Thermal Issues in Emerging Technologies, THETA 1, Cairo, Egypt, Jan 3-6th 2007

MICROSCALE AND NANOSCALE THERMAL CHARACTERIZATION TECHNIQUES

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ABSTRACT

Miniaturization of electronic and optoelectronic devices and circuits and increased switching speeds have exasperated localized heating problems. Steady-state and transient characterization of temperature distribution in devices and interconnects is important for performance and reliability analysis. Novel devices based on nanowires, carbon nanotubes and single molecules have feature sizes in 1-100nm range and precise temperature measurement and calibration are particularly challenging. In this paper we review various microscale and nanoscale thermal characterization techniques that could be applied to active and passive devices. Solid-state micro refrigerators on a chip can provide a uniform and localized temperature profile and they are used as a test vehicle in order to compare the resolution limits of various microscale techniques. After a brief introduction to conventional micro thermocouples and thermistor sensors, various contact and contactless techniques will be reviewed. Infrared microscopy is based on thermal emission and it is a convenient technique that could be used with features tens of microns in size. Resolution limits due to low emissivity and transparency of various materials and issues related to background radiation will be discussed. Liquid crystals that change color due to phase transition have been widely used for hot spot identification in integrated circuit chips. The main problems are related to calibration and aging of the material. Micro Raman is an optical method that can be used to measure absolute temperature. Micron spatial resolution with several degrees temperature resolution has been achieved. Thermoreflectance technique is based on the change of the sample reflection coefficient as a function of temperature. This small change in 10^{-4}-10^{-5} range per degree is typically detected using lock-in technique when the temperature of the device is cycled. Use of visible and near IR wavelength allows both top surface and through the substrate measurement. Both single point measurements using a scanning laser and imaging with CCD or specialized lock-in cameras have been demonstrated. For ultrafast thermal decay measurement, pump-probe technique using nanosecond or femtosecond lasers have been demonstrated. This is typically used to measure thin film thermal diffusivity and thermal interface resistance. The spatial resolution of various optical techniques can be improved with the use of tapered fibers and near field scanning microscopy. While sub diffraction limit structures have been detected, strong attenuation of the signal reduces the temperature resolution significantly. Scanning thermal microscopy which is based on nanoscale thermocouples at the tip of atomic force microscope has had success in ultra high spatial resolution thermal mapping. Issues related to thermal resistance between the tip and the sample and parasitic heat transfer paths will be discussed.

1. Introduction

Different methods for temperature measurement on the scale of modern electronic and photonic devices are surveyed. Many properties of materials have a dependence on temperature that can be exploited for local temperature measurement. Good references explaining different thermal measurement techniques are Kolzer[1],Altet[2] and Cutolo[3]. Such methods can rely on coatings, mechanical contact, optical surface effects or even integrating thermal sensors into the device. These techniques have different spatial, thermal, and temporal resolution, and can be used for absolute or differential measurements. A summary of popular methods for high-resolution thermal measurement suitable for semiconductor structures is presented in Table 1.

2. Micro-Thermocouple

Perhaps the easiest of the above methods is to use a commercially available thermocouple for device characterization. A thermocouple is made by joining two different metals. The intrinsic Seebeck voltage is created at the junction between two metals when there is temperature difference. Thermocouples are cheap and accurate, but large; the smallest commercially available being 25-50 microns in diameter. Even at this size, great care must be taken in joining the wires and constructing a useful micro-probing set-up. Thermocouples can be used for absolute or differential measurements. Some disadvantages of the micro-thermocouple are that it cannot be used for imaging and there is a non-zero thermal mass of the thermocouple that can be significant considering the size relative to the device under test.

3. Liquid Crystal Thermography(LCT) method

A thin layer of liquid crystal is deposited onto the device under test, illuminated with white light and the color change of the light reflected from the crystal is related to the temperature. According to [4] there are

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Table 1. Summary of popular high-resolution thermal measurement techniques in micrometer-nanometer range.

