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Optotherm Sentris/Micro Application Note

Thermal Resistance Measurement

1 Importance of Thermal Characterization

As electronic semiconductor devices continue to decrease in size, heat generation and thermal dissipation are becoming increasingly important. Small feature size, increased transistor and circuit density, and faster circuit speeds are leading to large thermal gradients that can degrade performance and reliability. Given that device reliability depends largely on operating temperature, and because small changes in package design, material selection, and quality of manufacture can significantly affect junction temperature, accurate thermal characterization has become essential.

1.1 Junction Temperature

During semiconductor device operation, internal junction self-heating leads to a large concentration of heat at the junction. The peak temperature in a device is located at the junction and heat conducts outward from the junction into the package.

Semiconductor device thermal characterization is the determination of the maximum junction temperature under known operating conditions, as well as, the calculation of a device's thermal resistance parameters. Because device reliability degrades exponentially with temperature, junction temperature is directly related to the life of a product, and is used in reliability calculations to rate product life time. As a general rule, an increase of 10-15°C in the junction temperature can reduce product lifetime by more than 50%. For these reasons, accurate junction temperature measurement during device operation is an integral part of thermal characterization.

1.2 Thermal Resistance

A common method of characterizing the thermal performance of packaged devices is using the concept of thermal resistance, denoted by the Greek letter "theta" or Θ. Thermal resistance is the steady-state temperature rise of a device junction above the temperature of a reference point for each watt of power dissipated in the junction (units are °C/Watt). One of the most common thermal resistance parameters, Θ_{JC} (junction to case), is used to calculate the temperature difference between the junction and a device's case.

The thermal resistance method provides a means to calculate junction temperature under known environmental conditions and at steady-state device power levels. The concept of thermal resistance requires making simplified assumptions such as one-dimensional heat flow, which may not accurately model the three-dimensional conduction of heat in a real device. Actual devices contain material and boundary layers with thermal resistances and heat capacitances that result in complex heat flow. Furthermore, it is a common misunderstanding that each device has an intrinsic thermal resistance. Many external factors, such as interactions between adjacent devices, can affect the thermal resistance of a device when it is part of a complete system.

2 Traditional Thermal Resistance Techniques

Traditional methods of determining thermal resistance include mathematical modeling and forward bias voltage measurement. Both of these techniques will be discussed in this section. A relatively new method of measuring thermal resistance involves using a thermal emission microscope to measure junction temperature of devices in normal operation. Thermal emission measurement has several important advantages over traditional techniques including measurement speed and accuracy. Because devices are tested without altering their operational characteristics, truer thermal resistance values can be obtained. Thermal emission testing will be discussed in a later section of this application note.

2.1 Finite Element Analysis Modeling

Thermal analysis software programs can be used to model the thermal behavior of simple devices and systems. When confirmed using empirical data, models can be used to provide reasonably accurate predictions of the behavior of customized device configurations. Unfortunately, variable factors or characteristics that cannot be accurately modeled, such as airflow and circuit board spacing, can have a dramatic impact on package thermal resistance. In fact, the JEDEC packaging standard states that circuit board characteristics can result in thermal measurement variability as high as 60%.

2.2 Forward Bias Voltage Measurement

This method of determining thermal resistance involves measuring junction temperature by utilizing the junction itself as the temperature sensing element. Although there are several different approaches in utilizing semiconductor junctions as temperature sensors, the most common technique is to measure the junction forward biased voltage that is generated by a small sensing current.

2.2.1 Active Junction Measurement

The active junction in a functional device can sometimes be employed as the sensing element. To perform this type of measurement, special purpose electrical switching hardware is often required and device power must be periodically interrupted for brief intervals (e.g., 20 microseconds). In order to obtain meaningful results, devices must be configured to dissipate sufficient power in a manner that approximates actual operating conditions while allowing periodic junction temperature measurements to be conducted. Care must be taken when setting the measurement time interval, as setting a time that is too short will lead to erroneously high measurement values due to non-thermal switching transients. Setting a time that is too long will allow the junction to cool, leading to erroneously low measurements.

