Chemical Imaging of Compound Semiconductors

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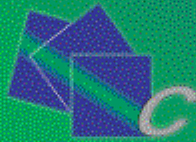


Chemical Imaging for Semiconductor Metrology (CHISM) Program

Joint venture of ChemIcon Inc. & II-VI Incorporated

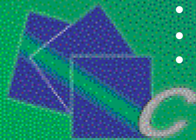
Problem: Compound semiconductors challenging to manufacture. Crystal growth & device processing defects hard to measure during manufacturing. Defective devices identified downstream. Yields low/costs high – impediment to market potential.

- silicon carbide (SiC) – ($50M '01)
- silicon germanium (SiGe) – ($1.8B '05)
- Gallium arsenide (GaAs) – ($2B '00)
- gallium nitride (GaN) – ($3B '06)
- cadmium zinc telluride (CdZnTe) – ($10B '08)
- mercury cadmium telluride (HgCdTe) ($250M '01)

Need: Metrology technology for non-destructive assessment of semiconductor material **defects** that **limit device performance** at various stages in the fabrication process.

Solution: High throughput screening system based on chemical imaging.

- Infrared (IR)
- Automated polarized light
- Photoluminescence
- Raman scattering



Chemical Imaging - Molecular spectroscopy and digital imaging for chemical analysis of materials

Conventional Imaging
Low Contrast

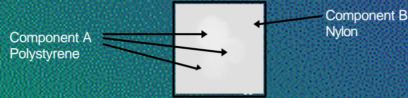
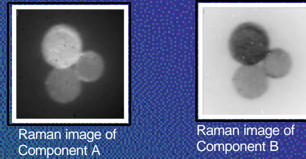


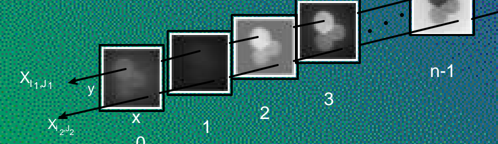
Image Contrast Based on Composition, Structure & Concentration Without Sample Preparation

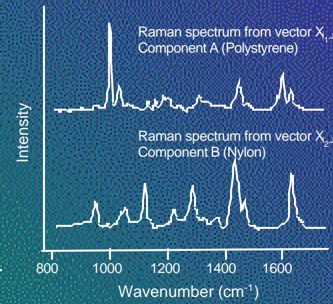


Raman image of Component A

Raman image of Component B

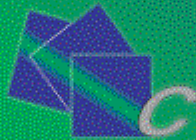
Chemical Imaging
Massively Parallel Spectroscopy





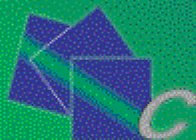
Why Chemical Imaging?

- Fast
- Noncontact & nondestructive
- High information content
- Spectroscopy provides fingerprint for material

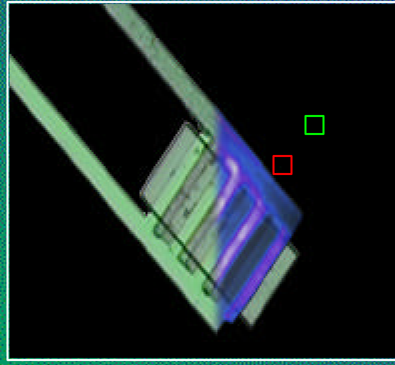


Accessible Semiconductor Properties

Semiconductor Property	Optical Method			
	PL	Raman	IR	PLM
Band				
Gap	•		•	
Band offset	•			
Free Carrier				
Concentration		•	•	
Mobility		•	•	
Scattering time		•	•	
Resistivity		•	•	
Lattice				
Alloy composition	•	•	•	
Orientation		•		•
Crystallinity	•	•		•
Stress	•	•		•
Impurity and Defect				
Presence and type	•	•	•	
Concentration	•	•	•	
Microstructure				
Layer thickness		•	•	•
Surface behavior	•	•		•
Interface behavior	•	•		•
Layer-by-layer behavior			•	•



