2008 Solar Annual Review Meeting

M&C PDIL Integrated and Stand-Alone Tools

Session: PDIL / Measurements & Characterization Capabilities

Organization: NREL

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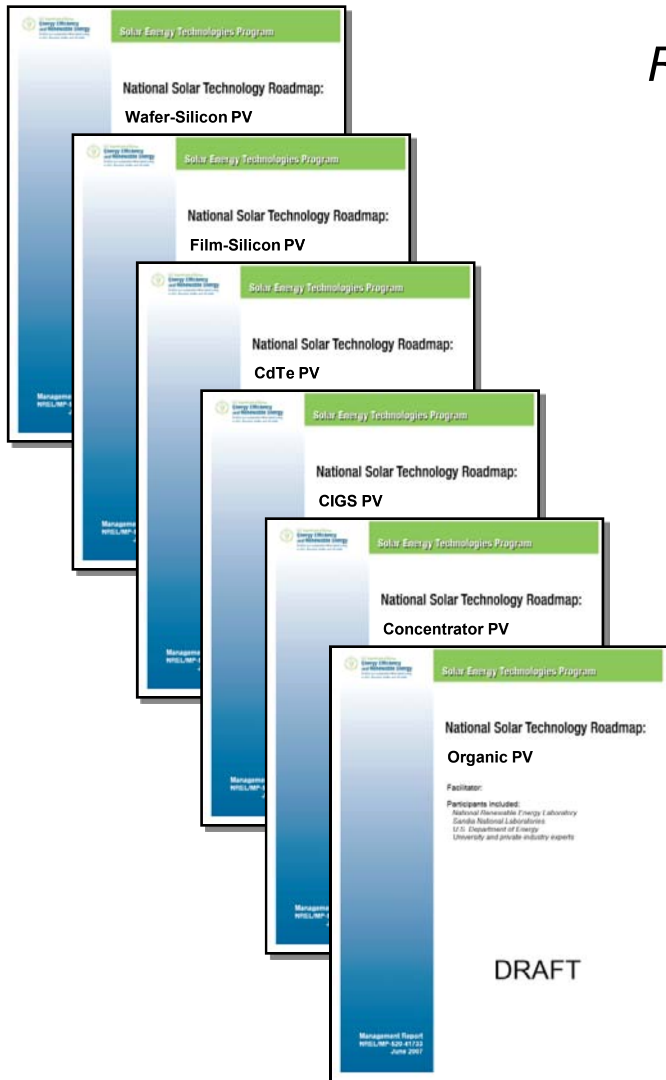
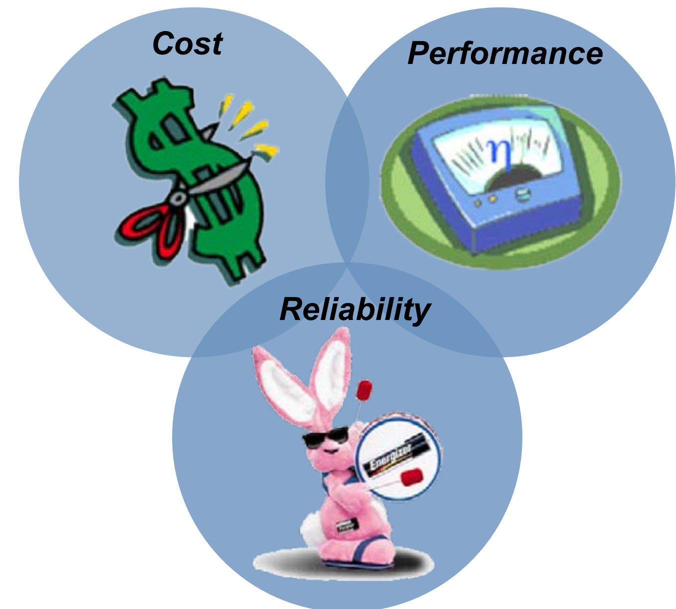
NREL/PR-520-43197
Presented at the Solar Energy Technologies Program (SETP) Annual Program Review Meeting held April 22-24, 2008 in Austin, Texas

M&C PDIL Tool Selection: Roadmap Alignment



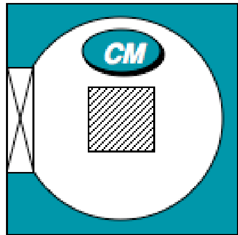
Common Roadmap Elements

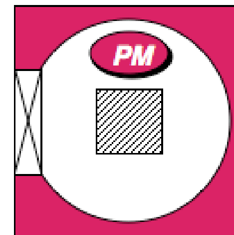


Summary of Technologies Supported (by tool)**:**

a-Si	c-Si	CdTe	CIGS	III-V	OPV	TCO	Reliability

M&C PDIL Tool Selection





Characterization Tools:

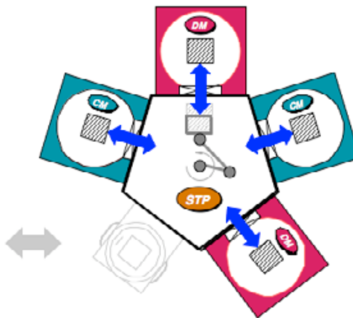
- *Surface Morphology Characterization*
  SEM, AFM, SE, Reflectometer
- *Structural Characterization*
  EBSD
- *Chemical/Compositional Characterization*
  AES, XPS, EDS
- *Electro-Optical Characterization*
  RC-PCD, CL, EBIC, PL/IR Imaging

Processing Tools:

- *Surface Preparation/ Modification*
  Wet Chemistry, Thermal Anneal, Plasma or Sputter Etching
- *Compositional/Structural Property Modification*
  Thermal Anneal
- *Diffusion Barrier or Surface Passivation Layer*
  PECVD, Sputter Deposited Films

M&C PDIL Tool Summary

Integrated Tools



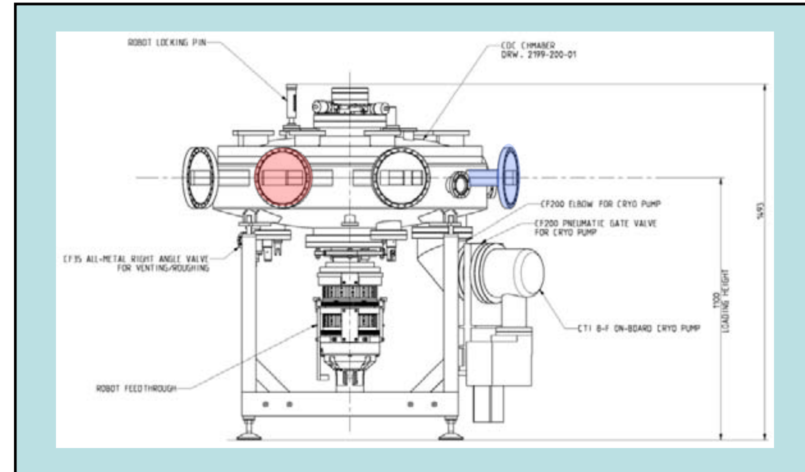
Tool Description
UHV Robot *G. Teeter*
Auger System *G. Teeter*
RCPCD Tool *S. Johnston*
PL Imaging Tool *S. Johnston*
Spectroscopic Ellipsometry *S. Choi*
PECVD Tool *S. Asher*
Sputter/Plasma Etch Tool *S. Asher*
Open Bay for Industry Tool
Transfer Pod

Stand Alone Tools

Tool Description
Wet Chemistry Workstation *B. Sopori*
Semilab Tool *S. Johnston*
Optical Processing Furnace *B. Sopori*
Reflectometer *B. Sopori*
Atomic Force Microscopy System *H. Moutinho*
Scanning Electron Microscopy System *M. Romero*
X-Ray Photoelectron Spectroscopy System *J. Pankow*

UHV Robot: Integrated tool sample transfer "hub"

Computer controlled robotic UHV chamber for transferring NREL platens between analysis, processing, and deposition chambers



Industry/Collaborator Open Port

70°

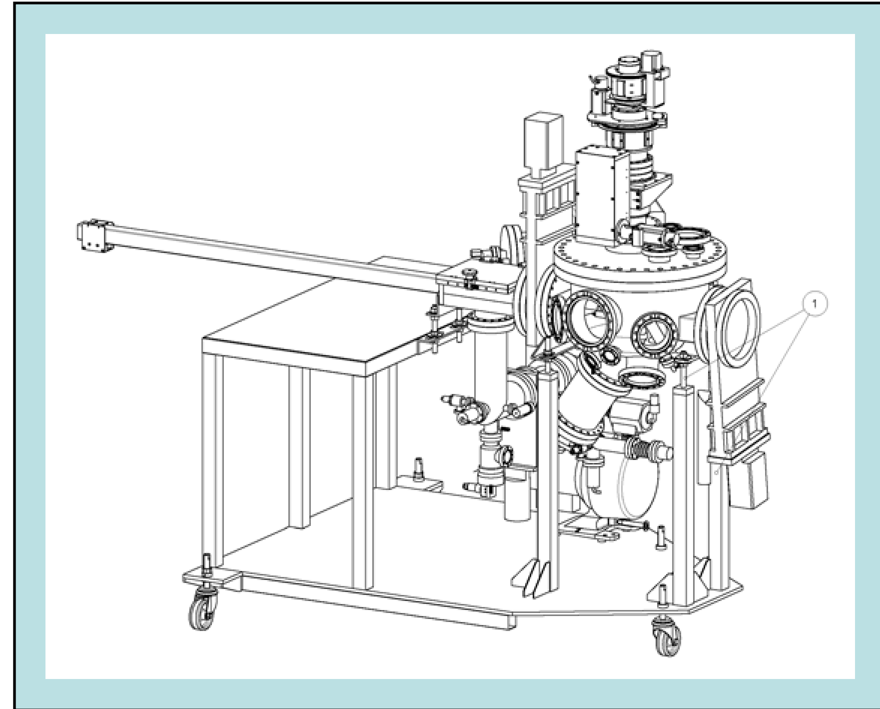
Transport Pod Port

39°

Auger Electron Spectroscopy (AES) Tool

AES Tool Characteristics:

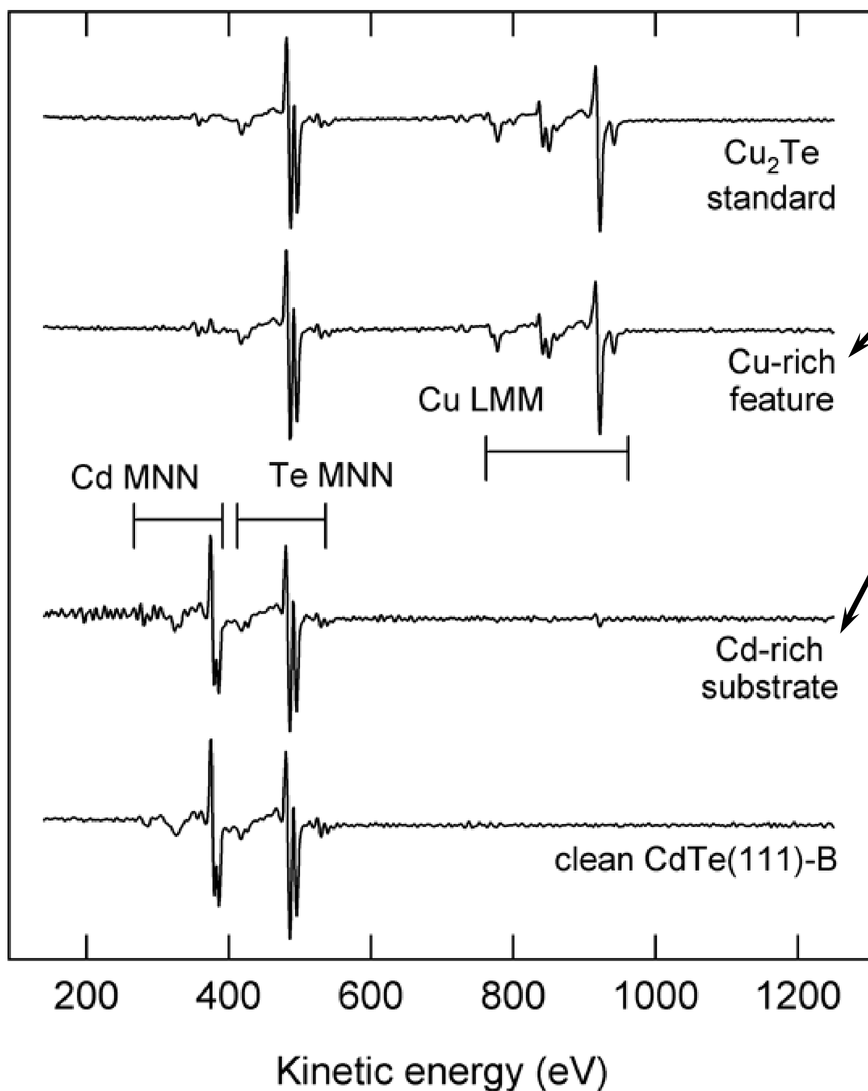
- Non-destructive (surface scan mode)
- Elemental surface analysis (Li to U)
- Compositional analysis (~ 0.1 atomic %)
- Very surface sensitive (~15Å)
- Energy resolution > 1 eV
- Depth-profiling capable (up to 50 nm/min)
- 2-D mapping capability (combinatorial applications)
- Full 6” × 6” sample access
- Standalone or integrated operation

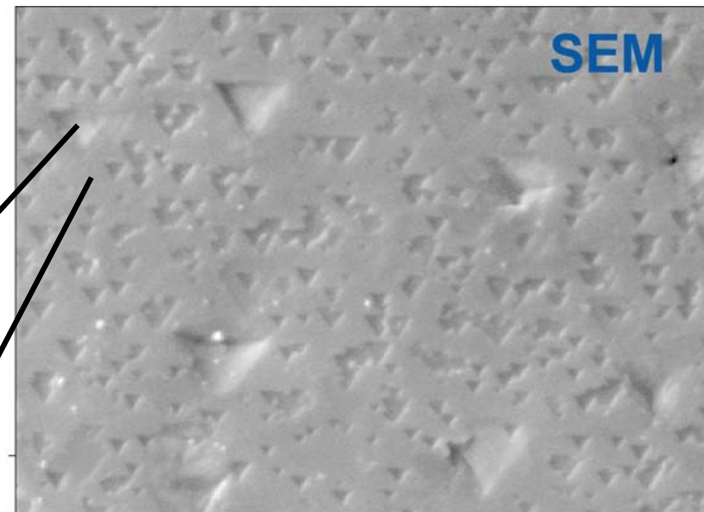


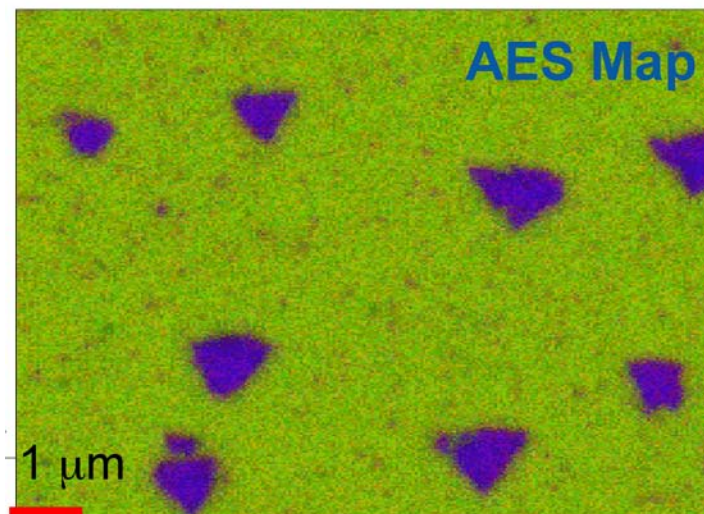
Summary of Roadmap Technologies Supported:

a-Si	c-Si	CdTe	CIGS	III-V	OPV	TCO	Reliability

AES Tool
Application Example: AES mapping Cu/CdTe surface

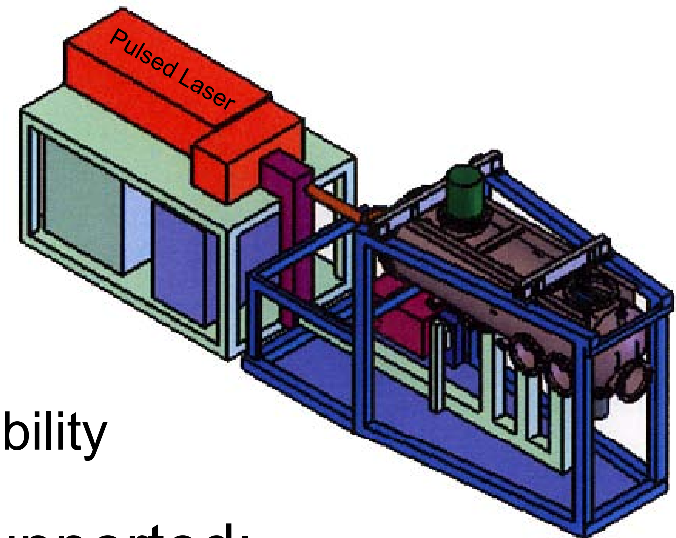






Resonant Coupled Photo Conductive Decay (RC-PCD) Microwave Photo Conductive Decay (μ-PCD) Tool

- Minority-carrier lifetime spectroscopy is a contactless, nondestructive method to study the recombination processes in materials. Measures the return of photoexcited carriers back to equilibrium providing the lifetime of the excess carriers.
- Excellent technique for evaluating material quality and surface passivation
- Capable of accessing the entire 6” x 6” substrate area in a controlled environment
- Excitation source is pulsed laser with OPO (~5 ns pulse width, Wavelength tunable from 420 nm to 2300 nm)
- Stepper motor stage provides mapping capability



