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Tech Note: TN-001A

THERMOREFLECTANCE IMAGING: WHAT IS IT?

Introduction

The ***thermoreflectance*** (TR) technique for thermal imaging exploits the change in a material's reflectivity due to a change in its temperature. This imaging technique uses a probing light source in the visible range to achieve sub-micron spatial resolution. Since the thermoreflectance technique is not based on blackbody radiation it is not subject to the same spatial resolution limitations as infrared (IR) imaging, which is in the order of 3 to 10 µm. Thermal images are typically obtained with illumination sources with wavelengths between 365 and 900 nm for a Si detector and 900 to 1700 nm for an InGaAs detector. The probing light can also be pulsed to measure the temperature at specified time delays with respect to the device biasing pulse. The amount that the reflectivity coefficient changes with temperature is called the ***thermoreflectance coefficient***. 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 (SNR) to achieve good temperature resolution. Using a Near-IR illumination source, as with the Microsanj NT310B, enables thru-the-substrate imaging. This also enables the collection of emission images (EMMI) along with the thermoreflectance images.

The shorter illumination wavelength improves the spatial resolution of the thermal image considerably compared to other thermal imaging techniques. This improved spatial resolution is important for obtaining accurate locations for peak temperatures of the device under test. Microsanj transient thermoreflectance imaging systems can achieve:

- ✓ 0.25 µm Spatial Resolution
- ✓ 0.8 ns Temporal Resolution
- ✓ <0.5 °C Temperature Resolution

Thermoreflectance Advantages

Thermal imaging based on the thermoreflectance principal achieves a level of performance necessary to meet the demands of today's advanced high-speed microelectronic and optoelectronic devices.

- ✓ **Spatial Resolution:** Diffraction-limited spatial resolution for thermoreflectance imaging is **0.2-0.3 µm** with illumination wavelengths between 365 nm and 780 nm and **0.8 µm** for near-IR wavelengths between 900 nm and 1700 nm used for through-the-substrate thermal imaging (NT310B and NT410A). This is a factor of 3 to 10 better spatial resolution compared to IR microscopy based on InSb which is about 3 µm. Additionally, high spatial resolution IR imaging suffers from “size of the source” effect which causes inaccuracy in the temperature measurement of small objects. Improved optics with thermoreflectance and illumination wavelengths in the visible range does not have this limitation.

- ✓ **Time Resolution:** Thermoreflectance imaging has the highest temporal resolution for measuring temperatures in ***full field images*** without scanning. The Microsanj commercial systems can achieve **50 nanoseconds** in a megapixel image and **800 picosecond** time resolution has been achieved with our ***‘Pico-Second Scientific Thermal Imaging System’***, the NT410A.

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

- ✓ **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. Transient analysis also enables the analysis of time-dependent thermal events that occur in logic devices.

- ✓ **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 can be done at room temperature and even below room temperature if there is a need to overdrive the device under test. Thermoreflectance imaging of devices has been done at cryogenic temperatures as low as **5 to 10 Kelvin.**

- ✓ **Simultaneous Emission and Thermal Imaging:** We can obtain reflection, emission, and thermal images simultaneously and overlay all three images of defects at **10 µW** power levels. InSb IR cameras can only obtain thermal images (3-5 microns). Emission microscopes can only observe emission in the 0.5 to 1.8 micron range with an InGaAs camera.

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Thermoreflectance Limitations

Thermoreflectance characterization has many advantages but it cannot detect ***"every"*** possible device defect. Some limitations of our transient thermoreflectance systems are as follows**:**

- ✓ **Temperature resolution not as good as lock-in IR thermography:** Temperature resolution is typically 0.1 to 0.5 °C with 30 minutes averaging and 6 mK has been demonstrated. IR thermography can achieve 0.01 to 0.05 °C when there is sufficient emissivity. Lock-in InSb infrared cameras can achieve temperature resolution in the range of 10 µK if the surface has high emissivity and long averaging times (a few hours) are employed. Lock-in IR thermography however, is typically much more expensive than thermoreflectance because of the cost of long-wavelength optical components and sensors.
- ✓ **Emission resolution is lower than cryogenically cooled InGaAs cameras:** Since we are 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. Our InGaAs camera has a thermoelectric (TE) cooler stage that is used to stabilize the sensor temperature near room temperature since this helps with the read-noise and pixel uniformity. Since there is no deep-cooling, the sensor is more robust. We can easily adapt our thermoreflectance hardware/software with cryogenically cooled InGaAs cameras but this will significantly increase the cost of the system.

Summary

Microsanj is a leading supplier of thermal imaging systems based on the ***Thermoreflectance*** principal. Shrinking device dimensions and complex 3-dimensional architectures have greatly exacerbated the thermal analysis and characterization of today's state-of-the-art microelectronic and optoelectronic devices. Microsanj has carefully configured their systems to be cost-effective solutions with the resolution necessary to meet these thermal imaging challenges.

