Package and Die Attach Material Comparisons for High Power GaN Devices

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Introduction

The design of high-frequency high-power amplifiers has benefited from the enhanced characteristics of gallium nitride (GaN) making it the technology of choice for many 5G/6G+ designers. GaN aids high-frequency high-power performance in a number of ways. Transistors have an upper limit of current output based on size. With output power proportional to voltage squared, the higher breakdown voltage of GaN enables a higher output power. The enhanced electron mobility of GaN enables a higher gain at higher frequency and GaN has a lower thermal resistivity providing a cooler performing design. While much attention is given to the GaN device and circuit design, what is often overlooked is the package in which the GaN device is attached and the way the device is attached to the package. The challenge is finding a suitable package for GaN because of its higher power density and the need to dissipate the heat while maintaining maximum device performance.

StratEdge has been designing and manufacturing packages for high power, high frequency compound semiconductors since the early 1990s, with much attention focused on gallium arsenide (GaAs) and GaN. It is well known that GaN device efficiency and reliability can be improved by reducing the chip-to-package junction temperatures (Tj) [1], which can be achieved effectively with a suitable package. The GaN power amplifier MMIC can produce much greater power density, and it is the package's job to help remove the heat that is generated. Therefore, it is important to provide the most efficient way to dissipate the heat so that the device can produce its peak performance, and isn't as likely to overheat and fail from normal operation.

What makes the package more suitable is a heat-spreading base made with a high thermally conductive material. The epoxy or solder material used to mount the GaN device onto the base is also important. But the thermal conductivity of the base material is not the only consideration. Its coefficient of thermal expansion (CTE) is also critical. The high temperatures produced by GaN require a base with high thermal conductivity and a CTE matched to the GaN device. Engineered materials like copper tungsten (CuW) composite and laminated copper-molybdenum-copper (CMC) were developed within the industry to construct robust packages.

While copper is an excellent heat conductor with a thermal conductivity of about 400 W/mK, it expands greatly when it becomes hot compared to the GaN device. Bases made with CuW composite combine the desirable thermal conductivity of the copper with the stiffness provided by the tungsten. Experimentation has determined that bases made with laminated layers of copper and molybdenum proved to be the best fit for GaN. Molybdenum, while not a great thermal conductor, is stiff and can be laminated to copper to provide a core that enables the entire base to have a good CTE match with the GaN device. CMC, constructed with a 1:3:1 ratio of the layer thicknesses, results in an optimum balance of thermal dissipation and thermal expansion of the base material. The effective thermal conductivity in the z-direction is close to that of CuW, which is about 190W/mK. What CMC provides that CuW does not is a layer of copper directly beneath the GaN device. This enables the heat to spread away from the hot spots on the bottom of the device, which helps reduce the Tj.

Purpose of This Paper

StratEdge recently conducted a series of thermal simulation to compare how well heat is dissipated from a GaN device and to support the statements made in the previous paragraph. The purpose of this paper is to explain the boundary conditions of the simulations and to present the results using various die attach and base materials. For the purposes of this study, materials were used that have CTEs known to match that of GaN-on-SiC, therefore the effects of potential mismatches are not discussed. So too for the die attach materials. The modulus of elasticity of solder alloy verses organic polymers can be important as are many other factors, but the focus of this study is on heat transfer and Tj of the device. The Tj is the highest operating temperature of bottom on the GaN device in the package. As mentioned above, the Tj has a direct correlation to reliability; the lower the Tj, the longer the device lasts.

A useful tool in considering electronic package designs is to consider the package as a series of stacked layers. Working with and thinking about packages in terms of layers can simplify thermal dissipation analysis. Viewing packages as layers is a useful way to understand 3D interactions in the package structure. This is the basis for thermal simulation modelling.

We will compare two different base materials, CuW (15% Cu/85% W), and CMC, to determine the effect they have on T_j, all other things being equal. These material properties are detailed in Table I. We then will also compare AuSn alloy solder to a traditional silver filled epoxy (H20E); the properties are shown in Table II.

