NREL
Advances in Technology at the
National Renewable Energy Laboratory

Technology Brief

Everything You Ever Wanted to Know about Solar Cells and Materials

NREL-Designed Instrument Maps Inside Story of Photovoltaics Performance

Jim Yost / PIX 03916

PVScan 5000 photovoltaics analyzer (at left with cover removed) made by Labsphere utilizes NREL scanning defect-mapping technology plus reflectance and photoresponse mapping for comprehensive silicon wafer and PV cell analysis—shown with computer screen displaying a grain-boundary defect map.

Using National Renewable Energy Laboratory (NREL) technology, the PVScan 5000 photovoltaics analyzer maps several key performance parameters for completed solar cells and for the silicon wafers from which they are made. Previously, mapping these parameters without the PVScan 5000 was highly impractical and seldom done. Now, this easy-to-use instrument, commercially available at moderate cost, readily provides these valuable data. The PVScan may not tell you absolutely everything you want to know about your crystalline wafers or photovoltaic (PV) cells, but it does provide a wealth of essential information for determining why solar cells are as good as they are and what keeps them from being better.

It Chops, It Slices, It Dices

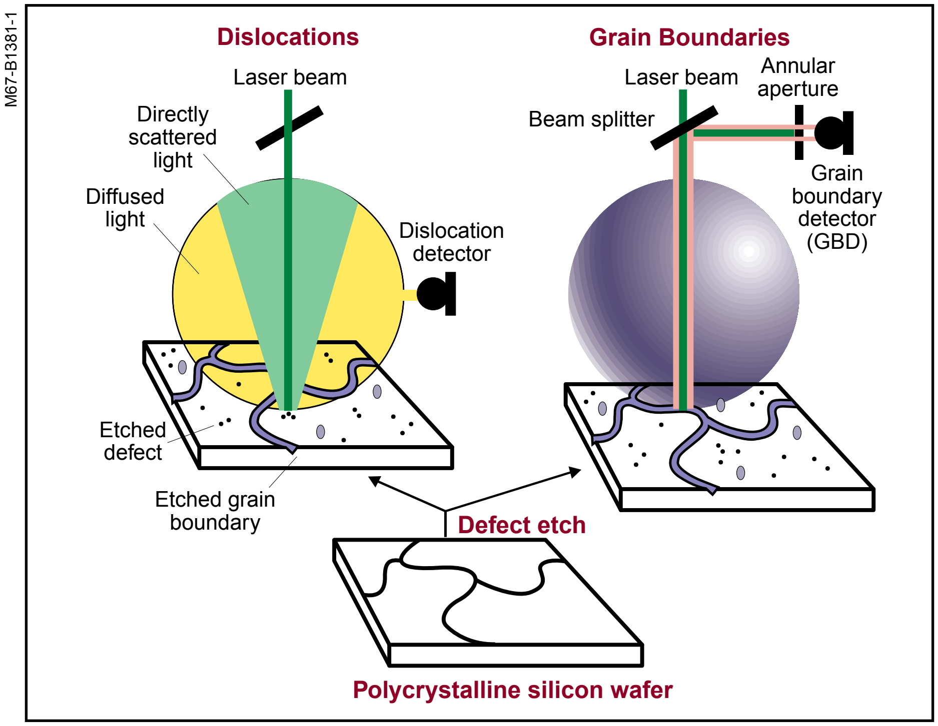
Take single-crystal or multicrystalline silicon wafers and apply a special etching solution. Put the etched wafers in the PVScan 5000 photovoltaics analyzer, and use its optical-scattering system to quickly map the defects in the material—one map for dislocations and one for grain boundaries. Use this defect-mapping information to adjust the crystal growth process. Etch and analyze the new wafers with the PVScan to assess the improvement.

Now, take a series of wafers made from adjacent slices of a silicon crystal—so they will be similar. Map the defects of some of the wafers with the PVScan and make PV cells from the rest. Use your new knowledge of where the defects are to minimize their impact. Incorporate gettering (to remove impurities), passivation (to reduce influence of defects), or other treatments into the cell-making process.

