Microsanj LLC
3287 Kifer Road
Santa Clara, CA 95051

Application Note

Understanding the Thermoreflectance Coefficient:

The Key to Achieving Optimal Temperature & Spatial Resolution for Thermal Imaging of Microelectronic Devices

The Future of Thermal Imaging is Here!!!

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Introduction

Thermoreflectance thermal imaging is dependent on the measurement of the relative change in the surface reflectivity as a function of temperature for a specific sample or semiconductor device. As the temperature of the sample changes, the refractive index, and therefore, the reflectivity also changes. A first order relationship between the change in reflectivity and the change in temperature can be approximated as:

$$\frac{\Delta R}{R} = \left(\frac{1}{R}\frac{\partial R}{\partial T}\right)\Delta T = \kappa \Delta T.$$

Where ***κ***, is the ***Thermoreflectance Coefficient***

The Thermoreflectance Coefficient is a basic material property. It is a function of the illumination wavelength, the ambient temperature, the material and material surface characteristics and, in some cases, may have some dependence on the material processing technique. For most metals and semiconductor materials of interest, the value of the Thermoreflectance Coefficient will be in the order of 10^{-2}/K to 10^{-5}/K. Thus, to detect a temperature change of 1 ºC it is necessary to detect a reflectance change of 1 part in 100 to 1 part in 100,000. It is important therefore, to have an accurate value for the Thermoreflectance Coefficient to achieve the best temperature resolution when doing thermal analysis on semiconductor devices. And, as will be shown in this application note, it is important to select an illumination wavelength that results in a Thermoreflectance Coefficient that is at or near its maximum value. The illumination wavelength also impacts the spatial resolution so in some cases a tradeoff may be warranted to achieve the desired results.

The purpose of this application note is to provide a better understanding of how ***κ,*** the ***Thermoreflectance Coefficient***, varies with respect to:

- Material Temperature
- Device Material Properties
- Illumination Wavelength
- Microscope Numerical Aperture

Material Temperature

Compared to IR emission for thermal imaging, the thermoreflectance technique has a significant advantage in that it can work over a very wide temperature range. As is the case with most material properties the Thermoreflectance Coefficient does have a dependence on the material temperature. Fortunately however, this dependence is relatively small and in most cases can be neglected. As an example, in an experiment studying the thermal performance of copper vias only a 2.7 % change in

Thermoreflectance Coefficient was detected for a temperature change of approximately 200 °C. Additionally, good thermal images of gold contact layers in small devices have been obtained with sub-micron spatial resolution over temperatures ranging from 10 K to 800 K. Obviously if one wanted the best possible precision it would be necessary to measure the Thermoreflectance Coefficient at operating temperatures of interest.

Material Properties

Processing Technique: For any given material, the Thermoreflectance Coefficient is not a strong function of surface preparation or the deposition process. Calibration for each device under test therefore, is generally not required. This differs from infrared emission where the emissivity can change substantially and as a result, must be calibrated each time to obtain accurate temperature data. We have measured the Thermoreflectance Coefficient of gold that was prepared by various thermal or e-beam evaporation techniques and always got consistent values. On the other hand, if there is a significant change in the visual color of the material due to major microstructures or porosity variations, the Thermoreflectance Coefficient can be significantly affected.

Dielectric Coatings and Passivation Layers: On the other hand, dielectric coatings or passivation layers will change the reflective properties and thus the Thermoreflectance Coefficient. For these cases, we recommend using temperature continuity on the surface if there are uncoated regions on the sample to calibrate the image. If this is not possible, Microsanj can determine the Thermoreflectance Coefficient of any coated material, if a small sample is provided.

Due to the nature of interference in thin film dielectrics, if the film thickness is not uniform across the sample, it is possible to observe oscillations in the reflected data. This is an inherent optical property of the device. One can conduct Thermoreflectance Coefficient measurements with different LED wavelength illuminations and by averaging; one can detect the envelope of the surface reflection oscillations and remove these optical artifacts.

Illumination Wavelength

For any particular material, the Thermoreflectance Coefficient is very strongly dependent on the illumination wavelength. As illustrated in the following graph[1], the Thermoreflectance Coefficient for aluminum is near zero at an illumination wavelength of 400 nm and orders of magnitude higher at 800 nm. In the case of Gold, the Thermoreflectance Coefficient has a positive peak value at about 470 nm, goes to zero at about 500 nm, and exhibits a negative peak value at about 520 nm. For optimal

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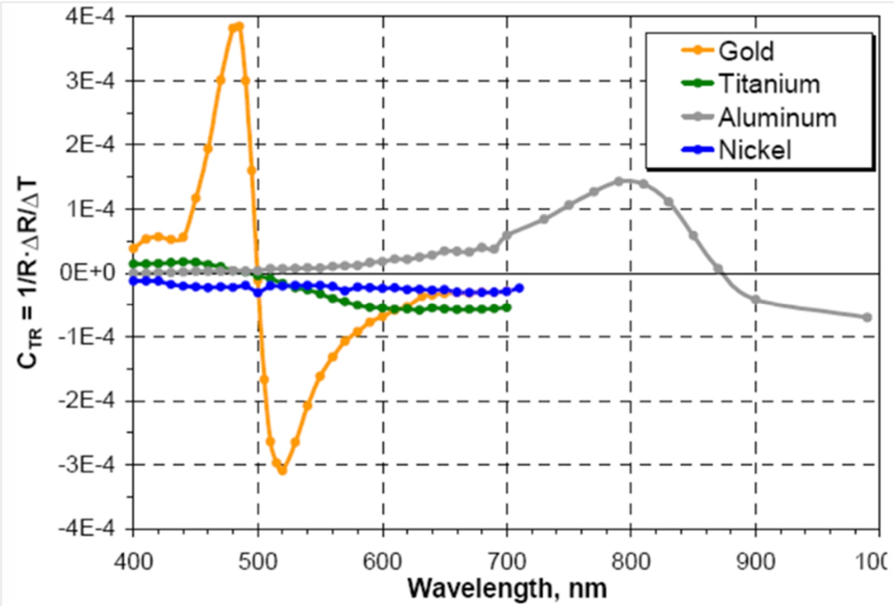
[1] M. G. Burzo, P.L. Komarov, and P. E. Raad, Thermo-Reflectance Thermography For Submicron Temperature Measurements, Feb 1, 2008

results, it is very important to select the appropriate illumination wavelength for the materials being analyzed.