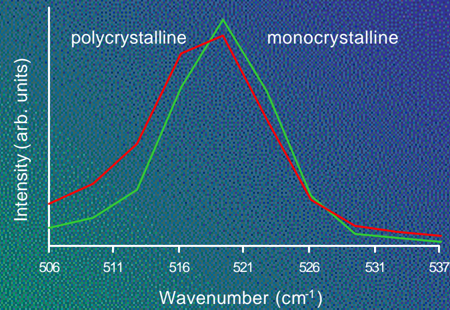
Raman Chemical Imaging
Silicon Polycrystallinity



Brightfield & Raman
Chemical Image Composite

- High definition
- High resolution (spatial/spectral)
- Real-time

Raman Spectra



CHISM Program Organization

ChemIcon Inc. (Scott Keitzer, PI)
- Project Leader
- Materials characterization and chemical imaging technology experts
- CHISM system & software development / commercialization

II-VI Inc. (Dan Reese)
- Joint venture partner
- II-VI semiconductor crystal grower
- CHISM testing

Sanders (Stephen Jost)
- III-V semiconductor device manufacturer
- CHISM optical design & system testing

WVU (Tom Myers)
- Materials characterization (XRD, PR, AFM)

NRL (Jerry Meyer)
- Bandgap modeling

CRI (Cliff Hoyt)
- LC & PLM technology development

Ray Wick
- EO technology consultant

Project Plan

Year 1 – R&D

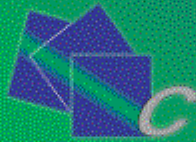
- Construct prototype chemical imaging instruments
- Apply chemical imaging to compound semiconductors
- Develop CHISM control software
- Develop CHISM specification

Year 2 - Engineering

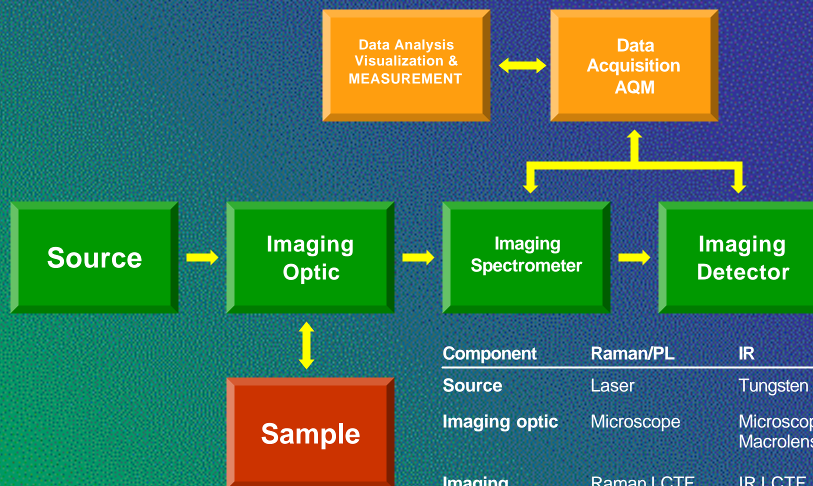
- Extend CHISM to IR
- Construct engineering prototype
- Develop data reduction and analysis software

