Transient Thermal Measurement and Behavior of Integrated Circuits

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Abstract

Thermal testing of integrated logic circuits (IC), or power electronic devices provides signatures of defects and failure modes in these complex structures where non-uniform temperature distribution and hot spots are generated. By using a lock-in transient thermal imaging technique, we observed the heating history due to a complex startup sequence in a series of 2D temperature maps over time. This is not achievable by conventional IR imaging or liquid crystal thermography. A microscope with 5x objective enabled us to view an area of 2.5 mm x 2.5 mm with 2.4 µm/pixel. We observed a regular powering up sequence of the IC from a cold start. Approximately 30 seconds of averaging (repeating the same sequence) was carried out to improve the temperature resolution and image quality. Depending on the load change in time, the thermal history of the localized hotspots was identified. When the irregular electric signal is detected from a sample, the thermal information in time helps to determine the location of a potential failure even when it is very small. We also demonstrated that the time response information is also applicable to the structural thermal analysis using network identification by deconvolution.

Keywords

thermoreflectance, thermography, transient, thermal identification

1. Introduction

Temperature mapping of today's high-density electronic devices has been a significant challenge for IC chip circuit and layout design, or even power devices. This leads to more and more difficulties in finding a significantly localized high temperature or a time-dependent thermal phenomenon. Such high resolution and transient thermal information is extremely useful for improving reliability or performance. In this paper, we study the thermal behavior in time for two different kinds of devices as examples by using high speed and high spatial resolution thermoreflectance imaging.

Thermoreflectance imaging exploits the change in material reflectivity due to a change in temperature. Transient use of this technique is introduced in [1] and [2]. A linear approximation of this relationship is often used when the temperature variation is small. This technique uses a probing light source to measure this change in reflected light rather than measuring the signal that is being emitted from the device. Because of this, the probing light can be pulsed to measure the temperature at specified time delays with respect to the biasing pulse. The amount that the reflectivity coefficient changes with temperature is called the thermoreflectance coefficient and it is non-zero for most wavelengths, thus visible light can be used to measure the change in reflectance. This increases 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 highly localized peak temperatures of the device under test.

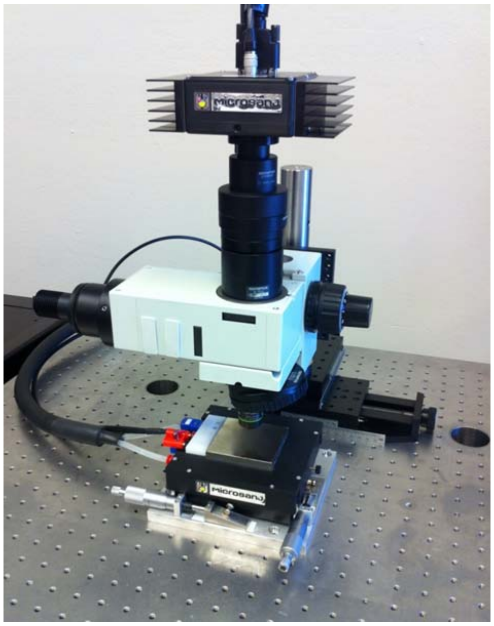
We have adapted a differencing technique to obtain a full field, mega pixel thermal transient for devices. Using this technique we can obtain a series of images showing how the device heating propagates in time. This is different from the lock-in technique that uses a periodic excitation with a 50 % duty cycle. Our current setup can obtain 100 ns time resolution and 800 ps results have been obtained in university research with a pulsed laser [3]. The transient system works by opening the camera shutter and pulsing the light source. The pulsed light source samples the change in temperature of the device at a given delay with respect to the start of the excitation pulse. This thermal transient information is particularly useful as it can show the heat diffusion from microscale hot spots or features in the chip down to the thermal interface material and the substrate.

To determine the thermoreflectance coefficient, we placed the sample on a thermoelectric cooler and modulated the temperature at low frequencies to insure uniform heating on the sample. We used a thermocouple to measure the temperature change of the stage. With this information we could determine the thermoreflectance coefficient for each material on our test device.

