

Changing the Face of Energy

Renewables for the 21st Century

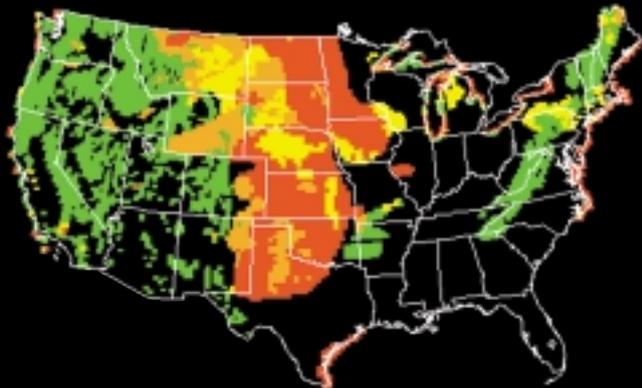
At the dawn of the millennium, humanity is faced with expanding economies; growing populations; spiraling needs for food, shelter, and goods; and burgeoning demands that burden Earth's ecosystems.

Underlying these trends is the increasing demand for energy—a demand that intensifies the world's growing predicament. In the last 20 years the world has increased its consumption of energy by over 40%, to more than 390 quads of energy per year. More than 85% of this comes from fossil fuels. Although fossil fuels have long driven the engines of economic growth, ominous consequences of their use are becoming apparent—dwindling supplies, acid rain, air pollution, and an alarming increase in atmospheric carbon dioxide, which portends grave repercussions in the form of global warming.

But imagine a world that is clean, beautiful, and bountiful. In which each nation has sufficient, inexhaustible sources of energy. In which energy for human enterprises is derived from renewable sources—nonpolluting and clean—and returned to the ecosystems for regeneration.

Such a world can be more than imagination. It is a definite possibility that daily stares us in the face in the sunshine, wind, plants, and even in the water that surrounds us.

At the National Renewable Energy Laboratory, we do more than simply imagine such a world. We explore its phenomena, synthesize the materials that exploit the phenomena, model the devices,



With today's wind energy technology and just a moderate use of land, the wind resource in the Great Plains states could supply the nation with more than one-and-a-half times the electricity it currently uses. In this map, areas with the strongest wind resources are shown in red.

Nevada's solar resource alone could provide enough energy to generate all of the nation's electricity. This would require only a 100-mile x 100-mile area with 10%-efficient PV systems installed.

engineer the systems, and develop the technologies that will help replace today's fossil fuel reality with the sustainable and clean world that all of us imagine. **Physics** is at the core of making this transition to a renewable energy world.

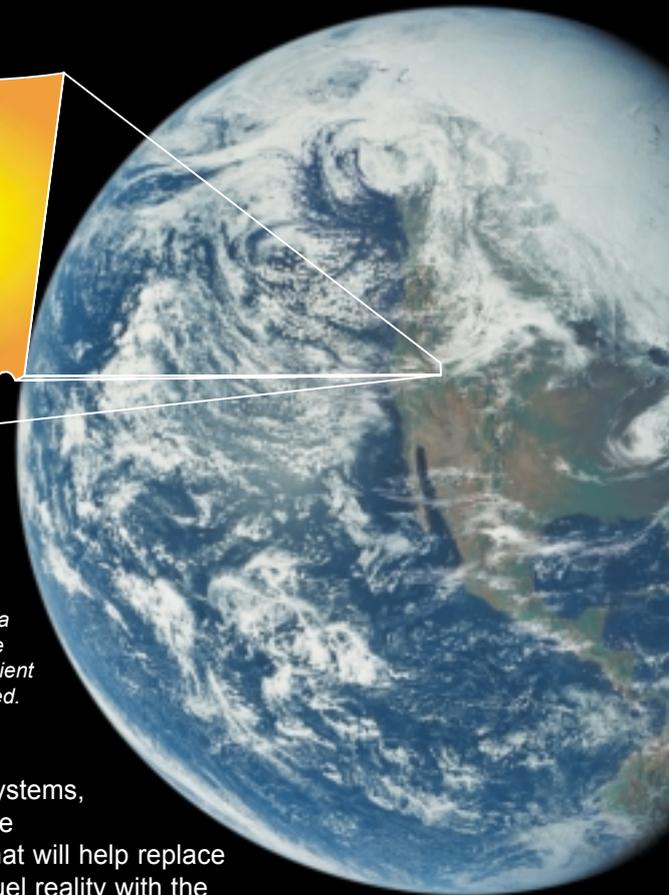
The interaction of light and matter

From the time of Newton, through the formulation of electromagnetism, through Einstein's conceptualization of relativity, to forging the foundations of quantum mechanics, light and matter and their interaction have lain at the heart of physics.

