

Design and Thermal Management of a Miniaturized Radio in 3D Package

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Abstract

The design and thermal management of a miniaturized thin radio system in a 3D package is presented. The system consists of memory chips, transceivers, power amplifiers (PA), baseband processor, LNA, and power management module. The typical footprint of the RF components in a cell phone is 10 cm². The present design target is to reduce the footprint to that of a microSD card at around 12mm x 12mm. It consists of seven radio bands, including a quad GSM and a tri-WCDMA. The envisioned functionalities include multiple network compatibility, smart power management, and sufficient computing power capable of voice command and control. Component level and system level thermal analysis is performed to study the temperature distribution under different operation scenarios. Several package designs and thermal management designs are evaluated.

I. Introduction

Over the past 30 years, military and commercial developers have been steadily improving the efficiency and performance of the radio systems through higher levels of digital CMOS integration. This has resulted in the development of versatile digital chipsets for the efficient handling of multiple digital waveforms as well as Software-Defined Radios (SDR) that can be modified on the fly and in the field.

The RF section of the radio, on the other hand, has not nearly kept pace with the digital section due to fundamental RF performance and integration challenges. As a result, many of today's military and commercial radio solutions use the same Super-het radio architectures that were utilized in the 1960's. With the number of radios per communication device rapidly increasing from approximately five radios today to over seventeen in 2015, this

substantial lack of RF integration will no longer be acceptable. In order to address this integration need, radio architectures will need to change, enabled by array of revolutionary technologies that address the challenges of the military and commercial radio markets. These technologies include:

- 1) Common RF semiconductor integration such as Silicon on Sapphire CMOS
- 2) Tunable components and materials such as BST
- 3) Next generation packaging and interconnect such as CSP, MCP, 3D-SiP, wafer level packaging, and embedded substrate technologies.
- 4) Engineered RF system architectures which specifically leverage the benefits of the cited technologies.

Today a modern cell phone requires a maximum of 8 in³ and integrates 2 or more cell phone waveforms, 2 or more data

interface waveforms, radios for external peripheral control, GPS tracking, and includes the ability to handle voice, 7.5 Mb/s data, e-mail, GPS mapping, spreadsheets, cameras and many other functions. In contrast the current handheld specifications for JTRS allow for 2 simultaneous channel operation with GPS in a 70 in³ package with a maximum 2 Mb/s data rate (see table below). The Universal Thin Radio approach can improve JTRS system performance by at least an order of magnitude while significantly reducing handset size and cost.

The Universal Thin Radio will provide tangible benefits to the soldier, radio manufacturer, and customer as follows:

- 1) **Reduced radio component count** – a 50% reduction in cost can be realized due to the use of tunability, SOS CMOS integration, and advanced 3D packaging technology and RF architectures.
- 2) **Simplified modular integration of radio elements** - “non-Radio” manufacturers can efficiently and effectively integrate radio functionality resulting in the integration of radios in a myriad of new applications not currently available.
- 3) **Real-time Tunability** - 20% or more increase in handheld battery lifetime due to improved RF power efficiency resulting from active PA matching optimizing PA efficiency, increased antenna efficiency, and reducing RF power losses in the radio.

The Universal Thin Radio can integrate within the existing radio supply chain, providing a sustainable solution to both the military and commercial radio markets. Due to the high power density of the components and highly miniaturized package, thermal design is critical in the beginning of the

architecture study, and will provide overall system guideline for conceptual mechanical design development.

The paper is organized into the following sections: section II describe the functional block diagram of the radio in package, key components and power dissipation, as well as the thermal requirement of the system. In section III we used commercial CFD software to model the thermal performance of various package design and operation scenarios, and used the insight gained to optimize the system design. In the end we summarize the findings and design guidelines.

II. Design of the thin radio module

Figure 1 plots the functional block diagram of the thin radio module. Envisioned functionality of the module includes GPS, RF transceiver with multiple network compatibility, multiband, for example, 9 band WCDMA, and Quad band GSM, small antennae, bluetooth peripheral interface, application processing, computing power capable of voice command and control, smart power management, etc.

The thin phone module consists of three layers and measures 12 mm x 12 mm x 1.6 mm. Each layer is 0.5 mm thick with the interconnect in between being 0.05 mm thick. There is shielding between layers and the external IO are 168 with 4 large ground/power pads. The main power dissipating components include the microprocessor and memory stack on the first layer, the transceiver on the second layer, and the WCDMA PA chip, GSM PA chip, and the power management chip sets on the third layer.

