2008 Solar Annual Review Meeting

Measurements & Characterization (M&C) Capabilities Overview

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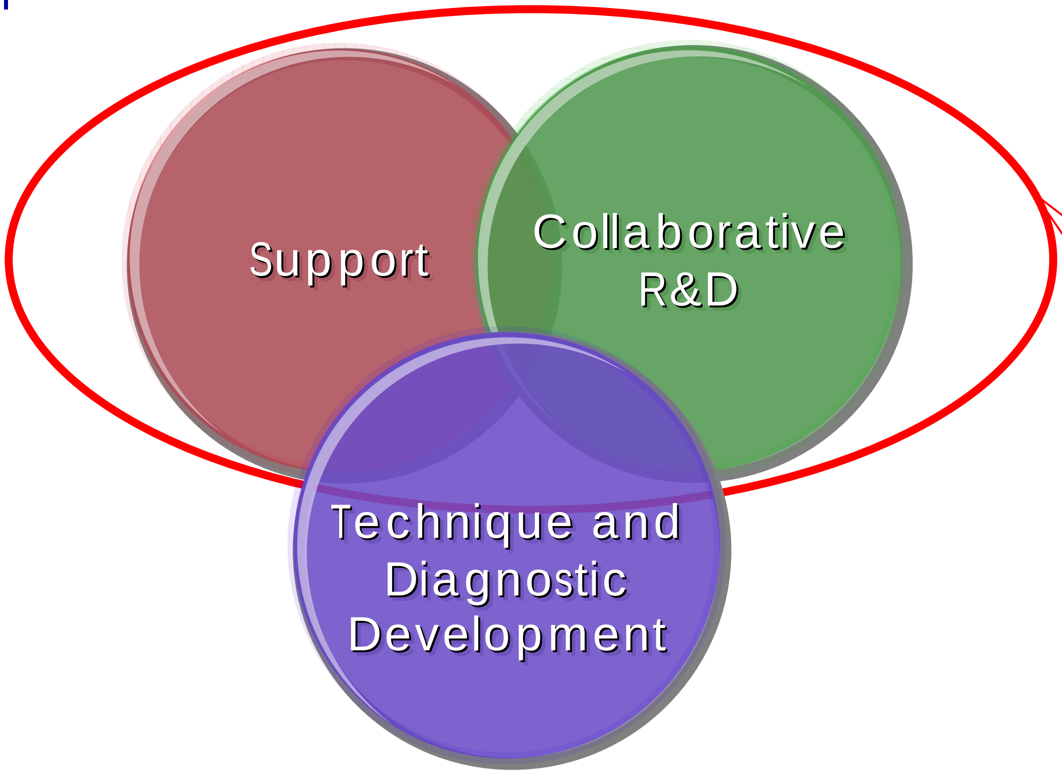
M&C Mission: Three Focus Areas



Support

Collaborative R&D

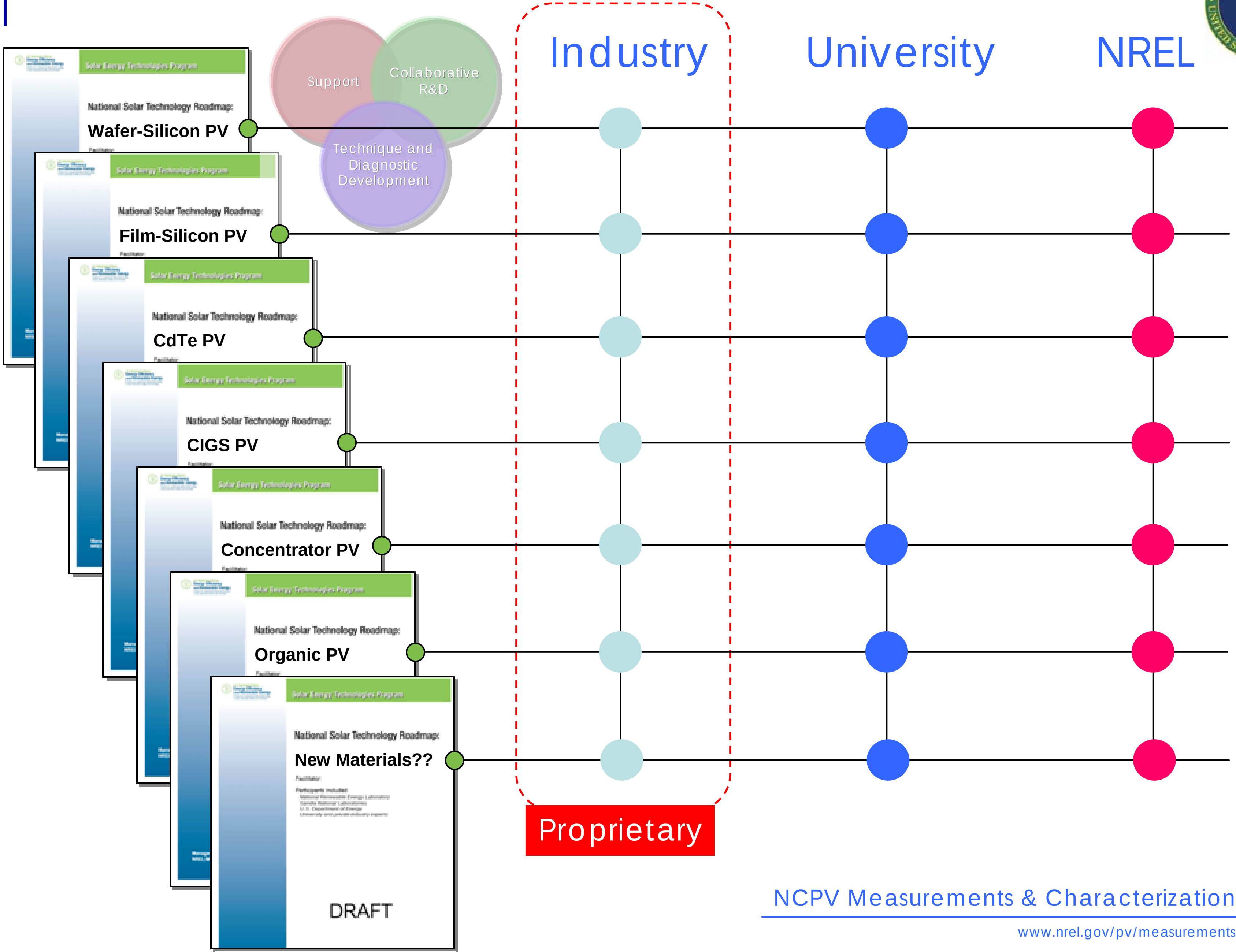
Technique and Diagnostic Development

A key component of our mission is to work with SAI subcontractors and help them realize their goals

