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A P R . 2 0 1 4
Agenda

• Things Get Hot – Setting Expectations

• Cooling Things Down – Some Examples

• Spreading the Heat – Mechanical Design

• Beating the Heat – i.MX 6 Series Processors
Things Get Hot – Setting Expectations

- **Highly integrated SOCs using ARM-based cores are powerful and can generate significant heat**
  - However, typically in the sub 5W range vs. 100W range for Intel

- **Heat is a function of what you are doing with the processor + memory**
  - The Thermal Design Power (TDP), also referred to the thermal design point, is of primary interest to the thermal solution designer and it represents the maximum sustained power dissipated by the processor, across a set of realistic applications.
    - Only running Video (~2W)
    - Only running 3D (~1.7W)
    - Video + 3D + 3 ARM Cortex A9s at high speed (4.6W)
    - Quad ARM Cortex A9s at high speed only (2.3W)
    - Note: all based on SOC + DDR3 power consumption

- **ALL modern day devices using ARM based processors have some sort of thermal management system in place**
  - Typically: cheap graphite heat spreader
  - Sometimes: metal tabs for conducting heat
  - Almost never: a full active heatsink
Cooling Things Down – Some Examples
RIM Playback – Thermal Heat Spreader Example

- Teardown : RIM Playback
- TI OMAP4 @ 1.2 GHz
- Source: [http://www.ifixit.com/Teardown/BlackBerry-PlayBook-Teardown/5265/1#.T8kAB1KRMgc](http://www.ifixit.com/Teardown/BlackBerry-PlayBook-Teardown/5265/1#.T8kAB1KRMgc)

Graphite heat spreaders are cheap. Easily cut into any dimension to spread heat into other components.
Amazon Kindle Fire – Thermal Heat Spreader Example

- Teardown: Amazon Kindle Fire
- Processor: TI OMAP4 @ 1.2 Ghz
- Source: [http://www.ifixit.com/Teardown/Kindle-Fire-Teardown/7099/1#.T8kCmlKRMgf](http://www.ifixit.com/Teardown/Kindle-Fire-Teardown/7099/1#.T8kCmlKRMgf)
- Source: [http://www.youtube.com/watch?v=MGLn1TVAITQ](http://www.youtube.com/watch?v=MGLn1TVAITQ)

CPU/Memory Complex

Shield and thermal contact

Metal sheet (heat spreader and rigidity). Direct contact with CPUs metal shield

Highly likely thermal pad + flex cushion) underneath the processor
Apple iPAD3 – Thermal Heat Spreader Example

- Teardown: Apple iPAD3
- Processor: 800 MHz Dual Core A5
- Source: http://www.ifixit.com/Teardown/iPad-3-4G-Teardown/8277/3

EMI shield is in direct contact with the back of the device. Thus serves as an EMI Shield as well as thermal spreader
Samsung Galaxy Tab – Thermal Heat Spreader

- Teardown: Samsung Galaxy Tab
- Processor: 1.5 GHz NVIDIA Tegra 3 Quad Core
- Source: http://www.ifixit.com/Teardown/Samsung-Galaxy-Tab-Teardown/4103/1#.T8kG31KRMgc
- Source: http://www.youtube.com/watch?v=urGUKerJOhg

Samsung uses EMI shield + heat spreader metal similar to the Apple iPad

Back cover metal heat spreader in direct contact with EMI shield
Google Nexus 10 – Dual Core A15

Equinox A15 CPU (under heat spreader)

Aluminum Heat Spreader for CPU/Memory

Equinox A15 CPU

CPU Aluminum Heat Spreader attached to massive heat spreader backplane on LCD side and a Graphite strip on the backside case

Heat spreader backplane

Graphite strip which adheres to top of CPU assembly's aluminum heat spreader
Here’s Why – A15 CPU = Up to 10 Watts of Power

- Tested Nexus 10 running CoreMark MT (CPU test) + Modern Combat 3 (Game)
- Measured GPU, CPU power consumption
- CPU or GPU consume between 4.0 to 5.5 Watts each
- Test below has user switching between game/CPU test – with only one app running at a given time, not concurrently
- If apps running concurrently: 9.5 to 10 Watts!

