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Application Note

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Comparing Thermoreflectance with Infrared Imaging for the Thermal Characterization of Electronic and Optoelectronic Devices

The Future of Thermal Imaging is Here!!!

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Introduction

Infrared and near infrared imaging has been used for many years as a means for measuring and characterizing the thermal performance of electronic and optoelectronic devices and microelectronic systems. In recent years Thermoreflectance imaging has continued to evolve and has been demonstrated to provide a complementary approach for the thermal characterization of devices. Thermoreflectance imaging has proven to be especially useful in the characterization of devices with sub-micron features. This application note describes the thermoreflectance imaging process and provides some comparisons with infrared imaging.

Infrared Imaging

Infrared imaging is a well understood imaging technique based on blackbody radiation. All physical bodies emit electromagnetic radiation which is governed by Plank's Blackbody Law, which can be simplified to the Stefan-Boltzman Law when integrated for all wavelengths. At temperatures near 300 °K objects emit radiation in the infrared band which, due to diffraction, limits the spatial resolution of the thermal images to a range of 3 μm to 10 μm .

The degree to which an object emits blackbody radiation is dependent on the emissivity of the material; typically between 0 and 1. The emissivity for metals and other reflective objects is very low, while darker objects that absorb more light are much higher. Aluminum, for example can have an emissivity of ~ 0.04 to 0.07 depending on its roughness, while graphite has an emissivity of ~ 0.45 . This difference in emissivity directly relates to the thermal signal coming from the device. Therefore the signal to noise ratio (SNR) difference between aluminum and graphite would be approximately 10 times. Also, since the emissivity of a material is highly surface and material dependent, pixel-by-pixel calibration for each sample must be done for each new sample under test. Additionally, if the sample moves during the measurement, sample calibration must be repeated. Sample movement such as thermal expansion at high magnifications also can be problematic for devices with many sharp features. For infrared imaging, it is common to coat the sample with a thin layer of material such as graphite to improve the emissivity and thus the signal to noise ratio. Surface coating is also used to avoid the need for feature by feature calibration.

Thermoreflectance Imaging

Thermoreflectance imaging exploits the change in material reflectivity due to a change in material temperature. This thermoreflectance technique uses a probing light source to detect the change in magnitude of reflected light as opposed to measuring the signal that is being emitted from the device due to blackbody radiation. Because of this, the probing light can be pulsed to measure the temperature at specified time delays with respect to

the biasing pulse. This can also be done at cryogenic temperatures since we are not limited by photons emitted by blackbody radiation. The amount that the reflectivity coefficient changes with temperature is called the **thermoreflectance coefficient (C_{th})**. The thermoreflectance coefficient, is non-zero for most wavelengths, thus visible light can be used to detect the change in reflectance. The shorter wavelength improves the spatial resolution of the thermal image by a full order of magnitude compared to IR imaging. This greater spatial resolution is important for obtaining more accurate peak temperatures of the device under test.

Thermoreflectance Imaging Concept

Figure 1 illustrates the basic setup for high spatial-resolution CCD-based thermoreflectance. The setup consists of a visible light CCD camera and a light emitting diode (LED) illumination source that is focused onto the device under test (DUT) by a microscope.

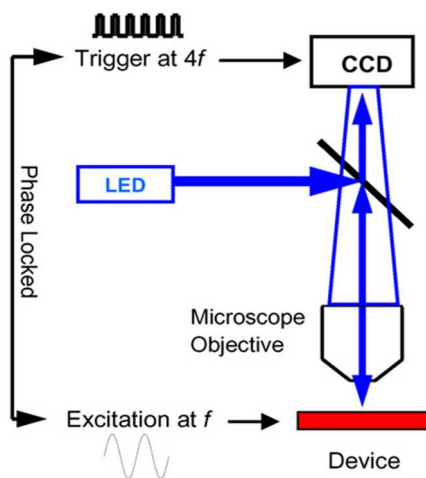


Figure 1: Basic Setup

The reflected light to the CCD in response to modulation of the DUT temperature is then analyzed by SanjVIEW™, a flexible, user-friendly computer software program developed by Microsanj™. The use of an incoherent light source (LED) instead of a focused laser beam eliminates speckle or fringe type interference patterns that may occur with coherent illumination. Various modulation schemes can be used to detect the relative change in reflectivity of the surface of the DUT surface, including the homodyne method, the heterodyne method and transient effects. Since the thermoreflectance coefficient is strongly dependent on the illumination wavelength, the LED choice plays an important role in determining the sensitivity of CCD-based thermoreflectance. The relation between the relative change in reflectivity and the temperature change can be approximated to a first order as:

$$\frac{\Delta R}{R} = \left(\frac{1}{R} \frac{\partial R}{\partial T} \right) \Delta T = C_{th} \Delta T$$

Where C_{th} , which is typically of the order of 10^{-2} to 10^{-5} per °K, is the thermoreflectance coefficient. C_{th} depends on the sample material, the wavelength of the illuminating light,

the angle of incidence (and thus, by extension, the surface roughness) and, in the case of multi-layer structures, the composition of the sample.

