
2008 Solar Annual Review Meeting

M&C PDIL Integrated and Stand-Alone Tools

Session: PDIL / Measurements & Characterization
Capabilities

Organization: NREL



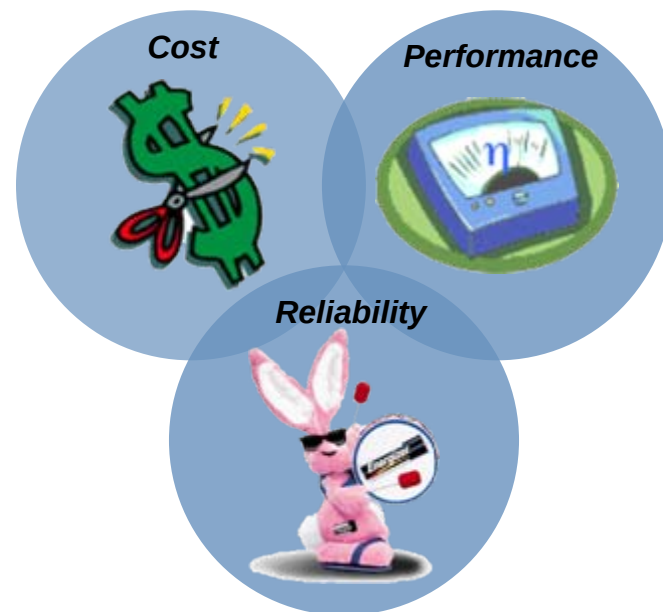
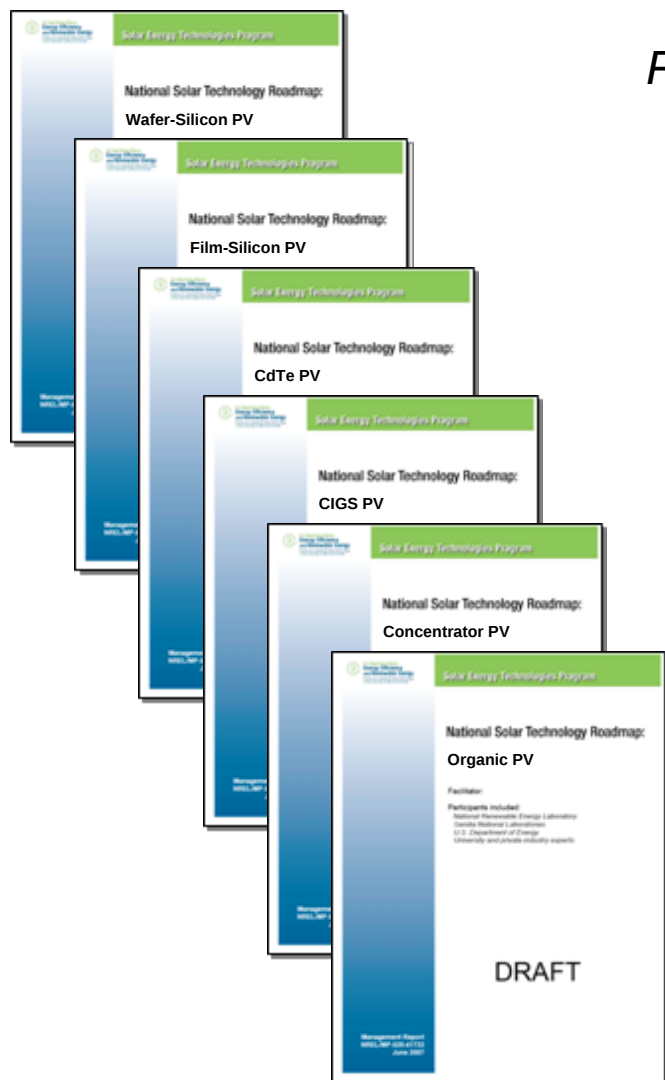
Peter Sheldon
Measurements and Characterization
NREL
1617 Cole Blvd.
Golden, CO 80401



M&C PDIL Tool Selection: Roadmap Alignment



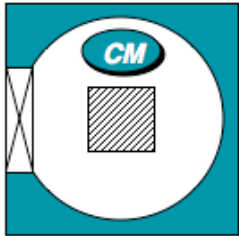
Common Roadmap Elements



Summary of Technologies Supported (by tool):

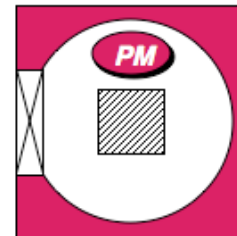
a-Si	c-Si	CdTe	CIGS	III-V	OPV	TCO	Reliability
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M&C PDIL Tool Selection



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



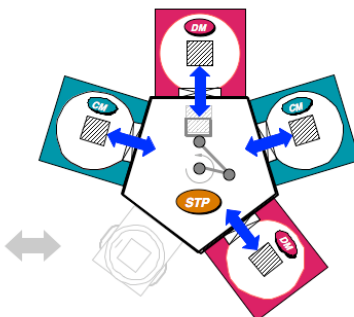
Processing Tools:

- *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

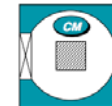
M&C PDIL Tool Summary



Integrated Tools



Stand Alone 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

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

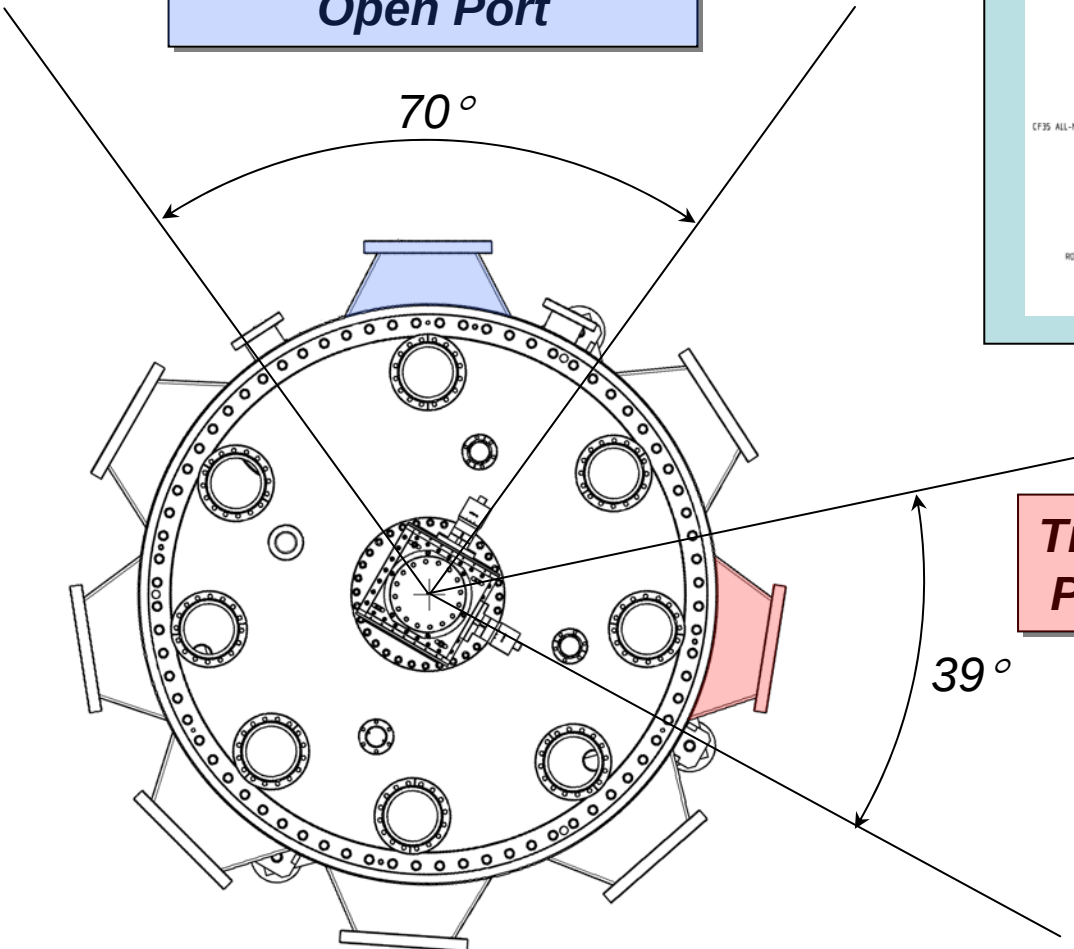
UHV Robot: Integrated tool sample transfer “hub”