Graphite or Copper heat spreaders cannot handle more than 5.7W unless covering the entire platform enclosure (high cost)

<table>
<thead>
<tr>
<th>i.MX 6Quad Package</th>
<th>Heat Spreader Option</th>
<th>Max Power that can be dissipated (To maintain 85Deg C within the enclosure &amp; &lt;=105Deg Tj on die)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Un-lidded</td>
<td>None</td>
<td>2.3 W</td>
</tr>
<tr>
<td>Un-lidded</td>
<td>Graphite (eGraph SS500)</td>
<td>5.6 W</td>
</tr>
<tr>
<td>Un-lidded</td>
<td>Copper (0.2mm)</td>
<td>4.6 W</td>
</tr>
<tr>
<td>Un-lidded</td>
<td>Copper (0.6mm)</td>
<td>5.7 W</td>
</tr>
</tbody>
</table>
Spreading the Heat – Thermal Design
Overview: Thermal Management

Consume Less Power - Generate Less heat

Heat in an embedded system is a by-product of power and the best way to generate less heat is to consume less power. Once heat is generated, the job then becomes to transfer it effectively by providing an efficient path from the device to the environment via thermal pads, epoxy or any method that makes use of conduction, convection, or facilitates radiation.

The general strategy for thermal management focuses on:

- **Increasing the heat-dissipation** capability of the thermal solutions
- **Expanding the thermal envelopes** of systems
- Minimizing impact of local hot spots by improving heat spreading
- Developing thermal solutions that meet cost constraints
- Solutions that fit within form factor considerations of the product chassis

Thermal Management Strategies

There are basically two types of thermal management strategies:

- **Active** thermal management techniques available for embedded systems provide lower thermal resistances and better heat dissipation, however are expensive and have large form factors
- **Passive** thermal management techniques by enhancing conduction and natural convection provide more cost effective solutions, up to certain power levels without introducing any reliability concerns
Overview: Thermal Dissipation
Activity Profile

The activity profile of the application can have a significant impact on the thermal management techniques that need to be employed, and on the thermal design power. The main types of activities can be classified as follows:

- **Short Bursts** below thermal time constant
  - Short bursts of intensive processing followed by long intervals of the IC/System being idle can automatically regulate the heat without much external intervention.

- **Long Bursts** above thermal time constant
  - Long bursts of intensive processing followed by long intervals of the IC/System being idle may require some external intervention such as SW Thermal management.

- **Continuous Operation** at an average power
  - However continuous high performance usage without any idling can cause the system temperature to rise, hence making it necessary to have other forms of thermal management.

The more intensive the use case with all major power contributors active such as the ARM Cores and Graphics Processing Unit (GPU) the higher the potential thermal energy that needs to be effectively dissipated.
Thermal Management Techniques

• Passive thermal management techniques that are typically used are listed below:

• Thermal Gap Fillers

• Thermal Interface Materials

• Heat Spreaders
  – Copper
  – Graphite

• Heat Shields – Aluminum backing plates
A Gap filler is typically placed between the top/bottom of the high power component and case, removing air gap around the package, which is a thermal barrier due to very minimal air circulation. The thermo-elastic gap filler material is often found in the handheld device for thermal management purpose as well as for better shock resistance.

The use of a Gap filler with a higher thermal conductivity will result in better thermal dissipation capability. It helps in reducing $T_j$, however, if used in isolation the direct heat path from the package to the system enclosure results in the skin temperature rise, generating hot spots.

Complete elimination of the air gap inside the system using a gap filler material has significant thermal benefits however the thermal benefit from the use of gap filler is significantly limited by the heat spreading capability of the system enclosure.

Proper attachment of the gap filler is important as well as using the correct thermal contact adhesives. Improper application can severely reduce the thermal conductivity of the filler. Data will be presented in subsequent thermal simulation section for comparisons.
 Thermal Management Techniques: Heat Spreaders

• A thermally conductive heat spreader can be placed on the high power components and this heat spreader can enable spreading and evening out of the hot spots and could be designed to make direct contact with the system enclosure as shown below:

• This design concept significantly increased the power dissipation capability, by reducing overall system thermal resistance.

• The type of heat spreader to be used is dependent on the customers’ application available enclosure space and budget considerations
Thermal Management Techniques
Copper Heat Spreaders

- The excellent thermal conductivity of copper (400W/K) in all directions (x, y & z) makes it an effective heat spreader.

