J. Phys. IV France **125** (2005) 493-498
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DOI: 10.1051/jp4:2005125115

Nano and microscale thermal transport experimental measurements

D. Fournier, C. Filloy, S. Holé, J.P. Roger and G. Tessier

CNRS, UPR A0005/UPMC/ESPCI, Laboratoire d'Optique, 10 rue Vauquelin,
75005 Paris, France, e-mail: fournier@optique.espci.fr

Abstract. Modern Silicon microelectronic components are nowadays in the nanometer scale regime. The thermal transport can be modified by the close proximity of interfaces and the extremely small volume of heat dissipation. The thermal management being more and more difficult to achieve, strong efforts have been done both on theoretical and experimental points of view. In this paper we will discuss the advances in measurement methods such as: Raman and photoluminescence spectroscopies, modulated thermoreflectance set-ups and scanning thermal microscopy which enable new capabilities for nanometer and micrometer scale thermal metrology. The optical methods will be presented and discussed in details, specially their lateral resolution, and their sensitivity for thermal mapping and thermal properties determination. The paper will be illustrated with examples taken in the microelectronics and material science fields.

1. INTRODUCTION

The physical behavior of nano objects and nano structures is the challenge of this new century. The advances made in this field are spectacular in material science (quantum dots, semiconductor nanowire, carbon nanotubes..), in optics (nano laser, photonic crystals..), in electronics (CNTFET, nanometric MOSFET, spintronic, MRAM...). Physical and in particular thermal effects at micrometer and nanometer scales have to be investigated. Microelectronic components are good candidates for studying this kind of new effects : the determination of temperature distribution in the sub-micron range has become fundamental in the microelectronics industry. In this paper, we want to discuss the performances of some of the actual experimental methods used for thermal mapping and for the determination of the thermal parameters at nanometer and micrometer scales. In the first part we will present how to achieve thermal imaging of electronic components under biasing, and in the second one we will describe how to determine the thermal properties of micronic and submicronic samples.

2. THERMAL MAPPING

At macro and micro scales, a temperature measurement can be achieved with contact (liquid crystals, thermal sensors) or non contact methods (optical measurements). Among the optical methods for the micronic thermal mapping of integrated circuits under biasing, Raman and Photoluminescence spectroscopies, infrared imaging and thermoreflectance offer the best potential for non contact thermal imaging. The achievable resolution of any optical technique being diffraction limited, infrared thermography is not suitable for the submicronic size of the modern microelectonic components.

2.1 Raman and photoluminescence

In Raman spectroscopy, a laser beam is directed onto the sample. A small fraction of the photons passing through the sample are scattered at frequencies that are characteristic of the Raman active bonds in the sample. The Raman spectroscopy is a very efficient tool in microelectronics from an analytical point of view and to determine directly the electronic and optical properties of the sample. A Raman spectrum exhibits generally two lines (fig 1) , whose ratio gives an absolute determination of the temperature of the sample [1,2]. This measurement is difficult and needs several minutes by point. In the case of temperature measurement of a Silicon transistor under biasing, the accuracy is around 10°C with a spatial resolution associated to the diffraction limit. This measurement is limited to Si and SiC The Micro Raman setups can be equipped with a confocal microscope and micropositionners which allow a very precise positioning of the sample.

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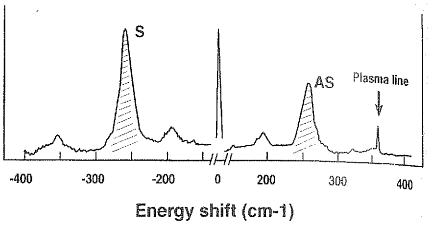

Figure 1. Stokes and Antistokes Raman lines. The ratio of the two lines is an absolute measurement of the temperature.

Commercial companies offer setups allowing both Raman and Photoluminescence spectroscopy [Jobin Yvon]. Photoluminescence spectroscopy is a contact less non destructive method of probing the electronic structure of materials. Light (usually a laser) is directed onto the sample, where it is absorbed and imparts excess energy into the material in a process called "photo-excitation". One way this excess of energy by the sample is through the emission of light. called "photoluminescence" and is commonly observed with III-V semiconductor materials. The intensity and spectral content of this photoluminescence is a direct measure of various important material properties : material composition, stress …. The photoluminescence spectrum is temperature sensitive as it is shown on fig 2. After a calibration it is possible to measure the local temperature with an accuracy of 2°C in a few seconds [3]. The photoluminescence technique is not applicable to Silicon and SiC which do not give any photoluminescence at room temperature.

