Thermal Measurement Methodology of RF Power Amplifiers

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INTRODUCTION

This document explains the methodology used by Freescale for thermal measurement of high power RF (Radio Frequency) power amplifiers (RFPA). Semiconductor device reliability heavily depends on device operating temperature so the accurate thermal characterization of these high power devices is crucial in establishing the reliability of the systems that use such devices.

DIE SURFACE TEMPERATURE (T_J) MEASUREMENT

Infrared (IR) microscopy is used to determine the die surface temperature (T_J) during amplifier operation. Because this IR measurement method requires a direct view of the die, the protective ceramic lid is removed and replaced with a modified lid that has an opening to view the die. In the case of overmolded plastic packages, the center portion of the mold compound is etched away until the die is sufficiently exposed. Because the heat flow from the device to the 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 coated with a high emissivity coating (see Appendix) to obtain a fixed emissivity value for IR thermal measurement. This coating greatly improves the accuracy of the IR measurement because it eliminates the need for any emissivity correction procedure used by the IR microscope. The emissivity correction procedure recommended by IR microscope manufacturers is ineffective at compensating for the translucent nature of silicon [1]. With the IR microscopy procedure, the maximum die surface temperature ("hot spot") in the measurement field can be located. The hot spot temperature is selected as the die temperature (T_J) for thermal resistance (θ_{JC}). The thermal resistance calculations are described later.

CASE TEMPERATURE (T_C) MEASUREMENT

The case temperature (T_C) of the package is measured by a 0.020″ diameter stainless steel sheath thermocouple (Type J; Omega part # JMQSS-020G-12) that is mounted within the heatsink of the RF circuit. It is mounted from the bottom and protrudes through the mounting interface to contact with the bottom surface of the package (Figure 1). A 0.032″ diameter hole is drilled through the circuit heatsink to permit thermocouple passage. This small hole provides minimal disturbance to the heat flow path and interface integrity. The thermocouple model is selected based on its sensitivity combined with excellent durability. A spring mechanism is added to the thermocouple to guarantee constant mechanical contact with the bottom side of the flange. The placement for this thermocouple is centered relative to the centermost active transistor in the package (Figure 2).