Year 3 - Testing

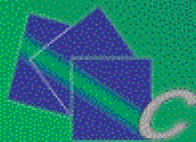
- Test in manufacturing environment

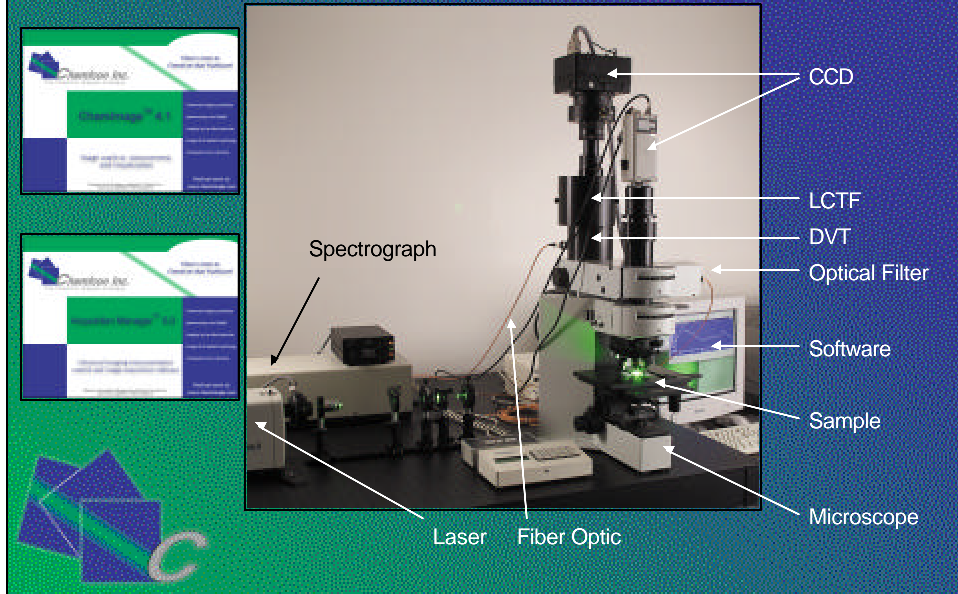


Chemical Imaging System Components



Component	Raman/PL	IR
Source	Laser	Tungsten
Imaging optic	Microscope	Microscope Macrolens
Imaging Spectrometer	Raman LCTF	IR LCTF
Detector	Silicon CCD	IR InGaAs FPA

