Lock-in IR-Thermography - a novel tool for material and device characterization

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Keywords: IC-testing, defect imaging, thermography, GOI defects

Abstract. A novel non-destructive and non-contacting technique for the spatially resolved detection of small leakage currents in electronic devices and MOS materials is presented. Highly-sensitive lock-in infrared (IR-) thermography is used to localize leakage current induced temperature variations down to 10 μK at a lateral resolution down to 5 μm. Leakage currents of about 1 mA can be localized within seconds and some μA may be detected after less than 1 h measurement.

Introduction

Grown-in or structural defects in electronic materials as well as electronic discharges or conducting particles are possible reasons of unwanted leakage currents in electronic devices. These currents may result in a decrease of the efficiency of a produced device or even in its complete failure. The localization of such leakage currents is the first step for a detailed analysis of the defect origin.

There have been several approaches to detect local heat sources in electronic devices by using microscopic IR thermography [1], nematic or thermochromic liquid crystals [2], or fluorescent microthermal imaging (FMI) [3]. However, the temperature resolution of all these techniques is in the order of 100 mK, which is not sufficient to detect a local heat source caused by a dissipated power of only some μW, which may produce temperature contrasts well below 1 mK in silicon components. Moreover, in many cases it is not allowed to cover the surface of a device with an additional layer, which is necessary for liquid crystal and FMI investigations. Another common technique to detect leakage currents in ICs is the detection of visible or near-IR luminescence light, which is generated in ICs under high electric field conditions. However, purely resistive heat sorces don't show any luminescence, and the luminescence intensity drops drastically with decreasing supply voltage. Thus, there is an urgent need for highly sensitive thermal imaging techniques for electronic device testing.

The signal resolution of any technique can be improved considerably by using the lock-in principle, hence by periodically modulating the signal and correlating and averaging it over many periods. Lock-in thermography has been used previously for non-destructive testing of materials and for thermomechanical investigations. The first commercial IR camera based lock-in thermography system was a lock-in option to the AGEMA Thermovision 900 mirror scanner thermocamera, which was developed based on the work of Busse et al. [4]. This system showed a noise level of 15 mK [5], which is only a slight improvement over previous thermal techniques. Dynamic Precision Contact Thermography (DPCT [6]) was the first lock-in thermography technique which allowed to detect temperature modulations below 100 µK. However, this technique worked in contacting mode and showed a spatial resolution of about 30 µm, hence it was not applicable to investigate integrated circuits.

Starting from 1997 a highly sensitive IR camera based lock-in thermography system was developed at MPI Halle, which was designed to reach an ultimate thermal sensitivity. Having 128x128 pixel resolution and a noise level of 0.02 mK after an acquisition time of 1000 s, this was the first system which could demonstrate the advantages of microscopic lock-in thermography for integrated circuit testing down to a spatial resolution of 5 µm [7]. Based on this development Thermosensorik GmbH Erlangen [8] has developed the commercial system TDL MC 384 "lock-in". With a resolution of 384x288 pixel and a noise level of 0.035 mK after an acquisition time of 1000 s this system presently is the highest sensitive and highest resolution lock-in thermography system on the market. In this contribution we present the technique of lock-in infrared thermography and the technical realization of the TDL MC 384 "lock-in" thermography system. Finally, the application of this new technique to the investigation of solar cells, integrated circuits and gate oxide integrity defects are discussed.

