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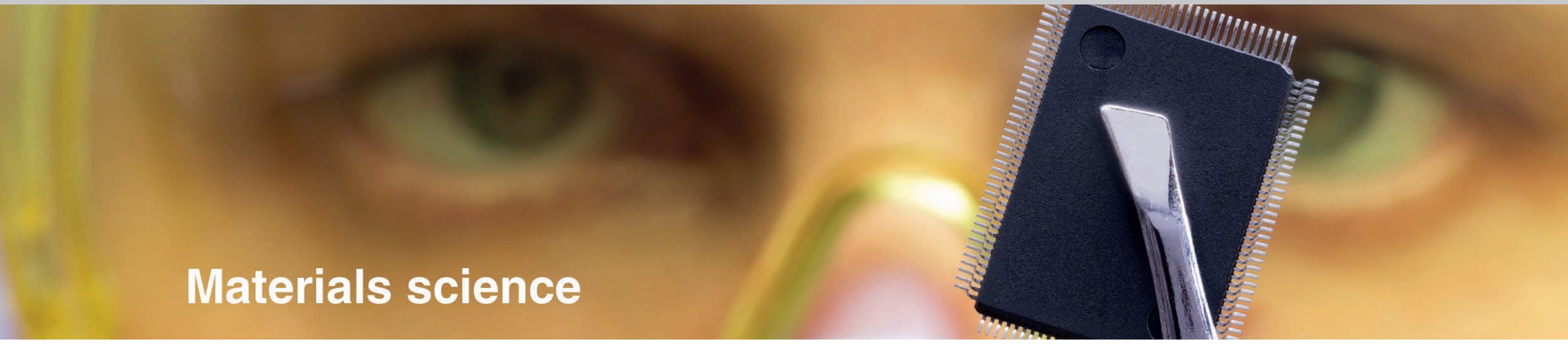
Analyse compound semiconductors with the inVia™ Raman microscope



Over the last decade compound semiconductors have attracted a great deal of attention because they offer properties suitable for next generation devices in a wide range of application areas. Historically, the fabrication of these devices has been hindered by material challenges. While these have mainly been conquered at the research level, problems still persist when scaling up to industrial production.

Renishaw's inVia Raman microscope is a non-invasive, non-destructive characterisation tool which provides sub-micrometre information on the vibrational, crystal and electronic structure of materials. When measuring compound semiconductors the system can be used to collect Raman and photoluminescence (PL) spectra allowing the following information to be obtained:

- Chemical identification
- Alloy percentages
- Strain/stress
- Dopant concentrations
- Thin film thickness
- Crystal structure type and orientation
- Crystal quality and defect levels
- Sample uniformity
- Particulate analysis e.g. SiC inclusion
- Contamination identification
- Sample topography (wafer bow)
- Sample temperature (in operating devices)

In this application note we provide a few examples to demonstrate the power of the inVia Raman microscope and its ability to investigate material challenges.

Renishaw inVia Qontor® confocal Raman microscope

Evaluation of AlGaN/GaN heterostructures

For many years the development of GaN based devices was hindered by low quality material. While this is no longer the case, the scale-up required for mass production is still challenging, as is the process for getting new equipment online and operating at optimum efficiency. Here we illustrate how the inVia Raman microscope can be used as a quality control tool to investigate wafers. The wafer analysed is composed of a 30 nm $Al_{0.28}Ga_{0.72}N$ layer on a 2 µm GaN layer grown on a 300 µm sapphire substrate. Raman and PL spectra were collected with different laser excitation wavelengths allowing different layers in the structure to be investigated.

Figure 1 and Figure 2 illustrate spectra collected from the different layers of the structure, using different excitation wavelengths. Analysis of these modes allows crystal quality, stress, free carrier concentration and aluminium content to be quantified.