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



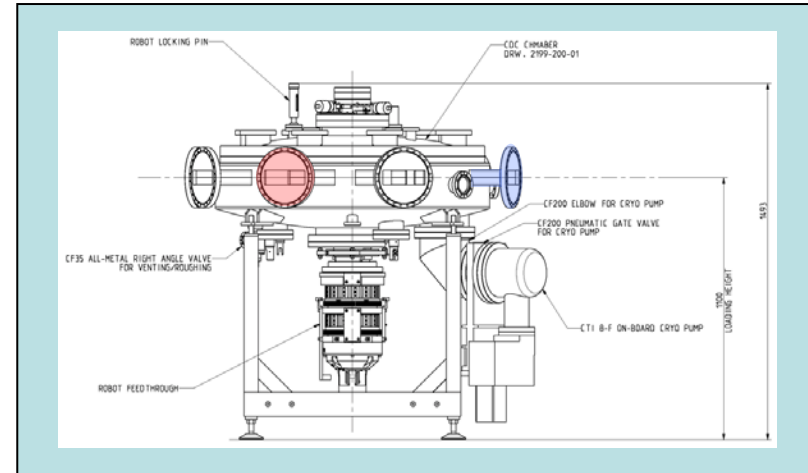
**Industry/Collaborator
Open Port**

70°



**Transport
Pod Port**

39°

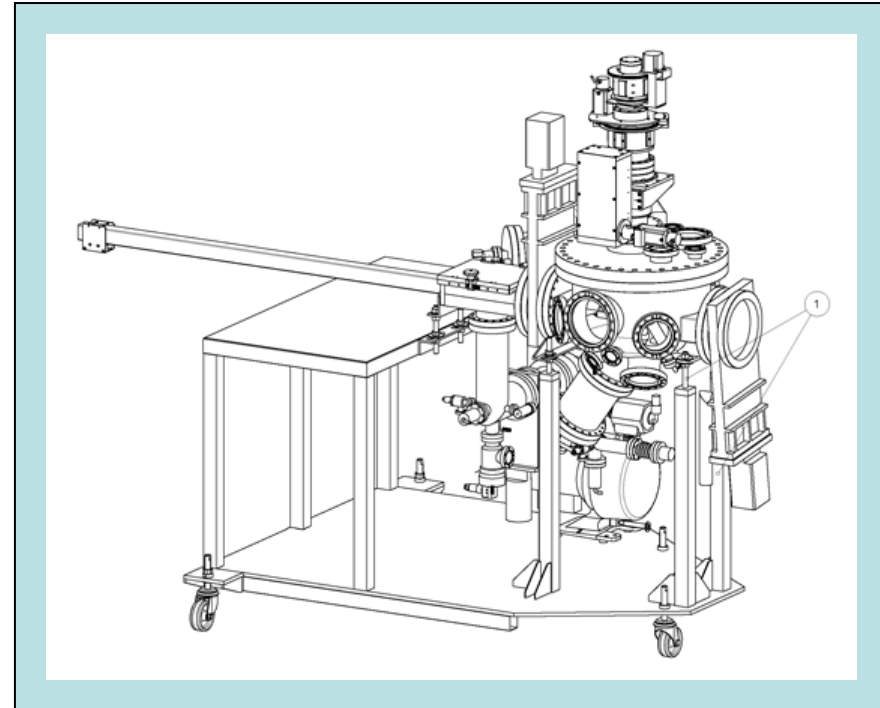


Auger Electron Spectroscopy (AES) Tool



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:

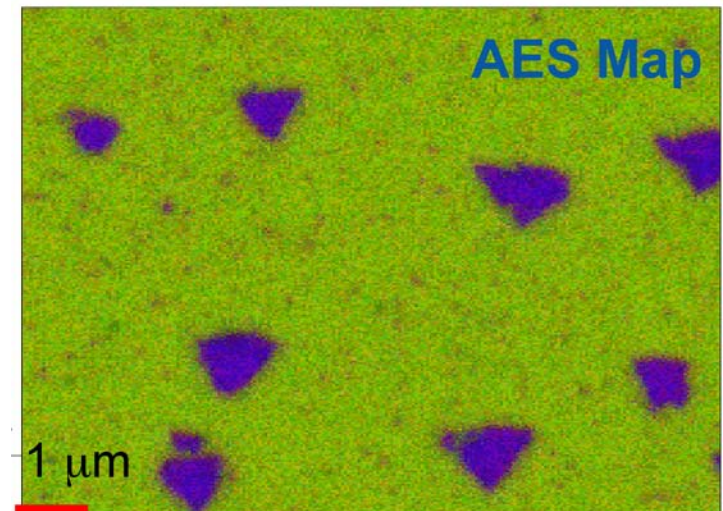
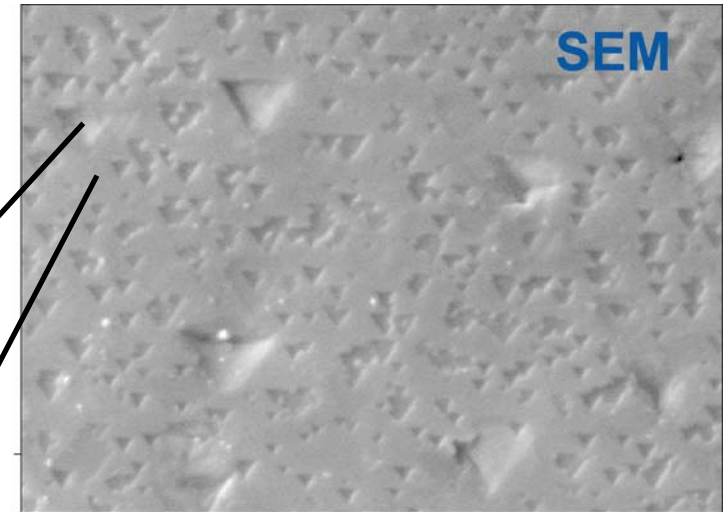
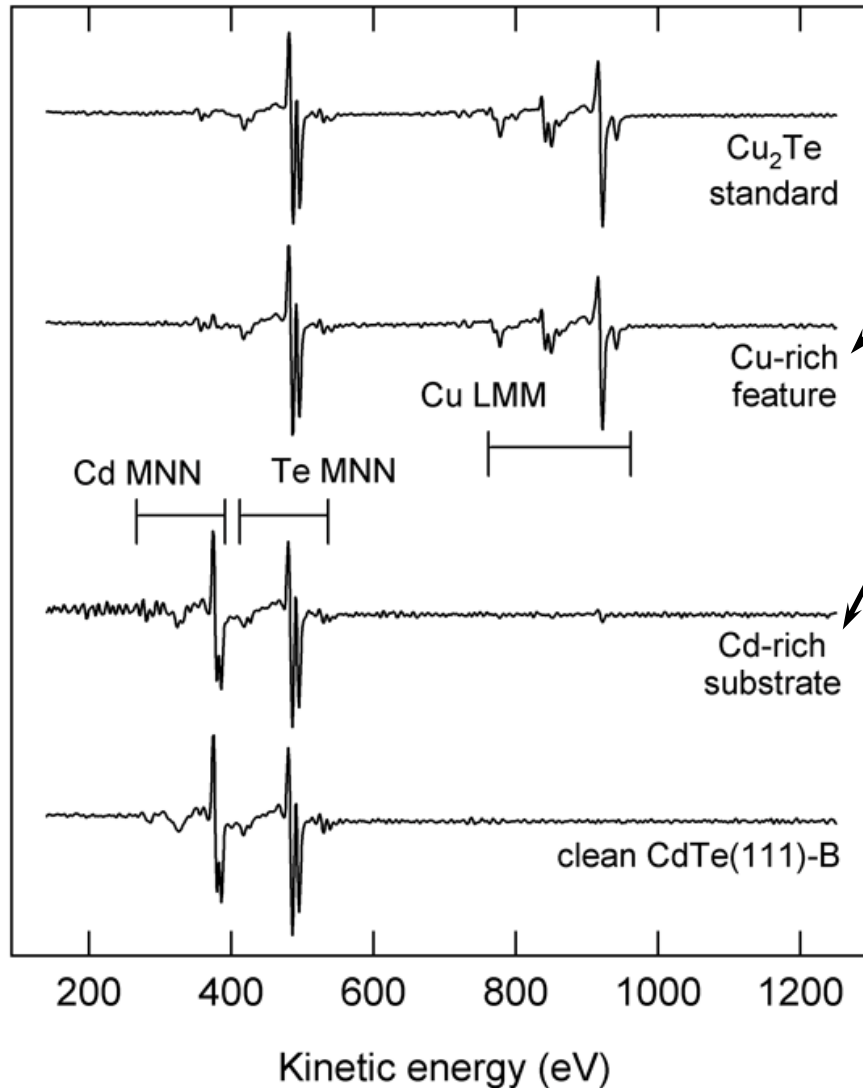
a-Si	c-Si	CdTe	ClGS	III-V	OPV	TCO	Reliability
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AES Tool

