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Annual Progress Report: Photovoltaics

FY 1985

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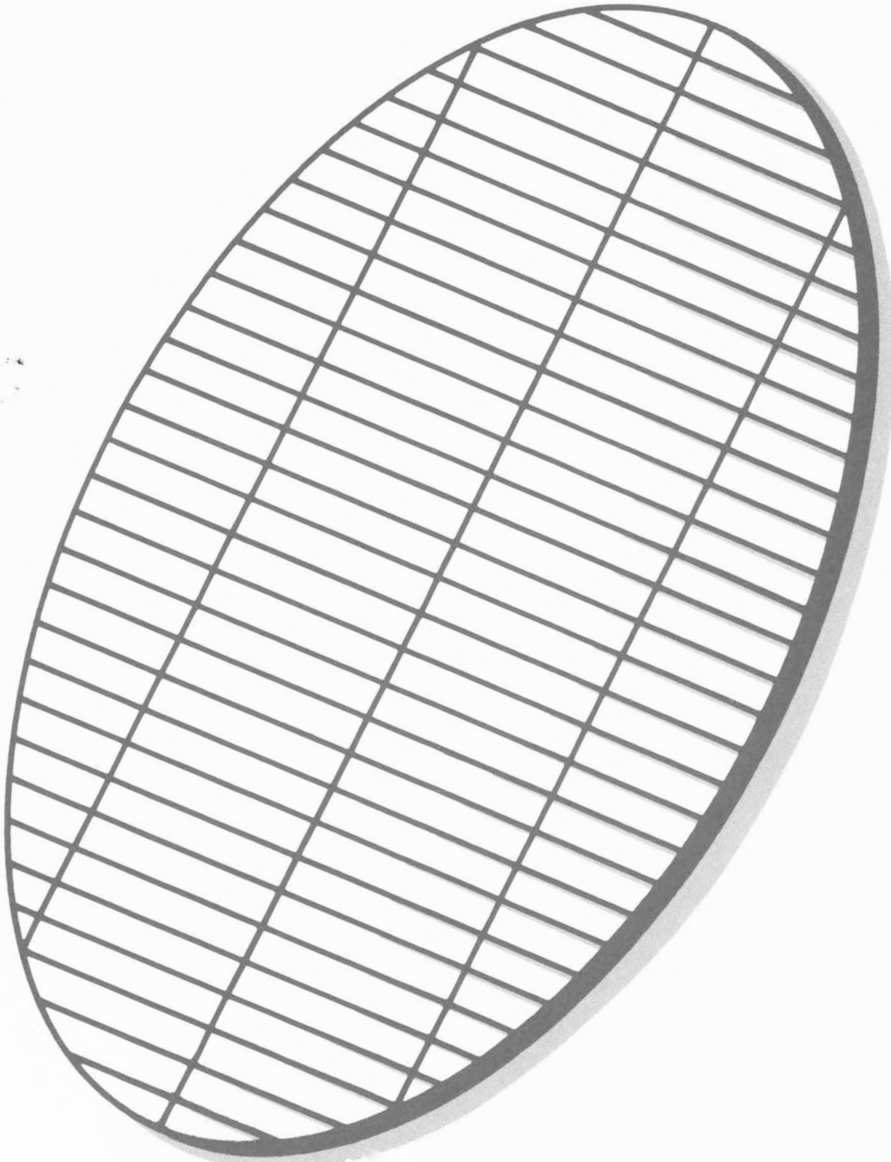
April 1986



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U.S. Department of Energy
Assistant Secretary, Conservation and Renewable Energy
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Prepared for:
U.S. Department of Energy
Assistant Secretary, Conservation and
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Washington, D.C. 20585

Prepared by:
The Solar Energy Research Institute
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Contents

Introduction

The Emergence of Photovoltaics

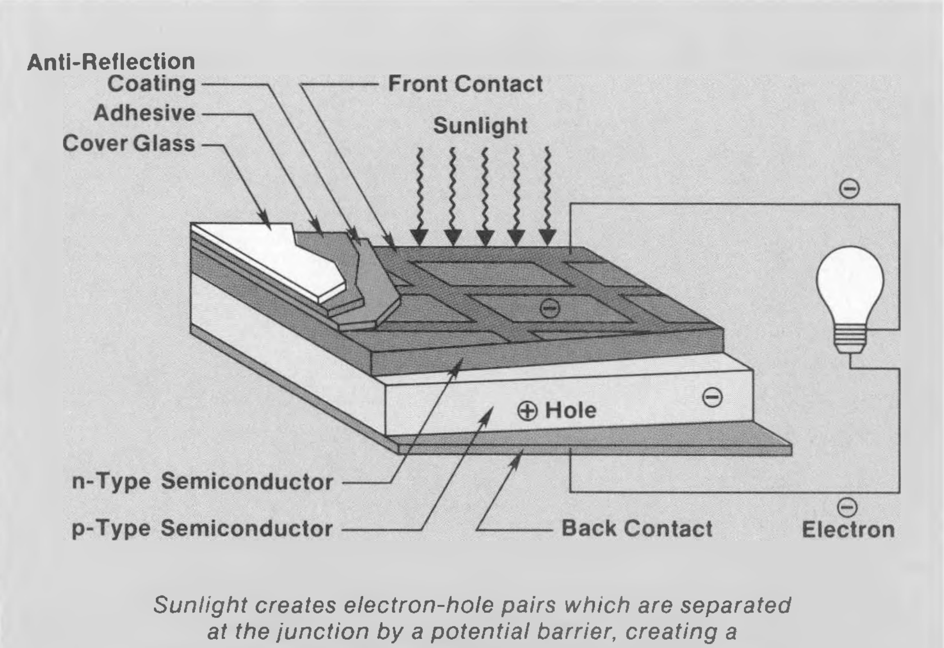
Everyone is touched by energy — the rich, the poor, the old, the young, individuals, groups, and nations. And all aspects of our lives are affected — information, health, shelter, work, entertainment, transportation, education, and the economy.

During the last century, the nation and the world have come to depend increasingly upon fossil fuels and other forms of conventional energy, including hydroelectric power and nuclear fuel. But these are just a portion of the world's potential resources and cannot be expected to carry the burden forever. Supplies will dwindle, demand will increase, costs will rise, and pollution will grow.

Renewable energy is needed to alleviate the pressures on conventional sources of energy, to help nations grow, economies stabilize, and the world to prosper. Solar energy is an integral partner in a healthy energy formula and photovoltaics (PV) is an important part of solar energy.

Photovoltaics, the direct conversion of sunlight into electricity, is one of the most promising of all solar energy technologies. And its modularity makes it extremely versatile. Photovoltaic power generates milliwatts to megawatts, runs wrist watches and giant central utility plants, and powers remote installations, residential systems and everything in between. Clean and nearly inexaustible, PV depends upon some of the most plentiful natural resources on earth, among which are sunshine and silicon. With these attributes, PV promises to play a leading role in America's energy future.