Next, put the finished cells in the PVScan 5000 photovoltaics analyzer. Its optical system will map the cells' surface reflectance—a major source of efficiency loss for PV cells that is often overlooked. Its laser-beam-induced-current (LBIC) scanner will map the photovoltaic response. Its computer will deduct the reflectance losses to produce an internal response map that tells the real story of how well the cell itself is operating. The PVScan 5000 will also map the minority-carrier diffusion length, a basic parameter of PV performance.

Mapping these key parameters without the PVScan 5000 was highly impractical and seldom done.

Finally, take the internal response maps and compare them with the defect maps of the raw wafers. Common patterns show how crystalline defects affect the performance of the finished cells.



In its defect-mapping mode for silicon wafers, the PVScan 5000 uses differentially reflected light to distinguish between defect types. After treatment with a special etch, dislocations scatter the incoming laser beam in a cone-shaped pattern which the PVScan captures with an integrating sphere (left). Grain boundaries reflect the beam nearly directly and the PVScan redirects a portion of that reflection to a separate detector.

Less than $50,000 to Identify Underlying Problems

Semiconductor crystal growers, solar-cell researchers, and solar-cell manufacturers have used a variety of tests to measure current, voltage, and other performance parameters. But until now, underlying problems could only be inferred from performance, and directly identifying limitations on performance was not possible. Correcting these underlying problems has become a particularly clear need in the last few years. Manufacturers now make cells that, in general, are fairly efficient—so defects and cell areas that generate limited power stand out as obstacles to improving performance. Also, recent research has shown that poor power-generation areas of cells act as current sinks, strongly reducing the performance of surrounding areas, as well.

Until now, underlying problems could only be inferred from performance.

Defects in the crystalline structure of silicon wafers are critical factors in how solar cells made from them perform. Knowing the distribution of defects allows various measures to be taken to limit their impact. Previously, mapping wafer defects was arduous and unreliable, but the PVScan 5000 makes it easy to produce reliable, easy-to-read maps. For completed solar cells, the PVScan readily maps photovoltaic response and surface-light reflection, and other key performance parameters that it derives from those two measurements. Such diagnostics for finished cells were previously not generally available in commercial instruments. The basic external photoresponse reading could be measured only by expensive scanning microscopes designed for other purposes, or by laboratories that built their own systems. None of the other PVScan 5000 diagnostics for solar cell performance could be measured at all. Now all of these diagnostic tools are available in a single, easy-to-use instrument from Labsphere, Inc., of North Sutton, New Hampshire. With a license for the technology from NREL, Labsphere is producing and selling the PVScan 5000 for less than $50,000. The PVScan 5000, a complete system that includes software, comes ready to be hooked up to a computer and color printer.

None of the PVScan 5000 diagnostics for finished cells were previously available in commercial instruments.

Mapping Defects Quickly and Accurately

The PVScan 5000's capabilities are built around the scanning defect mapping system (SDMS)—a winner of the prestigious R&D 100 Award. The key to this optical-scattering technology was finding a way to distinguish between grain boundaries and dislocations. The former are boundaries between separate grains in multicrystalline silicon, and the latter are breaks in the crystal pattern within an individual grain.