These two techniques can be invasive because the high light density associated to the excitation laser can induce an excess of photo created carriers which can damage the component under biasing.

To increase the resolution it is possible to achieve SNOM Raman which is a new and emerging technique that is still in a state of relative infancy from an industrial point of view. Very nice works have been published recently specially on the near field Raman spectrum of carbone nanotubes which are very promising for the microelectronics (MOSFET, Memory ..nanotube vias...) [4,5].

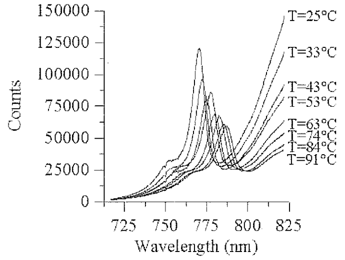

Figure 2. Shift of the photoluminescence spectrum versus the temperature.

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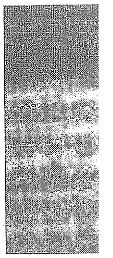

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2.2 Thermoreflectance

This technique is based on the variation of the refractive index with the temperature. It is then possible to follow the local temperature changes by imaging the light reflected by the heated area. Monodetector thermoreflectance microscopy has already demonstrated that it is a very convenient tool for the thermal mapping of opto or micro electronic components[4-7]. Nevertheless, the high flux density of the probe is a very heavy handicap, when the samples under investigation are semiconductors. The thermal information revealed by the variation of the reflected probe beam can be mixed with information about the carriers created by the high density laser probe beam [8].

To avoid this artifact and to obtain thermal images without scanning, we have replaced the photodiode by a matrix of detectors with the goal of obtaining a full image within minutes[. We have used recently a Dalsa 1M30 camera (1024 x1024 pixels) limited to a 30 frames per second rate, which images the surface of the component illuminated by a visible incoherent source (LED or filter and white lamp). To obtain submicronic thermal mapping of electronic components operating at various frequencies, we have worked in different directions. To image thermal phenomena over a wide range of frequencies from 0.25 Hz up to 300 MHz we have used stroboscopic technique : the temperature field which induces variation of the reflection coefficient and the incident probe light are modulated at two different frequencies. This permits a mixing which shifts the thermal information towards low frequencies, which can then be sampled at the CCD camera rate. To enhance the sensitivity of the technique, we have chosen very carefully the wavelength of the illumination [9-11]. Moreover most microelectronic components being covered with a very thin layer of silicon nitride or silica, the presence of interferences can completely cancel the thermo-optical signals for particular wavelengths. In order to obtain quantitative results, we have to achieve a calibration of the image. The alternative variation of the temperature can be measured with a micro thermocouple on various parts of the device. More recently, we have achieved a calibration using a Peltier element to heat the sample to a known temperature. This temperature is then associated to the value of the variation of reflectivity measured on the same locations on the modulated image. An absolute periodic temperature can then be obtained for each part of the device. With visible light illumination we have reached the diffraction limit for the spatial resolution (figure3).

Recently we have enhanced the spatial resolution and largely enhanced the convenience of the setup by using ultraviolet illumination [12].

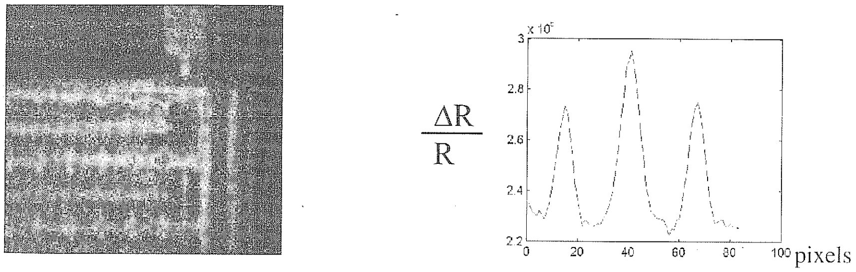

Figure 3. Thermoreflectance image of a microelectronic component under biasing : the FWMH width of the line correspond to 7 pixels and to 340 nm.