Measurement principle and technical realization

The principle of lock-in thermography consists of introducing periodically modulated heat into an object and monitoring only the periodic surface temperature modulation phase-referred to the modulated heat supply. Hence, if the surface temperature is measured via an infrared (IR) thermocamera, lock-in thermography means that the information of each pixel of the image is processed as if it were fed into a

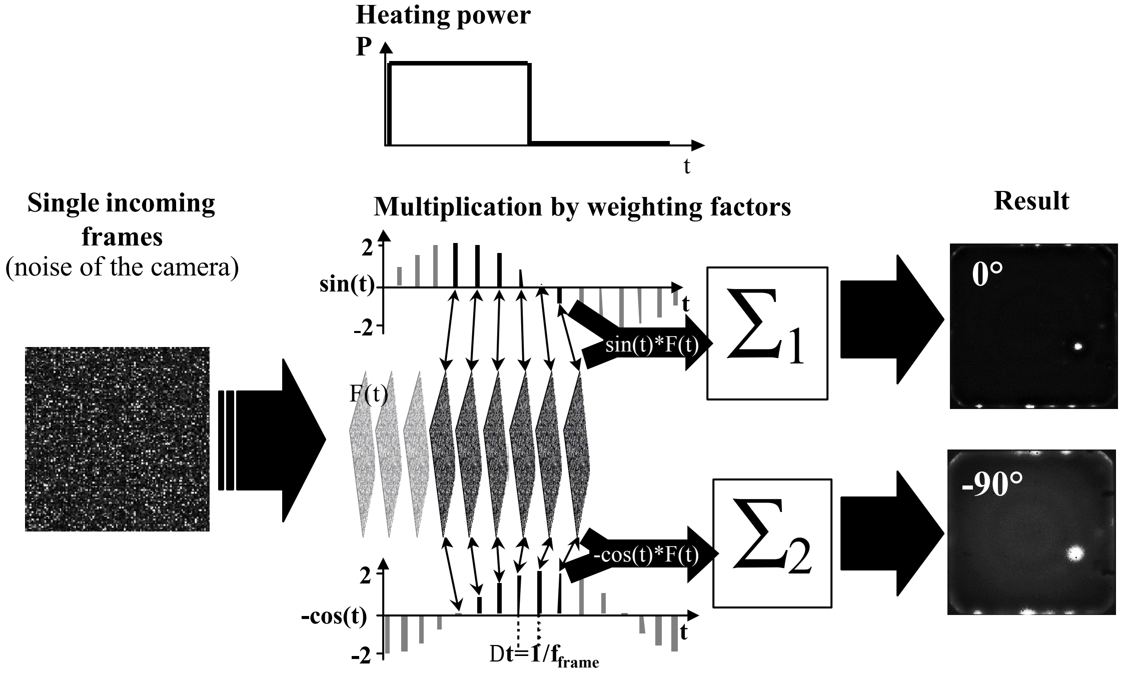

Fig. 1: Principle of Lock-in IR-Thermography.

lock-in amplifier. As Fig. 1 shows, the digital lock-in correlation procedure consists in successively multiplying the incoming IR images by a set of weighting factors and summing up the results in a frame storage. The weighting factors are approximating a harmonic function and are synchronized to the pulsed bias applied to the sample. Since amplitude and phase of the measured surface temperature modulation may change with position, a two-phase lock-in correlation has to be used. Thus, a lock-in thermography measurement can yield either an amplitude and a phase image, or an in-phase (0°) and a quadrature (-90°) image, referring to the phase of the periodic heat supply. For non-destructive testing purposes, the phase image is often more informative than the amplitude one, which strongly depends on the local IR emissivity. For the detection of local heat sources in electronic devices, on the other hand, the amplitude signal is the more informative one, since it is directly related to the locally dissipated power. The advantage of lock-in thermography over stationary methodes is not only its significantly improved sensitivity owing to the ac averaging technique but also an improved spatial resolution of the image. While in any stationary thermography the lateral resolution is strongly affected by lateral heat conduction, in lock-in thermography the periodic heat source acts as the origin of temperature waves, which are strongly damped [9]. Owing to the detection wavelength of 3 ... 5 µm the spatial resolution of IR lock-in thermography is limited to this range.