In this case, analysis of the GaN layer illustrates a high level of uniformity with subtle variations in stress as seen in the E_2 peak position, Figure 3 a). The AlGaN layer was found to have significant variation in Al concentration at the edge of the wafer (up to 5 mm inward radius) of as much as 0.5%. One of the added benefits of the inVia Qontor Raman microscope is that the topography of the sample is measured simultaneously to Raman measurements, allowing the bow of the wafer to be determined. This is illustrated in Figure 3 b) and c).

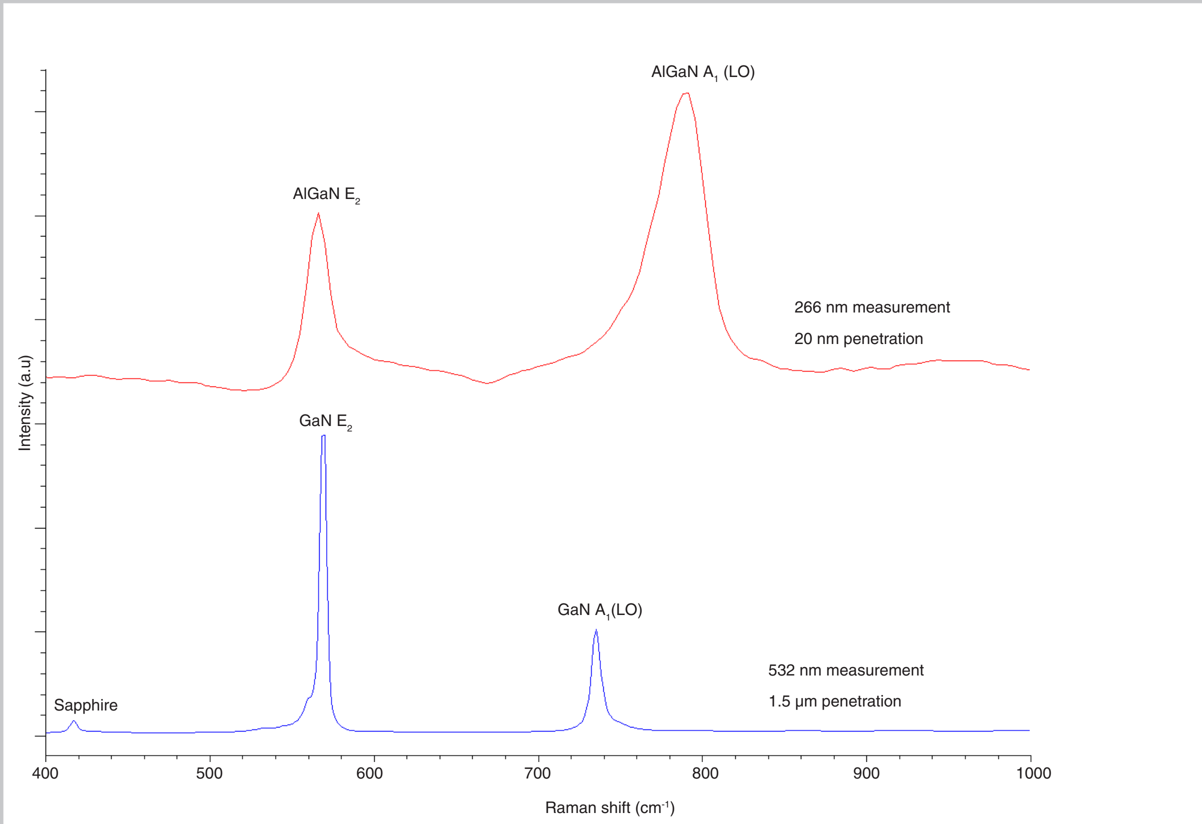


Figure 1. Raman spectra of different layers in a AlGaN/GaN heterostructure. The depth probed by Raman spectroscopy is dependent on the excitation wavelength. Here a UV excitation laser is used allowing the ultrathin AlGaN layer to be measured.