Table I. Base materials and thicknesses

CMC Base Composition, Layer Thickness (inches)	CuW Base Composition, Layer Thickness (inches)
Copper (401 W/m K), 0.002	CuW (190 W/m K), 0.010
Mo (139 W/m K), 0.006	
Copper (401 W/m K), 0.002	

Table II. Die attach materials and bond line thicknesses

	EPO-TEK® H20E	AuSn
Bond Line thickness (inches)	0.0015	0.00025
Thermal Conductivity (W/m K)	2.5	57

GaN Amplifier MMIC

The high power amplifier designed by Obsidian Microwave and the subject of this StratEdge thermal study is an asymmetrical K-band Doherty design. The Doherty design is a high-efficiency design method where the amplitude modulated communications signal is split into the average power signal where the amplifier performs in the high-efficiency mode and the high-power mode for the peaks of the modulated signal. This means that the peaking path of the amplifier is only on when the signal is greater than the average signal generally quantified as the peak-to-average ratio (PAPR) of the signal. The asymmetrical Doherty design allows a higher PAPR and means that the peaking path produces the greater amount of power and in this design has been targeted to have a higher power density [2]. As a result, the thermal analysis is crucial to ensure the reliability of the overall power module.

The GaN MMIC chip is 0.1498" in length from RFin to RFout, and 0.1134" wide. The output stages are evenly spaced 0.0375" from the output end of the device and each generates 3.333 Watts. The device is attached to a metal heat spreader that is the base of a ceramic package. Both package and heat spreader are .450" square in size. The metal base is .010" thick. The device is .004" thick.

Simulation Model of Package and Device

To perform the steady state thermal analysis, a model was created that mirrors the packaged device assembly, as shown in Fig. 1. As in the actual assembly, the device is offset from the center of the package. The package modeled was an off-the-shelf StratEdge leaded laminate package (LL-style), part number LL4545-0-2, with broad band RF performance from DC to 63 GHz. The device's RF output port was aligned next to an RF pad on the package as close as possible to the cavity wall so that the ribbon connecting the device to package was as short as possible, minimizing the losses. Short wires or ribbons are electrically less lossy and therefore preferred in RF assemblies.

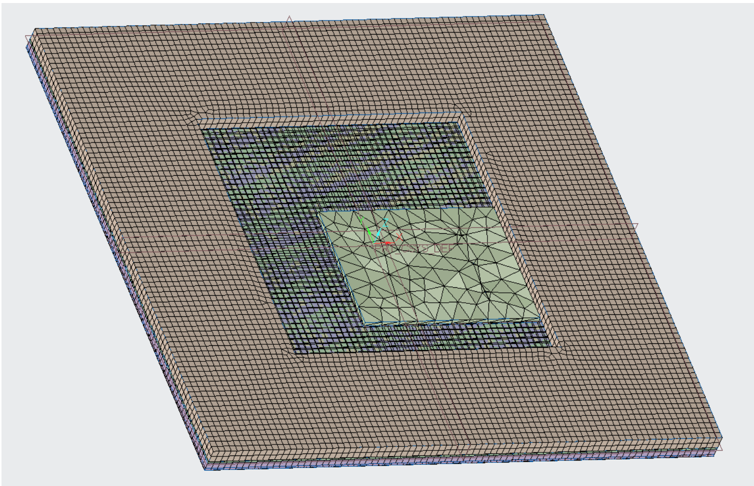

Figure 1. Simulation Model

The simulation software used was PTC CREO developed for use with Ansys. The boundary conditions for the model were a .00025” wide border within the perimeter set at a constant 75°C. The 10 Watts generated by the device was divided equally over the three output stages. Each stage was .00039” wide by .00087 long. The software program allowed each stage to be divided into eight .00015” square elements with .00009” spacing between them. See Fig. 2 for one of the simulations illustrating the hotspots on the surface of the chip.