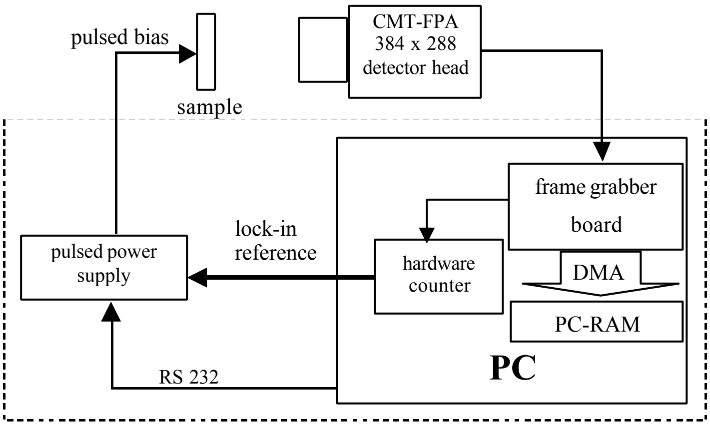

Fig. 2: Scheme of the TDL 384 M "Lock-in" system

The goal of the development of the TDL 384 M "Lock-in" system was to provide a commercial system combining an ultimate detection sensitivity with an industrially proven rugged construction and high resolution. The scheme of the system is shown in Fig. 2. The IR detector head is based on a Stirling-cooled mercury cadmium telluride (MCT) mid-wave (3 ... 5 µm) focal plane array having a resolution of 384x288 pixel. This array has a single detector size of 20x20 µm and can be equipped with a number of high brilliance (down to F#1.5) IR objectives. With a special microscope objective a spatial resolution of 10 µm is obtained, which may be lowered down to 5 µm by inserting a lens extender ring. In full frame mode the maximum possible frame rate is 140 Hz, which corresponds to a pixel transfer rate of about 15.5 MPixel/s. However, it is possible to select sub-frames of 288x288, 256x256, and 128x128 pixels with nearly the same pixel transfer rate, where the frame rate may increase up to 850 Hz. The higher the frame rate, the lower is the degradation of the spatial resolution caused by lateral heat conduction in the sample. The PC used is a 2x800 MHz dual Pentium III system running under Windows NT. As a frame grabber board a Matrox Vision board is used, which writes the captured frames cyclically by direct memory access (DMA) into a certain part of the RAM, where the PC software picks them up for correlation. A programmable hardware counter is provided, which is controlled directly by the frame grabber board and is used to provide the lock-in reference trigger and to ensure that only lock-in periods with a complete number of frames are used for correlation. The power supply for the sample bias is pulsed by a solid state relay switching unit. The whole electronics including the PC, the pulsed power supply, and the power supply for the detector head is combined within a rugged roll container, which is connected with the detector head by a 5 m long cable. If this system has to be used for investigating small objects like ICs, it can be equipped with a stable vertical support and an x-y-z movable device testing stage. Alternatively, for investigating larger objects like wafers, solar cells, or modules, it can be used in a horizontal arrangement. The achieved temperature resolution is 35 µK (effective value) after 16 min measurement time and further reduces with 1/(measurement time)$^{1/2}$.

