Infrared Temperature Characterization of High Power RF Devices

Mali Mahalingam, Senior Member, IEEE and Eddie Mares

Wireless Infrastructure Systems Division, Semiconductor Products Sector, Motorola Inc.
2100 East Elliot Rd., Tempe, Arizona 85284

***Abstract* —** Infrared Microscopy measurement methodology has been refined to measure high power RF device temperatures accurately at high frequencies (1 GHz, 2+ GHz). Special difficulties due to translucent nature of Si are resolved. The methodology is applied to practical Si Bipolar, Si LDMOS and GaAs RF power devices.

Product thermal performance characterization method is established. Methodology is also applied in product development efforts.

I. INTRODUCTION

Why Infrared Microscopy?

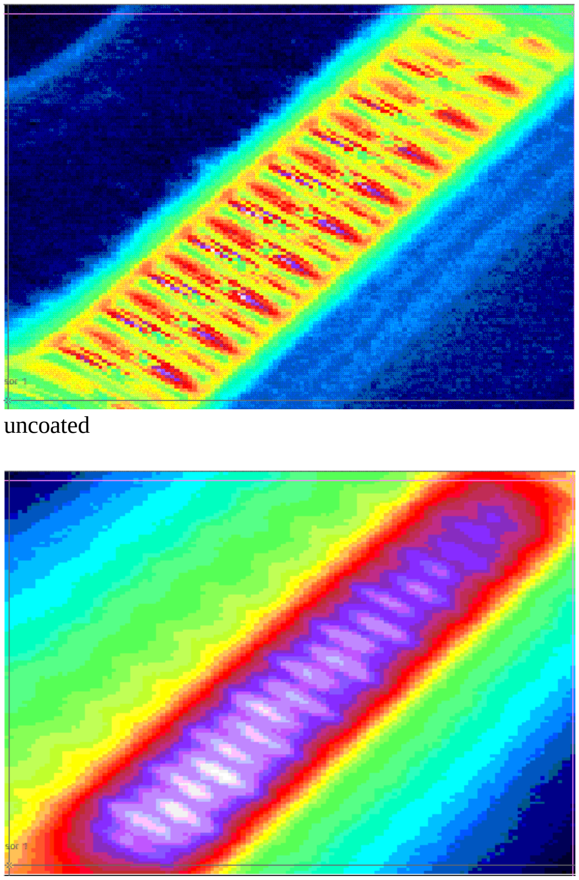
Semiconductor device reliability depends on the device operating temperature [1]. Accurate thermal characterization of semiconductor devices is important in establishing the reliability of the systems using such devices. High power radio frequency (RF) semiconductor devices power RF transmitters in cellular basestations and radio/TV broadcasting. Techniques to measure the operating temperature of a semiconductor device can be broadly grouped into two categories, direct and indirect methods. Infrared (IR) Microscopy [2, 3], Liquid Crystals [4], and Thermographic Phosphors [5] allow direct mapping of the surface temperature of the device. Among these direct techniques, IR Microscopy is the only technique capable of quantitative temperature measurement; other two techniques are more qualitative. The indirect technique uses a temperature sensitive electrical parameter of the semiconductor device (such as Vf for a diode, Veb for a bipolar transistor, and Vds for a FET) to measure the device temperature [6]. However, this technique typically provides only an average temperature for the chip. Thus IR Microscopy is the most promising and valuable technique to provide direct, quantitative mapping of device temperature. Hence the authors selected this technique to perform quantitative temperature characterization of high power RF semiconductor devices

II. ISSUES IN EMISSIVITY DETERMINATION

CompuTherm III IR microscope manufactured by Quantum Focus (formerly Barnes Engineering) is used in this study. The IR transmitting lens system of the microscope unit collects the heat radiation from the DUT (device under test) and focuses it onto a liquid nitrogen cooled InSb detector. The signal from the detector is processed by suitable electronics and displayed as a color image. The color image is converted to a quantitative temperature map by a calibration procedure. Since the radiant energy from the DUT is a function of both the temperature and the emissivity of the surface, the emissivity need to be known to arrive at the temperature from the image. The emissivity of a typical Si DUT surface can have large variations, in the range of <0.1 (metallization that can be reflective) to ~ 0.8 (passivated Si surface). Current day IR microscopes have specialized algorithms to determine the emissivity of a DUT pixel-by-pixel through measurement of radiant images at known temperatures. However, these procedures are less than satisfactory for material like Si that is IR translucent. The IR radiation collected by the lens from a Si DUT originates from the surface as well as underlying layers of the DUT. Radiation from the surroundings reflect of underlying metal layers such as device backmetal and metallurgical diebond, and contribute to a large error i.e. the collected radiation is not a true representation of the device temperature. None of the algorithms in the market that help determine the emissivity are smart enough to correct for this error. This difficulty is known among the practitioners for some time [2,3].

