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Application Note

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Analysis of Time-Dependent Thermal Events in High Speed Logic Integrated Circuits

The Future of Thermal Imaging is Here!!!

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Introduction

Analyzing the thermal behavior in today's logic ICs is greatly exacerbated with the scaling of the device features and increased use of complex 3-dimensional structures. At the same time the need to understand and address thermal anomalies is critical to ensure long-term device reliability. The scaling of device features results in a significant reduction in time response and an increased sensitivity to transient events. A very small localized 'hot spot' can occur due to an unintended functional anomaly in a circuit with a tight design margin or a timing perturbation resulting from a small change in a parameter elsewhere in the circuit. Thermoreflectance thermal imaging offers a cost-effective approach for detecting and analyzing hot spots on a sub-micron scale and, with the additional capability of transient analysis, offers the potential to identify time-dependent temperature events with nanosecond resolution.

This application note is focused on the ***time-dependent*** aspect of thermal analysis. It will provide some insight as to the spatial and time resolution that is achievable and describe an actual device example to illustrate the transient thermal imaging results that can be obtained.

The Thermoreflectance Concept

Thermoreflectance imaging is simply based on the fact that a material's surface reflectivity is a function of the material's temperature and by using illumination wavelengths in the visible range, can provide spatial resolutions in the sub-micron range. See [1], [2]. or [3] for a further discussion of thermoreflectance thermal imaging.

Transient Thermal Imaging

Transient thermal imaging is a standard capability available with several thermal imaging systems in the Microsanj Nanotherm-Series product line. By applying a bias pulse to the device under test at a low duty cycle, the heating is concentrated in the activated area of the device as opposed to the surrounding substrate. This improves the ability to detect and observe localized hot spots compared to a steady-state thermal image. It also enables the detection of time-dependent temperature behavior for the many active components on the IC. Analyzing and understanding the time-dependent profiles is critical for predicting the performance and reliability of today's complex logic ICs.

The Transient Imaging Module and High Speed Signal Generator are the Nanotherm Series hardware components that provide transient functionality. The basic concept is illustrated in Figure 1, which shows the timing relationship between:

- The bias pulse, '***DUT Voltage***', applied to the device under test (DUT)

- The '***CCD Exposure***'
- The pulse, '***LED Pulse***', applied to the LED illumination source
- The resulting thermorelectance signal, '***Device Temperature***', caused by the DUT temperature change

The ***time delay, τ***, between the start of the device excitation and the LED illumination can be varied to map the device temperature as a function of time.

The Nanotherm-Series Transient Imaging Module provides the ability to set the parameters for transient analysis. Namely:

- The width and duty cycle for the pulse applied to the DUT. This is generally set to a value high enough to allow hot spots to get to maximum temperature and low enough for the temperature to cool down to the stage temperature between pulses. Typically a duty cycle value between 25% and 35% is recommended.
- The length of the LED illumination pulse sets the integration (or averaging) time for the thermal image. This is generally in the order of 100 µs.
- The period of the signals applied to the LED and the DUT

The thermal signal, indicating the temperature at the observed location on the DUT rises and falls in accordance with the applied bias pulse. For illustrative purposes the **'Device Temperture'** is shown in Figure 1 to begin rising at the same time as the applied bias pulse. This would be the case for heating at or close to the surface. A delay in the observed heating with respect to the applied bias could be an indication of heating taking place in an underlying layer in a multi-layered device.