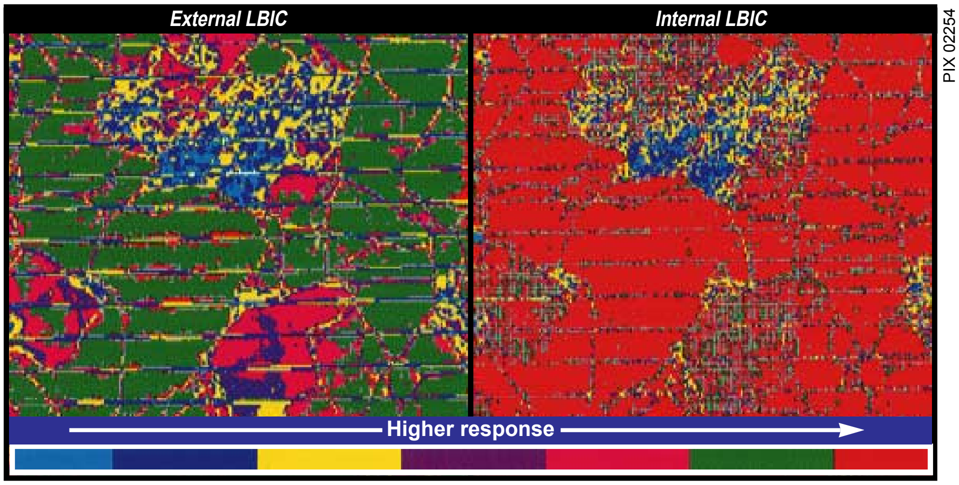
To assess defects in a wafer without the SDMS, the sample was etched to accentuate defects by producing etch

Some PVScan 5000 Advantages

- Produces precise, easily readable color maps of
  - The dislocations and grain boundaries for silicon wafers
  - The reflectance, minority-carrier diffusion length, and external and internal LBIC response for completed solar cells
- Internal LBIC map gives a picture of how a cell really performs with the light actually available to it
- Operators with minimal training can make a defect map of a 10-cm x 10-cm (4-in x 4-in)(solar-cell-size) wafer in 1 hour; conventional techniques would require between 2 weeks and 2 months of effort by highly skilled personnel using expensive equipment
- Designed for etch that works at room temperature in 30 seconds (versus several hours for some other etches) and has no metals to contaminate work area

pits at the defect sites, and then the etch pits were counted under an optical microscope. Even with a computerized image analyzer, this process was slow, tedious, expensive, and unreliable. Other methods, such as X-ray topography and transmission electron microscopy, are not suitable for multicrystalline substrates.

NREL researcher Bhushan Sopori, an expert in optical testing, had long been convinced that an automated system for assessing defects could be built with optical collectors and sensors. The problem—particularly for multicrystalline materials, for which the need was greatest—was that grain boundaries would overshadow dislocations. Sopori found the answer by developing a special etching solution. Hydrofluoric, acetic, and nitric acids, in a ratio of 36:15:2, produce V-shaped grooves at grain boundaries and circular or elliptical etch pits at dislocations.



"External" (left) and "internal" (right) laser-beam-induced-current (LBIC) photoresponse maps made by the PVScan 5000. By mapping reflectance and adjusting the external LBIC readings to consider the amount of light that never actually penetrates a solar cell, the PVScan can map the internal LBIC response that more accurately represents the capabilities of the cell design. Note that while the internal LBIC map has generally higher response, it also has a more uniform response. Weaker areas in the lower half of the cell—that might otherwise be attributed to other problems—are shown to be the result of reflectance (probably caused by grain orientation). Only the one area in the upper center (probably caused by a dislocation cluster) remains substantially weak in the internal map.

The grooves produced at the grain boundaries scatter light in a streaklike shape perpendicular to the length of the grain boundary. The etch pits produced at the dislocations scatter light primarily in a well-defined cone with an angular spread of about 20 degrees.

The SDMS—and now, the PVScan 5000—moves the wafer across a stationary laser beam and maps the defects for each location on the wafer. An integrating sphere (the inside surface of a hollow sphere) collects the diffuse light scattered by the etch pits and directs it to a detector. Because the etch pits all have the same optical scattering cross-section, the amount of light reflected and detected from an area is proportional to the dislocation density for that area and provides a direct statistical count of the number of dislocations. Part of the streaks from the grain-boundary grooves that reflect close to the direction of the incoming light passes back out through an opening in the integrating sphere and is directed to a separate detector that maps the grain boundaries.