The basic building block of a PV system is the *solar cell*. This device is made from semiconductor materials which are treated (doped) with special elements that make the device sensitive to light. Sunlight striking the cell creates pairs of electrons and holes (chemical bonds missing electrons) in the semiconductor material. The free electrons and holes carry the electrical current through the cell. The junction (intersection) formed between dissimilarly-doped semiconductor layers sets up a potential barrier in the cell which separates the light-generated electrons and holes. (Otherwise electrons would fall back into the holes and no electricity would flow). This potential barrier induces an electric current and a voltage. In most cells, the electricity is collected by metallic contacts placed in a grid-like fashion on the surface of the cell. (In some thin-film cells, electricity is collected by a transparent conductive oxide film).



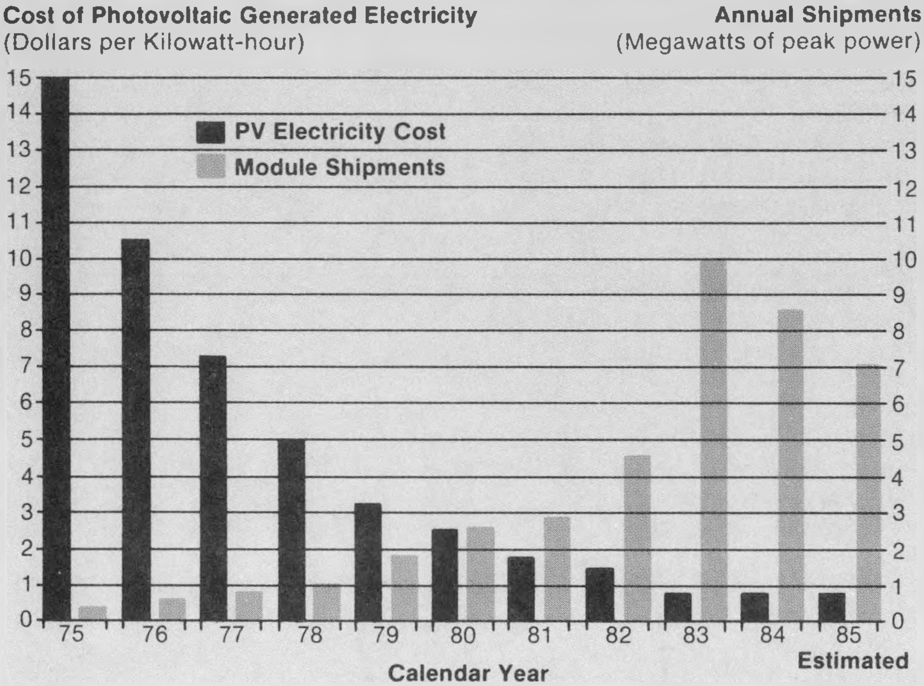
Sunlight creates electron-hole pairs which are separated at the junction by a potential barrier, creating a voltage that drives a current through an external circuit.

For higher voltages or currents, PV *modules* are formed by mounting groups of cells together on a rigid plate and connecting them in series (much like a battery) or parallel. For greater power levels, the modules can be connected in larger groups to form *arrays*. The direct current (dc) electricity generated by the PV array usually passes to a power-conditioning unit that converts the electricity to more commonly used alternating current (ac).

Photovoltaics has come a long way since 1839, when French physicist Edmund Becquerel first discovered the PV effect in a weak conducting solution. However, researchers didn't study it in a solid material (selenium) until the 1870s. The effect remained a laboratory curiosity until 1954 when Bell Laboratories made the first silicon PV cells. Though their first successful cell was only 4% efficient, within a short time they achieved an 11%-efficient cell. But, because of the high cost relative to the small amount of electricity generated, solar cells were not commercially feasible at that time. Further advances in PV technology awaited the U.S. space program. Solar cell technology, which has been part of the space program since its infancy, has powered space vehicles from early Vanguard satellites to contemporary space shuttle missions.

Solar cells came "back to Earth" during the energy crises of the early 1970s when the federal government started a program to develop alternative sources of energy, including PV. Since 1975 the federal government and the U.S. photovoltaic industry have pursued low-cost, high-performance PV systems.

Over the last ten years, the U.S. government has invested $750 million in long-range, high-risk PV research and development — R&D industry is unlikely to take on due to the costs and risks involved. Private industry, with millions of its own dollars, has undertaken near-term PV technology development and product commercialization. Together they are finding the



After its humble beginnings in the 1970s, the U.S. flat plate PV industry rapidly brought the cost of photovoltaic-generated electricity down to approximately $0.75 per kilowatt-hour, where it has remained for the past three years. Module shipments increased steadily until 1983, when abundant oil supplies began to curtail the PV industry's growth.

technical solutions required to establish PV as a long-term, competitive energy alternative.

This government-industry partnership has led to improved performance, reliability, and economics. The conversion efficiency of single-crystal silicon cells produced in the laboratory has surpassed 20%, while that of cells made from advanced thin-film materials has risen to over 11%. Flat-plate module efficiencies greater than 10% are now common. Modules now cost one-tenth of what earlier versions cost, while the useful lifetime of a PV system has increased tenfold. Life expectancies may reach 20 or 30 years in the near future.

These technological advances have spurred the market from its fledgling beginnings to one that is rushing past $200 million per year in sales and 10 MW of power per year in module shipments in the United States. Over 200 U.S. companies take part in some aspect of PV research, manufacturing, or marketing. Available products include a wide range of modules, control electronics, batteries, hardware, and many different functional systems.

PV systems for communication, rural electrification, water pumping, navigational aids, remote lighting, and hundreds of other applications have been sucessfully installed at thousands of locations around the world.

The National Photovoltaics Program

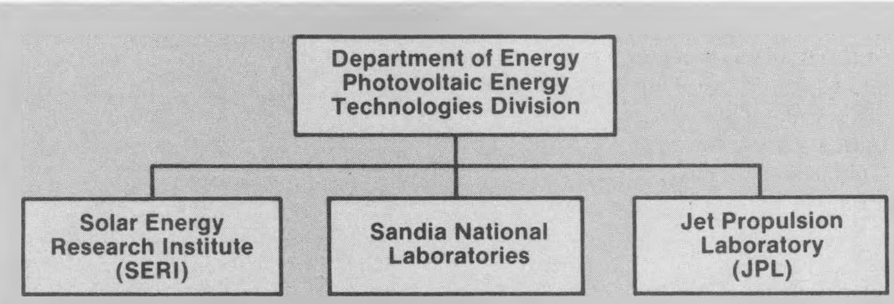
These achievements underscore America's world leadership in PV products and technology. In spite of this, the cost of PV-generated electricity remains too high and the conversion efficiencies too low for PV to compete effectively with conventional energy sources in many large electrical markets. To make PV more competitive, to maintain leadership and to keep the energy picture, the economy, and the PV industry balanced and healthy, greater technological advances must be made. Costs of PV-generated electricity have to be brought down considerably, while the conversion efficiency, reliability, and life expectancy of PV components and systems have to be substantially improved. This is the mandate of the **National Photovoltaics Program.**