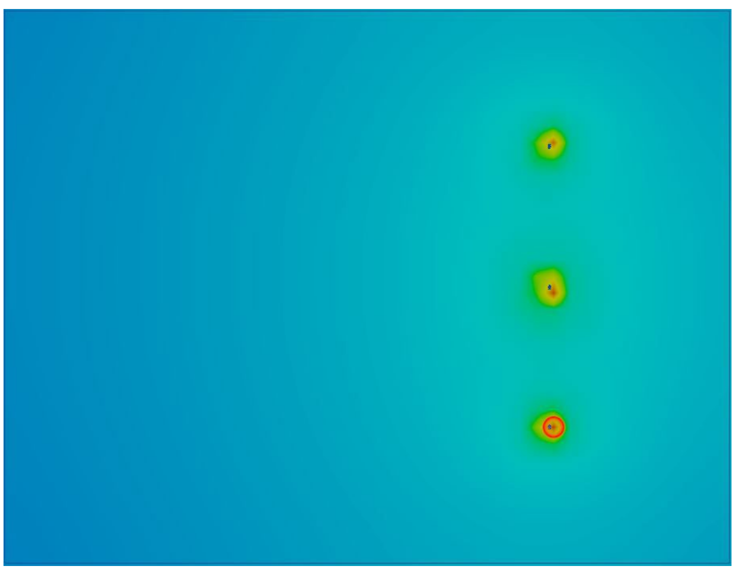

Figure 2. Hotspots on the three-stage power amplifier

Comparisons of CuW to CMC and silver-filled conductive epoxy to AuSn solder

Using the described model, the peak output stage temperature of the device attached using H20E on a base made from CuW (15% copper) was compared to the same mounted on a CMC base. The Tj for the model with the CMC base was 272.9°C, which was 8.9°C cooler than the model with the CuW base. Then the model with the CuW base and H20E die attach material was compared to the same base with AuSn solder die attach material. The Tj for the model with AuSn was 257.3°C, which was 24.5°C cooler than the model with the H20E. When the model for die attached to CuW with H20E was compared to CMC attached with AuSn, the Tj dropped to 247.3°C, which was 34.5°C cooler. The simulated results are compared in Table III.

Table III: Junction temperatures for different combinations of base material and die attach material (all temperatures in degrees Celsius)

	H20E Epoxy	AuSn Solder
CuW base	281.8	257.3
CMC Base	272.9	247.3

The simulation indicates that the device mounted onto a CMC base using AuSn with a bond layer of about .00025" runs at a significantly cooler temperature than the device mounted on an industry standard base material with silver filled die attach epoxy. The result was consistent with those reported by a StratEdge customer who made thermal measurements of a high power GaN amplifier assembled under the same two configurations.

Summary and Conclusions

StratEdge developed a proprietary AuSn eutectic die attach technique that, in conjunction with its leaded laminate (LL) packages with CMC bases, was found to achieve superior thermal dissipation. There are different methods for AuSn die attach. StratEdge chose scrubbing, which is the process of heating with mechanical agitation. It's the extremely thin bond line, that can only be achieved with the scrubbing process, that optimizes heat transfer. In addition to providing superior thermal performance, AuSn solder can be used for high reliability applications because it won't outgas, and it is unlikely to fail if done properly.

To quantify the benefit of mounting GaN devices with AuSn solder with ultra thin bond lines into a package with a CMC base, a model was created for a 10-Watt high power GaN amplifier. The simulation showed that attaching this device to CMC with AuSn created a Tj that was 34.5°C cooler at the hottest junction for the same device mounted on CuW using H20E. Measured verification of the study results is in-process but not yet available. Using StratEdge's proprietary eutectic die attach method to attach a GaN chip to a StratEdge leaded laminate package made a huge difference. By using packages with CMC bases and a AuSn eutectic die attach method that uses mechanical agitation and heat, chip temperatures are reduced, which improves efficiency and reliability of the device. The result is improved performance of the device with increased power output and longer life for high-frequency, very high power, extremely demanding GaN devices.

References

[1] S. J. Pearton and F. Ren, “GaN Electronics,” Advanced Materials, vol. 12, no. 21, pp. 1571-80, Nov. 2000.

[2] T. Kitahara, T. Yamamoto and S. Hiura, "Asymmetrical Doherty amplifier using GaN HEMTs for high-power applications," *2012 IEEE Topical Conference on Power Amplifiers for Wireless and Radio Applications*, Santa Clara, CA, USA, 2012, pp. 57-60, doi: 10.1109/PAWR.2012.6174929.

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