Microsanj LLC
3287 Kifer Road
Santa Clara, CA 95051

Application Note

Comparing Thermoreflectance (TTI), Infrared (IR), Near Infrared Emission (EMMI), and Optical Beam Induced Resistance Change (OBIRCH) Imaging Techniques:

Which characterization method is best for your application?

The Future of Thermal Imaging is Here!!!

Revised April 2018 **AN-004**

Introduction

The growing complexity and continued emphasis on speed in today's microelectronic devices has led to smaller and smaller geometries and, in turn, has placed increased demands on the need for adequate thermal and defect characterization techniques to ensure device reliability and performance. Several approaches are commercially available to designers and reliability engineers for electronic and optoelectronic characterization. These systems can be costly and may not always meet all of the requirements necessary to fully understand the properties of the devices being analyzed. In this application note we will provide a brief overview of four commercially available imaging techniques; Infrared (IR), Near infrared (N-IR) Emission Microscopy (EMMI), Optical Beam Induced Resistance Change (OBIRCH), and Thermoreflectance Thermal Imaging (TTI). IR, EMMI, and OBIRCH systems have been commercially available for some time, whereas TTI has only recently evolved from being a university research tool to a commercially available thermal imaging system.

Overview of Thermal Characterization Techniques

Infrared Microscopy (IR) is a general description for imaging techniques that detect infrared emitted light from the target device. This technique is based on black-body radiation to obtain device thermal profiles. Near room temperature, cameras with a sensitivity of 4-7 microns (InSb) or 8-12 microns (HgCdTe or Quantum Well Infrared Photodetectors –QWIP) are typically used. Although IR systems can provide excellent temperature resolution, time and spatial resolution[1] are only fair. At times special sample preparation (e.g. coating by black paint) is required and for accurate temperature measurement, calibration is necessary since surface emissivity is fabrication dependent. Typical temperature resolution is 25 mK at 60 to 80 °C. IR systems for microscale chip thermal characterization tend to be expensive.

Emission Microscopy (EMMI) detects Near-Infrared light emitted from the target device. There are two failure categories that can be detected by Emission Microscopy:

(1) The light wave generated in the target device by electron-hole recombination, and

(2) The electron emission by colliding (thermalized) electrons with emissions in the Near-Infrared wavelength region.

The light generated by a defect is typically very faint. Therefore to detect the failure, the imaging device must have very high photon sensitivity in the wavelength of interest (typically 1.0 to 1.8 microns using InGaAs or deep-depleted Silicon CCDs).

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[1] See Microsanj application note MS-AN-001 for additional details on 'Emission Microscopy'.

Optical Beam Induced Resistance Change (OBIRCH) is an imaging approach that uses a laser to induce a resistance change in the device-under-test (DUT). This technique can be used to identify differences between areas on the device that are defect-free relative to areas that may have defects. Changes in the device input current are measured to determine the resistance change. A region of interest is selected on the device-under-test and the selected area is scanned by a laser. The current of the DUT is monitored and any changes in the current are noted along with the laser position at the time of the change. In regions with no defects there will be good thermal spreading and very small current change. Regions with defects however, will exhibit greater changes in resistance resulting in a large current change. When displayed on a device image the regions with higher current (resistance) changes are displayed as bright spots.

OBIRCH systems can detect temperature changes due to the incident laser illumination in the micro-Kelvin range and spatial resolution is somewhat improved over IR systems but is not in the sub-micron range. Some systems have an option for time domain imaging with lock-in capability to the laser scan. This provides hundreds of milliseconds for the time resolution. Due to the scanning laser illumination, systems are also expensive and take up considerable floor space.

Thermoreflectance Thermal Imaging (TTI) is a technique that exploits the change in material reflectivity due to a temperature change. Since the thermoreflectance coefficient is very small for most materials of interest, a lock-in technique is employed to enhance the signal-to-noise ratio to achieve good temperature resolution. The illumination sources are in the 400 to 800 nm wavelength range, resulting in sub-micron spatial resolution. Using a Near-IR illumination source, as with the Microsanj NT300A-series, enables thru-the-substrate imaging. This also enables the collection of emission images along with the thermoreflectance images.

TTI Advantages

Time Resolution: Thermoreflectance imaging has the highest temporal resolution for measuring temperatures in full-field images. The Microsanj commercial thermal imaging systems can achieve 50 nanoseconds in a megapixel image and 800 picosecond time resolution has been achieved with our newest visible wavelength thermoreflectance system, the NT410A.

The full-field time resolution of the IR camera on the other hand, is limited by the frame rate which is in tens of milliseconds. It is sometimes possible to go to one millisecond time resolution with IR cameras but this requires pixel binning resulting in lower resolution images.

Spatial Resolution: Diffraction-limited spatial resolution for thermoreflectance is 245-600 nm with illumination wavelengths in the UV and visible band and about 800 nm for near-IR with 1.0-1.5 micron illumination wavelength used for thru-the-substrate measurements (NT310B and NT410A). This is a factor of 3 to 10 better spatial resolution compared to IR microscopes based on InSb.

Sample Heating: With thermoreflectance there is no need to heat the sample to 50 to 70 °C as is required for most IR imaging systems to get good temperature resolution. Thermoreflectance imaging of chips can be done at room temperature or even below room temperature if there is a need to overdrive the chip. We have done thermoreflectance imaging of devices at cryogenic temperatures as low as 5 K.