The National Photovoltaics Program is managed by the Director of the Photovoltaic Energy Technologies Division at the U.S. Department of Energy (DOE). The Division helps define the Program and ensures that the Program conforms to national energy policy, priorities, and directives. With the advice of special PV advisory boards and participants from the Program, industry, and research, the Division establishes long-term technical goals to guide the Program toward successful completion of its mandate. Specifically, the Program

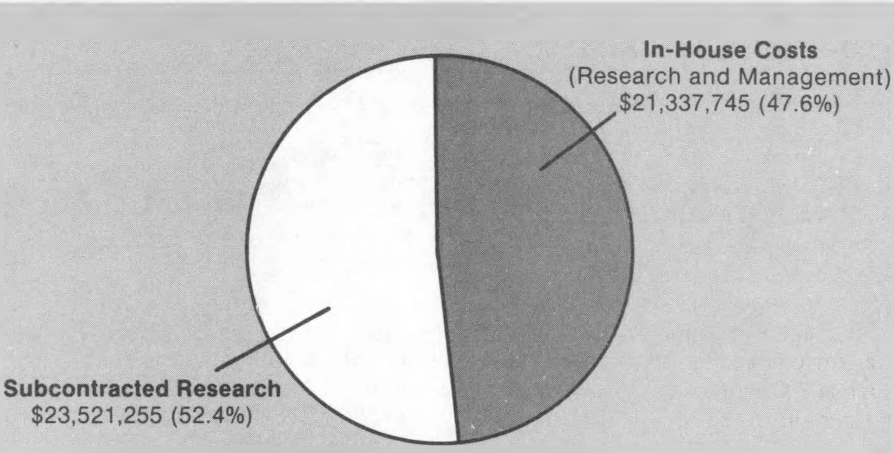
Long-Term (Late 1990's) Technical Goals[a]

Goals	Flat Flate Systems	Concentrator Systems
Module Efficiency[b]	13% - 17%	23% - 29%
Module Costs	$40 - $75/m^2	$90 - $160/m^2
Balance-of-System Costs		
Area Related	$50/m^2	$100/m^2
Power Related	$150/kW	$150/kW
System Life-Expectancy	30 yrs	30 yrs
PV Electricity Costs[c]	$0.065/kWh	$0.065/kWh

[a] 1982 dollars
[b] Measured at 28°C and AM 1.5
[c] Levelized constant 1982 dollars



Management structure of the National Photovoltaics Program under DOE.



Of nearly $45 million allocated to PV in FY 1985, over $23 million was awarded to industry, universities, and other private research entities. The rest went for in-house research and program management at the three participating research centers, SERI, Sandia, and JPL.

has devised an overall goal of improving PV systems to the point where, by the late 1990s, they could be used to generate electricity at a 1982-dollar cost of 6.5 cents per kilowatt-hour.

To achieve these long-range objectives, the National Photovoltaics Program divided the technology into three research phases: materials research, collector research, and systems research. Under each phase, the Program identified several research tasks, establishing five-year interim goals for each.

With *Materials Research,* the Program intends to overcome both theoretical and practical barriers which limit cell efficiency and increase the cost of PV cells. The theoretical conversion efficiency of PV cells is limited by the portion of the solar spectrum to which the cell's semiconductor material can respond and by the extent to which these materials can convert each photon to electricity. The practical efficiency is constrained by the amount of light captured by the cell, the cell's uniformity, and a variety of loss mechanisms for the photogenerated carriers. Cost is affected by the expense and amount of materials required, the complexity and efficiency of processes for forming films or sheets of the appropriate materials, and the complexity and efficiency of converting these materials into cells.

Under *Collector Research,* the National Photovoltaics Program is developing cell and module designs for flat-plate and concentrator collectors. In the long-term, this research will establish the technology which industry can apply to cost-competitive PV collectors. To achieve this goal, researchers identify and verify design and formation techniques which improve the efficiency and life-expectancy, and decrease the cost of cells and modules produced from the most promising materials and material configurations.

Success in establishing a technology base suitable for further development by industry requires verifying the performance of critical components and subsystems. To support this development, *Systems Research* verifies module and subsystem performance, tests these components again after they are integrated into systems, and identifies improvements in module and subsystem designs. This effort will increase the efficiency and life-expectancy of PV systems while decreasing their cost.

The ultimate responsibility for meeting the technical goals of the Program rests with three research centers: the Solar Energy Research Institute (SERI) in Golden, Colorado; the Jet Propulsion Laboratory (JPL) in Pasadena, California; and Sandia National Laboratories (Sandia) in Albuquerque, New Mexico. These centers manage daily research activities, both those performed in-house and those contracted to other institutions. To provide guidance for evaluating the progress and direction of research tasks, the centers also assist DOE in setting technical milestones and program assessment points.

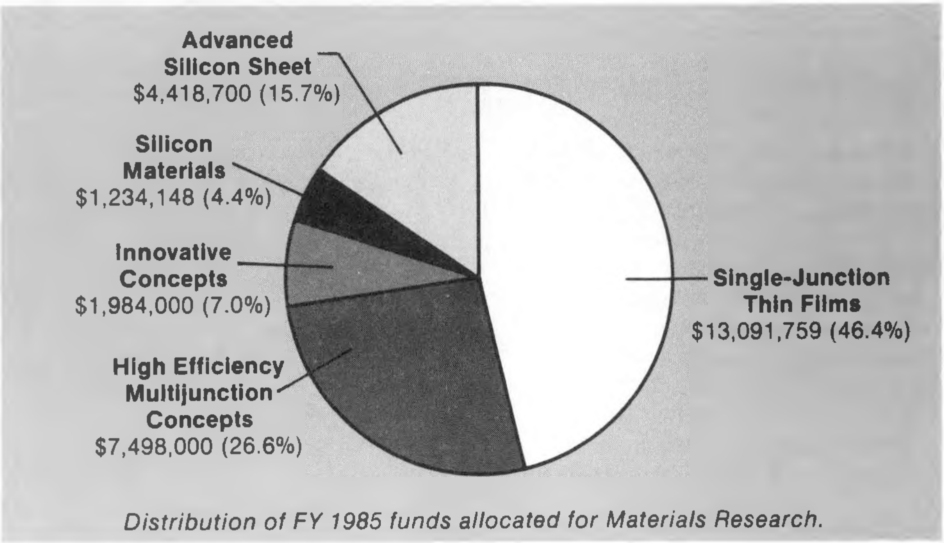
The research centers allocate more than 50% of their resources to projects performed by universities, private companies, and research institutions to encourage a federal/industry partnership in PV research. The remaining resources are used for research and management at the centers. In fiscal year FY 1985, a total of $44,859,000 was allocated for the National Photovoltaics Program. Of this amount, $23,521,255 was awarded to various subcontractors.

Over the last year, this $45 million investment paid off in numerous technical achievements, many of which are presented on the pages that follow.