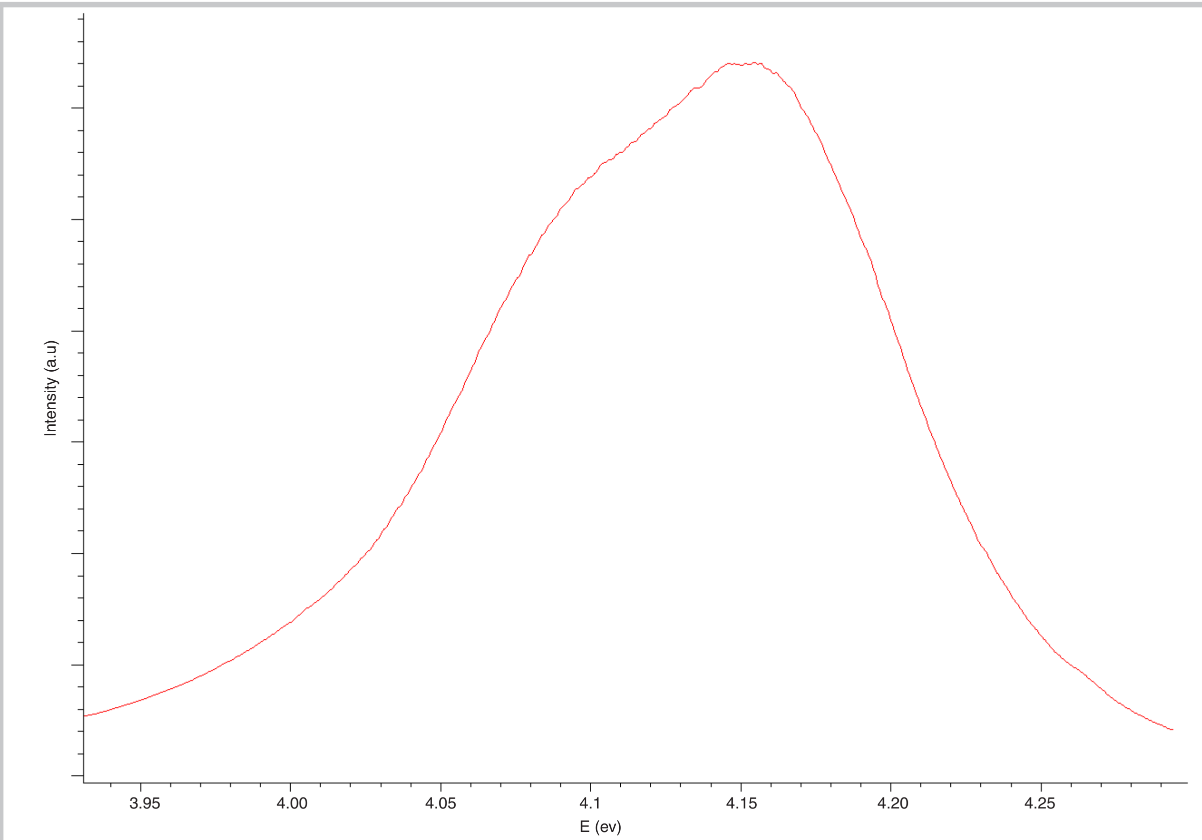


Figure 2. Photoluminescence (PL) spectrum of the AlGaN layer.

