Transient Thermal Imaging Using Thermoreflectance

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Abstract

Lock-in thermoreflectance imaging has proven effective in obtaining thermal images of active electronic and opto-electronic devices with submicron spatial resolution and 10-50mK temperature resolution. Thermoreflectance systems that use a lock-in method capture the steady state thermal signal but provide limited information about the thermal transient. We present a simple time series thermoreflectance method based on pulsed box-car averaging and a novel differencing technique to obtain transient thermal images with millisecond and microsecond time resolution and submicron spatial resolution. The technique relies on precise adjustment of the phase between the pulsed thermal excitation of the device and the illumination pulse used to measure the thermoreflectance change on the device. The full thermal transient pattern is reconstructed and captured in a charge coupled device (CCD) camera in a matter of minutes. Images are presented of the time evolution of the thermal signals on 40x40, and 100x100 micron square gold heaters.

Keywords

Thermoflectance imaging, transcient, thermal, temperature

1. Introduction

As power management becomes an issue of increasing importance in semiconductor components, greater emphasis is being placed on methods of thermal modeling and characterization. Techniques for high resolution thermal characterization applicable to semiconductor devices typically employ embedded sensors, use coatings, or rely on physical contact with the device under test (DUT). Thermoreflectance imaging is a proven effective non contact, non-destructive thermal characterization method that is based on the very small ($\sim 10^{-4}$) temperature dependence of material reflection coefficients. Temperature resolution to 10-50 mK has been demonstrated using this method [1-8]. Because thermoreflectance imaging uses visible light (e.g. 470nm), submicron spatial resolution is possible. In comparison, thermal imaging with infrared emissivity has a typical diffraction limit of several microns.

2. Differential Thermoreflectance

Absolute (DC) measurement of the thermoreflectance change are not practical because the wavelength and materialdependent thermoreflectance coefficients are not tabulated, and the small magnitude of the coefficient is easily lost in the noise of the imag change are not practical because the wavelength and material dependent thermoreflectance