Applications

Originally, this technique had been developed for the characterization of shunts in solar cells. Shunts are sites of locally increased forward current density and therefore degrade the IV-characteristic of a solar cell. Since a solar cell is forward biased in operation, any shunt current reduces the efficiency of the solar cell. Shunts may be caused by electrical defects of the pn-junction, which may be generated by lattice defects, as well as by technological imperfections of the production process. Lock-in IR-thermography has been successfully used to detect local variations of the current density across solar cells [10]. Fig. 3 shows the LBIC image (light-beam induced current), and the amplitude images of two lock-in thermography measurements of a 10x10 cm^2 sized multicrystalline silicon solar cell in two different scalings. These measurements have been made at a resolution of 288x288 pixels at a lock-in frequency of 3 Hz within 2.5 min and 1/2 hr measure time, respectively. In order to achieve a high and homogeneous IR emissivity, the sample was covered by a 20 µm thin black-painted plastic film, which was sucked to the surface by a vacuum [10]. Fig. 3 b, which was scaled to a maximum signal of 3 mK, shows that the dominant shunts are essentially point-like and are lying both at the edges and within the wafer. If the image is scaled to 0.3 mK (Fig. 3 c) the dominant shunts appear artificially blurred, but a large number of additional weak shunts becomes visible. The edge shunts are caused by an insufficient "opening" of the pn junction at the edges, which was performed by mechanical grinding in this cell. Some of the shunts in the area are lying below grid lines, pointing to the generation of shunts by the emitter metallization. Once these shunts are localized by lock-in thermography, additional microscopic and analytical investigations have to be used to clarify the nature of the shunts and to find ways how to avoid them. The comparison in Fig. 3 shows that LBIC and lock-in thermography produce complementary information: LBIC reveals the defects degrading the short circuit current, and thermography reveals the defects degrading the open circuit voltage and the fill factor of the cells. Thus, lock-in thermography is a valuable tool for optimizing the efficiency of solar cells by avoiding shunting activities. Another very useful application of lock-in thermography is the functional testing of other electronic devices like integrated circuits [7]. These investigations are performed without any

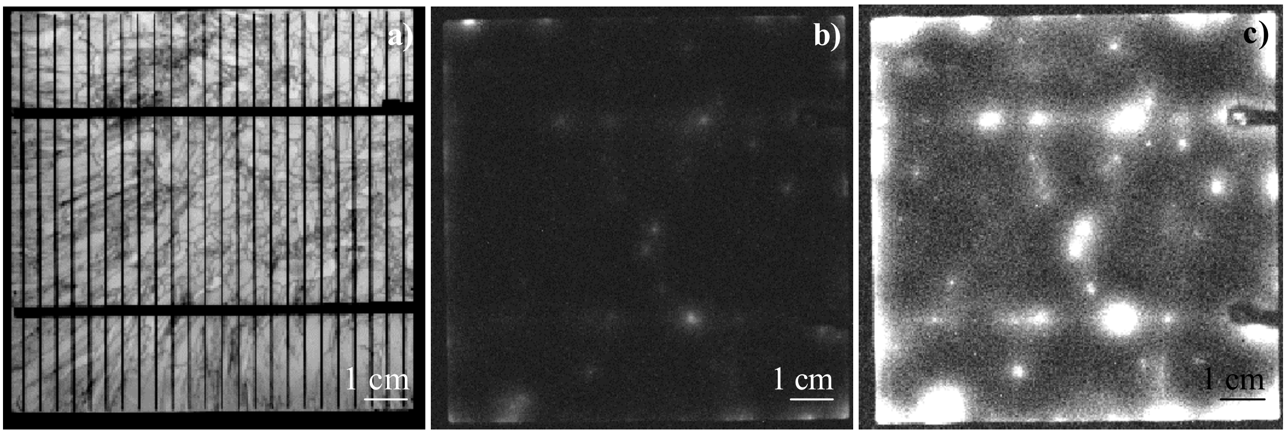

Fig.3: LBIC image (a) and lock-in thermogram (amplitude image) of a solar cell scaled up to 3 mK (b) and 0.3 mK (c).

surface preparation on the bare dies. Since there are large differences in the IR emissivity between metallizations and bare silicon layers, the circuit layout usually remains visible in the lock-in thermograms. However, this "emissivity contrast" may also be corrected after the measurement using an IR image of the sample at elevated temperatures [1]. Fig. 4 shows the amplitude image of an IC measured at a lock-in frequency of 54 Hz within 1/2 hr measure time. This was a CMOS IC in dynamic operation employing an own clock generator, whose supply voltage was switched on and off with the lock-in frequency. Hence, the heat sources visible in Fig. 4 are not only resistive heat sources but are also indications of the dynamic operation of the IC. In this sense lock-in thermography not only expands the detection limit of previous microthermal imaging techniques by at least two orders of magnitude, but it also may detect regions of dynamic operation in CMOS ICs, which could be detected until now only by light emission microscopy. Due to the continuing trend to reduce the supply voltage of CMOS ICs, light emission microscopy becomes more and more inapplicable since at low voltages light is not generated anymore.