Method	**Principle**	**Resolution**			**Imaging?**
		Spatial (microns)	**Temperature (K)**	**Time (sec)**	
Micro-thermocouple	Seebeck effect	**50**	**0.01**	**10-100**	No
Infrared Thermography	Plank blackbody emission	**3-10**	**0.02-1K (if blackbody)**	**20 µ**	Yes
Liquid Crystal Thermography	Crystal phase transitions (change color)	**2-5**	**0.1 (near phase transition)**	**100**	Yes
Thermo-reflectance	Temperature dependence of reflection	**0.3-0.5**	**0.01**	**0.006-0.1 µ**	Yes
Scanning thermal microscopy (SThM)	Atomic force microscope with thermocouple or Pt thermistor tip	**0.05 (sample surface morphology)**	**0.1**	**10-100 µ**	Scan
Fluorescence Thermography	Temperature dependence of quantum efficiency	**0.3**	**0.01**	**200 µ**	Scan
Optical Interferometry	Thermal Expansion, Michelson type	**0.5**	**0.0001 (1fm)**	**0.006-0.1 µ**	Scan
Near Field Probe (NSOM)	Use near field to improve optical resolution	**0.05**	**0.1-1 (S/N dependent)**	**0.1-10 µ**	Scan
Built in temperature sensors	Fabricate a thermal sensor integrated into the device	**100's**	**0.0002-0.01**	**1 µ**	No

different types of liquid crystals that can be used. One method relies upon the nematic-isotropic phase transition giving a spatial resolution of 2 microns and a thermal resolution of 0.1K. The phase transition causes a dark spot to be seen under a polarizing microscope. Since the phase transition only occurs at one temperature for a certain liquid crystal, the temperature must be measured relatively. The stage temperature must be set relative to the transition temperature, and then the surface temperature can be determined. To generate a series of isothermal lines, the experiment must be repeated many times at different stage temperatures, which can limit the temperature range over which it is useful.

Recent advances in thermochromic liquid crystals, however, have increased the ease of the LCT method. Thermochromic liquid crystals change from red to blue over a specified temperature range. The crystals are specified by the temperature they activate, and the range over which they work. For example 'R40C5W' means the crystals will turn red at 40C and the full range is 5C, thus reflecting blue at 45C. The minimum range of the red to blue color change is 2C, and the claimed thermal resolution is 0.1C, while the spatial resolution is limited by visible light diffraction <1 micron. The steps to realizing a thermal image of a particular device include painting the sample surface with a 'thin and uniform' coat of black paint, to increase the resolution on the reflected light from the liquid crystals. In addition, the range of the temperature must be known prior to a measurement to select the appropriate liquid crystal.

For some samples, the black paint and liquid crystal coating might affect the device under test. This leads to some questions: What is the thermal conductivity and heat capacity of the coating? How can one paint a sample uniformly that is only 10x10 microns, and exhibits some topography? Can this method be used for vertical structures, for example a laser facet?

4. Infrared (IR) Thermography

The most popular method of thermal imaging is to use an infrared sensitive camera. Anything above absolute zero emits infrared radiation, and a class of objects called blackbodies has a well-known wavelength distribution. Classical infrared thermography uses Plank's blackbody law to determine the temperature of a hot object. By measuring the radiation intensity at a specific wavelength and making the blackbody assumption, absolute temperature can be determined.

In collaboration with Oak Ridge National Labs, a synchronous IR camera was used to measure the temperature on a 180x90 microns square cooler under pulsed operation (see Figure 1). In the thermal image we can see heating around the active device but we can't clearly measure cooling on top of the largest coolers. The heating from the current probe dominates the image.

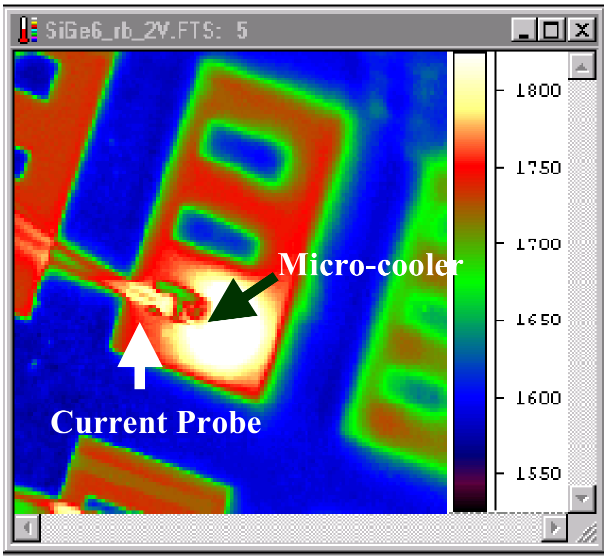

Figure 1. IR image of a large micro-cooler using liquid nitrogen cooled focal plane array (in collaboration with Oak Ridge National Lab, Dr. Hsin Wang)

In practice, few objects are true blackbodies and Plank's law needs to be scaled by a factor called the emissivity. Thus knowledge of the emissivity for each surface in the image is needed to obtain accurate thermal maps. In fact, most materials with high reflectivity such as metals are very poor blackbodies.