The precise, easily read defect maps produced by the PVScan are invaluable for improving crystal-growth processes and for manufacturing an economically competitive silicon

Definitions

single crystal/multicrystalline — Silicon and other semiconductors used for solar cells and microelectronics are crystalline in structure. Single-crystal material consists of one grain of continuous crystal structure. Multicrystalline material has many separate grains. Minority-carrier flow—which is basic to the photovoltaic effect—takes place more readily within a crystal or grain than across grains of multicrystalline material.

recombination centers — The minority carriers generated in a solar cell by incoming light produce the useful current that delivers power to the external system. Impurities and irregularities or defects in the lattice structure of a crystal reduce minority carrier flow by allowing recombination with majority carriers, thereby reducing external power delivery.

grain boundaries — These surfaces between crystal grains generally contain many recombination centers. They therefore can reduce the photovoltaic efficiency of a solar cell.

dislocations — These linear breaks (defects) in the crystal lattice also act as recombination centers and reduce performance.

impurities — Undesired materials within the silicon (or any semiconductor) act as recombination centers. Concentrations of impurities can be reduced to extremely low levels, but this substantially increases material cost.

gettering — The most frequent way to reduce impurity levels in silicon wafers or substrates is by gettering. Typical gettering processes for solar cells heat the wafer either after depositing a layer of aluminum or treating the surface with phosphorus. This causes the impurities to migrate out of the silicon and into the gettering layer, where they have relatively little impact on cell performance.

passivation — One way to treat solar cells to reduce impact of grain boundaries and dislocations is passivation. Heating the cells in the presence of material such as hydrogen or oxygen causes the added element to migrate to the defects and attach to loose bonds, thus reducing the number of recombination centers.

minority-carrier diffusion length — The average distance that a minority carrier will travel within a semiconductor before recombining is a key measure of performance of semiconductors and solar cells.

LBIC — Laser-beam-induced current (sometimes referred to as OBIC—optical-beam-induced current) is a technique for mapping photoresponse by illuminating small areas and measuring current output (alternative EBIC or electron-beam-induced current).

internal/external LBIC — The current produced by laser scanning is the "external" photoresponse. By also mapping reflectance, the PVScan 5000 can calculate and map a solar cell's performance on the basis of the nonreflected light that actually reaches the cell. This "internal" response is a better measure of the effectiveness of the material.

integrating sphere — This optical device uses the inside surface of a spherical shell to collect diffuse light for detection.

solar cell. Dislocations indicate thermal stress during growth, and the distribution of defects—not just the total number of defects—determines the cell's conversion efficiency. Defect mapping has also produced important findings that apply to the manufacture of all silicon PV cells. Using the PVScan, Sopori's research team showed that although gettering to remove impurities—one of the most frequent treatments for PV cells—is generally helpful for the rest of the cell, it is not very effective where there are major defect clusters. Thus, two top priorities for research and development for the entire industry are to (1) improve crystal growth to avoid developing defect clusters and (2) improve cell processing to passivate defect clusters that do develop.