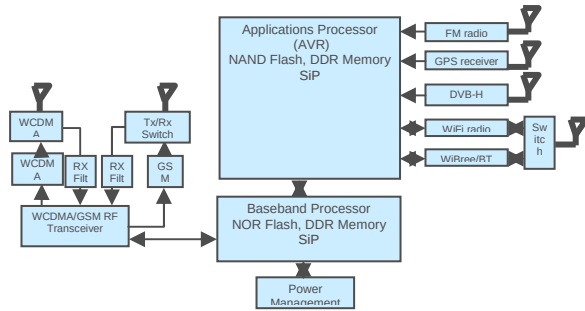


Figure 1, Functional block diagram

During worst case operation scenario, the power dissipation from each active components is listed in the table below. Only one power amplifier (PA) is active at any time. The module dissipates less power ($\sim 2\text{W}$) when operating in WCDMA mode than in GSM mode ($\sim 4\text{W}$). Next we performed systematic thermal modeling and design iteration using commercial CFD software.

Table 1, power dissipation from the active components of thin phone

Processor /memory stack	Transceiver	WCDMA	GSM	Power management
0.5W	0.3W	1.1W *	3.0W	0.15W

*: Assumes 40% PAE and 4dB tangential loss.

III. Thermal modeling and analysis

First, model of each layer of the package is created using Flotherm 7.1, a CFD software that solves the conjugate heat transfer problem using finite volume method. The ambient temperature is set at 20°C . The package is put in still air, and the heat is dissipated through natural convection. Figure 2 and 3 show the Flotherm model of the first layer. Figure 4 plots the temperature distribution of the first layer. Due to the small surface area and small amount of air flow induced by the temperature gradient, the peak temperature rises to about 160°C

with 0.5W power dissipation from the microprocessor and memory stack.

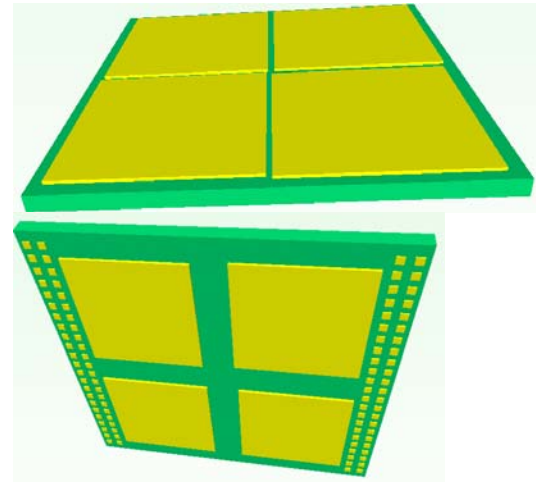


Figure 2, Layer 1 top view and bottom view of the first layer

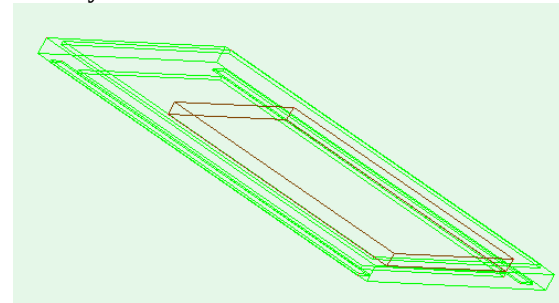


Figure 3, transparent view of layer 1, with microprocessor and stacked memory

One way to reduce the junction temperature is to improve the heat spreading. Instead of 4 metal layer for electromagnetic shielding, a single layer should be used to reduce spreading resistance. Figure 5 demonstrates the effect, with junction temperature reduced from 160°C to 131°C .

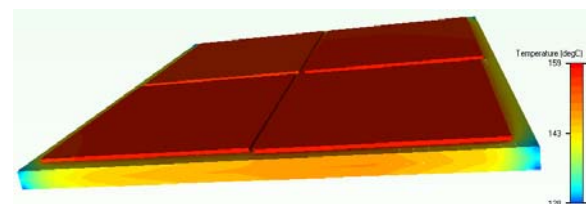


Figure 4, Temperature profile with layer 1 only, natural convection, 20°C ambient

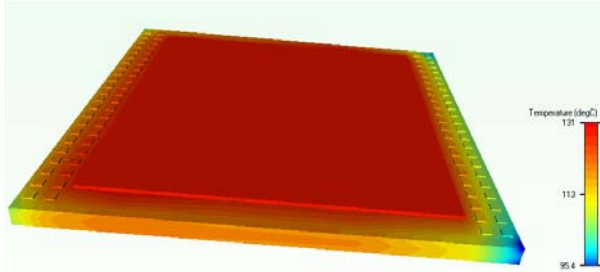


Figure 5, Temperature profile with layer 1 only, with one metal layer for better spreading

Next we simulate the third layer, which includes the PAs and power management, therefore dissipates the most heat among the layers. Under GSM mode, the GSM PA dissipates around 3W in worst case. Figure 6 depicts the temperature profile on the layer; it runs up to 900 °C. When the operation switch to WCDMA mode, power dissipation is reduced by 2 watts, therefore the maximum temperature is also reduced by more than half, as shown in Figure 7.