2. Time Series Thermal Imaging

The technique is based on lock-in thermoreflectance, which is already commercialized [4]. Synchronizing the exact timing of imaging and device biasing is a key enabling technology [5]. Figure 1 shows the setup for transient thermal imaging. We used the SRS DS345 Function Generator with a current buffer to bias the device with a 3 ms square wave at 10 % duty cycle [6] to supply the pulse to drive the powering circuit for the target IC as well as supply the synchronized pulse to the LED light source as a probe to detect the reflected intensity. By shifting the timing illumination, with a very small delay, the time response signal of the reflection is collected by a CCD imager (1024 pixels x 1024 pixels). A time series of images are averaged for a number of repeated sequences. Finally, a movie can be created with the series of images by the SanjVIEW™ 2.0 software.

a)



b)

Figure 1: a) microscope and optical setup section, b) signal synchronization circuits for illumination, biasing, and imaging as well as data processing component of the equipment, respectively.

3. Imaging Example I – Logic IC

Figure 2 shows the optical image of the example device, which is decapsulated, wire-bonded, and mounted on a PCB board. The size of this Si-based chip is 1.6 mm x 1.1 mm with 500 μm of thickness. We biased this example device through the 8 gold wire-bonded connections to the pad areas as shown in Figure 2. The circuit is initialized, and then we apply a pulse signal to V_{dd} of 0 V – 5.4 V to operate the active portion of interest for temporary extreme conditions. Under these conditions the current is latched until the supply is cycled off and on again.

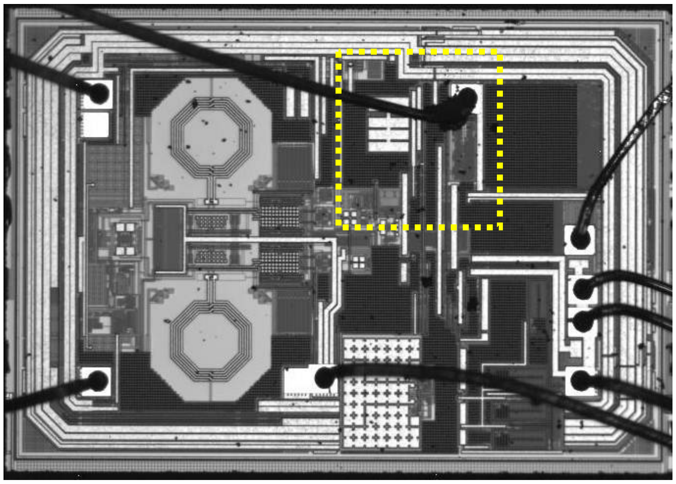


Figure 2: Optical image of the decapsulaed and wire-bonded IC. A yellow rectangular indicates the area of interest, where we zoomed in for thermal imaging.

Figure 3 shows the thermal intensity map in time from 0.5 ms up to 3 ms. At the very beginning a local circuit at the top left corner is quickly heating up. After 1.0 ms, the temperature of the location declines. Then, another circuitry at top center begins heating. Figure 4 shows the intensity map at time 1.2 ms. The vertical axis shows the temperature calibrated by the surface light reflectance coefficient of this IC for a 470 nm wave length.

Figure 5 shows an overlay of the thermal intensity on an optical image of the IC device. In this particular device, a few logic sections located at the lower right undergo latchup and cause 250 mA of current to flow through V_{dd} rather than the typical 10 mA. This large current causes the power path to heat up. This path is clearly visible in the thermal image. Additional measurements with an alternative power configuration confirmed that the bottom right is the location of latchup.