Application Example: AES mapping Cu/CdTe surface



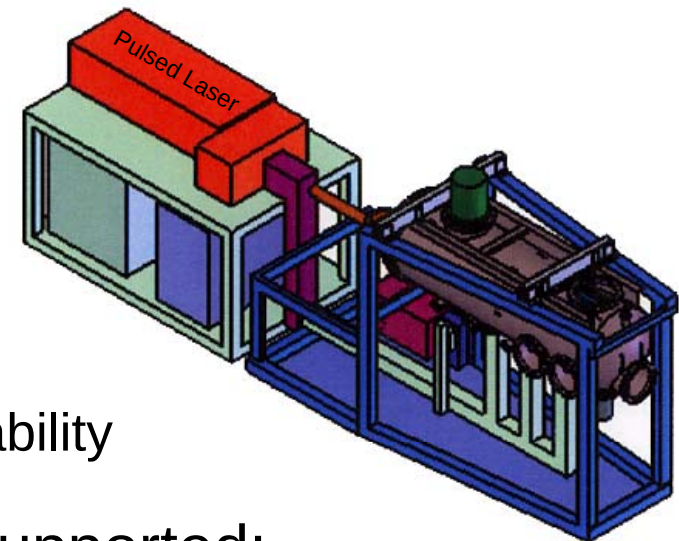
Auger intensity (arbitrary units)



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



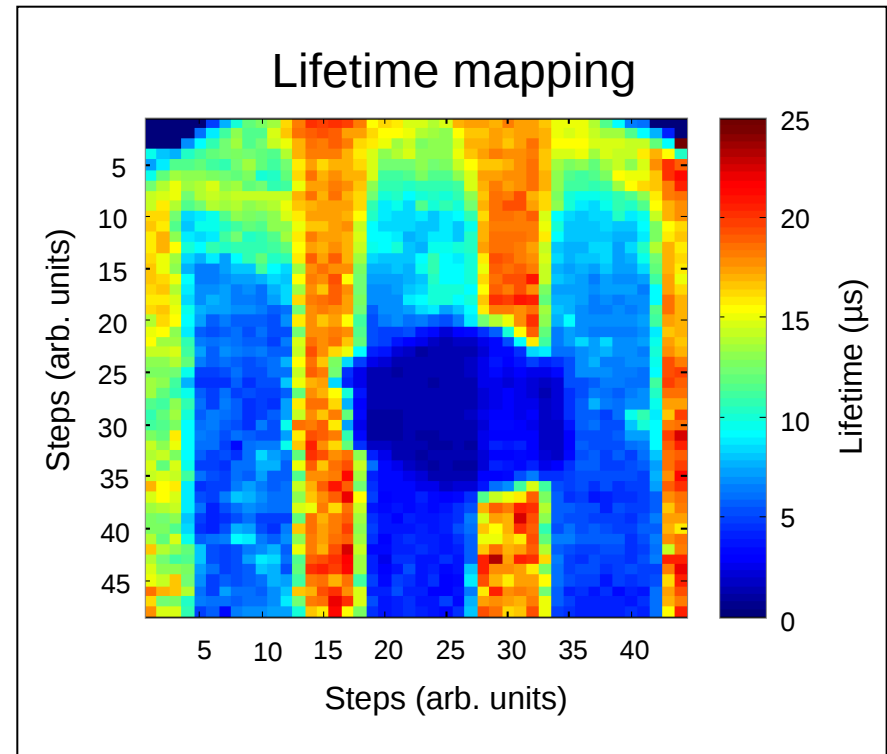
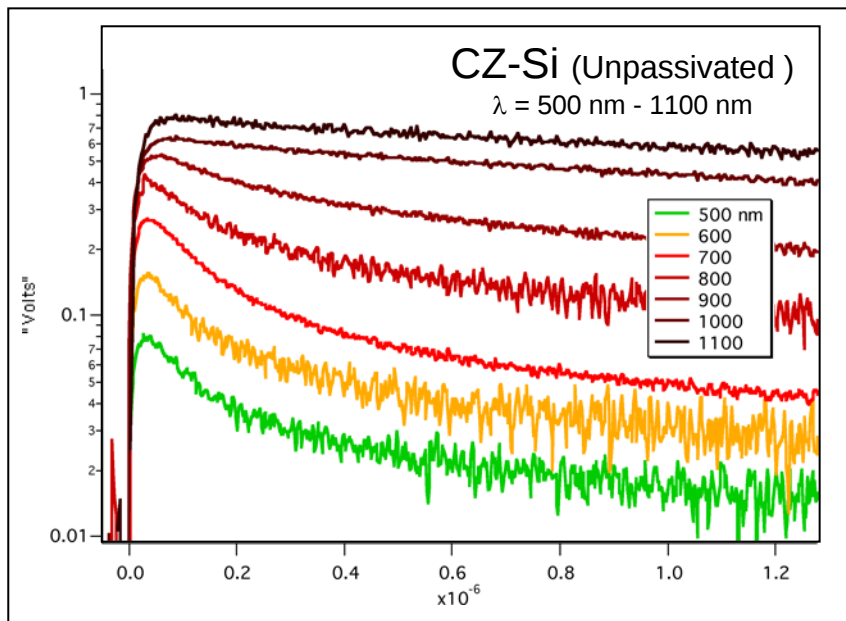
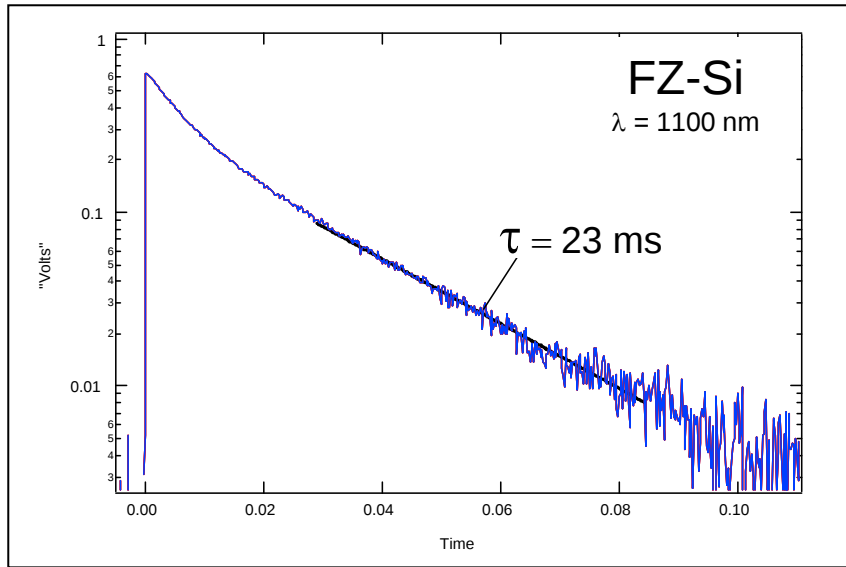
- Minority-carrier lifetime spectroscopy is a contactless, nondestructive method to study the recombination processes in materials. Measures the return of photoexcited carriers back to equilibrium providing the lifetime of the excess carriers.
- Excellent technique for evaluating material quality and 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



Summary of Roadmap Technologies Supported:

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

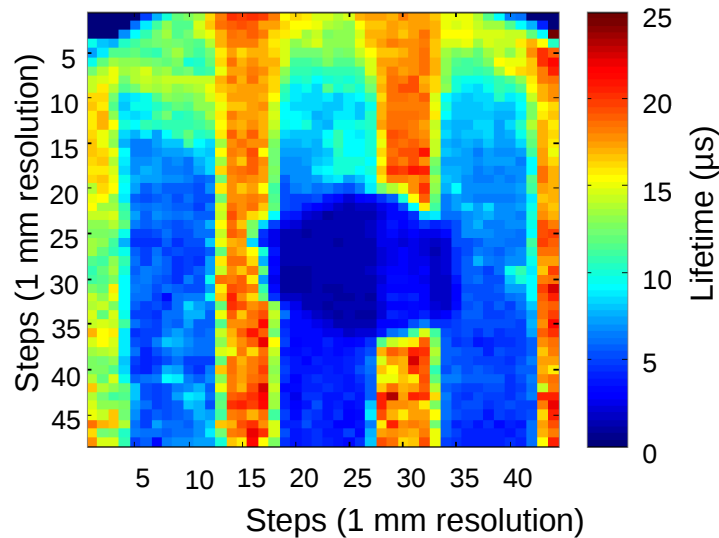
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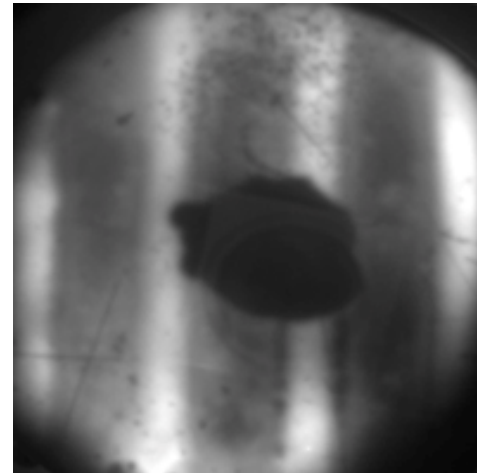
PCD and Imaging Tool Comparison



RC- PCD Mapping



PL Imaging



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 μ m/pixel*

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



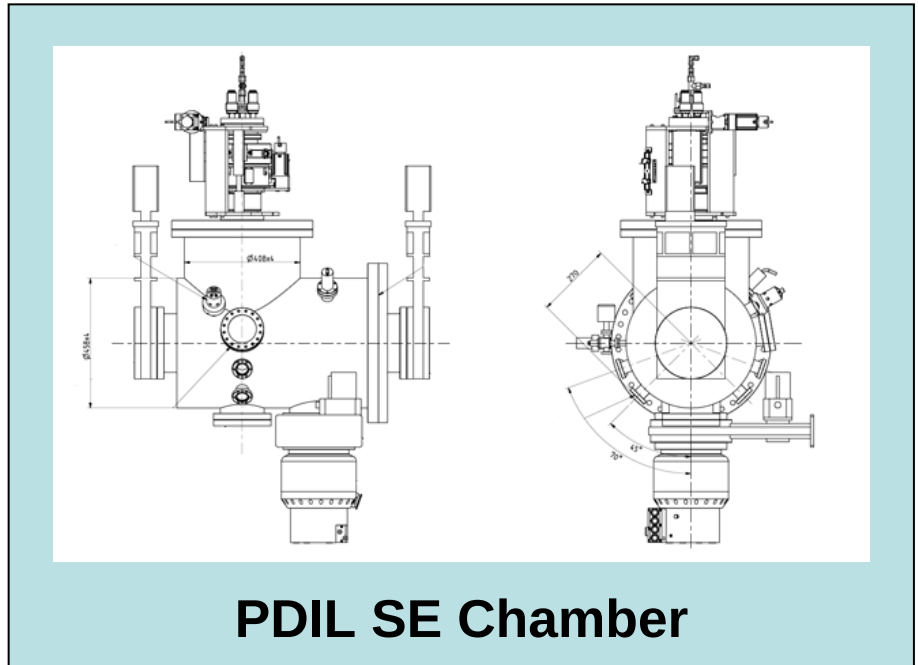
Spectroscopic Ellipsometry (SE) Tool

SE Tool Characteristics:

- Non-destructive technique
- Wide spectral range (245 - 1690 nm)
- Fast data acquisition
- Temperature: RT to $\sim 850^{\circ}\text{C}$
- High Pressure to UHV capable
(dose samples w/ gases such as O_2 or H_2O)
- Full sample access

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:

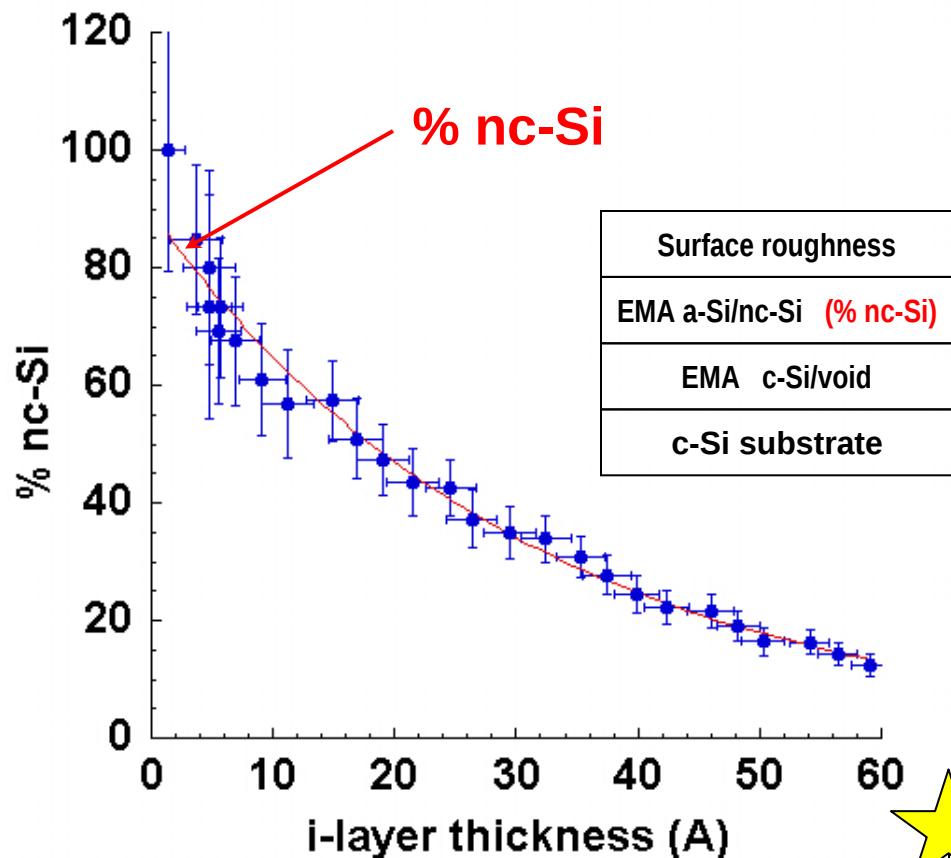
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SE Tool: Application Example - Monitoring Si Crystallinity