Examples

Figure 2 clearly shows the difference in spatial resolution between infrared and Thermoreflectance imaging. Both images show the non-uniform heating across the area of the chip due to variations in the die attach. The thermoreflectance image however, provides greater detail with its inherent spatial resolution advantage.

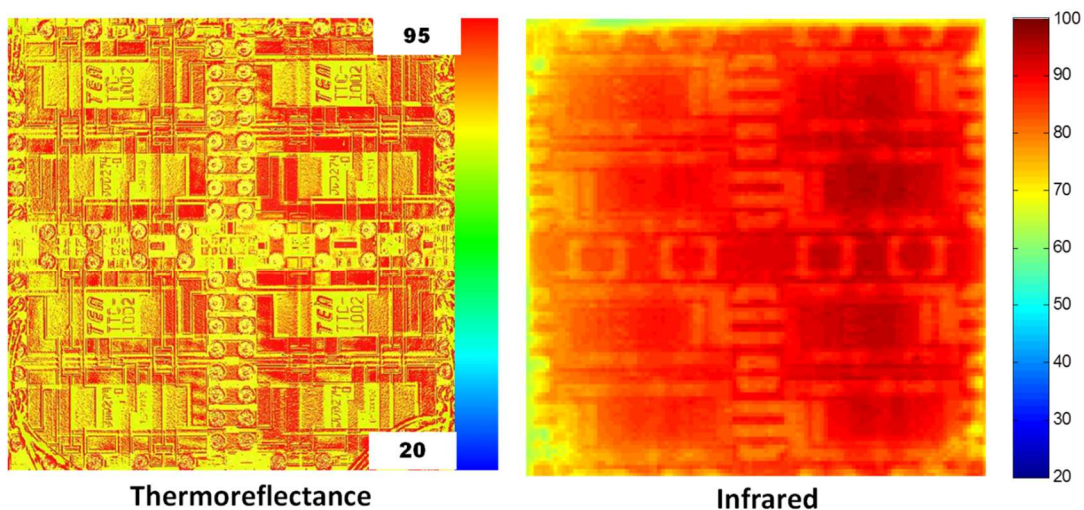


Figure 2: Spatial Resolution in Thermoreflectance Image

Figure 3 shows a comparison for a DUT under high magnification. By performing an AC measurement and pulsing the DUT, much more localized peak temperatures can be detected since diffusion length is inversely proportional to the square root of the frequency. The thermoreflectance images clearly show sharp temperature peaks on the surface of the 4 μm wide heater lines.

Figure 4 illustrates another high magnification example which, in this case, shows the presence of a hot-spot defect in a multi-finger MOSFET. The optical and thermal overlay shows the precise location of the 1.4 μm defect.

