2008 Solar Annual Review Meeting

Measurements & Characterization (M&C) Capabilities Overview



Peter Sheldon
Measurements and Characterization
NREL
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NREL/PR-520-43215

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





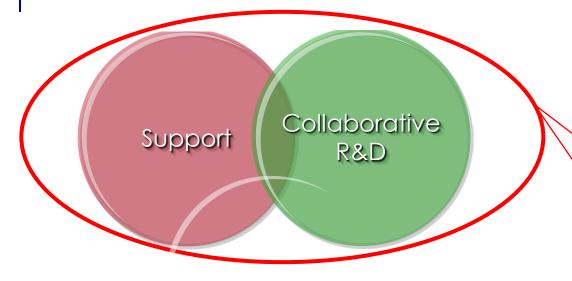
M&C Mission: Three Focus Areas





M&C Mission: Three Focus Areas





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

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

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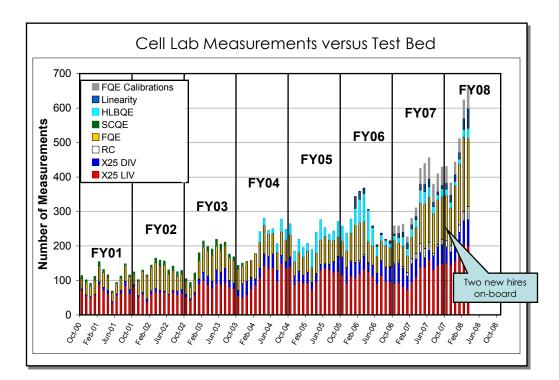
2008 Subcontractor Funding:	
Photovoltaic Systems R&D Technology Pathway Partnerships (TPPs)	~\$51M
PV Technology Incubator	~18M
University Photovoltaic Product and Process Development	~\$4M
Next Generation Photovoltaic Devices and Processes	~\$7M
TOTAL	~\$80M





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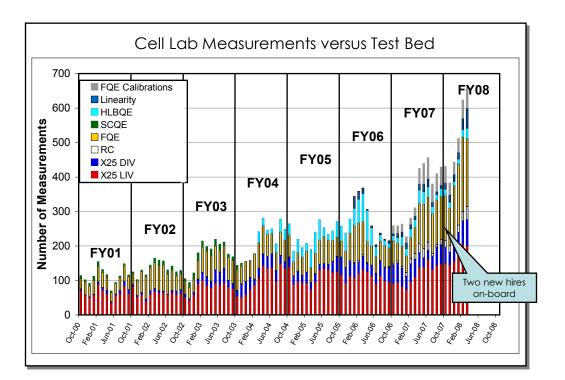






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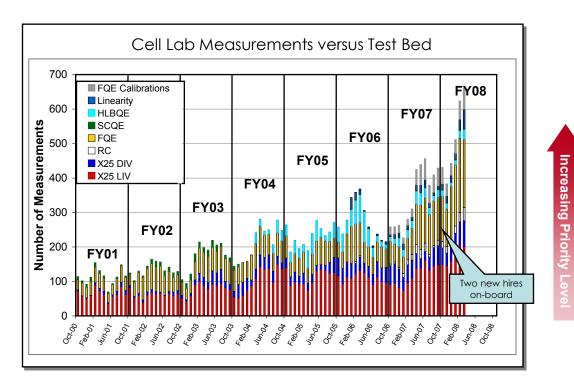
- Top priority/preferential treatment for SAI deliverables and stage gate reviews
- Support for all DOE-funded subcontracts on a first come first serve basis (no differentiation between TPP, Incubator, and pre-SAI subcontracts)
- Non-SAI funded PV industry requests





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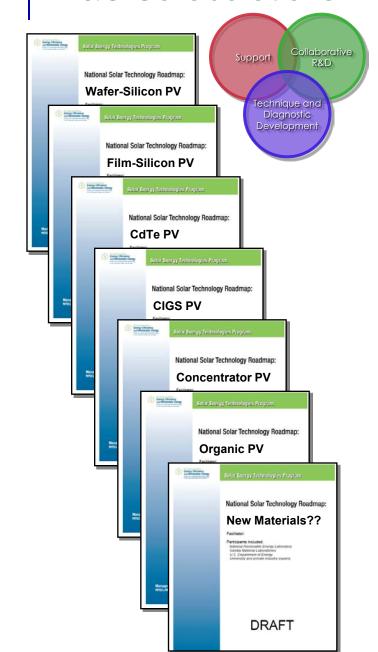