- Subcontract Stage-gate Review
- Test & Evaluation
- Process Development and Device R&D
- Cell/Module Failure Analysis R&D

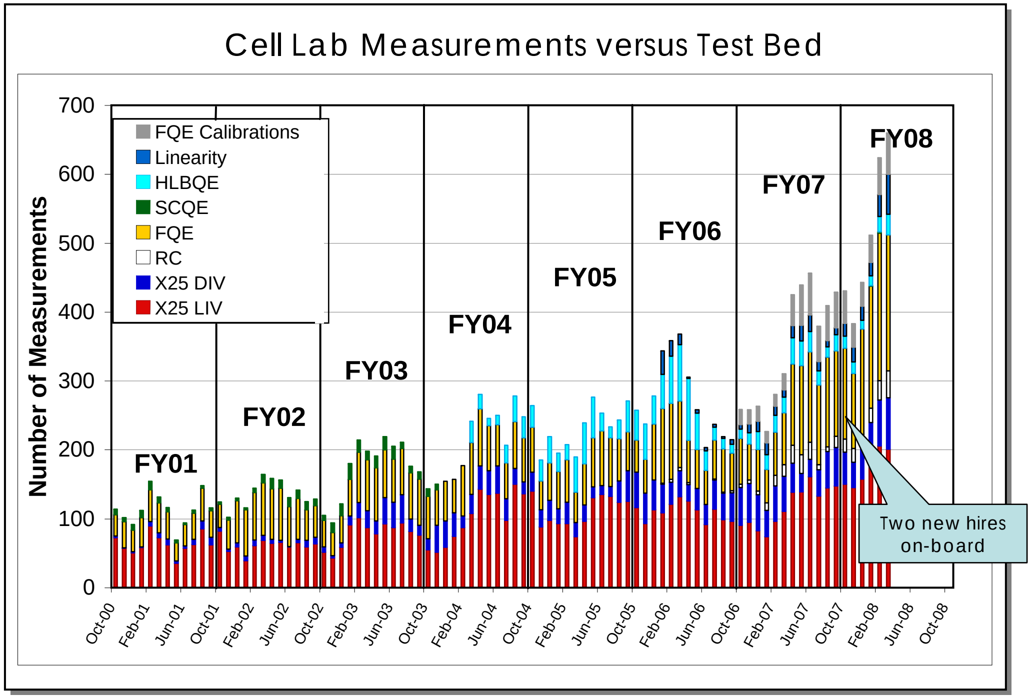
SOLAR AMERICA INITIATIVE

M&C Collaborations



M&C Supported Subcontracts

2008 Subcontractor Funding:	
Photovoltaic Systems R&D Technology Pathway Partnerships (TPPs)	~$51M
PV Technology Incubator	~18M
University Photovoltaic Product and Process Development	~$4M
Next Generation Photovoltaic Devices and Processes	~$7M
TOTAL	~$80M



Cell Lab Measurements versus Test Bed

Two new hires on-board

Increasing Priority Level

- Top priority/preferential treatment for SAI deliverables and stage gate reviews
- Support for all DOE-funded subcontracts on a first come first serve basis (no differentiation between TPP, Incubator, and pre-SAI subcontracts)
- Non-SAI funded PV industry requests

M&C Core Competency Areas

National Center
for Photovoltaics (NCPV)

Measurements &
Characterization

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Device
Performance

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Electro-Optical
Characterization

Dean Levi
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Surface
Analysis

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Analytical
Microscopy

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www.nrel.gov/pv/measurements

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Cell and Module Performance Team

- *Independent facility for verifying device and module performance for the entire PV community*
- *ISO 17025 accredited for primary reference cell, secondary reference cell and secondary module calibrations*
- *Provide the U.S. PV industry with a calibration traceability path for peak-watt and efficiency measurements to reduce uncertainty in I-V measurements*
  - *Provide reference cell calibrations for the entire US terrsetrial community*
- *Develop hardware, software and procedures to accommodate new cell and module technologies. Assists industry in developing measurement system hardware and procedures*

Device Performance

ACCREDITED

Certificate Number 223601
ISO 17025 accredited for photovoltaic secondary cell, secondary module and primary reference cell calibration by the American Association for Laboratory Accreditation (A2LA)

Cell and Module Performance Team Capabilities

Device Performance

Application	Light Source	Test Bed
1-Sun Cells & Mini-Module		
Spectrolab X25	filtered 3 kW Xe Spectrolab X25 0.1 - 20 suns	30 cm x 30 cm
Concentrator Cells		
Continuous Illumination	1 kW Xenon or 3kW Tungsten 0.1 - 200 suns	1 cm diameter for Xe 5 cm x 10 cm for W
High Intensity Pulsed Solar Simulator (HIPSS)	Xe Flash Lamp 1 to 2000 suns	2 cm x 20 cm
Modules		
Spire 240A Solar Simulator	Xe flash lamp 0.1 to 1.2 suns	61 cm x 122 cm
Spire 4600 Solar Simulator On Order	Pulsed Light Source	137 cm x 200 cm
Spectrolab X200 Large-area Continuous Solar Simulator (LACSS)	Filtered 25 kW Xe 0.1 to 1 suns	122 cm x 152 cm
Standard Outdoor Measurement System (SOMS)	Sunlight	200 cm x 300 cm

Outdoor Test Facility Expansion Project

- *2,300 gsf of new and reconfigured space*
- *Required to accommodate large-area solar simulator necessary to support the SAI*
- *A new Spire 4600 simulator will allow test of modules up to 137 cm x 200 cm (a 265% increase in size)*

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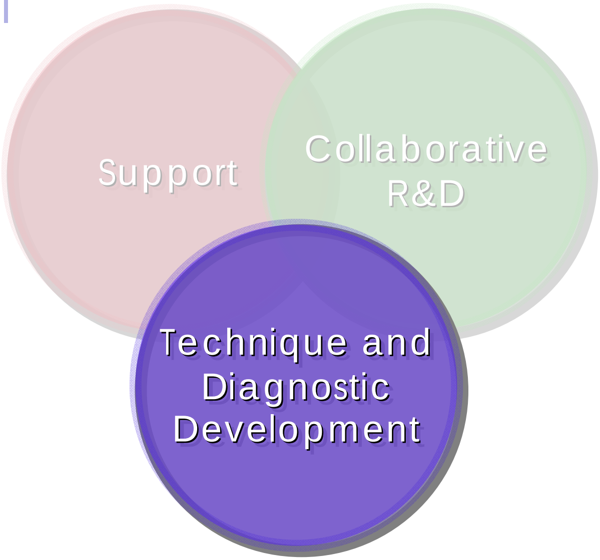
Electro-Optical Characterization Team Capabilities