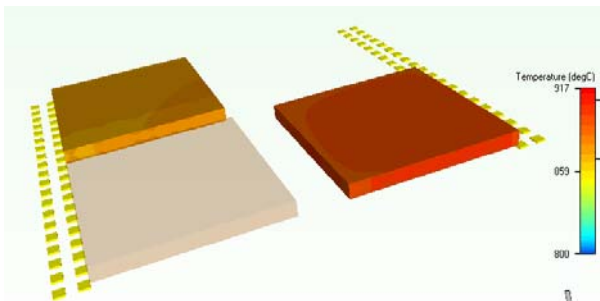


Figure 6, Temperature profile with layer 3 only, in GSM mode, GSM (3W) + power management (0.15W) + WCDMA (0W).

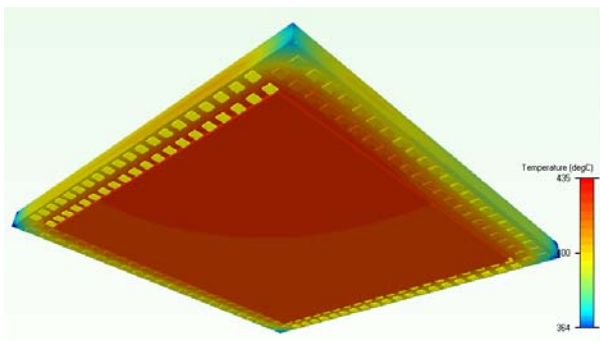


Figure 7, Temperature profile with layer 3 only, in WCDMA mode. GSM (0W) + power management (0.15W) + WCDMA (1.1W).

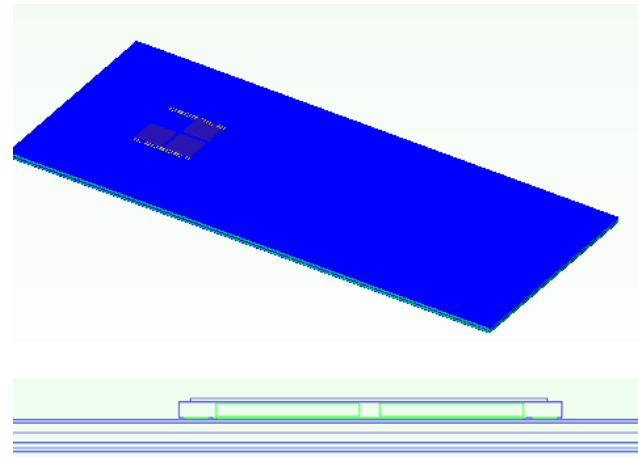


Figure 8, Layer 3 on a 90 x 45 x 1.0 mm motherboard.

This analysis illustrated the dependence of component temperatures on each individual's power level and total power dissipation. In a mobile phone application, the package is placed on a thin motherboard with typical dimension of 90 x 45 x 1.0 mm. The dielectric material is usually FR4, and consists of several signal and power/ground layers. Those thermally conductive layers will help spread out the heat over a much larger surface area. As shown in Figure 8, the peak temperature is at the WCDMA PA is reduced from over 400 °C to under 100°C.

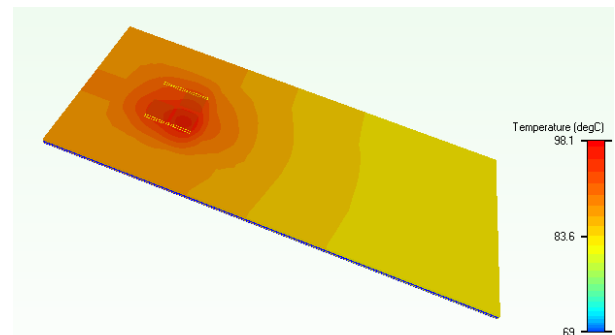


Figure 9, Layer 3 and motherboard (9 x 4.5 x 1 mm)

