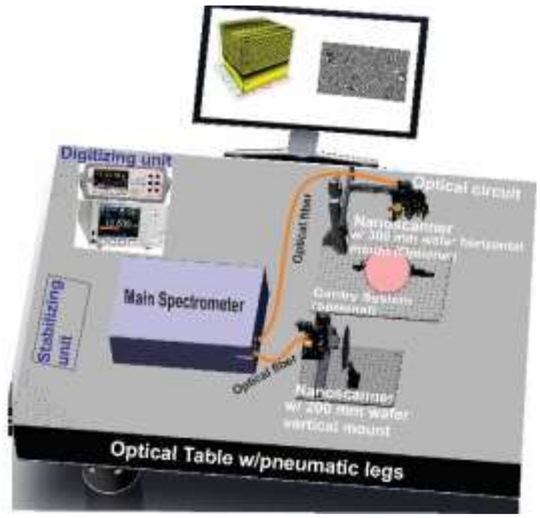
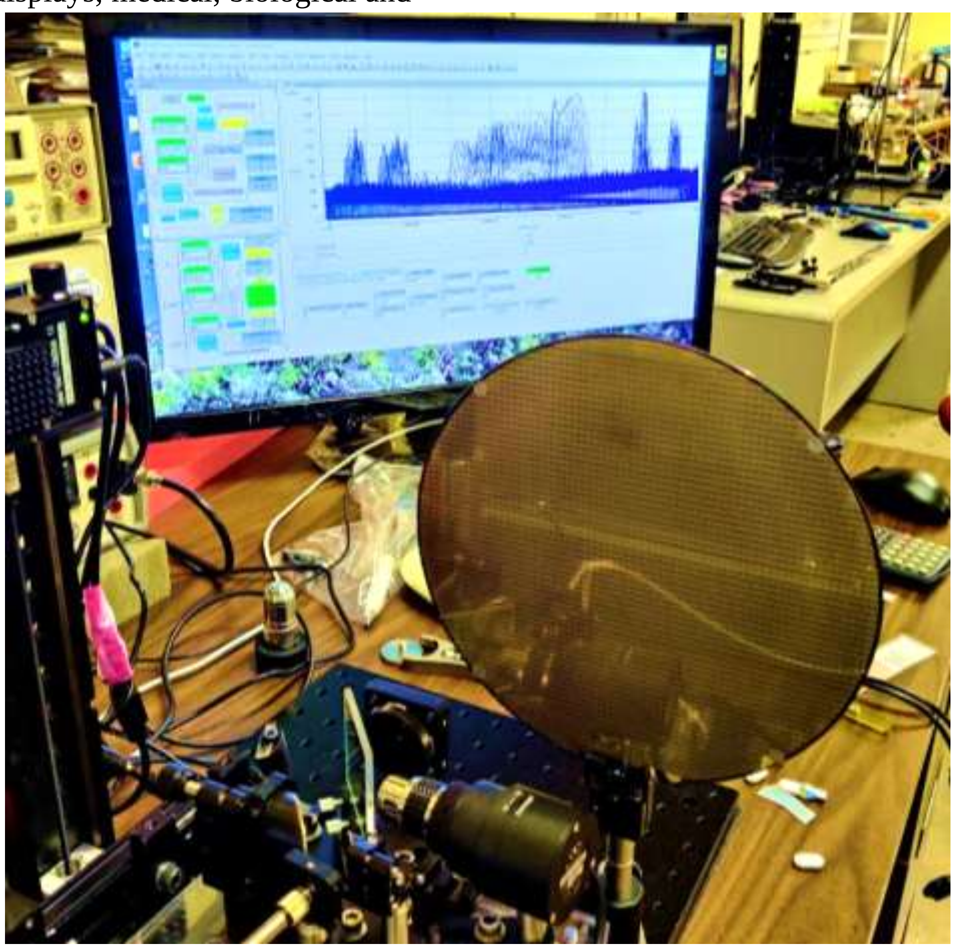
April 15, 2021

Terahertz Nanoscanning Spectrometer & 3D Imager (TNS3DI)
A new tool for semiconductor metrology



The Applied Research & Photonics model TNS3DI – Terahertz Nanoscanning Spectrometer and 3-D Imaging system, utilizing its proprietary Dendrimer Dipole Excitation technology to deliver what we have demonstrated is unsurpassed analytical, and imaging capability to enable the revolution in advanced materials and structures. The system has demonstrated the ability to pinpoint and catalyze the deep investigation and understanding scientists and engineers all over the world have been searching for, to solve some of the most challenging problems in advanced materials, semiconductors, and related devices, photonics and optoelectronics including displays, medical, biological and pharmaceutical applications, and atomic/nuclear level investigations. Two models are available: (1) TNS3DI-FC, fiber-coupled beam delivery for the most versatility, X, Y = 200 mm standard, up to 450 mm option. (2) TNS3DI-Fs, free-space beam delivery for small samples, X, Y $\leq$ 100 mm. The TNS3DI delivers combined capabilities of AFM, SEM, TEM, and Time-domain Spectrometer. It is also a diagnostic tool to be used in for the US Military and government laboratories who rely heavily on semiconductors (microchips) in day-to-day operations.