A. Solution via controlled emissivity

To overcome the above-described difficulties in emissivity determination, typically the surface of a Si DUT is uniformly coated with IR opaque, high emissivity material. This procedure assures fixed emissivity for the surface of the DUT and simplifies the temperature determination.



uncoated

coated

Fig. 1. Comparison of same device with high emissivity coating

Fig. 1 compares the IR images of an uncoated vs. coated Si RF power device. The image for the uncoated device erroneously shows inactive regions of Si as hot spots while the image for the coated DUT correctly captures the hot regions associated with active cells. The error introduced due to the temperature drop across the thickness of a typical coating applied on the surface of a DUT is estimated to be small.

B. Special issues with RF devices in controlling the emissivity

Coating the surface, though well established and practiced in the industry [7] for low frequency devices, introduces special difficulties for RF and microwave devices. The coatings typically introduce small additional parasitics (typically increased capacitive coupling) and affect the RF behavior of the DUT under RF test conditions. The challenge is in identifying coating materials that influence the least the RF behavior of the DUT. A systematic test procedure was developed to assess the RF influence of various coatings in a very repeatable way. Gain, Efficiency, and IMD (Inter Modulation Distortion) were selected as the RF response parameters to measure the influence of the coatings. Candidate RF power devices were selected for 880 MHz and 1930 MHz test conditions. Many suitable coating materials were tested and two candidate materials were identified that met our objectives. For these identified materials, gain changes were of the order of 0.07 dB, efficiency changes were of the order of 0.4%, and IMD changes were of the order of 0.3 dBc. Details of this evaluation and these findings will be presented at the conference.

III. Thermal Measurement Application

This IR thermal measurement methodology has been applied to high power bipolar, LDMOS, and GaAs RF devices to determine the thermal device temperature under various RF signals and power levels.

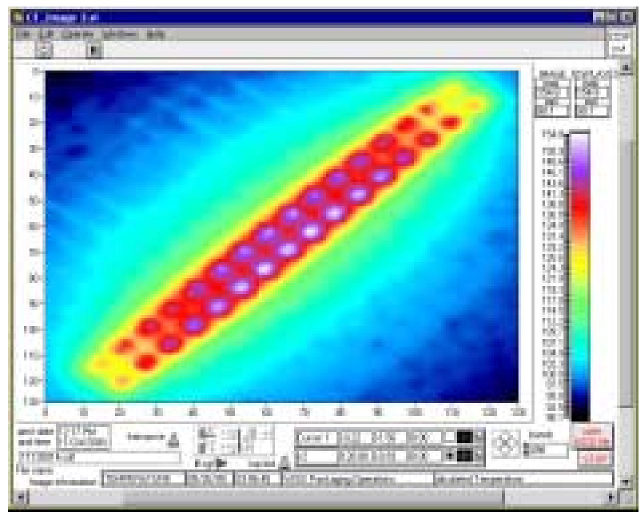


Fig. 2. IR thermal image of silicon bipolar RF power transistor

Thermal scans of the entire device as shown in Fig. 2 make it possible to determine the cell sharing of power within the device by analyzing the temperature spread across the entire die surface. At a power dissipation of 42.5W the resulting maximum die temperature of this device was 155°C at a 85°C case temperature. The measured temperature delta between the hottest and coldest cells was 31°C.

