APPLIED RESEARCH & PHOTONICS INC

TeraSpectra

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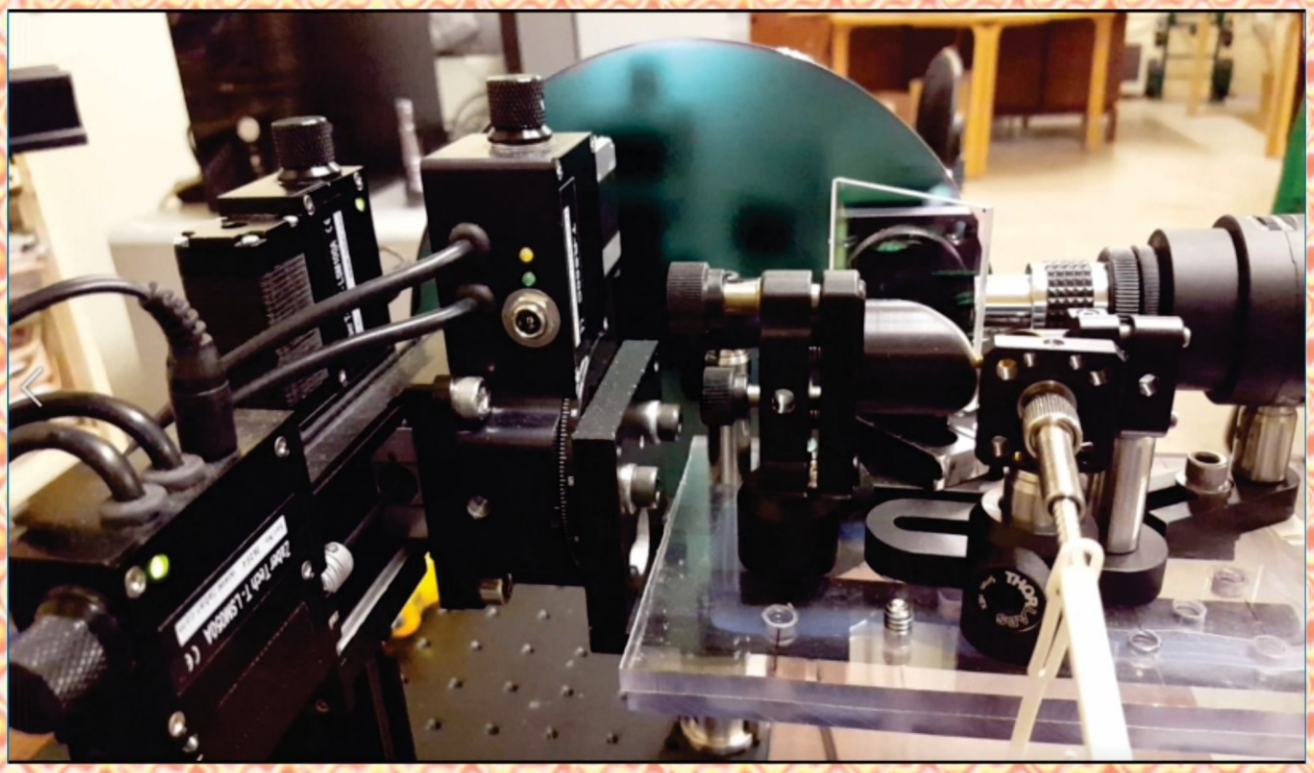
THz

TNS3DI

Nanometrology
Lattice Imaging
Deep-level Spectroscopy



Dear Industry Leader:

We are pleased to bring to you a new nanometrology product that helps solving critical metrology problems. The semiconductor industry's concerns with current inspection technologies are known. We at Applied Research & Photonics, Inc. ("ARP") are introducing a terahertz based groundbreaking instrument, providing the precision metrology required to measure critical, Angstrom size, surface, and sub-surface features on today's state of the art semiconductor chips, via a nondestructive and non-contact route. As these critical circuit features are now only a few nanometers, it is imperative that the measurements are made with a non-contacting probe which can accurately measure and graphically display such features of interest with a resolution of <1 Å to process control engineers.

ARP has demonstrated its capabilities to answer the critical metrology needs. For example, this is the first of its kind to see below the surface of the semiconductor wafers and other solid samples in a layer-by-layer fashion with lattice scale resolution, that even EMs cannot achieve. This brochure presents a few examples. More information available upon request.

Sincerely,

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The semiconductor industry's concern with current inspection technologies

- Surface contacting (Atomic Force Microscopes) can damage nanometer scale circuits.
- X-Ray inspection techniques impart high energy which can damage substrate lattice structures.
- Optical inspection at wavelengths of 256 nanometers (the current state of the art) are limited to a device's surface structure only and sub-surface defects are unobservable.
- Electron microscope measurements involve destructive and tedious sample preparation and impart high beam energies which perturbs the lattice and can be detrimental to circuit structures and yet can see only the surface.

ARP has demonstrated its capabilities to answer the above-mentioned needs

1. Overcoming the Abbe diffraction limit for lattice resolution imaging with bigger (T-ray) wavelength.
2. Replacing many functionalities of AFM/SEM/TEM by T-ray technique, it uniquely identifies location, depth, and type of defects, where it exists.
3. Only technology available to see interior (sub-surfaces) in a non-destructive route with layer-by-layer imaging and analysis

Why terahertz?

Terahertz radiation (T-Ray) lies between the infrared (IR) and microwave frequencies, as shown of the chart in Figure 1. T-ray is also known as the far-infrared (far-IR), millimeter wave, submillimeter radiation, terahertz waves, tremendously high frequency (THF), T-rays, T-waves, T-light, T-lux or THz [1].