Semiconductor and nanomaterials

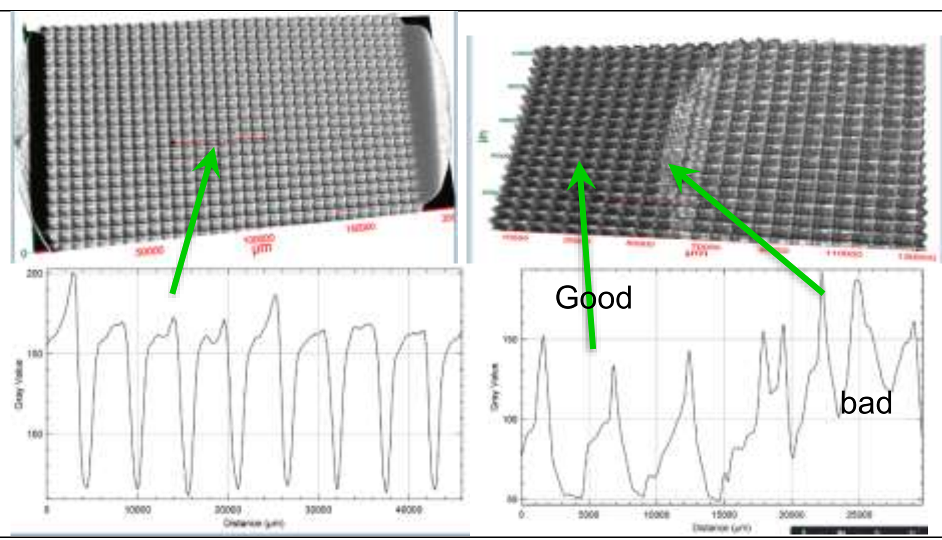
Terahertz radiation (T-ray) can penetrate semiconductors and most non-metals, so, one can probe both the surface and sub-surface regions in a non-destructive and non-contact route. Layer-by-layer imaging allows inspection of layers on a wafer one at a time. A few examples cited below showing the strengths. Other test protocols may be developed.

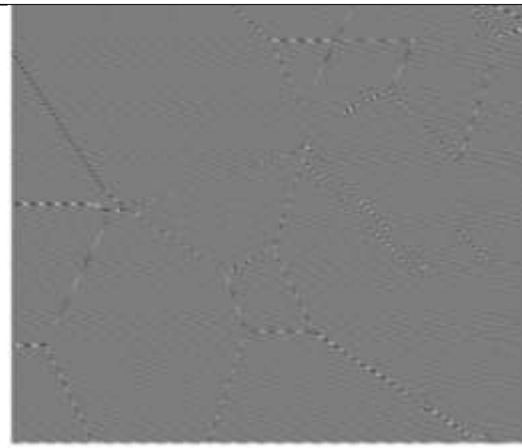
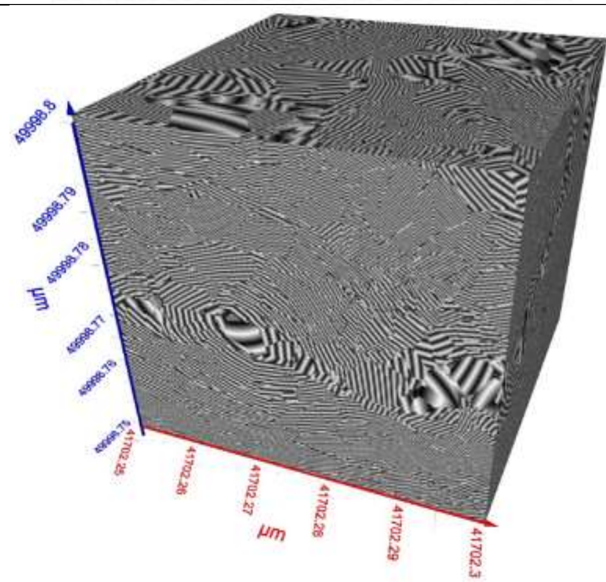
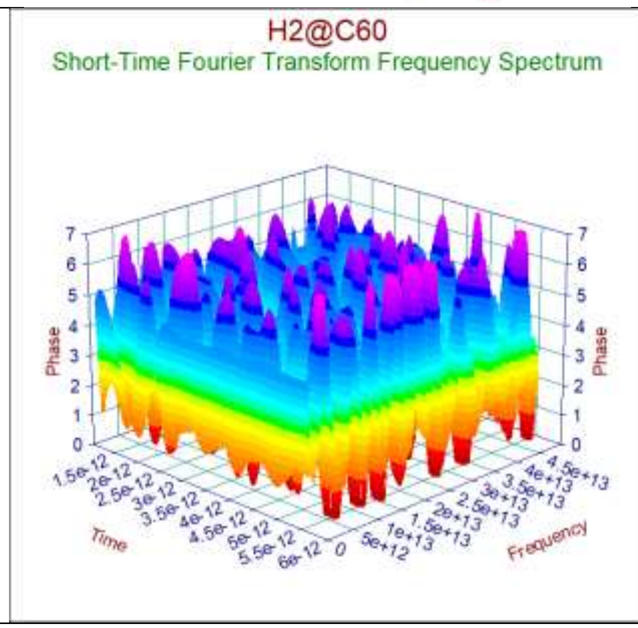
Fundamental breakthrough