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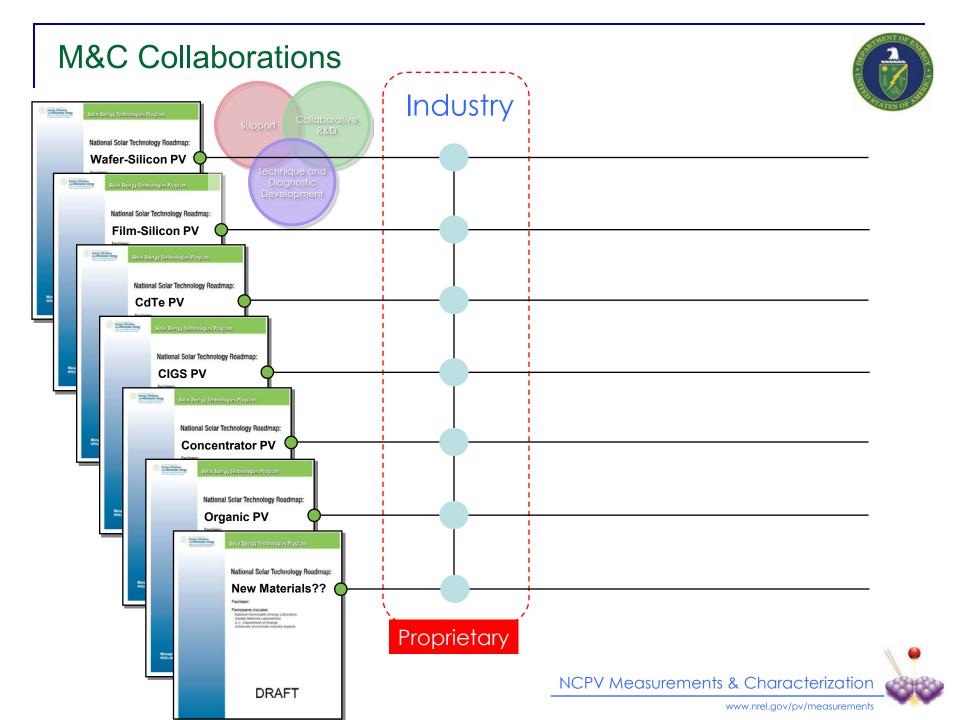


