Thermal Imaging of Electronic and Optoelectronic Devices

Dustin Kendig
Info@microsanj.com

3287 Kifer Road
Santa Clara, CA 95051
+1 (408) 256-1255

Thermal Design Center – Feb 14, 2012

Microsanj LLC

- Incorporated in 2007 with laboratory facility in Silicon Valley
- Microsanj has expertise & measuring tools to identify, & diagnose, thermal problems in submicron devices.
- Microsanj can integrate custom measurement systems to meet your research or manufacturing needs.
- Thermoreflectance-based technology developed in academia in the past ten years
- Microsanj has IPR and licensing agreement with University of California at Santa Cruz
Outline

- Review Thermal Imaging Techniques
- Comparing Techniques: Pros and Cons
- Thermoreflectance Imaging and Analysis
- NT210A System Description and Features
- Specific Analysis Examples & Capabilities
- Thermoreflectance vs. Infrared Imaging
- Summary

Classical thermal imaging techniques

<table>
<thead>
<tr>
<th>Method</th>
<th>Principle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Micro-thermocouple</td>
<td>Seebeck effect</td>
</tr>
<tr>
<td>Infrared Thermography</td>
<td>Planck blackbody emission</td>
</tr>
<tr>
<td>Liquid Crystal Thermography</td>
<td>Crystal phase transitions (change color)</td>
</tr>
</tbody>
</table>
### Advanced thermal imaging techniques

<table>
<thead>
<tr>
<th>Method</th>
<th>Principle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scanning thermal microscopy (SThM)</td>
<td>AFM with thermocouple or Pt thermistor tip</td>
</tr>
<tr>
<td>Optical Interferometry</td>
<td>Thermal Expansion, Michelson type</td>
</tr>
<tr>
<td>Micro Raman</td>
<td>Raman peak position and intensity is function of absolute T</td>
</tr>
<tr>
<td>Near Field Probe (NSOM)</td>
<td>Use near field to improve optical resolution</td>
</tr>
</tbody>
</table>

### Transient thermal imaging techniques

<table>
<thead>
<tr>
<th>Method</th>
<th>Resolution</th>
<th>Imaging?</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>x(μm)</td>
<td>T (K)</td>
<td>t (sec)</td>
</tr>
<tr>
<td>µ thermocouple</td>
<td>50</td>
<td>0.01</td>
<td>0.1-10</td>
</tr>
<tr>
<td>IRThermography</td>
<td>3-10</td>
<td>0.02-1</td>
<td>1μ</td>
</tr>
<tr>
<td>Lockin IR Thermography</td>
<td>3-10</td>
<td>1μ</td>
<td>NA</td>
</tr>
<tr>
<td>Liquid Crystal Thermography</td>
<td>2-5</td>
<td>0.5</td>
<td>100</td>
</tr>
<tr>
<td>Thermo-reflectance</td>
<td>0.3-0.5</td>
<td>0.08</td>
<td>800p-0.1μ</td>
</tr>
<tr>
<td>Optical Interferometry</td>
<td>0.5</td>
<td>100μ</td>
<td>6n-0.1μ</td>
</tr>
<tr>
<td>Micro Raman</td>
<td>0.5</td>
<td>1</td>
<td>10n</td>
</tr>
<tr>
<td>Near Field (NSOM)</td>
<td>0.05</td>
<td>0.1-1</td>
<td>0.1μ</td>
</tr>
<tr>
<td>Scanning thermal microscopy (SThM)</td>
<td>0.05</td>
<td>0.1</td>
<td>10-100μ</td>
</tr>
</tbody>
</table>
THERMOREFLECTANCE IMAGING AND ANALYSIS

Basic Concept

- Trigger at 4f
- LED
- Microscope Objective
- Excitation at f
- Device
Thermoreflectance Characterization of Chip Temperature

By modulating device temperature with precise timing a small change in surface reflectivity due to temperature variation can be detected.