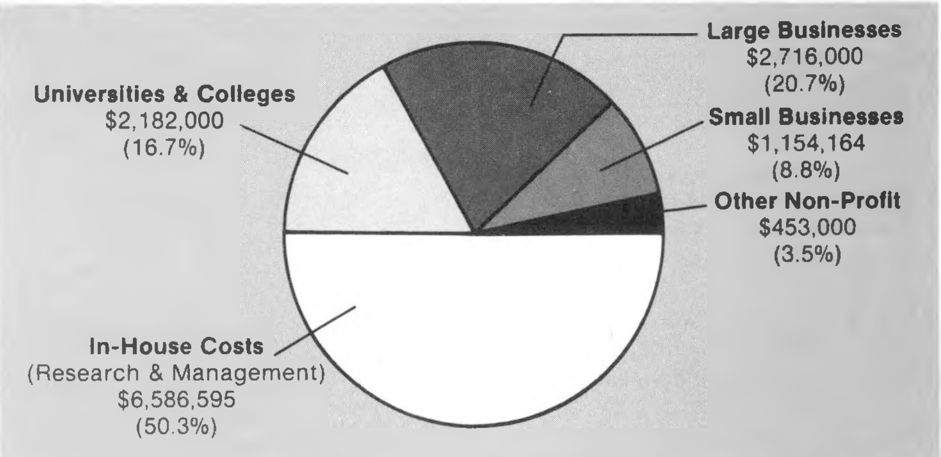
Materials Research

The Materials Research phase of the National Photovoltaics Program received 61.3% of the Program's funding in FY 1985: $28,226,607. This was distributed among the five research tasks which make up this phase of the Program:

- Single Junction Thin Films
- High Efficiency Multijunction Concepts
- Innovative Concepts
- Silicon Materials
- Advanced Silicon Sheet



Distribution of FY 1985 funds allocated for Materials Research.



Distribution of funds spent on Single Junction Thin Films in FY 1985.

Single Junction Thin Films

The cost of solar cells and their associated materials would be greatly reduced if thin-film cells could be made with good conversion efficiencies. A thin-film solar cell consists of a thin layer of semiconductor material deposited on a low-cost substrate such as glass, metal, or plastic. Such a cell requires materials other than conventional silicon; materials that can absorb all of the useful solar energy in short distances and convert it efficiently to electricity. While certain single-crystal materials show potential for application to thin-film cells, most research is concentrated on amorphous silicon alloys, several polycrystalline compounds, and gallium arsenide.

Single junction, thin-film cells have two primary advantages: low material requirements and the potential for low-cost production techniques (such as the continuous fabrication of entire modules rather than cells). At present, researchers are focusing their efforts on increasing the efficiencies of thin-film cells, understanding their basic properties and operating mechanisms, improving the stability of some cell materials, and devising better ways to make large-area cells and modules. During FY 1985, the Program allocated over $13 million to these research activities.

Achievements:

Government/Industry Partnerships

Amorphous silicon is one of the better bets for the Program and for the photovoltaic industry. It is inexpensive, can be deposited in thin layers only microns thick, and can be fabricated in continuous fashion over large areas. Reflecting these qualities, amorphous silicon cells have increased their share of the market to the point where, in 1984, they constituted 27% of worldwide PV shipments. Most of these were for the consumer market where the cells power commodities like wrist watches, calculators, and radios. But, if modules of amorphous silicon can be made more efficient and stable, other possibilities abound including generating electricity for homes or central utilities.

Seeing the enormous potential of amorphous silicon, in 1984 SERI began an intense effort to develop this technology. In an $18.6 million, three-year, cost-shared venture they joined with 3M, Solarex, and Chronar to devise creative approaches to improve the quality of amorphous silicon materials and solar cell devices. And though the program is still young they have already made significant strides. In FY 1985, they made 10% efficient small-area cells and submodules with efficiencies around 7% under outdoor test conditions; an approximately 15% improvement in efficiency over the previous year.

With these achievements, the partnership will probably meet its three-year goals of 12% efficiency for small-area cells (1 cm^2) and 8% efficiency for submodules of 1000 cm^2. This should spur them on to their next phase of research, which SERI is currently planning, and help propel the U.S. toward leading the world in amorphous silicon technology.

Light-Induced Effect in Amorphous Silicon

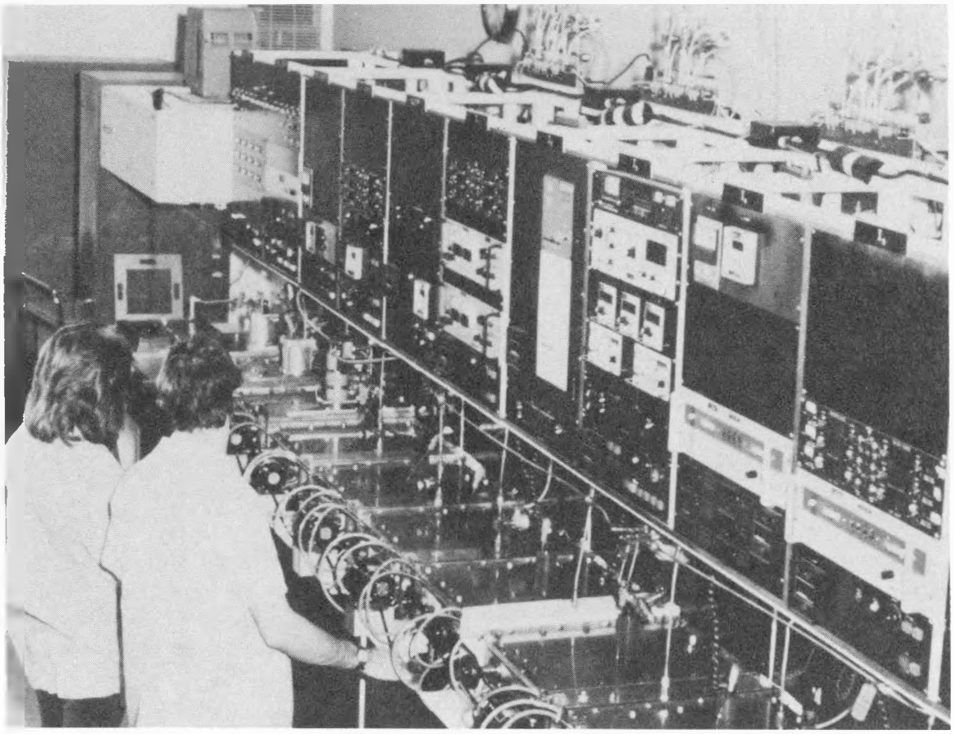
In 1977, Staebler and Wronski noticed that if hydrogenated amorphous silicon (adding a small amount of hydrogen to amorphous silicon makes the electrons and holes more mobile) solar cells are exposed to light for a long time, their efficiency drops off. Because long-term stability is crucial to cost-effective PV applications, scientists the world over have been trying to explain why and how the degradation takes place.

Two of the best efforts were recently made by Xerox and MIT, who proposed models that explain many of the major features of this problem. Xerox's model suggests that when an electron and a hole recombine they release enough energy to break a weak bond that can exist between two silicon atoms. This creates a defect, known as a dangling bond, where a chemical bond associated with an atom on the surface layer of a crystal does not join with another atom of the crystal, but points away from the surface. This creates a somewhat unstable condition with the dangling bond available to attract and hold (trap) a free electron or hole which subsequently can combine with its counterpart (hole or electron), degrading the performance of the cell.

