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USER GUIDELINES FOR IR THERMAL IMAGING DETERMINATION OF DIE TEMPERATURE

(From JEDEC Board Ballot JCB-95-69, formulated under the cognizance of the JC-25 Committee on Transistors.)

1 Purpose

The purpose of these user guidelines is to provide background and an example for the use of an infrared (IR) microscope to determine die temperature of electronic devices for calculations such as thermal resistance.

2 Terms and definitions

The following definitions and symbols are used throughout this document:

$T_{J(M)}$ **peak junction temperature** (in degrees Celsius)

$T_{J(AV)}$ **average junction temperature** (in degrees Celsius)

T_C **case temperature** (in degrees Celsius)

NOTE — Measured with a thermocouple that is attached as close as possible to the major heat flow path, usually on the bottom center of the device package or case for packaged parts. For wafers, this temperature is the die temperature. For surface-mount devices, this is the lead frame.

T_M **mounting surface temperature** (in degrees Celsius)

NOTE — Measured with a thermocouple inserted in an access hole terminated near the device/stage interface.

P_D **power dissipation** (in watts) of a single junction under test or of the entire package.

$R_{\theta JR}$ **thermal resistance between junction and a reference** (such as ambient ($R_{\theta JA}$) or case ($R_{\theta JC}$), measured in °C/W)

emissivity: A dimensionless factor that is a property of the material and its surface texture.

NOTE — Emissivity (ε) is represented by a number between 0 and 1 where $\varepsilon = 0$ represents a perfect infrared reflector and $\varepsilon = 1$ represents a perfect infrared absorber or "blackbody". A blackbody is also a perfect radiator or emitter of infrared radiation.

spatial resolution: The diameter of a spot, in micrometers, whose size is determined from the half-power points resulting from a point infrared source.

3 Apparatus

Some or all of the following list of equipment will be necessary to complete the procedure:

3.1 Infrared microscope

A microscope with a detector or array of detectors sensitive to infrared radiation is necessary. The microscope may be from any one of the three major families: single detector staring, single detector imaging, or array detector imaging. Each of the three families has price/performance advantages and disadvantages. The features and performance specifications of the IR microscope have a significant impact on the accuracy of the data collected.

a) Spectral response

The Indium Antimonide (InSb) detector with spectral response of 2-5 μm is used for applications where high spatial resolution specifications are desired. Mercury Cadmium Telluride (HgCdTe) with spectral response of 5-15 μm has advantages for room temperature applications but is inferior to InSb for resolution of small features and sensitivity at temperatures above room temperature.

b) Spatial resolution

The necessary spatial resolution (spot size) specification depends on the individual application. If the length or width of the feature to be measured is less than the spot size, the resulting data for that point will not be the true peak temperature and will be erroneously low since the desired feature and its surrounding area will be averaged into one data point.

c) Temperature resolution

Temperature resolution is the ability to detect small changes in temperature. An accepted minimum standard for temperature resolution is 0.5 °C at 60 °C, but instruments are currently available that are capable of 0.1 °C temperature resolution.

d) Emissivity correction

Emissivity is a dimensionless factor that is a function of the material and its surface texture. Emissivity can range from zero for a perfect reflector to one for a perfect emitter (blackbody). The maximum infrared energy which can be emitted from a body at any given temperature is that of a blackbody. Therefore, the infrared energy density emitted from a blackbody is a measure of its temperature.

The infrared microscope calculates temperature by either assuming that the DUT has high (near unity) emissivity or using an internal emissivity correction algorithm. If the IR microscope does not have an emissivity correction algorithm, the device must be coated with a uniform high emissivity layer. This layer must be thin (25-50 μm) and of a known, high emissivity ($\varepsilon \geq 0.95$) such as flat black paint or lampblack. The uniform high emissivity layer can reduce peak junction temperatures by as much as 2% (°K) due to alteration of the thermal characteristics of the die. The uniform high emissivity layer is typically permanent.