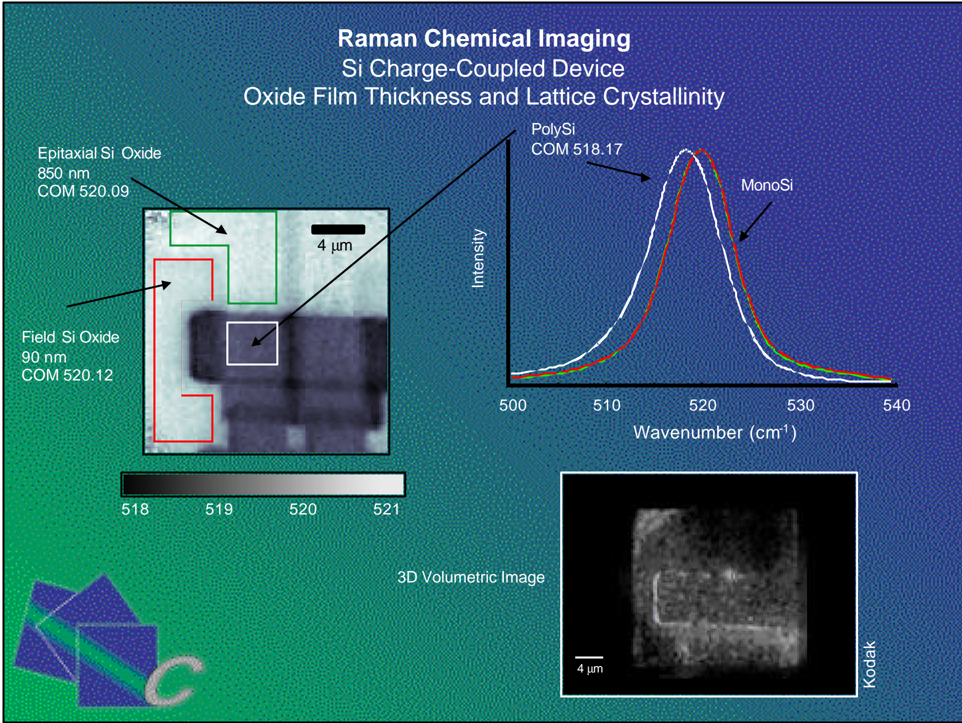




Application

Si Semiconductor Devices
Film Thickness & Lattice Crystallinity

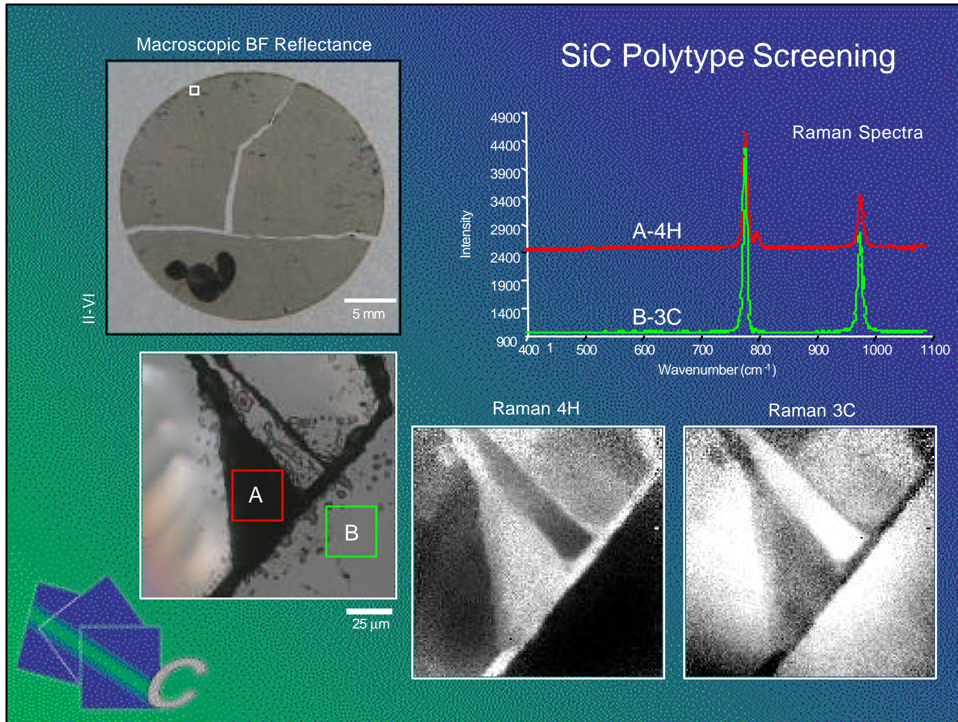
Raman 2D, 3D



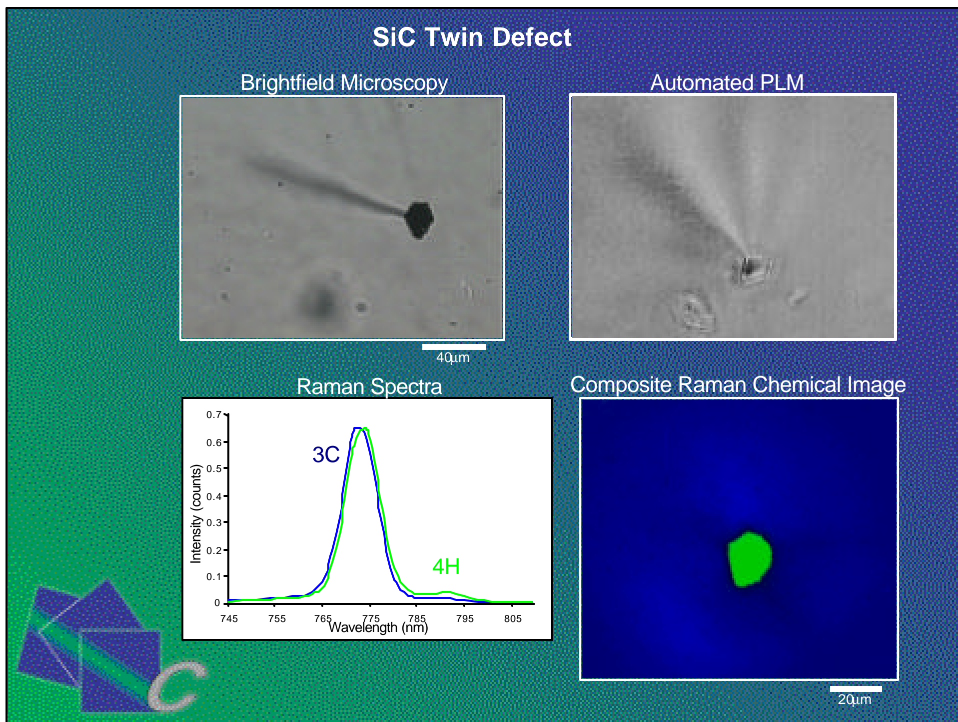
Application

SiC Wafers
Polytypes & Twins

Raman 2D
Automated PLM



SiC Polytype Screening
Macroscopic BF Reflectance
II-VI
5 mm
Raman Spectra
A-4H
B-3C
Intensity
Wavenumber (cm⁻¹)
A
B
25 µm
Raman 4H
Raman 3C