This role of light/matter interaction in physics will continue to dominate in the 21st century. In astrophysics and cosmology, it will provide an ever-deepening comprehension of the universe. In solid-state physics, it will give rise to optical discs and high-speed optical computers. And in our understanding of renewable energy sciences, it will spawn a revolution. At the vanguard of this revolution will be scientists from the National Renewable Energy Laboratory.

To the casual observer, solar phenomena may appear deceptively simple—photons interact with the atmosphere and biosphere to heat the earth, create the winds, fill the reservoirs, and grow the plants. But exploring the phenomena to advance sustainable technologies for generating, transmitting, and storing energy demands all the tools, techniques, and intellectual prowess of modern physics.

In this quest, NREL scientists pursue disciplines ranging from materials science to structural dynamics to condensed matter physics. In the process, their endeavors weave an intricate tapestry that deepens our understanding of the interaction of light and matter and that elevates the sciences and the well being of humanity.



Materials Synthesis & Characterization

A variety of materials—including photovoltaic, photoelectrochemical, and electrochromic materials—react with sunlight to produce electricity, to darken glass in the presence of sunlight, and to split water into oxygen and hydrogen. The challenge is to synthesize materials with optimal properties that can best exploit the phenomena.



Among the techniques NREL scientists use to synthesize materials are: an NREL-customized system that combines MBE, MOCVD, and in situ analysis to make III-V photovoltaic materials; and pulsed laser deposition, which is used for depositing a variety of thin films.

To meet this challenge, NREL scientists explore and develop state-of-the-art techniques for growing thin films. They devise original methods for synthesizing high-efficiency materials ranging from elementary silicon to more complex semiconductors—methods that enable them to precisely control important material properties. And they investigate novel materials, including nanoscale precursors and quantum dots for boosting conversion efficiencies; high-temperature superconductors for transmitting and storing energy; and carbon nanotubes for storing hydrogen.

Other NREL scientists analyze the synthesized materials to determine their defects, structure, and material, electrical, and optical properties. For these analyses, they employ proximal probe techniques, analytical microscopy, surface analysis, electro-optical characterization, and device-performance analysis to measure, image, and characterize materials from the atomic to the macroscopic scale. They also devise new techniques, and design custom instruments that allow them to move atoms around, perform nanoscale spectroscopy, and investigate nonequilibrium electron dynamics.



Used to analyze material surfaces, the static SIMS distinguishes elements and molecules whose masses range from 1 to >10,000 amu.

Device Physics

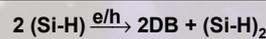
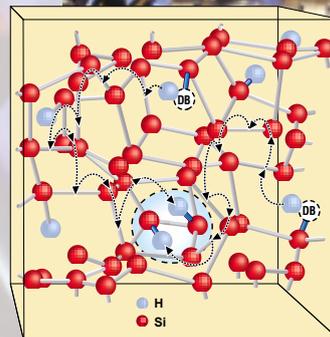
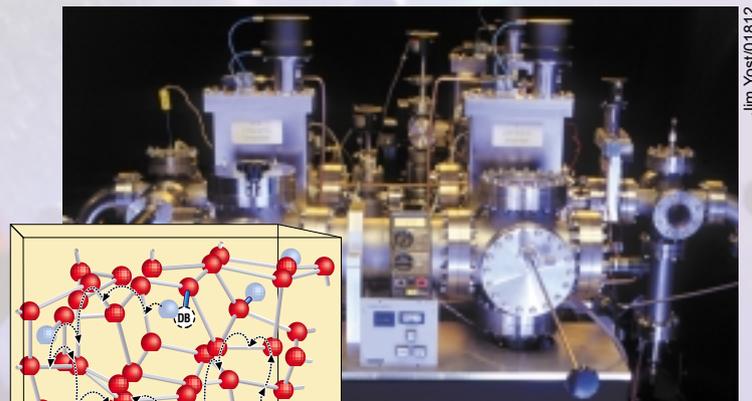
As world leaders in photovoltaic research, NREL scientists investigate a wide spectrum of devices, especially those based on silicon, II-VI, I-III-VI₂, and III-V materials and alloys.