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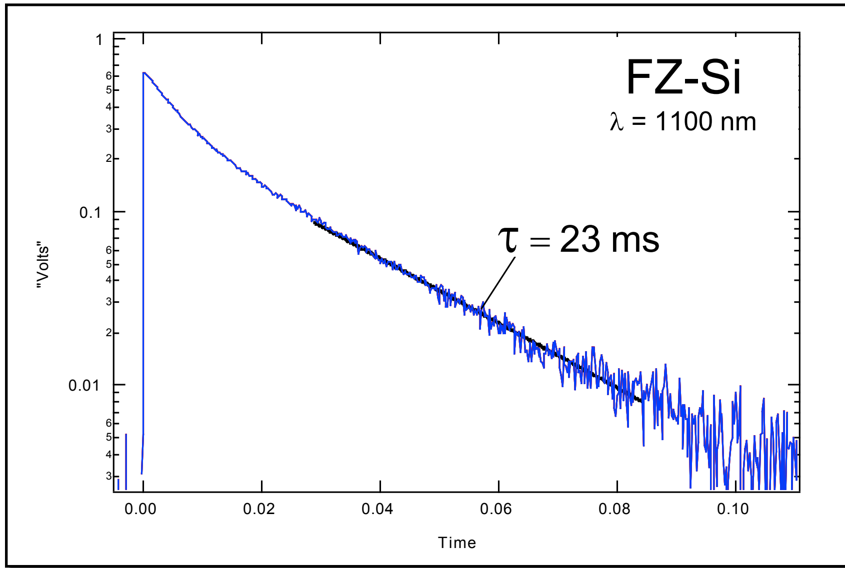
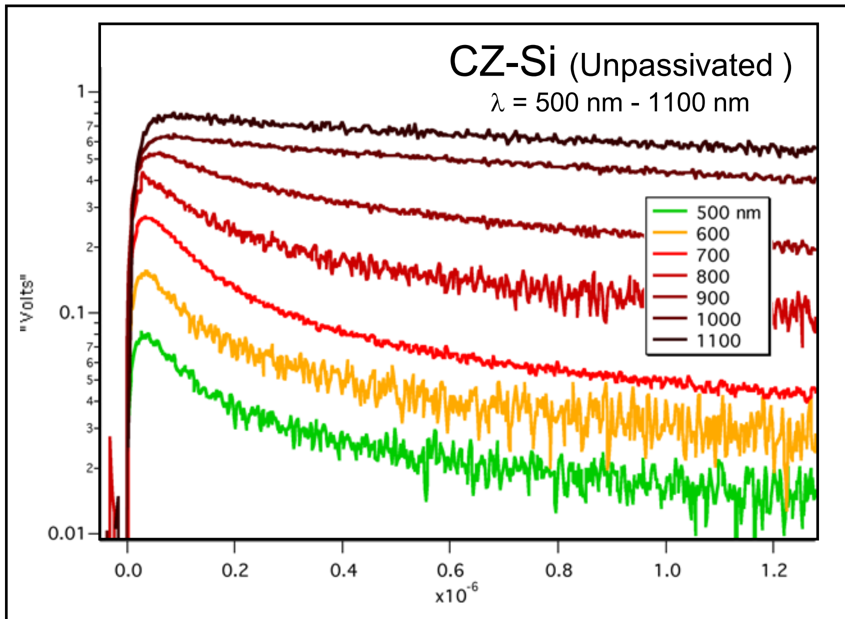
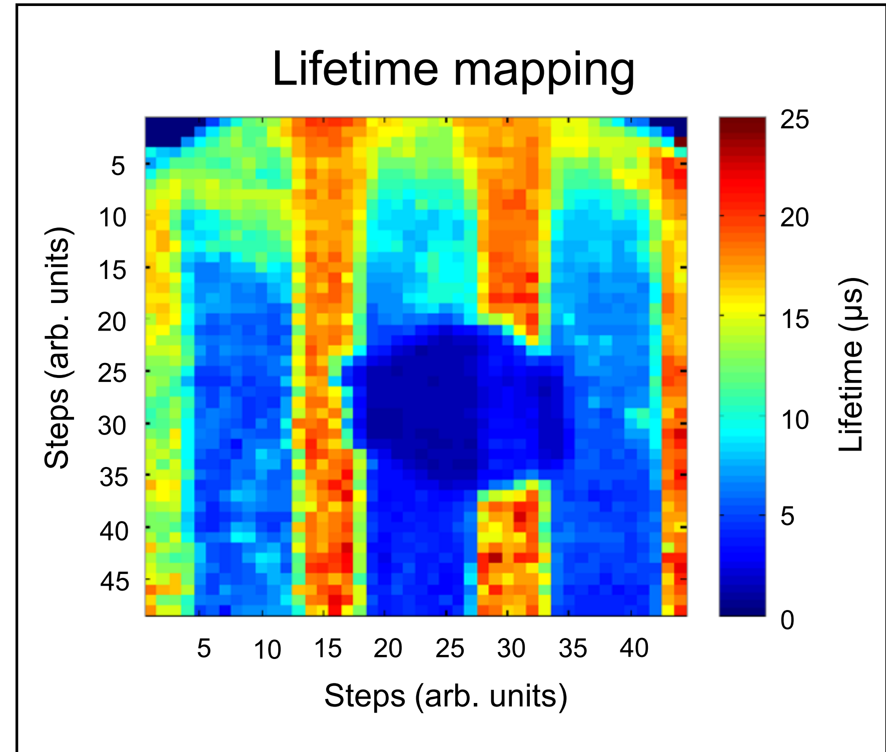
a-Si	c-Si	CdTe	CIGS	III-V	OPV	TCO	Reliability

RC-PCD/μ-PCD Tool: Application Example







Photoluminescence (PL) / Infrared (IR) Imaging Tool

- PL and IR imaging are recently developed contactless techniques that provide signals proportional to the minority carrier lifetime
- **Excitation source:**
  Fixed wavelength 60W laser diode (810 nm) illuminates the entire 6" x 6" sample area at ~1-sun intensity
- **Imaging/Detection Options:**
  High-resolution imaging cameras (~150 μm pixel resolution) provide a rapid measurement of the lifetime over the entire 6" x 6" sample area (1-30 sec.)
  - PL Imaging - Si CCD Camera detects PL signal emitted at 1100 nm
  - IR Imaging - InSb IR Camera (lock-in thermography) for carrier density imaging detects emission or absorption of IR by excess carriers
- Imaging shows steady-state values proportional to lifetime and may be applicable to most materials since time resolution is not a limiting factor

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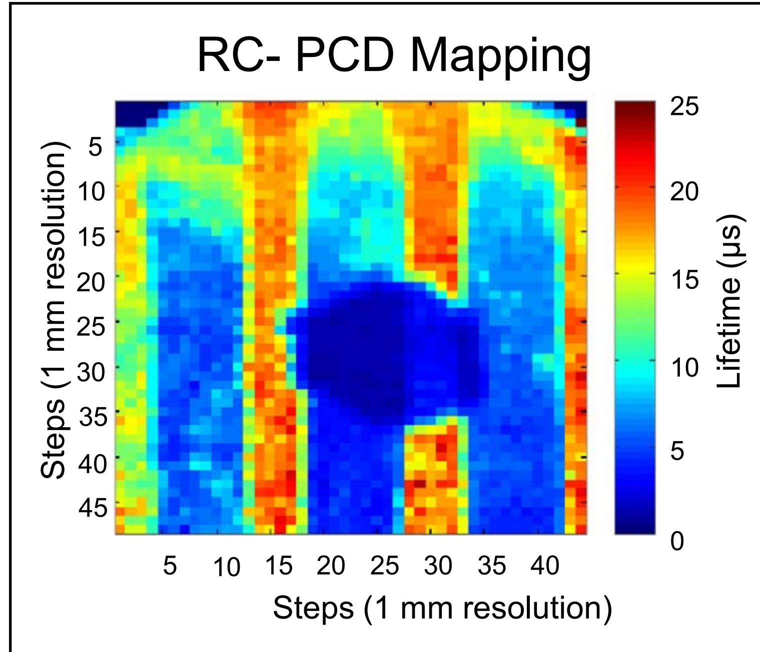
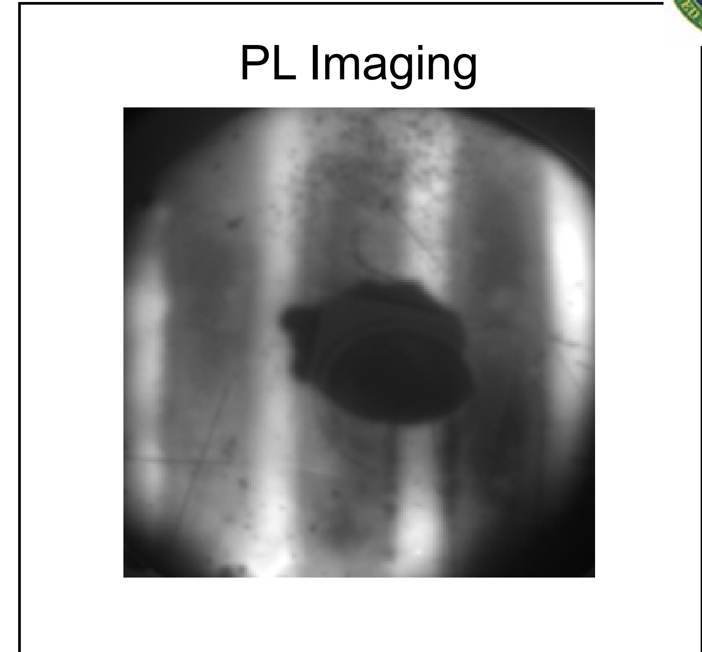
a-Si	c-Si	CdTe	CIGS	III-V	OPV	TCO	Reliability