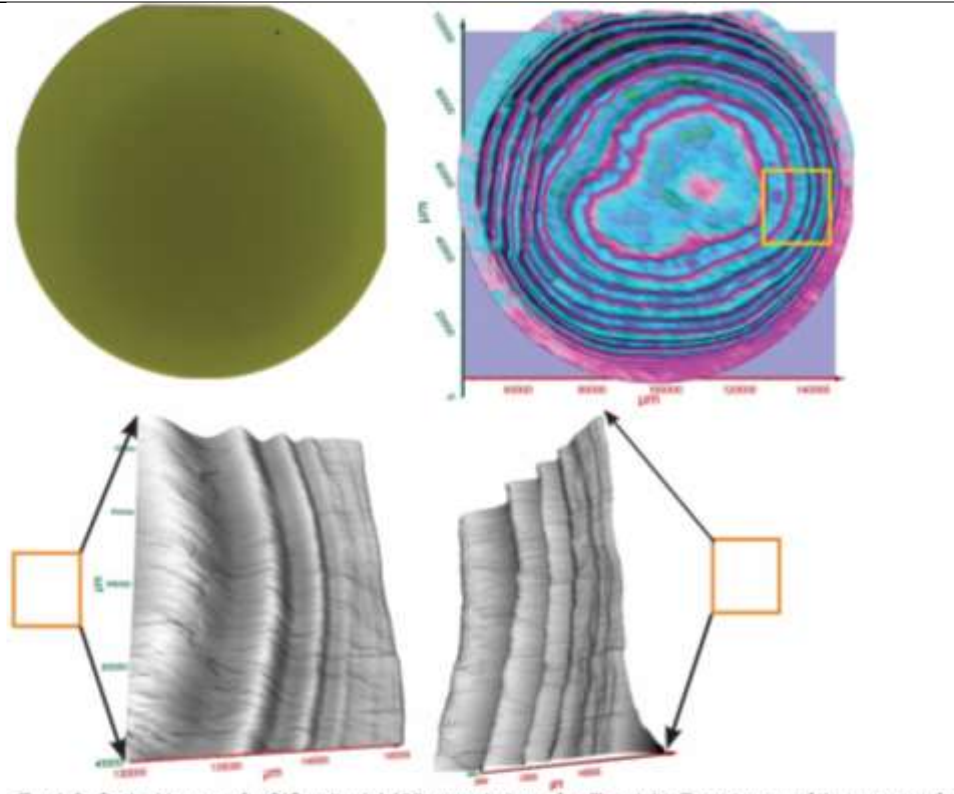
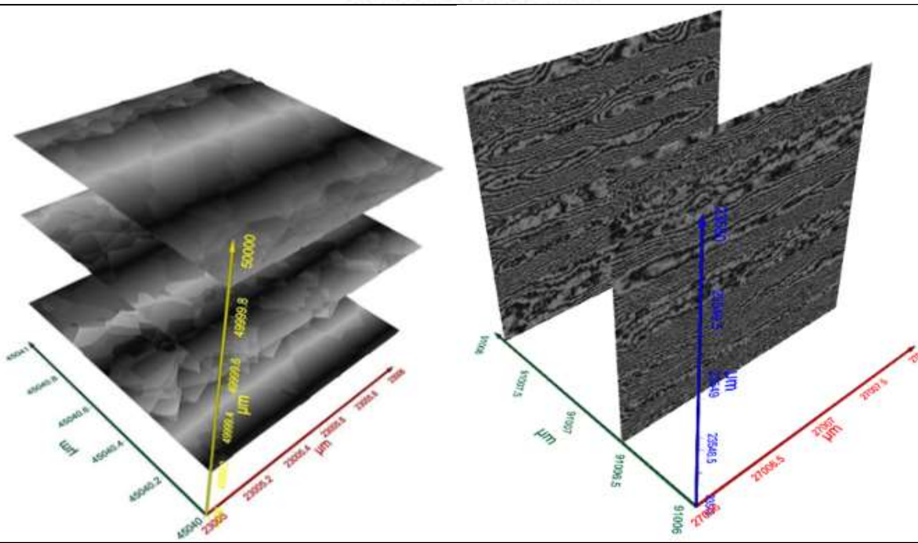
ARP's Terahertz Scanning Spectrometer (TeraSpectra) is a Terahertz Nano-Scanning Spectrometer/3D Imaging system that has a few key technology innovations:

1) A new terahertz generation mechanism, dendrimer dipole excitation (DDE), for high power, up to 30 THz, continuous wave, stable terahertz generation.
2) Overcoming the Abbe diffraction limit for lattice resolution image generation with bigger (terahertz) wavelength.
3) Replacing many functionalities of AFM/SEM/TEM by T-ray technique, it uniquely identifies location, depth, and type of defects, where it exists.
4) Only technology available to see interior (sub-surfaces) in a non-destructive route with layer-by-layer imaging and analysis

Currently, there is no measurement technology that has the capability to provide an equivalent richness of information that ARP's *TNS3DI* system can deliver *without* damage or destruction of the test sample. A few examples of specific applications are given below. Many more will be invented by the end users and experts in their respective areas.

Applications for the semiconductor and nanotechnology industry	
Test specification	**Exemplary Results**
Whole wafer inspection Whole wafer may be imaged at high speed and each die may be inspected separately Terahertz image of unpatterned metalized area shows higher reflection (bluish).	