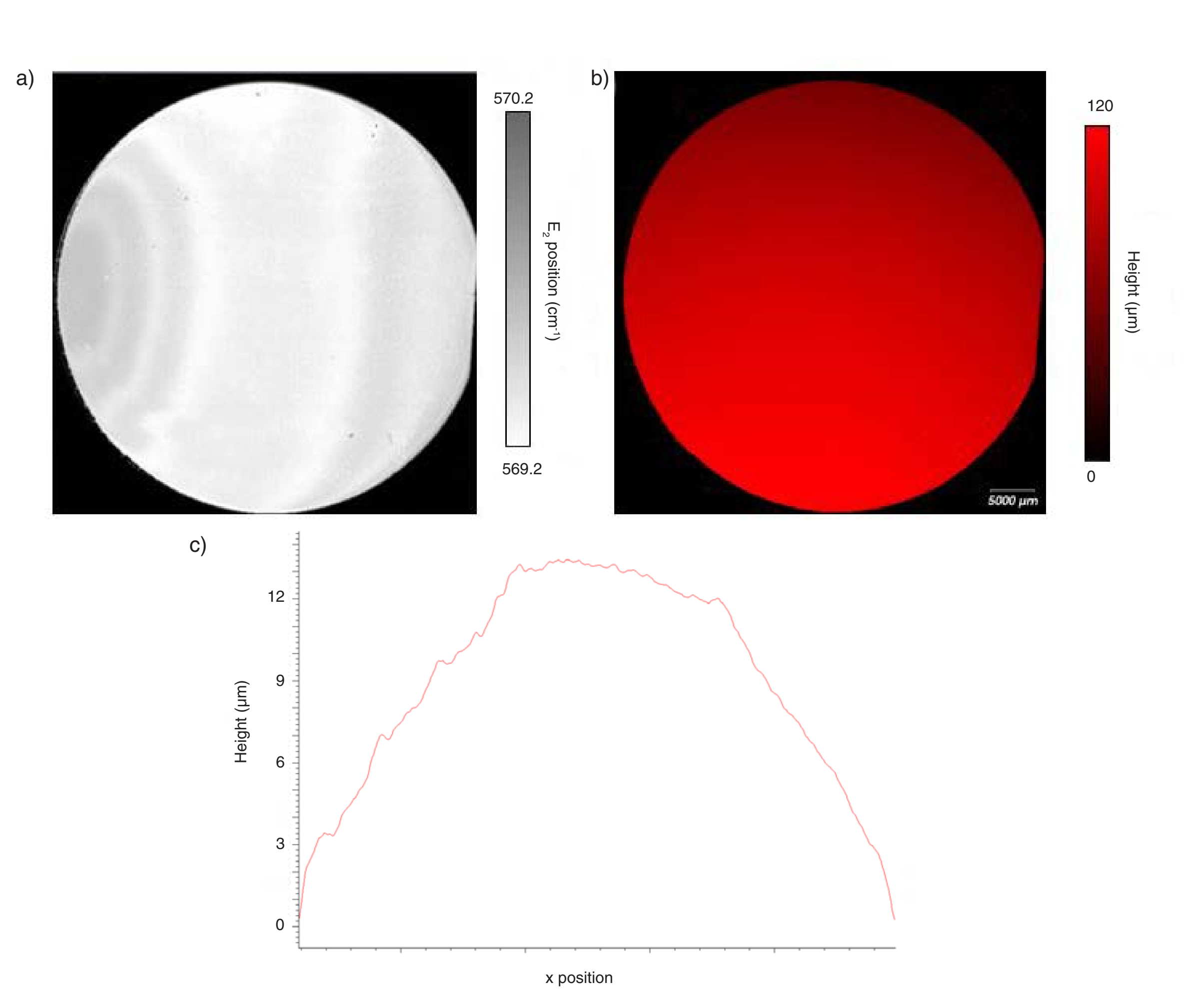


Figure 3. a) peak position of the E_2 mode illustrating stress across the wafer, b) topography image collected during Raman measurement, c) wafer bow (wafer tilt subtracted).

3D microstructure and stress characterisation of novel GaN structures

Threading dislocations in GaN act as scattering centres for both light and charge carriers, and can hinder performance in optoelectronic devices, such as LEDs. Better understanding and characterisation of the spatial distribution of threading dislocations allows for optimised layer growth using more novel methods. Here we characterise the microstructure and stress in a sample, grown with the epitaxial lateral overgrowth (ELOG) technique, using growth apertures that comprise a regular array of nano-dashes in order to control the coalescence process.

Raman measurements were conducted using a Renishaw inVia Raman confocal microscope equipped with a 150 mW 532 nm laser excitation source. Figure 4 illustrates a typical spectrum collected from the sample. 3D Raman data were collected from the sample, after growth, by focusing the laser at a range of depths. For comparison SEM images were collected during the growth process by interrupting growth and transferring the sample to a SEM. These images are shown in Figure 5.