PCD and Imaging Tool Comparison





Quantitative Data: *Fitted transients provide quantitative lifetime results*

Slow Data Collection: *Minutes to hours*

Lower Resolution: *1 mm/pixel*

R&D Emphasis: *Variable excitation wavelength and injection level provide valuable research information*
(τ vs depth and injection level dependence)

Qualitative Data: *Intensity is proportional to lifetime, linearity suffers when S is high*

Rapid Data Collection: *Seconds*

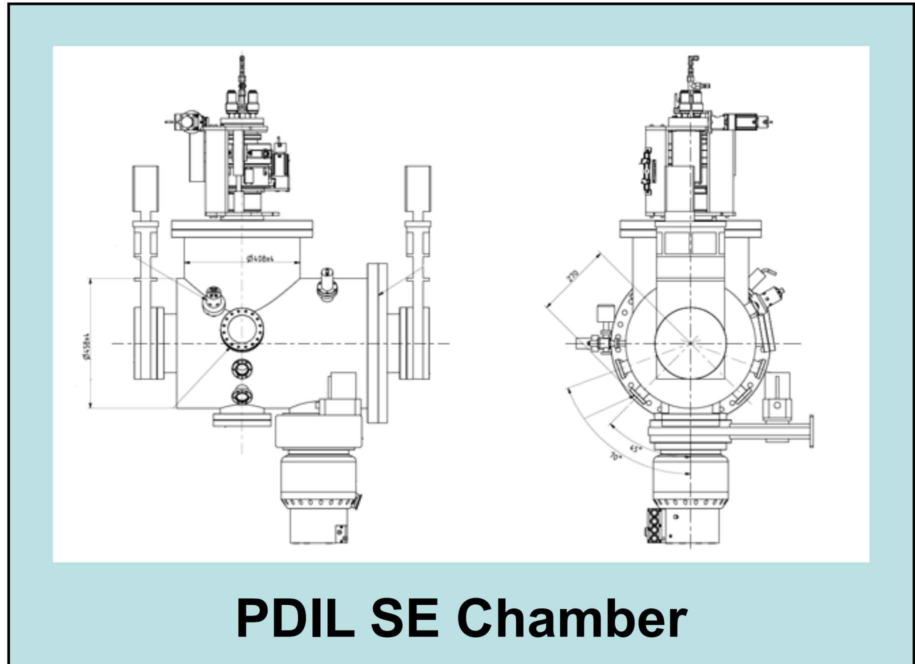
Higher Resolution: *150 µm/pixel*

Process Diagnostic Emphasis: *In-line capability for use as process control and feedback*

Spectroscopic Ellipsometry (SE) Tool

SE Tool Characteristics:

- Non-destructive technique
- Wide spectral range (245 - 1690 nm)
- Fast data acquisition
- Temperature: RT to ~850ºC
- High Pressure to UHV capable (dose samples w/ gases such as O_2 or H_2O)
- Full sample access



PDIL SE Chamber

SE Tool Applications:

- Thin-film thickness
- Surface/interface roughness
- Crystallinity
- Optical constants
- Alloy composition
- Electronic energy band structure information
- Real-time feedback for growth control

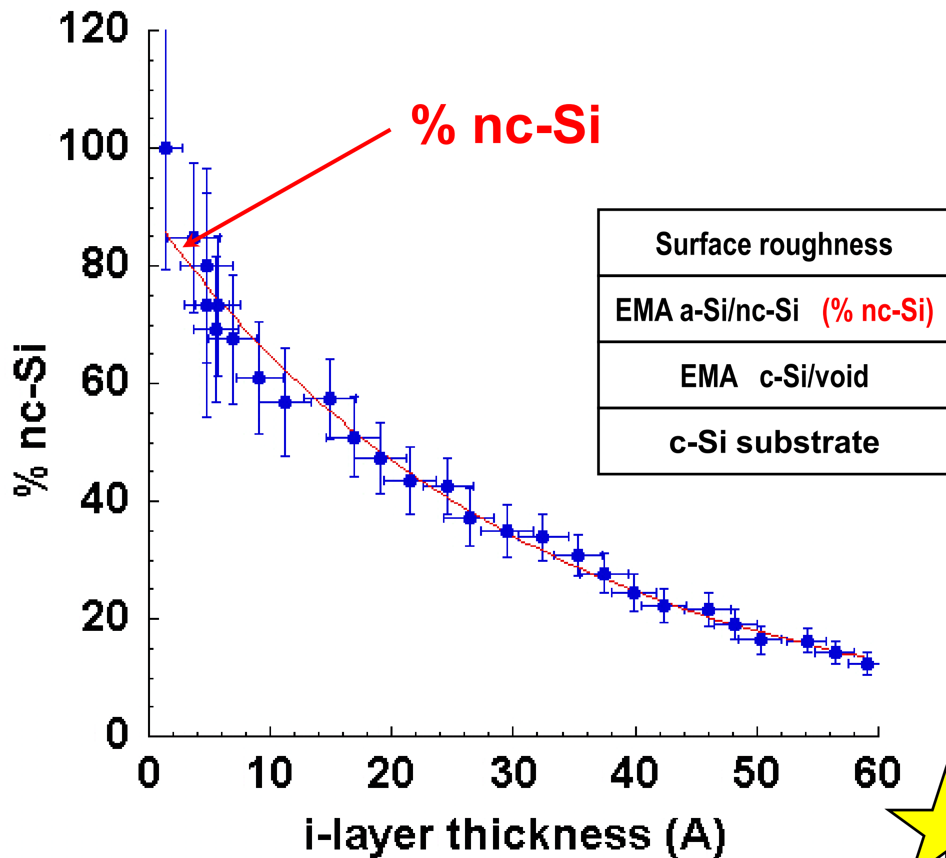
Summary of Roadmap Technologies Supported:

a-Si	c-Si	CdTe	CIGS	III-V	OPV	TCO	Reliability

SE Tool: Application Example - Monitoring Si Crystallinity

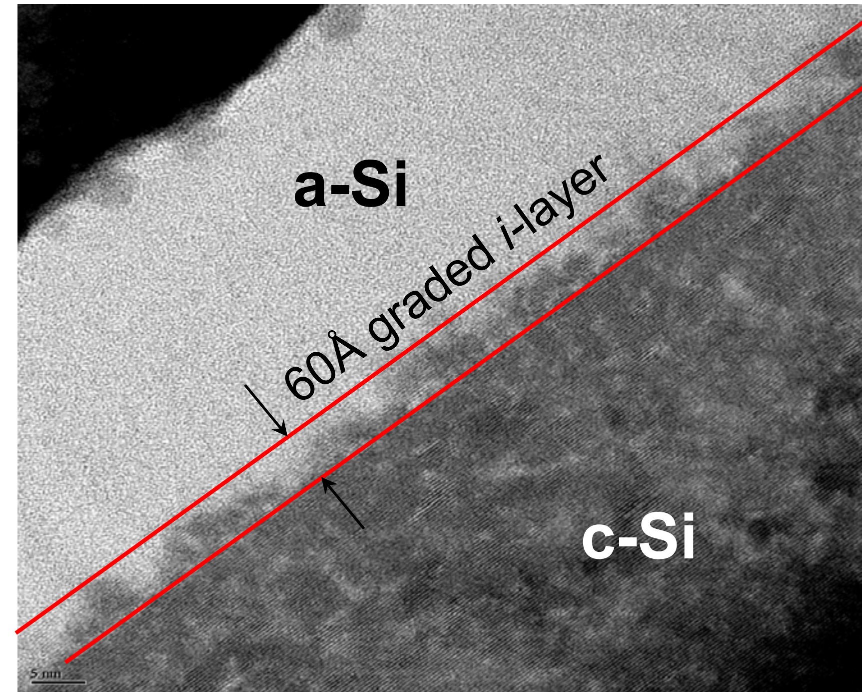
SE Data Modeling

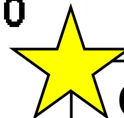
Graded *i*-layer: nc-Si ⇒ *a*-Si



TEM Cross Section

c-Si ⇒ nc-Si ⇒ *a*-Si



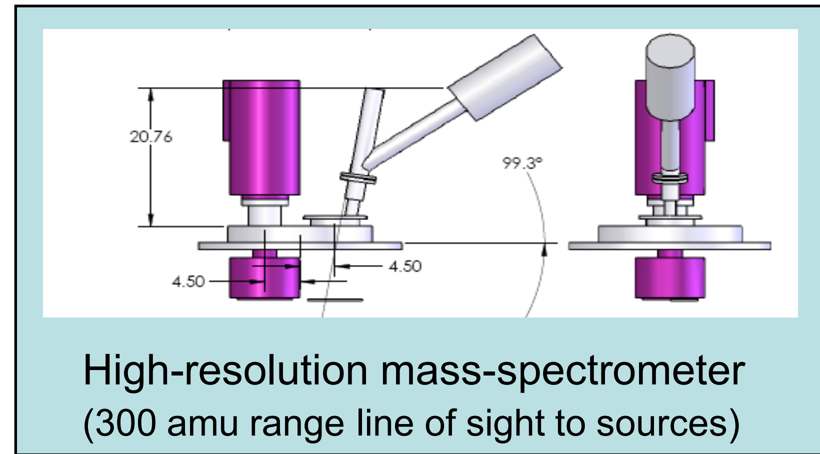


Other RTSE Monitoring Applications:
CIGS, CdTe, SiN_x, and TCO deposition

Sputter-Plasma-Diagnostic (SPD) Tool

Flexible platform for performing controlled ambient annealing experiments and for developing improved understanding of common industrial deposition processes and scale-up issues.

- RF and DC sputter deposition sources
- Plasma source (deposition & etching)
- High resolution mass spectrometer



High-resolution mass-spectrometer (300 amu range line of sight to sources)

Applications:

- Contacting studies
- Detection of active species in sputtering or plasma enhanced deposition processes
- Compare/assess sputter targets from different manufacturers
- Compare PECVD processes

Summary of Roadmap Technologies Supported:

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Plasma Enhanced Chemical Vapor Deposition (PE-CVD) Tool

General purpose plasma enhanced chemical vapor deposition tool (remote plasma) for the deposition of high-quality oxides, nitrides, and carbides of silicon.

PE-CVD Tool Applications:

- Silicon passivation studies using Si_xN_y:H and Si_xC_y:H
  - Optimum firing conditions for various film compositions
  - Compare/optimize for H-passivation, BSF, AR
- Deposition of moisture-barrier layers
  - Indirect plasma to minimize damage to polymer/other surface
  - Direct coating of cells and/or critical coatings for reliability studies
- Depositions for diffusion barrier layers on glass or other substrates

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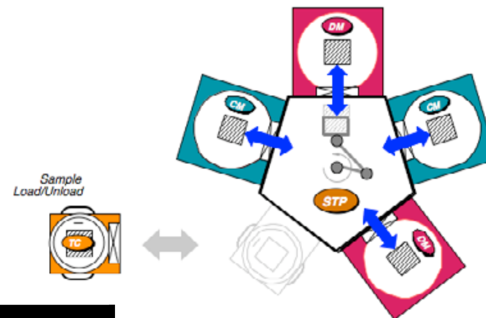
M&C PDIL Tool Summary

Integrated Tools



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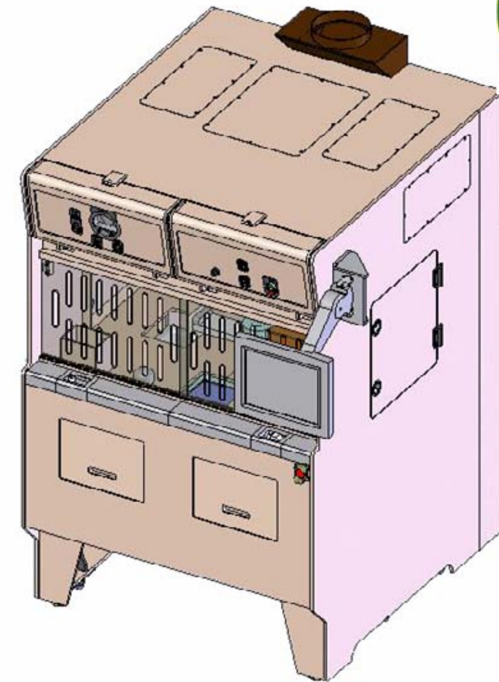
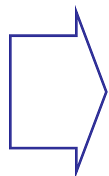
Wet processing station (WPS)

General user facility for Si processing: Semi automatic, wet processing station for reproducible Si wafer preparation and etching



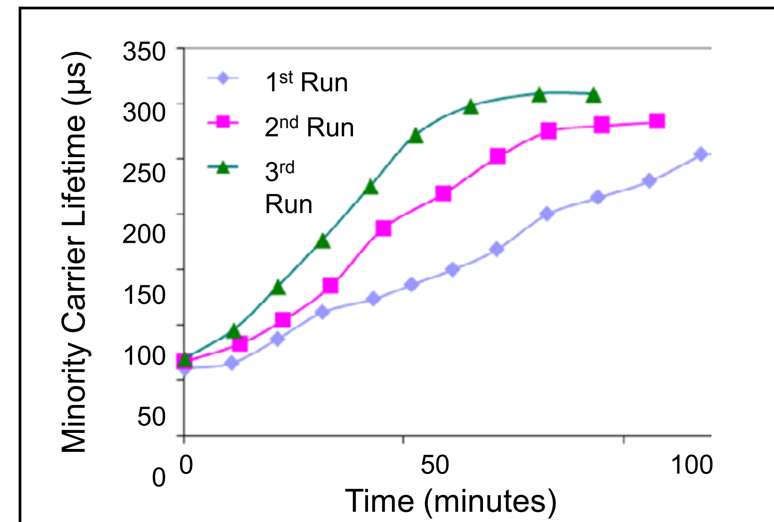
WPS Tool Applications:

- Wafer preparation/surface passivation for lifetime measurement
- Defect Etching
- Oxide Removal
- H-termination
- Planarization Etching



Reproducible surface preparation is critical

Surface Passivation

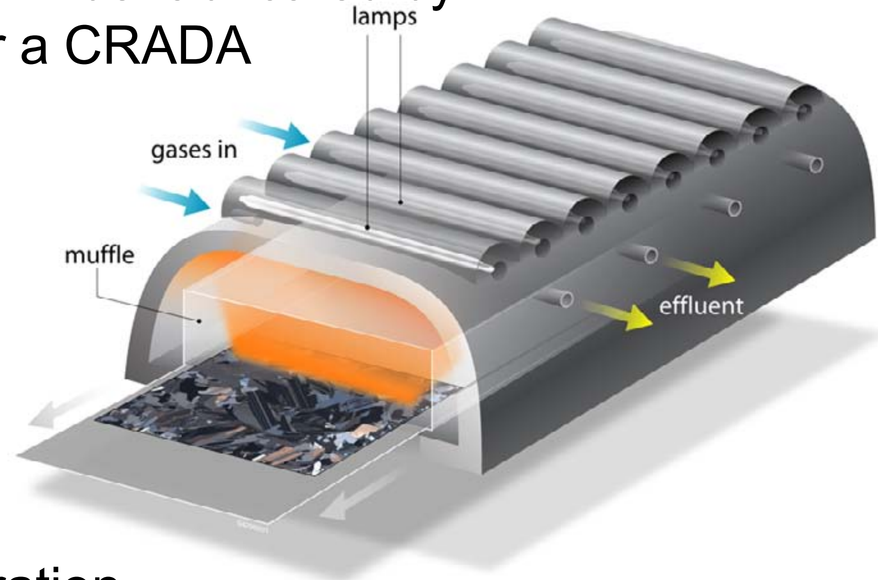


Technologies Supported:

c-Si

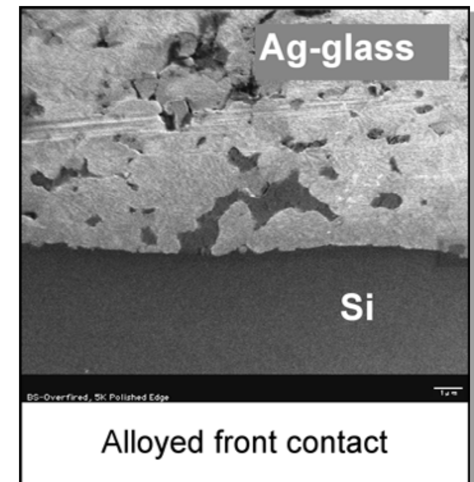
Optical Processing Furnace (OPS)

Optical furnace for processing 6” x 6” semiconductor wafers. Furnace was designed at NREL and will be fabricated by Applied Optical Sciences Corp. under a CRADA



OPS Tool Applications:

- Contact Formation
  (e.g., Alloying Al, fire-through front metallization on SiN:H)
- Hydrogen Passivation
- Thin-film Si Recrystallization
- Oxidation for Wafer Surface Preparation