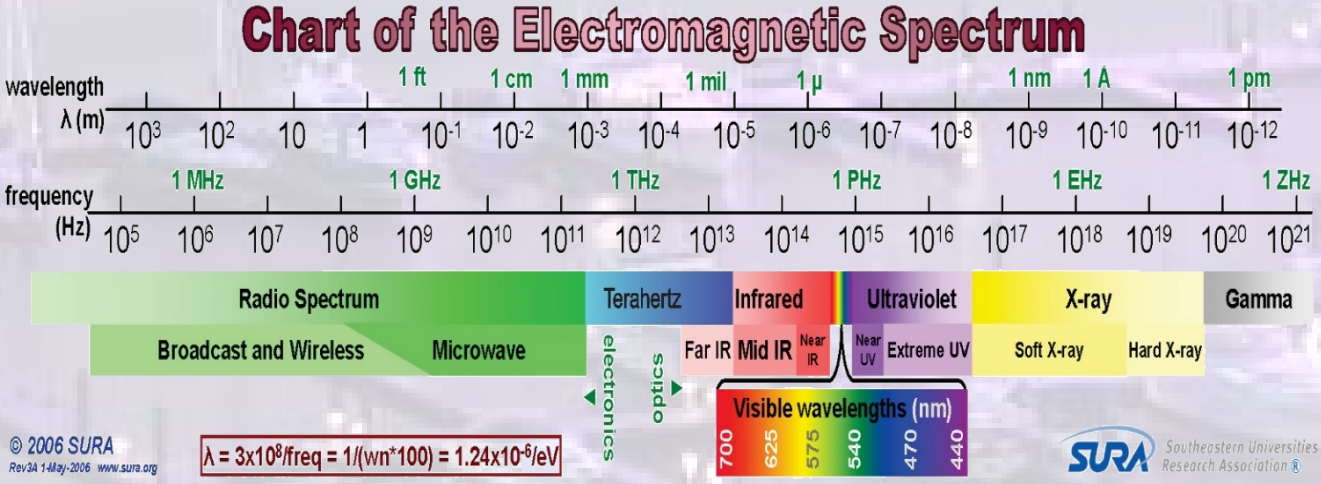


Fig. 1. Chart of the electromagnetic radiation

Why are terahertz frequencies useful than others?

- T-ray instrument has the unparallel capabilities that overlap some of the current art but offers additional capabilities that are not available from the current instruments.
- T-Ray energy is safe for delicate semiconductor structures because it is non-ionizing, and non-perturbing.
- Unlike X-rays, there is no bond-breaking, i.e., **no radiation dose or damage.**
- Higher resolution than optical techniques; **see examples on lattice resolution imaging with T-Ray**.
- Most materials are transparent to T-ray; so, **one can "see" under the surface,** and layer-by-layer, without destruction.
- T-Ray wavelength is suitable for probing delicate semiconductor materials. T-Ray fulfils crucial knowledge gaps for the semiconductor industry by providing important parameters and measurement capabilities.

What Problems Solving for Semiconductor Metrology?

- Whole wafer imaging (aka Wafer-scale imaging)
- Epitaxial Semiconductor and Interface analysis
- Lattice scale imaging and measurements
- Non-destructive, Direct 3D (volume) Imaging
- Layer-by-layer imaging/analysis
- Film Thickness measurement (nano scale)
- Electrical measurements
- Defect Inspection
- Failure Analysis
- High voltage induced lattice damage quantification
- High-temperature semiconductors
- Surface Properties Analysis
- Doping concentration profile of semiconductors
- Deep-level spectroscopy
- Terahertz Raman spectroscopy

What Problems Solving for Nanotechnology and Material Science?

- Nanoparticle size and size distribution measurement
- Nano-materials interactions (self-interaction and interaction with other nanomaterials)
- Nanotubes' length, diameter, and distribution
- Zero dimensional to three-dimensional nanomaterial imaging and analysis

What are the Application Examples?