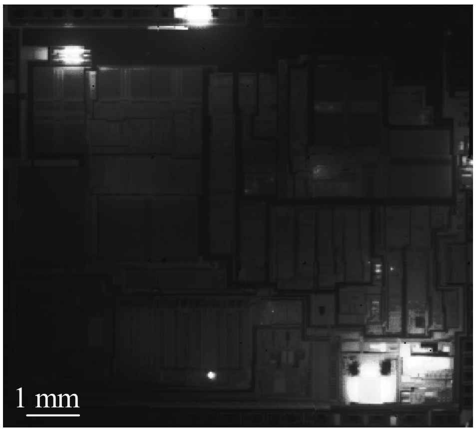

Fig. 4: Lock-in thermogram (amplitude image) of a CMOS IC in dynamic operation. The supply voltage was pulsed with 54 Hz.

A third application of lock-in IR-thermography is the localization of gate oxide integrity (GOI) defects in Cz-grown silicon MOS structures (see Fig 5). Gate oxide integrity defects are local sites of reduced breakdown voltage. For thermographic imaging, the GOI defects need to be broken or electrically activated. An electric bias puls of 100 µs time was shown to activate most defects in samples of some cm^2 size [11]. The breakdown field across the oxide is stepwise increased from 0... 12 MV/cm by increasing the bias puls voltage. After each breakdown pulse, a periodic bias of 2V is applied to the MOS structure and a thermogram is recorded for some minutes. That way the defect density in dependence of the breakdown field may be recorded [11]. The determined defect densities are in good agreement with electrical measurements. Typically, the lock-in frequency of the 2 V measurement voltage is in the order of about 20 Hz. MOS structures of sizes ranging from some cm^2 up to whole 8" wafers with an oxide thickness of 5 nm to 25 nm have been investigated, but this technique is also applicable to 12" wafers. An example of the investigation of a whole wafer is shown in Fig. 5a. A bias pulse of 32 V (E_{oxide} = 12.8

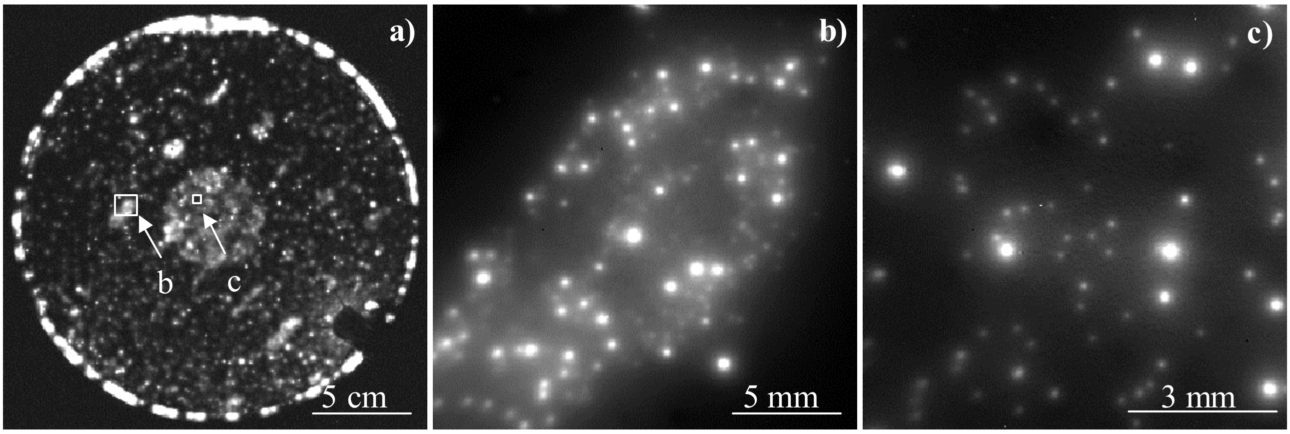

Fig. 5: Thermograms of a whole wafer (a), a defect agglomerat (b) and a 1x1 cm^2 area (c) for the determination of the defect density.