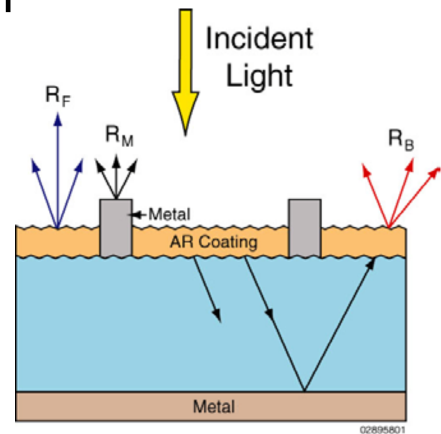
Alloyed front contact

Technologies Supported:

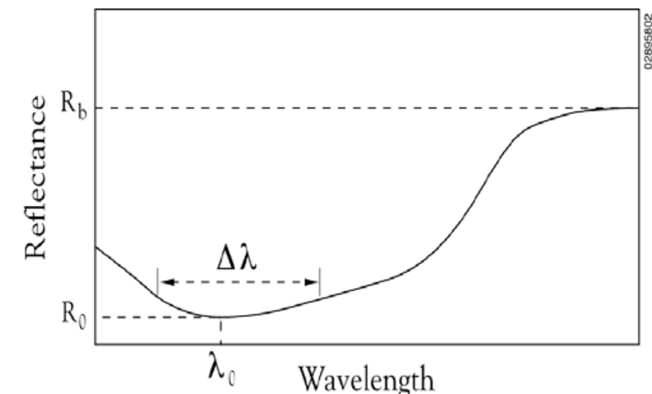
a-Si	c-Si	CdTe	CIGS

Reflectometer: Tool Characteristics

NREL developed technique that rapidly measures the reflectance spectrum over an entire 6” x 6” substrate as a function of wavelength and deconvolves the data to derive physical parameters of importance to PV cell manufacturing.



- Measures Reflectance in two modes:
  - Spectrometer mode $R_{avg}(\lambda)$
  - Imaging mode $R_{\lambda=const}(x,y)$
- Indirectly Measures:
  - AR coating thickness (λ_0)
  - Surface roughness ($\Delta\lambda$)
  - Wafer thickness ($R_{abs.\ edge}$)
  - Metallization fraction (R_0)
  - Back surface reflectance (R_b)
- Data acquired in < 1 s



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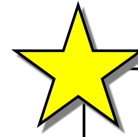
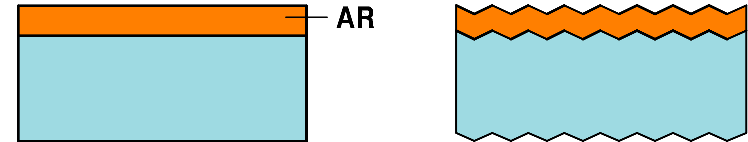
Reflectometer: Applications

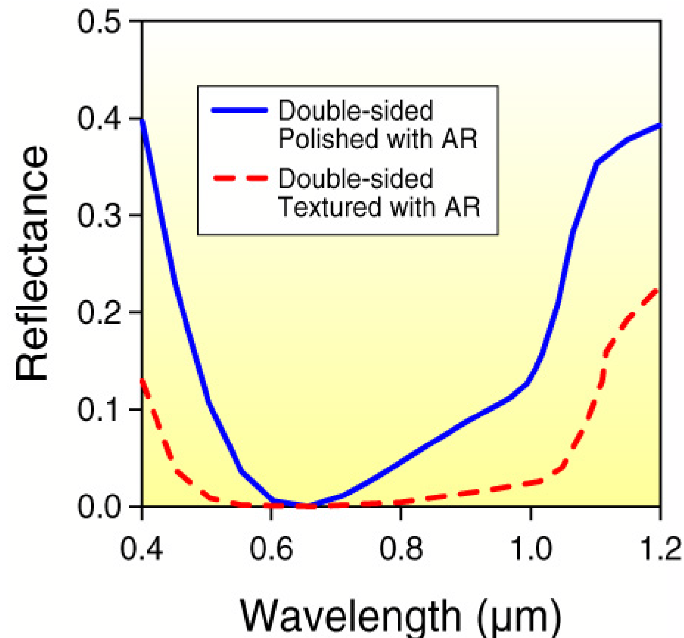


Licensed to GT Solar for commercialization

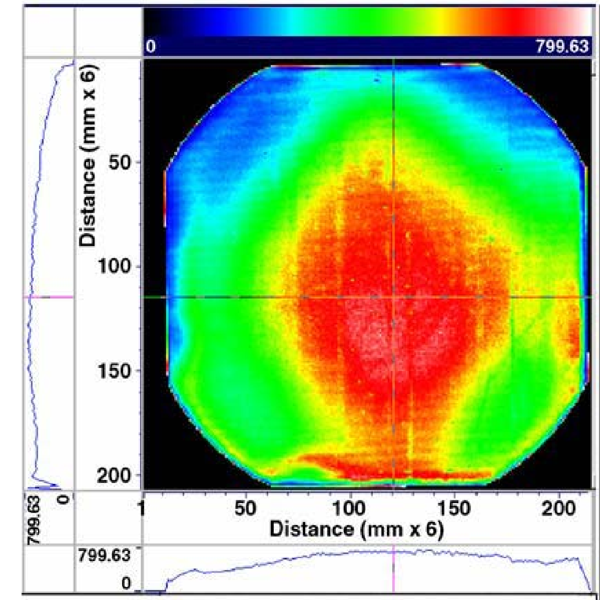
- **R&D process monitoring**
  - AR coating thickness (λ_0)
  - Surface roughness ($\Delta\lambda$)
  - Wafer thickness
  - Metallization area
  - Metallization height
- **Online monitoring compatible**



Spectrometer Mode



Imaging Mode

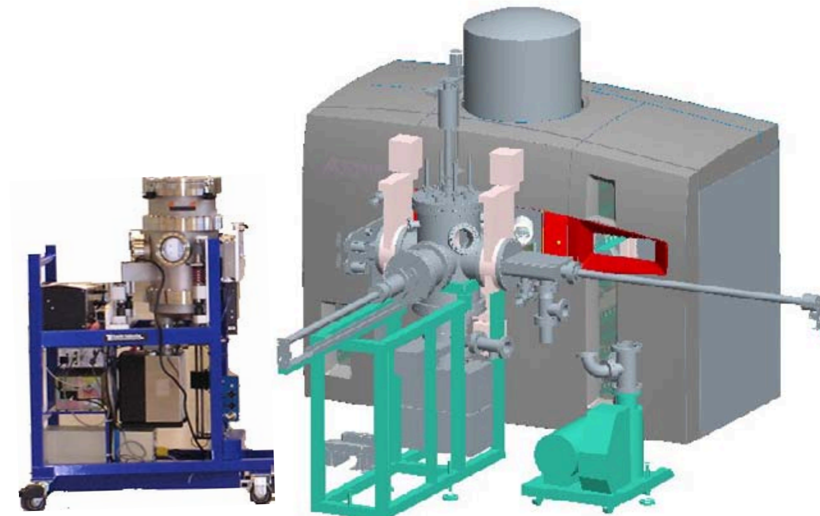


X-ray Photoelectron Spectroscopy (XPS) Tool

XPS Tool Characteristics:

- Quantitative evaluation of chemical bonding environment
  (valence state and chemical environment)
- Determination of band positions, alignments, Fermi edge, work function
- Elemental identification (Li to U)
- Compositional analysis (~ 0.1 atomic %)
- X-ray probe size ~10um
- Depth profiling capability
- Full 6” × 6” sample access
- “Face-up” analysis only

Kratos
Axis Nova



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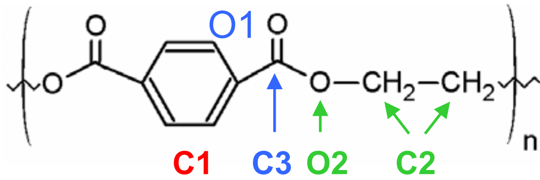
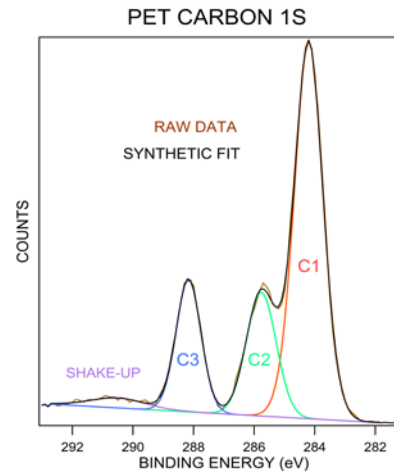
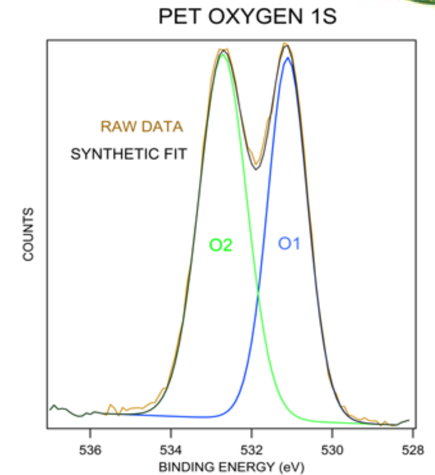
XPS Tool: Sample Applications