1. Epitaxial Semiconductor and Interface analysis by TNS3DI

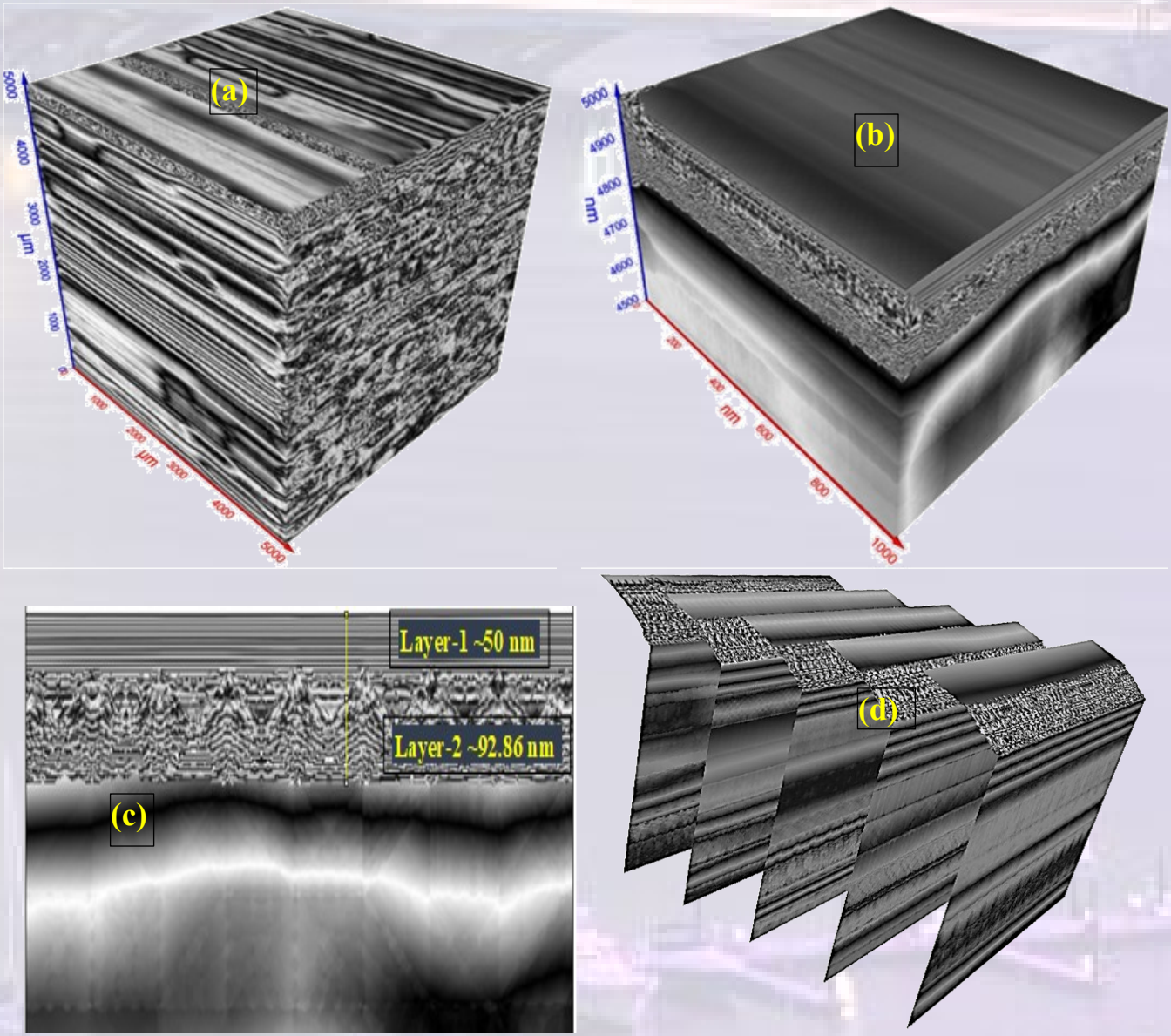


Fig. 2. (a) Volume image of epitaxial semiconductor layer(s), 5 µm × 5 µm × 5 µm. (b) 1 µm × 1 µm × 1 µm volume image extracted from the top of (a). (c) Y-Z face of (b) used from thickness measurement of top two layers. (d) Different X-Z slices extracted from (b).

Note: As evident from the above analysis, the TNS3DI is capable of resolving and quantifying epitaxial layers, layer-by-layer slices, and structural defects (if any). Interfaces between the layers are clearly visible. Different type of interface can be characterized.

2. Whole wafer or partial wafer imaging (aka Wafer-scale imaging)

Imaging of whole wafer at different stages of manufacturing process. Here is an example of imaging of a patterned wafer over different areas. The whole wafer image helps identifying good dies from bad ones.

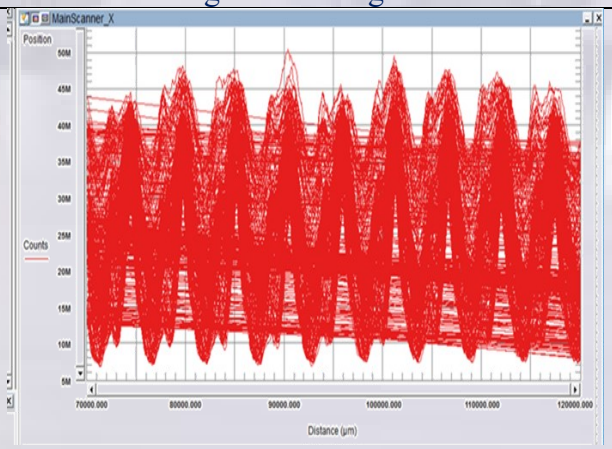
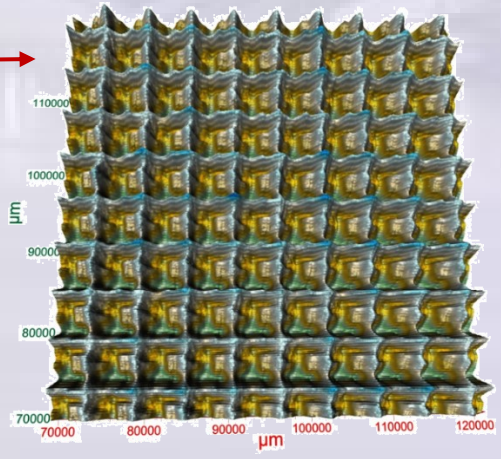
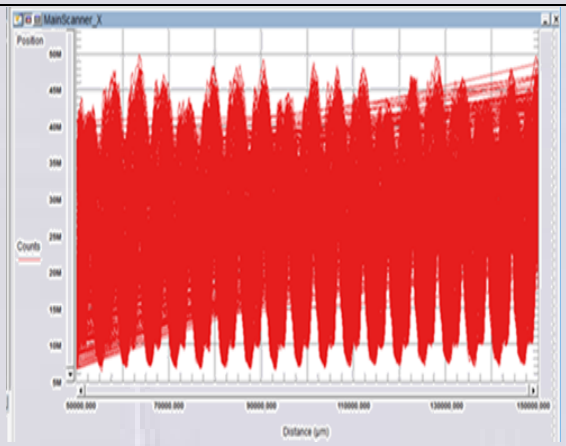
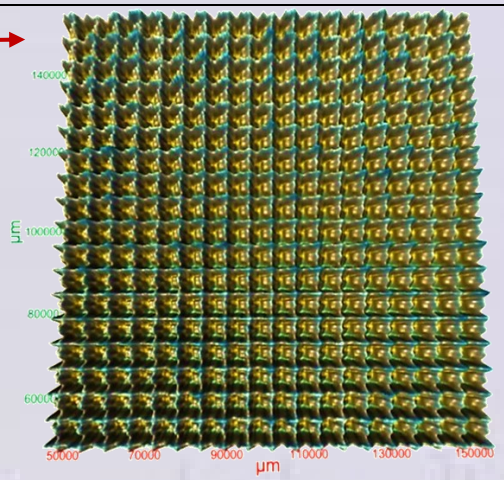
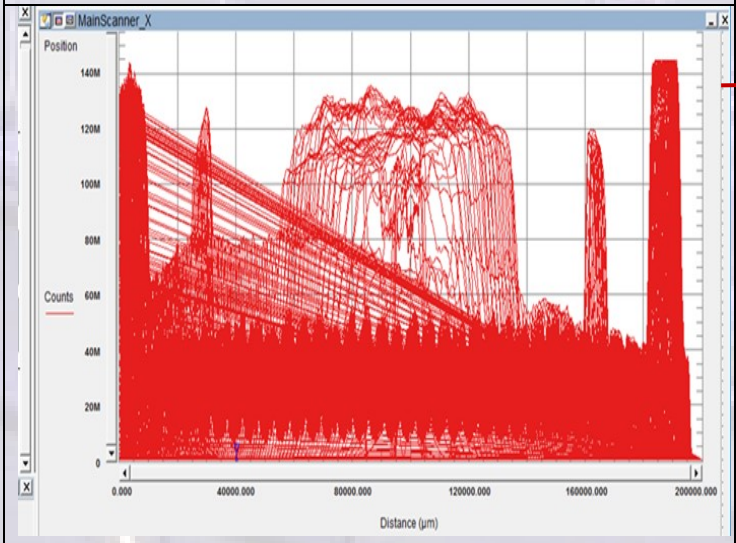
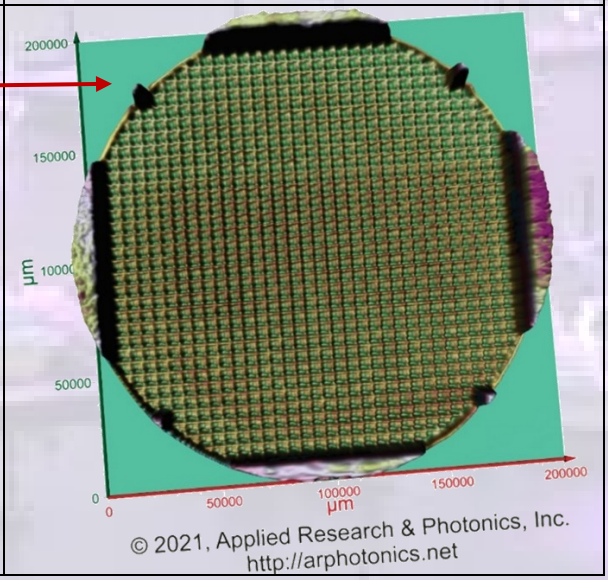
Left: Scanned intensity traces as measured and used to generate image.	Right: Image generated from the scanned intensity traces shown on left.
 Scan area: 50 mm x 50 mm	
 Scan area: 100 mm x 100 mm	
 Scan area: 200 mm x 200 mm	