Microsanj provides illumination (LED) wavelengths with their imaging systems that work well with materials typically encountered with microelectronic devices. Other LED wavelengths are also available from Microsanj. In the following table some materials that are likely to be encountered are listed along with an LED source that will result in a Thermoreflectance Coefficient close to its maximum value. Note that two alternatives are shown for Gold, one for the positive peak and one for the negative peak. Two sources are also indicated for Nickel and Titanium since the peak values for both of these materials are quite broad.

Microsanj can provide Thermoreflectance Coefficients for basic materials used in ICs for varied illumination wavelengths. For other material systems, one can easily extract the Thermoreflectance Coefficient if there is an embedded temperature sensor on the chip near the region of interest. The calibration procedure entails heating the entire chip uniformly using an external thermal stage. The thermoreflectance change across the full sample is recorded by the CCD while the temperature is measured simultaneously with the thermocouple. The calibration image and thermocouple measurements are correlated to produce values for κ for each region-of-interest on the chip.

In the absence of a temperature sensor, the Thermoreflectance Coefficient can be determined by Microsanj if provided with a sample of the chip with small thermal mass (e.g. 1x1 mm^2 up to 1x1 cm^2 die).

Material	470 nm (Blue)	530 nm (Green)	585 nm (Yellow)	660 nm (Red)	780 nm (Near-IR)	1050-1300 nm
Gold (Au)	■	■				
Aluminum (Al)					■	
Nickel (Ni)			■	■		
Titanium (Ti)			■	■		
Silicon (Si)	■					
Gallium Arsenide (GaAs)	■					
Indium Phosphide (InP)	■					
Thru-the-Substrate Imaging						■

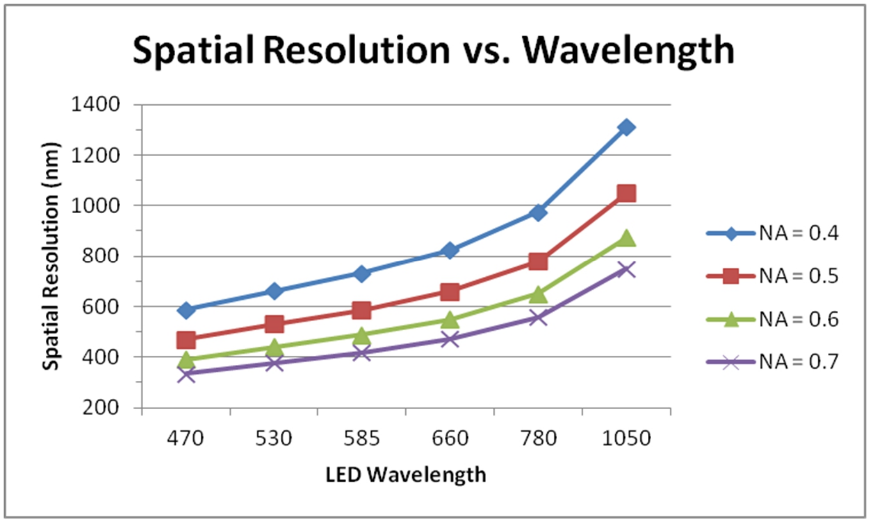
Microscope Objective Numerical Aperture (NA):

The magnitude of the Thermoreflectance Coefficient also has a dependence on the numerical aperture of the microscope objective used in the imaging. This is due to the component of the light polarized perpendicular to the surface which can be non-negligible for high numerical apertures, e.g. NA > 0.5. Thermoreflectance Coefficients provided by Microsanj specify the microscope objective used in the system (as well as the illumination LED wavelength). The spatial resolution is also dependent on the NA and is given by the following expression:

$$\textit{Spatial Resolution} = \lambda/[2n\textit{Sin}(\vartheta)]$$

Where: $n\text{Sin}(\theta)$ = the Numerical Aperture (NA), and n = the index of refraction (1.0 for air) and θ = the half-angle of the cone of light exiting the microscope lens.

The above relationship is plotted in the following figure for wavelengths up to the near-IR range. Illumination wavelength sources in the 1000 nm range are used for thru-the-substrate thermal imaging.



If it is necessary to do precise measurements of temperature distribution with a high numerical aperture lens, it is recommended to:

a) Perform measurements initially with a low numerical aperture lens over a large area and
b) Without changing anything in the device, change the lens and scale the temperature data accordingly.

This approach works when relatively large areas of the sample surface are available for imaging (e.g. 50-100 microns diameter). If the region of interested is very small and only visible with a high numerical aperture lens, then direct calibration on a temperature controlled stage is necessary. Since small changes in the stage temperature can defocus the image seen by a high NA lens, autofocusing during calibration is required.

Conclusion

Having an accurate estimate for the Thermoreflectance Coefficient and selecting the right illumination wavelength are key ingredients for achieving the best thermal and spatial resolution for thermal imaging of microelectronic devices. For unique materials and devices without embedded temperature sensors, Microsanj can help when supplied with a small sample of the material.

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*