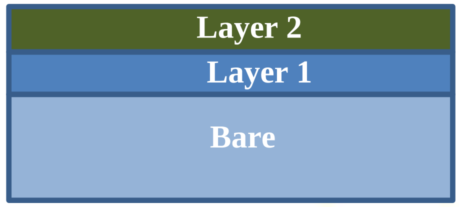
Lattice resolution imaging Lattice image of metallic nickel shown. Lattice parameter was measured: 0.353 nm.	
3D (volumetric) imaging Here a 3D image of alumina shown over (50 nm)^3 volume	
Phase contrast imaging via short-time Fourier transform frequency spectrum	

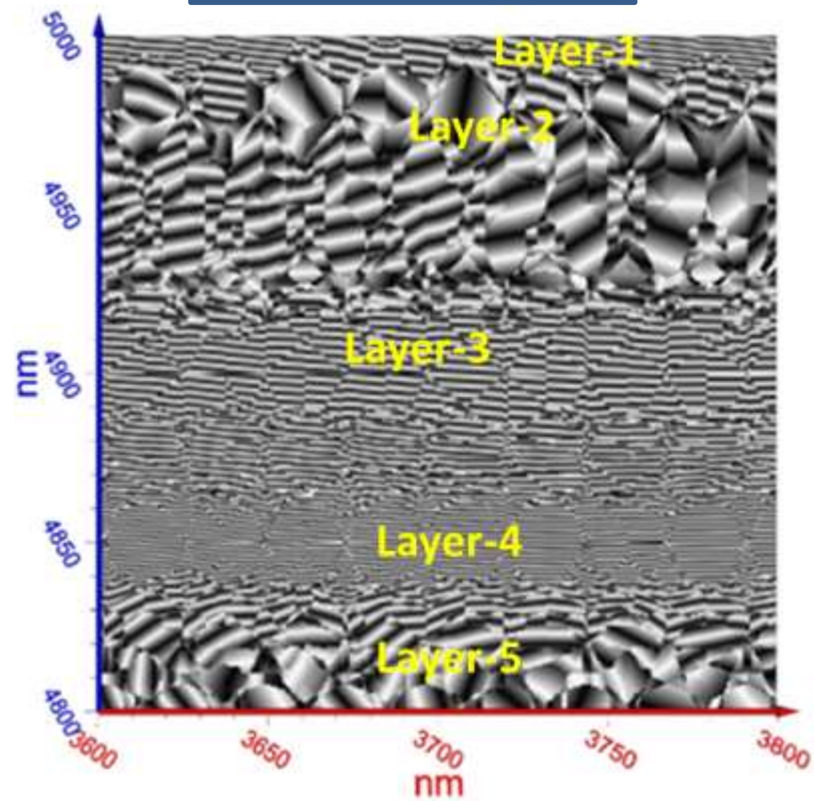
SiC wafer's surface inspection. T-ray sees more than anything else.	 Top left: Optical image of a SiC epitaxial 100 mm whole wafer. Top right: T-ray image of the same wafer Bottom: two different views of a zoomed in segment. Many features are seen from T-ray image that cannot be seen otherwise.
Layer by layer analysis via 3D imaging. A volume image may be sliced in to any number of layers on any of the orthogonal planes. XY-pane and XZ-pales are shown	

Semiconductor interfaces. Deposition involves transforming a solid material in to vapor phase and then back in to solid by the deposition process. The deposited materials' lattice will/may suffer from defects such as stacking fault and dislocations. Volume and 2D image across the interface allow critical metrology of parameters such as layer thickness and lattice defects.

Different kind of interfaces

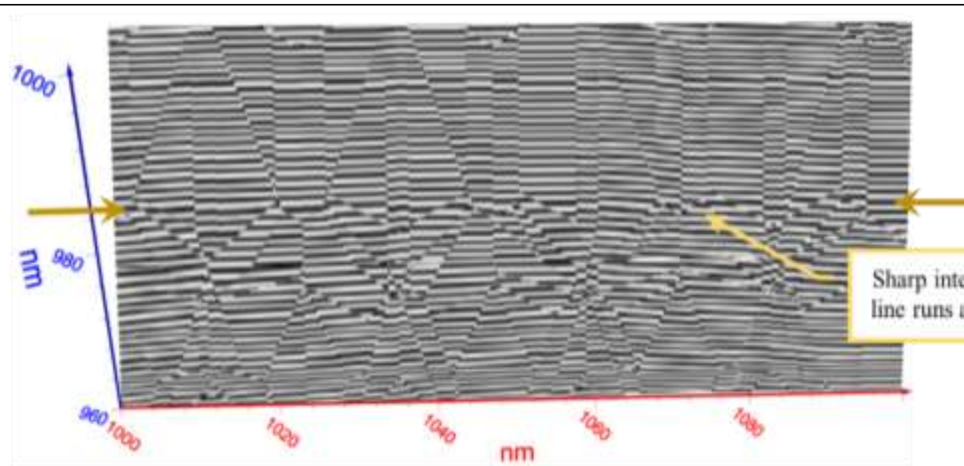
- Misfit-lattice interface (type-1)
- Rough surface interface (type-3) → Layer-1/Layer-2
- Diffusion type interface (type-4) → Layer-2/Layer-3