The spatial resolution of the infrared image is given by the diffraction limit of the wavelength used. The most sensitive IR cameras work at the 3 micron wavelength. It would appear that HgCdTe would work better for thermal imaging near room temperature, because it is sensitive to longer wavelengths; however, there is significantly less radiation for objects that are around room temperature. For microscopic, metallic targets without emissivity calibration and using a differential imaging technique, the temperature sensitivity can be tens of degrees.

This type of thermal imaging seems to be getting better and would provide a nice complement to thermoreflectance imaging. In general, materials with a high reflectivity are better candidates for thermoreflectance, whereas low reflectivity materials have a higher emissivity making them better for IR imaging.

5. Near Field Scanning Optical Microscopy (NSOM)

Typically, optical measurements are limited in spatial resolution because of the wave nature of electromagnetic radiation. The ability of a diffraction limited optical system to resolve two very close point objects is given by the Rayleigh diffraction criteria which depends on the wavelength of light used. One possible approach to optical imaging beyond the diffraction limit is to acquire the light from the sample in the near field as compared to typical far field imaging. If an imaging aperture is placed close enough to the object (a fraction of the wavelength), the solutions to Maxwell's equations become decaying exponentials. The spatial resolution in this case is given by the probe aperture width. This is the basis of Near Field Scanning Optical Microscopy (NSOM).

An NSOM probe is a single mode optical fiber or a specially designed atomic force microscope tip with an aperture on order of 50nm. Then by using sophisticated computer controlled translation stage, the probe is placed close enough to the surface of the device so that the near field can be transmitted through the tiny tip (aprerature). The electromagnetic radiation in the nearfield is a decaying exponential, but even with the substantial loss, the wave will be transmitted through the probe. The reported loss of the order of 80dB, which is substantial, but 50nm spatial resolution is impressive. The main complications of this method are the construction of a nanoscale aperture, and also positioning it close enough to the surface to measure the near field. To detect the near field the probe should be tens of nanometers from the object, but sudden contact with the surface can destroy the probe.

NSOM is generally used for topography measurements, luminescence and fluorescence experiments. In addition, for thermal measurements, experimenters have used NSOM for infrared blackbody measurements, and thermoreflectance probing. Vertikov[5] achieves good results using NSOM for visible light thermoreflectance measurements. The claimed spatial resolution is 20nm in the steady state, with thermal resolution given in terms of the reflection coefficient, ⊗R/R ~10^{-4} (~1 C temperature sensitivity). The main limiting factor is how much of the probe light can be coupled into the fiber before it sustains damage, which is indicated to be about 5mW into the fiber corresponding to 100-300nW reflected light incident on the photodiode. Another complication is that since the tip is in the near-field and very close to the sample, the tip itself can undergo heating with the sample and can change geometry slightly, which effects the reflected signal. NSOM is certainly an attractive method for increased resolution but the expense, complication, and image acquisition time are limiting.

6. Scanning Thermal Microscopy (SThM)

An atomic force microscope (AFM) utilizes a laser reflected of a cantilever arm to generate high-resolution topography maps of micro-devices. By fabricating a very small thermocouple on the tip of the AFM scanner very high resolution thermal maps are generated simultaneously with the topography map. Such a method can give resolution as high as 50nm. Measurements by Prof. Majumdar group at UC Berkeley on a carbon smooth nanotube show the temperature distribution at several different biasing conditions, and demonstrate the impressive spatial resolution [6]. Figure 2 shows an image of a nano-sized cantilever tip designed for topographic and thermal measurements on microrefrigerator sample. Point measurements on top of microcoolers can clearly show that cooling increases at low currents due to Peltier effect and it subsequently saturates and decreases due to Joule heating. On the other hand, scanning the probe on top of the cooler produces a noisy thermal map (see Figure 2a). This is due to the fact that, in contrast to carbon nanotubes, the surface of processed device has some roughness and the thermal contact between the scanning probe tip and the sample varies.