For crystalline silicon, scientists explore silicon growth processes, investigate the role of impurities and defects, and model light absorption. For amorphous silicon, they devise new device structures, develop deposition techniques, and model causes of material instability.

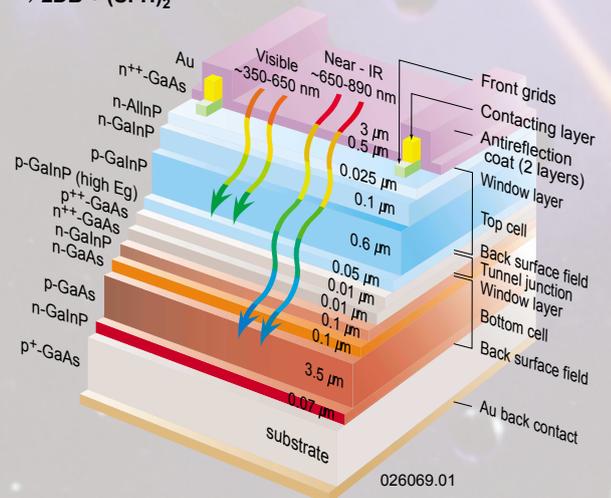
For I-III-VI₂ and II-VI materials—predominantly copper indium diselenide, cadmium telluride, and their alloys—they have pioneered devices with world-record efficiencies and have developed breakthrough methods for synthesizing stable, efficient devices.

They are using III-V materials to make some of the world's most efficient devices. One of these—a 30.2%-efficient device that uses a GaInP₂/GaAs, two-junction structure to effectively absorb high- and low-energy photons—is opening the door to 40%-efficient, four-junction cells.

They are synthesizing III-V materials with low-energy gaps, to make devices that convert IR photons to electricity. And they are exploring concepts that combine III-V photovoltaic structures with photoelectrochemical concepts and liquid interfaces—an approach that can be used to directly split water into oxygen and hydrogen with a record conversion efficiency of 12.4%.



Among NREL's efforts in amorphous silicon are: modeling studies to explain the material's "light-soaking" instability; and a customized hot-wire deposition system for improving the efficiency and stability of amorphous silicon materials.



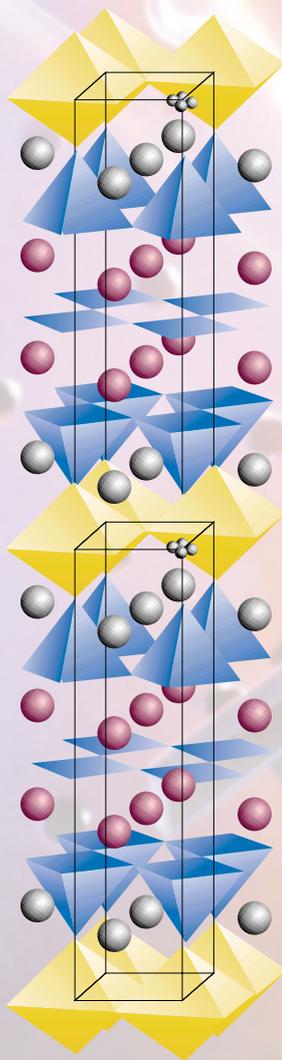
Device structure of 30.2%-efficient GaInP₂/GaAs two-junction PV cell. Success with this cell is leading toward three- and four-junction cells.

Physics at NREL

The Interaction of Light & Matter

Solid-State Spectroscopy

Researchers in solid-state spectroscopy employ state-of-the-art techniques to explore the fundamental mechanisms that limit the performance of photovoltaic, electrochromic, and superconductor materials. They also investigate devices with novel architectures and material compositions to optimize performance.