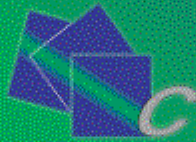


SiC Twin Defect
Brightfield Microscopy
Automated PLM
40µm
Raman Spectra
3C
4H
Intensity (counts)
Wavelength (nm)
Composite Raman Chemical Image
20µm

Application

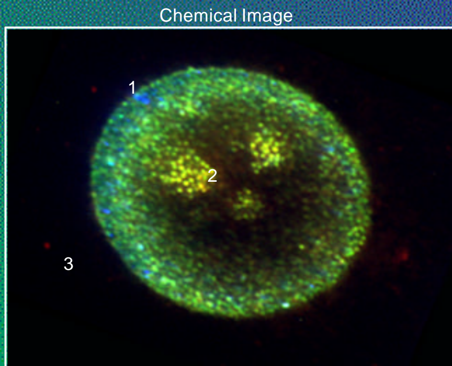
GaN Thin Films
Condensation Defects

Photoluminescence



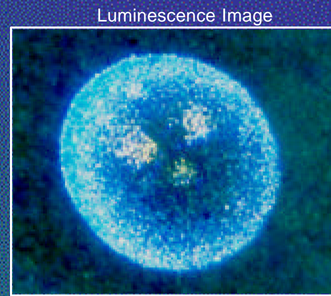
Luminescence Chemical Imaging
MBE Growth GaN Thin Film
Ga Condensation Defect Analysis