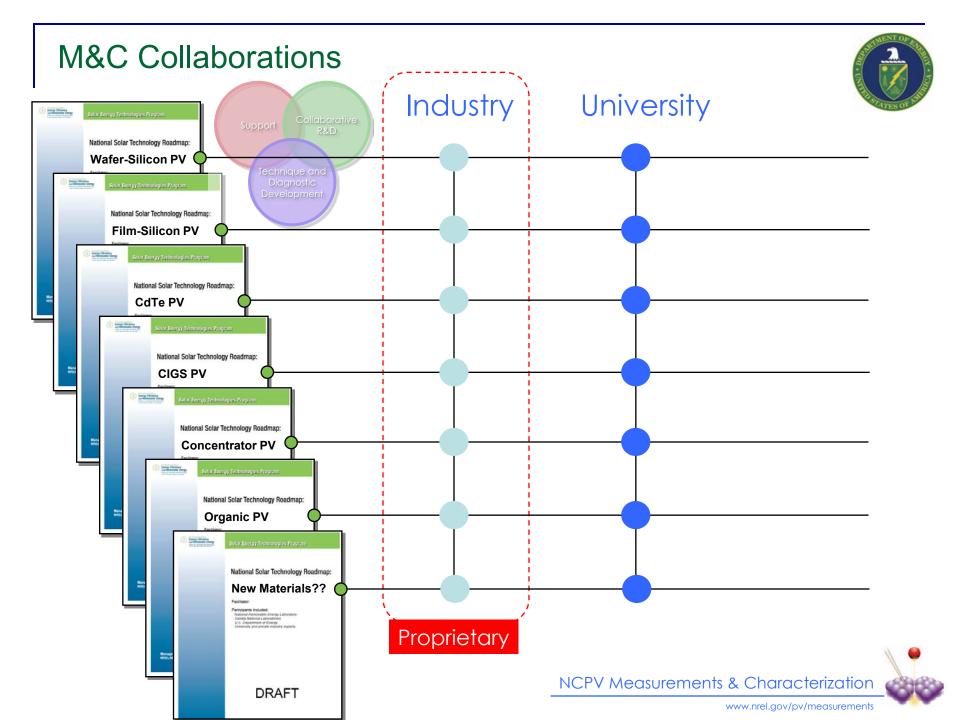
M&C Collaborations

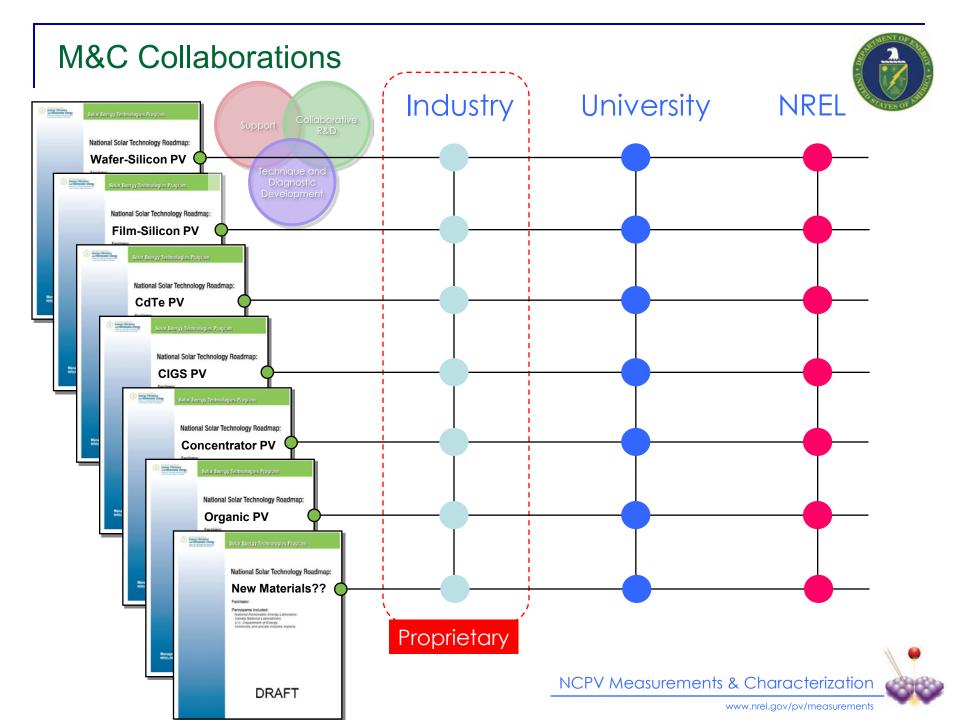




M&C Collaborations National Solar Technology Roadmap: Wafer-Silicon PV National Solar Technology Roadmap: Film-Silicon PV National Solar Technology Roadmap: CdTe PV National Solar Technology Roadmap: **CIGS PV** National Solar Technology Roadmap: Concentrator PV National Solar Technology Roadmap: **Organic PV** National Solar Technology Roadmap: New Materials?? (NCPV Measurements & Characterization DRAFT www.nrel.gov/pv/measurements







M&C Core Competency Areas





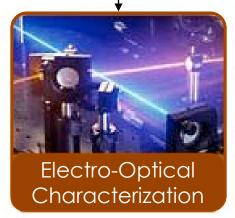
Measurements & Characterization

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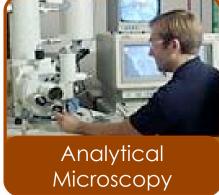
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Sally Asher sally_asher@nrel.gov



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M&C Core Competency Areas





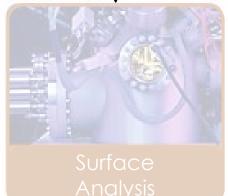
Measurements & Characterization

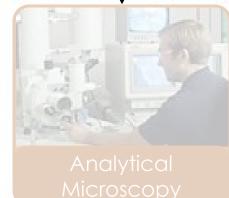
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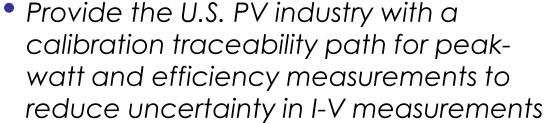


Keith Emery

keith_emery@nrel.gov

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 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





Certificate Number 223601
ISO 17025 accredited for photovoltaic secondary cell, secondary module and primary reference cell calibration by the American Association for Laboratory Accreditation (A21A)



NCPV Measurements & Characterization

Cell and Module Performance Team Capabilities

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 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



- 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)

M&C Core Competency Areas





Measurements & Characterization

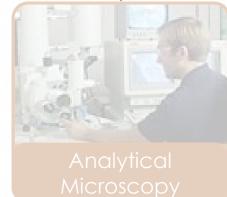
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Dean Levi

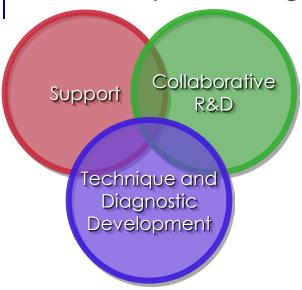
dean_levi@nrel.gov

Electro-Optical Characterization Team Capabilities

0 7
Electro-Optical
Characterization

Technique/Capability	Typical Applications Characterizati
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 Diagnostic Development



Development

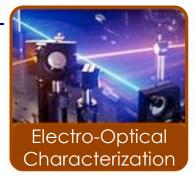




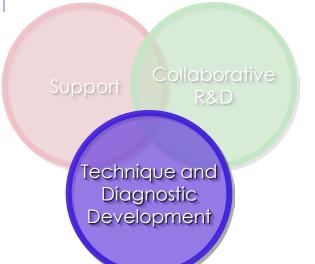


PV Reflectometer..... Licensed

• RC-PCD...... In- Process



Electro-Optical Diagnostic Development









Electro-Optical

Characterization

PV Reflectometer..... Licensed

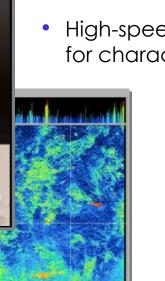
RC-PCD...... In- Process

GT-PVSCAN 8000



- Technology developed at NREL and licensed to GT Solar
- 8' x 8" sample size
- Measurement Modes:
 - Dislocation density
 - Reflectance
 - Light Beam Induced Current (LBIC)