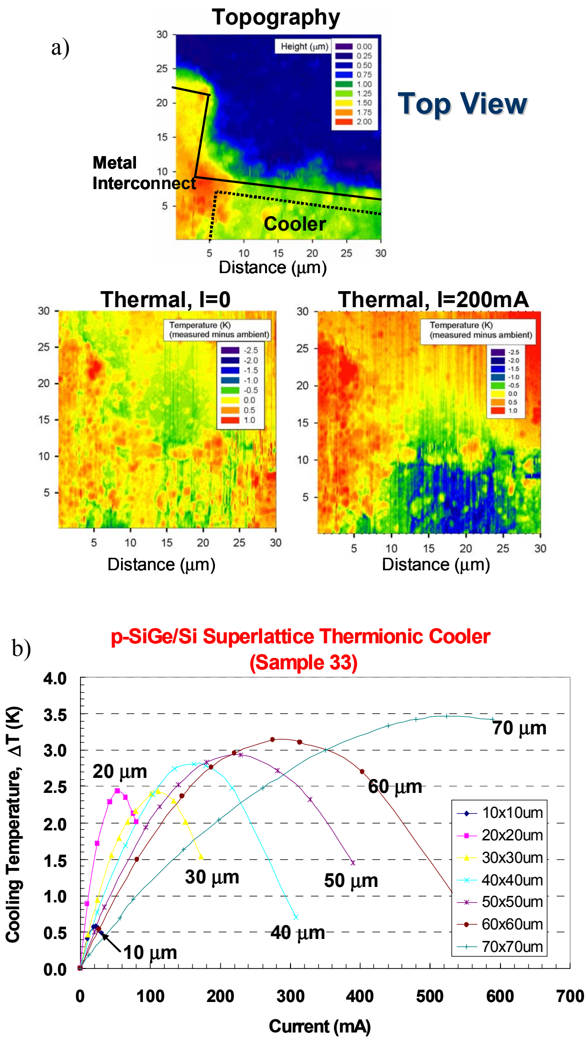

Figure 2: (a) Temperature measured on top of microcooler devices with different diameters using scanning thermal microscopy, (b) Thermal and topographical maps.

The advantages of scanning thermal microscopy are high bandwidth and excellent spatial resolution (on smooth objects), the drawbacks are calibration and being a very expensive and fairly complex imaging system. The highest resolution thermocouple tips are not commercially available, and due to the scanning method required, acquisition time of thermal images can be considerable. One complication of this method is that despite the fact that the thermocouple tip is fabricated to a very sharp nanometer sized tip, there is some discussion as to how much of the heating measured is from the side-conduction of the thermocouple [6]

7. Thermoreflectance Microscopy

The challenge in obtaining high quality thermal images arises when one considers the magnitude of the weak temperature-dependent reflection coefficient (thermoreflectance effect) in metals and semiconductors. The thermoreflectance coefficient is on the order of 10-4, 10-5 per degree Kelvin for most materials [7]. This coefficient is wavelength, material, and sometimes surface texture dependent [8], and in situ calibration e.g. with a thermocouple is necessary. To capture the thermoreflectance signal with reasonable signal-to-noise ratio, an active device is thermally cycled at a known frequency and lock-in technique is used. Images are detected by either a PIN diode array camera [9] or a special high frame rate intensified CCD (ICCD). The PIN array has a higher dynamic range and thermal resolution, while the ICCD yields superior spatial resolution and is better suited for low intensity

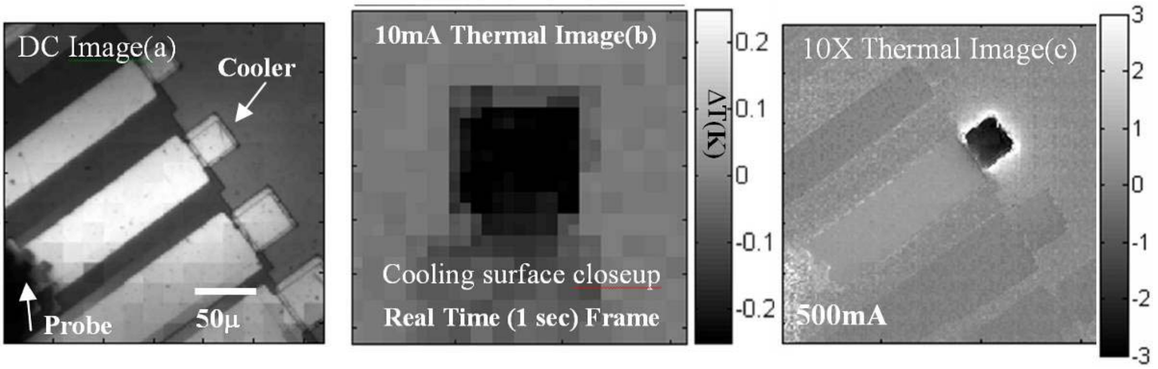

Figure 3. SiGe micro-cooling device image left, one second real-time thermal image frame, center, scanned and enhanced thermal image, right.