MIT's model gives another mechanism whereby dangling bonds are created to figure prominently in degrading cell efficiency. This explanation rests on the fact that small concentrations of defects form during deposition. These defects, where five or seven silicon atoms are bonded in pentagonal or septagonal ring-like structures, are either positively-charged ions that attract free electrons, or negatively-charged ions that attract free holes. Upon trapping a charge carrier, the charge within the defect is rearranged, deforming the structure to produce a dangling bond.

Though both models explain many aspects of the effect, scientists may be able to refine them by using results obtained by SERI researchers who discovered that, even under the best circumstances, holes in the n-layer (the semiconductor layer that is doped to contain an excess of unbonded electrons) are barely able to travel to the edge of the cell. So, it takes only slight changes in solar-cell structure to greatly reduce carrier transport. They also found that, in addition to creating dangling bonds, light exposure increases the capture rate for free electrons and holes at places where the crystal has been distorted. This increased capture rate means electrons and holes move more slowly, exist for a shorter time, and don't travel as far.

These results show steady progress toward understanding amorphous silicon material and its degradation due to light; crucial to developing cost-effective amorphous silicon solar cells and modules for commercial purposes.



In a cost-shared partnership with the government, Solarex was one of three companies who developed innovative methods to deposit amorphous silicon on inexpensive substrates; in this case, on glass.

Materials and Modeling Study of a-SiGe Alloys

A major emphasis in amorphous silicon research is the development of low-band-gap alloys, materials that absorb the low-energy light photons toward the red end of the visible spectrum. By incorporating such low-band-gap materials into tandem solar cell devices, where different cells are stacked on one another to absorb more of the sun's radiation, researchers hope to improve the efficiency of amorphous silicon solar cells enough to use them economically for central utilities.

The best approach to lowering the band gap (a measure of the amount of energy needed to knock an electron into the conduction band, where it is free to move through a conducting material) is to alloy amorphous silicon (band gap = 1.7 eV) with germanium. Unfortunately, increasing concentrations of germanium degrade a solar cell's electrical properties. By the time desired band gaps of 1.5 eV or lower are reached, the alloy material no longer generates useful electricity.

In 1985, SERI researchers undertook a systematic study of these alloys to understand why this happens. They compared experimental electrical measurements with those predicted by the Shockley-Read-Hall recombination model. (The model predicts where electrons and holes will recombine in a solar cell and explains how such recombination affects the cell's electrical properties.) The researchers found good agreement between the experimental results and the model for materials with band gaps between 1.7 and 1.5 eV. Below 1.5 eV, on the other hand, the photoconductivity (a measure of the electrical current produced by light) falls off faster than the model predicts. However, in explaining how increasing amounts of germanium degrade the electrical properties, the current model only considers the defects introduced by the germanium atoms.

The researchers are now investigating other factors that could contribute to the rapid decline in the alloy, electrical quality.

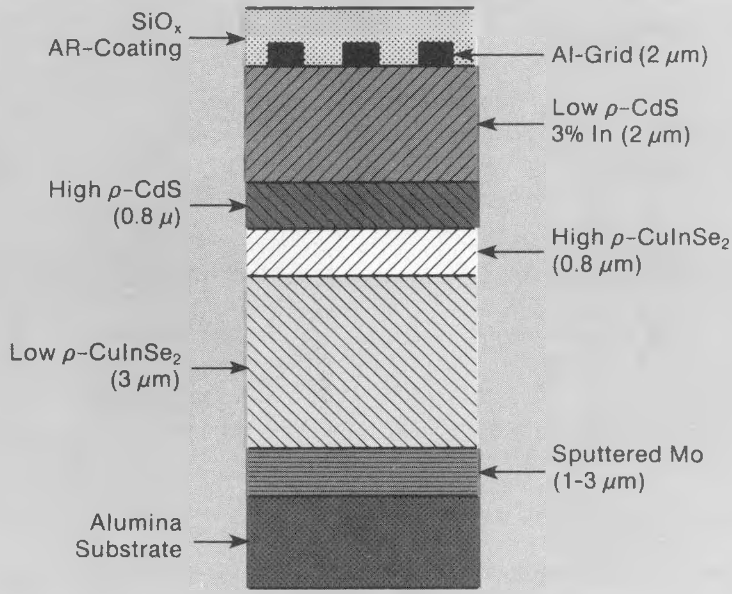
New Transparent Conducting Electrodes for Solar Cells

Many kinds of solar cells use transparent conducting films as electrodes. These films must transmit nearly all the sunlight that falls on a solar cell as well as conduct electricity efficiently. They should also be durable, stable when exposed to sunlight and the environment, inexpensive, non-toxic, and easy and safe to work with.

Amorphous silicon solar cells most often use conducting films made with fluorine-rich tin oxide. This material is stable, inexpensive, easily processed, has good electrical and optical properties, and is made from abundant chemical elements. Unfortunately, it is risky to make because the usual process uses a toxic liquid (tetramethyltin) that evaporates readily at room temperature.

During the past year, Harvard University and Solarex discovered two potential substitutes for tetramethyltin. Harvard showed the solid dimethyldichlorotin to be a promising candidate. And Solarex found that liquid tintetrachloride can be used to deposit textured, fluorine-rich tin-oxide films.

Both these substitute tin sources have produced films with electrical and optical properties similar to those made the usual way. But the new tin sources cost less, are less toxic, and easier to handle — a big plus from the manufacturing viewpoint.



This year SERI scientists developed a thin-film cell of copper-indium-diselenide and cadmium sulfide. The cell was efficient and stable.

Polycrystalline Thin Films

Polycrystalline materials are important alternatives to amorphous silicon in thin-film PV research. Semiconductors made from these materials range in thickness from a few tenths of a micron to several microns and can be made from as many as three or four different chemical elements. They have many of the advantages of amorphous silicon, including low materials costs and inexpensive fabrication techniques.

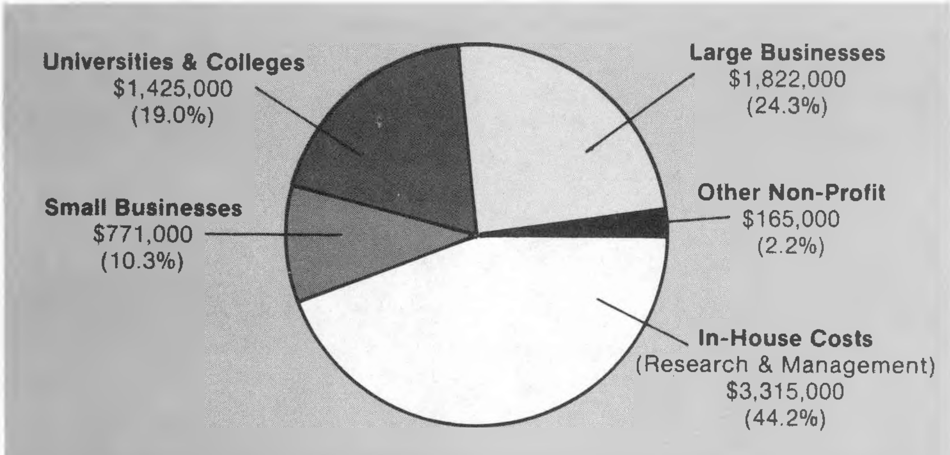
In 1985, SERI researchers fabricated a two-layer solar cell with one layer made of cadmium sulfide and the other of copper-indium-diselenide. At 10.3%, this cell had the highest efficiency of any thin-film cell measured at SERI. The new cell was also more stable than similar cells. This accomplishment was made possible by detailed studies of changes in the chemical and electrical properties of copper-indium-diselenide caused by defects or impurities.

