

3D Temperature Measurement in IC Chips using Confocal Raman Spectroscopy

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ABSTRACT

We have demonstrated the feasibility of depth and surface temperature measurements in active areas of semiconductor devices using confocal Raman spectroscopy. Using micro heaters, we created a 3D temperature profile across micron size volume. We determined the temperature profile with sub-micron resolution and obtained good agreement with calculations. Theoretical uncertainty in temperature determination has been discussed and generalized for 3D measurements.

INTRODUCTION

Thermal issues are one of the key factors that limit the performance and reliability of modern ICs. On one hand, as device feature sizes shrink down (to submicron scale) and switching speed increases, there is a large localized temperature non-uniformities (hot spots). For example, Temperature inside a microprocessor chip could vary 5 to 30C from one location to another [1]. On the other hand, failure rates resulting from electro migration and oxide breakdown are exponentially dependant on temperature. Therefore, temperature measurement technique at micron scale is of particular interest, especially in the cases where direct contact measurements can not be accomplished.

Raman spectroscopy is a powerful optical method for semiconductor material property characterization. Confocal Raman microscopy is an enhanced technique based on Raman spectroscopy, and it provides information about depth and buried structures of thin samples. The confocal microscopy provides not only the highest spatial resolution, but also allows the acquisition of depth profiles in three-dimensional thin structures. This method has been extensively used in polymers study and chemistry [2].

The present work is aimed to investigate three dimensional temperature profiles in micron size hot spots on the semiconductors chips. The feasibility of using Raman spectroscopy for remote temperature measurement in depth was investigated. This is of particular significance because it could potentially be used to provide information about buried structures in

heterostructures devices. For example the effect of the buffer layer used in lattice mismatched structures could be studied through the accurate determination of temperature profile. As for today, no technique has been reported that is suitable for direct depth temperature measurement. Invasive methods such as thermocouples generally only yield information about the surface temperature. Non contact methods of temperature measurement include near infrared thermo-reflectance has been used to detect temperature of active devices from the backside of Si substrate [3]. However, dominant reflection from the semiconductor/metal interface makes it impossible to obtain a 3D temperature distribution. Apart from the ability of depth measurement with confocal Raman spectroscopy, the sub-micron spatial resolution can be achieved.

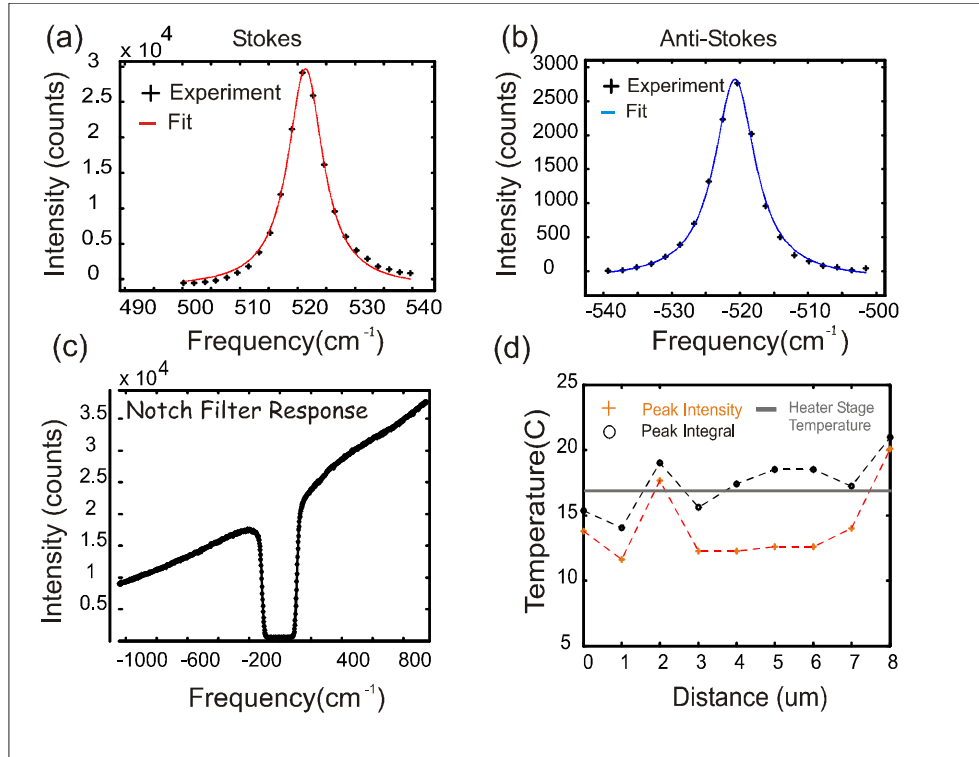


Figure 1. (a) Stokes band of Raman spectra for Si, the solid line is the Lorentzian fit to the data (b) Anti-Stokes band of Raman spectra (c) Confocal system notch filter response due to white light (d) Temperature calculated from equation 1. along 8 μm path.