Raman intensity images clearly illustrate the microstructure of the sample, reveal regions of increased dislocation density, and show excellent agreement with the SEM images. This demonstrates that after growth Raman can be used as a substitute for more complex interrupted growth and SEM analysis.

By examining the peak position of the E_2 Raman band (Figure 4) it is possible to investigate the distribution of stress in the sample, with a change of 2.7 cm^{-1} corresponding to 1 GPa. At a depth of -5 µm there is a clear correlation between the microstructure (intensity image) and stress distribution. Approaching the surface, the peak position variation in the layer becomes more consistent and upshifts towards the expected stress-free value (567.5 cm^{-1}) as illustrated in Figure 6. This demonstrates that the novel structure results in a reduction of stress magnitude by concentrating the stress in the layer as designed.

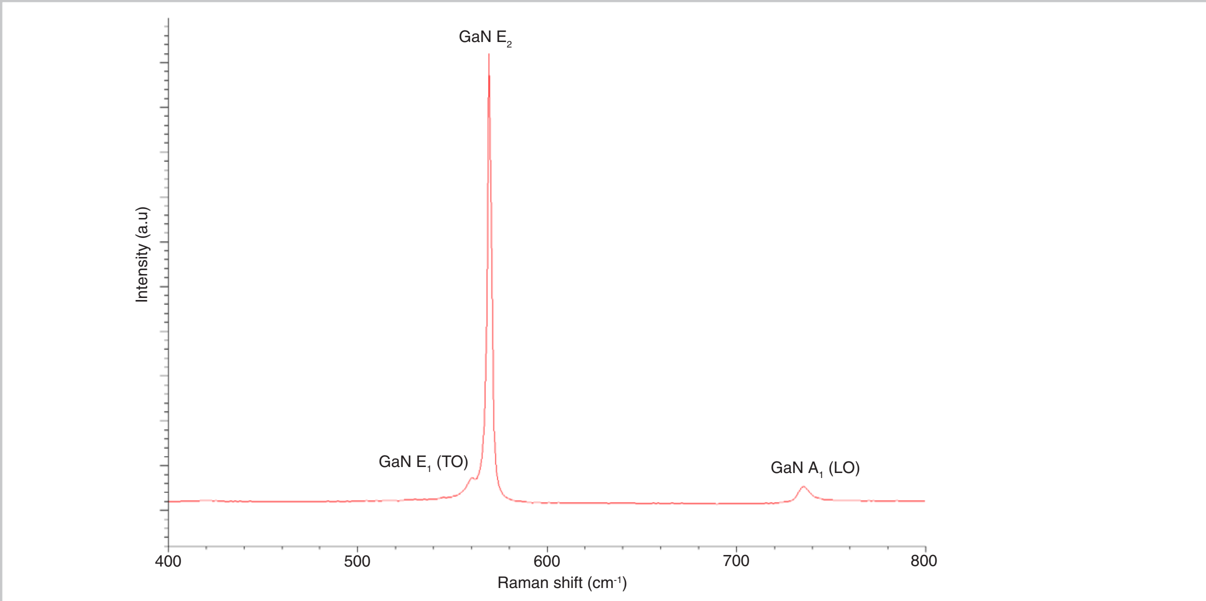


Figure 4. A typical spectrum from the novel nanostructure with GaN Raman modes labelled. The E_1(TO) mode is present due to off axis growth of the material.