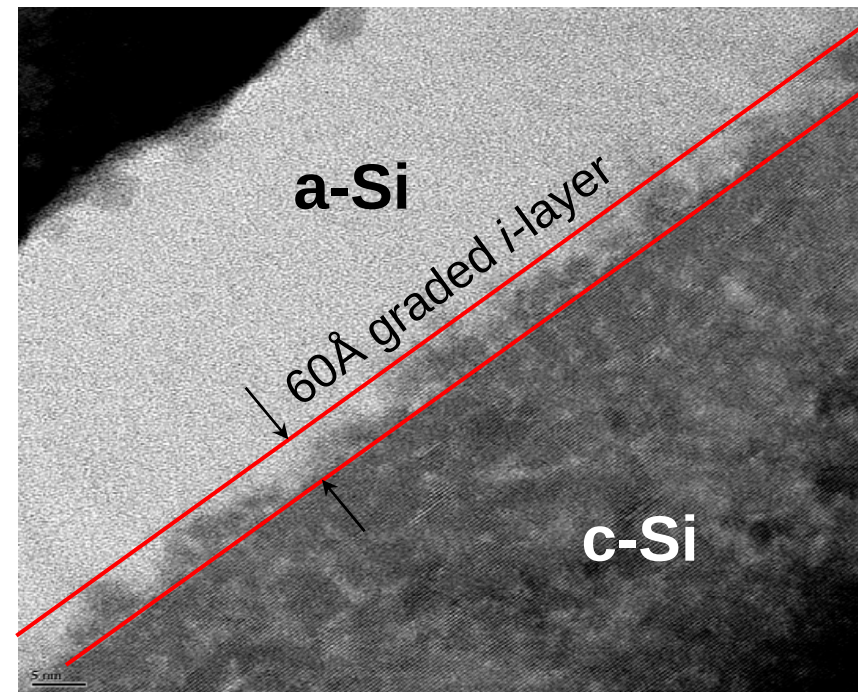
SE Data Modeling

Graded *i*-layer: nc-Si $\Rightarrow$ a-Si



TEM Cross Section

c-Si $\Rightarrow$ nc-Si $\Rightarrow$ a-Si



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

Sputter-Plasma-Diagnostic (SPD) Tool

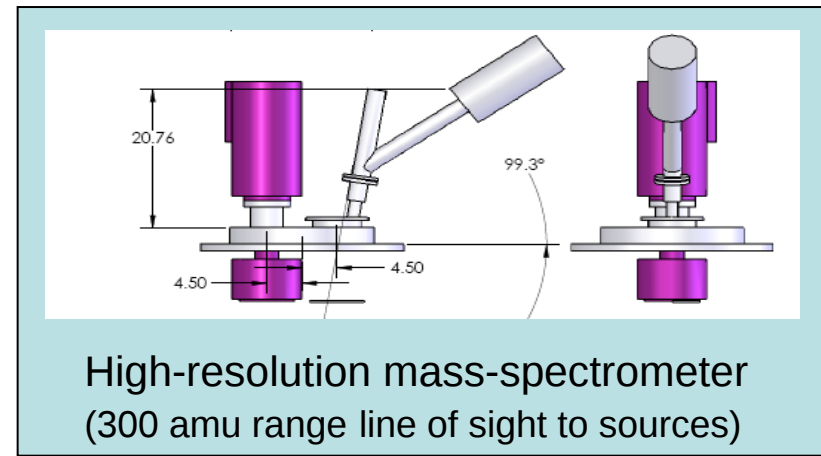


Flexible platform for performing controlled ambient annealing experiments and for developing improved understanding of common industrial deposition processes and scale-up issues.

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

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:

a-Si	c-Si	CdTe	CIGS	III-V	OPV	TCO	Reliability
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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 $\text{Si}_x\text{N}_y\text{:H}$ and $\text{Si}_x\text{C}_y\text{:H}$
 - 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

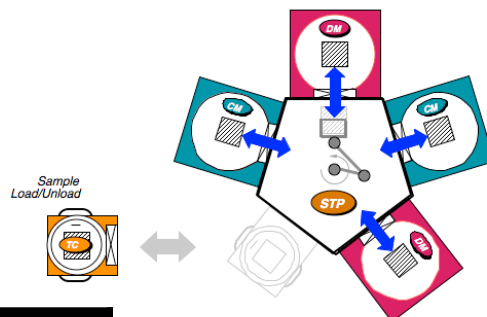
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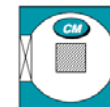
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Reflectometer

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Atomic Force Microscopy System

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Scanning Electron Microscopy System

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X-Ray Photoelectron Spectroscopy System

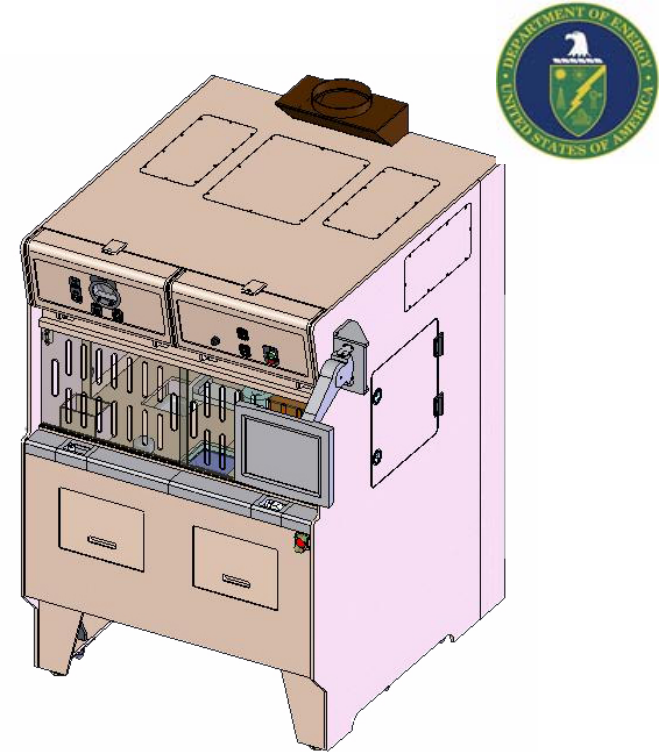
J. Pankow

Wet processing station (WPS)

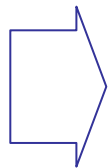
General user facility for Si processing: Semi automatic, wet processing station for reproducible Si wafer preparation and etching

WPS Tool Applications:

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



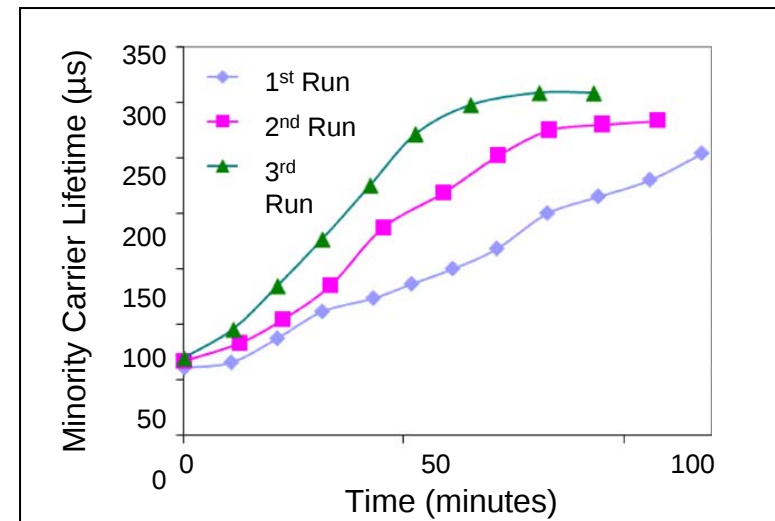
Surface Passivation



Reproducible surface preparation is critical

Technologies Supported:

c-Si



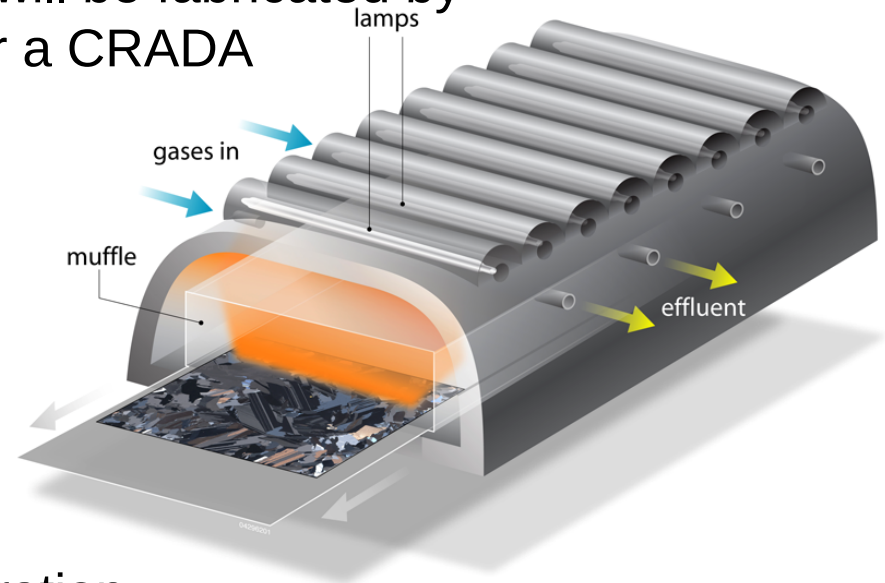
Optical Processing Furnace (OPS)



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

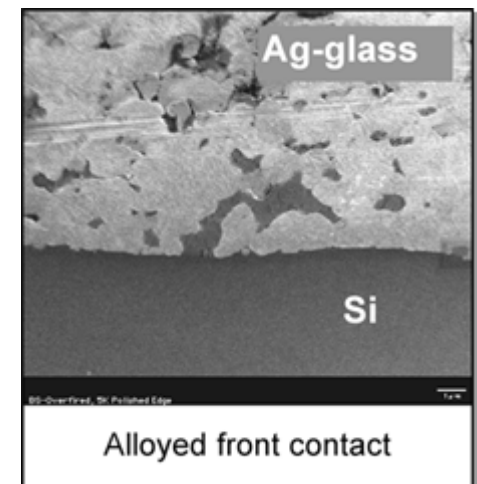
OPS Tool Applications:

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



Technologies Supported:

a-Si	c-Si	CdTe	CIGS
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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.

