# *Thermal Management of Solid-State RF Cooking Appliances*

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## Abstract

Recent advances in solid state LDMOS and GaN power transistors have enabled the production of transistors that can generate 250 watts in a single die and package, at a cost comparable to a single magnetron. Cooking with solid state power transistors enables precise control of the field patterns generated within the cavity to the point where cooking can become high quality, simple and fast all at once. The solid-state power transistor requires many supporting elements that are needed for its operation. One such element is the thermal management system which must be small, quiet, and low cost if the use of solid state cooking is to become widespread. In this paper, we present the trade-offs in the design of such a thermal management system.

## 1. Introduction

The art of cooking has always been a compromise between simplicity, speed and quality. The ability to deliver heat energy to food is key to all cooking techniques, the oldest of which are based on heat transfer through temperature gradients. These cooking techniques allow very high quality cooking, but at the expense of speed and/or simplicity. During the 1960's the microwave oven was introduced. Using electromagnetic waves to carry the heat energy along the wave propagation direction, it enabled cooking without dependence on temperature gradients within the food, but with very little control over the resulting heating patterns. In many cases, this reduces the quality if the cooking speed is too high.

Current microwave ovens utilize magnetrons as an RF power source. The magnetron is a high voltage vacuum tube in which perpendicular electric and magnetic fields cause the repetitive motion of electrons in a resonant cavity, which in turn generate radio-frequency (RF) power. It is constructed of metals and ceramic insulators, with the hottest internal part being the filament which generates the electron cloud, reaching temperatures of 900°C. Constructed as such, the magnetron is able to work with case temperatures reaching 140°C and above (see Fig. 1).

Such high temperatures, coupled with a heat dissipation of several hundred watts, place low requirements on the magnetron's thermal management system, enabling its widespread use in microwave ovens. A complete magnetron RF-power source, along with its cooling system and power supply, can reach a cost of $15 at production volumes of millions of units.

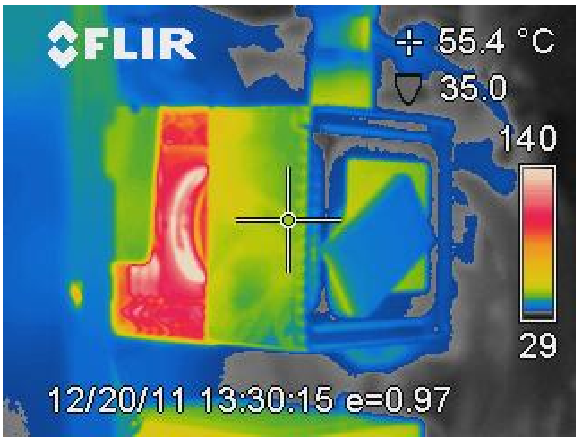

**Figure 1.** Thermal image of a magnetron operating in a microwave oven after 400 seconds of operation with a cavity load of one liter of water.

Compared to the magnetron, solid-state power transistors are much smaller devices, comprising a semiconductor die attached to a metal base, packaged and connected with bond wires to external conductors. The maximum operating temperatures of the die can reach around 200°C, translating to allowable metal base temperatures of about 100°C. The heat dissipation of a 250 watt RF output power solid state RF power transistor, which can reach 200 watts of dissipated heat, coupled with the transistor's small size, results in stringent cooling system requirements.

A comparison between the cooling requirements of the two technologies is provided in Table 1. Requirements for the cooling system heat-transfer coefficient are more stringent for the solid state power transistor compared to the magnetron.

**Table 1.** Cooling system requirements comparison for a magnetron and solid state power transistor

| **Parameter** | | **Magnetron Tube** | **Solid-State Power Transistor** |
|---|---|---|---|
| RF output power | [W] | 900 | 250 |
| Average heat dissipation | [W] | 400 | 200 |
| Cooling surface area | [cm$^2$] | 20 | 1 |
| Maximal baseplate temperature | [$^o$C] | 140 | 100 |
| Cooling system heat transfer coefficient | [W/(cm$^{2}\cdot{}^{o}$C)] | 0.2 | 3.3 |

## 2. Thermal Management

One of the advantages of using solid-state power transistors is the ability to precisely control RF output to cook each different food load appropriately. Such control is also advantageous in synchronizing operation of several transistors feeding the same cooking cavity, operating them in a manner whereby each transistor emits the same frequency, but at a different phase and/or amplitude. This, in turn, enables RF power reflections back to the transistors to be minimized (these are additional transistor heating sources when operating several transistors feeding the same cavity).

