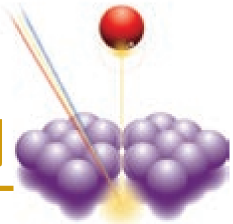
NREL National Renewable Energy Laboratory

Innovation for Our Energy Future

A national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy

Measurements & Characterization • National Center for Photovoltaics

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.

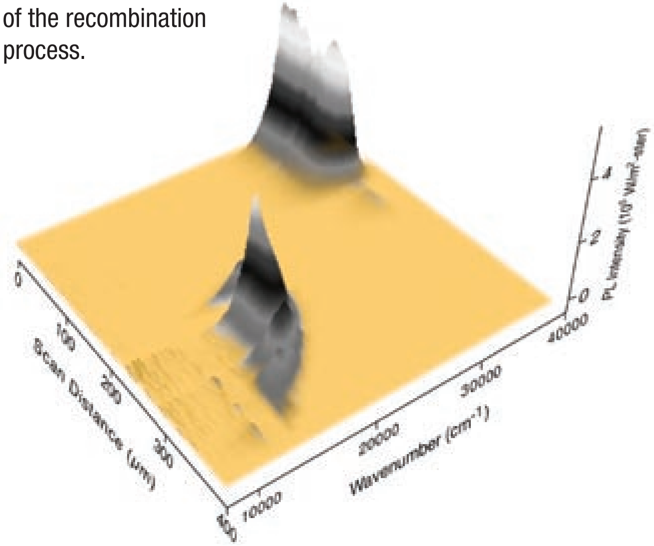
PHOTOLUMINESCENCE SPECTROSCOPY

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.

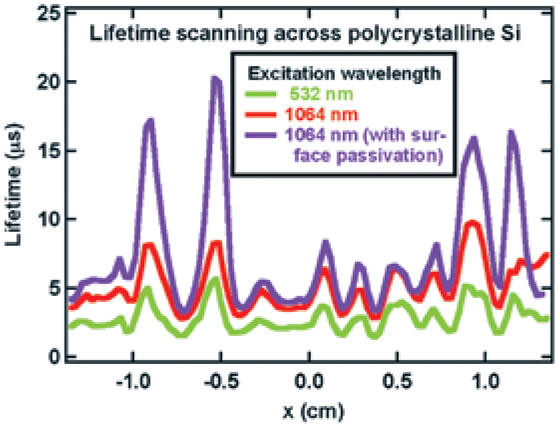


NREL researchers use scanning Fourier transform photoluminescence micro-spectroscopy to produce three-dimensional maps to determine the composition and quality of grown absorber materials.

MINORITY-CARRIER LIFETIME SPECTROSCOPY

Minority-carrier lifetime spectroscopy is a contactless, nondestructive method to study the recombination processes of materials. This technique monitors—either optically or electrically—the return of photoexcited carriers back to equilibrium as a function of time, providing a measure of the "lifetime" of the excess carriers. Our capabilities allow for varying levels of volume excitation and sample temperatures of 4 to 300 K. Specific techniques include:

- **Time-Correlated Single-Photon Counting or Time-Resolved Photoluminescence**—This optical detection technique provides exceptionally fast system response times of 20 ps (optical detection from 0.4 to 1.0 µm) and 100 fs (optical detection from 0.5 to > 2 µm).
- **Microwave-Reflection Photoconductive Decay (µ-PCD) and Resonant-Coupled Photoconductive Decay (RCPCD)**—These techniques monitor the change in conductivity and are suitable for both direct- and indirect-bandgap materials. They have a 5-ns time resolution for the µ-PCD systems (7 and 20 GHz) and ~50-ns resolution for RCPCD (~450 MHz) and are capable of one-dimensional and two-dimensional lifetime mapping with ~1-mm spatial resolution.



Maps of the polysilicon lifetime at various excitation wavelengths provide information on bulk, surface, and grain-boundary recombinations.

Applications

- **Minority-carrier lifetime.** The strong sensitivity of minority-carrier lifetime to the presence of defects detrimental to device performance makes it a particularly sensitive measure of material quality.
- **Recombination processes.** The dependence of lifetime on the level of photo-excitation and temperature is used to determine the underlying physics of the recombination process.
- **Surface/interface recombination velocity.** The dependence of lifetime on the geometry of the device being tested or