2.3 Scanning thermal microscope

A scanning thermal microscope operates by scanning a sharp temperature probe close to a sample surface. Thermocouple or resistive probes can be used. When a resistive probe comes in local equilibrium with the sample surface (passive mode), a temperature map is obtained, whereas if the temperature change is determined for a known heat flux (active mode), one could obtain the local thermal properties. The idea of thermal mapping was first proposed by Williams and

Wickramasinghe with their thermal profiler [13]. Tip sample heat transfer was used to achieve topographic image of insulating samples. Significant progresses were made in improving the thermocouple measurements whereas others techniques have been developed such as contact potential, electrical resistance and thermal expansion measurements. See the review of Majumdar [14] to get a large panorama of their development. Such studies have helped in identifying defects and failure mechanisms. Nowadays thermal probes are proposed by the companies which are selling AFMs. When a temperature sensor is mounted on the apex of the tip, both thermal image and topographic one are obtained (figure 4).

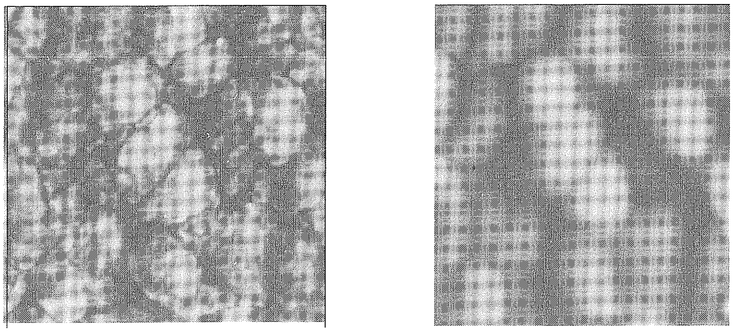

Figure 4. Thermal image (left) and topographic image (right) 3 x 3 μm^2 obtained with using a conventional Atomic Force Microscope (AFM) equipped with a thermal sensor. (courtesy of Thales).

Thermal and mechanical design of the probe, fabrication of the probe and understanding the tip-sample heat transfer are the three important elements which determine the performance of SthM measurements. Fabrication of probes by MEMS processes allows to batch fabricate hundreds of probes on a single wafer which enable better results. Recent studies have revealed the role of gas conduction, solid-solid conduction and conduction through a liquid film bridging the tip and the sample. Recent progress in the tip-sample transfer has allowed thermal imaging of nanostructures such as carbon nanotubes with 30-50 nm spatial resolution [15].

3. THERMAL PROPERTIES MEASUREMENTS

In the nanometer scale regime experiments have demonstrated that the close proximity of interfaces and extremely small volume of heat dissipation strongly modifies thermal transport. Field effect transistors exhibit nowadays a channel length smaller than 100 nm whereas new optical or magnetic

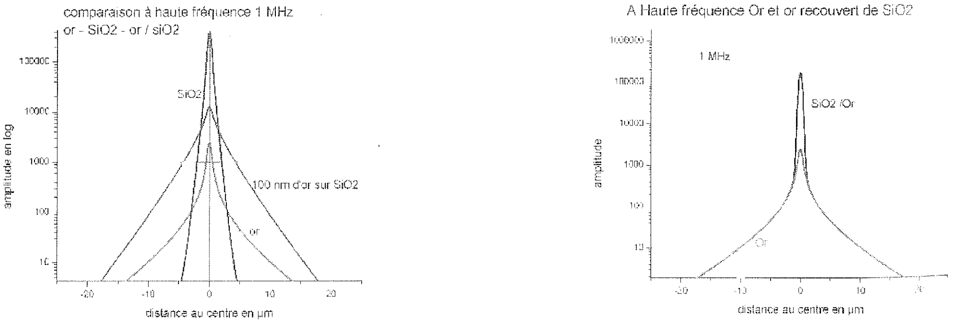

Figure 5. Surface temperature simulation versus the distance of the pump beam at r = 0 at 1 MHz frequency modulation : left 100nm gold layer deposited on silica; right 100nm of black silica deposited on gold . In the two cases it is possible to detect the presence of the layer and even to easily measure it (left).