Another critical aspect of thermal management is the design of the cooling system hardware. When designing a cooling system, there are several main factors to consider:

- Heat transfer coefficient
- Cost of goods
- Noise level
- Size and shape

Extreme solutions from both ends of the spectrum are divided into two main categories:

*(1) Noise-limited systems*

Such systems employ high-speed fans which generate very high airflows that are able to cool the power transistor, despite its high heat dissipation per unit area. The high air flows generate acoustic noise which must be limited.

*(2) Cost-limited systems*

Such systems employ very high heat conductivity solutions based on vapor chambers, heat pipes or copper blocks. The very high heat conductivity helps spread the generated heat over a large surface area, which can then be easily cooled either by natural convection or low air speed fans. High heat conductivity solutions are expensive due to the cost of raw materials (mainly copper) and the need for complex production methods.

## 3. Heat Sink Design Optimization

Solid-state power transistors are typically connected to a signal generation and measurement system, incorporated into a single solid-state RF power module that is integrated into an oven appliance. These modules have a metallic base plate support structure for the electronics, which is typically constructed from die-cast aluminum in order to minimize cost. It is also desirable to utilize the entire surface of the module's base plate for cooling the RF power module, in which the main heat source is the solid-state power transistor.

Cooling may be better accomplished by embedding a copper insert in the aluminum base plate due to the higher heat conductivity of copper (380W/(m·ºK)) compared to that of aluminum (205W/(m·ºK)). However, since copper cost-per-unit is about ten times higher than that of aluminum, care must be taken to select the optimal amount and shape of copper.

We can study the amount of copper needed using the model shown in Fig. 2. This consists of a radially symmetric RF-power module with a fixed radius of 60 mm, an aluminum heat sink with a variable height, and a copper insert with variable height and radius. The simplified model behaves similarly to the actual RF system, but allows simulations to be run quickly in comparison to a detailed model, thereby enabling multiple thermal simulations with different model parameters. In this model, we were able to run over 9000 thermal simulations within hours, using the thermal simulation module in the FEMM simulation software written by David Meeker.