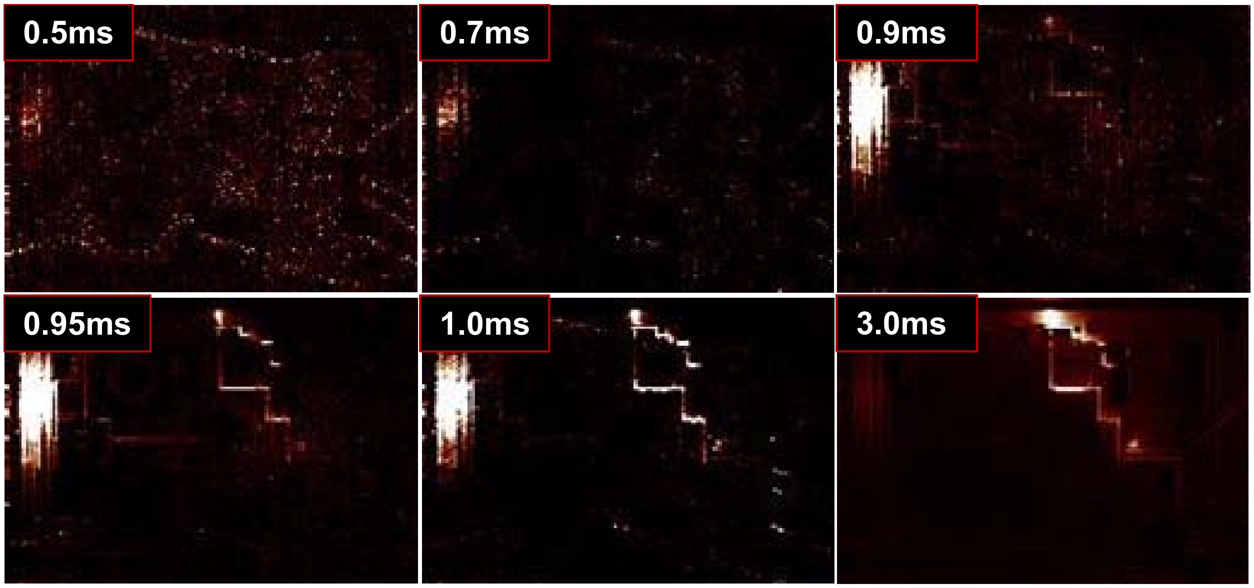


Figure 3: A series of thermal intensity contour maps versus elapsed time after applied bias. The brighter location indicates the higher temperature. The temperature scale is common for all six images. Note that the right side top portion heats up quickly after approximately 1 ms.

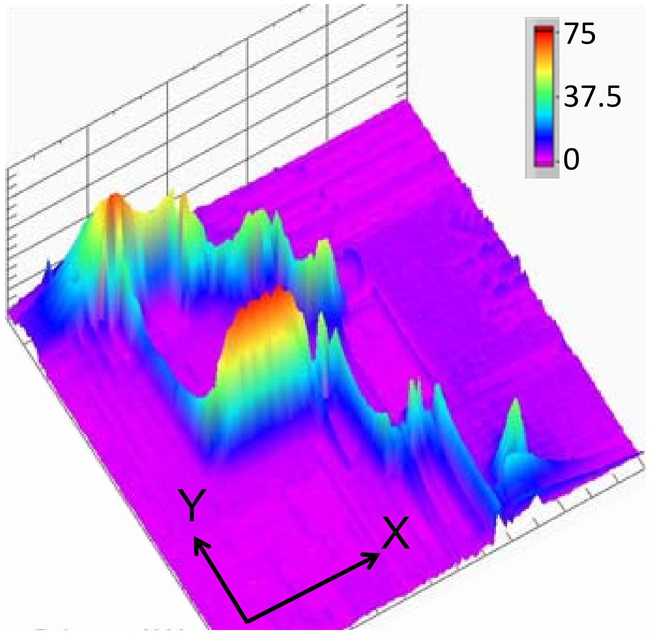


Figure 4: 3-D temperature contour plot zoomed at the right side at a delay of 1.2 ms. Height along Z-axis as well as color scale show the temperature increase.
Heating in the metal traces indicates current flow to the latchup location (see also Figure 5).

