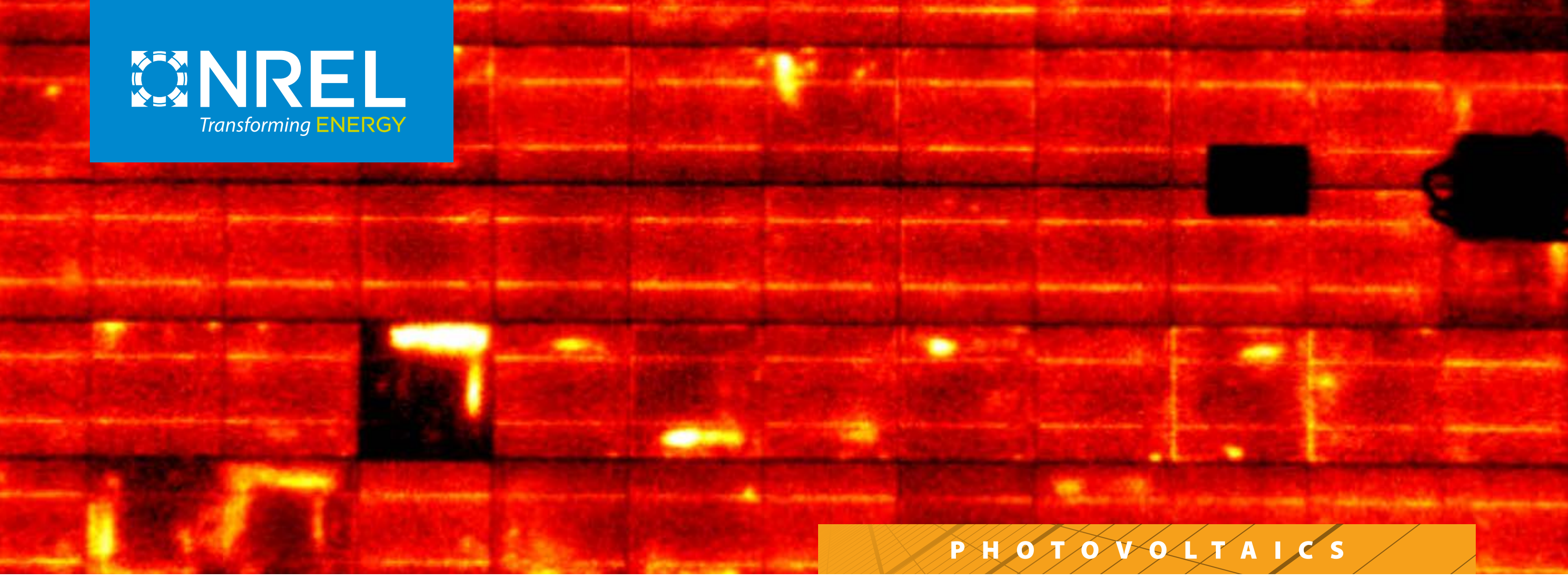
NREL Transforming ENERGY



Dark lock-in thermography image of a fielded module affected by potential-induced degradation. *Image by Steve Johnston*

Measurements and Characterization

The measurements and characterization scientists at the National Renewable Energy Laboratory provide characterization support, conduct collaborative research, and develop new measurement capabilities and diagnostics to advance materials science and photovoltaic (PV) generation of energy. We use state-of-the-art characterization tools to solve problems in all phases of material and device development. Results lead to an increased understanding that drives advances in the performance, reliability, cost, and manufacturability of PV materials, devices, and systems.

Measurements and characterization work is carried out within four closely integrated core competencies:

- Analytical microscopy and imaging science
- Interfacial and surface science
- Electro-optical characterization
- Cell and module performance.

Each area uses a wide array of state-of-the-art measurements and characterization techniques and has highly trained staff with extensive experience in PV materials and device characterization. This superb experience base, coupled with the breadth of our capabilities and our highly integrated approach, sets us apart from other organizations globally. We have a long history of working with the PV community to solve material, device, manufacturing, packaging, and reliability issues. We strive to develop a solid scientific foundation to help our customers advance their manufacturing process development, research, and reliability R&D to a higher level.