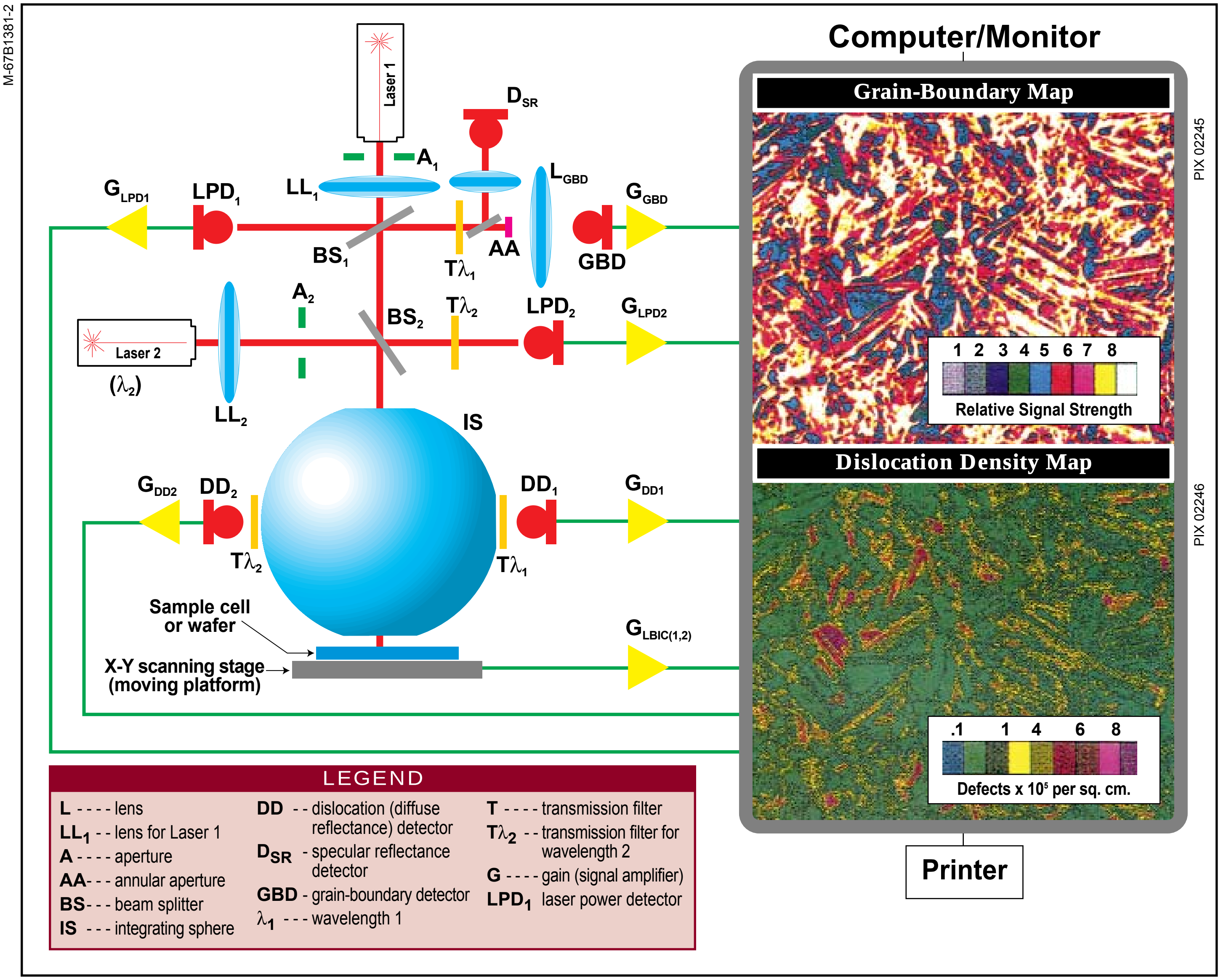
From Wafer Defects to Cell Performance

The scanning defect mapping system successfully collected and mapped both diffuse light (scattered by

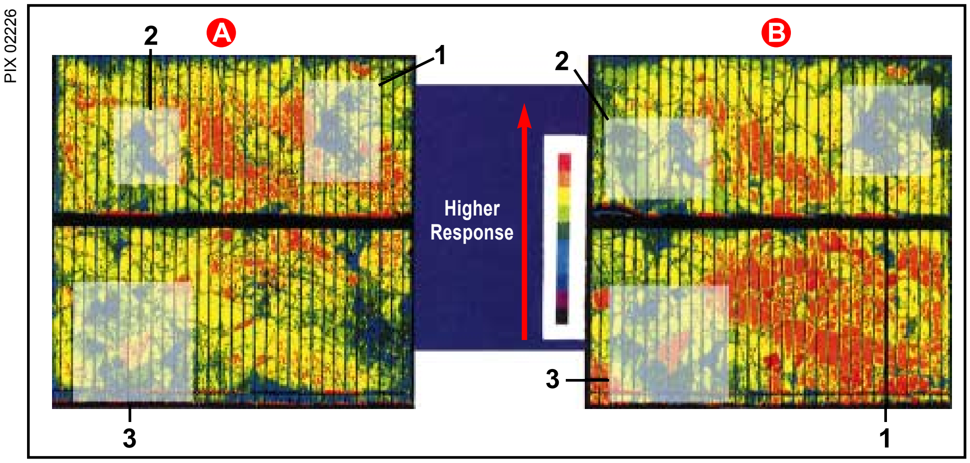
SPECIFICATIONS FOR THE PVSCAN 5000 PHOTOVOLTAICS ANALYZER