Thermoreflectance coefficient for different surfaces

R and $\frac{\partial R}{\partial T}$ vary sharply due to interference

Spatial selectivity: a few $\mu$m
Spectral resolution: ~1 nm
Sensitivity: $\Delta R/R \sim 3 \times 10^{-5}$ in 1 min

Tessier et al. (2006)
Applications

- Non-invasive surface temperature measurement of electronic & optoelectronic devices
- Thermal design validation of semiconductors
- Microelectronic component analysis & quality control
- Device defect & failure analysis
- Production line testing

NT210A TIA System Diagram

I. CCD Microscopy Head
- Microscope
- CCD Camera
- LED

II. Transient Imaging System
- High Speed Signal Generator
- Thermoreflectance Imaging Module & Biasing (TIM II)
- Computer (SanjVIEW™ 2.0 with Transient Thermal Imager SW Module)
Key Features

- Superior submicron spatial resolution (compared to 5 -10 μm for infrared microscopy)
- Very high temperature resolution (0.1 °C)
- High speed transient imaging
- Through-the-Substrate imaging
- Fully featured user-friendly software package
- Low cost solution
- Use visible light (no IR objectives)

Lock-in Imaging Result

- DC Reflection
- AC Reflection
  - Phase
  - Amplitude
- Mask
  - Identify different materials, cooling/heating regions

Acquisition time: 5 minutes
Through-the-Substrate Imaging

- Top view (visible light)
- Through-the-substrate view (IR light)

Backside Thermal Characterization

- Visible Light reflected from Top Surface
- Near IR Light reflected from Back Surface (metal)

Using near IR light, temperature profile from the backside through silicon is obtained.
Shunt defect along the back scribe line in a solar cell

Find and locate origin of manufacturing defects with sub-micron spatial resolution through encapsulation materials such as glass or plastic.

Verify interconnect and via integrity

Polysilicon via chain shows uniform power dissipation. If single element is causing higher resistance in the chain, it would have higher temperature compared to the other vias.

a) Optical image
b) Thermal image
c) Temperature profile
d) Merged optical/thermal image shows location of heating
SOA of Transistor Arrays

Catastrophic failure at Vds=37 V due to heating on source finger.

NLDMOS transistor array
Pulsed SOA
thermoreflectance: 2.5 ms pulse width, 8% duty, Vg = 2V, Vd = 1 to 50V.

Safe operating areas (SOA) of devices can be used to identify and troubleshoot reliability issues in electronic devices.

Ge/Si p-i-n Waveguide Photodiode

(a) Grayscale image of DUT (7.4 μm channel width)
(b) Thermoreflectance imaging result. Signal from unpassivated Al on p-contacts is below noise floor so these areas should be neglected
(c) COMSOL simulation result
(d) Surface temperature profile

Characterize Optoelectronic devices and verify thermal simulations

M. Piels et al., Proc. of Integrated Photonics Research, Silicon and Nanophotonics (IPRSN), July 2010

Copyright 2012 Microsanj, LLC
High Speed Thermal Imaging (800ps)

Study of heating in submicron interconnect vias

Temperature Change from Ambient

Delay in Nanoseconds


Copyright 2012 Microsanj, LLC

Heating in Electro Static Discharge Devices

Snapback current = 1.22A.

K. Maize, V. Vashchenko et al., IRPS, 2011. Copyright 2012 Microsanj, LLC
Hot-spot defect in Multi-finger MOSFET gate using Thermoreflectance. The hot-spot FWHM is 1.4 μm.

Overlay of optical & thermal image shows precise location of defect on transistor.

Infrared vs. Thermoreflectance Imaging System Comparisons
Overview

Thermoreflectance
- Based on change in reflectivity due to change in temperature
- Calibration required for new materials/processes
- Diffraction limited by 350-850 nm wavelengths for a Si-CCD.
- AC technique where lock-in is required

Infrared
- Based on blackbody radiation
- Point-by-point calibration required due to sample specific emissivity unless coated blackbody-like material.
- Diffraction limited by infrared wavelengths 3-10 μm.
- Silicon is transparent to IR & metals are poor emitters

TTC-1002 Thermal Test Chip
- Resistive Heater block (7.6 Ω)
- The TEA Thermal Test Chip TTC-1002 is based on a unit cell with two resistors and four diode temperature sensors in each cell. The two resistors in each unit cell are laid out to occupy 86% of the available area within the electrical contact pads.
- Diode Sensor
Thermoreflectance & IR Images

Non-uniform heating due to packaging is seen in both Thermoreflectance & IR imaging.