2.2.2 Secondary Diode Measurement

In many cases, due to the complexity of measuring an active junction, a substrate isolation diode or input protection diode is used as the temperature sensing element. In these cases, an assumption must be made that the sensing diode and active junction are equal in temperature.

2.2.3 Thermal Test Die Substitution

Due to the complexity of performing measurements on integrated circuits, thermal test die are often substituted for functional die when performing thermal characterization. The primary drawback of this approach is that the power dissipation characteristics of test die may not accurately replicate those of functional die. This is of particular concern when there are large thermal gradients (hot spots) on the device during normal operation that cannot be modeled effectively using test die.

2.2.4 Advantages and Disadvantages

Electrical junction temperature measurements can be useful for measuring the temperature of active junctions deep inside a device and when capturing fast thermal transients. In cases where a secondary diode is measured in place of the active junction, this method can only provide an average temperature for the device. Also, when performing measurements, care must be taken to prevent heating the junction by applying a sensing current that is too large.

Unless there is sufficient uniformity in the junction temperature response within a production lot of devices, a complete calibration is usually required for each device that is to be tested. The time required to calibrate and perform measurements on a single device is typically over an hour. As a general rule, the electrical junction temperature measurement method provides measurement accuracy of +/-5%.

3 Thermal Emission Microscope

3.1 System Hardware

The Optotherm Sentris thermal emission microscope is shown in Figure 1. The thermal imaging camera is sensitive to long-wavelength infrared (LWIR) energy and a number of infrared microscopic lenses are available, providing a range of spatial resolution and field-of-view. The camera is mounted on a vertical micrometer slide and can be precisely focused on the device-under-test. Devices are mounted on a thermal stage and can be heated or cooled during testing. The XY micrometer stage allows precise horizontal device positioning.

Figure 1 – Sentris thermal emission microscope

The integrated probing platform and visual camera enable electrical probing and powering of devices. An I/O module synchronizes device power with software tests. All hardware is mounted on a vibration-isolated optical table. Sentris was designed as a table-top system to allow easy integration with other test equipment.

3.2 System Software

The Thermalyze electronics analysis software is shown in Figure 2. Thermalyze provides sophisticated tools for thermal characterization and failure analysis of semiconductor devices. Users can measure the temperature at any point on a device, locate hot spots and leakage current, compare thermal behavior of defective and functional devices, record and play back thermal image movies, and create real-time strip charts of temperature statistics. Data can be saved in various formats so that it can be shared with colleagues.