NCPV Measurements & Characterization





M&C Core Competency Areas

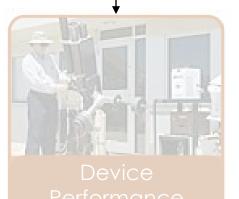


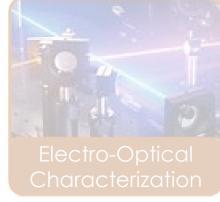


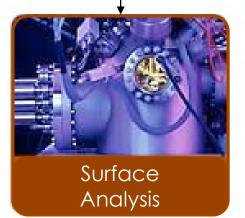
Measurements & Characterization

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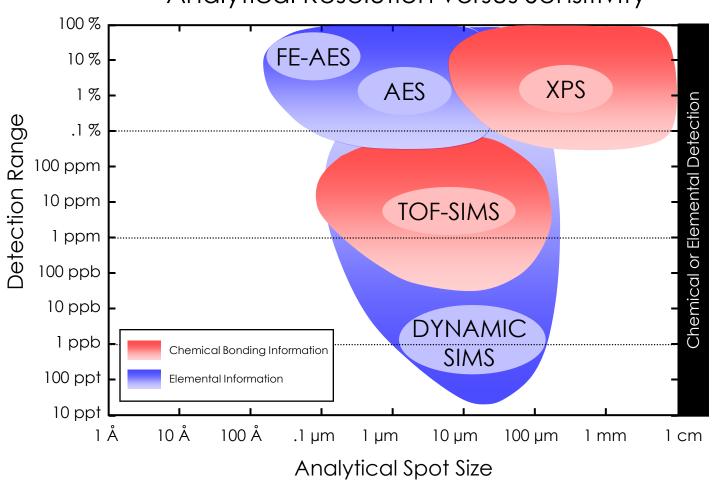




Sally Asher

Surface Analysis Team Capabilities







AES

Auger Electron Spectroscopy

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

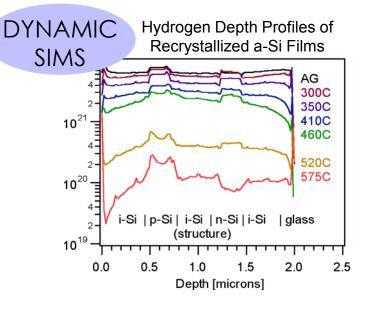
XPS

X-ray Photoelectron Spectroscopy

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



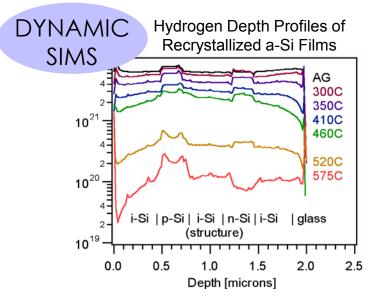
Secondary Ion Mass Spectrometry (SIMS) Time-of-Flight SIMS (TOF-SIMS)





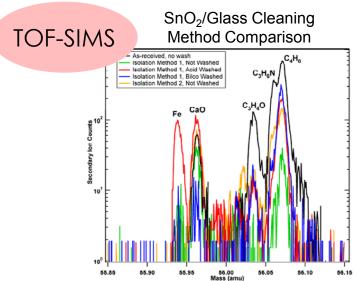
- Extremely sensitive Detects fractions in the range of parts per million (ppm) to parts per billion (ppb)
- Elemental detection of species ranging from H to U and all isotopes
- Quantitative technique when used with standards
- Depth profiles with resolution of <10 nm -Excellent technique for analyzing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

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





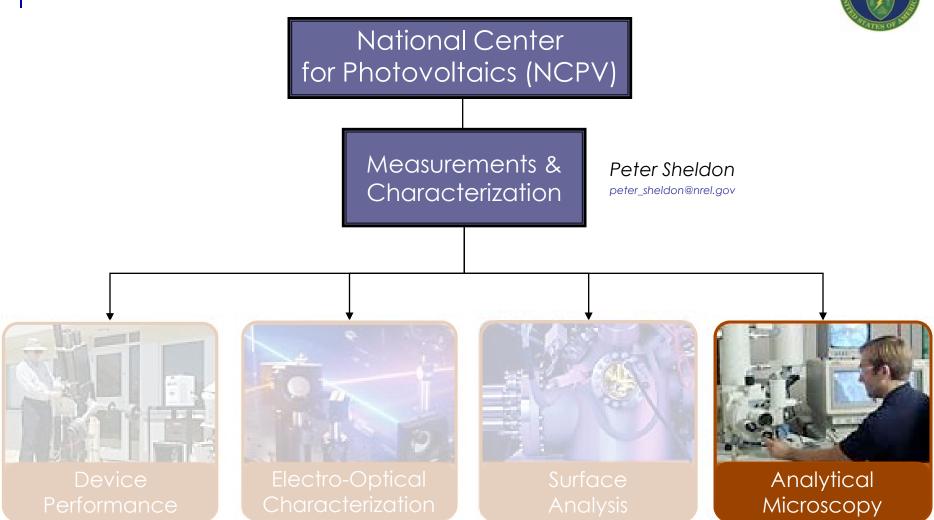
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- Extremely sensitive Detects fractions in the parts per million (ppm) range
- Elemental and molecular analysis- good for analyzing organics
- Surface sensitive technique can study the top few monolayers of material
- Elemental detection of species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