Polymer Analysis

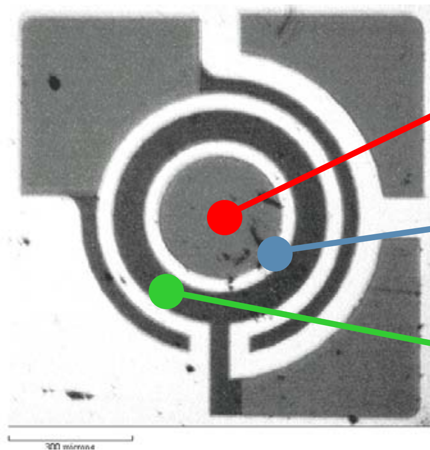


Polyethylene Terephthalate
(PET)





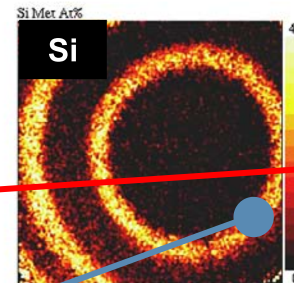
2-D Chemical Mapping

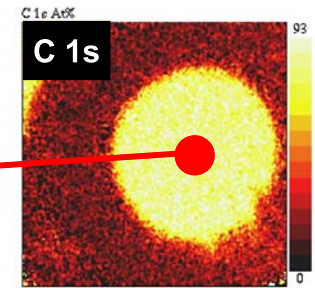


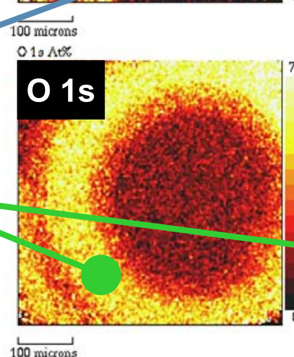
Photoresist

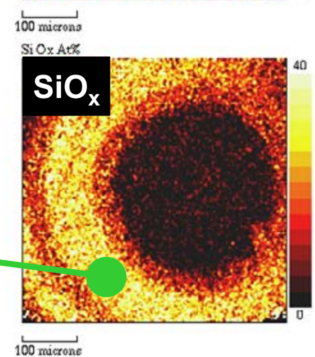
Si

Si oxide





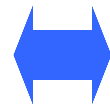




Scanning Electron Microscope (SEM) Tool

SEM Tool Characteristics:

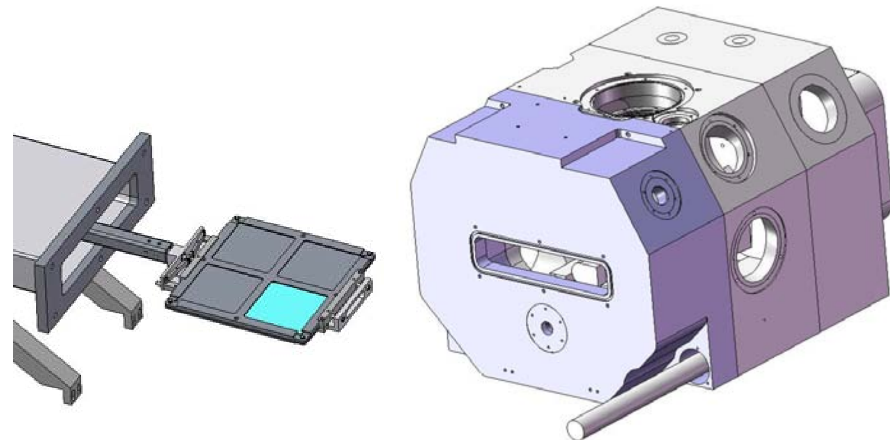
- Operating modes:
  - Secondary electron imaging (SE)
  - Backscattered electron imaging (BSE)
  - Cathodoluminescence (CL)
  - Electron beam induced current (EBIC)
  - Electron backscattered diffraction (EBSD)
  - Energy dispersive x-ray spectroscopy (EDS)
- Non-destructive
- Operating ambients:
  - High Vacuum 4.5×10^{-6} Torr
  - Low Vacuum 0.1-1 Torr
  - Environmental mode 1-20 Torr
- Resolution:
  - 3.0 nm (SE, 30 keV)
  - 4.0 nm (BSE, 30 keV)
- Full access to 6” × 6” sample area
- PDIL compatible



Information obtained:

Image contrast

Photon emission - recombination centers
Electrical activity - junction, GBs,
Structural data - orientation and phase
Compositional data - elemental mapping



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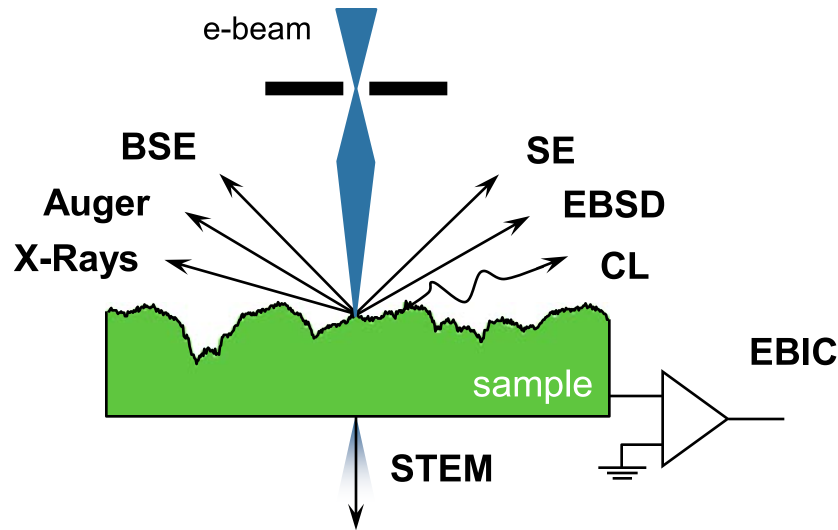
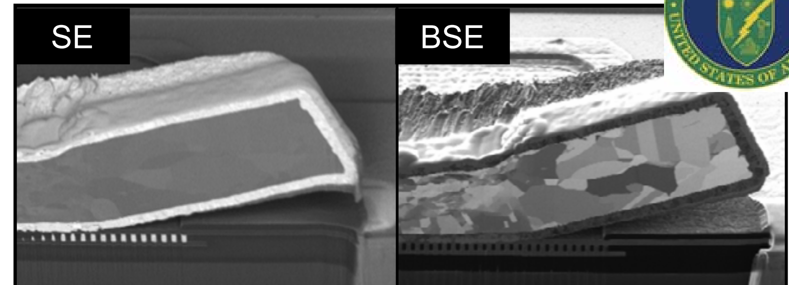
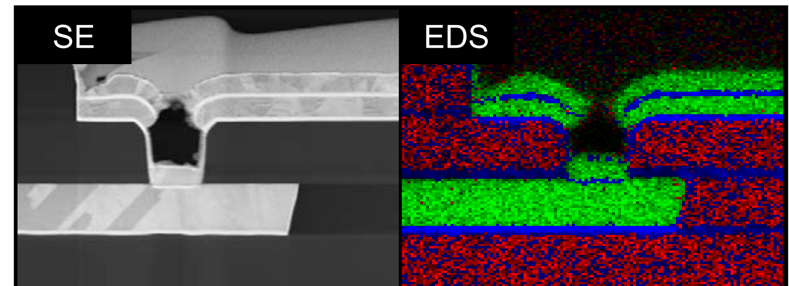
SEM Tool: Sample Applications