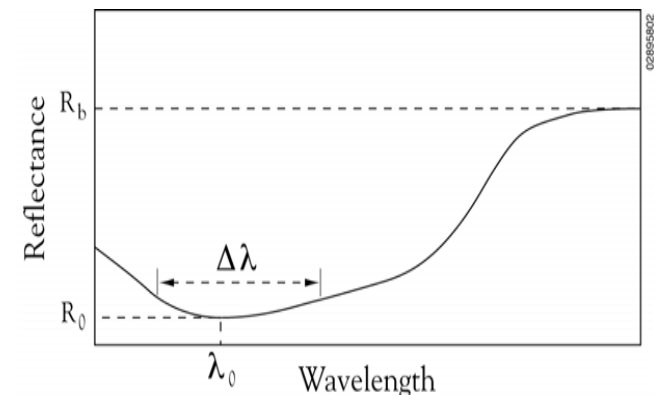
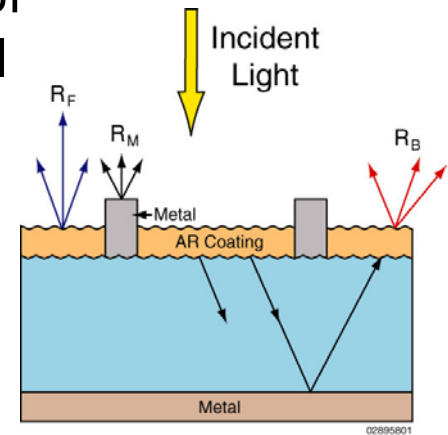
- Measures Reflectance in two modes:

- Spectrometer mode $R_{\text{avg}}(\lambda)$
- Imaging mode $R_{\lambda=\text{const}}(x,y)$

- Indirectly Measures:

- AR coating thickness (λ_0)
- Surface roughness ($\Delta\lambda$)
- Wafer thickness ($R_{\text{abs. edge}}$)
- Metallization fraction (R_0)
- Back surface reflectance (R_b)

- Data acquired in < 1 s



Summary of Roadmap Technologies Supported:

a-Si	c-Si	CdTe	CIGS	III-V	OPV	TCO	Reliability
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Reflectometer: Applications

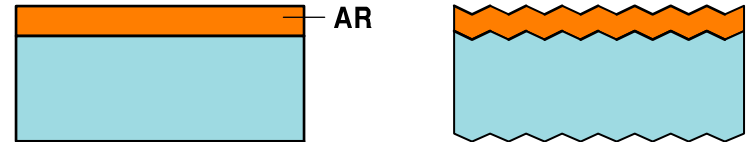
- **R&D process monitoring**

- AR coating thickness (λ_0)
- Surface roughness ($\Delta\lambda$)
- Wafer thickness
- Metallization area
- Metallization height

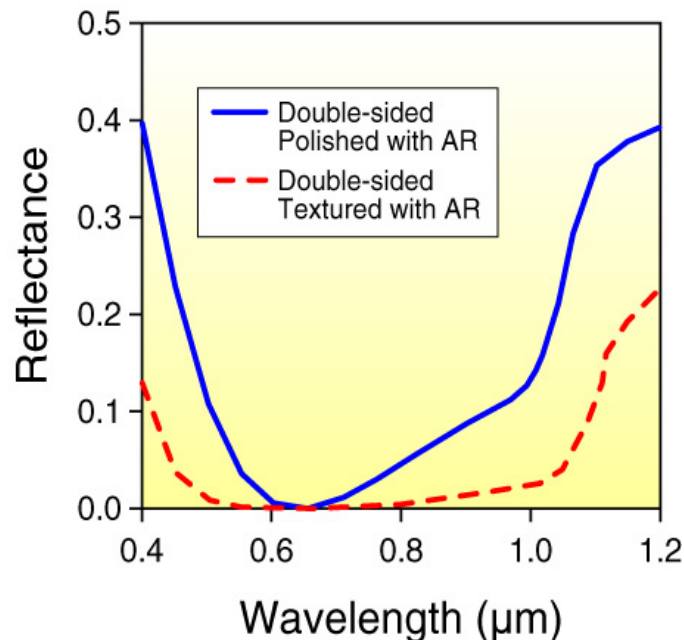
- **Online monitoring compatible**



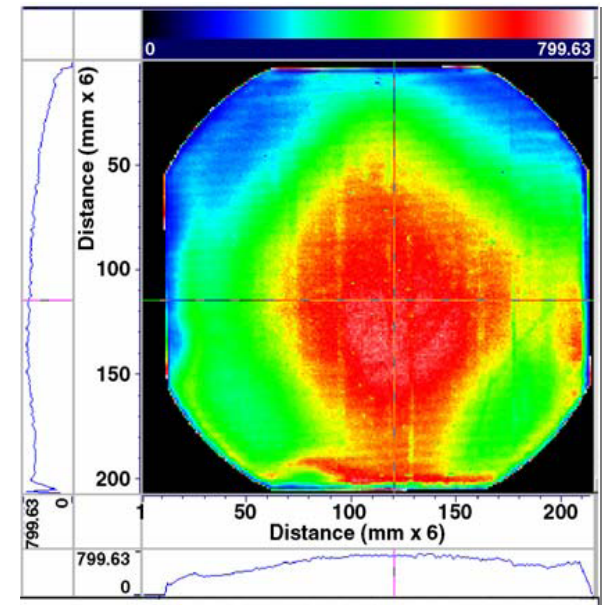
**Licensed to GT Solar
for commercialization**



Spectrometer Mode



Imaging Mode



X-ray Photoelectron Spectroscopy (XPS) Tool

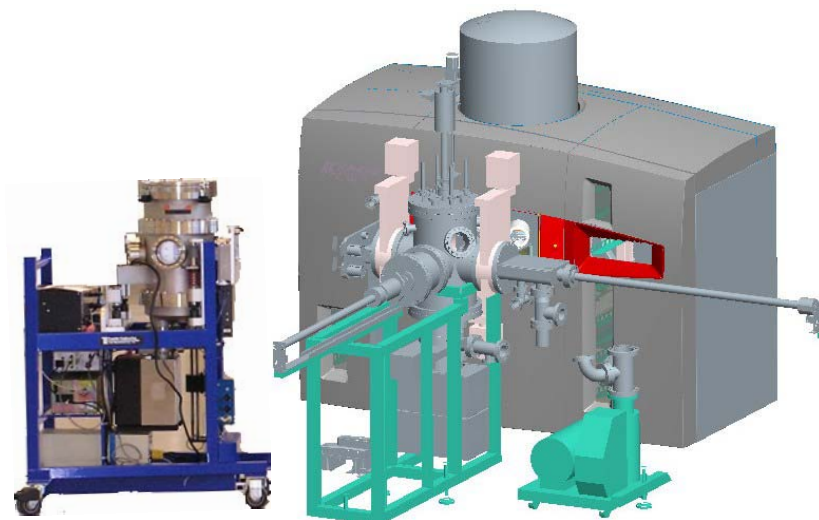


XPS Tool Characteristics:

- 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 $\sim 10\mu\text{m}$
- Depth profiling capability
- Full 6" $\times$ 6" sample access
- "Face-up" analysis only