Fig. 3. A fully manufactured semiconductor wafer contains a huge number of integrated circuits (ICs, or each individual one is a “die”) that are singularized before connectorizing and final packaging.

3. Resistivity mapping of whole wafer

The TNS3DI has also a built-in program for resistivity mapping of the whole wafer on a layer-by-layer basis. While the existing techniques can measure the resistivity on a single point and averaging the whole thickness, the TNS3DI can map the resistivity of different layers of an epitaxial semiconductor, for example.

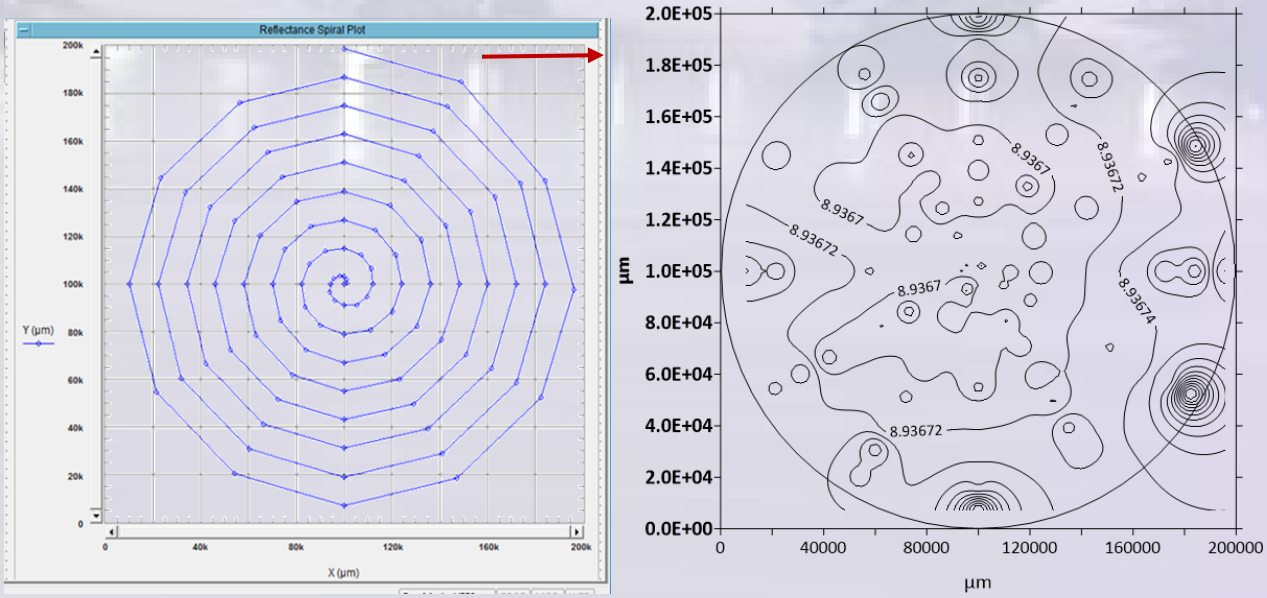


Fig. 4. Left: 99-point spiral scan of a 200 mm wafer. Right: Resistivity contour map created from the intensity map (left) utilizing a model.

4. Lattice Dilation

Fig. 5. Three-D Lattice image of a metal impregnated with alumina particle. The lattice planes have deformed due to the inclusion of alumina particle. This may be used for lattice constant measurement and for inspecting lattice perturbation across the depth. Graphical analysis along the cursor is shown in Figure 6. See ref. [3].

