Side-by-side comparison between infrared and thermoreflectance imaging using a thermal test chip with embedded diode temperature sensors

Dustin Kendig[1]*, Kazuaki Yazawa[1], Amy Marconnet[2], Mehdi Asheghi[2] and Ali Shakouri[3]**,
[1]Microsanj LLC, 3287 Kifer Rd, Santa Clara, California 95051, USA
[2]Stanford Microscale Heat Transfer Lab, 450 Serra Mall Stanford, CA 94305–2004, USA
[3]Birck Nanotechnology Center, 1205 W State Street, West Lafayette, IN 47907-2057
*dustin@microsanj.com, **shakouri@purdue.edu

Abstract

A side-by-side comparison between thermoreflectance imaging (TR) and infrared (IR) imaging is made using a specially designed thermal test chip with an embedded diode sensor array. IR thermal imaging is commonly used in industry. However, due to the infrared wavelength and the diffraction limit, IR has limited spatial resolution for chip level thermal characterization. In this paper we compare the spatial, thermal, and temporal resolutions of IR and TR methods and verify the results with integrated diode temperature sensors in the test chip. Thermoreflectance imaging showed higher spatial resolution, temporal resolution, and temperature accuracy on the metal heater. Infrared imaging showed to be less accurate on the metal without any coating to improve the emissivity. The TR measurement on the diode was within 1.7% of the diode reading, while the IR measurement was within 6%.

Keywords

Thermoreflectance, infrared thermography, transient

1. Introduction

Temperature mapping of today's high-density electronic devices has been a grand challenge for chip packaging in electronics design. It is very important to design the chip layout to achieve better temperature uniformity in order to utilize silicon real-estate more efficiently and improve reliability. In this paper, we study the resolution and practical limitation of two widely used techniques, infrared and thermoreflectance imaging. [1-5]

2. Experiment Method

Infrared and thermoreflectance images were obtained for the thermal test chip (TTC) at high and low magnification. Both steady state and transient thermal images were obtained. Transient temperature change gives important information to understand the thermal structure of components in the chip as well as the external contacts.

2.1. Thermal Test Chip

We used a CMOS thermal test chip TTC-1002 with modular design, built for general characterization of the thermally induced phenomena by TEA (Figure 1). Each unit cell of the test chip includes two titanium heaters which cover 86% of the device area and 5 local temperature sensors at the center and various corners. Heaters in each unit cell are individually accessible. The TTC was wire bonded and packaged without any surface treatment for infrared imaging. The thermoreflectance coefficient was calibrated for each material on the surface of the chip.

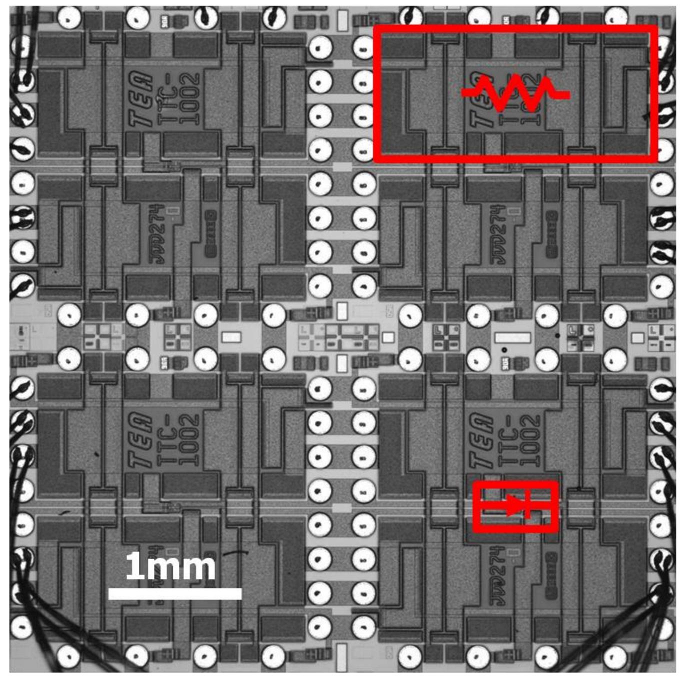

Figure 1: Optical Image of one TTC unit cell with highlighted (red) 7.6Ω heater and diode sensor

2.2. Infrared Imaging

Infrared imaging is a well known and well developed method that is based on blackbody radiation. All physical bodies emit electromagnetic radiation which is governed by Plank's Blackbody Law, which can be simplified to the Stefan Boltzman Law when integrated for all wavelengths. Objects at temperatures around 300K emit radiation in the infrared range which diffraction limits the spatial resolution of the thermal image to 3-10 microns.