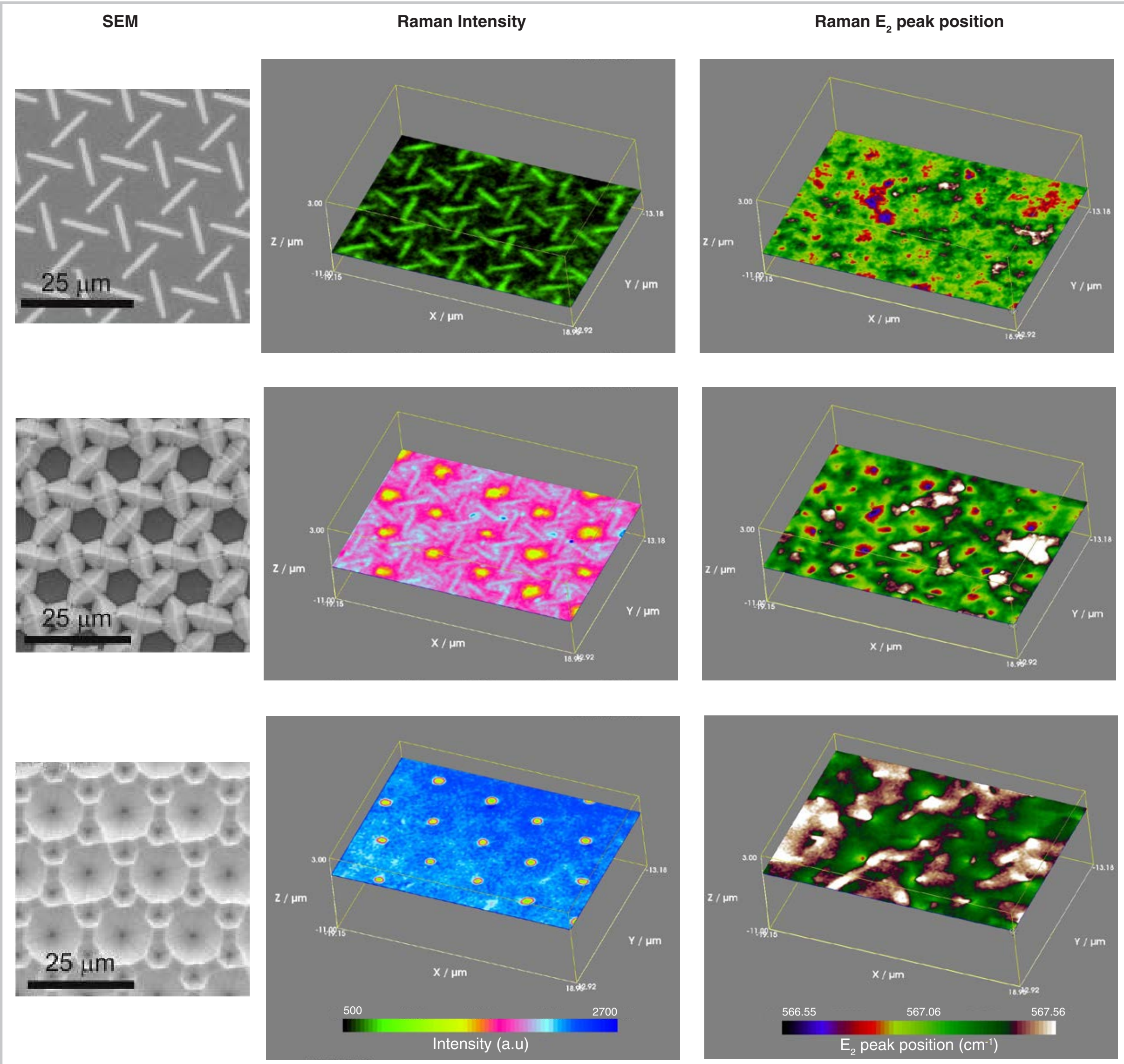


Figure 5. SEM and Raman images collected from the sample, z=0 µm is the surface. Raman intensity images illustrate the microstructure of the sample and correlate well with the SEM images. The peak position of the E2 band moves towards the stress-free value at the surface. The Raman measurement area was 38.1 µm × 26.1 µm × 14 µm, with a step size 0.3 µm × 0.3 µm × 2 µm.