This new solar cell can be used alone or as a high-performance bottom cell in a multijunction device (see below). Either way, this research is laying the foundation from which industry can launch its own efforts to develop promising polycrystalline thin-film solar cells.

High Efficiency Multijunction Concepts

Most solar cells use a single material (such as silicon) with a single band gap to absorb the sun. Ultimately, the efficiency of such a single-junction cell is limited. Incident light with energy less than the band gap cannot be converted, and much of it with energy greater than the band gap is wasted as heat. To overcome this difficulty, Program scientists are designing cells with *multijunctions* or *multiple band gaps* — often referred to as stacked-junction, cascade, or tandem cells.

In a multijunction device, solar cells with different band gaps are stacked on top of each other in decreasing band gap order. In this way, all the incident light with energy equal to or greater than the band gap of the top cell is absorbed by the top cell. All incident light with energy less than the band gap is transmitted to the next cell. This phenomenon recurs at each cell throughout the stack. Thus a large portion of sunlight is utilized. Theoretically, an infinite number of such layers can be used to gain a maximum



Distribution of funds spent on High Efficiency Multijunction Concepts in FY 1985.

efficiency of about 70% for flat-plate collectors and close to 80% for concentrator solar cells. But in practice it is practical to stack only two or three cells, restricting possible cell efficiencies to a more realistic level of 30% to 35%.

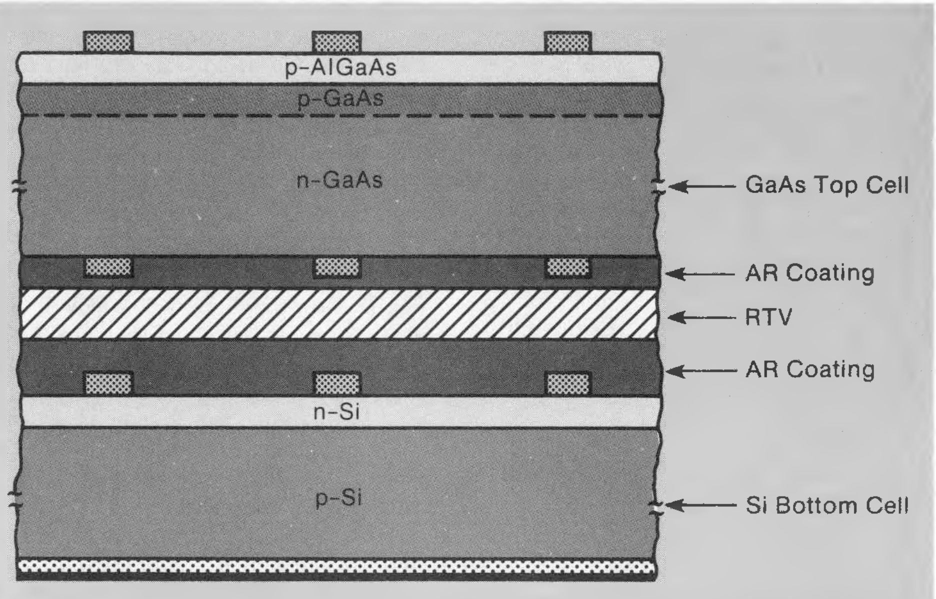
Program researchers are trying to identify and resolve mechanisms limiting the performance of materials, identify combinations of materials that yield high efficiencies, and understand and solve the problems that occur when materials are combined in a cascade arrangement. Initial research is focused on stacked amorphous thin-film cells and on crystalline multijunction cells, especially those using gallium arsenide and its alloys. Toward these efforts the Program spent $7,498,000 in FY 1985.

Achievements:

Progress in Mechanically-Stacked Multijunction Cells

Single-crystal gallium arsenide and single-crystal silicon solar cells hold records for the most efficient conversion of sunlight to electricity. The marriage of these two materials should lead to highly efficient multijunction devices. Silicon is an excellent choice for the bottom cell because of its low 1.1 eV band gap. Gallium arsenide, with a band gap of 1.42 eV, is less than ideal for a top cell, however. Aluminum-gallium-arsenide with a band gap of 1.75 eV is a better candidate.

Even so, Hughes Research, Applied Solar Energy Corporation, and Sandia have created a mechanically-stacked gallium arsenide-on-silicon device with a record efficiency of 24.7% under a concentration of about 70 suns. (A mechanically-stacked device is where the different cells are grown in separate sytems, and then physically stacked one on the other.) This two-junction cell is an important precursor to future, more efficient devices that use aluminum-gallium-arsenide on silicon. The next step will be to produce good quality, thin top cells made of aluminum-gallium-arsenide.



Hughes Research, Applied Solar Energy Corporation, and Sandia created this mechanically-stacked gallium arsenide-on-silicon device structure, which produced a record efficiency of 24.7% for a two-junction device.

This accomplishment suggests researchers will soon develop multijunction devices with higher efficiencies than the best single junction device (a Varian gallium arsenide concentrator cell with a 26% efficiency). And, such mechanically-stacked devices will probably be the first multijunction solar cells to be incorporated into advanced high efficiency modules.

Varian Successfully Makes Transition Layer for High Efficiency Cell

Last year Varian reached a key point toward the development of a 30%-efficient two-junction device. They used aluminum-gallium-arsenide for the top cell and indium-gallium-arsenide for the bottom cell. When tested separately under a full spectrum of light, each cell was over 20% efficient. Much remained to be done, however. The next challenge was to get excellent performance from both cells in a monolithic stack. (A monolithic stack is where the different cells are grown in the same systems on the same substrate, one on top of the other.) This posed a whole new set of problems. Since the atomic spacing of their crystals is different, it is difficult to join the two cells in a single device and still maintain proper crystal structures and desired electrical properties. And because the optimum individual cells are grown at much different temperatures, it could prove unfeasible to stack them monolithically.

To solve these problems, especially the difference in atomic spacing, Varian chose to grow a graded layer of aluminum-indium-gallium-arsenide between the top and bottom cells. Such a layer would be optically transparent, allowing sufficient light to reach the bottom cell and, if graded properly, should match the atomic spacing of both cells. To grow this layer, Varian started with the indium-gallium-arsenide bottom cell. As growth proceeded they slowly substituted aluminum for gallium to give them aluminum-indium-gallium-arsenide. Then they graded this to aluminum-gallium-arsenide, matching the top cell, by reducing the indium in the source gases. During this investigation Varian was also able to reduce the difference in growth temperatures required to achieve high quality individual cells. This greatly simplified the procedure and allowed them to control the growth of the transition layer.