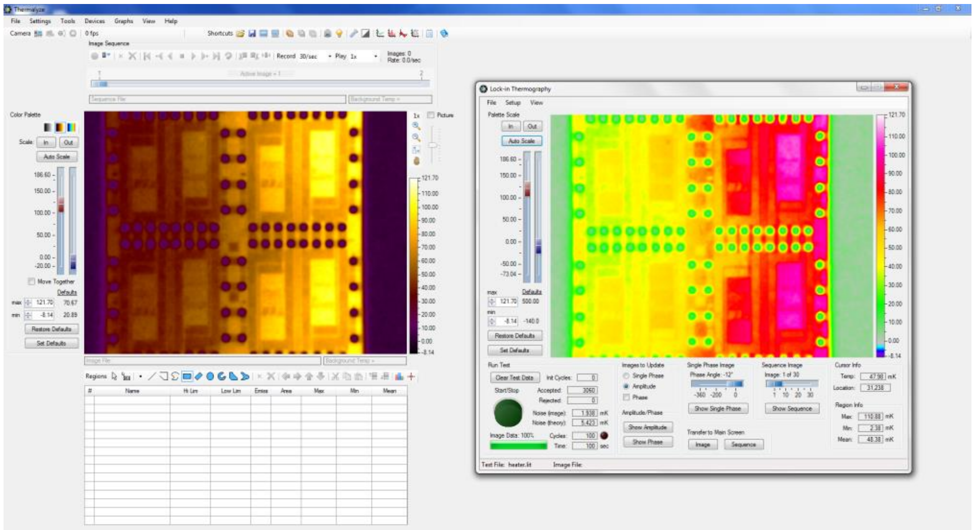

Figure 2 – Thermalyze electronics analysis software

3.3 Theory of Operation

All objects continuously emit infrared energy in a quantity that is a function of their temperature. As object temperature increases, the emitted infrared energy also increases according to an equation known as Planck's law of blackbody radiation. By measuring the energy an object emits, its temperature can be determined.

3.3.1 Response Time

Because the response time of thermal imaging cameras is large compared to the switching speeds of semiconductor devices, fast transient measurements (over 10 hertz) cannot be made using this technology. Measurements represent average temperature values over fractions of a second.

3.3.2 Emissivity

Emitted infrared energy also depends on a material property called emissivity. Emissivity is the ratio of energy emitted by a real object compared with the energy emitted by an ideal object, known as a blackbody. Whereas a blackbody has emissivity of 1.0, a real material, such as Silicon, may have an emissivity of 0.50, indicating that the Silicon emits 50% of the energy that an ideal blackbody would emit at a given temperature.

3.4 Measuring Device Temperature

Thermal emission microscopy provides a fast and direct way to measure the temperature of semiconductor devices. Although useful data can be obtained by imaging packaged devices, it is often necessary to analyze unpackaged or decapsulated devices in order to obtain detailed thermal information such as surface temperature mapping (see Figure 3) and junction temperature measurement. ***Note:*** *When flip-chip construction or large numbers of metal layers mask emissions from the top surface, it may be necessary to image the device from the backside.*

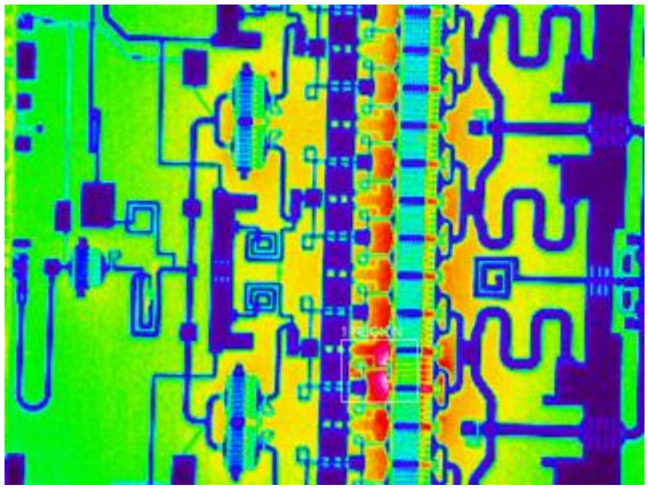

Figure 3 – Thermal image of unpackaged device

4 Calculating Thermal Resistance

Determining thermal resistance using a thermal emission microscope requires a line-of-site between the camera lens and die surface while the die remains in its package. This may require drilling out or removing the lid of a metallic case or decapsulating the plastic or ceramic package. Because the thermal resistance calculation assumes that junction temperature is measured on a fully-packaged device, it is important to minimize the removal of material when exposing the semiconductor surface for measurement.

After the die has been exposed, the package is mounted on the thermal emission microscope's thermal stage so that the case temperature can be precisely controlled during the measurement. Next, the device is powered and the temperature of the junction is measured. The junction temperature, thermal stage temperature (which is equal to the case temperature), and the device power are then used to calculate the thermal resistance.

4.1 Thermal Resistance Equation

The thermal resistance between the semiconductor junction and device package (i.e., case) is known as Θ_{JC} (units are °C/Watt) and depends on package design. Θ_{JC} can be calculated according to Equation 1 below. In order to calculate Θ_{JC}, the steady-state temperatures of the junction, case, and the dissipated power need to be determined.

$$\Theta_{JC} = (T_{junction} - T_{case}) / P_{dissipated}$$

Equation 1 – Thermal resistance calculation

4.2 Thermal Resistance Measurement Procedure

The procedure to calculate Θ_{JC} is as follows:

1. Measure the junction temperature according to the procedure in the following section.
2. Record the junction temperature, thermal stage temperature (case temperature), and applied power.
3. Calculate Θ_{JC} using equation 1.