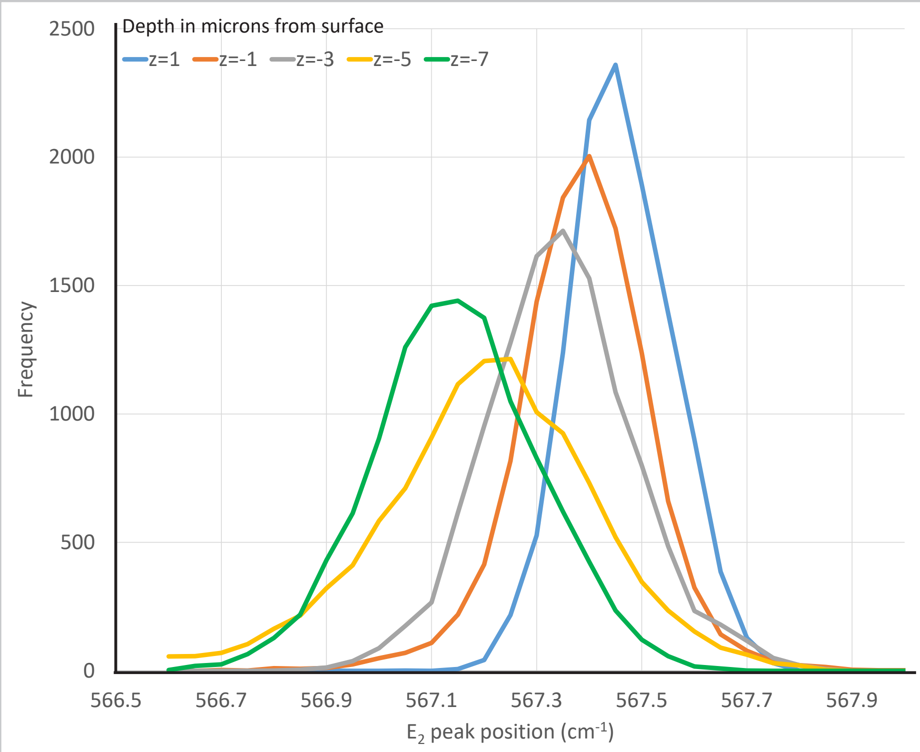


Figure 6. Histogram illustrating the variation in E_2 peak position for different depths in the structure. The typical peak position upshifts towards the stress-free value, 567.5 cm^{-1} and the distribution sharpens when moving from bulk to the surface of the sample.

Raman thermography

Peak operating device temperature is a critical parameter for estimating device lifetime and is used to simulate lifetime testing. Traditional methods (electrical and IR) have poor spatial resolution and typically give average temperatures across the device, often massively underestimating the peak temperature. Work pioneered by Martin Kuball *et al.* has demonstrated that Raman spectroscopy is an excellent tool for measuring peak operational temperature in active devices in both DC [1] and pulsed mode [2].

Raman thermography works on the principle that the phonon energies of a material change with temperature. Figure 7 illustrates the change in Raman band positions for an on and pinched off HEMT device. This change can be directly correlated with temperature. By conducting a Raman map over a device, it is possible to determine its temperature distribution with sub-micron resolution. Figure 8 illustrates the temperature distribution between the source drain for HEMTs fabricated on sapphire and SiC substrates. Here it can be seen that when operating devices at a peak temperature of 180 °C, devices on SiC can be run at more than 3× the power density. This is due to the better thermal conductivity of SiC in comparison to sapphire. In addition, the device on sapphire has a much flatter temperature distribution as the GaN has a higher thermal conductivity than sapphire resulting in horizontal spreading of the heat being preferred to vertical extraction.

