

## INFRARED THERMOGRAPHY APPLIED TO POWER ELECTRON DEVICES INVESTIGATION

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**Abstract.** *The aim of this paper is to give a presentation of the principal applications of Infrared Thermography for analysis and testing of electronic devices. Even though experimental characterization could be carried out on almost any electronic devices and circuits, here IR Thermography for investigation of power semiconductor devices is presented. Different examples of functional and failure analysis in both transient and lock-in modes will be reported.*

**Key words:** *Infrared Thermography, thermal measurement, power device, Lock-in Thermography*

### 1. INTRODUCTION

As it is well known, Infrared Thermography systems are widely used in several engineering fields as a powerful investigation tool, thanks to their many attractive features. Among all possible applications, the analysis of the operation of electronic devices and circuits is of particular interest. Specifically, non-destructive contactless testing of electronic components, circuits, semiconductor devices, solar cells, ICs, etc., is possible [1-3].

Thanks to the commercial availability of fast, high-sensitivity infrared sensors 2D-arrays, which have completely replaced single sensor systems, nowadays many different IR cameras can be used to monitor temperature distribution across a semiconductor device.

Temperature gradient might arise during devices operation, because heat is generated, according to Joule's effect, due to current flowing within it. Gathering information on temperature maps can be, for example, used for complete thermal characterization and functional analysis of semiconductor components. Application of IR technique to monitoring such situations has been extensively reported in literature (e.g. [4-8]), showing its flexibility and usefulness.

In this paper, attention will be focused on employing Infrared Thermography analysis for the investigation of power semiconductor devices. Electron devices for high power

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applications usually have to operate in harsh environments and conditions. For this reason, in recent years, power devices performances and reliability have become a major concern for industry and research, where the development has focused on increasing ruggedness.

In the next section, basic concepts of IR Thermography will be briefly recalled for readers' convenience. After that, fundamental applications of this technique applied to power devices will be reported.

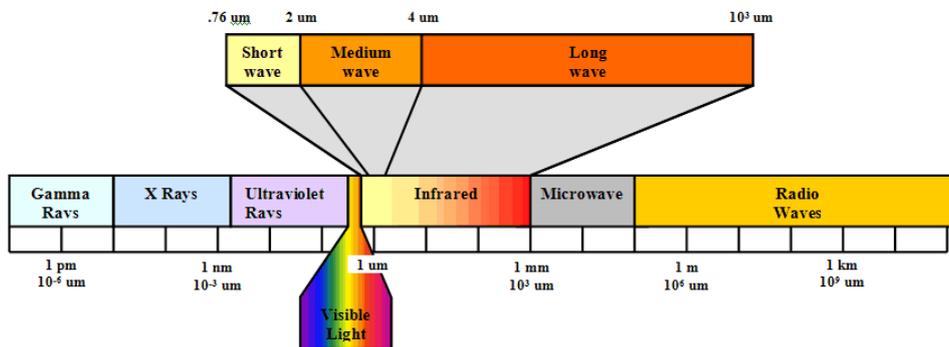
## 2. INFRARED EMISSION

Electromagnetic radiation is emitted by any object at a given temperature  $T$  different from zero Kelvin, whose amount of energy, called spectral radiance, is described by Planck's law:

$$W(\lambda, T) = \varepsilon(T) \frac{2\pi hc^3}{\lambda^5 \left( e^{\frac{hc}{\lambda kT}} - 1 \right)} \quad (1)$$

where  $h$  is the Planck constant,  $k$  is the Boltzmann constant,  $c$  is the speed of light,  $\lambda$  is the wavelength of the emitted radiation, and  $\varepsilon$  is the emissivity of the body depending on material and temperature (with  $0 < \varepsilon < 1$ ). The emissivity takes into account that any real object differs from ideal black body (i.e. it emits less energy).

The range of infrared wavelengths used in thermography is generally located between about  $1\mu\text{m}$  and  $10\mu\text{m}$ , usually indicated as *thermal infrared*, even though longer wavelengths might be employed. The majority of IR sensors are designed to detect radiation in these ranges and convert it into a digital signal, making it possible to measure the surface temperature of any object. The choice of the IR camera is imposed by the trade-off between sensor sensitivity and speed: faster sensors are the only choice if rapid thermal transients have to be detected. On the other hand, more accurate steady-state temperature values can be obtained with high-sensitivity sensors.



