Infrared Thermography application to failure and functional analysis of electron devices and circuits

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Outline

• Introduction and history
• Detection of Infrared Radiation
  – Single point sensors
  – IR Cameras
  – Emissivity calibration
• Measurement Approaches
  – Steady-state and Real-time
  – Lock-in
  – Ultrafast methodologies
• Applications and Results: flexibility
• Conclusions
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1956: The Evaporograph

“Boston: Dr Bruce Billings, is shown with Evaporograph, a device which will take pictures in compete darkness, Once it was closely guarded military secret, now it is audience of the American Research and development.”
Six years later: 1962

• Few years later, from Applied Optics vol.1

Thermal imaging is the process of producing a visible two-dimensional image of a scene by virtue of the differences in radiation reaching the aperture of the imaging device which apparently originate at various parts of the scene. This process depends upon the fundamental property that all bodies at temperatures above absolute zero emit thermal radiation in predictable amounts that depend upon the nature of the surface and its absolute temperature. The radiation actually reaching the imaging device is modified by other factors as will be shown.

G. McDaniel and D. Robinson, “Thermal Imaging by means of the evaporograph”
Rigorous definition of an IR camera

From the same paper...

Any thermal imaging process requires three elements:

1. An optical system which collects radiation reaching the aperture of the device and brings it to a focus to form an image of the scene.

2. A transducer which absorbs the radiation so focussed, thereby undergoing some change in its characteristics.

3. A presentation system which forms a visible image from the changes in the transducer characteristics and thus enables the eye to “see” the thermal image.
The experimental setup

Fig. 1. Simplified schematic diagram of Evaporograph.

Fig. 6 Model KR-1 Evaporograph.
The first thermal images

Fig. 8. Evaporograph image of a girl holding a glass of cold water.

Fig. 9. Evaporograph image of a seated man afflicted with phlebitis of the left leg.
Today

• Commercial distribution of IR cameras has boomed after the 9/11 attacks for rescuing purposes (fire brigades, FEMA). Application nowadays include: heating efficiency, cabling inspection etc.

• Application of IR investigation to electron devices and circuits has become popular in the 80s and has gained an increasing attention as faster and more accurate sensors have been made available
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Single Point setups

• IR detectors (bolometers, semiconductor sensors typically II-VI compounds) are commonly used as single point temperature sensors.
• The most common setups are referred as radiometers. Commercial equipment (i.e. Barnes) was available since the early 70s.
• The small size of the active area and the easy analog readout of the signal allows for efficient cooling and low parasitic capacitance -> larger bandwidth
• Temperature distribution over a wide area can be (slowly) reconstructed by mechanical scanning of the sensor (device) position
Schematic example

A single point radiometer is usually setup as a **microscope**.

The microscope objective has to be chosen to be efficient in the wavelength spectrum of interest.

Usually metallic lenses are used in **Cassegrain** or **Swartzschild** double-reflector arrangements.

Stacked Peltier (preferred to liquid N) **cooling** is used to keep the sensor at a fixed temperature to minimize its noise figure.
Camera-based setups

• In order to **overcome the drawbacks** (speed, alignment of pixels) of the raster scanning, IR cameras are nowadays preferred to single point sensors.

• Arrays of IR detectors (as CMOS detectors are used in VIS cameras) are used, arranged in Focal Plane Array (FPA) configuration. More than 1Mpixel cameras are available.

• A full thermal image can be taken as a **snapshot** with minimum temperature resolution in the mKs range.

• The speed of the readout circuit (ROIC) limits the single frame integration time in the **microsecond** scale.

• Cooling of the entire FPA is achieved by means of an **Stirling cooler** integrated within the sensor.
A general IR setup
IR camera setups

Setup for device/circuit characterization

Karl Suss PM5 probe station equipped with an IR camera
Emissivity calibration

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Room temperature IR image of a GaAs-HPA. Brighter areas have higher emissivity while metal presents very low value of this parameter and appears as a darker area. The entire device is at the same temperature.
Emissivity calibration

- The radiometric signal (single-point or image) cannot be scaled to absolute temperature if the *emissivity* of the material is unknown.

- Emissivity of different materials (nitrides, polymmides, metals) is *unfortunately* *temperature dependent*.

- Black painting is **not** a good choice if transient measurements have to be performed as *the coating changes the thermal behavior* of the device/circuit. Moreover some black coatings (i.e. graphites) are *transparent* in the IR region of interest.