How well an object emits this radiation is dependent on the emissivity of the material, which is between 0 and 1. The emissivity for metals and other reflective objects is low, while darker objects that absorb more light are much higher. For example, aluminum can have an emissivity of ~0.04 to 0.07 depending on roughness, while graphite has an emissivity of ~0.45. This difference in emissivity directly relates to the thermal signal coming from the device, and thus the signal to noise ratio (SNR) difference between aluminum and graphite would be ~10x different. Also, since the emissivity of a material is highly surface and material dependent, pixel-by-pixel calibration for each sample must be done for each new sample, even if it is the same material and manufacturing process. If the sample moves during the measurement, sample calibration must be redone. Sample movement such as thermal expansion at high magnifications also can be problematic for devices with many sharp features. For infrared imaging, it is common to coat the sample in a thin layer of material such as graphite to improve the emissivity and thus the signal. Often, surface coating is used in order to avoid feature by feature calibration and easy-to-use.

To improve SNR and temperature resolutions, lock-in thermography (LIT) techniques can be used to average out ambient noise and achieve temperature resolutions of µK with enough averaging. [6] At room temperature, radiation from other objects can give noisy data which reduces the detection limit of the system. To increase the possibility of detecting a small change in temperature, you can place the sample on a thermal stage and raise sample above room temperature. Since the radiation is proportional to the cube of the absolute temperature, a small change in device temperature will produce a much stronger signal at 50 or 60 C compared to room temperature. The ambient radiation of the detector is also an issue for the IR detector. This is remedied by using liquid nitrogen to cool the detector to temperatures where the radiation is negligible.

For measuring transient responses, IR cameras provide very crude resolution that is limited by the video frame rate. Single pixel IR detector can be used to achieve microsecond time resolution.

For this paper we used an older 256x256 pixel IR camera. Please note that there are newer cameras with 512x512 and 1024x1024 pixels, but this does not improve the ultimate spatial resolution of the system. Please also note that the IR system was not used with the lock-in thermography option and thus the temperature resolution/precision is larger. This however is negligible at the high temperatures the images were taken at and the accuracy of the temperature measurement was ultimately determined by the calibration for each material.

2.3. Thermoreflectance Imaging

Thermoreflectance imaging exploits the change in material reflectivity due to a change in temperature. 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 regards to the biasing pulse. This can also be done at cryogenic temperatures since we are not limited by photons emitted by blackbody radiation. 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 more accurate peak temperatures of the device under test.

We have adapted a differencing technique to obtain a full field, mega pixel thermal transient of devices. Using this technique we can obtain a series of images showing how the device heating propagates in time. This is different from the LIT technique that uses an excitation with 50% duty cycle and sine wave approximations of the thermal signal. Our current setup can obtain 100ns time resolution, and 800ps results have been obtained in university research with a pulsed laser. [7] 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 package.

To determine the thermoreflectance coefficient for the TTC, 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 coefficient for each material on our test device.

3. Results and Discussion

We obtained thermal images of the TTC under different bias voltages and magnifications and used the integrated diode sensors as the reference to compare the thermal images to. Point by point emissivity calibration was used for the infrared images. For the TTC sample using a 530nm LED, we obtained a thermoreflectance coefficient of -2.1E-4 for the unpassivated metal heater (grey) and -2.2E-4 for the passivated (dark grey) material on the heater in Figure 1. The current thermoreflectance image processing software allows only two coefficients to be mapped to thermal image at a time, so the TR images in this paper will only be calibrated for the metal heaters.

3.1. Thermal Image Results

Thermal images of the TTC from the different measurements agreed well (Figure 2). Although the test device is designed to be uniform physically, a non-uniform temperature map was observed in all of the measurements. This temperature non-uniformity was measured to have 8% variation when looking at the diode temperature data. The infrared measurements showed a 15% temperature variation between the left and right side, and thermoreflectance measurements showed a 16% difference. The data shown here is a good example of why thermal imaging is important for device design and characterization. The roughness and other device features show in the thermoreflectance images more due to the high pixel count in Figure 2a. Small changes in reflectivity due to the passivation and roughness can be overcome by taking an average over a region of interest

(ROI). For further data analysis, ROIs of the thermal images will be used to reduce error. In Figure 2b we can see in the thermal image where the differences in emissivity show device features similar to the TR images. The graphite coating in Figure 2d gives a uniform emissivity and removes any of the artifacts due to emissivity differences or surface roughness. This is ideal, but then we are slightly altering our device by putting this coating on. The TR image was taken at 29V, while the IR image was taken at 30V. Room temperature was added to TR images to make values absolute values in Celsius.