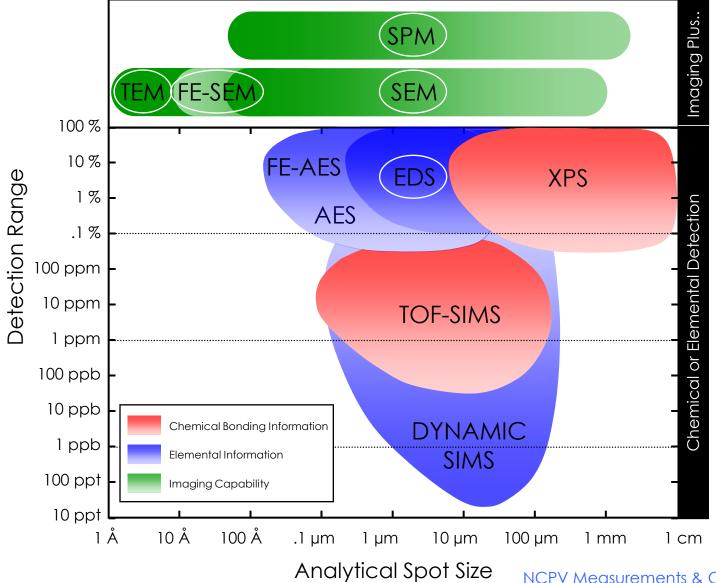
M&C Core Competency Areas





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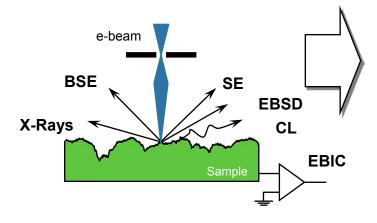
Analytical Microscopy Team Capabilities





SEM and SPM Capabilities

SEM Operational Modes

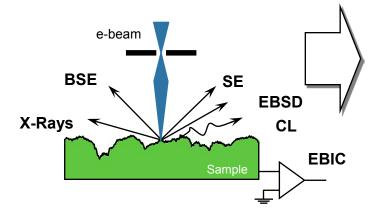


- Secondary Electron (SE) Imaging
- Back Scattered Electron (BSE) Imaging
- Cathodoluminescence (CL)
- Electron beam induced current (EBIC)
- Electron backscattered diffraction (EBSD)
- Energy dispersive x-ray spectroscopy (EDS)



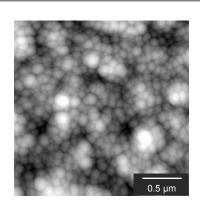
SEM and SPM Capabilities

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)



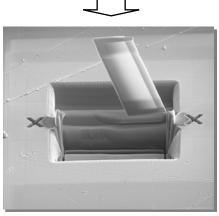
Transmission Electron Microscopy (TEM)

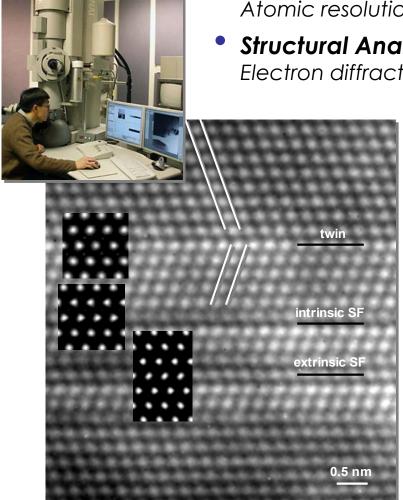


Structural Analysis -Electron diffraction and diffraction contrast analysis



Cross-Sectional Analysis - New Focused Ion Beam (FIB) capability facilitates cross-sectional sample prep with pin-point accuracy.