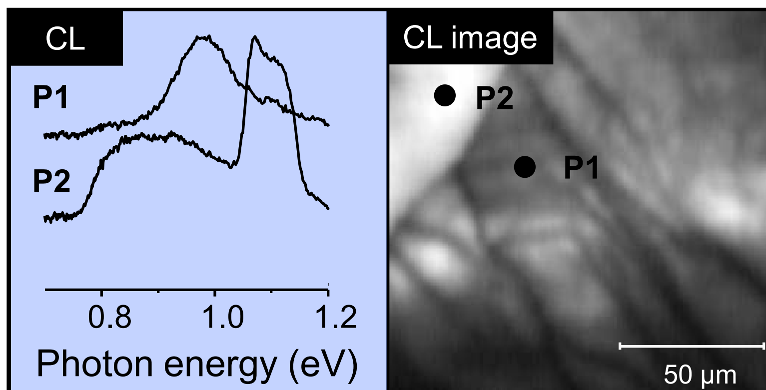




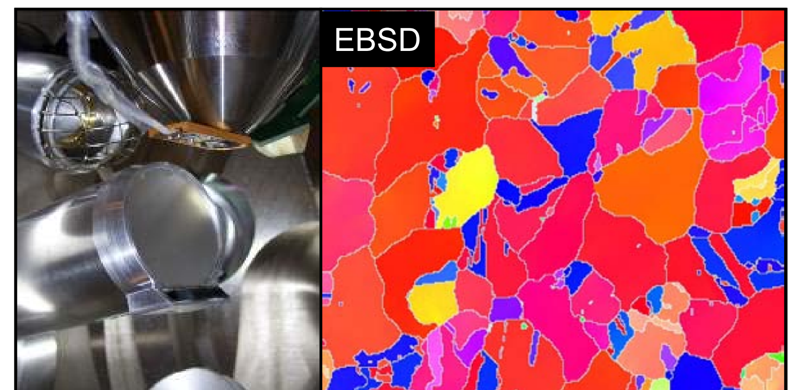
Complementary Image Contrast



Compositional Analysis



Optical Emission

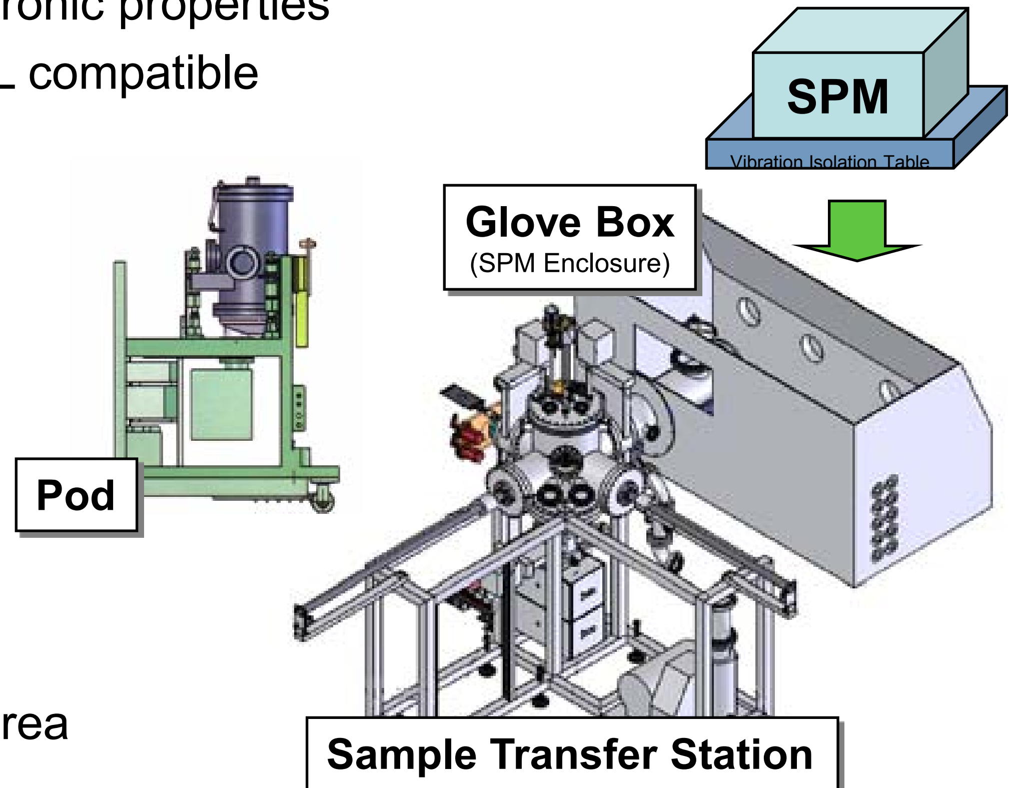


Structural Analysis

Scanning Probe Microscopy (SPM) Tool

SPM Tool Characteristics:

- Operating modes provide information on topographic and material electrical and electronic properties
- Non-destructive technique, PDIL compatible
- Can analyze materials ranging from conductors to insulators
- Excellent Spatial Resolution:
  - x, y < 1.80 nm
  - z < 0.05 nm
- 2 µm stage repeatability
- Operating ambients:
  - Atmospheric pressure
  - N_2, Ar or other ambients
- Full access to 6” × 6” sample area

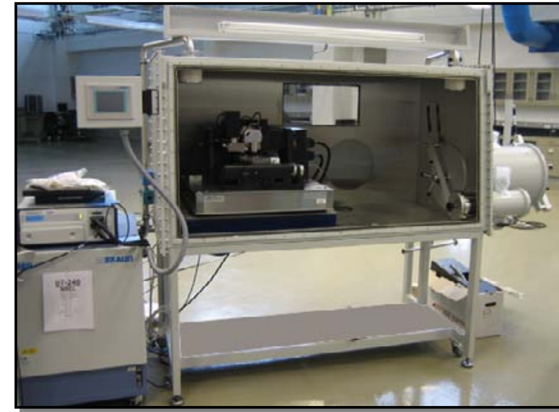


Summary of Roadmap Technologies Supported:

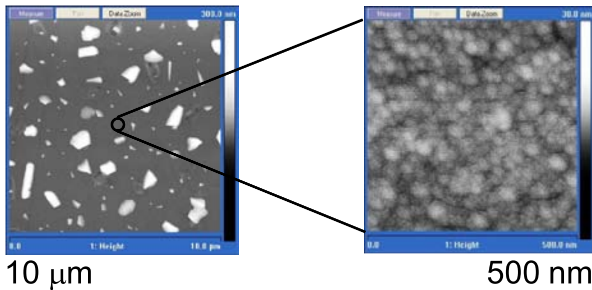
a-Si	c-Si	CdTe	CIGS	III-V	OPV	TCO	Reliability

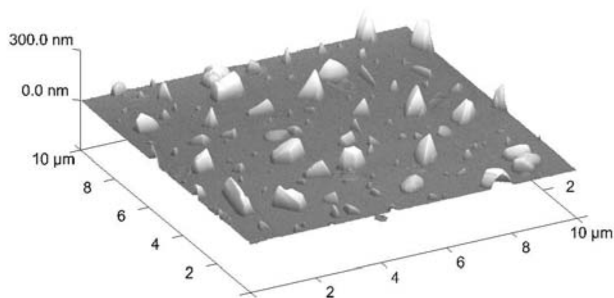
SPM Tool: Sample Applications

- Surface Imaging: topography (AFM)
- Electrical and electronic properties: surface potential (SKPM), carrier concentration (SCM), electrical conductivity (C-AFM)

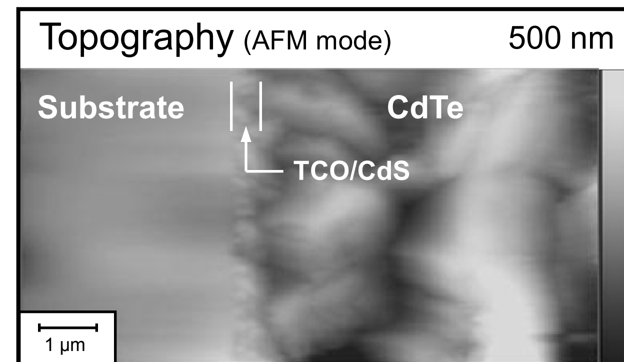


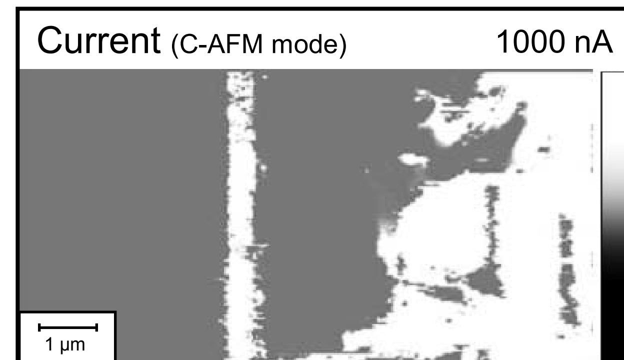
Cd_2SnO_4 after annealing





CdTe/CdS solar cell





M&C PDIL Tools: Current Status/Estimated Installation

Tool Description	Current Status	Estimated Installation Date
UHV Robot	***Final Design Complete, Tool Purchased***	***03/09***
Auger (AES) System	***Final Testing at Vendors Site***	***07/08***
RC-PCD Tool	***Preliminary Design Complete, Prototype Tested***	***03/09***
PL/IR Imaging Tool	***Preliminary Design Complete, Prototype Tested***	***03/09***
Spectroscopic Ellipsometry	***Specifications Complete***	***09/08***
Sputter/Plasma Etch Tool	***Final Design Complete, Tool Purchase Initiated***	***02/09***
PECVD Tool	***Preliminary Design Complete***	***04/09***
Wet Chemistry Workstation	***Final Design Complete, Tool Purchased***	***11/08***
Semilab Tool	***Installation Complete***	***03/08***
Optical Processing Furnace	***CRADA signed, Conceptual Design Complete***	***03/09***
Reflectometer	***CRADA Negotiated, Prototype Design Complete***	***02/09***
Atomic Force Microscopy (AFM)	***AFM Installation Complete*** *(Glove Box & Transfer Station Installation Pending)*	***04/08***
Scanning Electron Microscopy (SEM)	***Tool Construction Near Completion***	***06/08***
X-Ray Photoelectron Spectroscopy (XPS)	***Final Design Complete, Tool Purchased***	***11/08***

M&C PDIL Tool Layout

April 2009