Electro-Optical Characterization

Technique/Capability	***Typical Applications***
Photoluminescence Spectroscopy	*Measure bandgap and alloy composition; identify defects; provides a quick measure of material quality*
Minority Carrier Lifetime *TRPL, RC-PCD, and µW-PCD*	*Measure minority-carrier lifetime, material quality, surface/interface recombination and surface passivation; identify dominant recombination mechanisms*
Fourier Transform Infrared Spectroscopy	*Identify chemical composition, chemical bonding; analyze in-situ reactions and concentration of impurities; measure inhomogeneity*
Spectroscopic Ellipsometry *VASE and RTSE*	*Determine optical constants; layer thicknesses; surface/ interface roughness; as well as composition crystallinity, alloy composition, and growth dynamics of films*
Capacitance Techniques *C-V, DLTS, AS, and DLCP*	*Measure carrier concentration profiles, interface state densities, and deep-level properties*
Computational Modeling	*2-D solar cell modeling and simulation of measurement techniques (TRPL, RC-PCD, EBIC, QE, IV, CL, C-AFM)*
Diagnostic Development	*PVSCAN, PV Reflectometer, RC-PCD, PLI, and CDI*

Electro-Optical Diagnostic Development

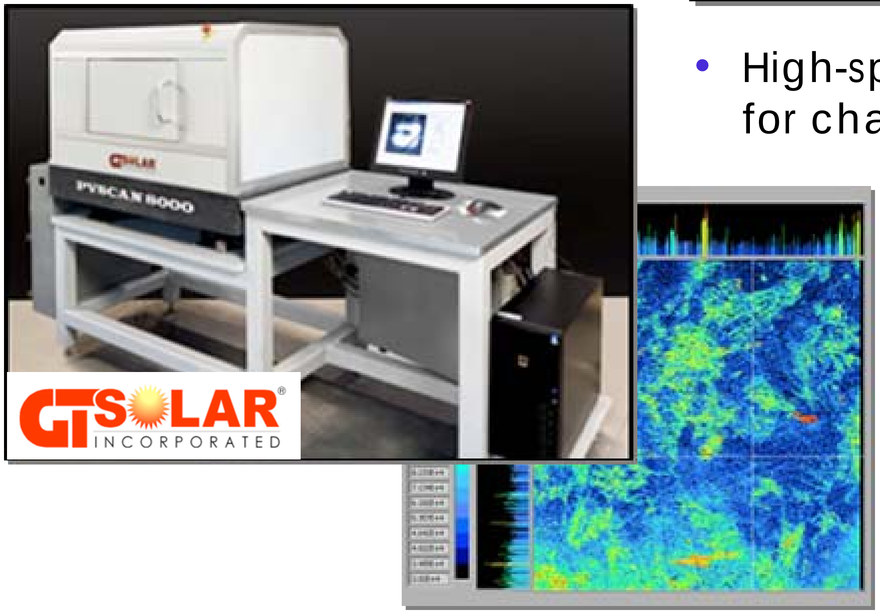
Electro-Optical Characterization



NREL Developed Diagnostics:

- ***PV Scan***..................... Licensed
- ***PV Reflectometer***...... Licensed
- ***RC-PCD***..................... In- Process

GT-PVSCAN 8000



- High-speed optical scanning system designed for characterization of PV materials and cells
  - Technology developed at NREL and licensed to GT Solar
  - 8’ x 8” sample size
  - Measurement Modes:
    - Dislocation density
    - Reflectance
    - Light Beam Induced Current (LBIC)

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Device Performance

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Surface Analysis

Analytical Microscopy

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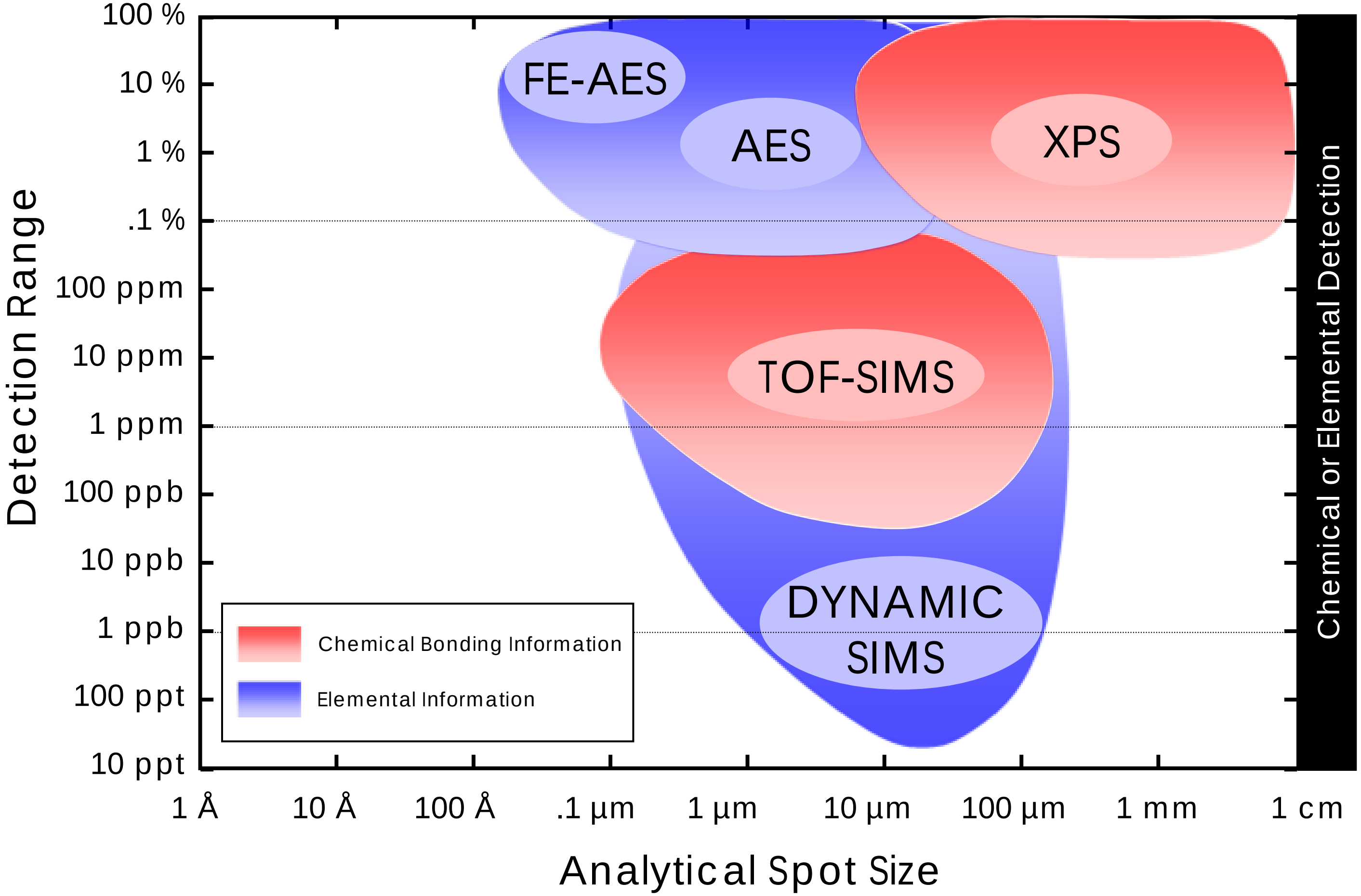
Surface Analysis Team Capabilities