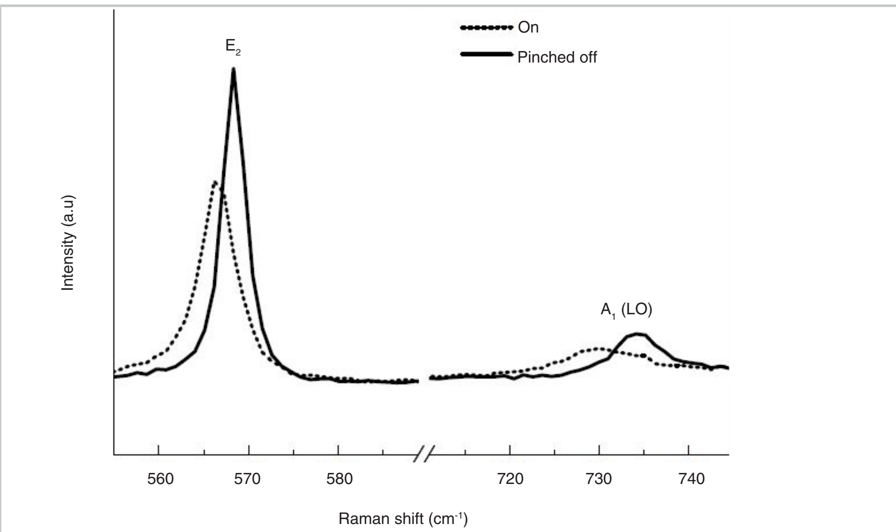


Figure 7. Comparison of Raman spectra for an on (hot) and pinched off device (cold).

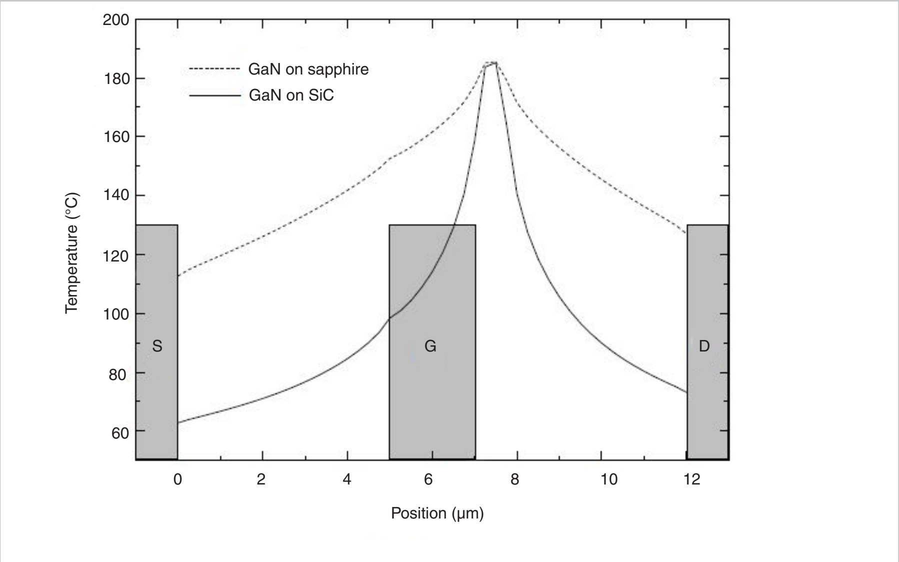


Figure 8. Temperature distribution of HEMTs fabricated on sapphire and SiC substrates. Devices were operated at different power densities to produce a peak temperature of 180 °C.

Conclusion

These examples illustrate how the inVia Raman microscope can be used to investigate the properties of compound semiconductors including:

- Chemical composition
- Stress/strain
- Device temperate
- Crystal structure
- Defects
- Photoluminescence

For more information on the Renishaw inVia Raman microscope and its capabilities when applied to compound semiconductors please contact your local Renishaw office

Acknowledgements

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References

[1] Kuball, M., Hayes, J. M., Uren, M. J., Martin, I., Birbeck, J. C. H., Balmer, R. S., & Hughes, B. T. (2002). Measurement of temperature in active high-power AlGaN/GaN HFETs using Raman spectroscopy. IEEE Electron Device Letters, 23(1), 7-9.

[2] Kuball, M., Riedel, G. J., Pomeroy, J. W., Sarua, A., Uren, M. J., Martin, T., ... & Wallis, D. J. (2007). Time-resolved temperature measurement of AlGaN/GaN electronic devices using micro-Raman spectroscopy. IEEE electron device letters, 28(2), 86-89.