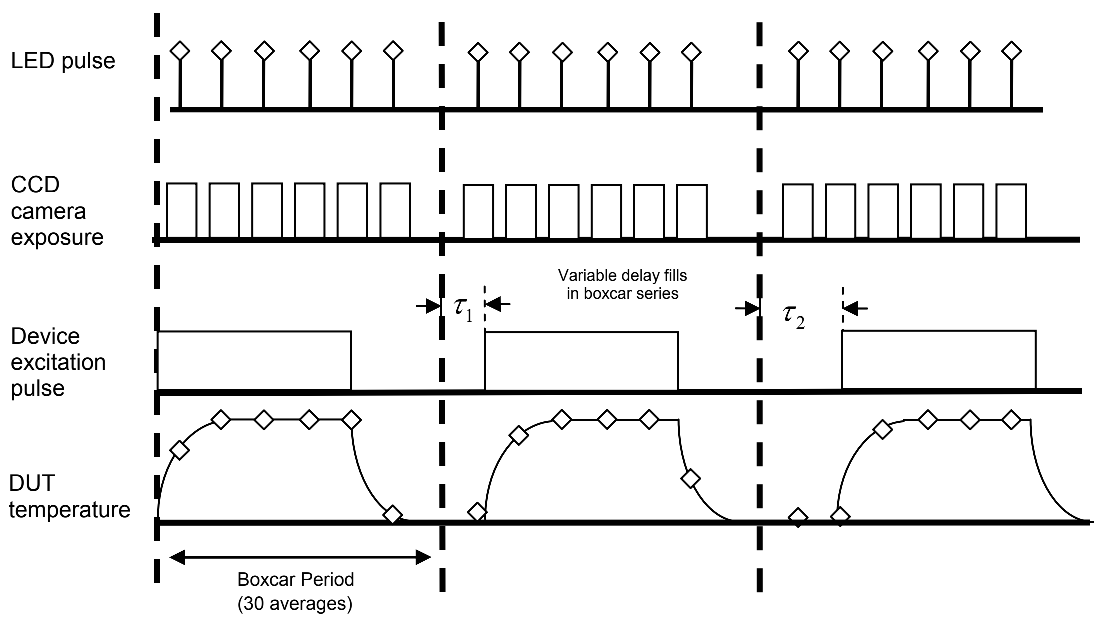

Figure 1: Timing diagram depicting 'pulsed boxcar' averaging scheme

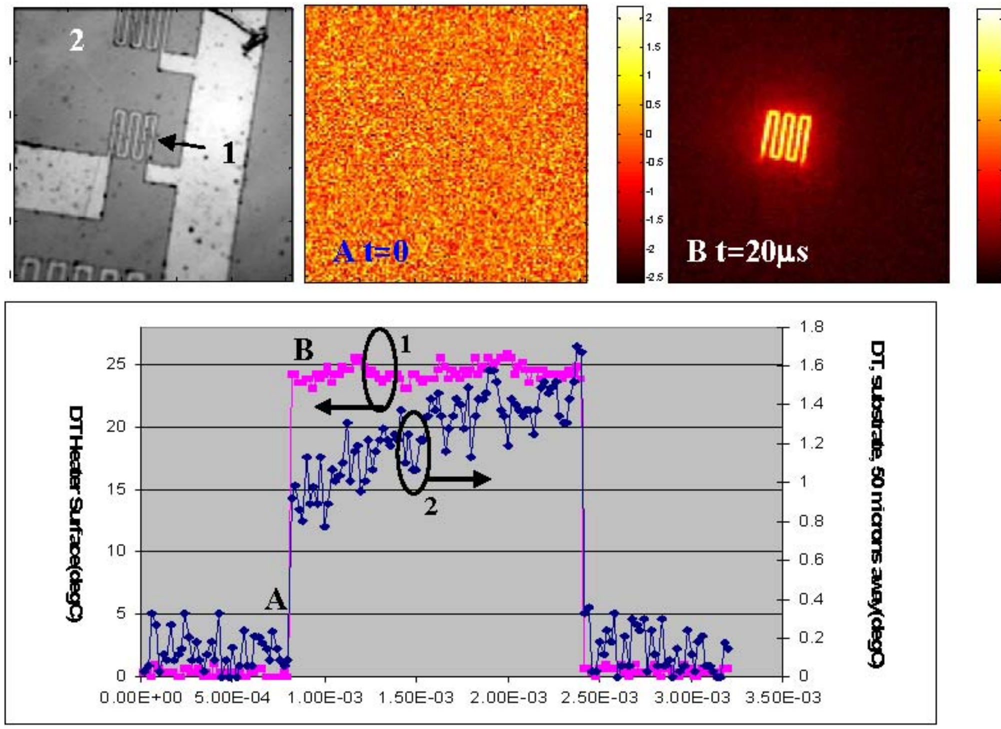

Figure 2: Time series of data point on heater (1), and data point 50 microns away (2) on the substrate. The device metal has faster heat diffusion and achieves uniform heating more rapidly

coefficients are not tabulated, and the small magnitude of the coefficient is easily lost in the noise of the imaging sensor or illumination source.

Consequently, thermoreflectance measurements are usually obtained using a lock-in method with an actively cycled device. Calibration for each material's thermoreflectance coefficient is necessary using an in-situ method [9-11], typically with an external heating source (e.g., micro-peltier device) and sensor (e.g., Micro-thermocouple).We have previously demonstrated that by cycling the device at various frequencies and with the use of [1] a fast fourier tansform (FFT) algorithm operating on a series of frames from a CCD camera, the magnitude and phase information of the thermal signal is obtained with good signal to noise (SNR). Analysis in the frequency domain is used to reduce broadband noise and is a convenient way to extract the small thermoreflectance signal. Although this approach gives accurate thermal images of the steady state heating of an active device, in many situations it is desirable to observe how devices thermally evolve in time. Due to the size of typical electronic and opto-electronic devices, thermal effects can occur on the millisecond to microsecond time scale and faster. Previous work has show that point measurements of the thermal transient are possible using a laser and a fast photodetector [12], and can be combined with a position scanner to obtain transient thermal images [13]. While the signal to noise (SNR) in such systems are impressive, the drawback is the time and expense to obtain the images. We show that by using a pulsed LED and a scientific grade CCD camera, transient thermal images can be acquired ~100 times faster without the need for a laser and scanning translation stage.

