Thermal Imaging Microscope for Thermal Characterization and Failure Analysis

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Semiconductor Thermal Characterization

Need for 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.

Need for Junction Temperature Measurement

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 at the junction itself and heat conducts outward from the junction into the package. For this reason, accurate junction temperature measurement during device operation is an integral part of thermal characterization.

Thermal Resistance Approach

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/W). 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 way to calculate junction temperature under known environmental conditions and at steady-state device power dissipation 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 materials and boundaries layers with thermal resistances and heat capacitances that result in complex heat flow.

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.

Thermal Characterization Defined

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 produce life time. As a general rule, an increase of 10-15°C in the junction temperature can reduce product lifetime by more than 50%.

Finite Element Analysis

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%.

Electrical Junction Temperature Measurement

This method of junction temperature measurement utilizes the junction itself as the temperature sensing element. Although there are several different approaches in utilizing semiconductor junctions as a temperature sensor, the most common is to measure the junction forward biased voltage that is generated by a small sensing current.

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.

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 approximately the same temperature.

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.

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 can generally provide temperature values with best-case accuracy of +/-5%.

Thermal Imaging Microscope

Theory of Operation

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

The amount of infrared energy an object emits is also dependent on a surface property called emissivity. Emissivity is the ratio of energy emitted by a real object compared with that emitted by an ideal object, also know as a blackbody. Whereas a blackbody has emissivity of 1.0, a real object, such as plastic, may have an emissivity of 0.92, indicating that the plastic emits 92% of the energy that an ideal blackbody would emit at a given temperature.

Description

A typical thermal imaging microscope system is shown in Figure 1. In this example, the thermal imaging camera employs an uncooled microbolometer detector that is sensitive to infrared energy with a wavelength between 7-14 microns. Because the detector does not require cooling, measurements can be made immediately after powering the camera. Thermal images are captured and displayed at a rate of 30 frames per second. Temperature measurements can be made from 0 to 300°C with a sensitivity as low as 0.05°C. For analyzing semiconductor devices, a 1.5x magnification lens provides 20 microns/pixel image resolution and 6.4 x 4.8 mm field-of-view. A wide angle lens is also provided to image larger devices and small circuit boards.

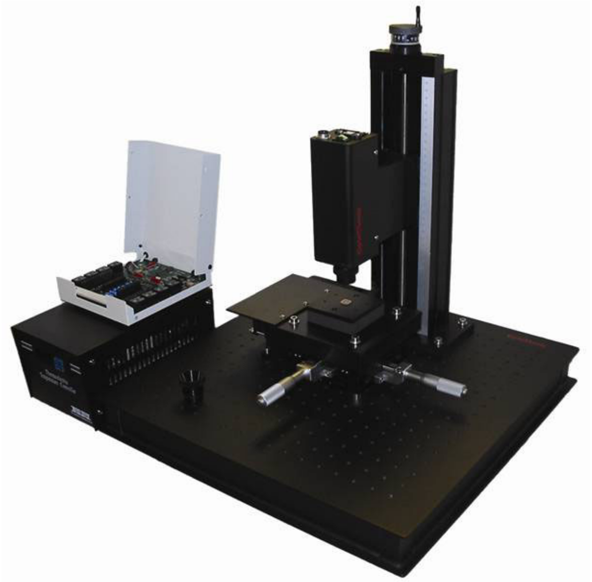
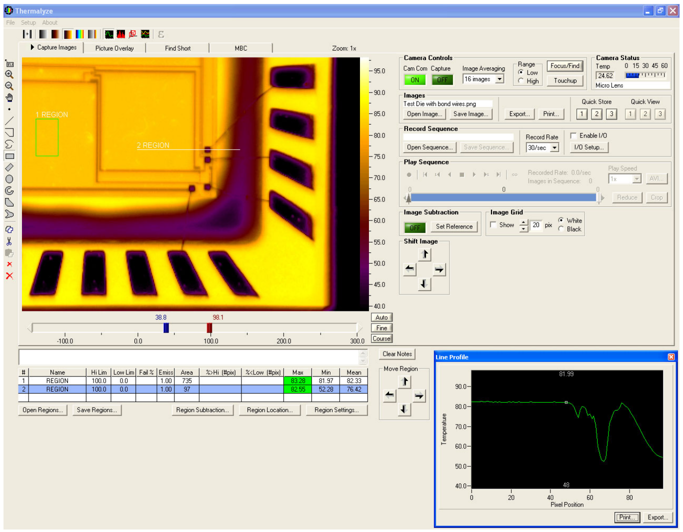


Figure 1 – Thermal imaging microscope system

This system was designed in a table-top configuration to allow integration with other test instrumentation. For precise temperature control during analysis, devices are mounted on a thermal stage that is heated or cooled to precise temperatures between 0 and 100°C using the included thermoelectric temperature controller. The thermal stage is attached to an XY table for precise horizontal positioning of devices. A vertical micrometer table is mounted to a sturdy optical table and positions the camera above a device for precise focusing. An output module provides eight programmable relays to synchronize device power with software tests.