Laser wavelengths	633 nm; 905 nm
Sample spot size	0.5 mm
Maximum scan area	4.0“ x 4.0“
Maximum sample size	4.0“ x 4.0“
Scanning-step sizes	0.0001“ - 0.010“
Typical scan time*	1 hour
Data rate	100 kHz
Maximum data file size*	4.5 Mb
Dimensions	(W) 25 “ x (D) 24 “ x (H) 26 “
Shipping weight	200 lbs.
Input power requirements	105 -120 VAC; 50/60 Hz
Computer requirements	Windows™ 3.1; 4 Mb RAM

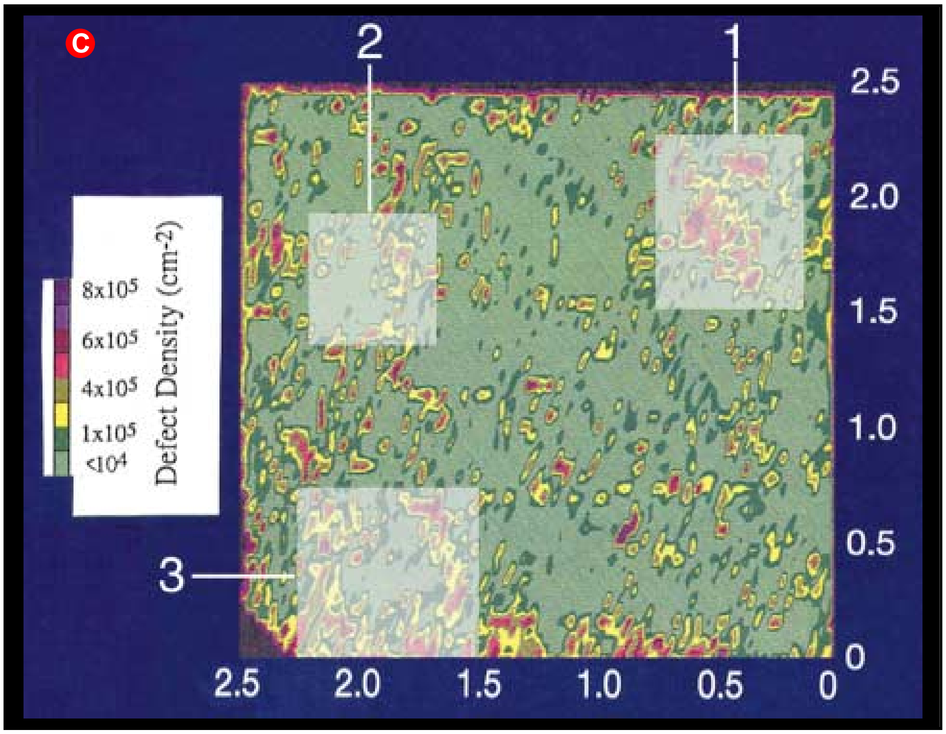
*at typical sample size and typical scanning-step size



Basic schematic diagram of the PVScan 5000. For silicon wafers, the PVScan uses Laser 1 (638 nanometer). The light reflects differently off the dislocations and grain boundaries (shown on the "screen" of the diagram) of the specially etched wafers and is captured for mapping by two separate detectors. For completed solar cells, the PVScan uses both Laser 1 and Laser 2 (905 nanometer) to generate two separate photoresponse maps. The shorter-wavelength Laser 1 produces response near the cell surface only, Laser 2 from the bulk of the cell. The PVScan also measures relectance, which it can automatically factor in to map the internal or true performance of a solar cell.