Surface Analysis

Analytical Resolution versus Sensitivity



AES

Auger Electron Spectroscopy

- Elemental information
- Detects Li - U
- 0-100Å depth resolution
- Depth profiling capable
- Imaging capability

XPS

X-ray Photoelectron Spectroscopy

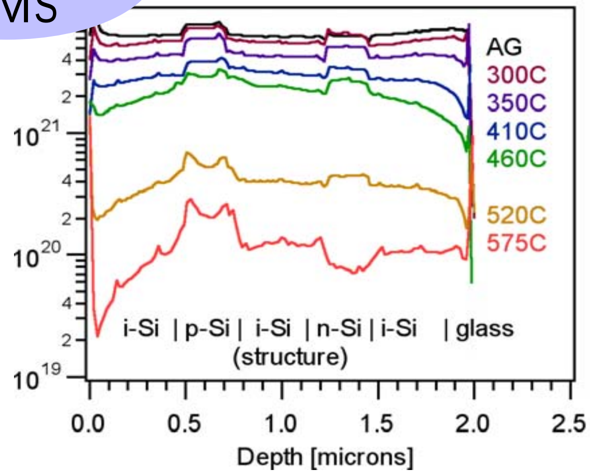
- Chemical Bonding Info.
- Detects Li - U
- 0-100Å depth resolution
- Depth profiling capable
- Imaging capability

Secondary Ion Mass Spectrometry (SIMS)
Time-of-Flight SIMS (TOF-SIMS)

Surface Analysis

DYNAMIC SIMS

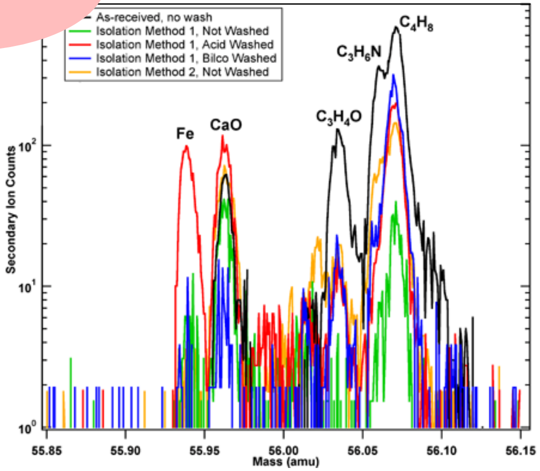
Hydrogen Depth Profiles of Recrystallized a-Si Films



- Extremely sensitive - Detects fractions in the range of parts per million (ppm) to parts per billion (ppb)
- Elemental detection of species ranging from H to U and all isotopes
- Quantitative technique when used with standards
- Depth profiles with resolution of <10 nm - Excellent technique for analyzing interfaces

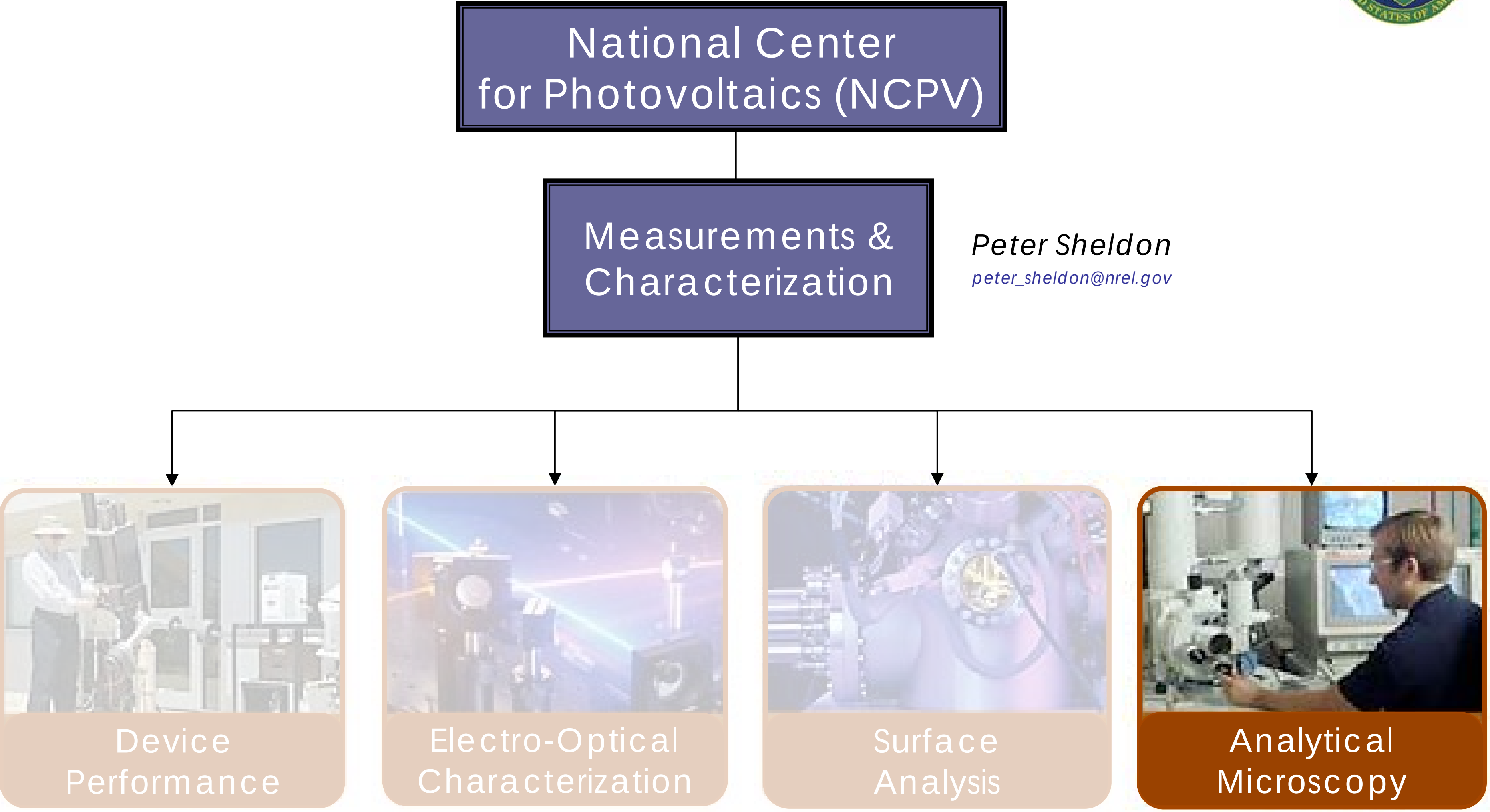
TOF-SIMS

SnO_2/Glass Cleaning Method Comparison



- Extremely sensitive - Detects fractions in the parts per million (ppm) range
- Elemental and molecular analysis- good for analyzing organics
- Surface sensitive technique - can study the top few monolayers of material
- Elemental detection of species ranging from H to U and all isotopes
- Depth profiles with resolution of <5 nm