Thermal Image Analysis Software

An example of thermal image analysis software is shown in Figure 2. Image analysis software programs provide many sophisticated tools for thermal characterization and failure analysis of semiconductor devices. Users can measure the temperature at any point on a device, locate subtle hot spots, 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.



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Capture: OFF
Image Averaging: 16 images
Range: ● Low ○ High
Temp: 24.62
Micro Lens
Test Die with bond wires.png
Record Rate: 30/sec
☐ Enable I/O
Recorded Rate: 0.0/sec
Images in Sequence: 0
Image Subtraction: OFF
☐ Show 20 pix ● White ○ Black

#	Name	Hi Lim	Low Lim	Fail %	Emiss	Area	%>Hi (#pix)	%<Low (#pix)	Max	Min	Mean
1	REGION	100.0	0.0		1.00	735			83.28	81.97	82.33
2	REGION	100.0	0.0		1.00	97			82.55	52.28	76.42

Figure 2 – Thermal image analysis software screenshot

Device Temperature Mapping

Thermal imaging provides a fast and direct way to map the temperature over the surface of a semiconductor device. Although useful data can be obtained by imaging a packaged device, it is often necessary to analyze unpackaged or decapsulated devices in order to obtain detailed thermal information (see Figure 3). 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.

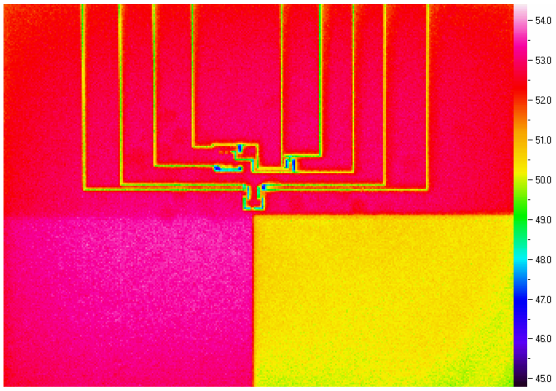


Figure 3 – Temperature map of unpackaged device

The emissivity of semiconductor devices when measured at long infrared wavelengths (7-14 microns) is generally within a range of 0.40 to 0.70. The precise emissivity of a particular device depends on a number of factors including material makeup, die thickness, doping, and surface conditions. Because semiconductor materials are not highly reflective at long wavelengths, emissivity values in this range imply that semiconductor materials are partially transparent.

Due to their partial transparency, semiconductor temperature measurements represent average temperatures throughout the material thickness. As a result, microscopic hot spots are averaged with cooler adjacent material layers. 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 dimension under 1 micron to be measured accurately using thermal imaging equipment with 20 micron pixel resolution.

In order to measure junction temperatures more accurately, it may appear beneficial to increase lens power and image resolution. There are, however, several advantages to limiting the microscopic lens power to 1.5x (20 microns/pixel). Increasing lens magnification leads to a larger airy disk radius (blur spot size), reducing the ability to measure small spots accurately. Additionally, when testing devices under higher magnification, thermal expansion/contraction and miniscule device movements can invalidate testing procedures such as pixel-by-pixel emissivity correction.

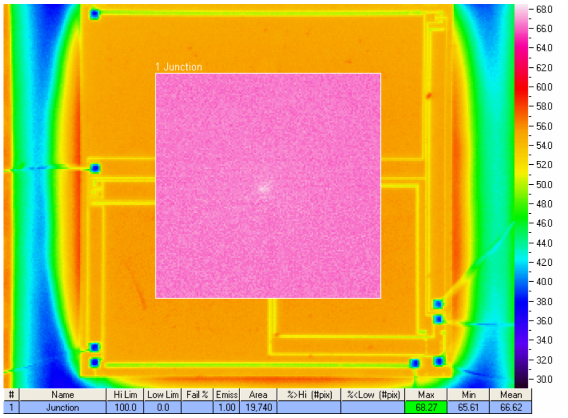
Thermal imaging microscopes can help guide device layout and aid in establishing thermal design rules. They can also be used to identify die attach voids and defects and to verify finite element analysis estimates of die surface and package temperatures. At the board level, they are a useful tool for evaluating thermal coupling between components.

When making thermal resistance measurements, it is often necessary to measure surfaces with low thermal conductivity, such as the tops of packages and board components. Measuring these surfaces accurately using contact probes can be difficult, as the relatively large thermal mass of the probes can significantly lower the temperature of these surfaces during measurement. By conducting measurements without contact, thermal imaging microscopes can be used to acquire accurate temperature information at a multitude of locations simultaneously.

Measuring Junction Temperature

In order to accurately measure device junction temperature, a correction for the non-uniform emissivity across the surface of the die must be calculated using the following procedure.