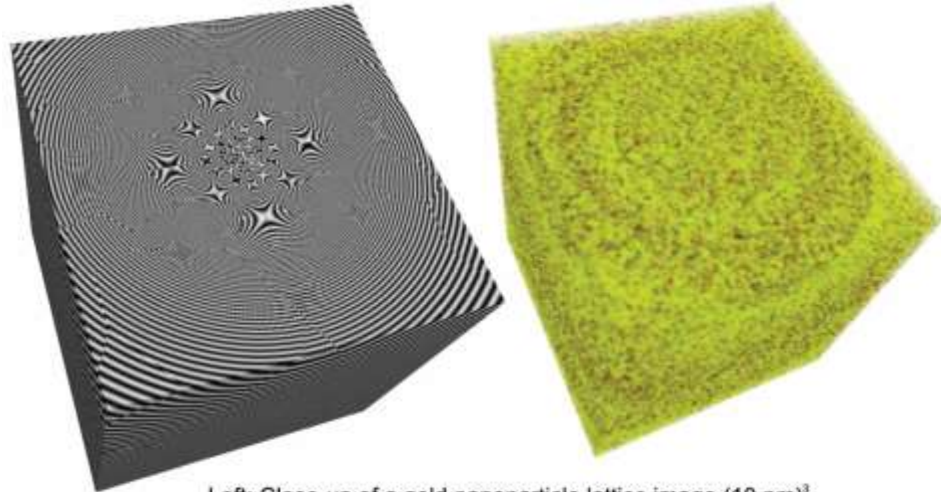
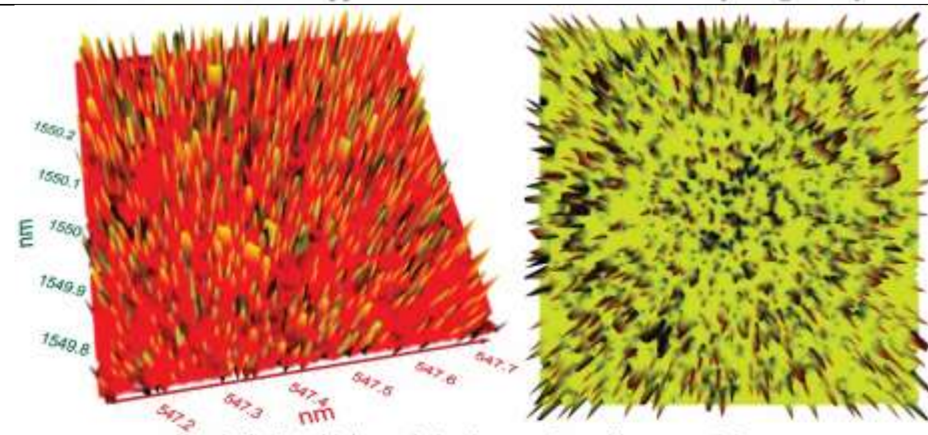
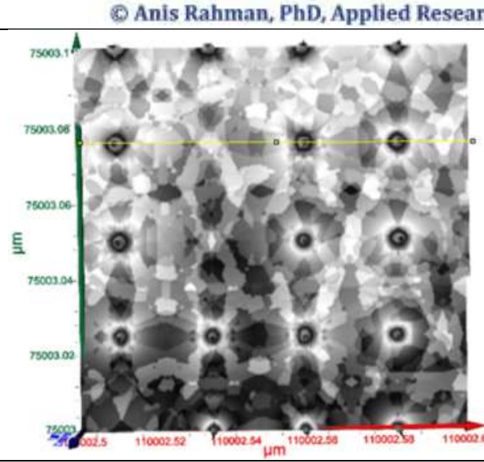
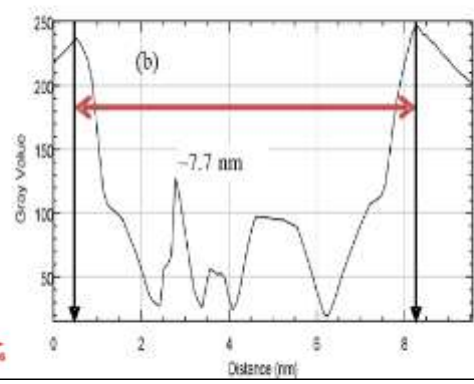