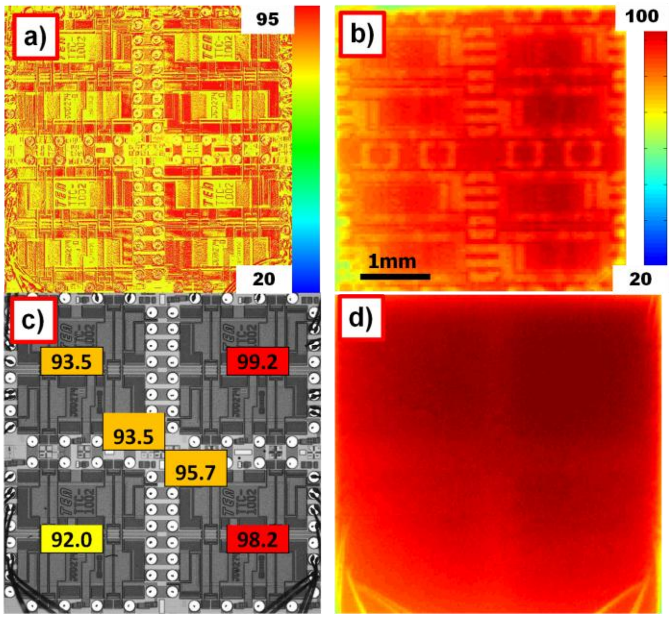

Figure 2: a) TR image calibrated for metal heaters only, b) IR image, c) diode temperature map, d) graphite coated IR thermal image

Thermal image sweeps were taken up to 30V to characterize the accuracy of the measurements. The 30V IR measurement was made at 5x magnification in the specified ROI. The measurements show good correlation overall, with the TR measurement within 1.7% of the diode and the IR measurement within 6%. Some of the error in the IR measurement could be due to the low emissivity of the metal or error due to thermal expansion and sample movement.

The two systems were also tested with a 120µm heater that has been fabricated on top of a microcooler with an insulating oxide layer in-between. This image pushes the spatial resolution limit of the IR system (3µm/pixel). These images also show the difference between a lock-in transient measurement and a DC measurement. With the DC IR thermal image, the heat has time to diffuse to throughout the device structures and substrate. The transient TR measurement is pulsed, thus not allowing the heat to completely propagate throughout the device. This is due to the diffusion length being proportional to $1/\sqrt{f}$. The faster you excite the device, the more localized the heating will be. The TR thermal image shows the 4µm heater lines clearly at 20x magnification (600nm/pixel), however this still does not push the ultimate ~250nm limit of the system.