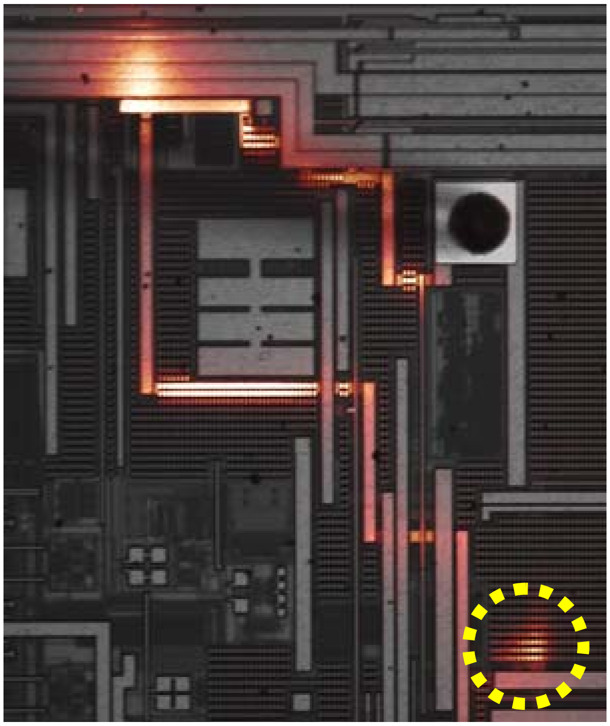


Figure 5: Thermal intensity map over an optical image of the device at 20x as in Figure 4. The location latchup is circled in yellow.

4. Imaging Example II – Power diode

High-speed transient thermal imaging can also give the thermal response of small electronic devices with up to 800 ps temporal resolution [3]. This thermal transient data is used in conjunction with structure function analysis in order to extract 3D heat flow in the device.

The device under test is a 100 µm wide diode with top gold contacts. Thermal image and the intensity overlay on the optical image are shown in Figure 6 a) and b), respectively. The images are measured at 1 ms after the pulsed bias 715 mA is applied to the terminals with probes. Figure 7 shows the mean temperature response (averaged over several repeating cycles) at the marked location of the left contact (anode). This particular image shows the thermal map at $1\text{x}10^{-3}$ s after starting the step power input to the device. Higher temperature is observed in the anode due to the accumulation of charged carriers at the junction, while the opposite terminal (cathode) does not heat up as much. The bow-like shape of the heated region (red in color) is due to the effect of the thermal boundary at the top edge and the bottom edge of the terminal electrode. Even with millisecond time resolution, the transient thermal map looks similar to the steady-state.

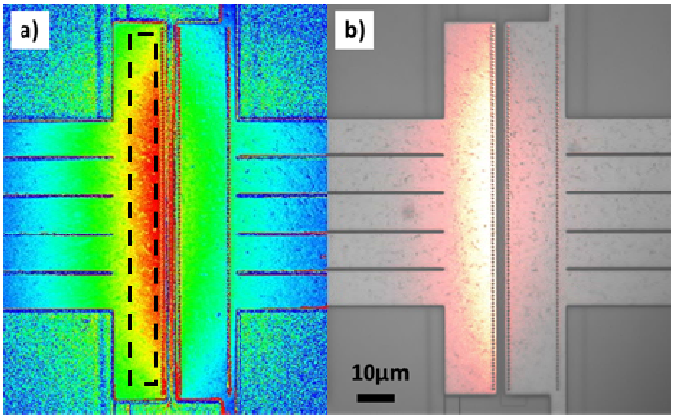


Figure 6: a) Color scaled thermal contour and b) Thermal intensity contour, both on optical image of the power diode device.

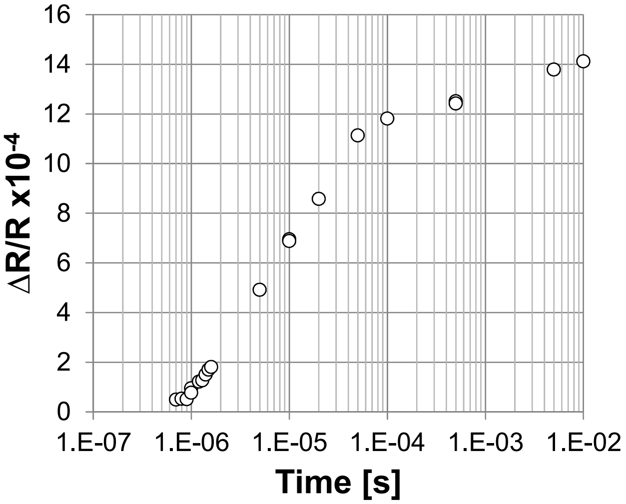


Figure 7: Time response of the relative reflectance change, which linearly correlates to the temperature change. This shows the behavior of the transient thermal response of the diode device.