M&C Core Competency Areas



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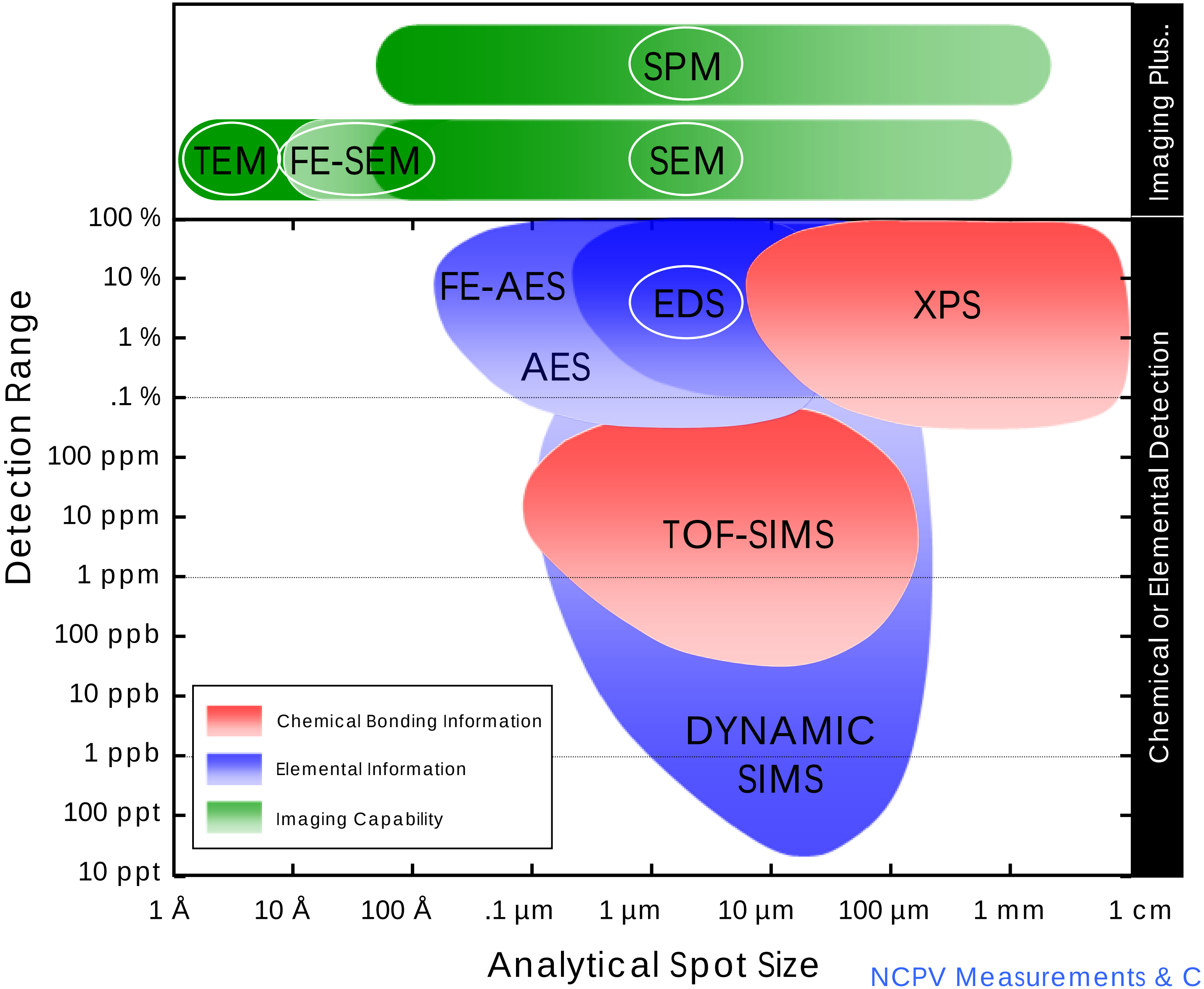
Analytical Microscopy Team Capabilities

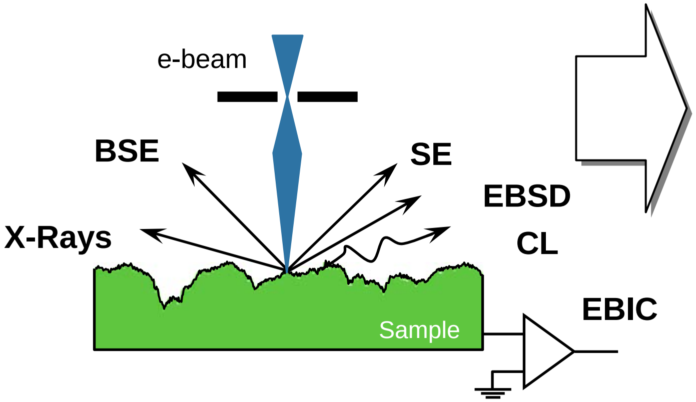
Analytical Microscopy



SEM and SPM Capabilities

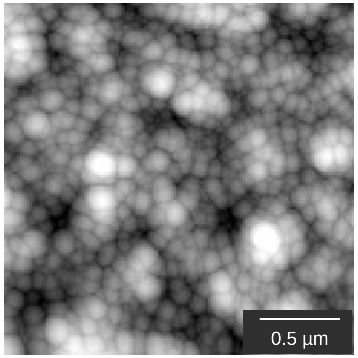
Analytical Microscopy

SEM Operational Modes



- Secondary Electron (SE) Imaging
- Back Scattered Electron (BSE) Imaging
- Cathodoluminescence (CL)
- Electron beam induced current (EBIC)
- Electron backscattered diffraction (EBSD)
- Energy dispersive x-ray spectroscopy (EDS)