3. Pulsed Boxcar Average

By switching from a frequency domain technique to a box-car averaging scheme, it is possible to directly see the time evolution of the thermal signal. In the simplest case, the thermal transient can be found directly when the transient is within the frame rate of the camera. However fast CCD cameras are limited to ~500Hz sampling, thus in order to obtain thermal transient images faster than the frame rate of the camera, it becomes necessary to employ a 'pulsed boxcar technique'. In this technique the boxcar average is combined with a short LED pulse, which is cheaper than a fast (nanosecond) shutter.

Figure 1 shows the general timing for a pulsed boxcar average to obtain the transient thermal image. For each exposure of the CCD there is one LED pulse, effectively reducing the camera exposure to the time duration of the LED pulse width. The figure depicts a boxcar average of 6 frames for each thermal cycle of the device excitation. For the next integration period of the CCD, the phase between the LED pulse and the device excitation is advanced by a small, known amount. Thus, the in-between data points are filled in by combining multiple boxcar averages. Figure 2 shows a thermal time series with a two millisecond heating pulse at 250mA applied to a 40x40 micron square heater. The thermal time series was generated by choosing a pixel within the thermal image and processing across the 160 frames. Shown in the figure are two different regions in the thermal image. On the top of the heater we see that the heater heats rapidly,

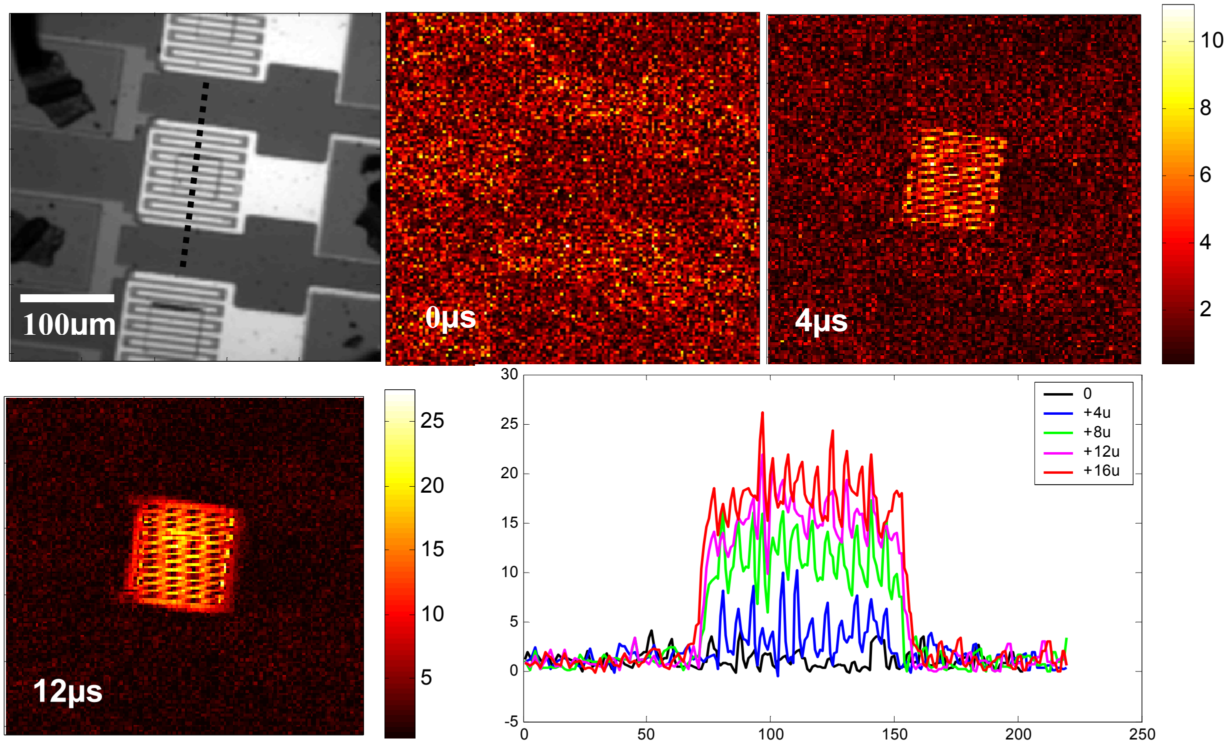

Figure 3: Short timescale response of 100 micron heater showing rapid heat diffusion on the device metal. Thermal cross sections are indicated by the dotted line. Thermal images are in ΔT (degrees C).