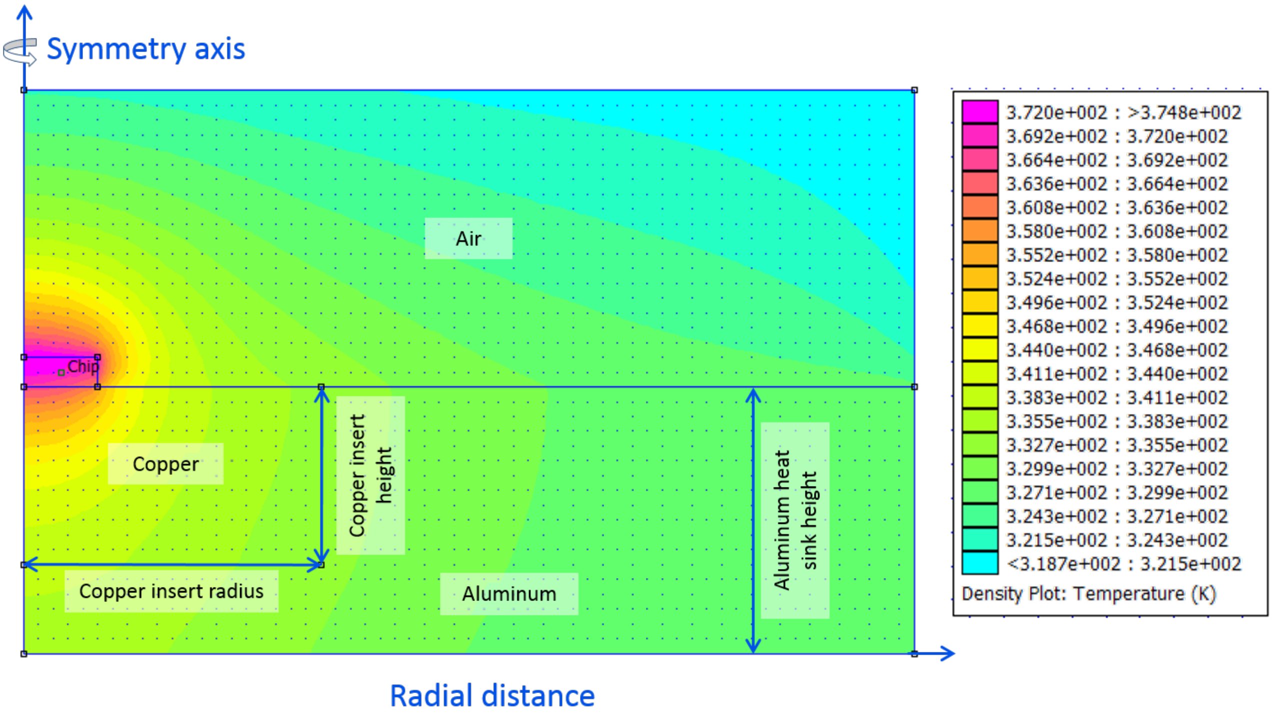

**Figure 2**. Model base plate design with radial symmetry, in which a solid-state power transistor is placed at the center of the RF power module. The colors indicate temperatures.

The simulation results are shown in Fig. 3. All system parameters are shown versus raw material costs, for both worst and best-case thermal performance. The worst performing thermal design gives the highest chip case temperature for a given raw materials cost, while the best gives the lowest case temperature for the same raw materials cost. Additionally, the differences between die-cast and CNC-based aluminum processing are shown and are found to be negligible in this model. It is notable that, in almost all cases, selecting a copper insert which covers the entire aluminum metal base plate is the worst possible use of the copper raw material.

To conclude, we can see in Table 2 that the cost difference between an optimal (best-case) and worst-case thermal design with the same cooling performance is a $3.3 increase in raw materials cost, and a 440 gram increase in overall base plate weight. When dealing with low-cost home appliances, such cost savings are critical and need to be implemented across all design disciplines, in order to reach mass consumer market.

