AN1955

Thermal Characterization Methodology of RF Power Amplifiers

Rev. 2 — 11 July 2024 Application note

1 Introduction

This document explains the methodology used by NXP for thermal characterization of RF (Radio Frequency) high power amplifier (RFPA) products, which include LDMOS and GaN active devices. The thermal measurement characterization used for each device technology is the same. However, the reporting of thermal performance for GaN devices is modified due to their structure. This application note describes the reporting methodology for each. Accurate determination of thermal operating conditions can be derived from the reported thermal performance, which is crucial for establishing the reliability of systems that use NXP RFPA GaN or LDMOS devices.

2 Measurement technique

Infrared (IR) microscopy is used to characterize the die surface temperature during NXP RFPA operation. IR microscopy allows for the surface temperatures within the field of view to be measured during test. Maximum surface temperatures are measured and used to make the thermal resistance calculations.

The IR microscope is outfitted with a 1 kW temperature-controlled stage with the ability to be heated and cooled. The RF circuit is secured to the stage, and the temperature of this stage is adjusted to achieve the desired case temperature (usually between 80°C and 125°C) of the device under test (DUT) during power testing. When the device is secured into the test circuit, the IR measurement is initiated, and the desired electrical stimuli are applied. Once the target case temperature is reached and stable, the IR image is captured along with all corresponding electrical data. This data is recorded and later compiled and analyzed. The corresponding thermal resistance value can then be calculated and reported.

Because the IR measurement method requires direct viewing of the active die, the device is opened to expose the die. For a metal ceramic package, the protective ceramic lid is removed and replaced with a ceramic lid that has been modified with a window opening to view the die. For overmolded plastic packages, the mold compound is etched away until the die is sufficiently exposed. Since the heat flow from the die to the package heatsink is dominated by conduction, the measurement error caused by the removal of the lid or removal of the mold compound around the die surface is negligible.

The exposed die is then coated with a high emissivity substance (see Section 13 Appendix) to obtain a fixed emissivity value for IR thermal measurement. This coating greatly improves the accuracy of the IR measurement by eliminating dependence on the emissivity correction algorithm used by the IR microscope, which has been found to be ineffective at compensating for the translucent nature of silicon and silicon carbide [1]. The maximum die surface temperature, typically located at the center of the die, is used as the die surface temperature in the thermal resistance calculations described later in this document.

3 Thermal measurement sequence

Larger high power devices, which typically have a metal heatsink, are inserted into the RF test fixture, using the heatsink as a cold plate. A solder that is liquid at room temperature is used as the thermal interface material (TIM) and applied to the heatsink of the DUT. An IR clamp is used to apply downward force to the top surface and leads of the package (see Figure 1). This clamp fastens the DUT to the heatsink using two #4-40 stainless steel cap screws, each tightened to 5 lb.-in. of torque.

Smaller, lower power surface mount devices, such as those in DFN and LGA packages, are solder mounted directly to the RF evaluation board (EVB). An IR clamp and TIM are not required.

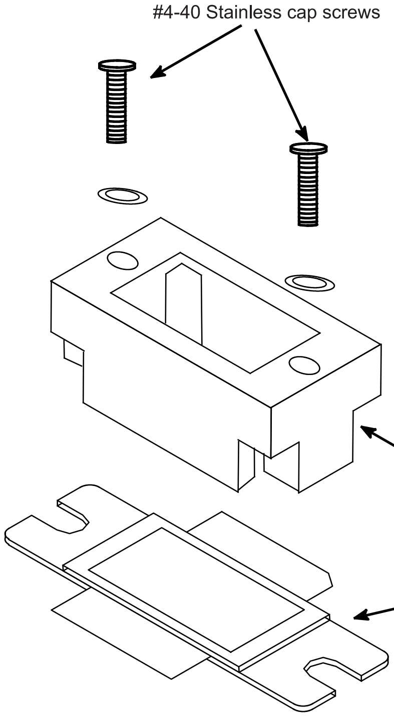

Figure 1. Exploded view of typical clamping scheme used for decapsulated or delidded high power DUT with eared or earless flange

4 Die surface and channel temperature

NXP RFPA products may consist of either GaN or LDMOS active devices, or both. For LDMOS devices, the maximum die surface temperature is the effective channel temperature and thus is, and has been, historically designated as T_J. Unlike LDMOS, the GaN device structure is such that the channel temperature (T_{CH}) is located beneath the GaN die surface (T_S) and is not viewable by IR. The maximum channel temperature must then be derived using an FEA thermal model of the specific GaN structure and validated by the GaN surface temperature as measured by IR. Every released GaN device is characterized using specific FEA thermal simulation and is validated by thermal and electrical data collected during IR measurement. Both GaN T_S and T_{CH} are used to calculate the reported thermal resistances.