SPM Operational Modes



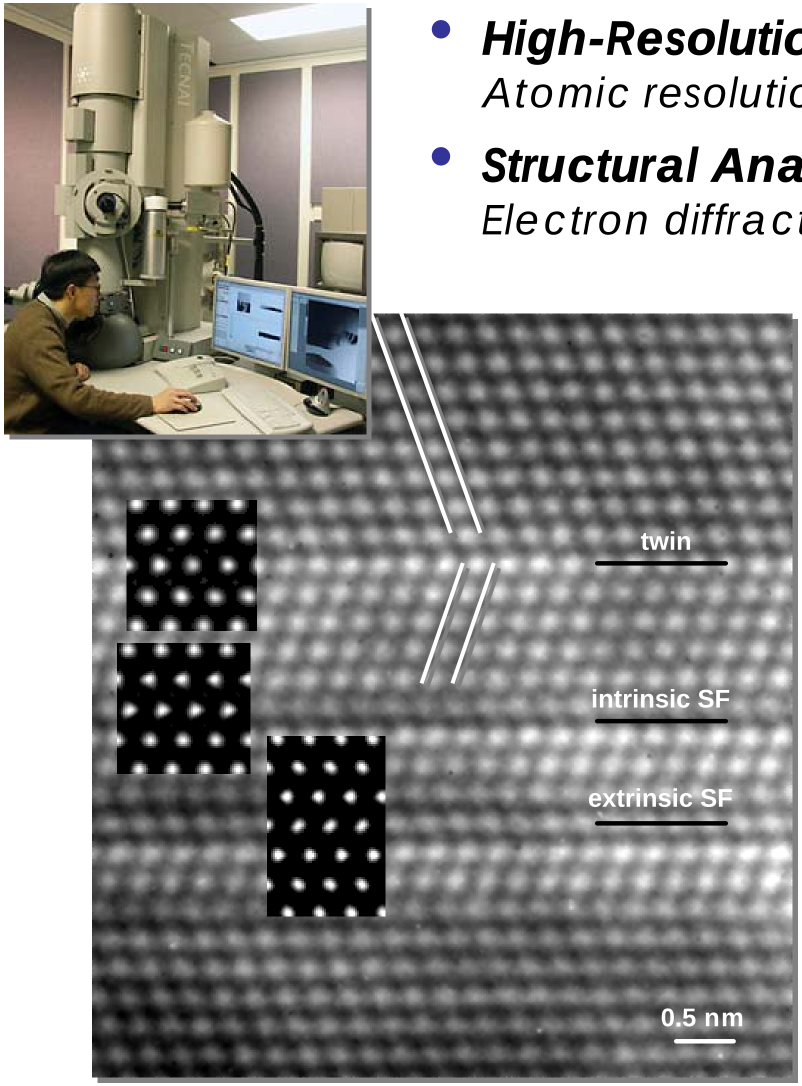
- Atomic Force Microscopy (AFM)
- Conductive AFM (C-AFM)
- Scanning Capacitance Microscopy (SCM)
- Scanning Kelvin Probe Microscopy (SKPM)

SEM-based

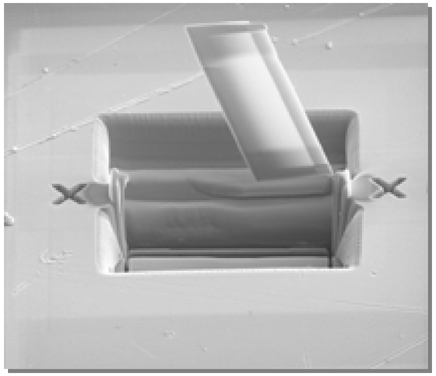
- Scanning Tunneling Luminescence (STL)
- Electroluminescence (EL) Mapping
- Near-field cathodoluminescence (NFCL)

Transmission Electron Microscopy (TEM)

- ***High-Resolution Imaging*** - *Atomic resolution (1.4 Å)*
- ***Structural Analysis*** - *Electron diffraction and diffraction contrast analysis*

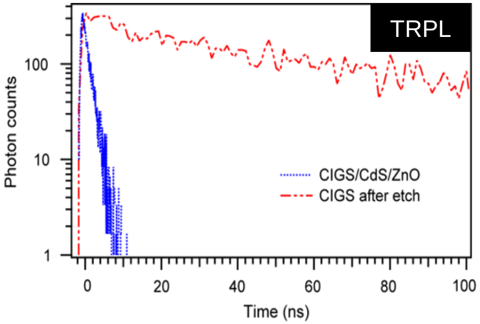


- ***Compositional Analysis*** *- Energy dispersive spectroscopy (B to U, ~0.5 at%)*
- ***Cross-Sectional Analysis - New Focused Ion Beam (FIB) capability facilitates cross-sectional sample prep with pin-point accuracy.***