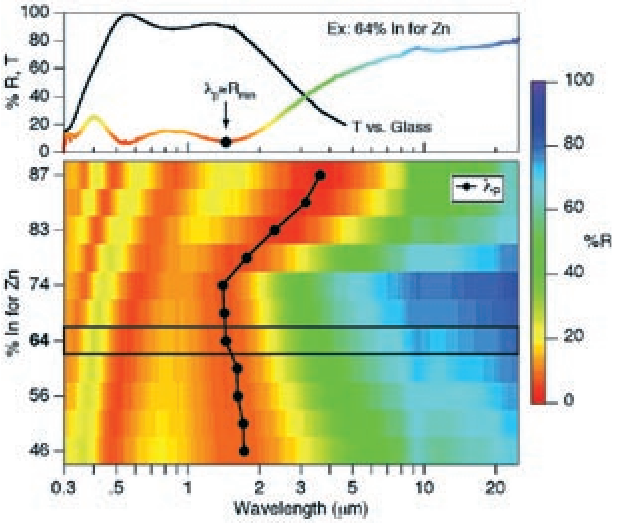
excitation wavelength used can serve to distinguish between recombination processes occurring in the bulk of the device and those occurring at interfaces or boundaries.

FOURIER-TRANSFORM INFRARED AND RAMAN SPECTROSCOPY

Infrared spectroscopy is a nondestructive, highly sensitive technique that provides information about impurities, their chemical environment, and free-carrier properties. Performing both Fourier transform (FT)-Raman and Fourier transform infrared (FTIR) spectroscopy on a sample gives a complete picture of its bonding structure. Both techniques benefit from high FT sensitivity and can be used with database searches of our extensive libraries of FTIR and FT-Raman spectra to chemically identify samples and sample components.

Applications

- **Reflectance and transmittance spectroscopy.** Includes large-area mapping of samples up to 8 inches in diameter. Useful in analyzing properties of transparent conducting oxides and silicon wafers.
- **Contaminant identification.** Can be done over a large area, or in spots as small as 2 to 50 µm in diameter, depending on the technique used.
- **In-situ reaction analysis.** Gas-solid reactions, relaxation in liquid crystals, solid-solid phase transformations, and aqueous fermentation reactions, on time scales ranging from microseconds to days.

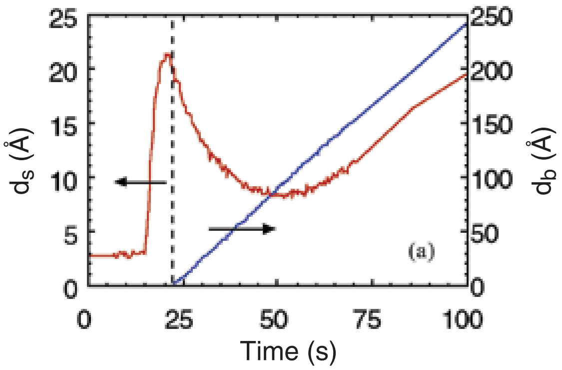


FTIR mapping capabilities are extremely useful for the quick, nondestructive characterization of heterogeneous free carrier properties of combinatorial growth research on transparent conducting oxides.

- **Impurity and doping concentrations.** Done either at room or cryogenic temperatures using FTIR spectroscopy. We can obtain sensitivities as high as parts per billion.

SPECTROSCOPIC ELLIPSOMETRY

Spectroscopic ellipsometry (SE) measures the near-IR/visible/near-UV optical response of a sample. In bulk samples, SE can determine electronic transition energies, which provide knowledge of alloy composition, crystallinity, doping, temperature, and any other variables that affect the electronic transitions in the material. In thin-film samples, including multilayer thin films common in solar cells, SE can determine layer thickness, surface roughness, interface roughness, and optical properties. SE operates in any transparent ambient, including vacuum, gases, liquids, and air.



In-situ ellipsometry measurements of surface roughness and film thickness in the earliest stages of the deposition process shed light on the film nucleation process.

This versatility allows ellipsometry to be applied in-situ and/or in-line to monitor the deposition and processing of materials. NREL has pioneered the use of in-situ real-time SE (RTSE) to monitor the growth of extremely thin films of a-Si:H used in silicon heterojunction solar cells. Our current capabilities cover a spectral range from 0.2 to 1.7 µm, acquisition times less than 1s, and mapping capabilities for samples as large as 10 cm x 10 cm.

Applications

- **Material parameters.** Including the determination of composition, crystallinity, temperature, electronic structure, and other variables that affect optical properties.
- **Thickness of thin films and multilayer structures.** Including the determination of thickness, interface roughness, and homogeneity in multilayer structures with thicknesses from sub-monolayer to tens of micrometers.
- **In-line or in-situ monitor of the growth and processing.** Monitoring of bulk or thin-film materials in real time inside the growth or processing chamber.