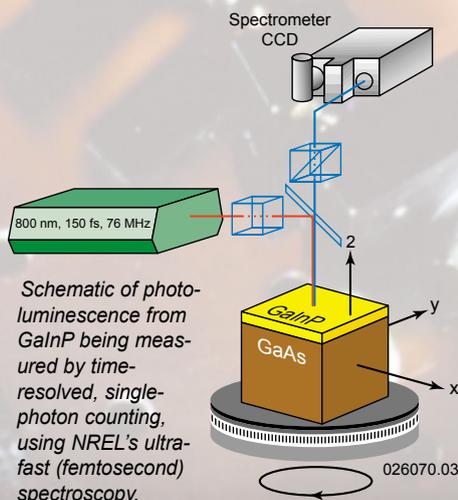


Atomic structure of single-layer, thallium-based high- T_c superconducting material being investigated by NREL researchers. This material exhibits favorable attributes—including a high transition temperature and promising superconducting properties.

A fertile research area is the spontaneous ordering that some III-V semiconductors exhibit under certain growth conditions. By controlling growth parameters, material properties can be adjusted for specific applications. Of particular interest is the ordering of GaInP_2 and its use in tandem photovoltaic cells—the study of which has involved Raman spectroscopy and spatially resolved photoluminescence, among other advanced techniques.

Researchers are also investigating minority-carrier lifetimes and carrier transport in CdS/CdTe heterostructures. These investigations involve ultrafast spectroscopy for time-resolved photoluminescence, continuous-wavelength spectroscopy to measure absorption over a wide spectral range, and scanning confocal microscopy to map out the spatial variation in photoluminescence intensity.

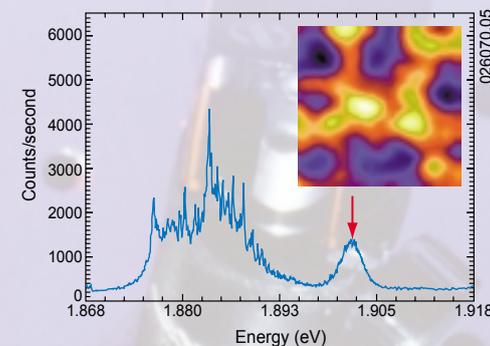
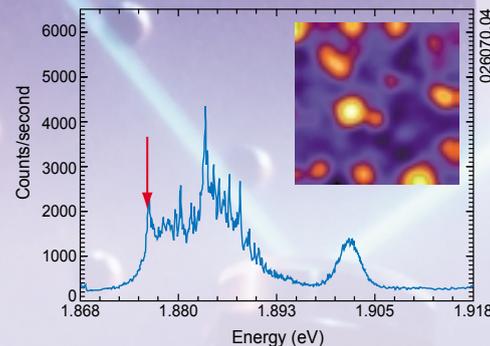
Other research topics include low-band-gap nitrides, which can be used



Schematic of photoluminescence from GaInP being measured by time-resolved, single-photon counting, using NREL's ultrafast (femtosecond) spectroscopy.

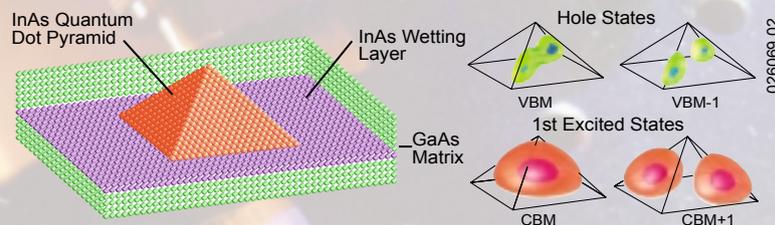
to lower the band gaps of ternary III-V alloys; composition modulation in semiconductor alloys, which offers possibilities for spatially separating free holes and electrons; and transition metal oxides, which make excellent cathodes in lithium-ion batteries.

Spatially resolved photoluminescence. Each frame shows the photoluminescence spectrum taken at the center of a 5- x 5- μm area of a GaInP_2 epilayer. Each inset shows the spatial variation in the photoluminescence at the indicated spectral energy.



Condensed Matter Physics

Investigating the theoretical foundations of photovoltaic materials, quantum nanostructures, and order-disorder phenomena in semiconductor alloys constitutes just some of NREL's research in condensed matter physics.