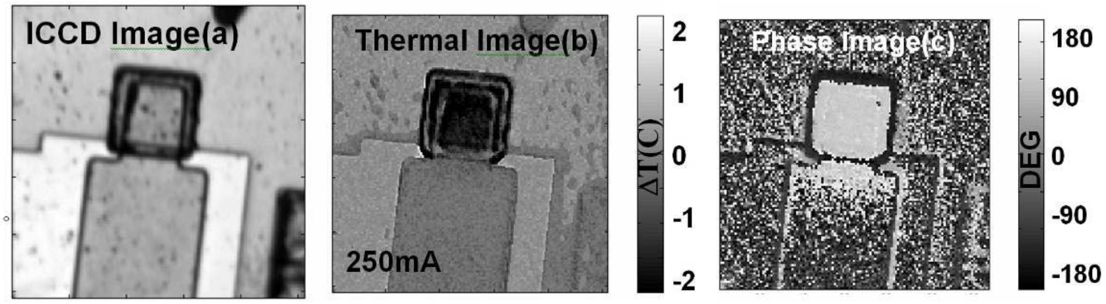

Figure 4. Thermoreflectance Imaging using an ICCD. Micro-cooler illuminated with blue LED, left, thermal image center, and phase image, right.

illumination.

The UC Santa Cruz PIN diode array camera achieves thermoreflectance imaging with 10mK resolution in one second, while spatially enhanced images, the result of combining multiple frames, take minutes. This camera consists of a 16x16 diode array, where each pixel has a dedicated AC coupled analog amplifier, and precision 24-bit, 40KHz, A/D converter. Figure 3 shows a typical thermal imaging result from the UCSC thermoreflectance camera, of an active 40x40 micron Heterostructure Integrated Thermionic (HIT) microcooler [10]. On the left, Figure 3(a) is an image of the micro-cooling device, Figure 3(b) center, shows a raw 16x16 pixel, one second thermal image, at low 10mA bias current. This demonstrates 10mk temperature sensitivity on the surface of the microcooler. Figure 3(c), on right, is an enhanced, processed thermal image, the result of combining 100 frames which took several minutes of acquisition. The thermal image shows more than 3K cooling below the ambient temperature on the micro-cooler surface, while there is minimal heating at the current probe, when the device is biased to 500mA.There are some advantages to using a CCD based system rather then a PIN diode array for thermoreflectance imaging. Overall, the PIN array camera has a higher dynamic range and sensitivity, because the AC coupling at each pixel can allow the signal to be boosted without saturation of the DC component. Such performance however, comes at the price of only 16x16 pixels while a CCD has a much greater pixel count. As suggested in [7], by choosing different wavelengths for different materials, the optimum thermoreflectance coefficient can be chosen, resulting in an overall higher sensitivity. Unlike the PIN array camera, which requires bright illumination of the target, an ICCD is more sensitive to low light levels, which is an advantage for selecting different color LEDs for optimal thermoreflectance properties.

Thermal resolution for CCD based thermoreflectance systems is generally assumed to be limited by the quantization threshold of the camera. Under ideal circumstances a 12-bit CCD would be able to measure temperature induced reflectivity changes with an accuracy equivalent to its quantization limit of $\Delta R/R=1/2^{12}=2.5\text{x}10^{-4}$. However, stochastic resonance processing [8] allows for the recovery of signals well below the quantization limit. Using this method of averaging, the discrete limit for the same 12-bit system can be extended to $\Delta R/R=2.5\text{x}10^{-6}$, with a corresponding expansion in dynamic range from 72dB to 114dB. Combined with appropriate selection of illumination wavelength, stochastic resonance CCD systems have achieved thermal resolution of 10mK and spatial resolution of 250nm [8].