Chemical Image



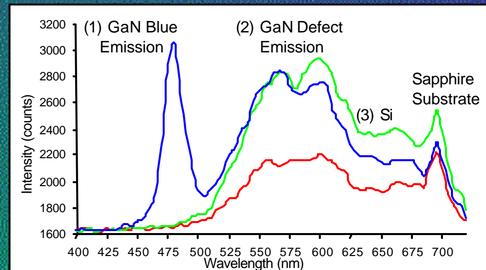
5 µm

Luminescence Image

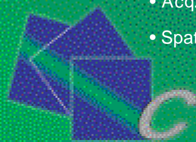


UCS B

Luminescence Spectra

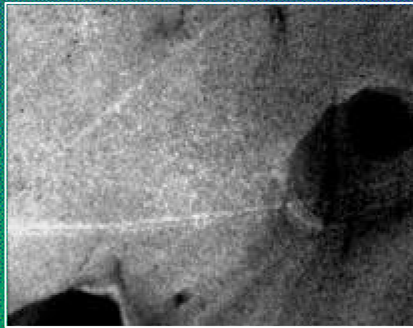


- # Spectra: 336,670
- Acq. Time: >1000 spectra/sec
- Spatial Resolution: 250 nm



Luminescence Chemical Imaging
MBE Growth GaN Thin Film
Blue Emission Screening

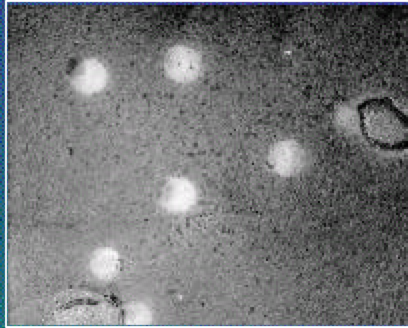
Surface Defects



λ= 425 nm
1 of 65 image frames
Filesize: 65 MB

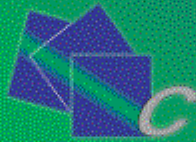
20 µm

Blue Emission



λ(COM)= 425 nm
1 image frame
Filesize: 1 MB

UCSB

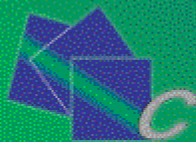


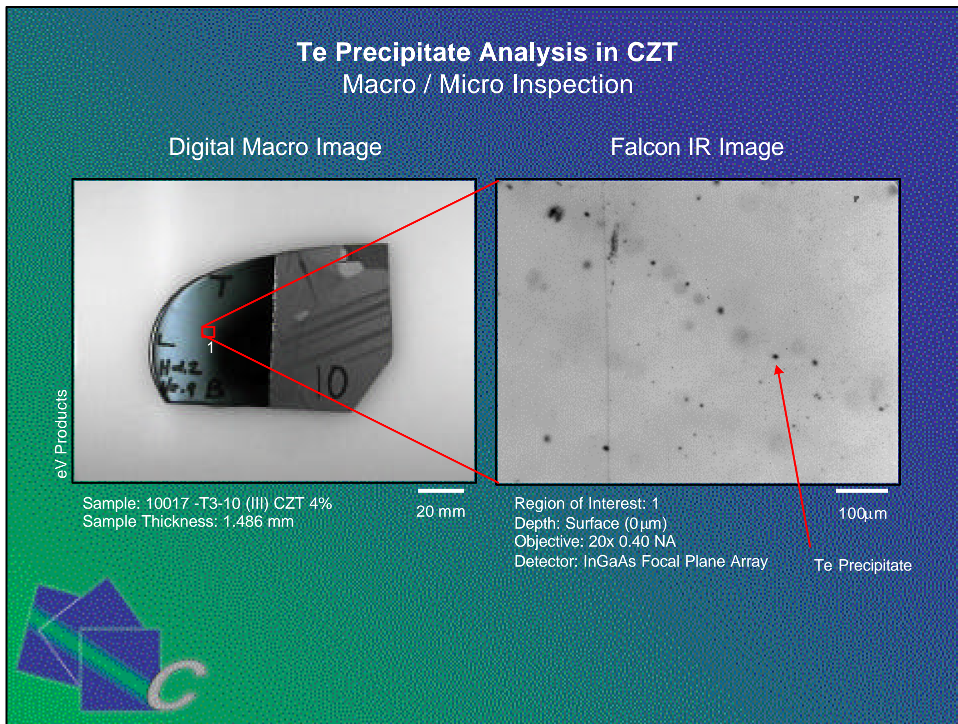
- Spectral band parameters (COM) reveal unique film properties
- Chemical image processing effective for data reduction and property screening