Varian used its hard-won expertise to prepare fully functional monolithic two-junction cells of aluminum-gallium-arsenide on indium-gallium-arsenide. Under cascade conditions their best results have been 16.3% efficiency for the top cell and 9% for the bottom cell. This is especially good for the bottom cell since the top cell allows only about half of the sunlight through to the bottom cell.

Varian is currently working to improve the reproducibility of crystal growth and device processing in its effort to make a monolithic cascade device that reaches the Program goal of 30% efficiency.

SERI Researchers Make Efficient Gallium-Arsenic-Phosphide Cell

One of the best structures for a two-junction device calls for top and bottom cells with band gaps of about 1.7 eV and 1.1 eV, respectively. A leading candidate material for the top cell is gallium-arsenic-phosphide. It has the desired band gap, is relatively easy to grow by a number of well proven techniques and, being an alloy commonly used for light-emitting diodes, has a strong technology base. Plus, it is relatively insensitive to defects in the crystal structure. This means it can be grown on substrates which do not match its crystal lattice (repeatable patterns of atoms or molecules that give the crystal its unique shape and properties) and can tolerate some inhomogeneities in its atomic structure without losing its PV properties.

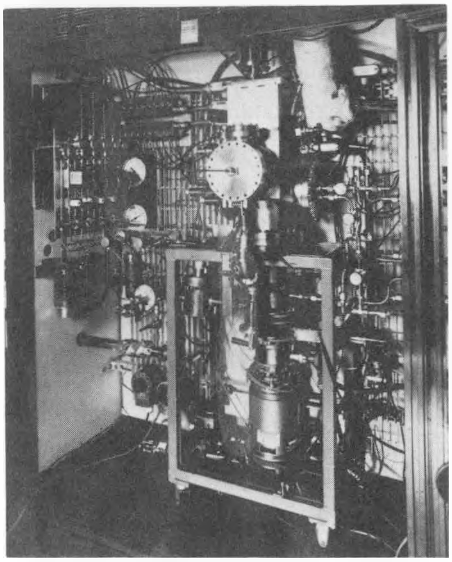
Taking advantage of these characteristics, SERI scientists used a standard deposition technique to make some of the most efficient devices ever achieved with gallium-arsenic-phosphide. Deposited on a lattice-mismatched substrate of gallium arsenide, the best cells have one-sun efficiencies greater than 15% and excellent fill factors exceeding 86%. (The fill factor is the ratio of a cell's actual power output to its theoretical power output — a key characteristic in evaluating cell performance.)

Futhermore, the researchers identified several areas for future study that should lead to efficiencies approaching 18% or 19%. When coupled with a bottom cell of similar efficiency, this material could then yield a two-junction solar cell that is close to meeting the Program's efficiency goal of 30%.

Chevron Controls Carbon Incorporation into Gallium Arsenide Growth

One way to make better component cells is by purifying the source materials out of which the cells are made. This is a tactic that Chevron Research Company has used in the past to produce high-quality cells. But some unwanted impurities cannot be removed by purifying the source materials. This is often the case, for example, when the most common source of gallium, trimethylgallium, is used to grow gallium arsenide. Carbon is uncontrollably incorporated into the film, limiting the researcher's ability to develop an optimum cell.

Chevron scientists used powerful diagnostic techniques available with their newly developed crystal-growth reactor to solve the problem. They grew gallium arsenide and monitored the byproducts to see how carbon became a part of the crystal. They found that methyl groups (groups containing molecules composed of one atom of carbon to three atoms of hydrogen) remained on the growing surface and decomposed to hydrogen and carbon unless another free hydrogen atom was available to react and form methane. As a result of these experiments they decided to use a different gas, triethylgallium, for the gallium source. This gas contains ethyl groups (groups containing molecules composed of two atoms of carbon to five atoms of hydrogen), which independently form ethylene and do not leave carbon behind.



During FY 1985 Chevron invented a new crystal-growth and diagnostic process, known as vacuum chemical epitaxy, that gave them the unique ability to understand and control the incorporation of carbon into gallium arsenide.

Chevron researchers used the new source gas not only to control the introduction of impurities into gallium arsenide and its alloys, but to increase the time that carriers (free electrons or holes) exist before recombining and to increase the ease with which carriers move through the crystal lattice.

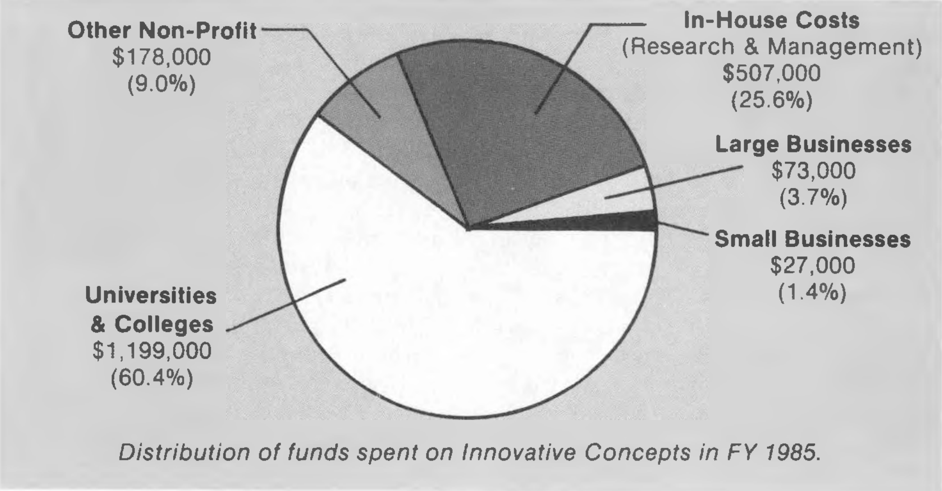
But researchers are also using their discovery in yet another way. When uncontrolled, carbon can be a nuisance. When under control, it can be beneficially incorporated into gallium arsenide to provide desirable stable electronic properties. So scientists are now investigating using the original gas, trimethylgallium, as a source for the controlled introduction of carbon into gallium arsenide.

Cadmium Telluride Alloy Top Cells for Cascade Cells

One way to make thin-film PV devices with efficiencies of 15% or higher is to combine two or more solar cells into a single multijunction device. The band gaps of cadmium telluride and copper-indium-diselenide allow them to be combined into a nearly optimal multijunction cell. This year, SERI and other laboratories developed copper-indium-diselenide bottom cells with efficiencies greater than 10%. In addition, Southern Methodist University (SMU) and the Institute of Energy Conversion (IEC) made progress on cadmium telluride-based top cells.

SMU researchers fabricated cadmium-zinc-telluride alloys with a band gap of 1.6 eV, the ideal band gap for use in this cascade cell. They also investigated window materials with high band gaps such as zinc oxide, cadmium oxide, and tin oxide. (Window material is used in the top layer of a cell, and is so-called because of its transparency to light. Such material should have a high band gap so it will not absorb radiation, but pass it through to the layers beneath.) Of these, cadmium oxide seemed most promising, for SMU researchers used it as a window layer in an efficient cadmium telluride solar cell.