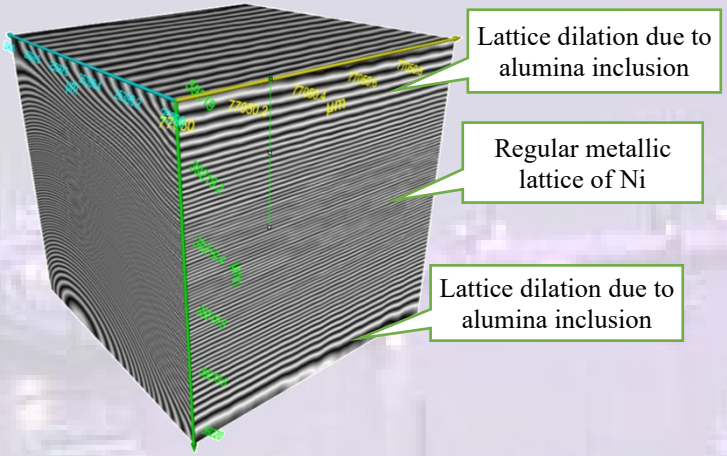
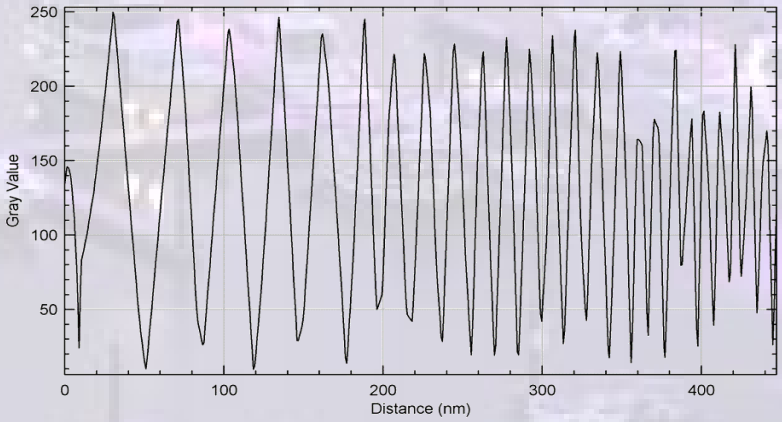


Fig. 6. Graphical analysis of the lattice plane perturbation along the cursor in Figure 5. Here, the lattice plane dilation due to the inclusion of alumina nanoparticle can be quantified.



5. Metal line 3D metrology

A SEM standard chip with line patterns was scanned (Fig. 7), and the intensity matrix was used for image generation and measuring the line width (Fig. 8).

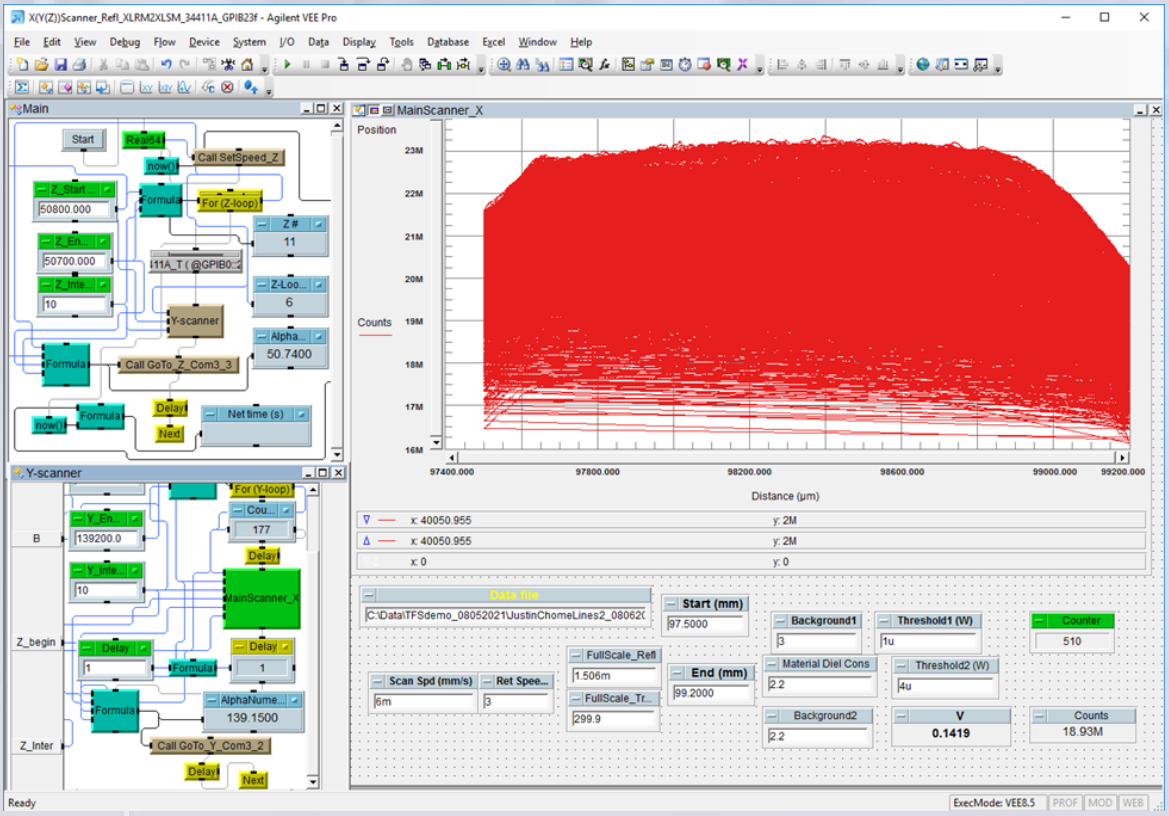


Fig. 7. Measured intensity traces of nano-size metal lines on a silicon wafer.