A TE cooled, 14-bit ICCD 128x128 pixels, 500 frames/sec camera from Andor technologies is used as a basis for our ICCD thermal imaging experiments. Even with a state of the art low noise ICCD, some signal processing is required to extract thermal images. Boxcar averaging and Fast Fourier Transform (FFT) of the acquired frames substantially reduces noise to the level that we can achieve about 50mK temperature resolution. By using a 455nm LED, the thermoreflectance coefficient is enhanced [7] compared to the typical white light illumination used with the PIN array. Figure 4 shows the thermal imaging result on a micro-cooler for a 100 time synchronous boxcar average of 340 frames at 340 frames/sec. Figure 4(a) shows the image of the 40x40 micron micro-cooler device, If one compares the result from the PIN array in Figure 3(a) to the ICCD, the gold surface appears different, and this is due to the blue LED used with the ICCD compared to the white light used with the PIN array. Figure 4(b) represents the processed thermal image of the micro-cooler biased at 250mA, and Figure 4(c) shows the phase image. When the device is cycled below the thermal transient, the phase image reveals information about the sign of the thermoreflectance coefficient and hence the thermal signal in the image. Measurements have shown that the substrate material and gold have opposite sign of the thermoreflectance signal, and thus the phase image indicates that the cooling of the device extends a few microns into the substrate. The acquisition time for the ICCD thermal image, Figure 4(b) is thus the same as the PIN array result shown in Figure 3(c), but the noise is slightly higher, reducing temperature resolution from 10mK to about 50 mK.

The thermoreflectance method is also well suited for high speed measurement of thermal transients. Instead of illuminating a large region for imaging, a semiconductor laser can be focused onto a small spot on the sample. The concentrated laser power substantially boosts signal, and because there are no frame rate limitations as with a camera, direct measurement of thermal transients is possible. Figure 5, left, shows a measurement of the thermal transient of 2 different size

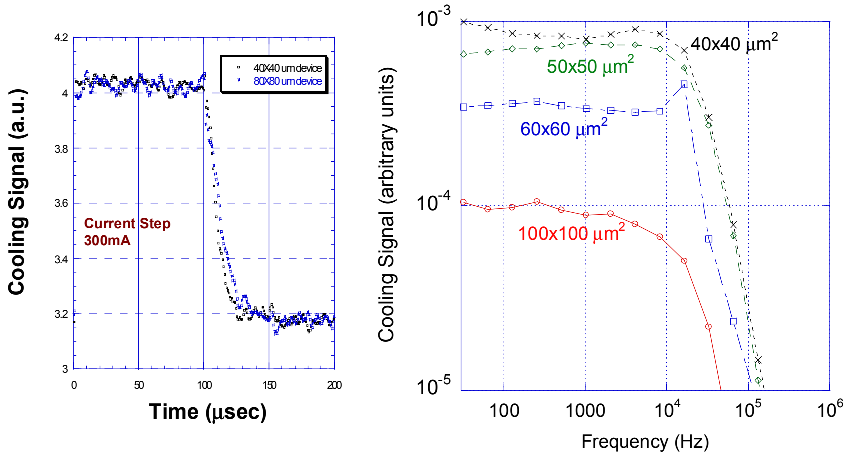

Figure 5. Laser point transient thermoreflectance results. On left is the thermal transient measured in the time domain for two different sized micro-coolers. Right shows a similar measurement acquired in the frequency domain with the lock-in amplifier.

micro-coolers in the time domain [11]. By sweeping the frequency of the lock-in amplifier, one can measure the transient response indirectly in the frequency domain, but with a higher signal to noise (see figure 5.)

8. Pump-Probe Picosecond Thermoreflectance

For nearly two decades, Pump-Probe Picosecond Thermoreflectance (PPPT) has been an effective tool for studying heat transfer in thin films and low dimensional structures (multilayers and superlattices) [12]. In contrast to the 3ω method [13], PPPT allows for the distinction between the thermal conductivity of thin films and their thermal interface resistance [14].

PPPT is a time resolved technique which can be presented as a new alternative to the conventional thermoreflectivity technique or flash technique, on which is added the optical sampling principle via pulse lasers for studying low dimensional structures. The multiple advantages of this technique, being an entirely optical, non-contact and nondestructive method, with a high temporal resolution (of the order of the laser pulse duration < 1ps), and high spatial resolution (10 nm in the cross-plain direction and <1μm in the in-plain direction), have conferred to it a particular place in the field of thermal properties metrology of thin metal and dielectric films. In this technique, an intense short laser pulse "pump" is used to heat the film, and a delayed weak short laser pulse "probe" is used to monitor the reflectivity change induced by the cooling of the thin film after absorption of the pump pulse. Semiconductor and dielectric structures are usually covered by a thin metal film which acts as a thermal capacitor [15].