Kratos
Axis Nova



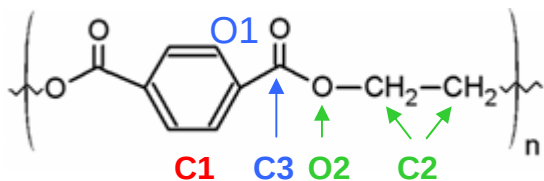
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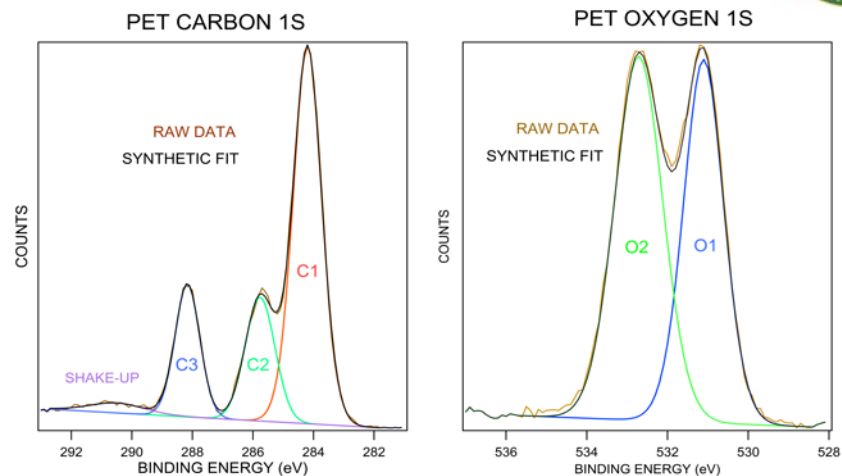
XPS Tool: Sample Applications



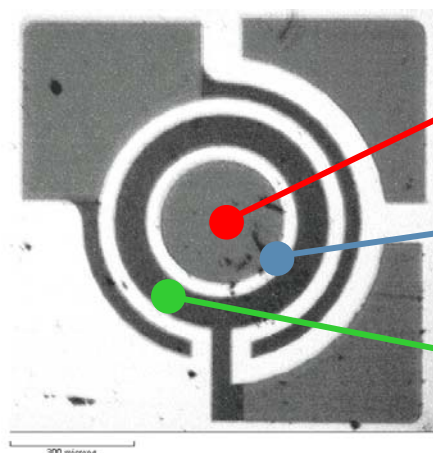
Polymer Analysis



Polyethylene Terephthalate
(PET)



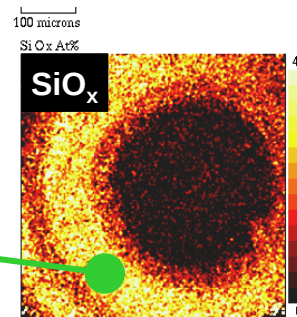
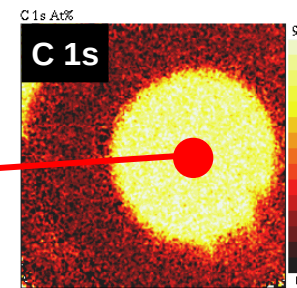
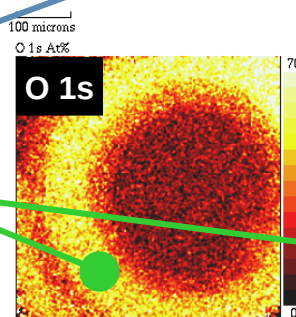
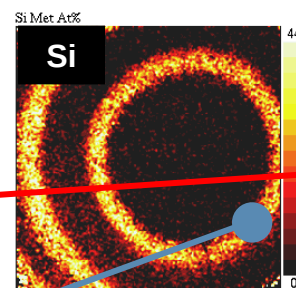
2-D Chemical Mapping



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)

Information obtained:

Image contrast

Photon emission - recombination centers

Electrical activity - junction, GBs,

Structural data - orientation and phase

Compositional data - elemental mapping

• Non-destructive

• Operating ambients:

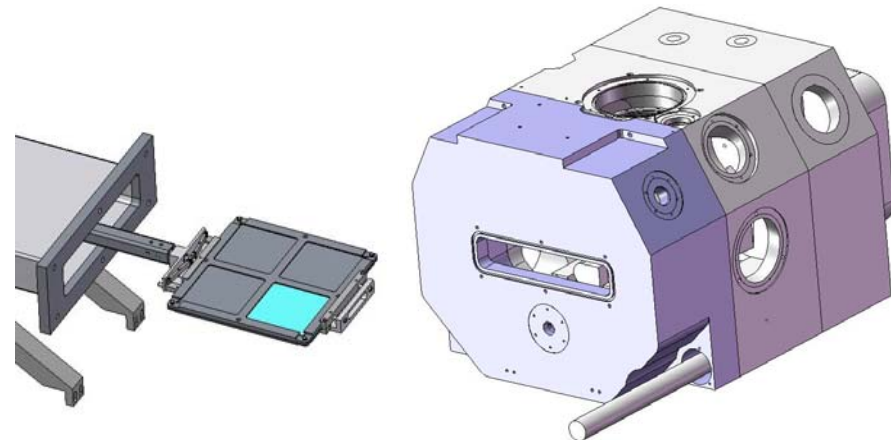
- High Vacuum 4.5×10^{-6} Torr
- Low Vacuum 0.1-1 Torr
- Environmental mode 1-20 Torr

• Resolution:

- 3.0 nm (SE, 30 keV)
- 4.0 nm (BSE, 30 keV)

• Full access to 6" × 6" sample area

• PDIL compatible



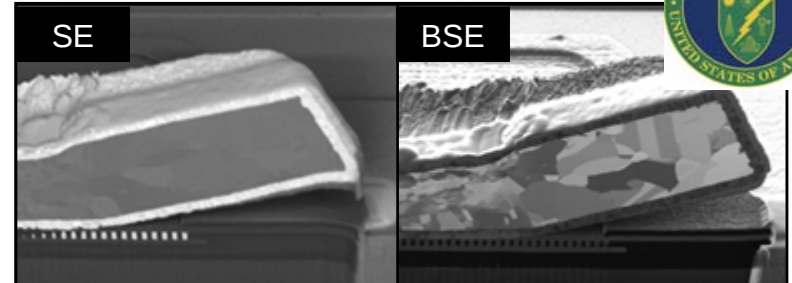
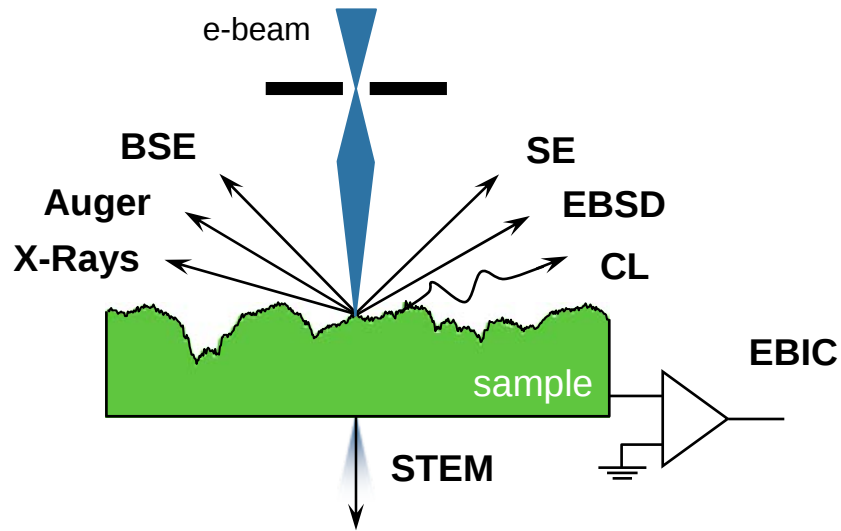
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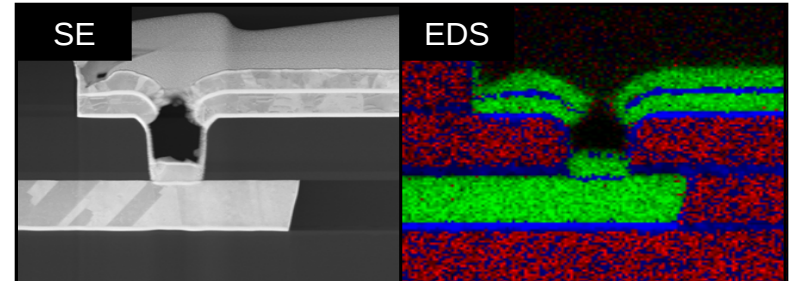
SEM Tool: Sample Applications