**Fig. 1** The electromagnetic spectrum.

### 3. IR ANALYSIS

In this section a review of IR Thermography applied to different analyses of power devices is presented, also with reporting several examples. Detection of steady-state temperature distribution is one of the basic tests that can be done, but it is of lesser interest in the study of power devices for which transient and lock-in inspection are preferred. As stated above, ruggedness of power devices is widely investigated and studied to gain better understanding of the phenomena that limit their reliability [9-10]. To this purpose, temperature maps allow to point out some useful information on device behaviour because of temperature that is directly related to current distribution within the device itself. Through IR thermography a complete thermal characterization can be obtained, and some unusual working conditions can be examined, such as hot-spots or non-uniform current spreading.

It has to be stated that one main issue to deal with in order to have temperature-calibrated images, that is to have quantitative evaluation of temperature, is the contrast in emissivity for materials on top surfaces of electronic devices. Moreover, the emissivity has a temperature dependence that cannot be neglected, especially when large thermal excursions are experienced.

Several compensation techniques have been proposed, including black painting of device top surface but this is not a reliable solution because the thermal response of the device is modified by this additional layer. The most accurate and robust approach is the off-line calibration of the thermal images by passive heating of the device and subsequent evaluation of emissivity map. This emissivity map can be used to transform the IR radiation map into a correct temperature map of the surface under test.

#### 3.1. Transient Thermography

Power devices might experience large temperature variations due to high power densities involved during their operation (e.g. if avalanche breakdown occurs). There is therefore the need to detect their heating/cooling transients to accurately monitor device behaviour. Unfortunately, modern IR cameras usually have an acquisition rate that hardly exceed some hundreds of Hz at full frame, because the read-out time to process the signal from the sensors array is still high. This of course, is a great limitation in the detection of thermal dynamics which are in the  $\mu\text{s}$  time scale. Higher acquisition frequency can be obtained if an equivalent time sampling method is used. With this approach the attainable maximum frame rate is theoretically limited only by the minimum integration time, which usually is  $1\mu\text{s}$ , or smaller, for state-of-art IR sensors. In this way equivalent sampling frequency of 1MHz can be easily achieved [11]. The only restriction to the use of this method is that the experiment to be observed must be periodically repeated, and a precise synchronization of all signals has to be ensured.

Fig. 2 reports temperature distribution of an IGBT during transient avalanche condition, in subsequent time instants  $5\mu\text{s}$  spaced. Non uniformity in current distribution and motion of current flow across the entire device area are spotted out.

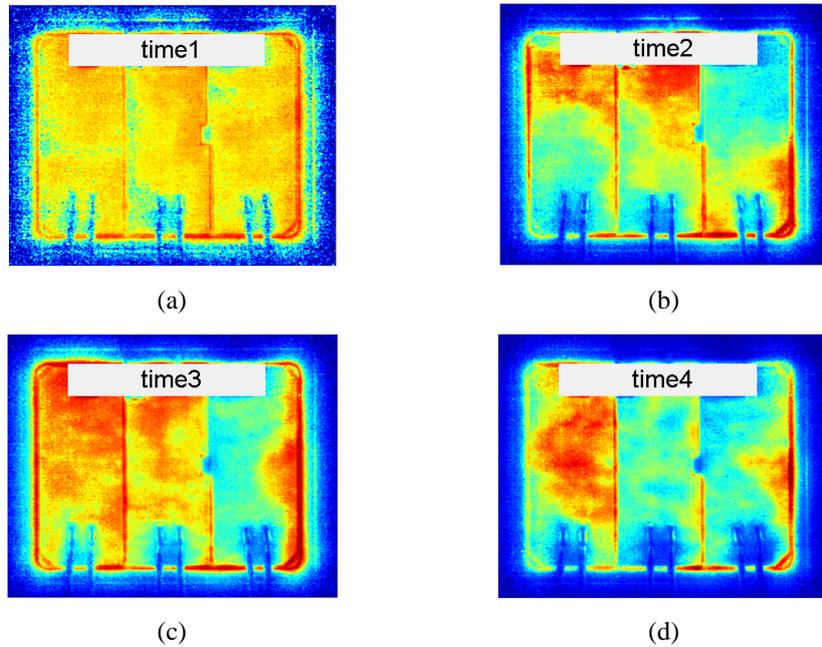


Fig. 2 Transient temperature maps during avalanche condition.

### 3.2 Lock-in Thermography

Lock-in technique [12-14] is generally used during temperature variation, or in other terms, the current flow is so low such that it is not possible to detect the signal with an acceptable signal to noise ratio.

The device heating is synchronously detected with a heterodyne demodulation method schematically reported in Fig.3.