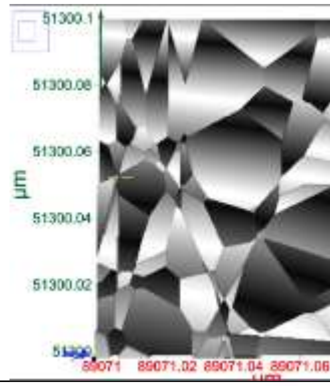
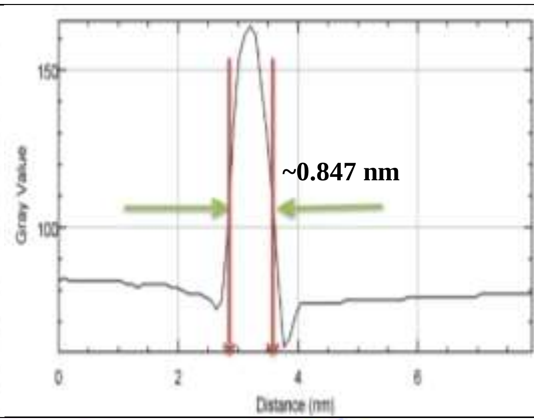
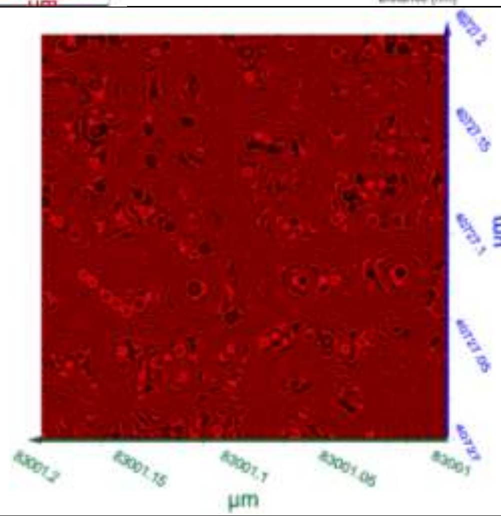
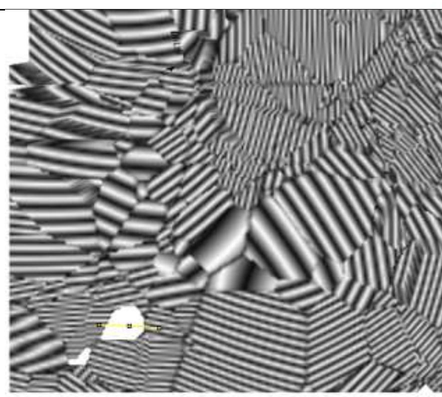
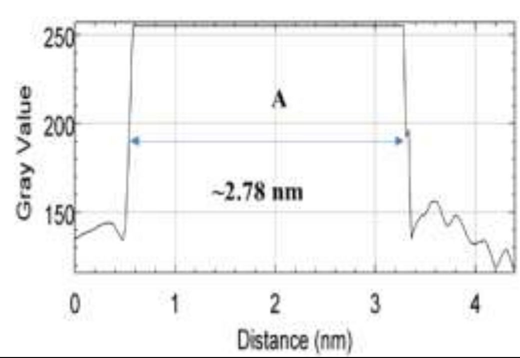


A single face 2D image across the depth, 200 nm × 200 nm. Sharp interface line runs across between the layers. The layer thicknesses may be measured.

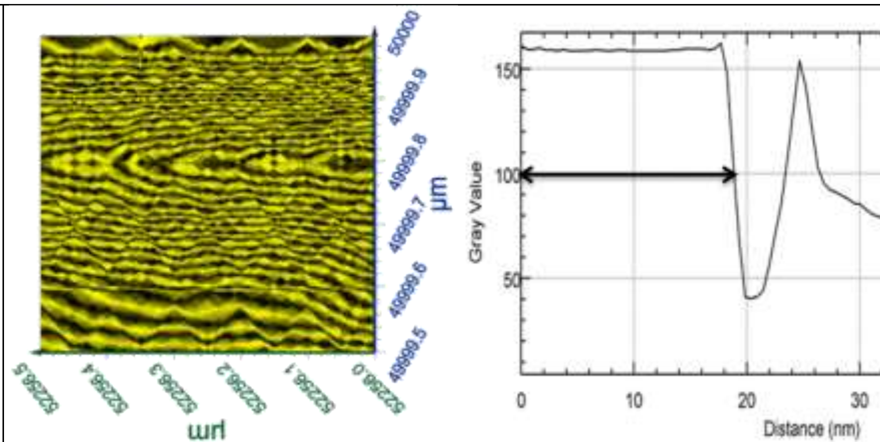
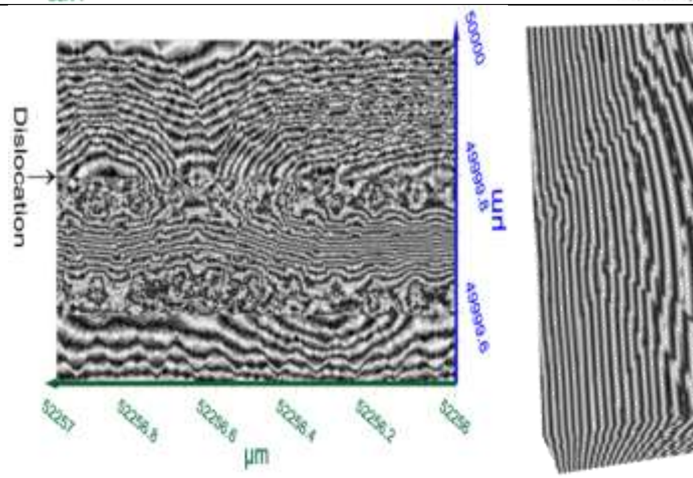
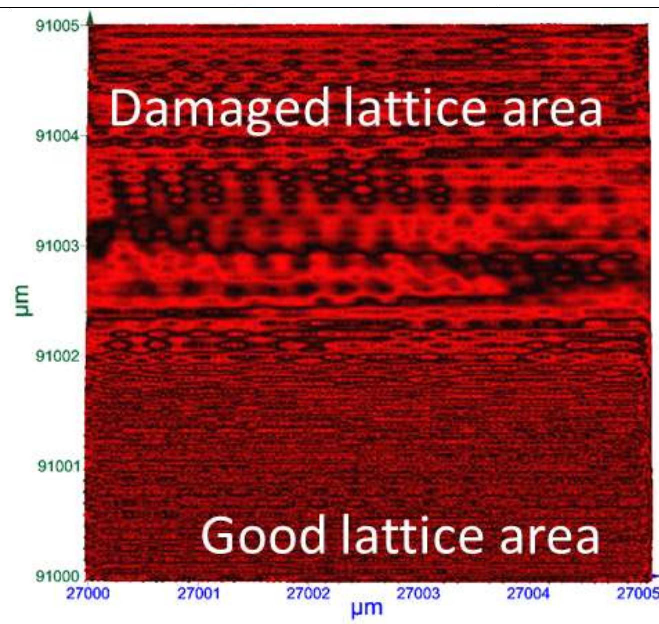
- Identical lattice interface (type-2)