0-7803-6540-2/01/$10.00 (C) 2001 IEEE

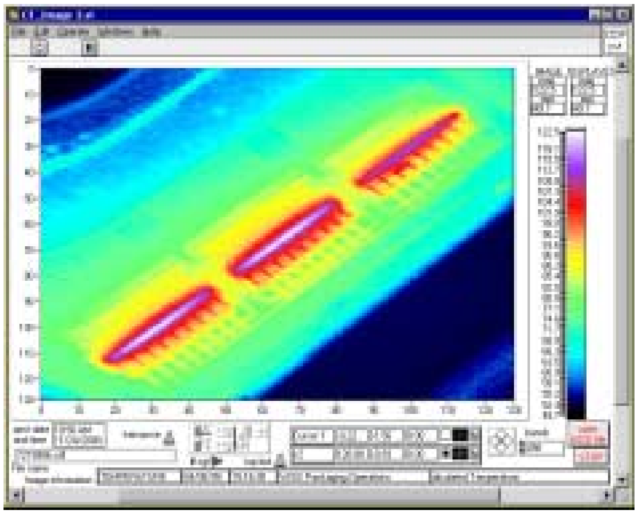


Fig. 3. IR thermal image of silicon LDMOS power transistor with multiple die

Fig. 3 shows the temperatures of multiple die placed within one package operating under a CDMA RF signal. For a power dissipation of 81W the resulting maximum temperatures of each die was 122°C, 123°C, and 114°C left to right respectively for a 87°C case temperature.

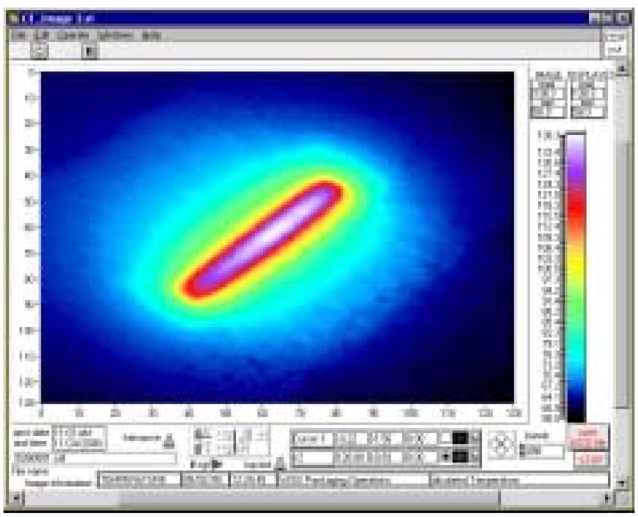


Fig. 4. IR thermal image of GaAs power transistor

Fig. 4 shows the temperature distribution for a high power GaAs FET transistor operating under DC conditions at 10.8W dissipated power. The maximum die temperature was 138.3°C at a 55°C case.

Differences have been noticed in the temperature spread under different electrical conditions. Typically under DC power the heat is congregated in the center portion of the die while under high efficiency RF power the heat is spread more evenly across the die surface. Typically the device exhibits higher temperatures during lower RF efficiency. Examples of this trend will be further discussed in the presentation.

IR thermal measurement of the device aids in guiding the geometric layout design of fingers and cells to promote efficient spreading of heat within the die itself.

IR thermal measurement also allows the ability to pinpoint thermal impact of die attach voids occurring in the assembly manufacturing of these high power RF devices. The temperature increase over a voided area can have a detrimental effect on the reliability and performance of these devices.