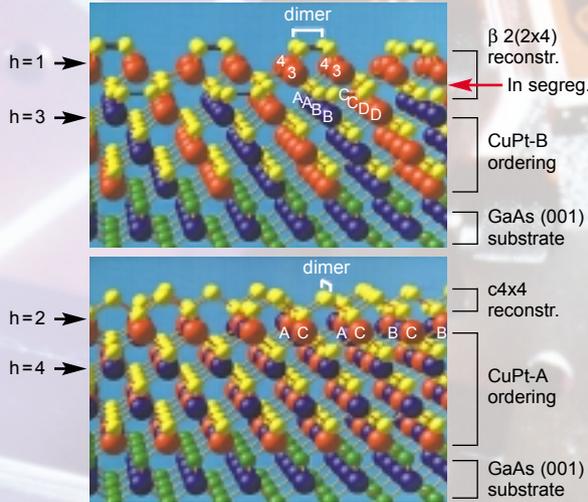


Pseudopotential calculations of the electronic structure of a pyramidal InAs quantum dot embedded in GaAs.

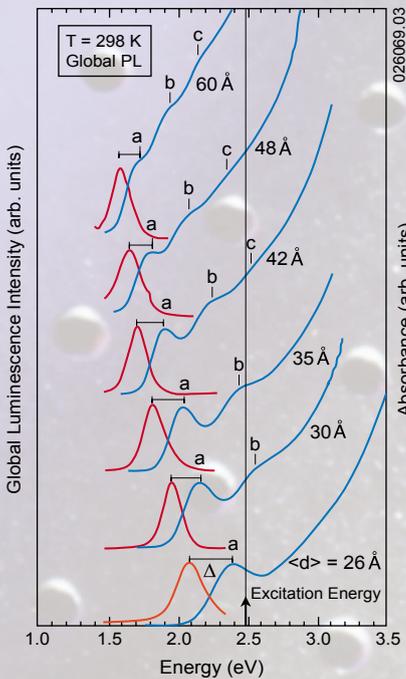
For photovoltaic materials, NREL physicists pioneered theoretical research into the material properties and electronic structure of chalcopyrite semiconductors, indicating increased conversion efficiencies through the addition of Ga to CuInSe_2 . Currently, this group is using first-principles electronic-structure theory to explain the nonstoichiometry of CuInSe_2 and the appearance of ordered-vacancy compounds.

The group also applies first-principles electronic-structure theory to explain why some III-V alloys exhibit spontaneous long-range order under certain growth conditions, whereas others undergo

Illustration of predicted lowest-energy configurations of a film of GaInP_2 ($\text{Ga} = \text{Blue}$, $\text{In} = \text{Red}$, $\text{P} = \text{Yellow}$) on a GaAs substrate ($\text{As} = \text{Green}$), showing the relationship among surface reconstruction, surface segregation, and subsurface ordering.



short-range phase transitions between order and disorder under other growth conditions. Their calculations show changes in material properties that depend on the order or disorder of the material, including changes in band gap and the anisotropy of effective masses of electrons and holes.



Absorption (blue) and emission (red) spectra of InP quantum dots show a shift toward higher energy with decreasing dot size.

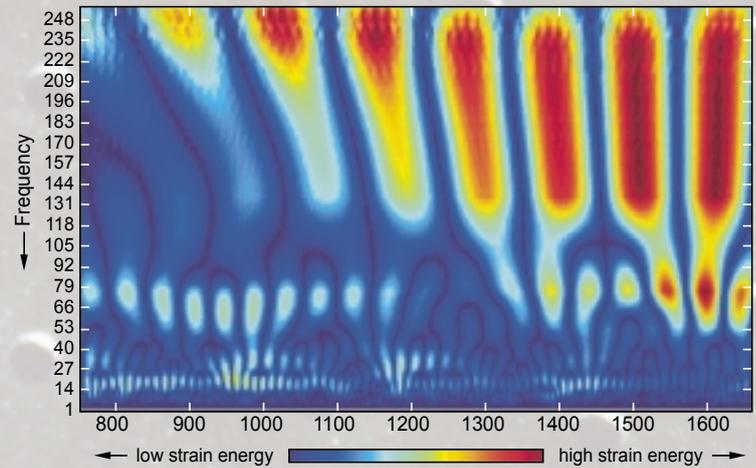
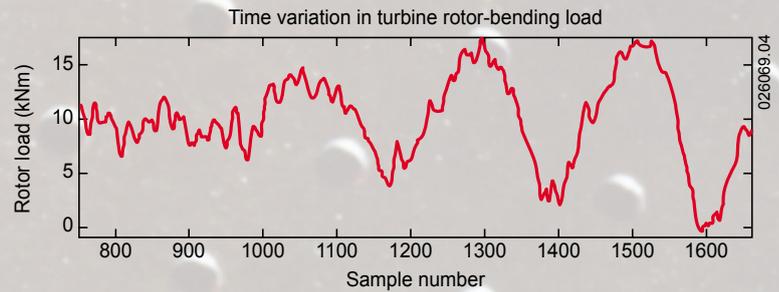
For nanostructures, NREL theorists use a variety of theoretical methods to calculate the electronic, optical-transport, and structural properties of semiconductor quantum dots.

