2008 Solar Annual Review Meeting

M&C PDIL Integrated and Stand-Alone Tools

Session: PDIL / Measurements & Characterization Capabilities

Organization: NREL

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

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<th>Tool Description</th>
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<td>Wet Chemistry Workstation</td>
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<td>X-Ray Photoelectron Spectroscopy System</td>
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<td>Open Bay for Industry Tool</td>
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<td>Transfer Pod</td>
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## 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.
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:

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AES Tool
Application Example: AES mapping Cu/CdTe surface

AES Map

SEM

Auger intensity (arbitrary units)

Cu$_2$Te standard
Cu LMM
Cd MNN
Te MNN
Cd-rich
substrate

Kinetic energy (eV)

200 400 600 800 1000 1200

1 µm
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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Pulsed Laser
RC-PCD/μ-PCD Tool: Application Example

**FZ-Si**

\[ \lambda = 1100 \text{ nm} \]

\[ \tau = 23 \text{ ms} \]

**CZ-Si (Unpassivated)**

\[ \lambda = 500 \text{ nm} - 1100 \text{ nm} \]
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**

**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 O₂ or H₂O)
- 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

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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

- Surface roughness
  - EMA a-Si/nc-Si (% nc-Si)
  - EMA c-Si/void
  - c-Si substrate

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

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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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  - 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

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
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 \( (\lambda_0) \)
  - Surface roughness \( (\Delta \lambda) \)
  - Wafer thickness \( (R_{\text{abs. edge}}) \)
  - Metallization fraction \( (R_0) \)
  - Back surface reflectance \( (R_b) \)
- Data acquired in < 1 s

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Reflectometer: Applications

- **R&D process monitoring**
  - AR coating thickness ($\lambda_0$)
  - Surface roughness ($\Delta\lambda$)
  - Wafer thickness
  - Metallization area
  - Metallization height

- **Online monitoring compatible**

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**Spectrometer Mode**

![Spectrometer Mode Diagram](image)

**Imaging Mode**

![Imaging Mode Diagram](image)
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 ~10 µm
- Depth profiling capability
- Full 6” × 6” sample access
- “Face-up” analysis only

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XPS Tool: Sample Applications

**Polymer Analysis**

Polyethylene Terephthalate (PET)

**2-D Chemical Mapping**

Pet Carbon 1s and Oxygen 1s spectra for PET, showing synthetic fit.

Polymer Analysis

PET CARBON 1S

PET OXYGEN 1S

Photoresist

Si

Si oxide

SiOx
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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: $4.5 \times 10^{-6}$ 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
SEM Tool: Sample Applications

**SEM Operational Modes**

- SE (Secondary Electrons)
- BSE (Backscattered Electrons)
- Auger
- X-Rays
- EBSD
- CL (Cathodoluminescence)
- EBIC
- STEM

**Complementary Image Contrast**

- SE (Secondary Electrons)
- BSE (Backscattered Electrons)

**Compositional Analysis**

- SE (Secondary Electrons)
- EDS (Energy Dispersive X-rays)

**Optical Emission**

- CL (Cathodoluminescence)
- P1 and P2
- Photon energy (eV)

**Structural Analysis**

- EBSD (Electron Backscatter Diffraction)
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 µm stage repeatability
- Operating ambients:
  - Atmospheric pressure
  - \( \text{N}_2, \text{Ar} \) or other ambients
- Full access to 6” × 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)

\[ \text{Cd}_2\text{SnO}_4 \text{ after annealing} \]

\[ \text{CdTe/CdS solar cell} \]

- Topography (AFM mode) 500 nm
- Current (C-AFM mode) 1000 nA
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<th>Current Status</th>
<th>Estimated Installation Date</th>
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<td>Final Design Complete, Tool Purchased</td>
<td>03/09</td>
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<td>Final Testing at Vendors Site</td>
<td>07/08</td>
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<td>Installation Complete</td>
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<td>Optical Processing Furnace</td>
<td>CRADA signed, Conceptual Design Complete</td>
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<td>Reflectometer</td>
<td>CRADA Negotiated, Prototype Design Complete</td>
<td>02/09</td>
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<td>Atomic Force Microscopy (AFM)</td>
<td>AFM Installation Complete (Glove Box &amp; Transfer Station Installation Pending)</td>
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<td>Scanning Electron Microscopy (SEM)</td>
<td>Tool Construction Near Completion</td>
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