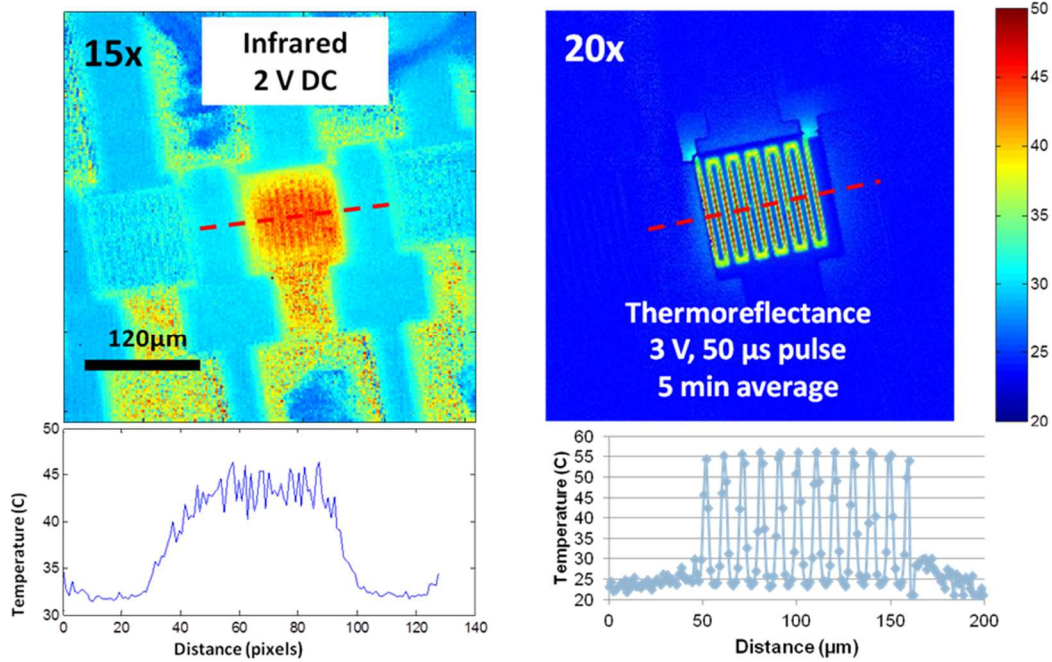


Figure 3: Detecting Localized Temperature Peaks

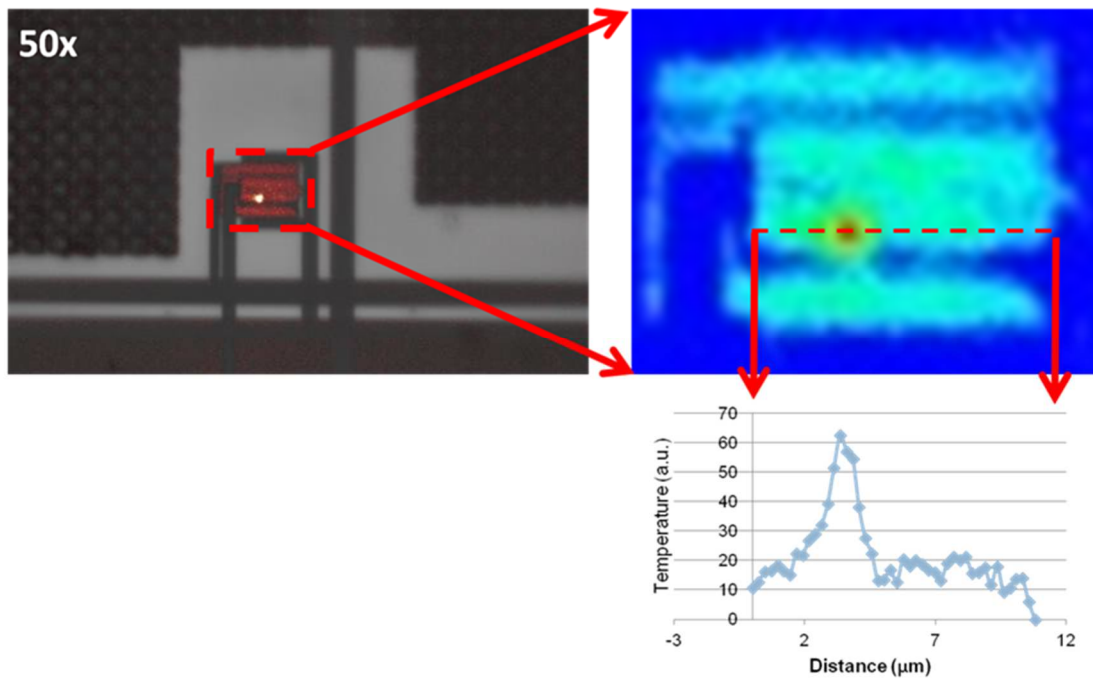


Figure 4: Detecting a Hot-Spot Defect in DUT

Summary

The following table summarizes the key attributes of optical thermoreflectance and infrared imaging for electronic and optoelectronic device thermal analysis. The examples cited above highlight some of the key benefits enabled by the use of thermoreflectance for thermal imaging.

	Thermoreflectance	Infrared
Concept	Based on change in reflectivity with change in temperature	Based on blackbody radiation
Calibration	Required for new materials or processes	Point-by-point calibration required due to sample-specific emissivity unless coated with blackbody-like material.
Resolution	Diffraction limited to 0.25 μm to 0.80 μm for a Si-CCD. (dependent on illumination wavelength)	Diffraction limited by infrared wavelengths to 3 μm to 10 μm .
Other	AC technique where lock-in is used for improved signal to noise	Silicon is transparent to IR and metals are poor emitters

The emergence of optical thermoreflectance combined with digital signal processing and advanced software algorithms provides engineers a highly versatile tool for non-invasive microelectronic thermal analysis with spatial resolutions consistent with today's high frequency, high speed devices. By providing a better understanding of the device thermal properties through enhanced thermal imaging, thermoreflectance imaging analysis can lead to improved device performance and assured reliability.

Microsanj™ is a leading supplier of Thermoreflectance Imaging Analysis systems, tools, and consulting services. For more information see www.microsanj.com or inquire at: info@microsanj.com