We enthusiastically welcome industry, manufacturing, university, and government enterprises to collaborate with us. We are motivated to share our expertise and knowledge base and to collaborate on research, problem-solving, and commercial product development.

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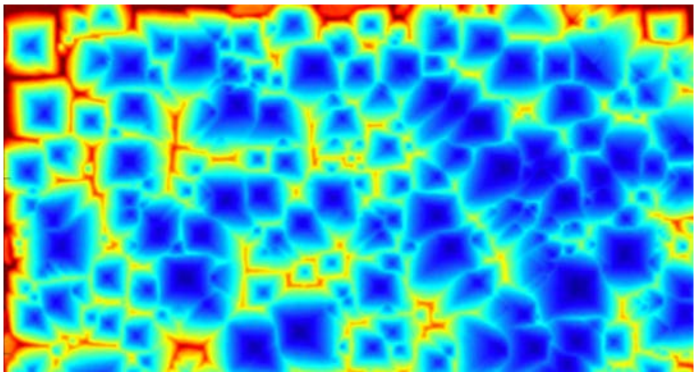
www.nrel.gov/pv/measurements.html

Analytical Microscopy and Imaging Science

Core Competencies and Capabilities

We use various microscopy, spectroscopy, and imaging techniques to obtain information about materials on a length scale from meters to angstroms. These tools are some of the most powerful available for understanding the basic structure, chemistry, morphology, and electrical and optical properties of materials. We use two complementary types of analytical microscopy—electron microscopy and scanning probe microscopy—along with a variety of state-of-the-art imaging and analytical tools to capture data about PV materials and devices.



Electron-beam-induced current map of a pyramid-textured poly-Si/SiO_2 passivated-contact cell. *Image by Harvey Guthrey*

Our capabilities are briefly summarized below:

- Scanning electron microscopy (SEM)
- Transmission electron microscopy (TEM/STEM)
- Cathodoluminescence (CL)
- Electron-beam-induced current (EBIC)
- Electron backscatter diffraction (EBSD)
- Focused ion beam (FIB) microscopy
- Electron energy loss spectroscopy (EELS)
- Energy dispersive X-ray analysis (EDS)
- Scanning probe microscopy techniques:
  - Atomic force microscopy (AFM)
  - Scanning capacitance microscopy (SCM)
  - Scanning spreading resistance microscopy (SSRM)
  - Scanning tunneling microscopy (STM)
  - Kelvin probe force microscopy (KFPM)
  - Electrochemical AFM (EC-AFM)

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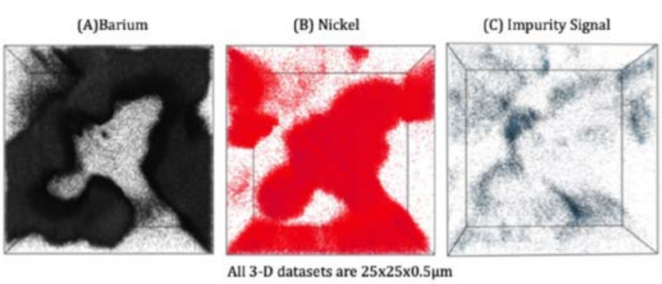
www.nrel.gov/materials-science/analytical-microscopy-imaging-science.html

Interfacial and Surface Science

Core Competencies and Capabilities

We use a complementary array of techniques to determine the chemical, elemental, and molecular composition and electronic structure of material surfaces and interfaces, which play critical roles in many renewable energy technologies. For example, band offsets between PV absorber materials and carrier-selective contacts must be carefully optimized to enable high performance. And in batteries, the formation and evolution of the solid-electrolyte interphase plays a dominant role in performance and cyclability. Using ions, electrons, and X-ray or ultraviolet photons in high vacuum, we probe surfaces and interfaces of a material or device to 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.