EXPERIMENT

We used a micro-Raman system from JobinYvon/Horiba, with an excitation laser at 514.5nm wavelength. Scattered laser light was rejected by a notch filter. We used 600 grooves/mm grating in combination with multi-channel detection to measure Stokes and anti-Stokes bands simultaneously. Sample was mounted on a high precision x-y translation stage. Sample substrate temperature was fixed at 290K by a thermoelectric cooling (TEC) stage. The laser power was limited below the threshold value where the surface temperature starts to rise due to heating by incident light.

Raman scattering is a phenomenon whereby when a specimen is irradiated with light, incident photons undergo inelastic scattering due to lattice vibration specific to the material of the specimens. So that the frequency of the irradiating light shifts by an amount equivalent to the lattice vibration frequency (ν_l). The effect of temperature is well known on the intensity of the Stokes and anti-Stokes lines in a Raman spectrum [4]. The number of atoms in each state, and therefore the anti-stokes/stokes intensity ratio obeys Boltzmann factor relation:

$$r = \frac{n_{as}}{n_s} = \frac{(\nu_0 - \nu_l)^3}{(\nu_0 + \nu_l)^3} \exp\left(-\frac{h\nu_l c}{kT}\right) \quad (1)$$

Equation (1) is based on an assumption that Boltzmann relation holds over the range of interested frequencies and temperatures. Figure 1(a) and (b) shows data for the peak of Si at 520cm^{-1} , where the solid line is a lorentzian fit to the data. We calibrated the notch filter response of our system by shining uniform white light through the optics and measuring the spectra. Figure 1(c) shows the result. By applying an inverse filter response to the lorentzian peaks in figure 1(a) and (b), we calculated the temperature using equation 1 with two different methods. First we have used the peak intensities of Stokes and anti-Stokes peak. Second, we have integrated the peak area within its bandwidth. Temperature results versus distance (0~8um along x direction) are shown in figure 1(d). Without introducing any fitting parameter the temperatures has been calculated and are within $\pm 3K$ of the stage temperature.

Although by using low-noise detectors, one can improve the Raman temperature measurement; there is a theoretical limitation on the accuracy of any measured temperature [5]. The thermodynamic uncertainty relation between energy and temperature shows that:

$\Delta\left(\frac{1}{T}\right)\Delta U \approx k_B$, where U is the energy and T is the temperature. If the photon energy has been transferred totally to a two level system, we can write the temperature uncertainty in terms of wavelength uncertainty for temperature measurement: $\frac{\Delta T}{T^2} \frac{\Delta \lambda}{\lambda^2} \approx \frac{k_B}{hc}$. To deduce the temperature

uncertainty from the Raman spectroscopy, we derive that $\Delta T \geq \left(\frac{kT^2}{hc} \frac{\lambda_{Laser}^2}{\lambda_{shift}}\right)$. Typical number for

this uncertainty for room temperature and 514.5nm wavelength is about 0.07 Kelvin which become appreciable when using longer wavelength lasers (0.28 Kelvin at 1um laser source wavelength). This shows a fundamental uncertainty limit in spectroscopy analysis. However, the dominant uncertainty usually lies in detector. This can be considered as an uncertainty in stokes and anti-stokes peak intensities which will cause the uncertainty in temperature, as shown in equation (2).

$$n_{as} + \Delta n_{as} = (n_s + \Delta n_s) \frac{(\nu_0 - \nu_l)^3}{(\nu_0 + \nu_l)^3} \exp\left(-\frac{h\nu_l c}{k(T + \Delta T)}\right) \quad (2)$$

Usually, the variation in temperature is small respect to the absolute temperature. Therefore we can approximate the exponential term and simplify the equation for temperature uncertainty:

$$\Delta T = \pm \left(\frac{kT^2}{hv_l c} \right) \frac{\Delta n_{as} \frac{(v_0 + v_l)^3}{(v_0 - v_l)^3} - \Delta n_s \exp\left(\frac{-hv_l c}{kT}\right)}{(n_s + \Delta n_s) \exp\left(\frac{-hv_l c}{kT}\right)} \quad (3)$$