Thermal network analysis by using network identification by deconvolution and the structure function method [7] is generally applicable for these relatively simple structures. Using T3Ster™[8], the acquired time series data is converted to the analog signal through a D/A converter (Figure 8) and put into the T3Ster system to obtain the differential structure function (Figure 9) and the cumulative structure function (Figure 10) as shown. These are based on the time series of 300 s at the same location as marked in Figure 7. The analysis results show that there are four major thermal resistances in the thermal network and those are; the active device portion of the semiconductor, the interface to the electrode, the electrode pattern, and the thermal path through the substrate to the thermal ground.

The time response function for these microscale devices requires a time resolution ranging from 10^{-8} to 10^{-6} seconds. It is achievable with lock-in thermoreflectance method, but not feasible for conventional IR imaging technique, nor liquid crystal thermography.

Accurate thermal structure analysis function requires even higher time-resolution due to the mathematical process, which is a de-convolution of the time series data [9]. Lock-in technique is important for the data processing not only for a precise timing and time averaging for image quality but also to support further thermal network analysis.

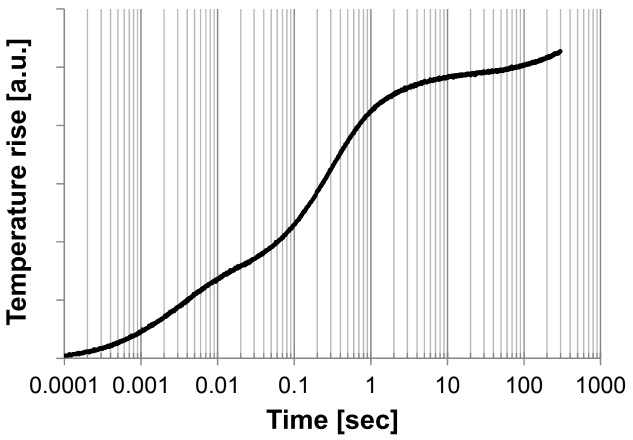


Figure 8: Time response to thermoreflectance. This shows the temperature change in time on auxiliary scale.

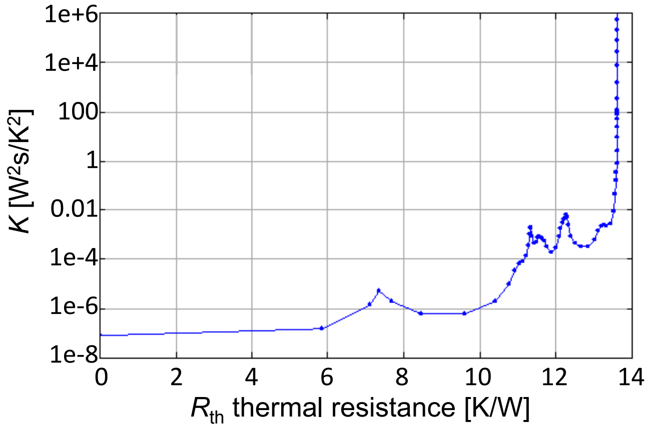


Figure 9: Differential structure function K vs Thermal resistance R_{th}.

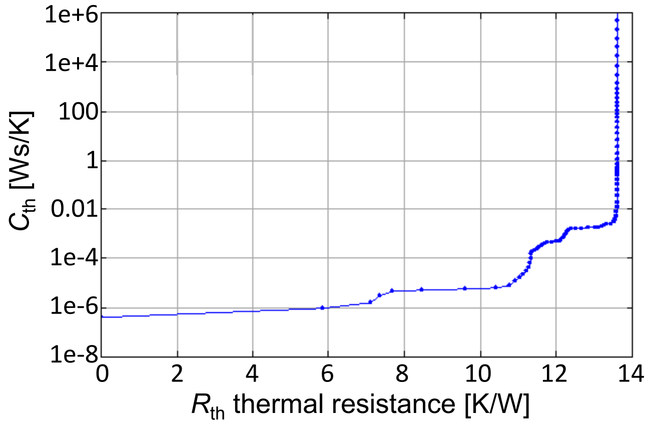


Figure 10: Cumulative structure function C_{th} vs Thermal resistance R_{th}.

5. Conclusions

We have shown that by using transient imaging, we can observe unique transient thermal behaviors of integrated circuits and power devices. This high resolution temperature time response provides information about heating in a small location or a time-dependent effect. Hence, this technique is another way to characterize failure modes in devices. Transient thermal measurements can also provide data that can be used to determine thermal network characteristics of devices with structure function analysis.

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