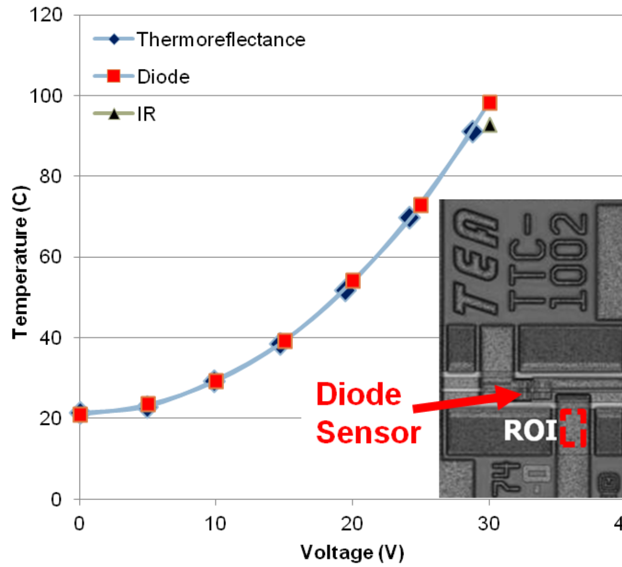

Figure 3: Temperature measurements of ROI next to diode

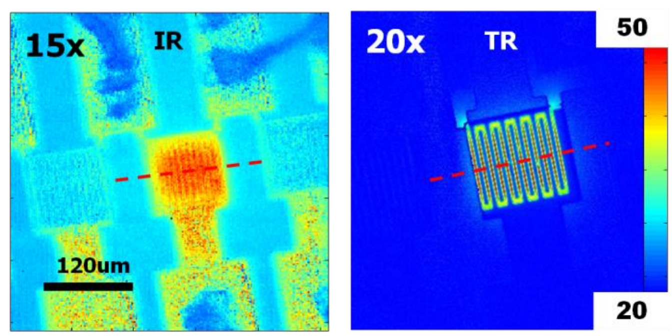

Figure 4: 2V DC IR and 3V/50 µs transient TR measurements of a microheater

3.2. Transient Data

Thermal transient data was obtained with the IR camera at 10Hz (full frame) and TR measurements were made up to 1MHz. IR measurements showed the slow turn on of the TTC which took about 500ms to reach 90% of the peak temperature. A transient TR image sweep was made at shorter time-scales to see how the heat propagated initially. Figure 5 shows that the heat from the heater blocks has not propagated to the substrate or interconnects 100µs after turning the TTC on. This data also shows that at these faster time scales the temperature between each heater is more uniform. There is no longer the 15% temperature gradient across the TTC. This hints that the non-uniformity is not a device issue, but a packaging/heat sinking issue which could be caused by how the die is attached. The thermal transient data in Figure 6 shows the sharp and fast thermal transient on top of the heater (μs regime), while the substrate thermal transient is much slower (ms regime). Heating under 10μs was negligible.

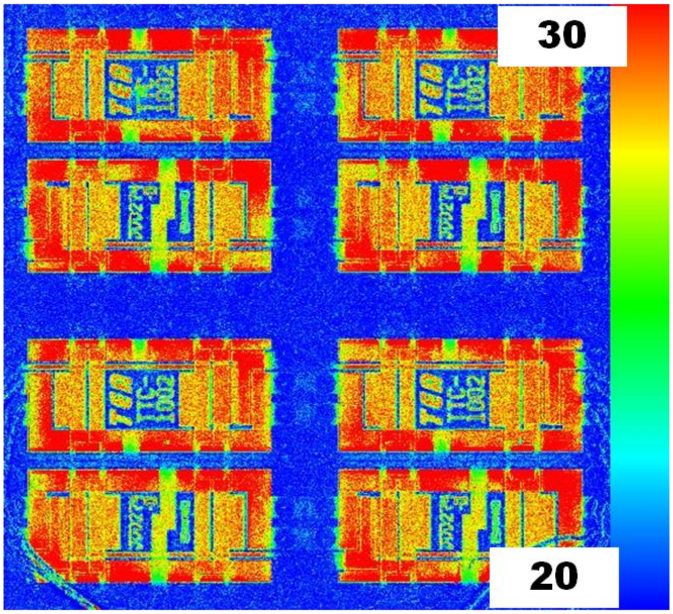

Figure 5: Transient TR image @ 100μs and 60V

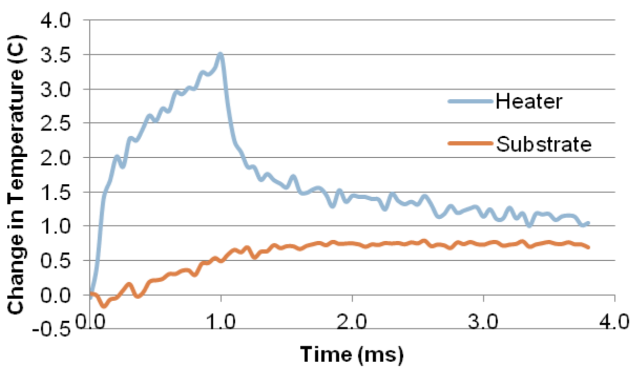

Figure 6: Thermal transient TR data of TTC at 30V, 1ms bias pulse, 10μs/ data point

4. Conclusions

We have shown data that compares infrared and thermoreflectance thermal images and verified results with a thermal test chip with integrated diode temperature sensors. These results showed a temperature gradient across the TTC with the IR data within 6% of the diode value and the TR data within 1.7%. Images of a microheater with 4μm heater lines showed the spatial limitations of IR. Transient TR image series were taken to view the thermal transient of the heater and substrate. These results showed the μs response time of the metal heater, while the substrate responded in the ms regime.

Both measurements had issues with thermal expansion and surface roughness at higher magnifications. The graphite coating on the sample solved this issue for the IR images and made a more uniform and smooth temperature map. Sources of error for the IR measurements could be due to low emissivity of the metal leading to a weaker signal or calibration discrepancies. Error in the thermoreflectance measurement is due to surface roughness/passivation non-uniformities and SNR in the determination of the thermoreflectance coefficient.

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