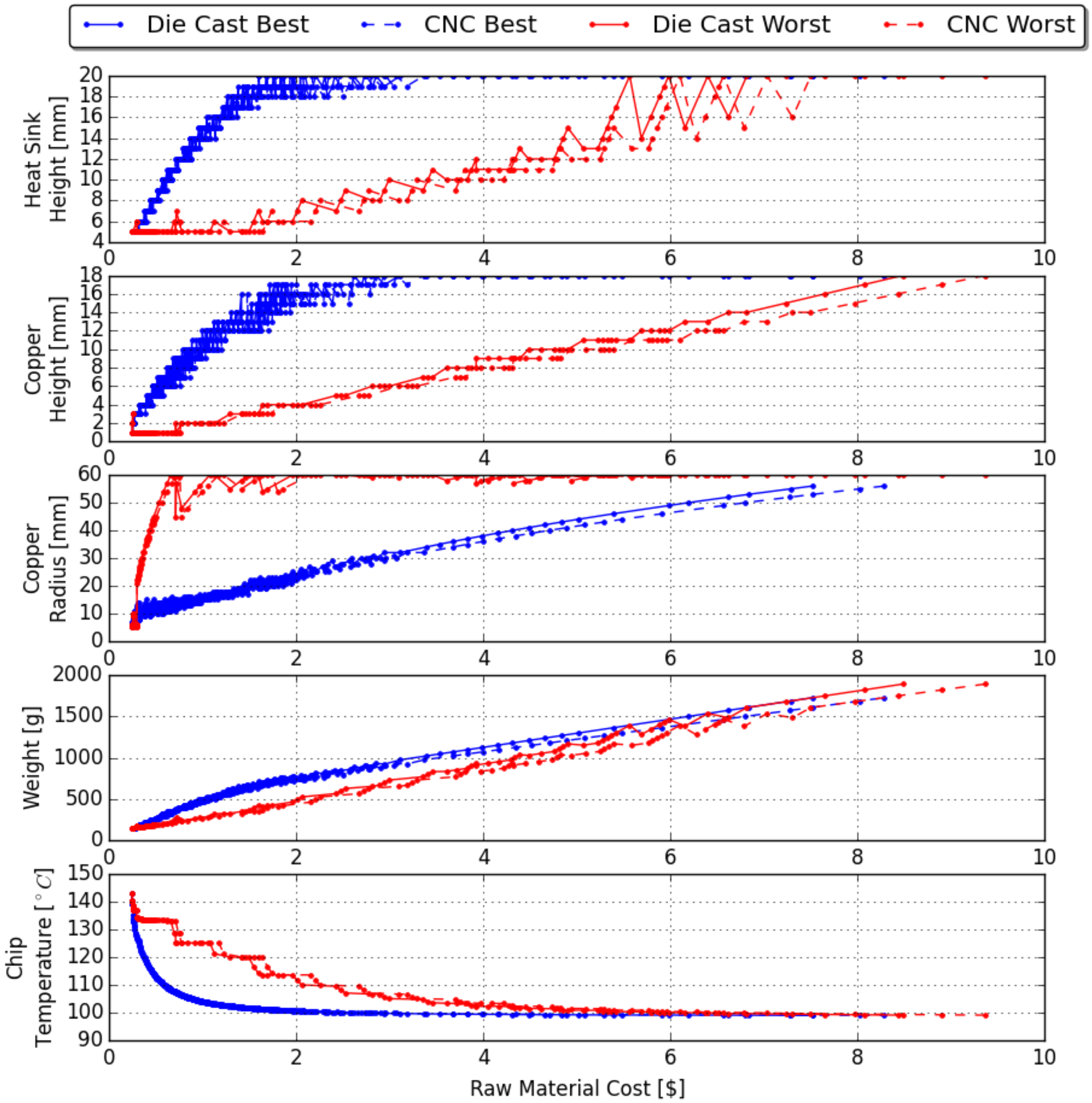

**Figure 3.** Optimal (blue) and worst-case (red) design outcomes versus base plate allocated raw material costs. Both CNC (dashed line) and die-cast (solid line) production methods are shown.

**Table 2.** Comparison table showing an increase in raw materials cost of $3.3 between worst-case and best-case design with the same chip temperature (this difference is significant when considering target costs which are suitable for the mass consumer market).

| **Design Parameters** | | **Raw Materials Cost** | | |
|---|---|---|---|---|
| | | **$2 Best Case** | **$2 Worst Case** | **$5.3 Worst Case** |
| Chip Temperature | [°C] | 100.6 | 112.0 | 100.6 |
| Overall Weight | [g] | 760 | 490 | 1220 |
| Heat Sink Height | [mm] | 19 | 7 | 14.5 |
| Copper Insert Height | [mm] | 16 | 4 | 11 |
| Copper Insert Radius | [mm] | 25 | 60 | 60 |

## 4. Summary

The goal of bringing the precision and speed of solid-state RF cooking to the mass consumer market requires design optimization, taking in a compromise between cost and performance. In this paper, we presented a sample of such optimization as it relates to the thermal management of solid state RF power amplifiers. This work was undertaken at Goji's research center, the first to introduce a fully-integrated complete solid-state RF cooking system into a home appliance, using its Vecton™ RF module.

## About Goji Food Solutions

Goji develops and markets RF cooking technologies for household, commercial and industrial applications, and provides a full range of licensing, design and manufacturing services to commercial and white goods appliance manufacturers.
For more information, visit:
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## About the Author

**Ben Zickel** is the CTO of Goji Research. Mr. Zickel joined Goji in 2011 and has over 15 years' experience in the research and development of multidisciplinary systems. Prior to joining Goji, he managed the RF System Engineering Group at Wavion, where he was responsible for product definition, development and productization. Previously, Mr. Zickel was selected to participate in the elite Israeli Defense Forces 'Talpiot' program. He subsequently served for six years in the electronic systems division of the Directorate of Defense R&D within the Israeli Ministry of Defense, where he led the research and development of new technologies for military systems. Mr. Zickel holds a BSc in Physics and Mathematics from the Hebrew University and an MSc in Theoretical Physics from the Technion – Israel Institute of Technology.