CAPACITANCE TECHNIQUES

These techniques monitor the movement of electronic charge within a semiconductor device and provide a measure of free-carrier and electrically active defect-state properties. Measurements are taken of the charge storage capacity, or capacitance, across a rectifying junction.

- Capacitance-voltage (C-V) measurements determine the concentration of majority carriers in the bulk of the device, and/or energy levels of interface states that often exist between the surfaces of dissimilar materials
- Deep-level transient spectroscopy (DLTS) examines the time-dependent flow of charge into and out of localized energy states associated with defects in the semiconductor. DLTS can detect trap concentrations as low as 10^{12} cm^{-3} and as high as the doping level (constant-capacitance DLTS); distinguish between minority- and majority-carrier traps; determine activation energy

and capture cross-section. Our capabilities allow the use of electrical or optical pulses to fill traps and a sample temperature range of ~20 to 475 K. DLTS is a nondestructive complement to secondary-ion mass spectrometry and Auger electron spectroscopy.

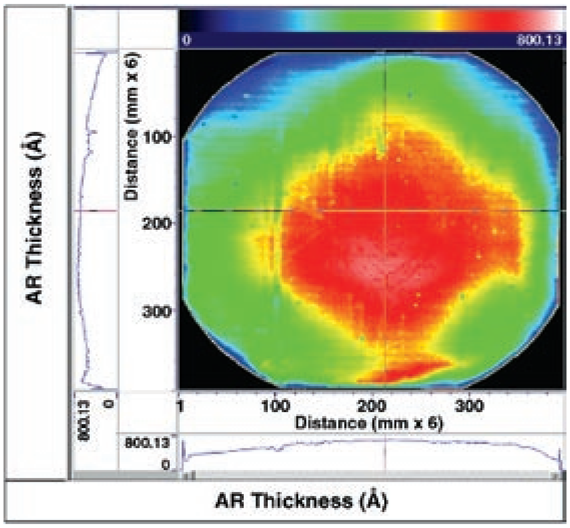
- Admittance spectroscopy is used to characterize defect levels by measuring capacitance with varying frequency and temperature.

SCANNING DEFECT-MAPPING SYSTEM

Defect mapping uses optical scattering to quickly and accurately map defect distributions in silicon semiconductor wafers. To map defects, a wafer is first treated with an NREL-developed etch of hydrofluoric, acetic, and nitric acids to enhance the light scattered by the defects. The scanning defect-mapping system (SDMS) moves the treated wafer across a stationary laser beam and maps the defects for each location on the wafer. The amount of light reflected from an area is proportional to the dislocation density for that area and provides a direct statistical count of the number of dislocations.

Applications

- **Dislocation mapping.** Quickly and accurately maps dislocation defects in silicon wafers.
- **Grain-boundary mapping.** Quickly and accurately maps grain boundaries in silicon wafers.
- **Photovoltaic response mapping.** The photocurrent maps may be compared with the dislocation and grain-boundary maps to show the effect of defects and crystalline discontinuities on photovoltaic response.
- **Reflectance mapping.** The SDMS can also map the reflectance of a completed cell (i.e., the amount of light that does not penetrate the cell). By mapping reflectance, the SDMS can calculate a cell's performance based on the light actually absorbed by the cell, which is a better measure of the effectiveness of the cell material.
- **Minority-carrier diffusion length.** The SDMS can measure the minority-carrier diffusion length—the average distance traveled by light-generated electrical carriers—in a completed solar cell.



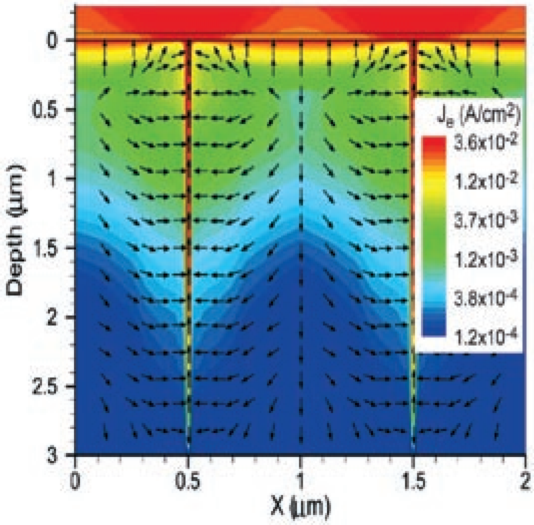
Antireflection film thickness is one of many parameters that can be mapped quickly and accurately.