Determination of the cross-plane thermal conductivity of the sample under study and the thermal interface resistance with the metal film is done by comparing experimental cooling curves to theoretical curves and optimization of free parameters to get the best fit [15].
Figure 6 shows a PPPT experimental result obtained on a Si/SiGe Superlattice covered by a thin Al film over 1ns of the time delay between the pump and the probe. Superimposed upon the thermal decay are acoustic echoes. In fact, PPPT has also proved a powerful tool for the characterization of acoustic properties of thin films and low dimensional structures [16], a technique sometimes called picosecond ultrasonics.

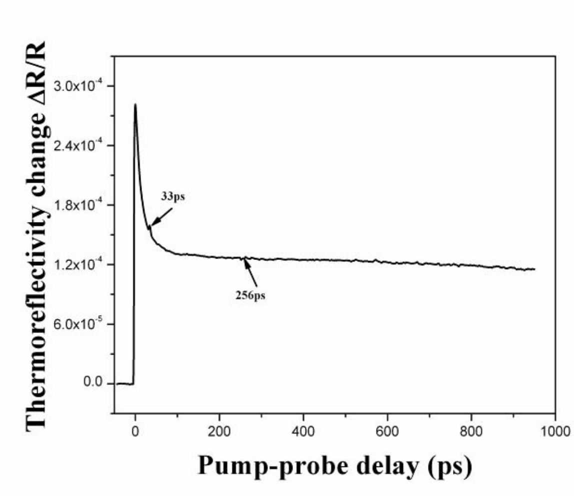

Figure 6. Experimental PPPT result obtained on Si/SiGe Superlattice structure covered by 100nm Al film.

9. Raman Measurements

In Raman scattering, the energy of the photons scattered from the sample is different from the incident photons. This is due to the inelastic scatterings and the exchange of energy with lattice vibrations in the material. The effect of the temperature is well known. We need to analyze the amplitude of the Stokes peaks (down shifted photons) and that of the Anti Stokes peaks (up shifted photons). As temperature increases, the number of phonons in excitation mode increases and this will enhance the ratio between the Anti Stokes and Stokes peaks. Using this ratio, one can calculate the absolute temperature. Invention of lasers and CCD detectors has made Raman temperature sensing practical [17]. One can also use the shift in Raman frequency with temperature. Detailed calibration of the Raman intensity is not necessary, but temperature resolution is smaller.

Raman spectroscopy uses short wavelength from an Ar or He-Ne laser which will allow spatial resolutions of less than 1μm - not accessible using infrared techniques which have diffraction limited spatial resolution of several micrometers. Temperature accuracy of the measurements can vary between 5-20K depending on the Raman spectral resolution, background and optics [18,19]. For practical absolute temperature measurement, it is necessary to calibrate the Raman spectrum prior to the experiment. Recently, temperature characterization using confocal Raman spectroscopy has been studied. This allows acquisition of three dimensional temperature profiles inside the silicon chip near an active device [20].

Figure 7 shows Raman surface temperature measurement results obtained near a 40x40 microns square micro-heater (at a distance of about 1.5μm). The data obtained with a microthermocouple are also shown. With increasing bias current, the surface temperature increases quadratically and the results from Raman and thermocouple are in good agreement.

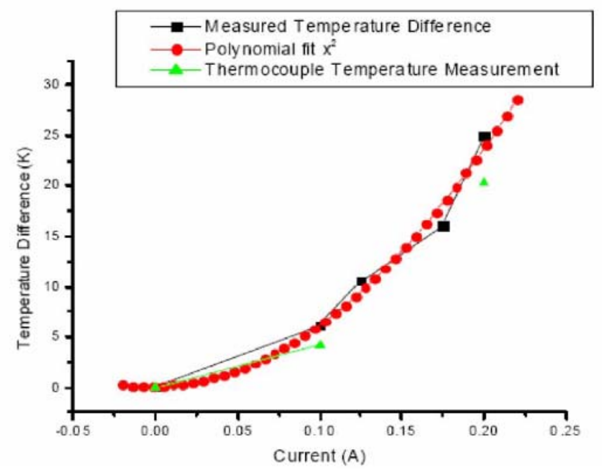

Figure 7. Thermocouple and Raman measurements of the surface temperature as a function of microheater bias current.