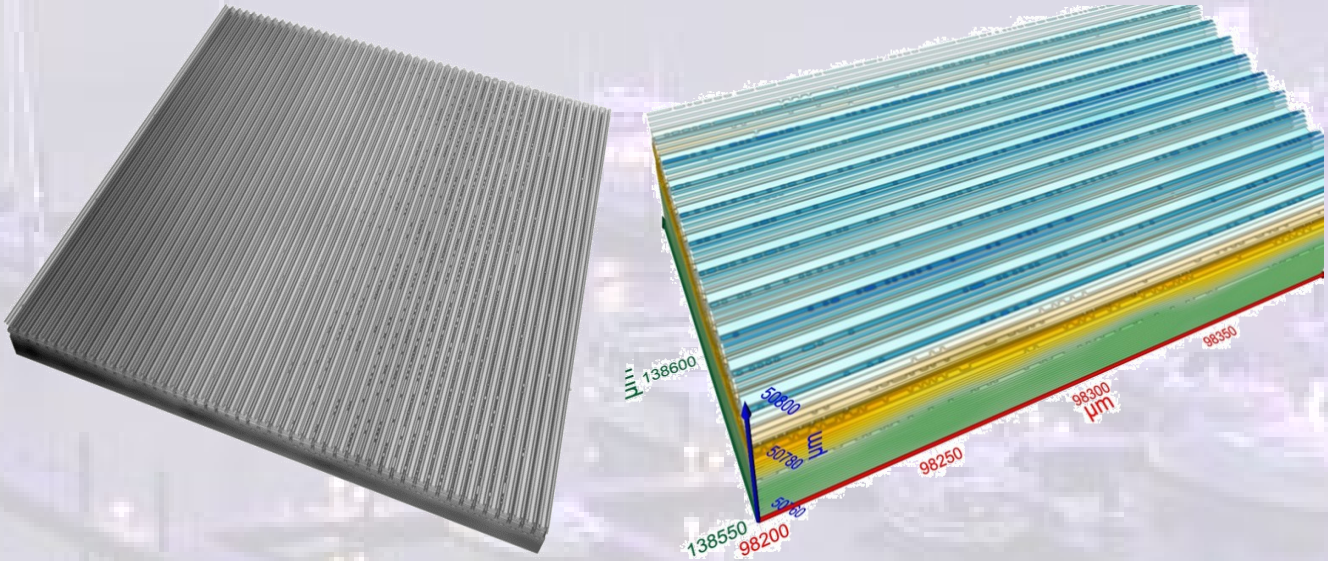


Fig. 8. Three-D image of metal lines on a silicon wafer is used for metrology or calibration.

6. T-ray Raman and deep-level spectroscopy

a. T-ray Raman

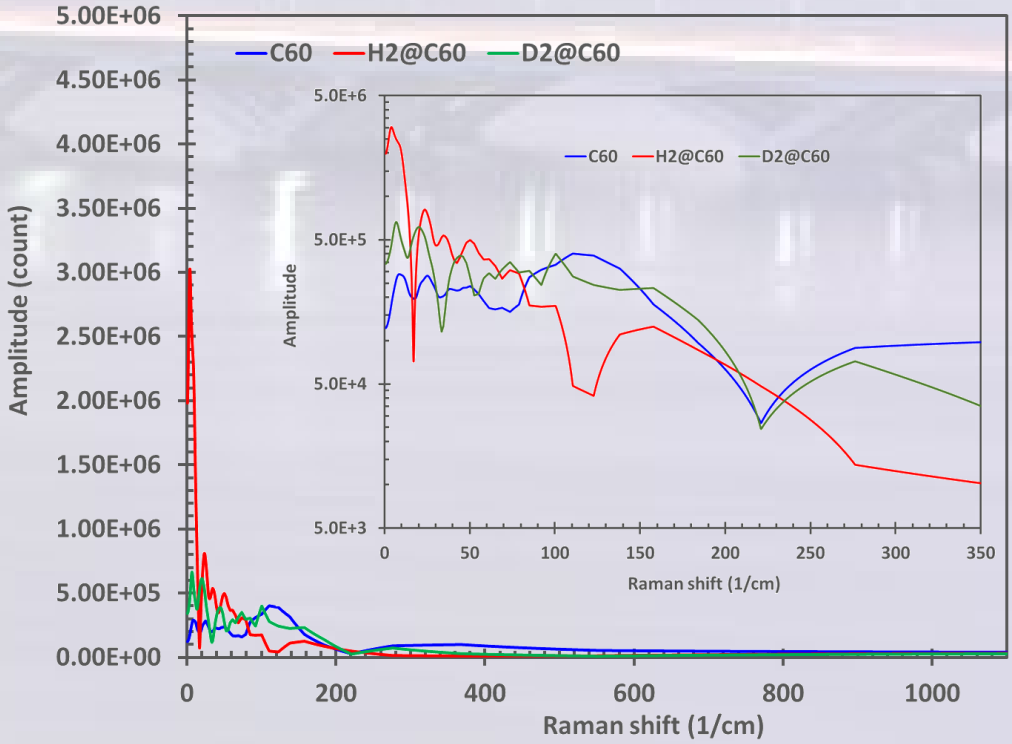


Fig. 9. T-ray Raman spectra of Fullerene (C60) and endohedral hydrogen and deuterium in Fullerene, exhibiting Raman activities of these samples within 1–350 cm^{-1} (shown in the inset). It is seen that there is no Raman activity of these samples beyond ~350 cm^{-1}. Thus, regular Raman spectroscopy is not effective as T-ray Raman.

b. Deep-level T-ray spectroscopy

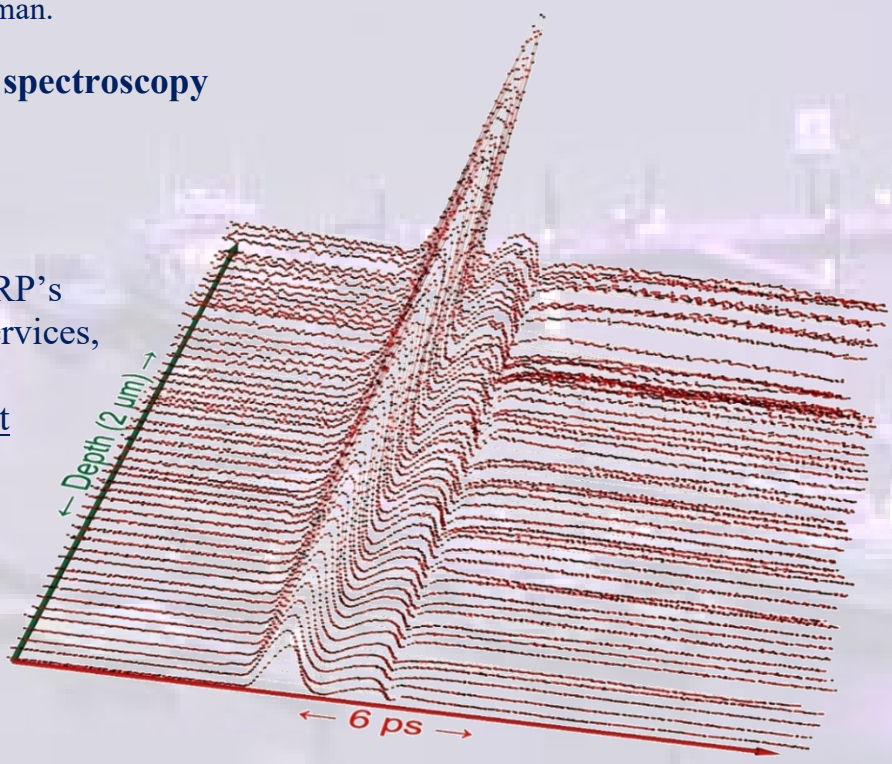


Fig. 10. Deep-level T-ray Spectra (interferogram) ("DLS") of GaN film on Si substrate. DLS is used to analyze the composition on the surface and sub-surfaces of a sample.