REFLECTANCE SPECTROSCOPY

The PV Reflectometer measures the reflectance spectrum of an entire wafer or cell, up to 6-in. x 6-in. The measured reflectance plots are deconvolved to derive physical parameters including surface roughness and texture, antireflective coating thickness, metallization area and height, and backside metallization properties. The PV Reflectometer makes the entire measurement in a fraction of a second.

COMPUTATIONAL MODELING

Solar cell models generally have been limited to one dimension and primarily have focused on current-voltage curves and quantum-efficiency spectra. At NREL, we can simulate two-dimensional solar cells, as well as many electro-optical measurements such as time-resolved photoluminescence, electron-beam-induced current, near-field scanning optical microscopy, and photoconductive decay.



Computational modeling sheds light on the effect of grain-boundary potential on short-circuit current.

In addition, PV Optics is a software package developed at NREL specifically for designing solar cells and modules. It uses a combination of wave optics and ray-tracing techniques to handle thin-film solar cells, wafer-based cells, and the entire module (including non-planar or textured interfaces). PV Optics can be used to optimize the optical performance of single- and multijunction cells and modules. We are also developing a new software package for a simplified electronic design of single- and multicrystalline silicon solar cells. This package will eventually be combined with PV Optics to yield a robust, accurate design package for all solar cells and modules.

TECHNIQUE DEVELOPMENT

Drawing on the diverse expertise and deep experience of our team members, we are extending existing techniques and developing completely new ones to address particular issues related to materials or devices. Two current examples are the following:

- Lifetime mapping of multicrystalline silicon wafers with ~1-mm resolution requires increased sensitivity beyond measuring a large sample area. As-grown, unprocessed multicrystalline silicon wafers tend to have microsecond lifetimes, so sensitivity

ELECTRO-OPTICAL CHARACTERIZATION TECHNIQUES/CAPABILITIES

Technique/ Capability	Typical Applications	Detection Range	Temperature Range	Non-Destructive?	Image/ Mapping?
Photoluminescence spectroscopy	Determine bandgap, material quality. Identify defects	0.4–2.7 µm	4–300 K	Yes	Yes
Minority-carrier lifetime spectroscopy	Measure minority-carrier lifetime, surface recombination. Determine dominant recombination mechanism	Optical: 0.4–1.0 µm with $2x10^{-11}$ s resolution Optical: 0.4– >2.0 µm with $1x10^{-13}$ s resolution PCD: $5x10^{-9}$ s resolution	4–300 K	Yes	Yes
Fourier-transform infrared (FTIR) and Raman spectroscopy	Identify contaminants. Analyze reaction in situ. Measure impurity concentration, inhomogeneity	1.3–100 µm	8–300 K	Yes	Yes
Scanning ellipsometry	Determine film thickness, crystallinity, composition, roughness, temperature, optical and electronic properties	0.2–1.7 µm	Room temperature	Yes	Yes
Capacitance techniques	Measure carrier concentration profiles, interface state density, deep-level properties	Quasistatic to 100 MHz frequencies	77–360 K	Yes	Yes
Scanning defect mapping	Map dislocation and grain-boundary distributions in silicon wafers	10^3 to 10^8 defects/cm^2	Room temperature	No	Yes
Reflectance spectroscopy	Determine numerous solar cell physical parameters, including surface roughness, film thickness, metallization properties	Reflectance to 1% accuracy from 0.4–1.1 µm	Room temperature	Yes	Yes

improvements must still maintain adequate time response. We continue to research new sample coupling designs to improve measurement sensitivity and mapping speed of RCPCD. And we are also improving and adapting other lifetime measurement techniques such that lifetime can ultimately be used as a parameter for monitoring solar cell material in a manufacturing line and be useful for process control and performance feedback.


Jim Yost/PIX109869

We have developed photoconductive decay techniques to measure lifetime on materials with indirect bandgaps, small bandgaps, and long lifetimes using low-pulse-rate lasers or inexpensive flashlamp and LED light sources.

- As part of developing manufacturing diagnostics, we are working on high-speed methods for monitoring solar cell fabrication processes. We recently developed a technique to predict wafer breakage during solar cell processing. This technique can be valuable in screening wafers that tend to break during solar cell fabrication by a known process schedule.
- We developed PVSCAN, a high-speed optical scanning system that characterizes silicon solar cell materials and devices. Its output—spatial maps of dislocation density, grain distribution, reflectance, and photoresponses from near-junction and the bulk of a solar cell—helps crystal growers achieve high-quality material and process engineers develop processes for higher efficiency devices. PVSCAN was available from NREL for many years, but is now licensed for commercial manufacture to GTSolar (Nashua, NH).

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