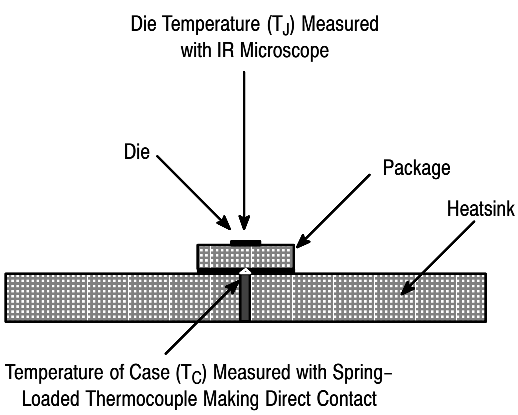

Figure 1. Case Temperature Measurement

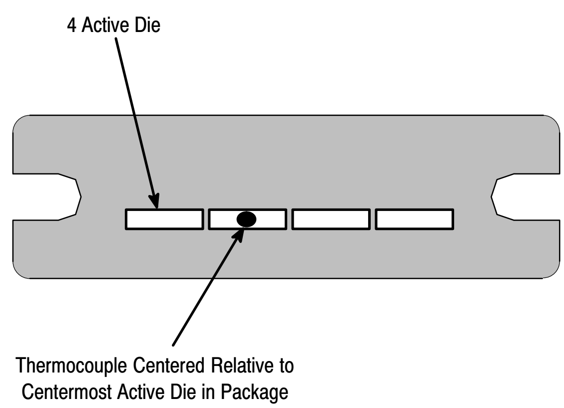

Figure 2. Positioning of Thermocouple

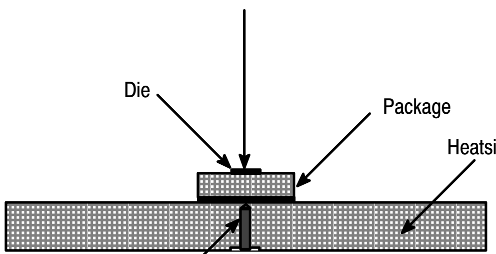

Figure 3. Heatsink Temperature Measurement

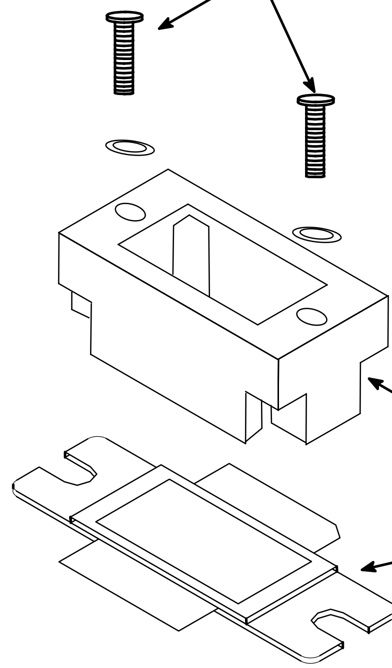

Figure 4. Exploded View of Clamping Scheme for Metal Ceramic Devices

HEATSINK TEMPERATURE (T_H) MEASUREMENT

The heatsink temperature (T_H) directly beneath the mounting interface of the RFPA to the circuit heatsink (Figure 3) must be measured in certain situations. In these cases, the 0.032″ diameter hole drilled for thermocouple passage stops 0.010″ from the circuit heatsink surface. This method of heatsink temperature measurement is particularly useful in the following cases:

- If the RFPA is soldered into place where the spring-loaded TC cannot be used.
- For thermal resistance measurements that include various interface materials, such as thermal greases or thermal pads, to determine their performance in the thermal resistance stack-up.

THERMAL MEASUREMENT SEQUENCE

Before inserting each boltdown metal-ceramic part into the RF test fixture, a layer of thermal grease (Dow Corning® 340-heatsink compound) is applied to the bottom of the flange by a roller. A DuPont™ Delrin® material clamp is used to apply downward force to the ears and leads of the package (Figure 4). This clamp fastens the device to the heatsink using two #4-40 stainless steel cap screws, each tightened to 5 lb.-in. of torque.

With boltdown overmolded plastic devices, removing the mold compound in the center portion of the device compromises the mechanical rigidity of the part. This in turn affects the flatness of the unit, leading to poor thermal contact between the package and the heatsink. To correct this, a solder that is liquid at room temperature (Indalloy® 51 from Indium Corporation®) is used instead of thermal grease as the interface material.

The stage on which the RF circuit is secured has the ability to be electrically heated and cooled by liquid. The temperature of this stage is adjusted so that the desired case temperature (usually between 70°C and 90°C) for the part is achieved during power testing. When the device is secured into the test circuit, the IR scan is initiated and the desired RF signal and power are applied. Once the desired case temperature is reached for the part and is stable, the IR scan image is captured along with all corresponding electrical data. This data is recorded, and the corresponding thermal resistance value is calculated.

THERMAL RESISTANCE, θ_{JC}, CALCULATION

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

For a multi-die RFPA transistor product, the highest die surface temperature ("hot spot") measured by the IR scan is used as T_J in the thermal resistance calculation. Total power dissipated in the product is calculated as

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

Junction-to-case thermal resistance is calculated as

$$\theta_{JC} = (T_J - T_C) / P_{diss}$$

For a multi-stage RFIC product, the highest die surface temperature for each stage is measured by the IR scan and used in the thermal resistance ($\theta_{JC-stage}$) calculation for that stage. Power dissipated in each stage is determined and used in the thermal resistance calculation for that stage.

DATA SHEET θ_{JC} VALUE

Thermal resistance data reported on a Freescale RFPA technical data sheet is based on performance tests done on a sample size of ten parts, taken from different 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.

CONFIDENCE IN θ_{JC} DATA

A Gauge R&R (Reproducibility and Repeatability) assessment was used to demonstrate the methodology employed in measuring and reporting accurate thermal characterizations of Freescale 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 around 5%.

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 determine the die temperature (T_J) at high frequency (~2 GHz) under RF test conditions
- Using thermocouple measurements to accurately determine the case temperature (T_{CASE})
- Using the maximum die temperature of the device to calculate the junction-to-case thermal resistance (θ_{JC})
- Establishing confidence level in the measured θ_{JC} value
- Implementing this methodology to determine the θ_{JC} data for the Freescale RFPA technical data sheet.

This thermal measurement methodology is applied to both multi-die RF power transistor products and multi-stage power RFIC products.

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.

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.

REMOVAL AND REPLACEMENT OF PROTECTIVE LID FOR METAL CERAMIC PRODUCT 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 application of paint.

REMOVAL OF MOLD COMPOUND FOR PLASTIC PRODUCT EVALUATION

To permit thermal evaluation of an overmolded plastic package, the mold compound is etched away from the middle portion of the package without damaging the die and interconnects.

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.

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.

REFERENCES

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

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