1. The unpowered device is mounted onto the thermal stage. Thermal compound can be used to increase thermal conductivity between the stage and device.
2. The thermal stage is heated to a constant temperature, such as 60°C, and the device is given time to stabilize at a uniform temperature.
3. Thermal image analysis software is used to create an emissivity map of the device surface. The emissivity map is applied to the pixels in a rectangular region that is drawn to enclose the junction.
4. The thermal stage is controlled to the desired device case temperature and allowed to stabilize.
5. The device is powered and the maximum temperature measured near the junction is recorded (see Figure 4).



#	Name	Hi Lim	Low Lim	Fail %	Emiss	Area	%>Hi (#pix)	%<Low (#pix)	Max	Min	Mean
1	Junction	100.0	0.0		1.00	19,740			68.27	65.61	66.62

Figure 4 – Junction temperature measurement

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

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.

High Emissivity Coating

High power devices, such as laser diodes, are sometimes plated in gold to help dissipate heat. Gold has a very low emissivity (often below 0.05) and therefore, emits very low levels of infrared energy when heated. In order to accurately measure the temperature of gold, the surface is treated with a low viscosity polymer coating to increase surface emissivity to approximately 0.50. The material is airbrushed on the device, applying a uniform coating that is only 1 micron thick, in order to minimize the coating's insulation affect on the device. The polymer coating is nonflammable, contains no volatile organic compounds, and dries quickly to a transparent film. After measurements are completed, the coating can easily be removed using the coating solvent.

Failure Analysis

Activation energy (the minimum amount of energy required to trigger a temperature-accelerated failure mechanism) decreases exponentially as device temperature increases. High device temperatures can accelerate material migration, causing shorts and substrate cracking. Because device speed is a function of temperature, large thermal gradients (hot spots) can cause signal integrity and timing problems, which are often difficult to troubleshoot.

Thermal imaging microscopes can be used to detect and locate hot spots when assessing potential failure sites. Software algorithms are employed to detect and locate defects that dissipate power in the hundreds of microwatts (see Figure 5). And because this technology is non-invasive, devices are undamaged and uncontaminated so that they can be further evaluated, if necessary, using additional failure analysis techniques.

A number of semiconductor failure mechanisms cause hot spots. For example, hot spots often occur where a wiring pattern or insulating film is not manufactured correctly, and creates a new current path, resulting in local resistive heating. Thermal imaging microscopes are frequently used as a first step in failure isolation. Packaged devices can be imaged to quickly detect and locate resistive failures and to provide confirmation of a suspected failure mechanism, potentially eliminating the need for further analysis.

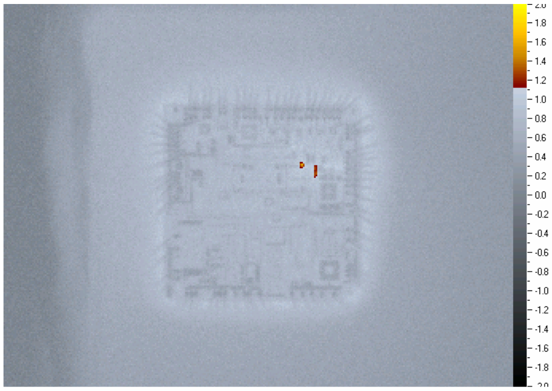


Figure 5 – Hot spot detection on decapsulated device

Liquid Crystal Thermography

Liquid crystal thermography is commonly employed to detect hot spots on the surface of bare semiconductor die. Liquid crystals are materials that change color as a function of temperature. They are applied in liquid form to the surface of a die and then imaged using a color video camera fitted with a microscopic lens. Applying the liquid crystal material requires a trained operator and the measurement process involves controlling the die to several precise temperatures above and below the liquid crystal activation temperature. Because this technology requires coating the die, it is often not the tool of choice when further analysis of a device may be required.

Although the spatial resolution of liquid crystal thermography can be as fine as 1 micron, the distance from junctions and defect sites to the liquid crystal material on the die surface can be tens of microns. As a result, the heat originating from these sources diffuses into the die, producing a thermal signature at the die surface that is many times its original size, and much larger than 1 micron. Liquid crystal thermography can also be used to measure die surface temperature; however, an extensive calibration procedure must be performed to correlate liquid crystal color changes to temperature values.

Conclusion

Because device reliability depends largely on operating temperature and due to the increase in circuit density and chip speeds, accurate thermal characterization is becoming increasingly important. Thermal imaging microscopes are used to guide device layout, verify finite element analysis results, evaluate thermal coupling between board components, and to identify die attach voids and defects. An important advantage of this technology is the ability to measure the junction temperature of functional devices quickly and without contact. Thermal imaging microscopes are frequently used as a non-invasive first step in failure analysis of both packaged and bare devices in order to locate resistive failures and to provide confirmation of suspected failure mechanisms.

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