5 Case temperature measurement

When feasible, the case temperature (T_C) of the package is measured by a 0.5 mm diameter stainless steel sheath thermocouple that is mounted within the metal heatsink of the RF fixture from the bottom and protrudes through the mounting interface to contact the bottom surface of the package (see Figure 2). A 1.0 mm diameter hole is drilled through the fixture heatsink to allow thermocouple passage. This hole typically provides minimal disturbance to the heat flow path. The thermocouple model is selected based on its sensitivity and excellent durability. A spring mechanism is added to the thermocouple to ensure constant mechanical contact with the bottom side of the flange.

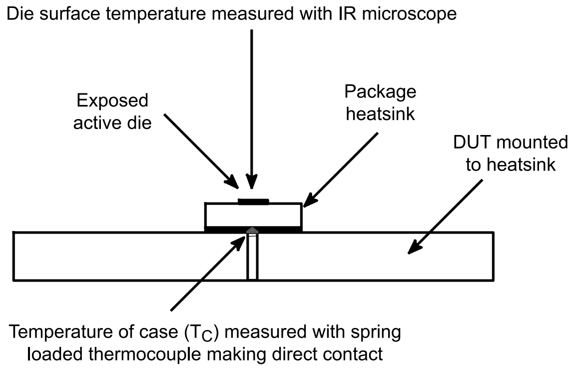

Figure 2. Case temperature measurement

The placement for this thermocouple is centered relative to the centermost active transistor in the package (see Figure 3). For Doherty devices, one thermocouple is placed underneath the centermost Carrier die and another under the centermost Peaking die. This enables accurate characterization of case temperatures collected during IR measurement, which are used in the thermal resistance calculations described later in this document.

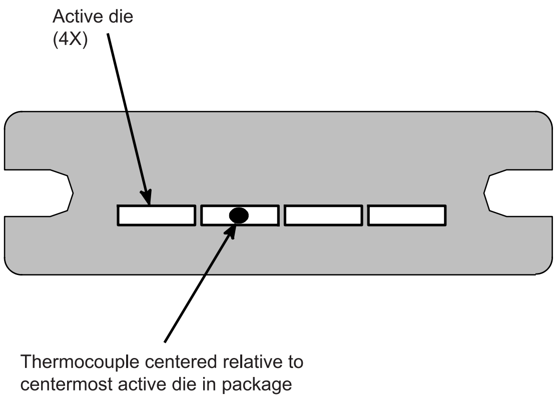

Figure 3. Positioning of thermocouple

For surface mount devices that are solder mounted (such as PQFN, DFN, MLF, LGA devices), the thermocouple to measure case temperature cannot be implemented because the hole for thermocouple passage introduces disturbance to the solder attach and the subsequent heat flow path. It is therefore necessary to compute the T_C based on thermal simulation. The thermal simulation model is validated by measured IR thermal findings for exposed adjacent surfaces in close proximity to the active die.

6 Power dissipated

Global power dissipated is calculated for all test conditions. The global thermal resistance value is based on the total power dissipated for the DUT and circuit. This is referred as global power dissipated, P_{D_Global}, which is calculated as follows:

$$P_{D\_Global} = (\text{RF input power} + \text{DC power } (I_D * V_D)) - (\text{RF output power} + \text{RF reflected power})$$

For a Doherty DUT that is configured with Carrier and Peaking sides, individually measured power dissipated may also be reported, one value for Carrier ($P_{D\_Carrier}$) and another value for Peaking $P_{D\_Peaking}$.

For thermal simulations used to determine the embedded GaN T_{CH}, the power dissipated is calculated by operating each side of the Doherty device individually under DC power only, where the respective measured T_S, T_C, and power dissipated (DC solo) are used as follows, where *i* is designated for either the Carrier or Peaking side. The respective DC solo $R_{\theta SC}$ value is measured at the equivalent die surface temperature exhibited during RF measurement. The P_{D_Global} may not be the same as $P_{D\_Carrier + Peaking}$.

$$P_{D\_i} = (T_S - T_C)i \,/\, (\text{DC solo } R_{\theta SC})i$$

7 IR thermal resistance calculation

The method for determining junction-to-case thermal resistance (θ_{JC}) under a chosen RF test condition is described for RFPA multi-die transistor devices, multi-stage RFIC devices and single and multi-stage Doherty devices. For a multi-die transistor device at a specified RF test condition, a single value is reported for the junction-to-case thermal resistance. For a multi-stage RFIC device, the junction-to-case thermal resistance is reported for each stage ($\theta_{JC\text{-}stage}$). For a single or multi-stage Doherty device, the junction-to-case thermal resistance is also reported for each stage.

For LDMOS devices, because the die surface temperature is equivalent to the LDMOS channel temperature (T_J), the following calculation is used:

$$R_{\theta JC} = (T_J - T_C) \,/\, P_{D\_Global}$$

In certain LDMOS devices with multiple stages, θ_{JC} and associated P_D are reported on a per stage basis and typically labeled as such ($R_{\theta JC\_stage}$).