MV/cm) and 100 ms was applied to the whole wafer (25 nm oxide, aluminum gate) and a thermogram was recorded using a 2 V, 24 Hz measurement voltage for 5 min. The signal at the circumference is considered to be an artifact. An inhomogeneous defect distribution is observed i.e. the defect density is higher in the center of the wafer than outside. There are also regions of locally increased GOI defect density. One of these regions (marked by a box in Fig. 5a) has been investigated in more detail and is shown in Fig. 5b. Single GOI defects are resolved in this agglomaration. The defect density inside the central area was determined to be $D_d = 68$ cm^{-2} by imaging a 1x1 cm^2 area (see Fig. 5c). In the other part of the wafer an area of 2x2 cm^{-2} was used to determine a defect density of $D_d = 22$ cm^{-2} which is in good agreement with the result of $D_d = 15$-40 from electrical measurements.

Conclusion

Lock-in thermography has been shown to be a versatile and very sensitive tool to detect local heat sources in electronic components. It has been used successfully for detecting local shunts in solar cells, for imaging the local distribution of gate oxide integrity (GOI) defects, and for the functional testing of integrated circuits (ICs). Especially the last application is very promising because lock-in thermography expands the detection limit of previous microthermal imaging techniques by at least 2 orders of magnitude from 0.1 K to well below 1 mK. This enables the thermal investigation of a lot of defects and processes in ICs that had been inaccessable for thermal investigations before due to lack of sensitivity. Especially, lock-in thermography may become an alternative to light emission microscopy, which cannot be used anymore if the trend towards lower supply voltages of CMOS ICs continuous. One limitation of IR based lock-in thermography is that its spatial resolution is limited to about 3 ... 5 µm by the wavelength of the detected light.

Acknowledgements

The authors are indebted to the German BMBF for financial support under contract Nos. 0329743 B and 01 M 2973 A. The help of J.-P. Rakotoniaina (Halle) in performing LBIC and thermography measurements and the cooperation with Thermosensorik GmbH (Erlangen) is acknowledged.

References

[1] www.quantumfocus.com
[2] G. Aszodi, J. Szabon, I. Janossy and V. Szekely, Solid-State Electronics **24**, 1127 (1981)
[3] P. Kolodner and J. A. Tyson, Appl. Phys. Lett. **40**, 782 (1982**)**
[4] G. Busse, D. Wu, and W. Karpen, J. Appl. Phys. **71**, 3962 (1992)
[5] O. Breitenstein, K. Iwig, I. Konovalov, and D. Wu, Proc. QIRT 96, ed. D. Balageas, G. Busse, and G.M. Carlomagno, Edizioni ETS Pisa, 383 (1997)
[6] O. Breitenstein and M. Langenkamp, Sensors and Actuators A **71**, 46 (1998)
[7] O. Breitenstein, M. Langenkamp, F. Altmann, D. Katzer, A. Lindner, and H. Eggers, Rev. Sci. Instr. **71**, 4155 (2000)
[8] www.thermosensorik.com
[9] H.S. Carslaw and J.C. Jaeger, conduction of heat in solids, Oxford Clarendon (1959)
[10] O. Breitenstein, M. Langenkamp, O. Lang, and A. Schirrmacher, Solar Energy Materials & Solar Cells **65**, 55 (2001)

[11] S. Huth, O. Breitenstein, A. Huber and U. Lambert, J. Appl. Phys., **88,** 4000 (2000)