3 Apparatus (cont'd)

3.1 Infrared microscope (cont'd)

e) Background Reflections

If the IR microscope has an emissivity correction algorithm, then reflections from the background must be corrected for. This capability is unnecessary for instruments that rely on the uniform high emissivity layer since a surface with high emissivity has low reflectivity.

f) Narcissus Effect Correction

The Narcissus Effect is an error that results from the cold (liquid-nitrogen cooled) detector "seeing" its own reflection on a surface with low emissivity. This effect is predictable and can be negated in software. Note that this phenomena is only apparent when the cold detector is staring at a low emissivity surface perpendicular to the axis of view.

3.2 Device holder

The DUT is mounted on a device holder which provides the following:

a) Ability to maintain die or case temperature at a stable known value, typically via a temperature controlled mounting surface.

b) Access for at least one of two thermocouples, depending on the following:

- Ideally and for most accurate measurement, a thermocouple is attached to the device case to acquire T_C, the case temperature. For most wafers (where T_C is the die temperature) and in many packaged part applications, this will be possible. In some cases, however, it is not feasible to attach directly to the case.

- If it not feasible to attach a thermocouple directly to the case, provide an access hole to allow mounting surface temperature, T_M, to be measured as close as possible to the bottom surface of the die or package. This value is then used as an approximation of T_C. Before inserting the thermocouple, fill the access hole with thermal grease or thermal conducting epoxy to assure heat flow to the thermocouple bead. Air pockets in the access hole should be avoided.

c) All interfaces such as die to adapter and adapter to temperature-controlled mounting surface must be coated with a layer of thermal grease or thermal conducting epoxy to assure good heat flow. This is particularly important in cases where T_M is being used to approximate T_C.

d) Allow for electrical connection so that the device can be brought to operating temperature. This can take the form of a PCB assembly with socket and breakout connectors for packaged devices or a probe station for devices in die form.

3 Apparatus (cont'd)

3.3 Thermocouple

A thermocouple is used for measuring case or mounting surface temperature. The thermocouple material can be copper-constantan (type T) or equivalent. The junction of the two thermocouple wires is welded to form a bead. The accuracy of the thermocouple and associated measuring system should be less than or equal to ±0.5 °C.

4 Procedure

4.1 Instrument calibration

The calibration of an IR microscope is checked with a blackbody source. If the temperature of the blackbody is measured with a thermocouple, that temperature is converted to infrared radiance with a lookup table or calculated with Planck's Law. The derived radiance is compared to the radiance measured with the IR microscope to verify calibration.

4.2 Device preparation

The DUT must be in precapped or decapped form to provide direct viewing of the die surface. If the uniform high emissivity layer method of emissivity normalization is used, the active area of the DUT is coated.

4.3 Test preparation

a) The DUT is mounted in the device holder on the temperature controlled stage and a thermocouple connected to measure T_C or T_M.

b) All electrical connections necessary to stimulate the DUT to its operating conditions are made.

c) The optics are focused and centered on the area of interest. Generally, maximum infrared energy indicates focus on the primary heat generation element or junction. Focus is accomplished in some systems by initially performing a visual focus (if a visual camera is present) and then changing to the IR system. This method assumes that the visual and IR systems are parfocal. If a visual system is not present (or to provide additional capability), an IR focus can be performed on the DUT by viewing the raw radiance image and manipulating focus until the sharpest image appears. The raw radiance image can be viewed from either its analog (fastest display rate) or digital signal.

4 Procedure (cont'd)

4.4 Test procedure

a) The case (or die for wafers) temperature is set to a known, stable value.

b) All necessary emissivity and background correction operations are executed. For a system with automated emissivity, background, and Narcissus correction, this procedure will take the following form [1,2]:

1) Basic relationship - The basic equation for radiance (where the object is considered to be opaque) is:

$$N_M = \varepsilon N_T + (1 - \varepsilon)N_A, \tag{1}$$

where N_M is the measured radiance, ε is the emissivity, N_T is the blackbody radiance at target temperature, and N_A is the blackbody radiance at ambient temperature.