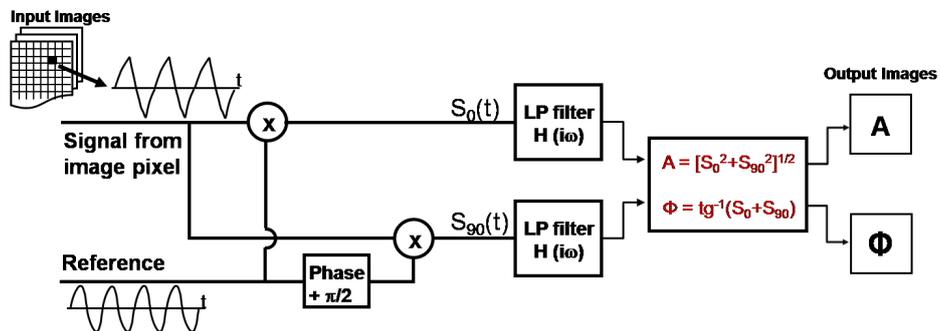


Fig. 3 Schematic representation of lock-in technique[13].

The basic principle is to amplitude-modulate the signal to detect, in this context the temperature, at a specified frequency  $f_{lock-in}$ . The IR images returned by the camera are multiplied by two weighting sinusoidal functions in quadrature. Amplitude and phase maps are subsequently obtained by low pass filtering, so that the noise falling outside this frequency is averaged out. Numerical filtering can be performed real-time with an appropriate software, allowing a temperature resolution less than  $100\mu\text{K}$  for most of state-of-art IR cameras.

For a lock-in detection approach the temperature of the device under test (DUT) is modulated by external biasing at the lock-in frequency  $f_{lock-in}$ :

$$S(x, y, t) = T_0(x, y) + A(x, y)\cos[2\pi f_{lock-in}t + \phi(x, y)] + n(x, y, t) \quad (2)$$

where  $T_0(x, y)$  is the initial temperature on chip and  $n(x, y)$  takes into account all the noise components.

After an integration of the sensor output for an acquisition time  $t_{acq} \gg 1/f_{lock-in}$  (i.e. if a reasonable number of periods are averaged), the in-phase and quadrature components can be obtained:

$$S_0(x, y) = A(x, y)\cos[\phi(x, y)] \quad (3a)$$

$$S_{90}(x, y) = A(x, y)\sin[\phi(x, y)] \quad (3b)$$

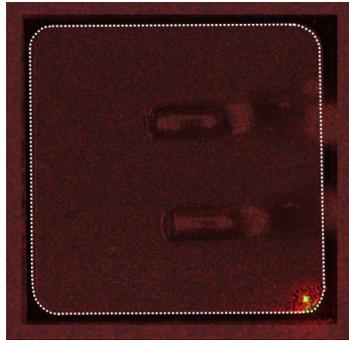
From (3) it is easy to calculate amplitude and phase of the lock-in signal as follows:

$$A(x, y) = \sqrt{S_0(x, y)^2 + S_{90}(x, y)^2} \quad (4a)$$

$$\phi(x, y) = \tan^{-1}\left(\frac{S_0(x, y)}{S_{90}(x, y)}\right) \quad (4b)$$

from which useful information on heat distribution and spreading can be obtained. It is important to note that emissivity contrast does not affect phase signal.

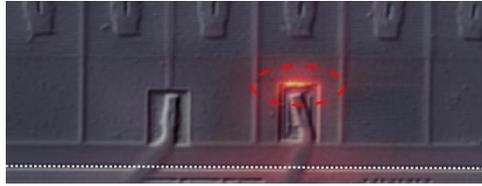
In the characterization of power devices, lock-in thermography is usually used to investigate the location where device breaks after a failure event. This is done by biasing with an extremely small current, in the range of tens mA, the tested device and detecting the heat by lock-in approach. As an example, Fig.4 shows the failure location of a power diode failed in avalanche condition after an Unclamped Inductive Switching (UIS) test.



**Fig. 4** Lock-in image superimposed on device geometry.

Furthermore, use of this technique is mandatory in the inspection of device failure when no evident damages could be spotted optically. This is depicted in Fig.5 where a Punch

Through IGBT is analyzed by means of lock-in thermography after a failure in avalanche, by using a small current at low voltage that will flow only in the damaged region and will lead to a small overheating in that area, thus indicating the failure location.