We are able to find an approximation for uncertainties based on the noise distribution. Assuming that stokes and anti-stokes peaks are Poisson like, we can use $\Delta n: \sqrt{\langle n \rangle}$ and after simplification we get:

$$\Delta T = \pm \left(\frac{kT^2}{hv_l c} \right) \frac{\pm \frac{(v_0 + v_l)^{3/2}}{(v_0 - v_l)^{3/2}} \exp\left(\frac{hv_l c}{2kT}\right) m1}{\sqrt{n_s} \pm 1} \approx \pm \left(\frac{kT^2}{hv_l c} \right) \frac{\pm \exp\left(\frac{hv_l c}{2kT}\right) m1}{\sqrt{n_s} \pm 1} \approx \pm \left(\frac{kT^2}{hv_l c} \right) \frac{\exp\left(\frac{hv_l c}{2kT}\right)}{\sqrt{n_s}} \quad (4)$$

Figure 2 shows dependence of error in temperature as function of Raman shift and temperature.

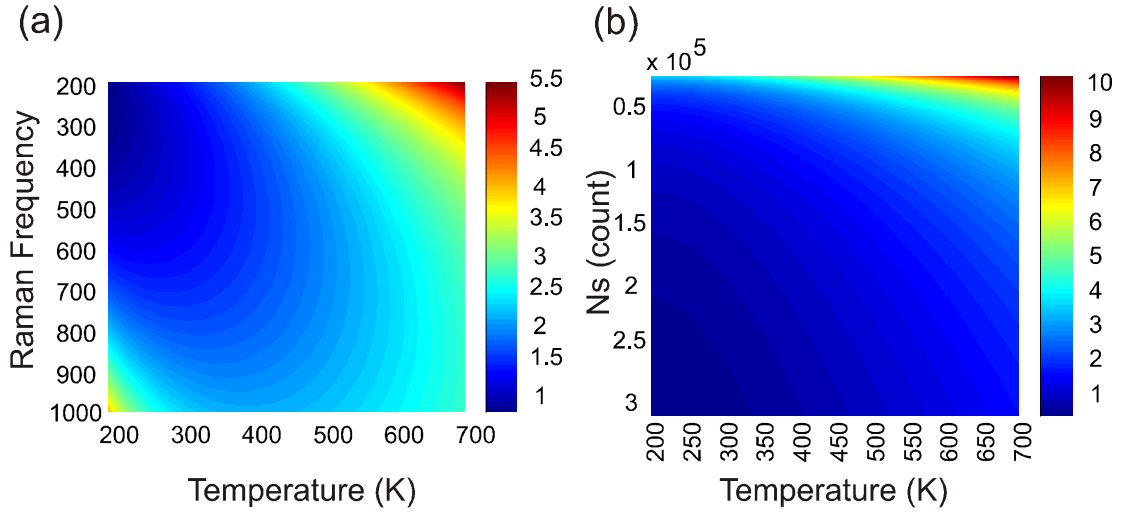


Figure 2. (a) Temperature uncertainty due to detector map for different temperature and Raman shift frequency (b) temperature uncertainty map for different temperature and stokes count for Si 520 cm^{-1} band.

It is clear that, depending on the Raman shift, there is always an uncertainty that is inherent in the detection process. The predicted temperature uncertainty at room temperature for 500 cm^{-1} is 2.5 K . This can be compared to the room temperature error from figure 1(d) where the experimental temperature uncertainty was approximately 6 K .

To perform a 3D temperature measurement, we have fabricated thin film micro-heaters on a Si chip having buried super lattice heterostructures. The fabrication and structure details can be found elsewhere [6]. The $40\mu\text{m} \times 40\mu\text{m}$ heater is capable of creating 20 K temperature difference by passing 200 mA . Figure 3(a) and (b) show typical Raman spectra for stokes and anti-stokes as a function of depth. The peak magnitude is attenuated due to light absorption inside material. The decay shows an absorption coefficient about $1\mu\text{m}^{-1}$, which is in agreement with values from literature [7]. We have performed a surface and depth scanning of Raman spectra at the positions shown in the Figure 3(c) and (d). These two graphs show the measured

temperature profiles for depth and surface scan, respectively. Dashed blue lines are exponential fitting curves. Experiment results show good agreement with finite element method simulation [8] A faster decay of temperature on depth scan has been observed.