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7. Side-by-side comparison with XRD, TEM, and Small-angle X-ray Scattering

The following examples exhibit a side-by-side comparison with current state-of-the-art standard techniques. T-ray image can reproduce the results of all standard techniques within the experimental limit including the additional benefits described in the above sections.

7.1. TEM vs. T-ray

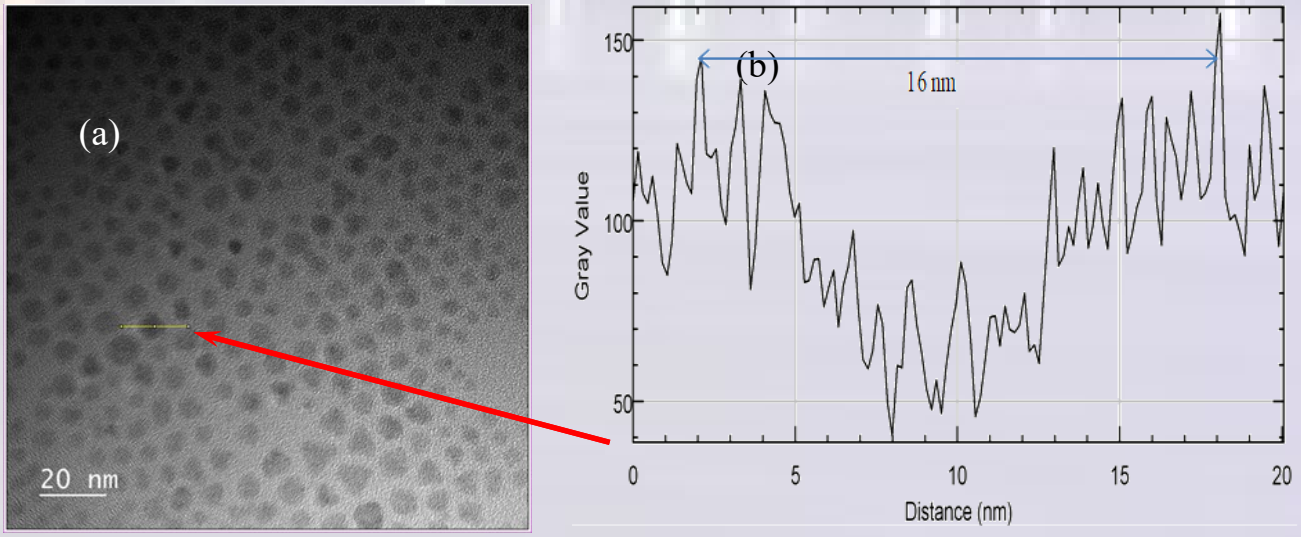

Fig. 11. (a) TEM micrograph of quantum dots (LANL-QDs) in ionic polymer matrix from Los Alamos National Laboratory. (b) Typical QD size ~11 nm [1] but polydispersity is visible.

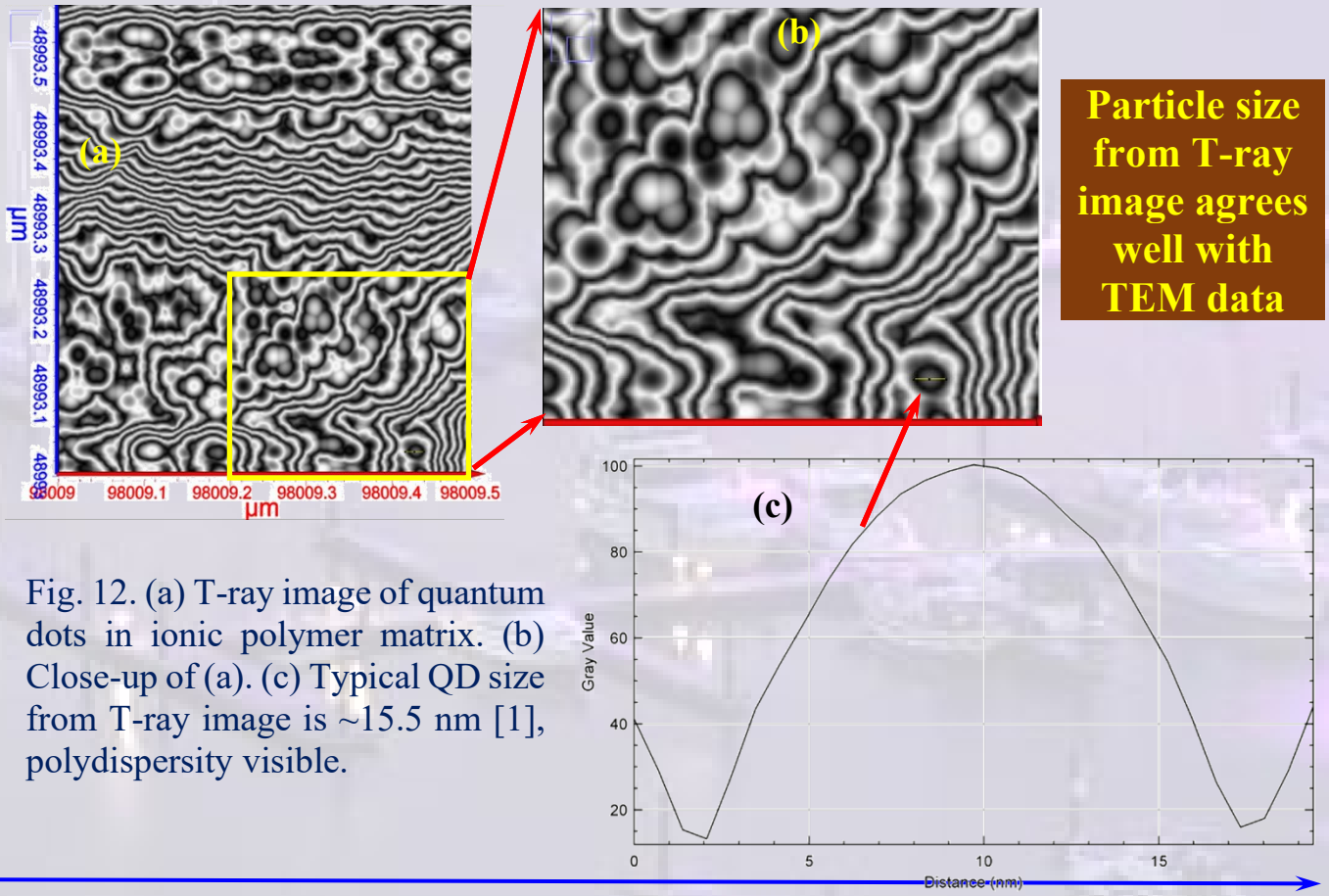

Fig. 12. (a) T-ray image of quantum dots in ionic polymer matrix. (b) Close-up of (a). (c) Typical QD size from T-ray image is ~15.5 nm [1], polydispersity visible.