Close-up 3D image of a gold nanoparticle	 Left: Close-up of a gold nanoparticle lattice image (10 nm)^3. Right: Further close-up of the same over (1 nm)^3.
Very high resolution image of a gold nanoparticle	 Left: Very high resolution image of a gold nanoparticle Right: A different view of the same.
Size and distribution of any nanoparticle in dry or wet form. Measured quantum dot size ~7.7 nm	 

Non-destructive, nano-scale testing and metrology down to <1 nm feature on and under the surface of a wafer.	 
Size and distribution of any nanoclusters in dry or wet form. Silica nanoparticles in isopropyl alcohol (nanoslurry) showing the distribution of nanoclusters in suspension. Nanoparticle size is ~10 nm Nanocluster size is ~17.5 nm	
Measurement of the nanovoids Measured nanovoid size ~2.8 nm	 

<table>
<tr><td>Epitaxial semiconductor layer thickness

Measured SiGe layer thickness ~18 nm</td><td></td></tr>
<tr><td>Dislocation in epitaxial semiconductor
Dislocations are a type of defect in crystalline structures where the atoms are out of position in the lattice. Dislocations are generated and moved as a result of an applied stress.</td><td></td></tr>
<tr><td>Lattice damage due to electric stress.
Here a GaN grown on silicon damaged by high electric field stress</td><td></td></tr>
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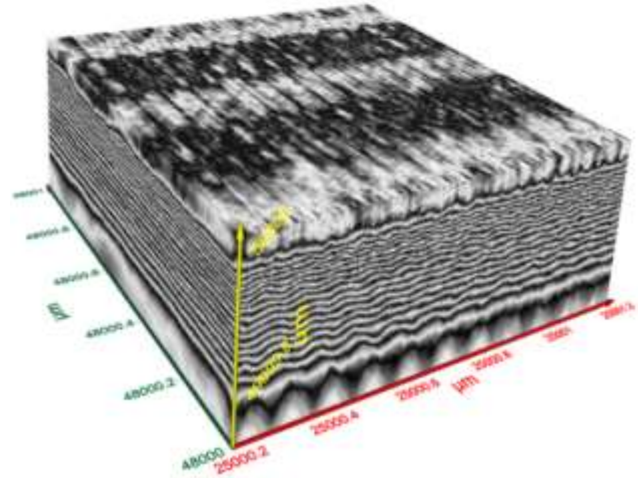
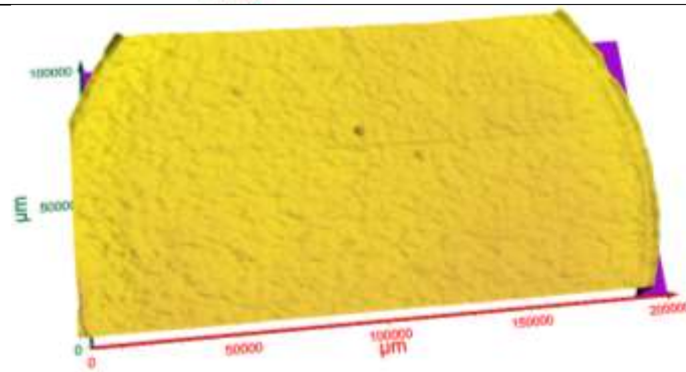