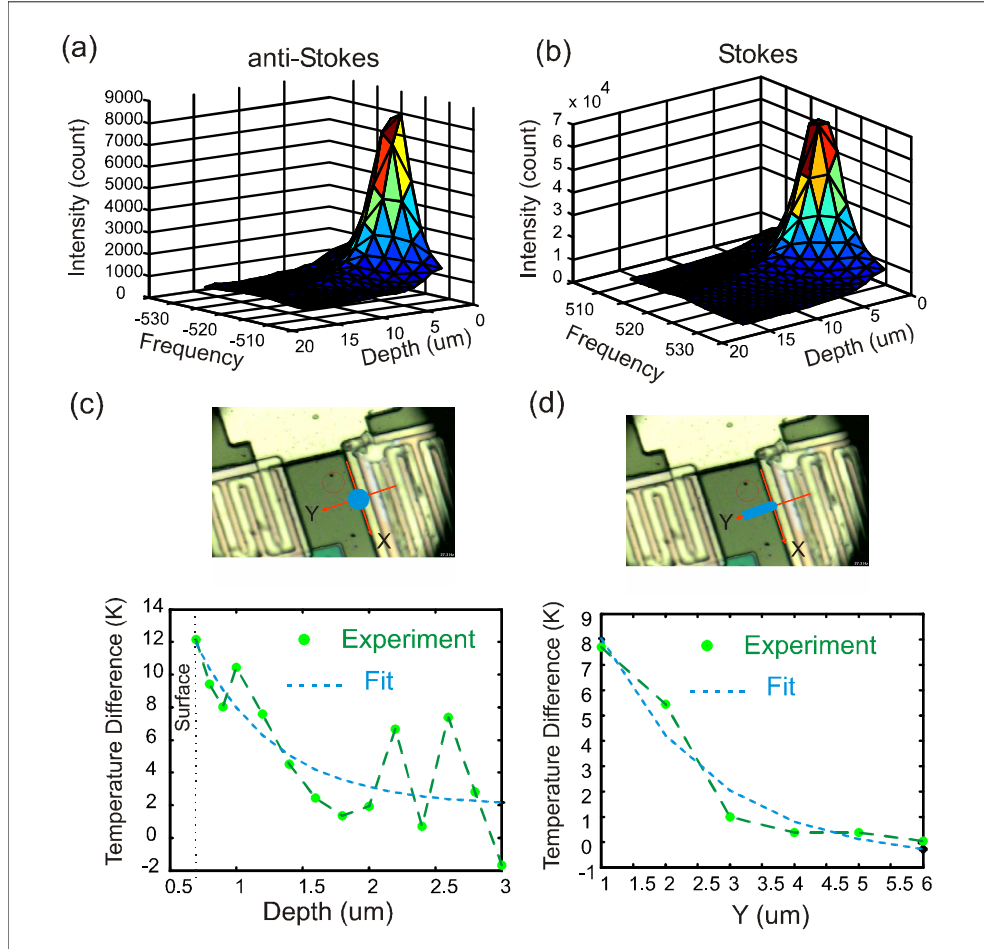


Figure 3. (a) anti-Stoke Raman spectra for different Z-scan (b) Stokes spectra for different Z-scan (c) temperature has been derived from confocal microscopy (d) x-scan temperature profile

For a 3D Raman temperature analysis, one can extend the calculation for temperature uncertainty as:

$$\Delta T = \pm \left(\frac{kT^2}{hv_l c} \right) \frac{\exp\left(\frac{hv_l c}{2kT}\right)}{\sqrt{n_s}} \exp(\alpha L/2) \quad (5)$$

Where α is the absorption coefficient for Si. From the decay of laser we have derived that the absorption coefficient is about $1 \mu m^{-1}$ for this sample. For temperature uncertainty we find an exponential increase with depth. Table 1 shows typical number for uncertainty for different depth. This high absorption will pose serious problem for extending the depth temperature monitoring. One solution to this problem is to use laser wavelength in the low absorption spectra.

For Si, at 1 μ m the absorption is about 0.001(1/ μ m). Another limitation of confocal microscopy comes from the fact that the material refraction index is high ($n \sim 3.4$) [9,10]. So in Z-scan we are probing more depth than the real Z movement. This is due to the fact that light rays get closer to perpendicular line as they enter from air into Si. This produces a challenge to design and investigate the limit of confocal Raman microscopy in temperature measurement and need further study.

	L=0.5 μ m	L=1 μ m	L=1.5 μ m	L=2 μ m	L=2.5 μ m	L=3 μ m
ΔT_{3D}	$\pm 1.6K$	$\pm 2K$	$\pm 2.6K$	$\pm 3.4K$	$\pm 4.4K$	$\pm 5.6K$

Table 1. Temperature uncertainties for different depth has been shown for Si

CONCLUSIONS

We have shown that confocal Raman spectroscopy is an effective tool for monitoring temperatures in buried semiconductor devices as well as surface temperatures. In order to provide a guideline for further development and applications, we have also studied the uncertainty due to experimental and theoretical limitations. We have shown the feasibility of mapping 3D temperature without fitting parameter. Using micro heaters we created a 3D temperature profile across a minute region where we showed that confocal Raman can be applied for depth temperature measurements with submicron resolution.

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