7.2. XRD vs. T-ray

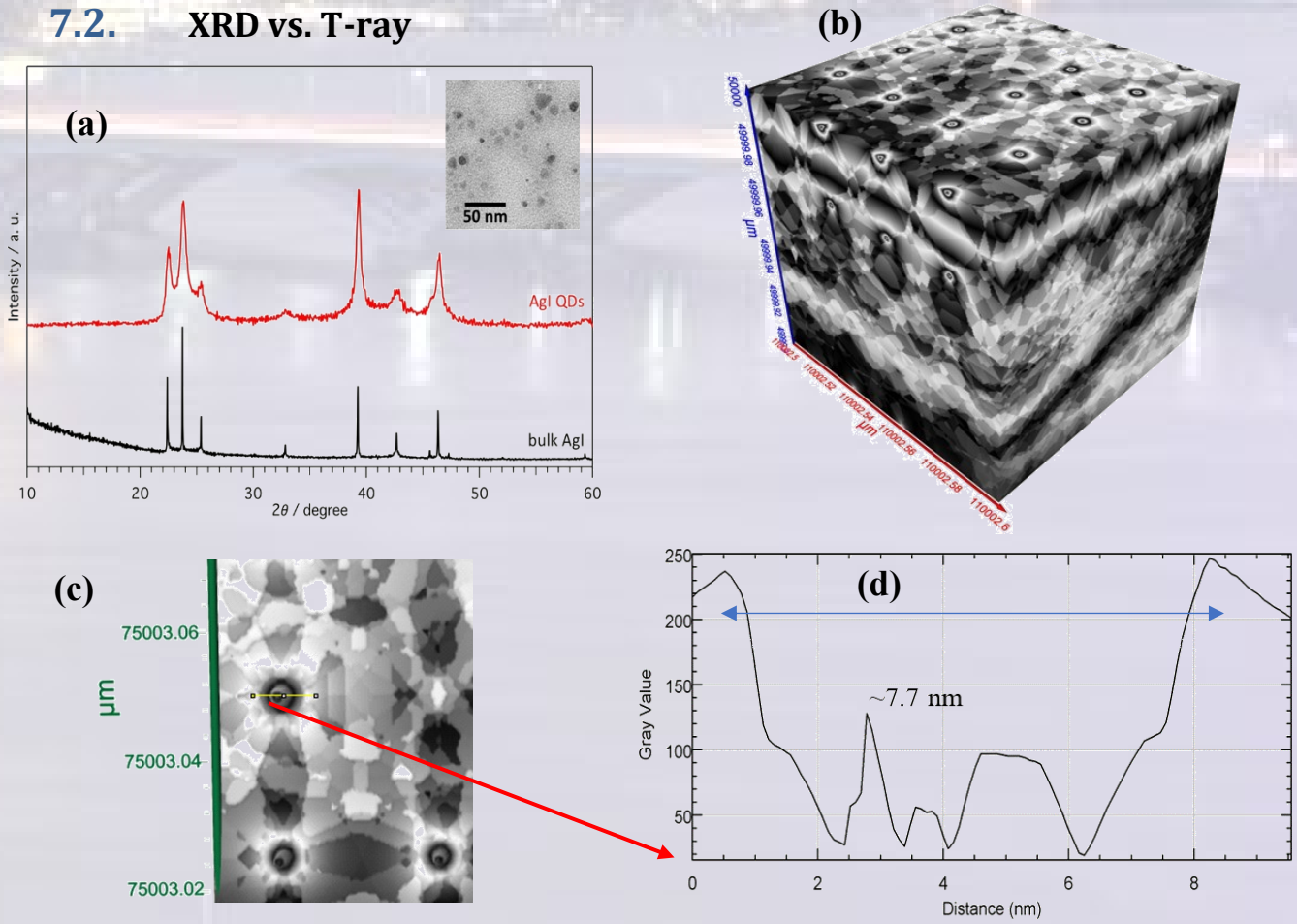

Fig. 13. Quantitative comparison with XRD.

a) PXRD and TEM analysis shows the AgI quantum dots (Kyoto-QDs) are (11 ± 4.5) nm [2].
b) T-ray volume image showing that the Kyoto-QDs are on the top layer when spun on Si substrate.
c) Close-up of the top surface of (b).
d) (d) Measured size of a Kyoto-QD from T-ray image is ~7.7 nm [2].

8. Summary

Material	Technique	Size	T-ray size/comment
LANL-QD	TEM	11 nm – 16 nm	9 nm – 15 nm
LANL-QD [1]	SANS	Phase and parameter match	Phase and parameter match
Kyoto-QD [2]	XRD	(11 ± 4.5) nm	7.7 nm – 13 nm
Metallic Nickel lattice [3]	Literature value	0.353 nm	0.353 nm

9. References

[1] P. Welch, et al., Macromolecules, 2020, 53, 2822−2833
[2] Rahman, A.; Rahman, A. K.; Yamamoto, T.; Kitagawa, H., "Terahertz sub-nanometer sub-surface imaging of 2D materials." J. Biosens. Bioelectron., 2016, 7:3
[3] Anis R, Francis T, Aunik K R, Carl Page, Robert Godes. "Lattice Dilation of Plasma Sprayed Nickel Film Quantified by High Resolution Terahertz Imaging." Nov Res Sci.2(4). NRS.000545.2019. DOI: 10.31031/NRS.2019.2.000545