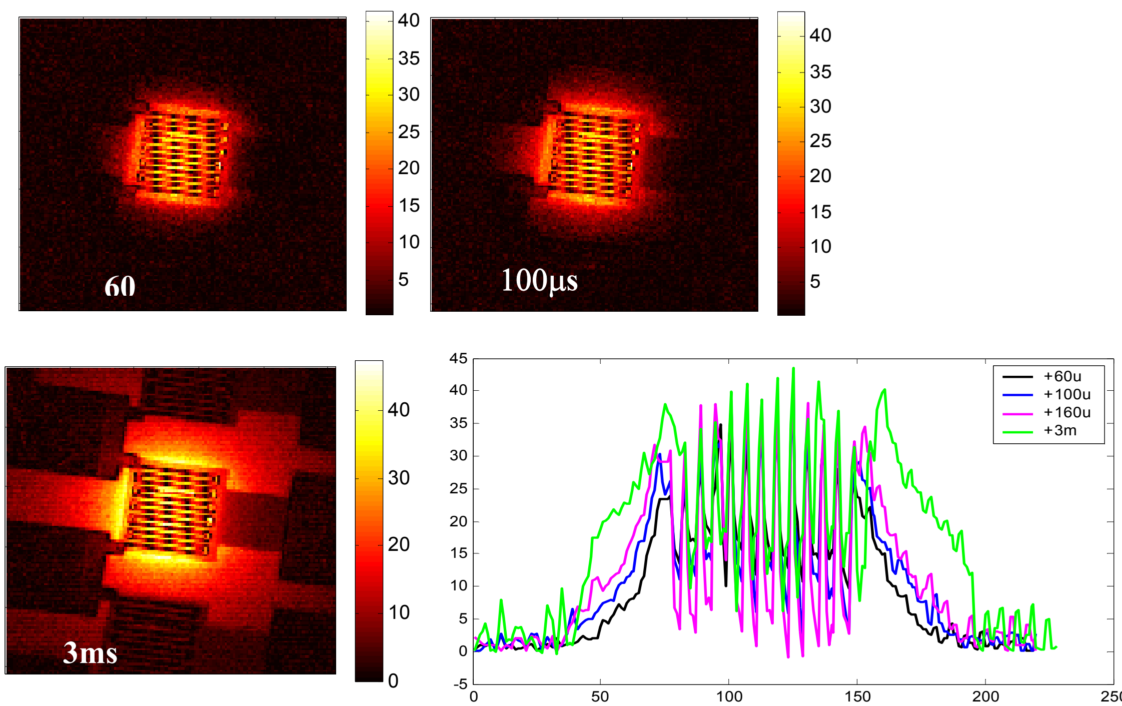

Figure 4: Long time scale (ms) response of 100 micron heater showing slower heat diffusion in the substrate. Thermal images are in ΔT (degrees C).

faster than the 10 microsecond integration time. However a short distance from the heater we see a longer thermal transient. This longer transient is due to slower heat diffusion through the substrate material. Each frame is integrated for ten microseconds and the frames are separated by 20 microseconds.

With our available equipment, the fastest transient image sequences were obtained at intervals of four microseconds. The key limit to time resolution is that with only one LED pulse per frame, reducing the duration of the LED pulse limits the number of photons, and hence SNR, for the thermal images. Figure 3 shows the thermal images acquired at four and 12 microseconds after the heating pulse and thermal cross sections across the heater. On the larger 100x100 micron heater, the cross-sections indicate that heat diffuses faster through the device metal than through the substrate. The result

is that at short time scales we see the device metal uniformly heating in the first 16 microseconds. Thermal images of longer time scales, up to three milliseconds after excitation are shown in Figure 4. Here the cross-sections show heat diffusion in the

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4. Conclusions

We have demonstrated transient thermal imaging with millisecond to microsecond time resolution using a pulsed boxcar averaging technique. Results compare the time evolution of rapid heat diffusion in the device metal to slower diffusion into the substrate. Such thermal images cannot be seen using steady state methods and give important information to design engineers for optimizing the performance of devices. One key advantage of these methods is the measurement time and cost relative to a scanned laser based system.

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