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4. CONCLUSION

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stacks or are constituted with a few nanometers thickness layers. Photothermal methods have already demonstrated their ability to achieve optical and thermal properties measurements on the surface or in the bulk of the samples. Thermal lensing and collinear mirage detection have proved the possibility to measure volume absorption coefficient as small than 10^{-7}/cm [16,17].

The thermoreflectance microscope setup [18] which allows to vary the modulation frequency of the pump beam between a few MHz to a few kHz , allows a thermal exploration of the sample thickness from about a micrometer to one hundred of micrometers. Figure 5 shows the sensitivity of this method of a 100 nm thin layer deposited on a substrate. In the case of layered structures experimental data have to be fitted with a thermal model taking into account the presence of thermal interfaces between the layers and the thermal properties of very thin layers which can be different of these of thick layers. Fig 6 shows the experimental data and the fits achieved on 140 nm YBaCuO layer deposited on La AlO3 crystal [19]. To fit the data a thermal resistance of about 10^{-7} (m2K/W)was taken into account between the coating and the bulk.

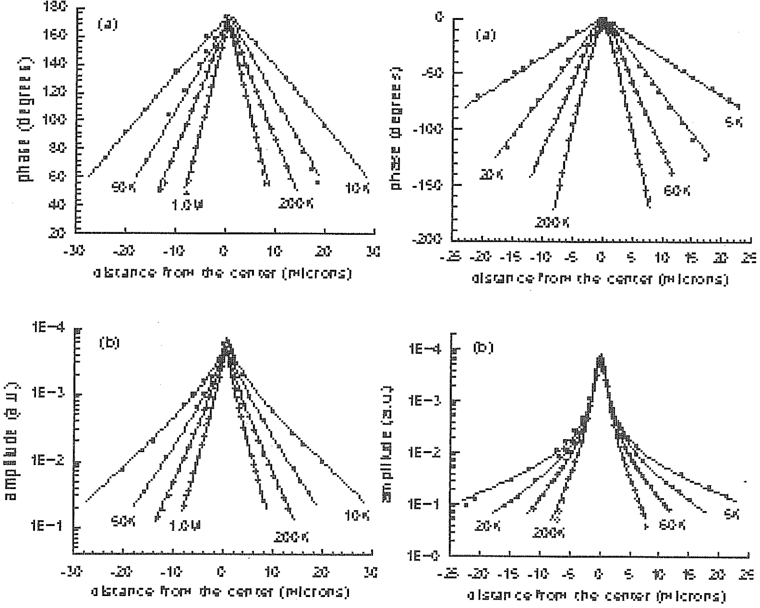

Figure 6. Experimental data and best fit of thermoreflectance results on 140 nm YbaCuO deposited on $LaAl_2O3$ (left) and 80nm gold deposited on ZrO_2 . The modulation frequency range is varying between 5 KHz and 1 MHz.

It is also possible to achieve thermal measurements with a SthM setup. The thermal conductivity of SiO_2 layers deposited on silicon and the thermal barrier measurements have been achieved with a SthM used in active mode [20]. Hammiche and co-workers used an resistive probe to study the thermal behaviour of different types of polymer blends [21]. Despite the successful use of these probes to obtain images of thermal conductivities a thorough analysis of the signal is very difficult as we have already mentioned.

4.CONCLUSION

This paper is a non exhaustive review of experimental methods which can be found in research and companies laboratory, used to do thermal imaging and thermal investigations at micrometer and nanometer scales. The spatial resolution of the non contact optical methods is diffraction limited but it is rather easy to reach the photon noise and so to get a rather good sensitivity. Optical absorption coefficient as small than 10^{-7} / cm are detected with mirage detection and thermal barrier at the boundary easily highlighted. Thermoreflectance microscope imager seems nowadays ready to be set near the more classical Raman and photoluminescence optical microprobes. The SthM presents good potentiality for a nanometer scale imaging but it is a contact method and the model which has to be taken into account to analyse the data has to be confirmed.

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G. Chen, R. Yang

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