Simultaneous Emission and Thermal Imaging: With Microsanj TTI systems one can obtain reflection, emission, and thermal images simultaneously with an InGaAs camera and overlay all three images. InSb IR cameras can only obtain thermal images and emission microscopes can only capture emissions in the 0.5-1.8 micron range.

Transient Thermal Imaging: Transient thermoreflectance imaging adds another dimension to thermoreflectance imaging. By pulsing the device under test at a low duty cycle, the overall heating is concentrated in the device active area as opposed to the surrounding substrate. As a result localized hot spots can be more easily observed compared to a steady-state thermal image.

Since today’s microelectronic devices often have complex time-varying workloads, the synchronization of various signals in the chip are very important. The thermal response, however, is sometimes not taken into account in the layout of the circuitry thus the temperature distribution resulting from such complex operational modes is often unknown during the design phase. The transient temperature profile therefore, is not characterized until after the devices are manufactured. Time dependent temperature profiles around various active components are critical for predicting the performance and reliability of the circuit. Transient thermoreflectance addresses this requirement.

TTI Limitations

Thermoreflectance characterization has many advantages but it is not a solution to detect ***“every”*** possible device defect. Some limitations of transient thermoreflectance thermal imaging systems are as follows**:**

Temperature resolution not as good as lock-in IR thermography: Our temperature resolution is typically 0.25 to 0.5 °C with 2 minutes averaging. 0.006 to 0.01 °C can be achieved when there is sufficient reflected light and averaging times of 20 minutes to hours. Lock-in InSb infrared cameras can achieve temperature resolution in the range of 10 micro Kelvin if the surface is painted black and long averaging times are employed. However, IR imaging’s spatial and temporal resolutions are limited (full-field images in millisecond and single pixel transient response in microseconds). Lock-in IR thermography is typically much more expensive than thermoreflectance because of the high cost of long-wavelength optical components and sensors.

Emission resolution is lower than cryogenically cooled InGaAs cameras: Since we are currently using a room-temperature InGaAs camera for thru-the-substrate thermoreflectance imaging, our dark current is not as low as cryogenically cooled systems optimized for emission characterization. The thermoreflectance hardware/software system can easily be adapted with cryogenically cooled InGaAs cameras but this will significantly increase the system cost.

Performance Summary

The **Thermoreflectance Thermal Imaging Technique** is one of the most robust and sensitive methods for obtaining ***full-field transient temperature profiles*** at a ***reasonable price.*** This thermal imaging tool should be viewed as an additional tool which can significantly outperform conventional IR and Emission Microscopy (EMMI) in ***many*** applications and provide thermal information that will ***complement*** that obtained by EMMI or OBIRCH in ***other*** applications. For example, heating in metal interconnects will not produce any detectable emissions for near IR and if the temperature non-uniformity is not large enough, there may not be an OBRICH signal.

	TTI	**IR**	**EMMI**	**OBIRCH**
Spatial Resolution	250 nm 1 - 2 µm*	~2 - 5 µm	~2 – 3 µm	~1.0 – 1.5 µm
Minimum power ** (1 hr. average)	~500 µW (50 µW with longer integration time	~100 mW (<10 µW lock-in)	10's µW	10's µW
Temperature Resolution	0.1 – 0.5 °C 1.0 °C* (6 mK demonstrated)	100 mK (10 µK lock-in)	Doesn't measure device operating temperature	Doesn't measure device operating temperature
Full Frame Time Resolution	50 ns Typ 800 ps demonstrated	10's ms	10's ms	> 100 ms
Sample Temperature	-265 °C to 500 °C demonstrated	>50 °C to 70 °C	Can be a wide range	Can be a wide range
Other	Simultaneous EMMI & thermal is possible	Metals have low emissivity	Only for defects that emit light	Small resistance changes may be missed
Relative Cost	$ to $$	$$ to $$$	$$ to $$$	$$$

**These values for TTI apply to Thru-the-Substrate imaging*

*** Minimum detected power depends on the size and location of the heat source. Typical numbers for micron size hot spots are given. 25 to 50 µW have been achieved under optimal conditions*

There is much to be considered when evaluating which thermal imaging approach is best suited to any specific application. In some cases more than one imaging solution may be necessary to adequately characterize the thermal behavior of the device in question and/or identify defects.

Conclusion

In preparing this application note, Microsanj has made a diligent effort, with the information we currently have available, to provide you with a fair assessment of how these four different thermal imaging techniques compare. Hopefully this information will provide you with some insights as to where each of these techniques, based on their respective benefits and limitations, may fit with your thermal analysis requirements. If you feel we have incorrectly stated any performance estimates or miss-characterized any of the thermal imaging techniques described here, please let us know. It is also important to remind you that all of these techniques are subject to ongoing development; thus system configurations, performance, specifications, and relative costs are subject to change over time. Since any of these alternatives represents a significant financial investment it is important to ensure that you have the most up to date information available prior to making a final decision.

For Thermoreflectance Thermal Imaging systems (TTI), the Microsanj team is always available for consulting services and they can perform testing on your devices in the Microsanj laboratory. If in doubt, as to how thermorflectance can address your thermal imaging requirements; a ***'try before buy'*** approach may prove to be the best strategy.

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*