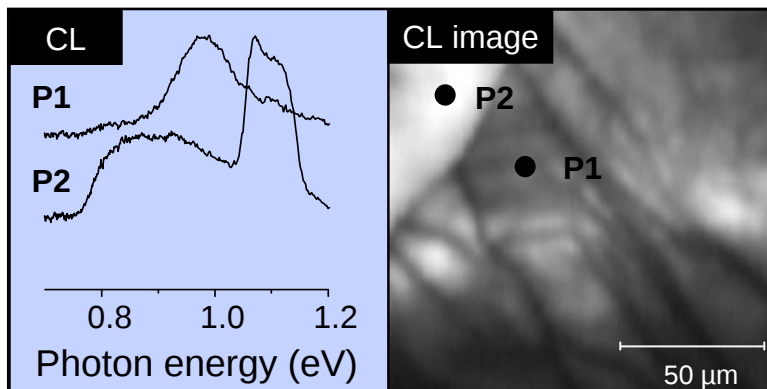
SEM Operational Modes



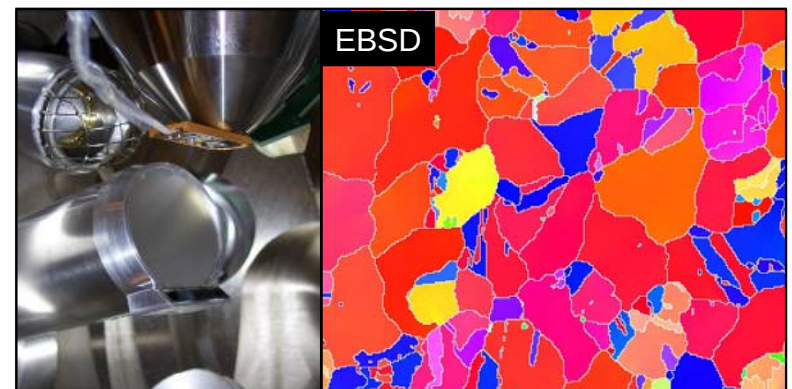
Complementary Image Contrast



Compositional Analysis



Optical Emission



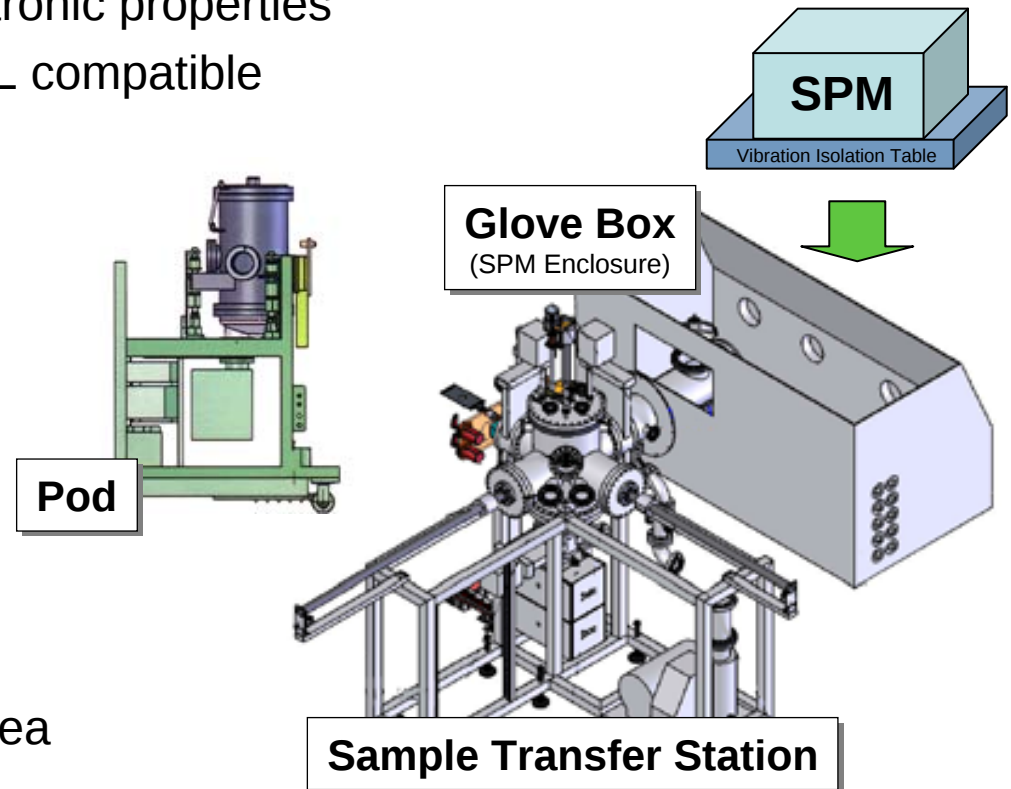
Structural Analysis

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:
 - $x, y < 1.80 \text{ nm}$
 - $z < 0.05 \text{ nm}$
- $2 \mu\text{m}$ stage repeatability
- Operating ambients:
 - Atmospheric pressure
 - N_2 , Ar or other ambients
- Full access to $6'' \times 6''$ sample area



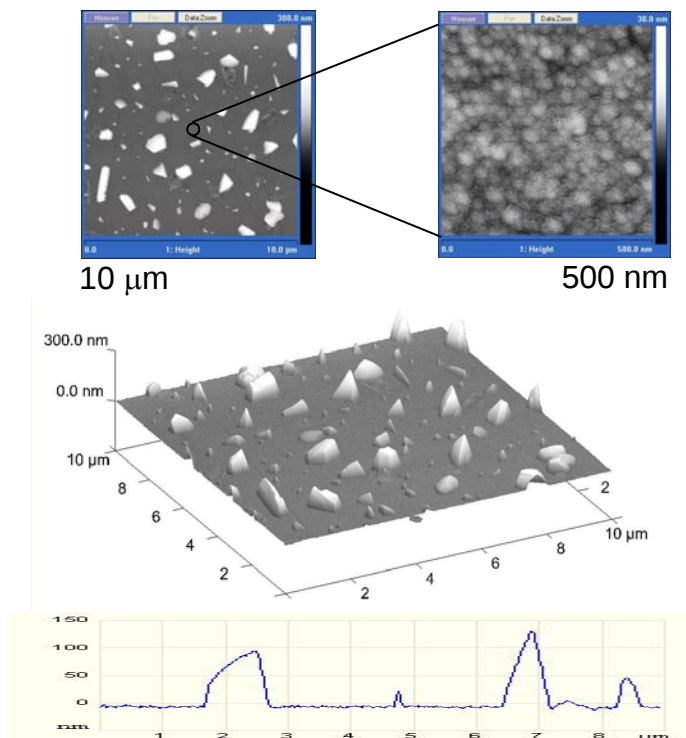
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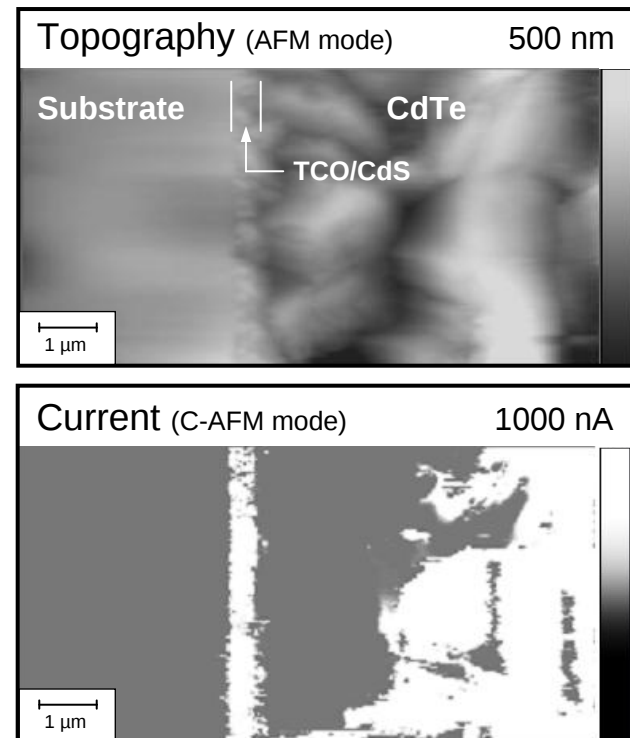
SPM Tool: Sample Applications

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

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