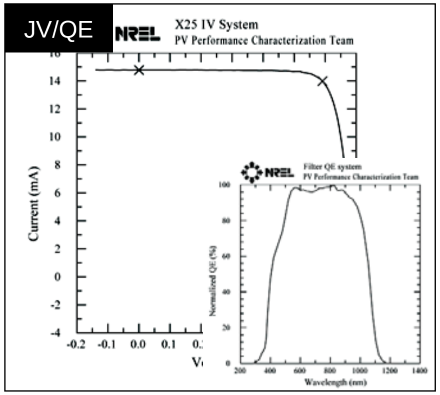


Combining Complementary Techniques

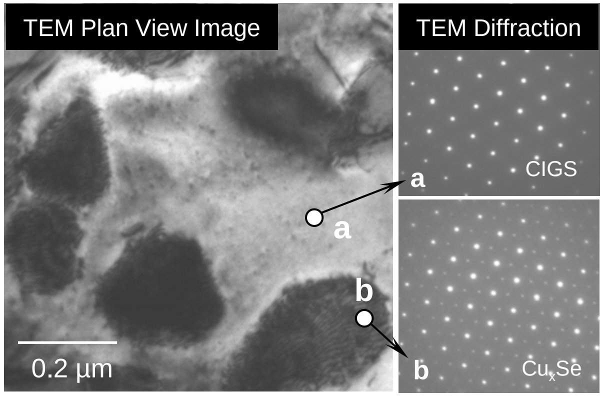
E-O Characterization



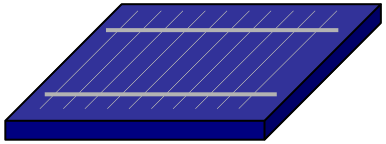
Device Performance



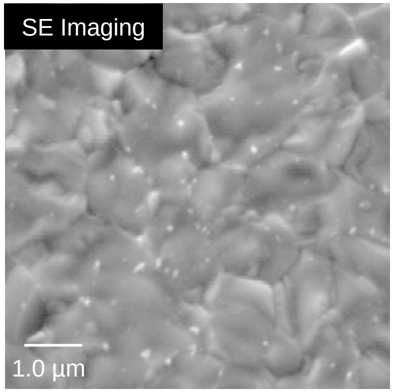
Structural Characterization



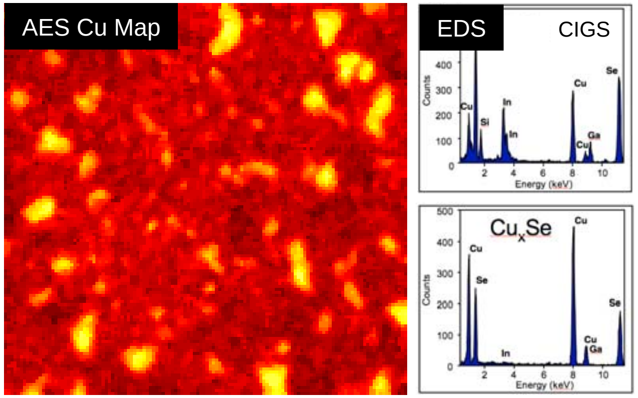
Process Knowledge



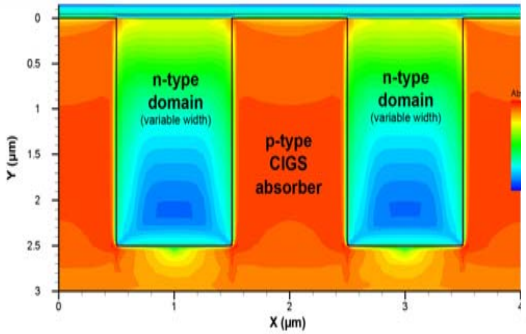
Topography



Compositional Characterization



Device Modeling



M&C Capabilities

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Surface Analysis

Surface analytical techniques help to determine the chemical, elemental, and molecular composition, and electronic structure of material surfaces and interfaces. The properties of the surface and outer few micrometers of a material often control the electrical, chemical, or mechanical properties of that material—hence, this region is of extreme importance.

Our techniques use ions, electrons, and X-ray or ultraviolet photons in high vacuum to probe surfaces and interfaces of a material. We map the elemental and chemical composition of specimens, study impurities and grain boundaries, gather bonding and chemical-state information, measure surface electronic properties, and perform depth profiles to determine doping and elemental distributions. We have analyzed a wide range of materials, including photovoltaics, microelectronics, polymers, and biological specimens.

We work collaboratively with you to solve materials- and device-related R&D problems. This sheet describes our major technique capabilities.

FIELD EMISSION AUGER ELECTRON SPECTROSCOPY (FE-AES) WITH SCANNING AUGER MICROSCOPY (SAM)

In Auger electron spectroscopy (AES), a sample surface is bombarded with a focused beam of high-energy (2- to 10-kV) electrons. The incident electrons lose energy to the sample atoms, generating Auger electrons that have discrete kinetic energies characteristic of the emitting atoms.

This technique is particularly useful for determining the elemental composition of the surface because Auger electrons have a limited escape depth. A key capability of the FE-AES is its ability to focus the electron beam to a small spot, with resolutions similar to an electron microscope. By scanning the electron beam across the surface, we can generate both element-specific Auger maps and secondary-electron microscope (SEM) images from the same region of the sample.

MAJOR INSTRUMENTATION FOR SURFACE ANALYSIS

Analytical Technique	Instrumentation	Typical Applications	Probing species	Spot Size	Signal Detected	Elements Detected
Auger electron spectroscopy	Physical Electronics PHI 670	Elemental surface analysis, small-feature analysis	Electrons	25 nm	Auger electrons	Li to U
X-ray and ultraviolet photoelectron spectroscopy	Physical Electronics PHI 5600	Elemental and chemical surface analysis, surface electronic properties	X-ray or ultraviolet photons	50 µm (XPS), 1 mm (UPS)	Photoemitted electrons	Li to U
Dynamic SIMS	Cameca IMS-5F & IMS-3F	Trace-element contaminant and dopant analysis	Ions (Cs, O, Ar)	1 to 200 µm	Ions (+/-)	H to U and all isotopes
Static TOF-SIMS	ION-TOF TOF SIMS IV	Surface elemental and molecular information	Ions (Ga, Ar, O)	To 0.2 µm	Ions (+/-)	H to U, all isotopes, mass range >10,000 amu

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Electro-Optical Characterization

We use various electrical and optical experimental techniques to relate photovoltaic device performance to the methods and materials used to produce them. The types of information obtained by these techniques range from small-scale atomic-bonding information to large-scale macroscopic quantities such as optical constants and electron-transport properties. Accurate, timely measurements of electro-optical properties as a function of device processing provide the knowledge needed to troubleshoot problems and develop the knowledge base for reducing cost, maximizing efficiency, improving reliability, and enhancing manufacturability. We work collaboratively with you to solve materials- and device-related R&D problems. This sheet summarizes our primary techniques and capabilities.

PHOTOLUMINESCENCE SPECTROSCOPY

Photoluminescence (PL) spectroscopy is a contactless, nondestructive method to probe the electronic structure of materials. Our capabilities include: various excitation wavelengths that allow for varying levels of volume excitation; a detection range extending from 0.4 to 2.7 µm; sample temperatures of 4 to 300 K; and mapping capabilities with 1- to 2-µm spatial resolution on the Fourier-transform-based system. The intensity and spectral content of the emitted photoluminescence is a direct measure of various important material properties, including:

Bandgap determination. This is particularly useful when working with new compound semiconductors.

Impurity levels and defect detection. The PL energy associated with these levels can be used to identify specific defects.

Recombination mechanisms. Analysis of PL helps to understand the underlying physics of the recombination process.

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Device Performance

We measure the performance of PV cells and modules with respect to standard reporting conditions—defined as a reference temperature (25°C), total irradiance (1000 Wm^{-2}), and spectral irradiance distribution (IEC standard 60904-3). Typically, these are "global" reference conditions, but we can measure with respect to any reference set.

To determine device performance, we conduct two general categories of measurements: spectral responsivity (SR) and current versus voltage (I-V). We usually perform these measurements using standard procedures, but we develop new procedures when required by new technologies.

We also serve as an independent facility for verifying device performance for the entire PV community. We help the PV community solve its special measurement problems, giving advice on solar simulation, instrumentation for I-V measurements, reference cells, measurement procedures, and anomalous results. And we collaborate with researchers to analyze devices and materials.