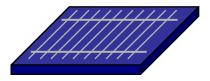




Analytical

Microscopy



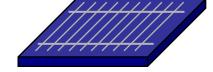




Process Knowledge

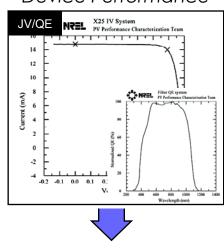








Device Performance



Process Knowledge

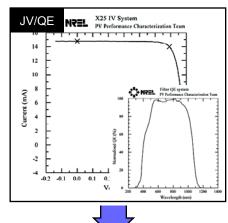








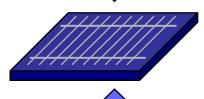
Device Performance



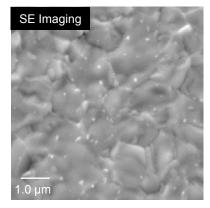
Process Knowledge





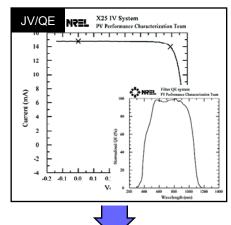








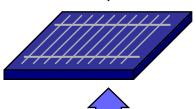
Device Performance



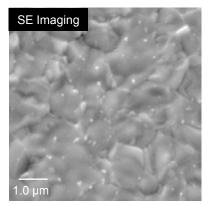
Process Knowledge





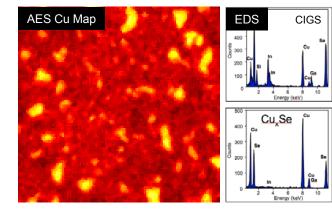




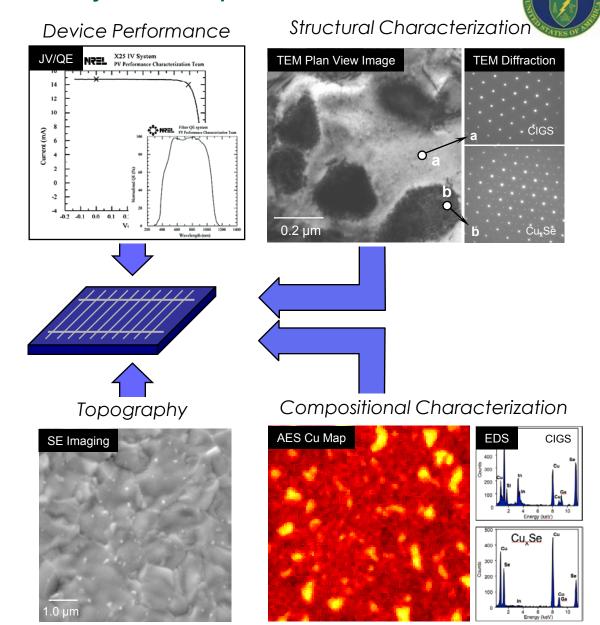


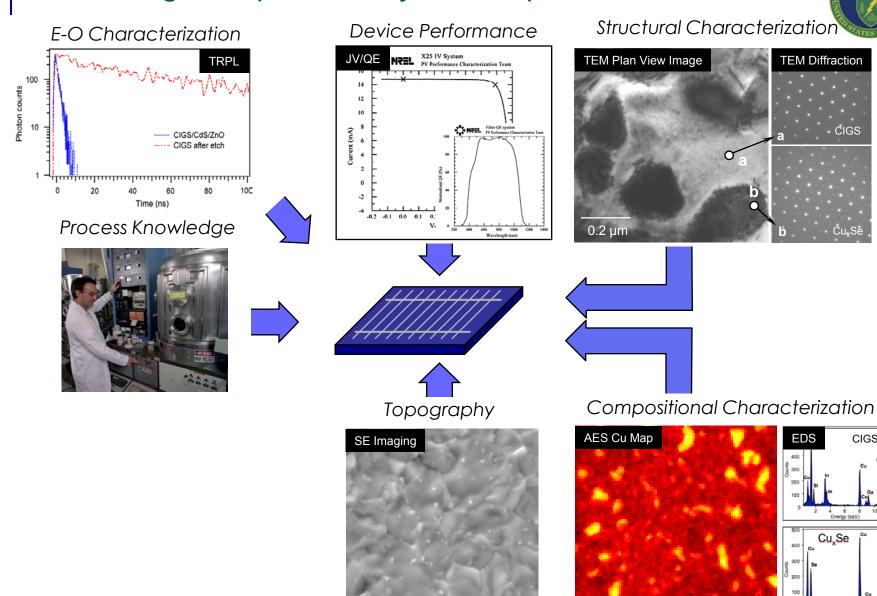


Compositional Characterization



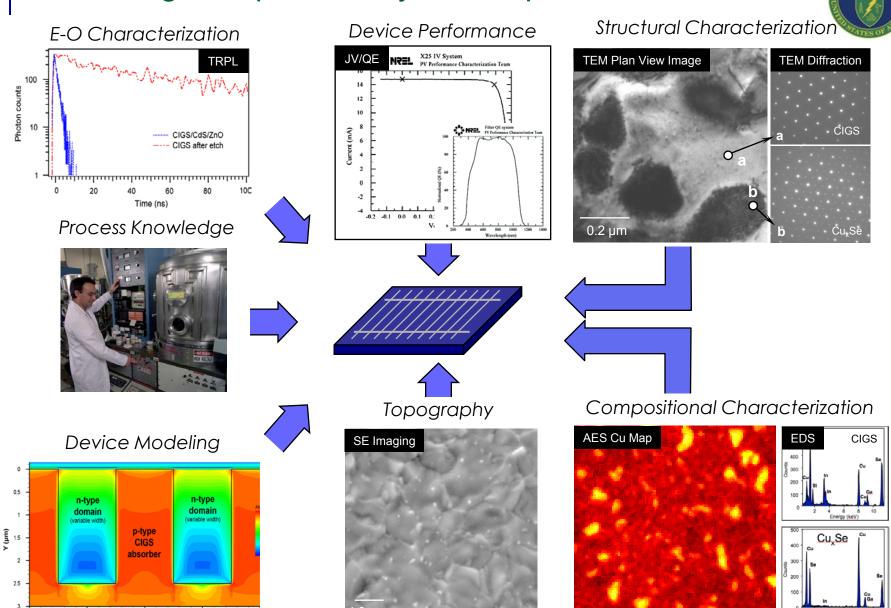
Process Knowledge





CIGS

X (µm)



M&C Capabilities



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www.nrel.gov/pv/measurements

Surface analytical techniques help to delemnine the chamical, elements, and molecular composition, and all althorise shutchin of material surfaces and interfaces. The proporties of the surface and outer from information of a material offse confrol the electrical,

Surface Analysis

Our techniques use ions, electrons, and X-ray or eltraviolet photons in high vacuum to probe surfaces and interfaces of a maturial. We in right industrial product an acceleration tracticated from instance, when phis alternated and chain facility composition of specifierins, shally impurities and grait boundaries, gather boulding and chamicat-slade information, resource variations electronic properties, and profession depirity and elemental statistications. We have variably as a risked range of instantists, including professionation, in loss electronics, polymers, and bid optical specifimens.

We work collaboratively with you to solve materials-and device-related RBD problems. This shout describes our major technique

FIFLD FINISSION AUGER ELECTRON SPECTROSCOPY (F.S. AES) WITH SCANNING AUGER NICROSCOPY (SAM)

In August electron spectroscopy (AES), a sample surface is in Augustus to the particular properties of the second to the second to

This technique is particularly useful for determining the elemental comportion of heuristic because Augor electrons have a limited except depth. A key capititity of the RE-ASS is leadily to because electron beam to a small spot with reach lines related to the electron introduced by seaming the electron beam across the surface, we can generate both element-specific Auger maps and secondary-election referoscope (SEM) images from the same region of the sample.