Next the 3 layers are stacked using small pitch solder balls, and the mother board is

placed in a magnesium enclosure, with dimension of 100 x 50 x 10mm. The thickness of the enclosure is about 0.3mm. The metal enclosure can be also utilized to improve spreading, if the top of the package is in contact with the enclosure through a layer of thermal interface material, with typical thermal conductivity of 1.0 W/mK. The package structure is plotted in Figure 10. The temperature distribution on the package and the motherboard is shown in Figure 11. At a total power consumption of 2.05W under WCDMA mode, the maximum temperature in the package reached over 200 °C at the WCDMA PA. The case temperature ranges from 160 °C to 180°C (Figure 12). Figure 13 also plots the air speed distribution on a cross sectional plane along the center of the package. The air flow is generated from the buoyancy force which resulted from the density gradient, caused by the temperature gradient. The natural convection produces air flow of less than 0.2 m/s, therefore the heat convection is limited. The worst case scenario occurs when the phone is positioned horizontally, where the gravitational force has a short path to accelerate the air flow.

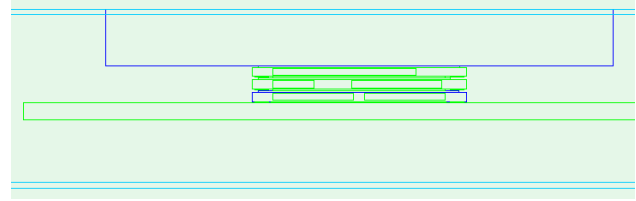


Figure 10, All 3 layers with PCB and 100 x 50 x 10 mm Mg case. The package is in contact with case through TIM (1.0 K/Wm). Total power = 0.5 + 0.3 + 0.15 + 1.1 = 2.05W. (top), 3D rendering of the package; (middle) cross section of the mobile phone model; (bottom) close up view of the package and the TIM layer.

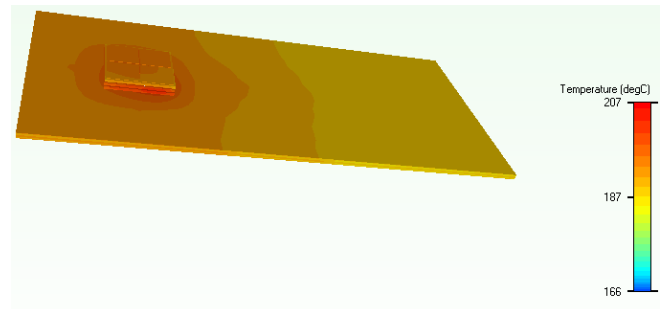


Figure 11, Package temperature profile within the package and the motherboard.

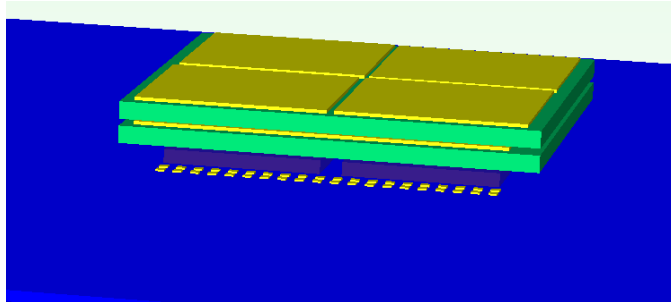
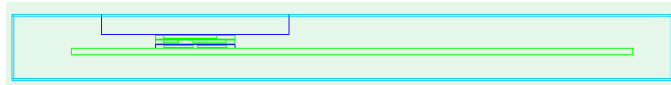


Figure 12, Case temperature distribution



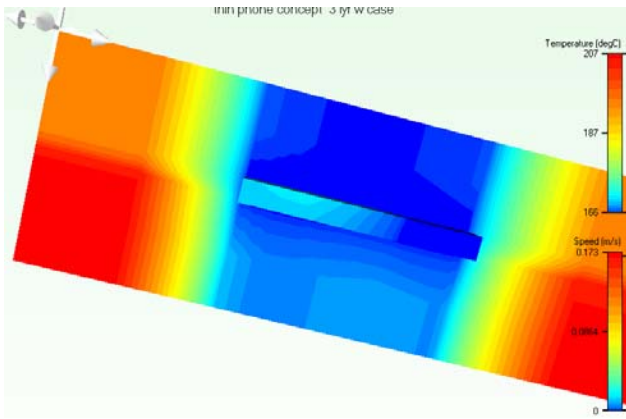


Figure 13, air flow speed contour on a cross sectional area.