5 Measuring Junction Temperature

5.1 Transparency of Semiconductor Materials

Many semiconductor materials, such as Silicon, are partially transparent in the LWIR region. The infrared energy that is detected by the thermal imaging camera is emitted from both the surface and from sub-surface material. Therefore, the temperature measurement of a Silicon device is an average of the device's surface temperature and the temperature of sub-surface material. This characteristic appears to preclude the accurate temperature measurement of small features, such as a semiconductor junction. Due to the high thermal conductivity of semiconductor materials however, the heat dissipated at localized hot spots diffuses rapidly into adjacent material. And because of the small cross-section of semiconductor die, heat diffuses rapidly through the die thickness, providing an isothermal area that is very close to the same temperature as the junction. This characteristic of semiconductor devices enables junctions with dimensions less than one micron to be measured using thermal imaging technology with pixel resolution much larger than one micron.

5.2 Emissivity of Semiconductor Materials

The emissivity of Silicon typically varies between 0.40 and 0.60. The precise emissivity of a particular semiconductor material depends on a number of factors including die thickness and doping. Additionally, emissivity can vary across the semiconductor surface due to internal device geometry. For these reasons, in order to perform an accurate junction temperature measurement, surface emissivity must be measured and software-corrected. Thermalyze software has the ability to calculate and then compensate for varying emissivity across a device surface.

One of the primary advantages of using thermal imaging microscopes to measure junction temperature is their ability to test functional devices that are operating in normal application mode. Additional benefits include rapid measurement, the ability to measure multiple junctions simultaneously, and the ability to test devices in non-steady-state conditions.

5.3 Junction Temperature Measurement Procedure

1. Mount the unpowered, decapsulated device on the thermal stage using thermal compound and hold-down clamps to assure good thermal conductivity between the device case and thermal stage.
2. Heat the thermal stage to a temperature at least 20°C above ambient temperature, such as 50°C or higher, and allow the device temperature to stabilize.
3. Open the Emissivity Table window in the Thermalyze software and create a single point emissivity table according to the step-by-step procedure in the Thermalyze HTML Help page: *Thermalyze/Emissivity Tables/Create Emissivity Tables*. A pixel-by-pixel emissivity map of the device is created and can be applied to thermal images to correct for emissivity variations across the device.
4. Heat the thermal stage to the desired device case temperature and allow the temperature to stabilize. ***Important:*** *If the thermal stage temperature is changed in this step, thermal expansion/contraction may cause the device to be misaligned with the emissivity table. Using the micrometer handles on the XY stage, carefully position the device to align its thermal image with the emissivity table.*
5. Power the device and allow the temperature to stabilize.
6. Record the maximum temperature measured within the region as the junction temperature (see Figure 4).

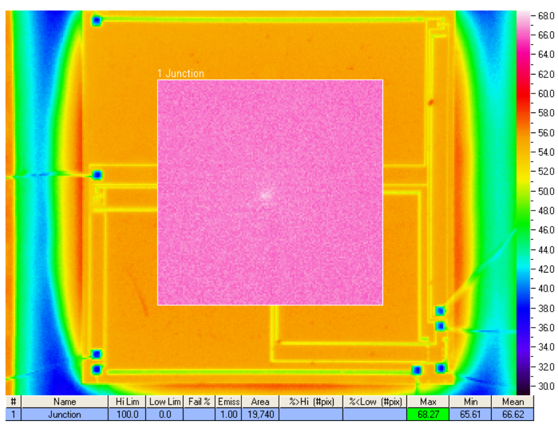

Figure 4 – Junction temperature measurement

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