MAJOR INSTRUMENTATION FOR SURFACE ANALYSIS								
Analytical Technique	iruta suo- talco	Typical Applications	Probing openion	Spot Stan	Oped Debeted	Demonits Delected	Date Brait	
Ager electron spectroscopy	Proposal Beckooks PH 670	Ebenosia i suriace uradysis, cesa S- louit.no una lysis	Decisors	25 nm	Ager	Lioi	L5-1	
X-ray and altraviolat photosisches spectoscopy	Prysical Sectionics PH 5600	Chemostal and dramital authors analysis, authors obstructs populies	X-exy or Liftronicibil photons	51 pm (655), 1 mm (455)	Problems and selections	Uloll	prej	
Dynamic SING	Comeca BIS- SF & MS-OF	Truce-element contains restand coperal analysis	(Co., O,Ar)	1 to 280 pm	par (+4)	If to U and all isotopes	jan Pa	
State 10PSBHS	EMFOF YOP SIMS M	Sertice elemental and resiscular information	(Ea, #, 0)	To 0.5µm	h+4	EtaU, all Indique, manage	-	

elements from

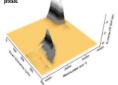
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Impurity levels and detect detection. The PL energy associate

the underlying physics



National Renewable Energy Laboratory

Measurements & Characterization • National Center for Photovoltaics Device Performance

> We measure the performance of PV sells and modules with respect to standard reporting conditions—defined as a reference tumperature (25°C), total irradiance (1000 Wm⁻²), and spectral tradiance distribution (EC standard 60004-3). Typically, it see are

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

We also serve as an independent tacility for verifying device performance for the units PV community. We halo the PV community. solve its special measurement problems, giving advice on solar almostition, instrumentation for I-V measurements, reference calls, measurement procedures, and apprecious results. And we



ACCREDITED col, socratary reference cell, and securitary mobile calibration

Our facility for calibrating primary reference calls is one of four tacilities certified in accordance with the world photovotate scale and that cooperates internal onally to provide the PV community. with a path of traceability to standards. We are according by the American Association for Laboratory Accreditation (A2LA) to ISO-17025 standards for primary reference cell, secondary reference cell, and secondary module callberlions for samples that meet the requirements. We halp a welo p consensus U.S. and international PV tandards through participation in ASTN and EC standards groups

For devices that some to us for invasurement, 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 by the manufacturer or we measure it on a representative self.