Experimentalists are also investigating nanostructures, because of the range of possibilities for innovative architectures and increased efficiencies for photovoltaic and photoelectrochemical devices. Currently, their research focuses on the preparation, characterization, and applications of III-V quantum dots prepared through colloidal chemistry.

NREL physicists investigate the aerodynamic and aeroelastic response of turbine components to steady and unsteady airflow. The airflow creates deterministic and stochastic loads and vibrations throughout the turbine. The resulting structural deformations create fatigue in turbine materials, which must be designed to withstand fatigue cycles for 20 to 30 years.

The investigations translate into structural criteria for designing wind turbine components. For this task, researchers meticulously select low-cost, long-life materials tailored to the correct strength, stiffness, and fatigue life. And they take care to design components that will not operate at natural resonant frequencies—which could quickly destroy blades and machine.

To predict performance and failure modes and to facilitate the design process, researchers also develop computer models. Among these are ones that simulate turbulent inflow, and resulting rotor loads and blade fatigue. To agree with reality, the simulations include total system interaction under steady and unsteady wind conditions.

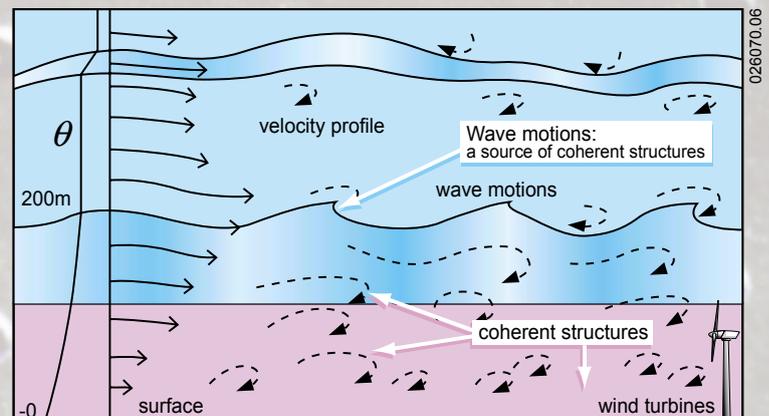


Wavelet analysis of rotor load transients shows the harmonic frequencies that correspond to the rotor-bending moment. The lower the harmonics (red areas), the higher the strain energy on the rotor.

Aero- and Structural Dynamics

To meet cost, lifetime, and energy demands, wind turbine components—especially rotor blades, drivetrain, and tower—must be well engineered. The rotor must capture large amounts of wind energy and convert it efficiently to electricity. This is a complicated task because of the elaborate intercoupling between aerodynamic forces and the structural dynamics of components.

Wind passing over components, especially the rotor, creates complex interactions. Turbulence or eddies contained in the wind vary in size, orientation, and strength. The interplay of these eddies with the rotor generates forces that may be many times those produced by steady winds.



At night, the boundaries between wind layers are typically stable and stratified, which keeps turbulence in the lower layers from being convected to upper layers. This can be destructive to wind turbines, because they operate in the lower layers.



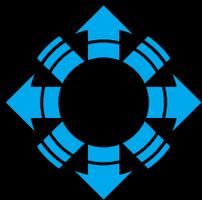
NREL Web sites:

National Renewable Energy Laboratory: <http://www.nrel.gov>

Center for Basic Sciences: http://www.nrel.gov/basic_sciences

National Center for Photovoltaics: <http://www.nrel.gov/ncpv>

National Wind Technology Center: <http://www.nrel.gov/wind>



NREL

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