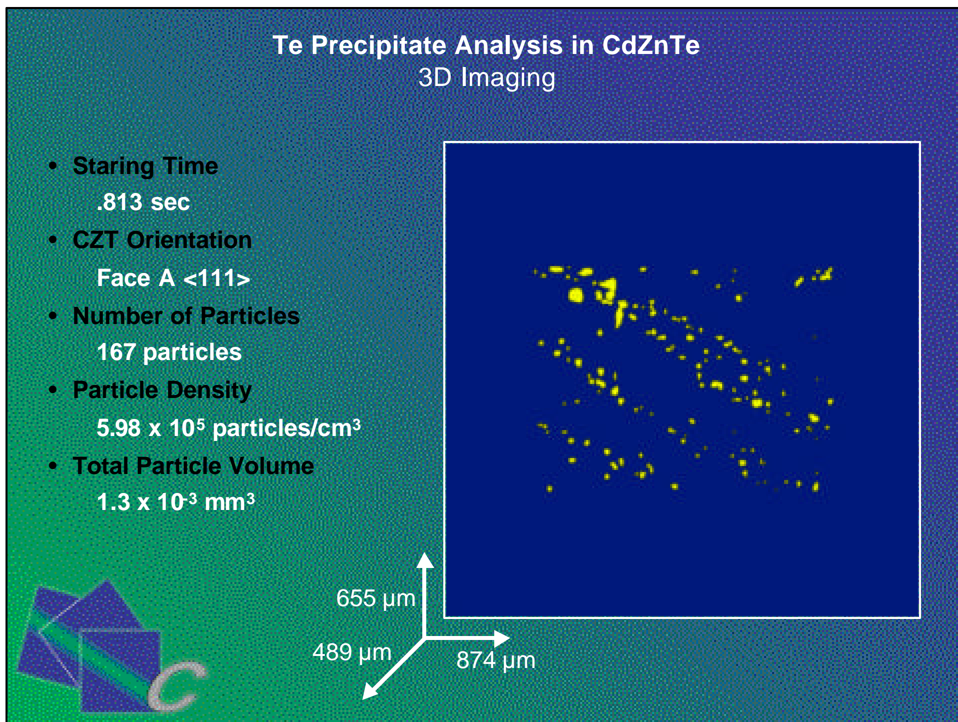
Application

CdZnTe (CZT) Semiconductor
Te Precipitates & [Zn] Stochiometry

IR 2D Macro, 3D Micro, Quantitative

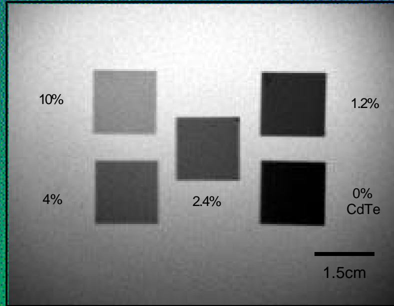



Te Precipitate Analysis in CZT
Macro / Micro Inspection
Digital Macro Image
Falcon IR Image
eV Products
Sample: 10017 -T3-10 (III) CZT 4%
Sample Thickness: 1.486 mm
20 mm
Region of Interest: 1
Depth: Surface (0 µm)
Objective: 20x 0.40 NA
Detector: InGaAs Focal Plane Array
100µm
Te Precipitate


Te Precipitate Analysis in CdZnTe
3D Imaging
• Staring Time
.813 sec
• CZT Orientation
Face A <111>
• Number of Particles
167 particles
• Particle Density
5.98 x 10⁵ particles/cm³
• Total Particle Volume
1.3 x 10⁻³ mm³
655 µm
489 µm
874 µm

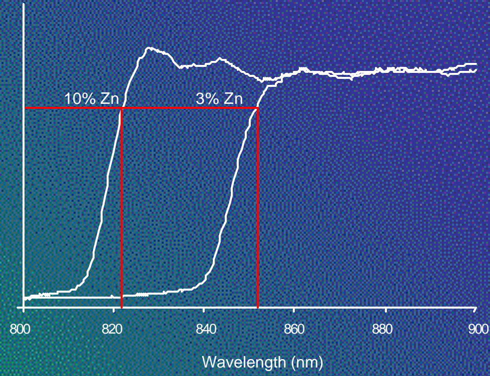
IR Chemical Imaging
Zn Stochiometry in CdZnTe
Calibration Standards

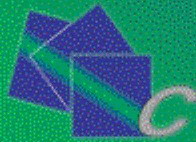
IR Transmission Image



Detector: Si CCD
Exposure Time: 1 Second
λ = 851 nm

IR Transmission Spectra

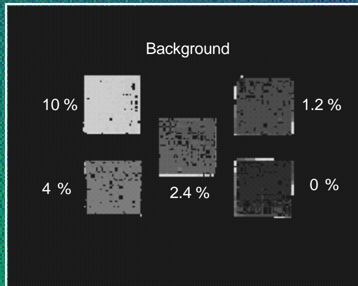




- Bandgap and transmission edge varies with [Zn]

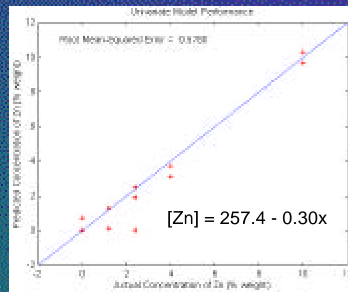
Quantitative IR Chemical Imaging
Zn Stochiometry in CdZnTe
Calibration Standards
Univariate Model