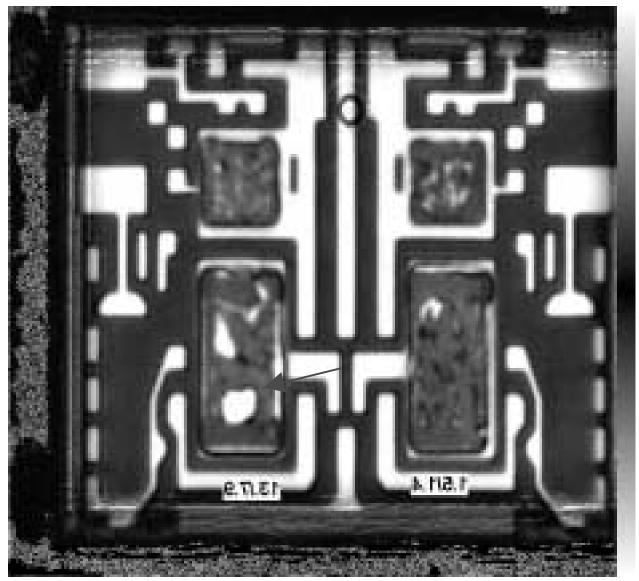


Fig. 5. Image of die attach void obtained through acoustic microscopy

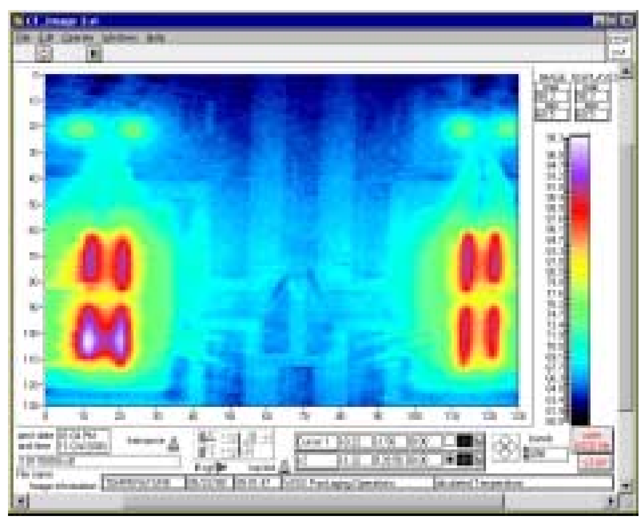


Fig. 6. IR thermal image displaying rise in temperature due to die attach void

Fig. 5 shows an acoustic microscopy image used to characterize the percentage of die attach void. IR thermal measurement as shown in Fig. 6 is then used to correlate the rise in die temperature due to the characterized die attach void(s). In this example the die void resulted in a temperature rise of 5.9°C. This represents about a 14% increase in temperature delta (between maximum die surface and case) compared to the die with no die attach voiding.

IV. Thermal Resistance

Die surface temperature (Tj) measurement under dissipated power (Pdiss) is also used in calculating thermal resistance of high power RF packages and their associated mounting conditions. The case temperature (Tc) is measured by a thermocouple attached to a self developed spring assembly that assures direct contact with the bottom side of the package. This thermocouple is centered directly beneath the active transistor(s) inside the package. The thermal resistance (θjc) applied to the entire package assembly is derived from the three measured quantities Tj, Tc, and Pdiss using definition (1).

$$(Tj - Tc) / Pdiss \qquad (1)$$

θjc as a metric for high power RFPA devices is a very useful parameter. Many product development efforts such as preferred device layout, preferred flange material in which to attach the power transistor, and required quality in die attach assembly process are directly guided by this metric.

In some cases the mounting resistance, i.e. interface thermal resistance, is desired to be included in the theta calculation (θjh). In this case, a thermocouple is buried within the heatsink (Th) within a known distance below the mounting interface. This permits the measurement of various interface materials to reduce the mounting interface resistance. This measurement method also permits the measurable impact on thermal resistance due to package flatness.

Examples will be discussed further demonstrating how these two metrics, θjc and θjh, are used in developing good RF power amplifier products.

V. Conclusion

Among the quantitative temperature measurement techniques available to measure semiconductor devices, IR microscopy has proven as the most suitable technique. The authors have resolved special difficulties in applying this technique to IR translucent device materials under RF test conditions. Extensive application experience of this refined technique by the authors to RF power devices of various technologies has helped them establish a robust characterization methodology. This methodology has proven very valuable in measuring product metrics such as θjc and θjh. The efforts of device and package development as well as end user application needs are being guided by this methodology.

Acknowledgement

The authors wish to acknowledge the assistance of Peter Aaen and Jeff Crowder in the evaluation of coatings as well as numerous electrical application engineers within Motorola WISD.

References

[1] D.S. Peck,"An analysis of data from accelerated stress tests," Proceedings 9th Reliability Physics Conference, pp.69-78, 1971.

[2] D. Peterman and W. Workman, "Infra-red radiometry of semiconductor devices," Microelectronics and Reliability, Pergamon Press 1967, vol.6, pp. 307-315.

[3] D.D. Griffin,"Infrared microradiometry-Precision and accuracy considerations applicable to microcircuit temperature measurements," Materials Evaluation, American Society for Nondestructive Testing, October 1968, pp.215-220.

[4] G. Fleurn,"Liquid crystal microthermography state of the art, Proceedings of Semitherm, 1986.

[5] D.J. Brenner,"A technique for measuring the surface temperature of transistors by means of fluorescent phosphors," NBS Tech. Note 591, July 1971.

[6] S. Rubin and F.F.Ottinger,"Thermal resistance measurements on power transistors," NBS Publication 400-14, pp.1-24, April 1979.

[7] M. Mahalingam and J.A. Andrews,"Thermal design studies of a high current transistor package," IEEE Trans. CHMT, pp.463-469, December 1982.