Time-of-flight secondary-ion mass spectrometry 3-D tomography elucidates distribution of impurities in BaZrCeYO /Ni 2-phase composite material: A) barium, B) nickel, C) impurity signals. *Images by Steve Harvey*

Our capabilities are briefly summarized below:

- Auger electron spectroscopy (AES)
- X-ray photoelectron spectroscopy (XPS)
- Ultraviolet photoelectron spectroscopy (UPS)
- Thermal desorption mass spectrometry (TDMS)
- Dynamic secondary-ion mass spectrometry (SIMS)
- Time-of-flight static secondary-ion mass spectrometry (TOF-SIMS)

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www.nrel.gov/materials-science/interfacial-surface-science.html

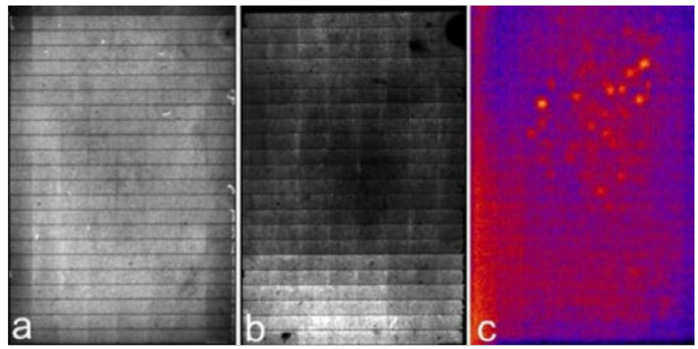
Electro-Optical Characterization

Core Competencies and Capabilities

We use a powerful combination of optical spectroscopies, electrical device measurements, and sophisticated computer modeling to understand the complex relationships between material properties, device processing, and device performance. Our techniques apply to virtually all PV technologies, and we bring world-class expertise to measuring critical parameters, such as minority-carrier lifetime, and the fundamental junction parameters in PV devices. Optical measurement techniques are inherently rapid and non-contact and are well suited to in-line manufacturing. We have a demonstrated track record of technology transfer and actively seek industrial partners for collaborative R&D on the critical problems facing the PV industry.

Our capabilities are briefly summarized below:

- Photoluminescence (PL) spectroscopy
- Minority-carrier lifetime: time-resolved PL (TRPL), microwave-photoconductance decay (μ-PCD)
- Fourier transform infrared spectroscopy (FTIR)
- Spectroscopic ellipsometry: variable-angle spectroscopic ellipsometry (VASE), real-time spectroscopic ellipsometry (RTSE)
- Capacitance techniques: capacitance-voltage (C-V), deep-level transient spectroscopy (DLTS), admittance spectroscopy (AS), drive-level capacitance profiling (DLCP)
- Imaging diagnostics and development:
  - Lock-in thermography (LIT)
  - Electroluminescence (EL) imaging
  - Photoluminescence (PL) imaging
- Laser-beam-induced current (LBIC)
- Conformal Raman and PL microscopy
- 2D and 3D computational device and measurement simulation modeling (also available within other capabilities)



Pre-stress images of CdTe module using (a) photoluminescence, (b) electroluminescence, and (c) dark lock-in thermography. *Images by Steve Johnston*

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www.nrel.gov/pv/electro-optical-characterization.html