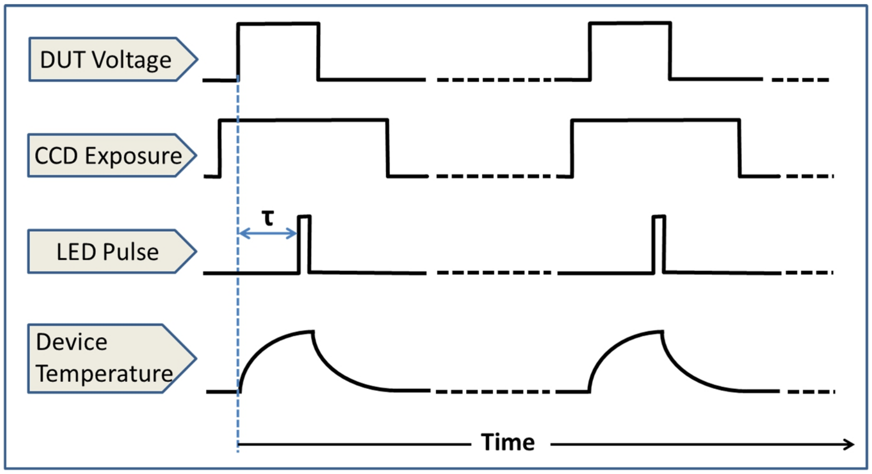

Figure 1: Timing Relationship for Transient Analysis

Time Resolution

Since heat diffusion is a function of time, the time resolution is related to the spatial resolution. If the temperature is known to within 1%, the time resolution can be approximated as follows: [4]

$$\Delta t = \frac{0.02}{\alpha} x^2$$

Where, *x* is the spatial resolution, in mm, and *α* is the thermal diffusivity of the material, in mm^2/s. For pure silicon with a thermal diffusivity of 8.8 m^2/s at 300 K, the time resolution would be approximately 6 ns for a spatial resolution of 5 µm.

Another contributing factor is the integrity of the transmission lines carrying the required high speed signals. A 100 MHz square wave, for example, is required for a pulsing cycle of 10 ns. At these frequencies, impedance matching is important to minimize reflections which could result in a shift in lock-in timing or a change in the bias conditions.

Microsanj offers several thermal imaging systems with transient imaging capability. The typical time resolution for these systems range from less than 1 ns to about 10 µs.

Example: Transient Thermal Imaging of a Logic Integrated Circuit

The following example demonstrates the transient analysis capability with a high speed logic IC as the DUT. The un-encapsulated chip is 1.6 mm x 1.1 mm and 500 mm thick. The chip is wire-bonded for thermal imaging from the top side. The optical image of the chip is shown in Figure 2. Figure 3 shows the resulting thermal intensity map at four different time intervals from 0.5 ms to 3.0 ms after the chip is powered on. The image in Figure 3a shows the left side of the chip heating almost immediately after the applied bias, reaching a peak at about 0.9 ms as shown in Figure 3b. At 0.95 ms, Figure 3c, another region in the upper central portion of the chip starts dissipating power and at 3.0 ms, Figure 3d, the left side of the chip has cooled down and another hot spot is noted in the right central portion of the chip.

Based on the circuit design, the initial heat up on left side of the device is an expected occurrence, while the heating at 3 ms was unexpected and related to a latch-up failure, the location of which is indicated by the circle on the 3D temperature plot shown in Figure 4.

These time-dependent thermal events would have gone undetected without transient thermal analysis. Once detected, it is left to the circuit designer to determine what these events indicate, some may not be harmful to the device performance or reliability and others may lead to an early catastrophic failure.

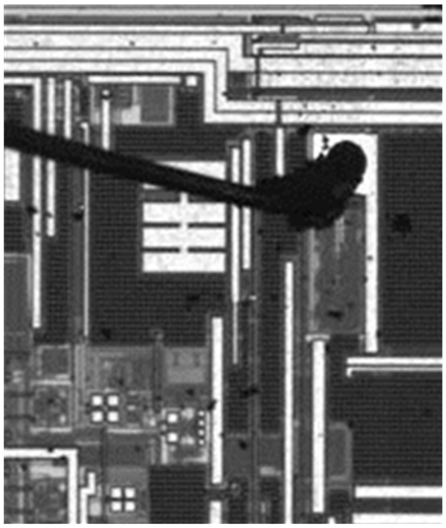

Figure 2: Optical Image of Logic IC (DUT)