Many technologies exist which reduce the high temperature on the PA, having a much higher power density than average. One example is to use high thermally conductive material such as graphite¹. Several thin layer of graphite is placed between the motherboard and keypad, and between the motherboard and the battery pack. The graphite layer has two functions; first as a heat spreader to address the high thermal conductivity in the lateral direction (in-plane) which is from 300W/mK to 700W/mK and reduce the high temperature around the PA. The other function is thermal shielding. The graphite has low thermal conductivity along the through plane direction (less than 1W/mK), therefore minimizes the heat conducted to the keyboard and the battery, where low temperature is desirable. The effectiveness of this design is studied in the thin phone model. As shown in Figure 14, the motherboard is sandwiched between two layers of graphite sheets, each of 1mm. The in plane conductivity is assumed to be 500 W/mK, and the through plane conductivity is 1W/mK. As plotted in Figure 15 and 16, the maximum temperature of the package is significantly reduced from 207 °C to 98 °C, and the case temperature is reduced from 170 °C to 96 °C. The thermal modeling performed here is based on

maximum 100% duty cycle on the PA and processors. In real operations, power dissipation of the components will be lower and the maximum junction and skin temperature of the module is reduced.

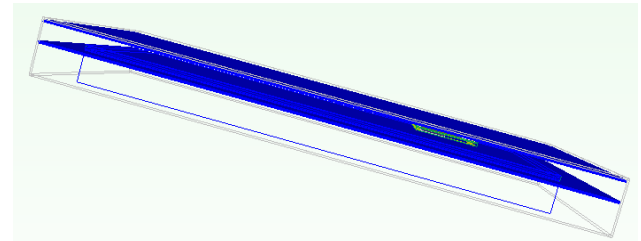


Figure 14, a graphite sheet cover the top of the package and underneath the motherboard. The sheets spread out the heat from the package, and reduce the maximum temperature from 207 °C to 110 °C.

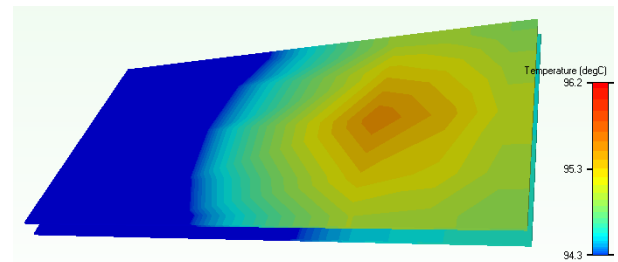


Figure 15, heat spreading effect of the graphite layer

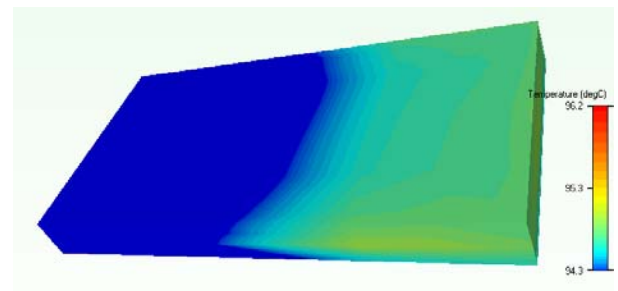


Figure 16, case temperature distribution.

IV. Conclusion:

The concept of a thin radio module in SiP is demonstrated. Digital and RF components are packaged into a 12 x 12 x 1.6 mm form factor. Flotherm is used to model the thermal characteristics of a three layer thin phone concept design. The total thermal

dissipation is between 2W to 4W, depending on the operation mode. When the package is hanging in the air, the temperature will reach higher than 400 °C due to the small surface area. In the real application, the package is placed on a motherboard and within a metal enclosure. Without enhanced conduction, the maximum chip temperature is around 200 °C under WCDMA mode. To further reduce the junction temperature, 2 graphite sheets are attached to both sides of the motherboard, and then put into contact with the magnesium housing through thermal pad. The graphite has high in-plane conductivity, which help to reduce the maximum temperature in the package by 50%. As shown in figure 17, compared with current mobile phone system, the miniaturized radio in a package will enables:

- 4 fold increase in channel capacity
- 75% reduction in electronics footprint
- 67% overall form factor reduction

and bring significant value to military and commercial communication systems.

Figure 17, (top) today's multi band smart phone – 2007 Nokia N95; (bottom) thin radio enhanced smart phone design (concept).

¹ <http://www.graftechaet.com/>