10. Built in Temperature sensors

In many situations it is desirable to fabricate a thermal sensor directly into the device under test. Altet[2] uses the example of two separate devices each of which thermally drives the emitter of a bipolar transistor into a differential amplifier. Because of the high sensitivity of the differential amplifier, high temperature resolution is achieved. Usually the geometrical layout is extremely important and the spatial resolution is limited.

References

[1] J. Kolzer, E. Oesterschulze, and G. Deboy, 1996, “Thermal Imaging And Measurement Techniques For Electronic Materials And Devices,” *Elsevier. Microelectronic Engineering*, vol.31, no.1-4, Feb., pp. 251-70. Netherlands.

[2] J. Altet, W. Claeys, S. Dilhaire, A. Rubio, “Dynamic Surface Temperature Measurements in ICs,” *Proceedings of IEEE*, vol. 94, pp. 1119-1533.

[3] A. Cutolo, 1998, “Selected Contactless Optoelectronic Measurements For Electronic Applications,” *Review of Scientific Instruments*, vol. 69, pp. 337-60.

4] A. Csendes, V. Szekely, and M. Rencz, 1996, “Thermal Mapping With Liquid Crystal Method,” *Microelectronics Engineering*, vol 31, pp 281-290.

[5] A. Vertikov, M. Kuball, A. V. Nurmikko, and H. J. Maris, 1996, “Time-Resolved Pumpprobe Experiments With Subwavelength Lateral Resolution,” *Applied Physics Letters*, vol. 69, pp. 2465-7.

[6] L. Shi, O. Kwon, A. C. Miner, and A. Majumdar, 2001, Design and batch fabrication of probes for sub-100 nm scanning thermal microscopy, J. Microelectromech. Syst., vol. 10, no. 3, pp. 370–378.

[7] G. Tessier, S. Hole, and D. Fournier, 2001, “Quantitative Thermal Imaging By Synchronous Thermoreflectance With Optimized Illumination Wavelengths”, *Applied Physics Letters*, Vol. 78, No. 16: pp. 2267-2269.

[8] Lueerssen, Hudgings, Mayer, Ram, 2005, “Nanoscale Thermoreflectance With 10mk Temperature Resolution Using Stochastic Resonance”, *21st IEEE Semi-Therm Symposium*, San Jose, Ca.

[9] J. Christofferson and A. Shakouri, Jan. 2005, “Thermoreflectance Based Thermal Microscope”, *Review of Scientific Instruments*, 76, 024903-1-6.

[10] A. Shakouri, J.E. Bowers, 1997, “Heterostructure Integrated Thermionic Coolers”, *Applied Physics Letters* 71, 1234

[11] A. Fitting, J. Christofferson, A. Shakouri, F. Xiofeng, Z. Gehong, C. LaBounty, and J. E. Bowers, Ed. Croke, Nov. 2001, “Transient Response Of Thin Film SiGe Micro Coolers”, *International Mechanical Engineering Congress and Exhibition (IMECE 2001),* New York, NY.

[12] A. Paddock and G. L. Eesley, 1986, “Transient thermoreflectance from thin metal films”, *J. Appl. Phys.* 60, 285.

[13] D. G. Cahill, 1990, “Thermal conductivity measurement from 30 to 750 K: the 3 omega method”, *Rev. Sci. Instrum*, 61, 802.

[14] D. G. Cahill, et al., 2003, “Nanoscale thermal transport”, *J. Appl. Phys*. 93, 793.

[15] Y. Ezzahri, et al., 2005, “Study of thermomechanical properties of Si/SiGe superlattices using femtosecond transient thermoreflectance technique”, *App. Phys. Let*, 87, 103506.

[16] C. Rossignol, et al., 2004, “Elastic properties of ultrathin permalloy/alumina multilayers films using picosecond ultrasonics and Brillouin light scattering”, *Phys. Rev. B*, 70, 094102.

[17] M. Malyj and J.E. Griffiths, 1983, *Appl. Spectrosc*. 37, 315.

[18] F. LaPlant, G. Laurence and D. Ben-Amotz, 1996, *Appl. Spectrosc* 50,1034.

[19] T. Yamaguchi, M. Ohkubo, N. Ikeda and T. Nomura 1999, Furukawa Review, 18, 73.

[20] J. Shabani, X. Wang and A. Shakouri, “3D temperature measurement in IC chips using Raman spectroscopy”, to be published in the proceeding of Material Research Society Meeting, (San Francisco, Apr., 2007).