Zn Concentration Map

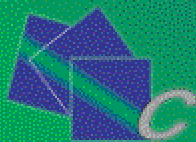


12 10 8 6 4 2 0

Univariate model



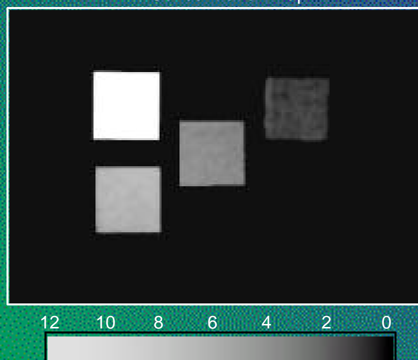
x = wavelength (microns) at ~65% transmission



- Large model error
- Univariate approach not suitable

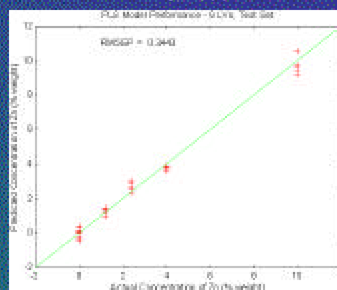
Quantitative IR Chemical Imaging
Zn Stochiometry in CdZnTe
Calibration Standards
Multivariate PLS Model

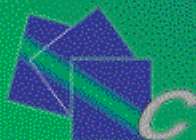
Zn Concentration Map



12 10 8 6 4 2 0

PLS Model

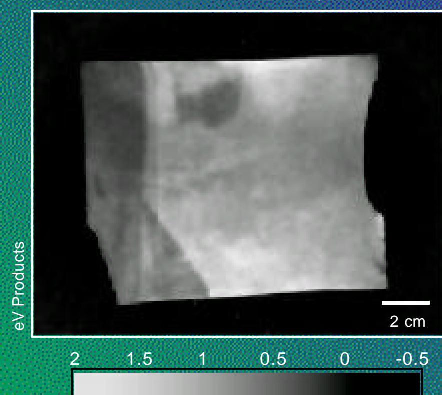




- Multivariate approach – more accurate and reliable than univariate approach
- First quantitative chemical imaging result

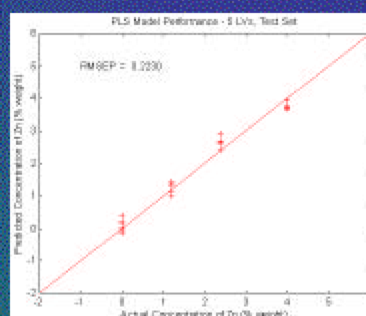
Quantitative IR Chemical Imaging
Zn Stochiometry in CdZnTe

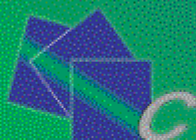
Zn Concentration Map



2 1.5 1 0.5 0 -0.5

PLS Model

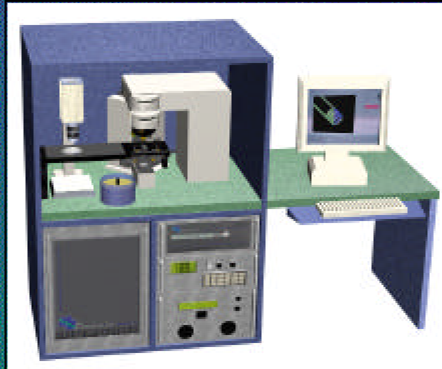


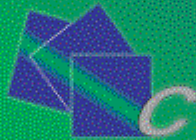


- Successfully employed PLS model to predict Zn in 0-2 weight % range

CHISM System
Concept

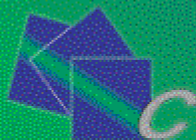
- Macro and micro inspection systems separated to ensure optimal imaging performance
- System configuration determined by semiconductor properties





Summary

- Need for improved metrology in compound semiconductor manufacturing
- Controlling device composition and structure, and screening for material defects at early manufacturing stages will improve yields and reduce the cost of semiconductors.
- Chemical imaging transforms conventional spectroscopic techniques into high throughput screening tools.
- Chemical imaging demonstrated applicability to Si, SiC, SiGe, GaN, GaAs & CdZnTe.
- Broadly applicable to compound semiconductors.
- Chemical image processing combines multivariate statistical analysis and digital image processing - necessary to extract the maximum amount of information from multidimensional data.
- Quantitative chemical imaging demonstrated for the first time.



Acknowledgements

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