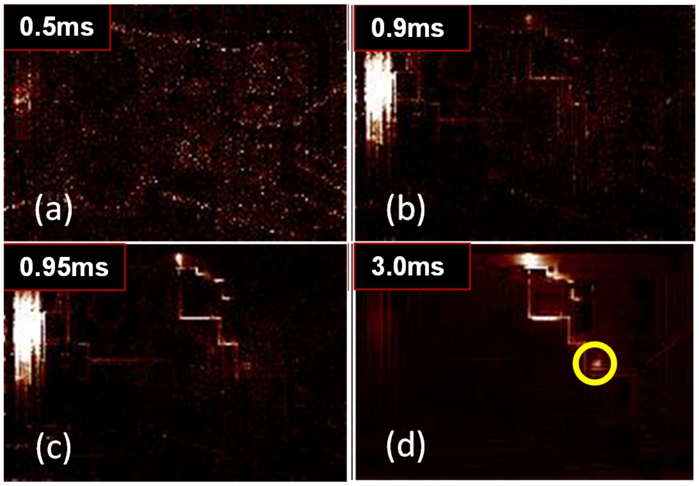

Figure 3: Thermal Intensity Map at 4 Time Intervals

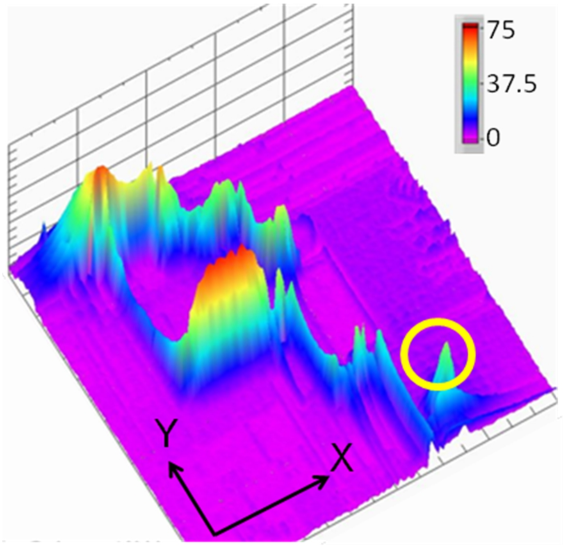

Figure 4: 3D Temperature Map at 3 ms

Conclusion

The analysis and understanding of the time-dependent thermal behavior of today's complex high speed logic integrated circuits can be critically important to ensure optimal performance and long operating life. Combining submicron spatial resolution thermoreflectance thermal imaging with high speed transient capability provides a thermal imaging tool that can provide the information required by the Circuit Designers to achieve the optimal trade-offs between device performance and device reliability. This capability also provides the Manufacturing and Quality Assurance teams with a non-invasive imaging tool to monitor manufacturing processes and weed out potential early device failures.

References

[1] AN-003: Understanding the Thermoreflectance Coefficient
http://www.microsanj.com/application-notes/understanding-thermoreflectan...

[2] AN-005: Detecting Hot-Spots and Other Thermal Defects on a Sub-Micron Scale in Electronic and Optoelectronic Devices
http://www.microsanj.com/application-notes/detecting-hot-spots-and-other-thermal-defects-sub-micron-scale-electronic-and

[3] Understanding the Thermoreflectance Coefficient for High Resolution Thermal Imaging of Microelectronic Devices

http://www.electronics-cooling.com/2013/03/understanding-the-thermoreflectance-coefficient-for-high-resolution-thermal-imaging-of-microelectronic-devices/

[4] Yazawa, K., Kendig. D., Hernandez, D., Maize, K., Alavi, S., and Shakouri, A., “High Speed Transient Thermoreflectance Imaging of Microelectronic Devices and Circuits”, *EDFA Magazine*, Vol. 15, 2013, pp. 12-22.
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