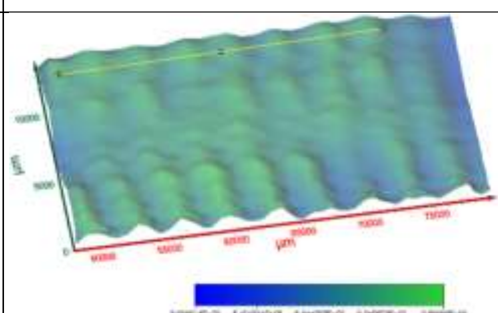
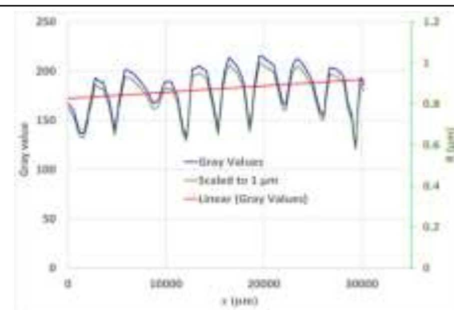
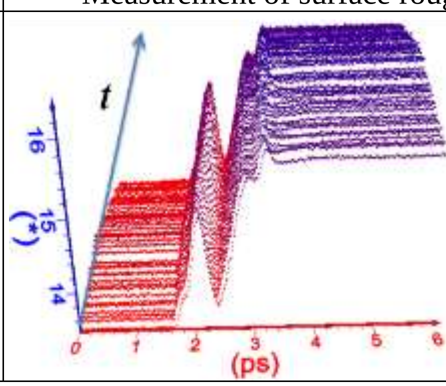
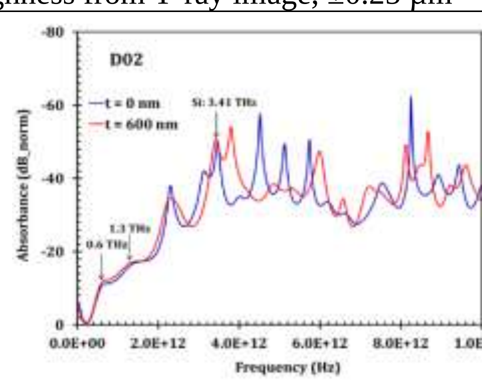
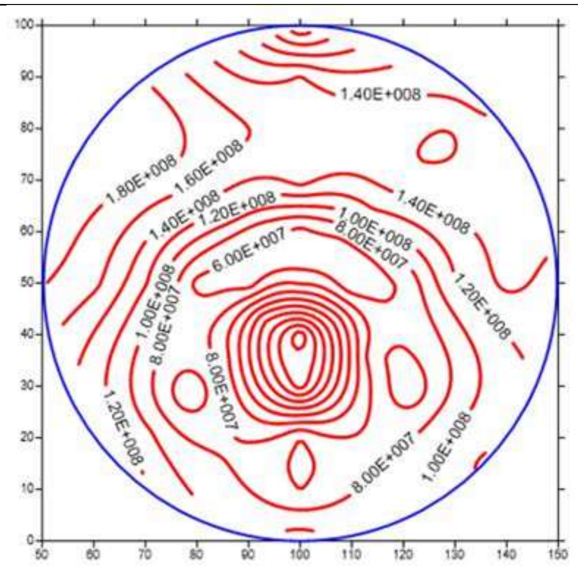
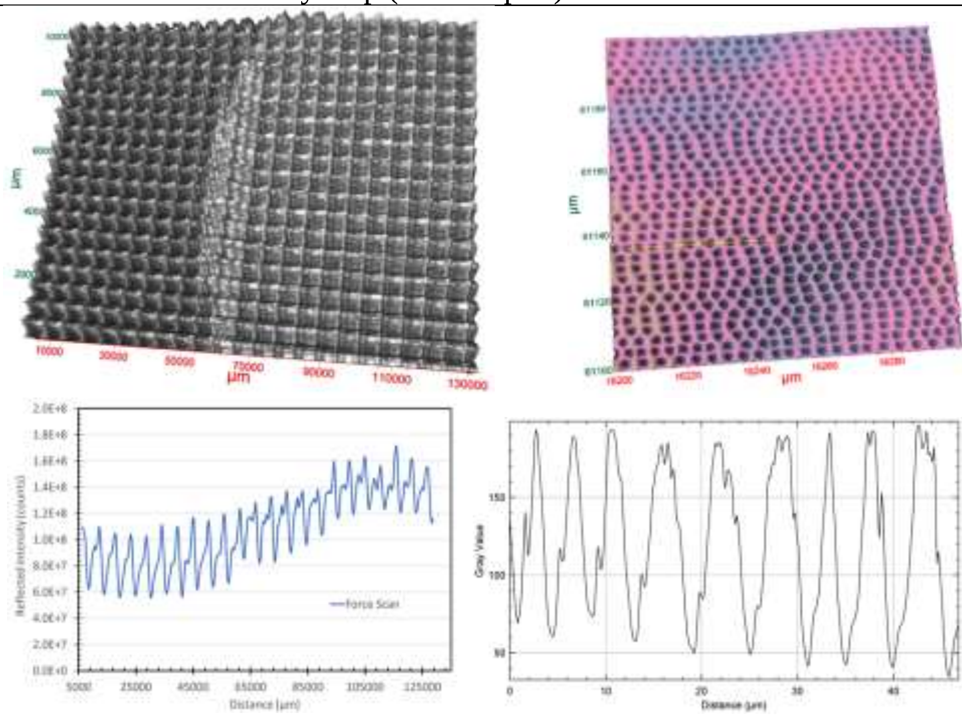
Graphene exfoliates' 3D imaging Number of layers in an exfoliate is measured Thickness of each layer is quantified	
Roughness of metalized wafer.  Optical image does not show the roughness	 T-ray image of the same wafer on the left. Defects are visible. Surface roughness may be quantified.
Surface roughness quantification	  Measurement of surface roughness from T-ray image, ±0.25 µm
Deep-level terahertz spectroscopy for detection of minute changes and/or molecular identification. ***t*** = 0 nm → surface, Ge ***t*** = 600 nm → Si <100> Shifts in peaks for Ge wrt Si Peaks at 0.6 THz and 1.3 THz are due to ambient moisture.	 

Resistivity map of the whole wafer – may be extended up to 450 mm	 Resistivity map (contour plot) of 100 mm wafer
Force scan (friction measurement). Demonstrated with a patterned semiconductor wafer and human stratum corneum.	 Top left: Image of a segment of a 200 mm patterned wafer. Bottom left: the frictional force variations as a function of scan distance. Top right: Human stratum corneum treated with FXII protein Bottom right: A lateral force scan (friction measurements).

Contact info

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