For GaN devices, thermal resistance values are based on maximum die surface temperature (T_S) as measured by IR:

$$R_{\theta SC} = (T_S - T_C) \,/\, P_{D\_Global}$$

8 FEA thermal resistance calculation

The thermal resistance value is based on the maximum channel temperature derived from the FEA thermal simulation:

$$R_{\theta CHC} = (T_{CH} - T_C) \,/\, P_{D\_Carrier + Peaking}$$

For certain GaN Doherty devices, two individual GaN channel thermal resistance values are reported, one value for Carrier and another value for Peaking:

$$R_{\theta CHC\_Carrier} = (T_{CH\_Carrier} - T_{C\_Carrier}) \,/\, P_{D\_Carrier}$$
$$R_{\theta CHC\_Peaking} = (T_{CH\_Peaking} - T_{C\_Peaking}) \,/\, P_{D\_Peaking}$$

The dissipated power in the above calculations is as follows:

$$P_D = (T_S - T_C) \,/\, (\text{DC solo } R_{\theta SC} \text{ value})$$

9 Data sheet thermal resistance value

The thermal resistance data reported in NXP RFPA technical data sheets is based on performance tests done on a sample size of five to ten parts taken from final manufacturing lots. Each part is powered to the desired RF condition and measured. The mean thermal resistance value of that group is then used for the data sheet.

10 Confidence in thermal resistance data

A Gauge R&R (Reproducibility and Repeatability) assessment was used to demonstrate the methodology employed in measuring and reporting accurate thermal characterizations of NXP high power RF power amplifiers. This assessment showed that the measured standard deviation (part-to-part variation plus measurement variation) expressed as a percentage of the measured mean is about 5%.

11 Summary

Thermal measurement methodology has been developed and implemented to accurately characterize high power RF power amplifiers. Integral to this measurement methodology are:

- Using infrared microscopy to accurately characterize die surface temperature and FEA thermal simulation to characterize GaN channel temperature under applicable RF conditions
- Using thermocouple measurements to accurately determine case temperature (T_C)
- Using the maximum die surface and maximum channel temperature of the device to calculate the applicable thermal resistance
- Establishing confidence level in the measured thermal data
- Implementing this methodology to determine the applicable thermal resistance for the NXP technical data sheet

12 References

1. M. Mahalingam and E. Mares, “Infrared Temperature Characterization of High Power RF Devices,” Proceedings of IEEE MTT-S International Microwave Symposium, May 2001.

13 Appendix: Coating methodology for infrared thermal measurement of RF power amplifiers

This appendix describes the coating recipe used to fix the emissivity value of target objects in the infrared (IR) thermal measurement methodology of metal ceramic and overmolded plastic RF power amplifiers. We have assessed that an IR microscope’s emissivity correction procedure does not work well when applied to uncoated IR translucent targets, such as an Si device [1]. In some cases, the nonactive regions of the die layout show up as higher temperature regions than the active regions. This issue is resolved once the device is coated with a high emissivity coating. Another issue is that the temperature is measured lower for noncoated devices in comparison to the same devices when coated and measured under identical operating conditions.

13.1 Removal and replacement of protective lid for metal ceramic device measurement

To allow viewing of the die for IR thermal measurement, the protective lid of the metal ceramic package must be removed. To do this, a metal ceramic package is placed on a hot plate at a temperature of ~ 280°C for about 45 seconds. It remains on the hot plate until the epoxy seal of the protective ceramic lid has sufficiently melted to allow removal. The unit is relidded with a modified lid that has an opening. The part is then ready for the application of paint.

13.2 Removal of mold compound for plastic device evaluation

To permit thermal evaluation of an overmolded plastic package, the mold compound is etched away to expose the active die without damaging the die and interconnects.

13.3 Selection of coating applied to device

Based on an internal study comparing six different coatings, the one with the least impact on RF performance (gain, efficiency and intermodulation distortion at both 1 GHz and 2 GHz) was chosen. This coating is applied with an airbrush.

13.4 Application of coating to device using an airbrush

The use of an airbrush to apply the coating permits accurate and even coverage of paint onto the device. An air pressure of about 20–25 PSI is supplied to the airbrush for spraying. The airbrush is held about 1/2″ away from the units during application. A few passes of paint application are made to all of the units. To expedite the drying process between application coats, the paint supply is shut off to allow only air to pass through. The units are then sprayed with air only until the paint is dry. The coating process is repeated until the active die has been adequately covered with paint. An emissivity measurement was run using this coating process and was determined to be 0.98. Therefore, a constant emissivity value of 0.98 is input into the IR microscope when performing thermal measurements with coated devices.

13.5 References

1. Mahalingam and E. Mares, “Infrared Temperature Characterization of High Power RF Devices,” Proceedings of IEEE MTT-S International Microwave Symposium, May 2001.

14 Revision history

The following table summarizes revisions to this document.

Table 1. Revision history

Document ID	Release date	Description
AN1955 Rev. 2	11 July 2024	• Updated to include GaN thermal measurement methodology
AN1955 Rev. 1	30 April 2014	• Added information for non-bolt down devices
AN1955 Rev. 0	22 September 2006	• Initial release of application note

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