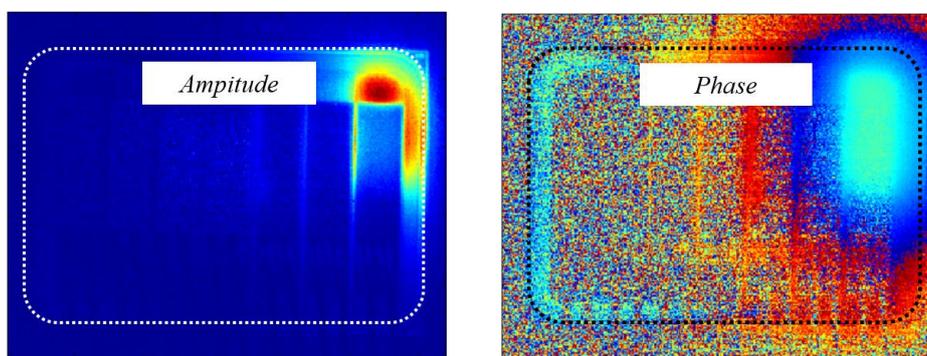


**Fig. 5** DUT failure area.

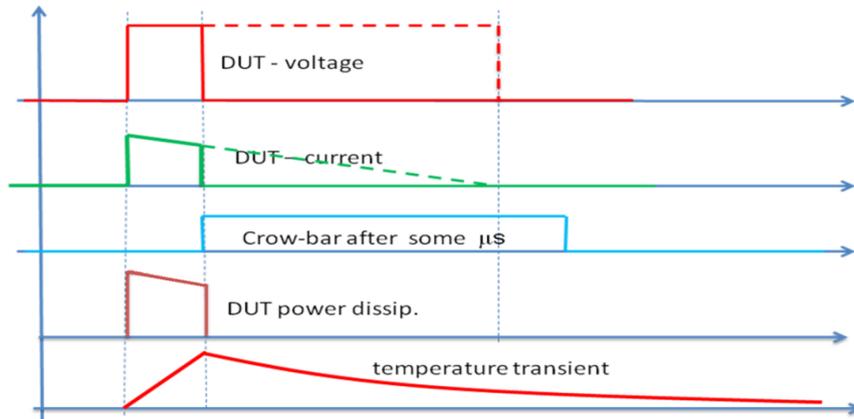
Lock-in thermography could be used in a more advanced analysis if an appropriate ad-hoc experimental system is employed, as shown in the following examples.

The IR set-up developed in [11] is able to synchronously repeat an experiment a given number of periods, detecting by lock-in method the temperature of a DUT. With this procedure a 1200V rated IGBT was analyzed during an UIS test. Results are reported in Fig.6, where it is clear that the current is not distributed uniformly on the entire device area. Current crowding is an undesirable situation because it can lead to a premature device failure. In this case precise information on the area effectively active where the current flows, can be obtained by the phase signal because, as said before, it is not affected by the emissivity problem.

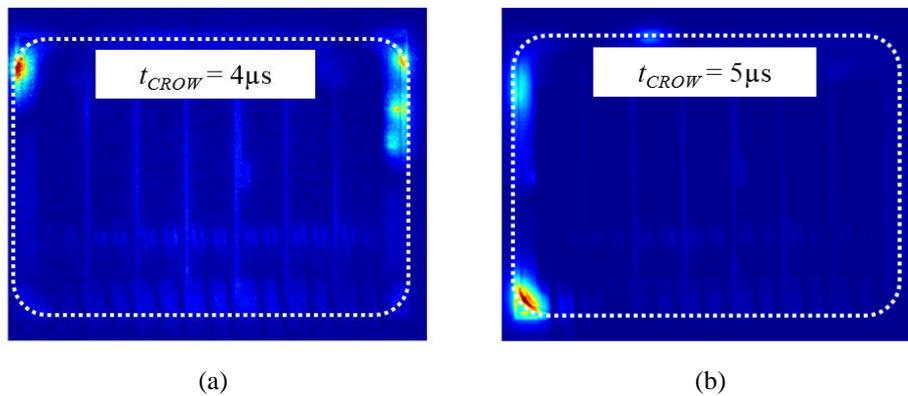
Another interesting analysis can be carried out using the system described in [15]. Without going into details, an UIS transient is repeated periodically, but the avalanche current is drained out from the DUT by activation of a parallel device (*crow-bar*) after a certain time (Fig. 6). In such a way, it is possible to observe just few  $\mu\text{s}$  of the transient. In that short time, temperature is again detected by lock-in technique. This kind of experiment is useful to study the possible activation of the termination area during avalanche, and therefore prove the influence of the termination design in the device breakdown behavior and reliability. It is visible in Fig. 8a and Fig. 8b that during the initial instant of avalanche condition the current flows in the termination area, moreover it is confined in just very narrow areas.



**Fig. 6** Amplitude (right) and Phase (left) images of an IGBT during unclamped inductive switching test.



**Fig. 7** Timing graph of modified UIS test [14].



**Fig. 8** Current distribution during first few  $\mu\text{s}$  of avalanche breakdown.

#### 4. CONCLUSION

In this paper, the use of infrared thermography applied to the characterization and monitoring of power semiconductor devices behaviour has been shown, giving a description of its many attractive features.

Transient and lock-in detection method have been presented, since they are probably the two main analyses employed for power devices investigation, with the aid of some experimental results.

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