ACCREDITED

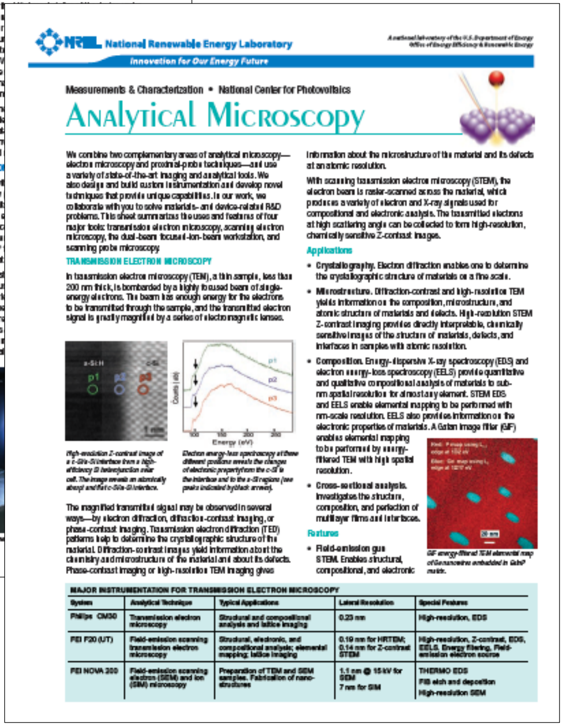
certificate number 2236.01
Accredited for primary reference cell, secondary reference cell, and secondary module calibration

Our facility for calibrating primary reference cells is one of four facilities certified in accordance with the world photovoltaic scale and that cooperates internationally to provide the PV community with a path of traceability to standards. We are accredited by the American Association for Laboratory Accreditation (A2LA) to ISO-17025 standards for primary reference cell, secondary reference cell, and secondary module calibrations for samples that meet the requirements. We help develop consensus U.S. and international PV standards through participation in ASTM and IEC standards groups.

TYPICAL MEASUREMENT FLOWS

For devices that come to us for measurement, we typically follow a procedure that ensures quality measurement and follow up. After logging in the device based on information from a cover letter or request form, we measure its area, which is crucial for determining its efficiency. We then obtain its spectral responsivity. For cells, we measure the spectral responsivity with one of two systems. For modules, however, spectral responsivity is generally provided to us by the manufacturer or we measure it on a representative cell.

Next, we use the information on spectral responsivity to calculate the spectral mismatch between the test device and a primary reference cell for the simulator that will be used for the subsequent I-V measurement. This is done because the intensity of the light source in a simulator system is set with a reference cell; and the correction factor for the spectral mismatch enables measurement of the sample's performance with respect to a reference spectrum.



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Analytical Microscopy

We combine two complementary areas of analytical microscopy—electron microscopy and proximal-probe techniques—and use a variety of state-of-the-art imaging and analytical tools. We also design and build custom instrumentation and develop novel techniques that provide unique capabilities. In our work, we collaborate with you to solve materials- and device-related R&D problems. This sheet summarizes the uses and features of four major tools: transmission electron microscopy, scanning electron microscopy, the dual-beam focused-ion-beam workstation, and scanning probe microscopy.

TRANSMISSION ELECTRON MICROSCOPY

In transmission electron microscopy (TEM), a thin sample, less than 200 nm thick, is bombarded by a highly focused beam of single-energy electrons. The beam has enough energy for the electrons to be transmitted through the sample, and the transmitted electron signal is greatly magnified by a series of electromagnetic lenses.

High-resolution Z-contrast image of a c-Si/a-Si interface from a high-efficiency Si heterojunction solar cell. The image reveals an atomically abrupt and flat c-Si/a-Si interface.

Electron energy-loss spectroscopy at three different positions reveals the changes of electronic property from the c-Si to the interface and to the a-Si regions (see peaks indicated by black arrows).

The magnified transmitted signal may be observed in several ways—by electron diffraction, diffraction-contrast imaging, or phase-contrast imaging. Transmission electron diffraction (TED) patterns help to determine the crystallographic structure of the material. Diffraction-contrast images yield information about the chemistry and microstructure of the material and about its defects. Phase-contrast imaging or high-resolution TEM imaging gives information about the microstructure of the material and its defects at an atomic resolution.

With scanning transmission electron microscopy (STEM), the electron beam is raster-scanned across the material, which produces a variety of electron and X-ray signals used for compositional and electronic analysis. The transmitted electrons at high scattering angle can be collected to form high-resolution, chemically sensitive Z-contrast images.

Applications

- Crystallography. Electron diffraction enables one to determine the crystallographic structure of materials on a fine scale.
- Microstructure. Diffraction-contrast and high-resolution TEM yields information on the composition, microstructure, and atomic structure of materials and defects. High-resolution STEM Z-contrast imaging provides directly interpretable, chemically sensitive images of the structure of materials, defects, and interfaces in samples with atomic resolution.
- Composition. Energy-dispersive X-ray spectroscopy (EDS) and electron energy-loss spectroscopy (EELS) provide quantitative and qualitative compositional analysis of materials to sub-nm spatial resolution for almost any element. STEM EDS and EELS enable elemental mapping to be performed with nm-scale resolution. EELS also provides information on the electronic properties of materials. A Gatan image filter (GIF) enables elemental mapping to be performed by energy-filtered TEM with high spatial resolution.
- Cross-sectional analysis. Investigates the structure, composition, and perfection of multilayer films and interfaces.

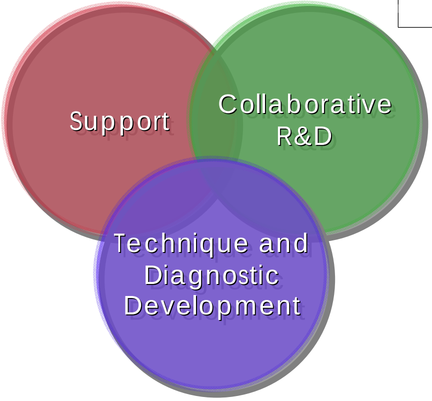
GIF energy-filtered TEM elemental map of Ge nanowires embedded in GaInP matrix.

Features

- Field-emission gun STEM. Enables structural, compositional, and electronic

MAJOR INSTRUMENTATION FOR TRANSMISSION ELECTRON MICROSCOPY

System	Analytical Technique	Typical Applications	Lateral Resolution	Special Features
Philips CM30	Transmission electron microscopy	Structural and compositional analysis and lattice imaging	0.23 nm	High-resolution, EDS
FEI F20 (UT)	Field-emission scanning transmission electron microscopy	Structural, electronic, and compositional analysis; elemental mapping; lattice imaging	0.19 nm for HRTEM; 0.14 nm for Z-contrast STEM	High-resolution, Z-contrast, EDS, EELS, Energy filtering, Field-emission electron source
FEI NOVA 200	Field-emission scanning electron (SEM) and ion (SIM) microscopy	Preparation of TEM and SEM samples. Fabrication of nano-structures	1.1 nm @ 15 kV for SEM 7 nm for SIM	THERMO EDS FIB etch and deposition High-resolution SEM



Support

Collaborative R&D

Technique and Diagnostic Development