- Simulations with the copper heat spreader always showed better heat dissipation capability when comparing a model without the heat spreader, again due to better heat spreading effect.

- Studies have shown approximately more than 50% better heat dissipation capability.

- HOWEVER: Cost of copper has become more inhibitive for mass deployment.

- Hence the area of the copper could be limited to the area on the enclosure that has metal fins to reduce cost or by using cheaper copper tape.
Thermal Management Techniques
Copper Heat Spreaders

• Copper Advantages
  - Copper has been used extensively in many thermal applications including heat spreaders
  - The excellent thermal conductivity of copper (400W/mK) in all directions (x, y & z) makes it an effective heat spreader
  - Simulations with the Copper heat spreader always showed better heat dissipation capability when comparing a model without the heat spreader, again due to better heat dissipation capability

• Copper Limitations
  - Although copper does have good thermal conductivity the increasing cost of copper has made it more inhibitive for mass deployment. Hence the area of the copper could be limited to the area on the enclosure to reduce cost or by using cheaper copper tape
  - The thermal conductivity of copper (400W/K) in all directions can be problematic since a hot spot could just translate vertically to a different location, possibly closer to the enclosure hence creating a hot spot on the case. Copper hence is not best suited for touch temperature reduction applications.

Hot Spot on a high power component can easily appear as a similar hot spot on a copper spreader if not sized correctly
Thermal Management Techniques

Graphite Heat Spreaders

- Graphite matches the thermal performance of copper in two directions (x, y), at a lower weight and cost. The high in-plane (basal) thermal conductivity results in spreading and evening out of the hot spots.

- Due its low cost the area that the graphite heat spreader covers, could be potentially larger covering all heat generating components.

- Flexible graphite heat spreaders give product designers the tools to overcome the complex challenges associated with thermal management.

- Some of the key product applications are listed below:
  - Cooling of sensitive components
  - Elimination of fans & active cooling
  - Touch temperature reduction
  - Thermal shielding of Li-Ion batteries
  - Cooling of LED and power components
    - Mitigation of AMOLED and LCD display hot spots
    - Improves brightness uniformity
    - Decreases image sticking and burn-in
    - Minimizes warping of back light unit and films
    - Reduces chassis distortion
    - Reduces the severity of stress-induced birefringence
Beating the Heat – i.MX 6 Series
Packaging and Qual Levels – 21x21 FCBGA Package

- **Lidded** – Auto and Industrial
  - Contains a metal lid covering the processor
  - More robust for industrial or automotive environments
- **Non-Lidded** – Consumer
  - Exposes the back side of the die (flipchip)
  - Lower Z-height for space constrained devices
  - Easier to attach custom heat spreaders
  - Three types of Qual for i.MX 6Series
- **Consumer: Highest Frequency**
  - Automotive: Maximum environmental support
  - Industrial: Longest duration (“always on”)
- **Only Non-Lidded packaging will be available in Consumer Temp**

<table>
<thead>
<tr>
<th>Type</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Consumer</td>
<td>• -20 to 105Deg Tj</td>
</tr>
<tr>
<td></td>
<td>• 5 year life cycle @ 50% duty cycle</td>
</tr>
<tr>
<td></td>
<td>• Max of 1.2Ghz CPU speed</td>
</tr>
<tr>
<td>Automotive</td>
<td>• -40 to 125Deg Tj</td>
</tr>
<tr>
<td></td>
<td>• 10 year life cycle @ 10% duty cycle</td>
</tr>
<tr>
<td></td>
<td>• Max of 1Ghz CPU speed</td>
</tr>
<tr>
<td>Industrial</td>
<td>• -40 to 105Deg Tj</td>
</tr>
<tr>
<td></td>
<td>• 10 year life cycle @ 100% duty cycle</td>
</tr>
<tr>
<td></td>
<td>• Max of 800Mhz CPU speed</td>
</tr>
</tbody>
</table>

FC-BGA Manufacturing
App note (Lid and non-Lidded)
Available on freescale.com
Geometry of Simplified Thermal Model

Batteries

21x21 FC-BGA i.MX 6Quad

Memory

Graphite Spreader
Example Duty cycle considered:

- 5s at max power, 25s at 80% of max power, 135s at max power/2 and 135s at low power
- System eventually reaches a steady state over time
Thermal Simulation Results
Simulated i.MX 6Dual/6Quad Power

Power = 2 W

i.MX 6Dual/6Quad reaches a temperature of 80 °C

Note: Colors denote the relative temperature and not absolute

LCD Temp 70 °C

Power = 5 W

i.MX 6Dual/6Quad reaches a temperature of 100 °C

LCD Temp 80 °C
Thermal Simulation Results

Heat Spreader Advantages
The goal of these simulations was to determine what is the maximum processor power to maintain 85Deg C within the enclosure and <=105Deg C Tj on the die, with different thermal management techniques applied. Various models were created that varied the package lid options as well as the heat spreader to be used in the tablet.

<table>
<thead>
<tr>
<th>i.MX 6Dual/6Quad Package Configuration</th>
<th>Heat Spreader Option (Assumes entire PCB dimension coverage)</th>
<th>Max Power (W) (To maintain 85Deg C within the enclosure and &lt;=105Deg Tj on die)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Un-lidded</td>
<td>None</td>
<td>2.3</td>
</tr>
<tr>
<td>Lidded</td>
<td>None</td>
<td>3.5</td>
</tr>
<tr>
<td>Un-lidded</td>
<td>Graphite (eGraph SS500 0.6mm )</td>
<td>5.6</td>
</tr>
<tr>
<td>Un-lidded</td>
<td>Copper (0.2mm)</td>
<td>4.6</td>
</tr>
<tr>
<td>Un-lidded</td>
<td>Copper (0.6mm)</td>
<td>5.7</td>
</tr>
</tbody>
</table>

The results show that using a heat spreader increases the thermal design power and hence allows running higher power consuming applications within the same thermal envelope.
The goal of these simulations was to determine what is the maximum processor power with different heat spreader dimensions to be used in the tablet. The table below shows results of different heat spreaders with varying dimensions including the spreader thickness.

<table>
<thead>
<tr>
<th>Heat Spreader Options</th>
<th>Max Power (W)</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>30% PCB Coverage</td>
<td>55% PCB Coverage</td>
<td>100% PCB Coverage</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Spreader dimensions: 43x37mm</td>
<td>Spreader dimensions: 43x71mm</td>
<td>Spreader dimensions: 43x127mm</td>
</tr>
<tr>
<td>Graphite (eGRAF SS600, Thickness: 0.127mm)</td>
<td>2.9</td>
<td>3.2</td>
<td>3.6</td>
<td></td>
</tr>
<tr>
<td>Graphite (eGRAF SS500, Thickness: 0.6mm)</td>
<td>3.8</td>
<td>4.4</td>
<td>5.2</td>
<td></td>
</tr>
<tr>
<td>Graphite (eGRAF SS400, Thickness: 0.6mm)</td>
<td>3.8</td>
<td>4.4</td>
<td>5.1</td>
<td></td>
</tr>
<tr>
<td>Copper (K= 389, Thickness: 0.6mm)</td>
<td>3.9</td>
<td>4.5</td>
<td>5.7</td>
<td></td>
</tr>
<tr>
<td>Copper (K= 389, Thickness: 0.2mm)</td>
<td>2.9</td>
<td>3.7</td>
<td>4.6</td>
<td></td>
</tr>
</tbody>
</table>

The results show that increasing the heat spreader coverage and thickness increases the thermal design power and hence allows running higher power consuming applications within the same thermal envelope.
Conclusions

• ALL current generation SOCs generate large amounts of heat
  - Exacerbated by complex use cases (3D, video, CPU)

• Traditional methods of cooling include:
  - Active heat management \( \rightarrow \) cost prohibitive and lower battery life
  - Passive heat management \( \rightarrow \) typically copper. Very cost prohibitive
  - Thermal Spreaders \( \rightarrow \) typically Graphite.

• Graphite heat spreaders are the recommended solution
  - Excellent at transferring heat in X,Y plane vs. Z plane with copper
  - Easily cut into any shape needed
  - Easily attached to any part of the system

• Refer to the AN4579 i.MX 6 Series Thermal Management Guidelines
  - Available on www.freescale.com/imx6series