2) Emissivity Calculation - By acquiring radiance measurements (with the device unpowered) at two temperatures (T1 and T2) which straddle the temperature at which you wish to test the device, you now know N_M at two points (N_{M1} and N_{M2}). In addition, from the calibration performed prior to the test (see 4.1), you know N_T at the two temperatures at which you acquired N_M (N_{T1} and N_{T2}). Substituting known values into equation 1, you have two equations in two unknowns (ε and N_A), and can solve for ε as

$$\varepsilon = (N_{M1} - N_{M2})/(N_{T1} - N_{T2}) \tag{2}$$

3) Ambient Radiance Calculation - By acquiring a radiance measurement (with the device unpowered) at the desired case temperature T_C (N_{M3}) and using the known blackbody radiance at T_C (N_{T3}), the ambient radiance can be calculated as

$$N_A = (N_{M3} - \varepsilon N_{T3})/(1 - \varepsilon) \tag{3}$$

Calculating ambient radiance at the desired case temperature corrects for the background reflections and Narcissus effect.

c) The DUT is then operated at a specified electrical operating condition (power vs. time). Allow enough time for the junction temperature to stabilize. At the same time, limit the time such that the reference temperature does not vary. Record all of the necessary electrical conditions and test circuits for the calculations to be performed.

d) The radiance, or temperature for corrected IR microscopes, is acquired and recorded. This data will be used to calculate thermal characteristics such as thermal resistance ($R_{\theta JR}$). For corrected systems such as described in step b, and using equation 1 and the known values, the blackbody radiance of the device is calculated as

$$N_T = (N_M - (1 - \varepsilon)N_A)/\varepsilon \tag{4}$$

Using Planck's law (or a power series expansion to this) gives the temperature of the device from the known blackbody radiance.

5 An example: $R_{\theta JR}$ Calculation

The ability of a semiconductor device, such as a power transistor, to dissipate generated heat to the environment is critical for reliable operation of that device. In order to predict the reliability of a new device or analyze the failure of an existing device, thermal characteristics must be determined.

The figure of merit used to describe the thermal characteristics of a microelectronic device is thermal resistance. Thermal resistance allows the representation of thermal characteristics in electrical terms. The most general expression of thermal resistance is

$$R_{\theta JA} = R_{\theta JC} + R_{\theta CA} \tag{5}$$

where

$R_{\theta JA}$ = Thermal resistance between junction and ambient (°C/W)
$R_{\theta JC}$ = Thermal resistance between junction and case (°C/W)
$R_{\theta CA}$ = Thermal resistance between case and ambient (°C/W).

The calculation of $R_{\theta JC}$ is used to quantify the thermal properties of a device and is defined as the difference between the junction and case temperatures divided by the power dissipation of the element.

$$R_{\theta JC} = (T_J - T_C)/P_D \tag{6}$$

Two options for measuring T_J exist.

l) Assuming that the spatial resolution of the IR microscope is sufficient to provide several measurements of temperature in the junction area, the individual measurements can be averaged to calculate $T_{J(AV)}$ over the junction . This measured average temperature can then be used to calculate (via substitution in equation 6)

$$R_{\theta JC(AV)} = (T_{J(AV)} - T_C)/P_D \tag{7}$$

This result is similar to those arrived at by using temperature-sensitive electrical parameters (TSEP) as a “thermometer” of the device. In both cases, the temperature arrived at is an average of the device's temperature.

2) The peak junction temperature can be significantly higher than the average junction temperature. As described in reference 3, peak junction temperature is the most important for predicting the reliability and operational characteristics of the device. Using peak junction temperature gives the best real world estimate of the thermal characteristics of the device. Substitution of peak values in equation 6 gives:

$$R_{\theta JC(peak)} = (T_{J(peak)} - T_C)/P_D. \tag{8}$$

6 References

1. Robert J. Stetson and Jonathan S. Shapiro, “Imager finds microelectronic hot spots”, *Laser Focus World*, PennWell Publishing Company, June, 1990.

2. Jay W. Shepherd, “A discussion of emissivity correction and its application in infrared microimaging”, *An International Conference on Thermal Infrared Sensing for Diagnostics and Control (Thermosense IX)*, SPIE, 18-20 May 1987.

3. F.F. Oettinger and D.L. Blackburn, *Semiconductor Measurement Techniques: Thermal Resistance Measurements*, NIST Special Publication 400-86, US Department of Commerce/National Institute of Standards and Technology, July, 1990.