- Similar edge-effect issue at high magnification due to sample movement
- Thermoreflectance images show influence of surface roughness of material. Average calibration coefficient can be obtained for the rough regions
### Calibration Comparison

<table>
<thead>
<tr>
<th>Thermoreflectance</th>
<th>Infrared</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Calibration on temperature controlled stage with thermocouple required for new materials &amp; manufacturing processes.</td>
<td>• For each image, sample must be placed on temperature controlled stage to obtain reference images between room temperature &amp; 40 °C to 60 °C. Must be done for each sample &amp; magnification.</td>
</tr>
<tr>
<td>• Thermoreflectance coefficient is material &amp; wavelength dependent</td>
<td>• Graphite or black paint coating can be used to make surface a near perfect blackbody emitter. Uniform emissivity can then be chosen for the image to eliminate need for constant calibration.</td>
</tr>
</tbody>
</table>

---

### Graphite-Coated IR Images

- Graphite coating significantly improved IR image quality & removed device features & edge-effects.
- Individual heater blocks can be seen more clearly than uncoated sample with device features.

---

Graphite-Coated
Infrared
25 V DC
Diode Temperature Map

Diode sensor temperature measurements were measured at 6 locations. 8% temperature variation was seen across the test chip with the diodes.

Temperature Correlation Between Measurements

- Thermoreflectance & diode measurements within 0.3% of each other, while IR measurement was within 6%.
- Error in IR measurement due to poor emissivity of metal surface & thermal expansion-induced image shift at high magnification.
**Transient Thermoreflectance Image**

- TTC heating in response to a 60 V, 100 µs device pulse.
- In first few milliseconds, heat from resistors has not been transferred to the substrate or other metal layers. *(the blue region in center of the resistor is due to passivation artifact)*
- At shorter time-scales the heating in the device is more uniform suggesting the temperature non-uniformity at DC is due to packaging.

**TTC Transient Response**

- (above) Thermal transient of TTC in response to a 30 V, 1 ms pulse. Note the slow response of the substrate
- (right) Thermal transient of TTC in response to 10 V step function. ~0.5 s for DUT to reach steady state.
High Magnification Comparison

- Performing AC measurement & pulsing the DUT, much more localized peak temperatures can be found since diffusion length is inversely proportional \( \sqrt{f} \).
- Thermoreflectance images show sharp peaks on top of the 4 µm wide heater lines.

Conclusions

- Infrared imaging works well for hot objects (>40 °C)
- Thermoreflectance imaging works well at room temperature since it is not dependent on blackbody radiation
- Infrared measurements of metal surfaces have greater error due to low emissivity
- Thermoreflectance is an active measurement technique that can measure thermal events on a sub-nanosecond time scale.
- Thermoreflectance spatial resolution is ~10x greater than Infrared imaging leading to more accurate peak temperature measurements
Microsanj TIA System Architecture

- Thermoreflectance Image Analyzer (TIA) is based on proprietary & patented technology with surface temperature change measured by detecting change in sample reflectivity.
- TIA system consists of a CCD Microscopy Head, Transient Imaging System, & Biasing Module. LED Module provides Illumination of Device under Test (DUT).
- System provides output trigger to pulse activate DUT and synchronize image acquisition to the on-off states of the device.
- SanjVIEW™ 2.0 SW provides intuitive user interface to view & position DUT, control data acquisition process, & display resulting temperature field.
- SanjANALYZER™ enables data recording & analysis.
System Configurations/Options

- **Nanotherm (NT) Series**
  - 1st Transient Thermoreflectance Imaging solution
  - NT210A
    - 100 ns, 0.25 °C, 250 nm
  - NT50A/100A
    - 10 μsec, 0.5 °C, 3 μm
  - SanjVIEW 2.0 3-D Imager & Analyzer
  - Thermoreflectance Coefficient Analysis Tool (TCAT)
  - Thermal Chuck Solution
    - 20 °C to 150 °C, 100 W, 50 mm x 50 mm service area

- **Helios Series**
  - 1st near infrared (near-IR) emission & Thermoreflectance Imaging solution

---

Microsanj Services & Consulting

**Thermal Imaging**
- Imaging & quantification of spot temperatures on micron-scale devices on a chip, for steady state and/or transient profile.
- Provide method and/or direct work to find short/open circuit defects in your chips/devices.

**Thermal Characterization**
- Characterize effective thermal conductivity of a layer (e.g. thin film) in your chip.
- Characterize thermal conductivity of suspended or embedded micro-features.

**Thermal Design Verification**
- Thermal characterization of packaged devices, e.g. thermal resistance qJC on JEDEC standard & non-JEDEC specific conditions. Small board level also available.

**Thermal Modeling & Validation**
- Modeling & analysis of specific devices in your system, with comprehensive validation using thermal imaging tool to identify future design improvements.