Hiod, we use the information on spectral responsivity to calculate the special information between the last device and a primary reference call for the simulator that will be used for the subsequent. I-V measure in mark. This is done because the interesty of the light source in a simulator system is set with a measure call; and the correction factor for the spectral intensich enables measurement of the sample's performance with respect to a reference spectrum.

simulatud condit purformance und results are trans we measure the can also adjust t concentrators to

concretion the cli amailysis, data, ar SPECTRAL RES

Spectral respons to selected nam terms of quantum circuit. These sys temperatures (10 temperatures (10 suns), and differe

We see two SR or typical minimum



scanning probe microscopy

TRANSMISSION ELECTRON MICROSCOPY

A national laboratory of the U.S. Department of Surger

National Renewable Energy Laboratory

We combine two complementary areas of analytical inicroscopy— electron microscopy and proximal-probe techniques—and use

a variety of state-of-the-art imaging and analytical tools. We also dealers and build custom is strumentation and develop novel

najor tooks transmission electron microscopy, scanning electron nicroscopy, the dual-beam focused-ion-beam workstation, and

In transmission placture migroscopy/TEM) is thin sample, loss than 200 mm thick, is bombarded by a highly boused beam of all gis-energy electron. The beam has enough energy for the electrons to be transmitted through the sample, and the transmitted electron signal to practly mappill in by a series of electromagnitic lenses.

Analytical Microscopy

The magnified transmits i signal may be observed in several ways—by electron diffraction, diffra los-contact imaging, or phese-contact imaging. Transmission electron diffraction (TEV) potierns ledy to determine the crystallog applie structure of the

national. Officedion-contrast images yield information about the cleanistry audimicrostructure 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

A nucleonal last contacty of the U.S. Department of Energy Office of Energy Efficiency & European & Energy

SOLAR AMERICA

With scauning transmission electron migroscopy (STEM), the produces a variety of electron and X-ray dignals used by compositional and electronic austyles. The transmitted electrons at high scatting angle can be collected to form high-resolution, charriedly sensitive Z-contast Images.

- Crystallography. Electron diffraction enables one to determine the crystallographic structure of materials on a fine scale.
- . Microstructure. Diffraction-contrast and high-resolution TEM wes resurentume. Untraction-contrast and eight-resolution flaw yields information on the composition, microstructure, and atomic structure of materials and delects. High-resolution STEM Z-contrast imaging provides directly interpretable, chemically sensitive images of the structure of materials, defects, and sensitive images of the structure of maserias interfaces in samples with atomic resolution.
- Composition, Energy-Alsperake X-say spectroscopy (EDS) and electron energy-loss spectroscopy (EELS) provide quantitative and qualitative composition classifies of materials to sub-nm apalial resolution it or almost any element. STEM EDS and EELS enable elemental mapping to be performed with nm-scale resolution, EELS also provides information on the
- enables elemental mapping to be performed by energy-fillered TEM with high spalled Cross-sortional analysis.
- Investigates the structure, composition, and perfection of mutilizator films and interfaces.
- Reld-emission gue
 STEM. Enables structural,
 Technologie



MAJOR INSTRUMENTATION FOR TRANSMISSION ELECTRON MICROSCOPY								
Dysines	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				
PEI 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 filering, Field- emission electron source				
FEI NOVA 200	Field-emission scenning electron (SISM) and ion (SIM) microscopy	Preparation of TEM and SEM samples. Fabrication of nano-structures	7 cm for SM	THERMO EDS FIS elsh and deposition High-resolution SEM				

NRSS... National Renewable Energy Laboratory Measurements & Characterization . National Center for Photovoltains Electro-Optical Characterization We use various electrical and optical experimental techniques to

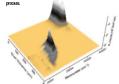
relate photosoliate device performance to the methods and materials used to produce them. The types of information obtained by these techniques range from small-scale atomic-bonding information to large-scale inscressopic quantities such as optical constants and electron-transport properties. Accusals, timely measurements of electro-optical properties as a function of device processing provide the knowledge needed to troublest cot problems and develop the knowledge besin for reducing cost, meath titing efficiency, improving relability, and enhancing manufacturability. We work collaboratively with you to solve materials- and divide-initiated R&D problems. This

sheet summerizes our primary techniques and capabilities

Photokeningscopes (PI) spectarscope is a materillas materials. Our capabilities include: verious excitation wavelengths heavise, our ception insorticates cross excitation is wiseway to that above for anyling levels of violune costistion; a direlation stay a extending from 0.4 to 2.7 µm; earn pile temperatures of 4 to 300 K; and inapping capabilities with 1-10 2-µm spatial insortion on the Relatio-time altern-based system. The inheatly and specified contact. of the emitted photo luminescence is a direct measure of various

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

with these levels can be used to identify specific dele Recombination mechanisms. Analysis of PL helps to uniterstand



Minority-carrier is nondestructive m of materials. This

as a function of

 Time-Cornel socupil on ally

0.5 to > 2µm

andtwo-dime

Hinority-cerris makes Ita sa

Collaborative Support R&D

> Technique and Diagnostic Development

> > NCPV Measurements & Characterization