- Pixel-by-pixel **offline passive calibration** is mandatory for calibrated measurements.
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Steady-state thermography

- In steady-state (DC) thermography the heat generation is **constant** or is **pulsed** but the device/circuit under test is allowed to reach its stable regime. By varying the duty-cycle the average power can be modulated.
In transient thermography the temperature is recorded along the temperature variation. This can be done within the \textbf{maximum frame-rate} of the camera. Cameras with frame-rate exceeding 1KHz (full frame) are actually on the market.

Usually temperature transients on electron devices are much faster so \textit{real time sampling is not possible}
Equivalent-Time thermography

- With **fast semiconductor sensor** based cameras the experiment can be sampled one time per period.

- If the subsequent frame is taken with some delay with respect to the previous one, a faster thermal transient can be reconstructed using the well-know **equivalent-time sampling** approach.

- The equivalent frame-rate can be in the MHZ range, limited by the inverse of the **minimum integration time** of the sensors (200-400ns).

Timing and delays

In order to guarantee a **correct temporal alignment** of subsequent frames, timing of the synchronization circuit has to be controlled in the ns range, with virtually negligible jitter.

To this purpose, high-end signal generators or customly designed timing circuits have to be used. They are commonly based on FPGAs.
In Lock-In thermography the heat generation occurs periodically at a certain *lock-in* frequency. For correct sampling of the thermal signal, the lock-in frequency has to be much lower than the frame rate of the camera.

Oscillating electrical power introduction → Device under test → Surface emission temperature
Lock-in thermography (II)

Synchronous **heterodyne demodulation** is applied (hardware or numerically) to retrieve the amplitude and phase of the lock-in signal.

One of the main features of lock-in approach is the **increase of S/N ratio**. In fact sensitivity below 0.1mK can be obtained at the expense of longer acquisition time.
Deconvolution of the source

The shape of the current source can be blurred due to heat diffusion during lock in experiments. **Numerical deconvolution techniques** can be applied in signal post-processing to retrieve the exact shape of the heat source.

![Before numerical deconvolution](image1.png)

![After numerical deconvolution](image2.png)
Lock-in & emissivity

As the phase signal is evaluated through the ratio between the in-phase and out-of-phase signals, it is inherently free from the emissivity contrast problem as both S0 and S90 are affected in a multiplicative way by the e(x,y,T) of the material.
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Fields of application

Dissipated Heat [W]

mW kW

nm Scale cm

Power Devices in S/C
Power Devices in Avalanche

RF HPA

Power Devices FA

Solar Cells

VLSI

Organic
HPA for radar application

- Driver and output stage of a GaAs HPA used for radar applications is here reported during pulsed power operation.
- The steady-state temperature distribution allows for a correct characterization of the thermal impedance of the device.
- This parameter is of paramount importance for the design of the cooling system.
Solar cells characterization

• The investigation of any cause of **loss of solar cells efficiency** has been among the first successful application of IR Thermography.

• **Defect locations** and **shunts** can be efficiently identified by IR imaging

• After the pioneering works of O.Breitenstein and coworkers, lock-in thermography is a well established characterization tool in most of the research labs in the field of photovoltaics
Current crowding

• The current crowding close to front contact fingers can be characterized using lock-in thermography

• The result can be used to optimize front contact geometry in order to achieve higher fill-factor and efficiency
An other example of investigation of causes of efficiency losses in concentration solar cells
Organic devices

- One of the main issues in the developments of organic devices (oFETs) is the achievement of uniform current distribution over the device area.
- This information is crucial for model calibration (i.e. mobility evaluation)
- Lock-in thermography can be applied to detect sub-mmA current flow
6-Tiophene FET

\[
I_D = \begin{cases} 
\mu \frac{\varepsilon_0 \varepsilon_r}{t_{ox}} \frac{W}{L} V_{DS} \left( V_{GS} - V_{TH} - \frac{V_{DS}}{2} \right) & |V_{GS} - V_{TH}| > |V_{DS}| \\
\mu \frac{\varepsilon_0 \varepsilon_r}{t_{ox}} \frac{W}{2L} (V_{GS} - V_{TH})^2 & |V_{GS} - V_{TH}| < |V_{DS}| 
\end{cases}
\]
VLSI devices

• The operation of VLSI circuits can be characterized only using the lock-in approach as the power dissipation is usually very low

• The synchronization can be successfully achieved by pulsing (or modulating) the VDD power supply

• To get additional information, repetitive operations can be performed and detected (i.e. READ/WRITE cycles on a memory chip)

• This can be achieved by low-level programming of the commonly used test benches (Kalos etc.) to synchronize them to the IR camera
Periodic Programming