Photocurrent maps (**A**) control cell, and (**B**) gettered cell, showing regions of unchanged and improved responses due to gettering and dislocation density map (**C**) of the silicon substrate from which the cells were made.



By using wafers from adjacent—and therefore similar—slices from a silicon boule, the PVScan 5000 can be used to analyze the effect of defects and cell-processing techniques. Note that while the gettered solar cell (B) performs significantly better than the control cell (A), there are poor performing areas of both cells that correspond to the defect clusters highlighted as areas (1), (2), and (3) in the silicon wafer (C) and that these areas did not improve that much with gettering. The frequently high concentrations of impurities in defect clusters and the ineffectiveness of gettering in removing them underscores the need to ameliorate defects as a first step in processing. This key finding was made possible by PVScan technology.

dislocation etch pits) and directly reflected light (nearly perpendicular reflection from the grain-boundary grooves). This suggested that it would also be possible to tackle reflectance—with its diffuse and direct components—a key analytical need for finished solar cells. And Labsphere, with its expertise in reflectance and light measurement, responded with interest to publicity about the SDMS. So the stage was set to use SDMS technology to measure and map total reflectance from solar cells. This, in turn, opened the door to develop a powerful instrument for analyzing finished solar cells.

Mapping photovoltaic response to measure solar-cell performance requires: a highly focused light or energy source, a scanning system to either move the light across the cell or the cell across the light beam, electrodes and an amplifier to measure the electricity generated by each spot as it is illuminated, and a computer system to record and map the response for each spot on the cell. The laser scan and computer mapping for an LBIC photovoltaic response system were already part of the SDMS. All that was needed was to add amplifiers to measure the current output from the electrodes of the test cell and to feed it to the computer for mapping. PVScan also adds a second laser with a wavelength of 905 nanometers, which is more appropriate for measuring PV current response and minority-carrier diffusion length.

The PVScan's reflectance-mapping capability then made possible an important additional step. Because reflectance is a major cause of efficiency loss for solar cells, LBIC measurements indicate their final or "external" performance. But the picture of what is actually going on inside the cell is somewhat clouded. By combining LBIC readings with reflectance losses, PVScan calculates and maps "internal LBIC" response. This internal LBIC assessment shows how well the cell performs as a function of nonreflected light that it actually receives—the core information for efforts to improve cell performance.

Finally, the PVScan also maps the minority-carrier diffusion length of the cell. This is the distance that light-generated electrical carriers will travel through the material—a key performance indicator in PV research and analysis. The scanner can map diffusion length because the beam from the 905-nanometer laser penetrates the cell, and because the local internal response of the cell is proportional to the diffusion length. Minority-carrier diffusion length could previously be measured in wafers, but the PVScan is the first instrument able to measure it in completed solar cells.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The PVScan 5000 photovoltaics analyzer is an easy-to-use, moderately priced instrument that quickly maps several key performance parameters for solar cells and for the silicon wafers from which they are made—parameters that were previously unavailable or obtainable only with great difficulty.

Many Uses for Silicon PV — Uses for Other Materials to Come

Labsphere is manufacturing and marketing the PVScan 5000 and has already demonstrated it in Europe and the United States. The machines are available now, and every crystal growth, PV research, and PV manufacturing laboratory will find numerous uses. Under a cooperative agreement in conjunction with the license, NREL continues to work with Labsphere to further improve the PVScan and to explore additional uses. One possible use—quality control of surface contaminants on microelectronic wafers and devices—has an enormous potential market.

The machines are available now, and every crystal growth, PV research, and PV manufacturing laboratory will find numerous uses.

Several PV and microelectronic industries are interested in using the PVScan technology for other crystalline materials such as gallium arsenide and germanium, and NREL expects to work soon on developing the appropriate etches and other modifications necessary to meet that interest. NREL already uses the PVScan as an integral part of its cooperative projects with PV manufacturers to improve their products.

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Patents and Publications

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