Cell and Module Performance

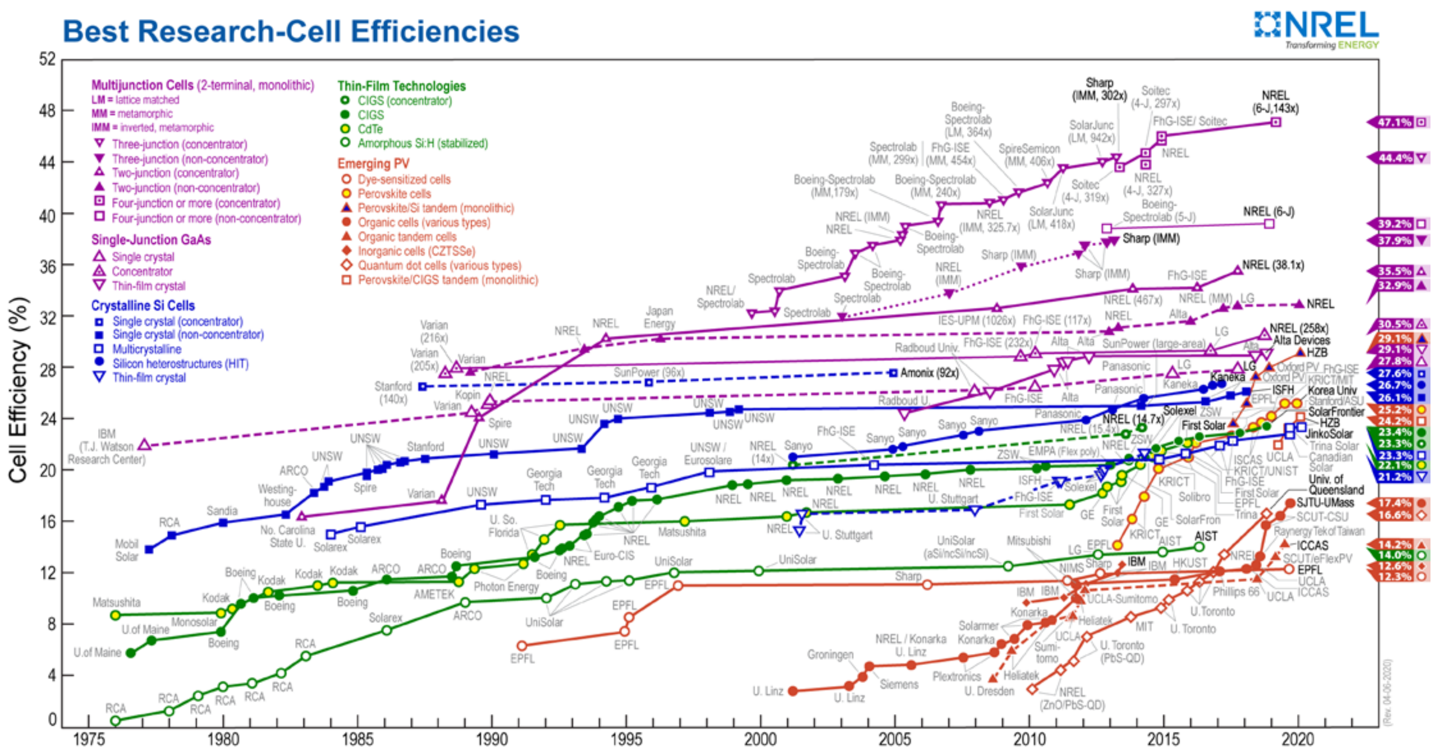
Core Competencies and Capabilities

We are the premier U.S. Department of Energy research laboratory for testing the performance of commercial, developmental, and research PV devices. We are one of only two laboratories in the world to hold an International Organization for Standardization (ISO) 17025 accreditation for primary reference cell and secondary module calibration, in addition to accreditation for secondary reference cell calibration under American Society for Testing Materials (ASTM) and International Electrotechnical Commission (IEC) standards. We are one of only four laboratories in the world certified in accordance with the IEC standard for calibrating terrestrial primary reference PV cells. We test cells and modules of any size, shape, or technology from around the world, putting all PV performance measurement "on the same page."

Indoor testing of photovoltaic module in NREL lab. *Photo by Nikos Kopidakis*

Our capabilities are briefly summarized below:

- Current vs. voltage (I-V) measurements
  - I-V at 1-sun standard test conditions
  - Cell I-V vs. concentration and temperature
  - Asymptotic cell (including tandem) and module I-V for slow-responding devices
  - Multisource simulator for multijunctions at 1 sun
  - Continuous and pulsed module simulators
  - Adjustable tilt test bed for 1-sun outdoor module I-V
  - 2-axis tracker for up to 10 concentrator modules
- Spectral responsivity (SR)/quantum efficiency (QE)
  - Single- or multijunction cells vs. temperature, light bias, and voltage bias
  - Non-destructive and fast module QE measurement and mapping
- ISO 17025-accredited primary reference cell
  - Secondary reference cell and secondary module calibration



NREL has a long history of accurately measuring and tracking the efficiencies and performance of photovoltaic devices. We maintain the above chart (*www.nrel.gov/pv/cell-efficiency.html*) of the highest confirmed conversion efficiencies for research cells for a range of photovoltaic technologies, plotted from 1976 to the present. A champion module chart is also available (*www.nrel.gov/pv/module-efficiency.html*).

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www.nrel.gov/pv/device-performance.html