Programming Frequency

- **4Hz frequency**

![Diagram showing periodic programming with functional and idle intervals, and a single-operation interval (t_{OP})](image-url)
Read 1 page / 1 block

- **READ (1)**
  - bytes: 2090
  - pages: 1
  - blocks: 1
Read 10 Pages/1 Block

- **READ (2)**
  - bytes: 2021
  - pages: 10
  - blocks: 1
Read 64 Pages/1 Block

- **READ (3)**
  - bytes: 2012
  - pages: 64
  - blocks: 1
Comparison

• By simply changing the number of pages it is possible to trigger the operation of different part of the circuits
Power Devices
characterization and FA

• One of the more recent application of IR thermography as a characterization tool is in the field of power devices
• The very high electro-thermal stress allows for easy detection of the temperature gradients across the device
• Unfortunately given the speed of the thermal transients, ultrafast detection is needed.
Smart power short-circuit

- During the **short-circuit phase** the device experiences very fast temperature rises.
- Equivalent time sampling is here used to perform ultrafast temperature characterization during **the SC protection phase** on a SMART-Power switch used for automotive application.
- The **calibration** of FEM simulation can lead to optimization of device layout (i.e. bondwire position) to improve long term reliability.
Avalanche operation: The UIS test

The **UIS test** is one of the most important characterization tool used in the power devices reliability/ruggedness research. It consists of loading and inductor and forcing it to discharge into the power device which enters the avalanche multiplication regime.

![ UIS test schematic diagram ]
Moving filaments in IGBTs

Non uniform current distribution during avalanche of power devices is recognized as one of the major causes of **reliability reduction**

Ultrafast thermography allows for the **exact determination** of the location of **current filaments** and the investigation of possible **device weakness**
Modified UIS test: using lock-in

The idea is to repeat periodically the transient UIS test and detect the temperature distribution in lock-in mode. To observe only few µs of the initial UIS transient, we operate a modified UIS test:
Modified UIS test

The experimental setup consists of a modified UIS tester and a lock-in thermography systems. The tester, differs from the standard one for the presence of a parallel and a series switches.
Electrical Measurements
Thermal Measurements

The thermal image clearly shows that during the time interval $\Delta t_1$, before the voltage drop, the current is **uniformly distributed** over the termination area. This shows a **well balanced termination** structure.
The thermal image with the protection activation after $\Delta t_2$ – i.e. after the voltage drop – shows that the current is now **concentrated in a small area** in the active device.
Failure localization

Failure during UIS test is detected as an abrupt drop of the VCE voltage.

- Lock-in thermography can be used to determine the exact location of the device failure without the need of ad-hoc sample preparation.
a) Drain current at different $V_{DS}$ with $V_{GS} = 19$ V; b) Drain current at different $V_{GS}$ values with $V_{DS} = 100$ V.

Temperature maps (scale in degree Celsius) at the end of short-circuit experiments for different gate voltages:

a) $V_{GS} = 10$ V, b) $V_{GS} = 12$ V, c) $V_{GS} = 15$ V, d) $V_{GS} = 18$ V.
SC TEST on SiC Power MOSFET (2/2)

Temperature distribution (scale in degree Celsius) during the short-circuit test: a) t = 100 µs, b) t = 200 µs, c) t = 300 µs, d) t = 400 µs.

Comparison between the elaborated IR temperature map and the failed device. The failure side is located in the top right corner on the source pad.
UIS TEST on SiC Power MOSFET

SiC MOS UIS Waveforms - 100 V - 3.6 mH

Drain Current [A]

Drain Voltage [V]

Time [us]
Previous measures in SC
Previous measures in SC (shunt)
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Conclusions

• Infrared Thermography is now a well established characterization tool

• This technique can be successfully applied to many of electronic devices and circuits characterization, from VLSI to cm-scale devices

• **Functional Information** as current distribution or defect locations can be retrieved

• **Failure inspection** on broken devices is feasible without the need of time and budget consuming sample preparation processes
In 1962 the following applications or IR imaging were foreseen:

1. Nondestructive testing of bonds and other joints.
2. Thermal studies of process equipment, such as heat exchangers.
3. Wind tunnel temperature observation.
4. Observation of electronic assemblies to locate hot spots.
5. Observation of in-service blast furnaces to locate dangerously thin areas in the furnace lining or the formation of scabs within.
6. Observation of high power switch gear and power distribution systems to locate faulty joints or contacts before actual burnout occurs.
Thank you for your attention!