As soon as high-efficiency cadmium telluride top cells are developed, they will be combined with high performance copper-indium-diselenide bottom cells. The resulting polycrystalline thin-film multijunction cells should reach 15% to 20% efficiencies. Such a breakthrough would lower the costs of solar cell devices and make thin-film technology a viable alternative for commercial PV applications.



Distribution of funds spent on Innovative Concepts in FY 1985.

Innovative Concepts

Photovoltaics is basically a semiconductor technology. As such, it is a wide-ranging and fast-paced technology with numerous untapped possibilities. There are many PV materials that researchers have yet to discover, let alone test, fabricate, and optimize. And of those that are known and under investigation, there are myriads of material combinations, device configurations, and fabrication, growth, passivation, and production techniques that have yet to be tried.

The Innovative Concepts Task identifies these new materials, device configurations, and concepts, and conducts preliminary research and development in the most promising areas. Every year the Program solicits ideas from universities, businesses, non-profit organizations, and government research personnel, and awards subcontracts to study the most promising concepts. After initial exploratory research, the Program supports further development of those ideas that show the most promise. In FY 1985, the Program spent nearly $2 million on Innovative Concepts.

Achievements:

University Participation Program

As with any technology, the future of photovoltaics depends on creative new research ideas and talented professionals to carry them out. To attract university research teams to the National Photovoltaics Program, the Innovative Concepts Task initiated the University Participation Program in 1985. The new program will provide funding to selected university research groups over a three-year period. This will allow universities to build and support research teams whose goal will be to broaden the PV knowledge base. By training students and by publishing research results in technical journals, the program will also support technology transfer to industry.

In September, the National Photovoltaics Program awarded more than $1 million to five universities selected to participate in the initial program. These include North Carolina State University, the University of Utah, the University of Southern California, Stanford University, and Brown University. Among the things they will investigate are electronic processes that take place in thin-film materials, new methods on how to grow high efficiency cells, and new ways to incorporate desirable impurities into semiconductor materials.

The new program will promote open-ended basic and applied research, rather than research directed at achieving a specified goal. In this way, the Program hopes to foster creative breakthroughs in this country's efforts to develop PV technology.

In September 1985, the National Photovoltaics Program's new University Participation Program awarded more than $1 million for PV research to Brown University, North Carolina State University, Stanford University, the University of Southern California, and the University of Utah.

Novel Ordered Structures of Semiconductor Alloys

For many technological applications scientists need to mix two or more semiconductor materials to create an alloy that has desired properties intermediate between those of its starting materials. For example, they may mix gallium phosphide with indium phosphide to result in some combination of gallium-indium-phosphide. But because of the large number of parameters that must be simultaneously controlled, finding the proper alloy is often a difficult task. This is where experimental scientists often work in close cooperation with theoretical scientists to find alloys with the preferred properties and crystal structures.

Theoretical scientists use solid-state theory to systematically study hitherto unknown materials, complementing the knowledge and methods of the experimentalist. Such was the role of solid-state physicists from SERI. Using sophisticated computer models in which the electronic properties and stability of crystals is calculated from first principles, they predicted that many semiconductor alloys could exist in forms more stable than previously known. They also showed that these forms are possible *where the atoms are ordered on a special crystal lattice.*

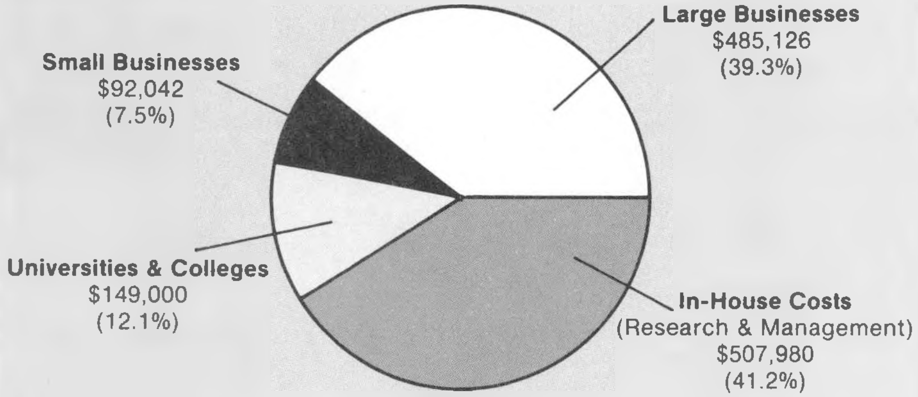
These novel ordered forms of semiconductor alloys have recently been prepared in a number of laboratories, and hold the promise of being superior materials. The realization of such interesting possibilities is a primary intent of the Innovative Concepts Task.

Silicon Materials

For nearly 30 years the semiconductor industry has used a slow, expensive, and energy-intensive method to produce pure silicon for electronic components. Such a costly and cumbersome technique is unsuitable for the high-volume, low-cost production required by the photovoltaic industry.

For the past 10 years, the National Photovoltaics Program has been developing a more efficient and economical silicon purification method, called the silane process. The first step in this process transforms impure, but silicon-rich material into pure silane, a compound containing only silicon and hydrogen. In the second step, a fluidized-bed reactor (FBR) heats up the silane until it breaks down into its silicon and hydrogen components. The silicon is then rapidly and continuously deposited on a bed of heated silicon seed particles. Large, high-quality silicon crystals grow around these tiny crystal fragments, called seeds.

The silane process should reduce the cost of semiconductor-grade silicon from its current price of $55 per kilogram to less than $20 per kilogram, meeting the Program's goal. In a project supported in part by the Flat-



Distribution of funds spent on Silicon Materials in FY 1985.

Plate Solar Array Project at JPL, Union Carbide built and currently operates a plant that produces up to 1200 metric tons of pure silane per year. Currently, old-style Komatsu reactors convert most of the silane to silicon. Once perfected, FBRs will perform this step more efficiently and at a lower cost.

During FY 1985, the Program allocated over one million dollars to optimize the FBR and demonstrate the purity of the silicon product.

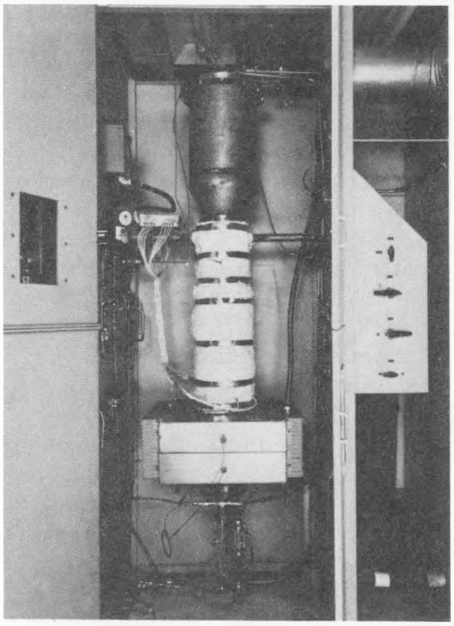
Achievement:

Program Successfully Transfers Silane Process to Industry

One of the principle intents of the National Photovoltaics Program is to transfer PV technology to the private sector. And perhaps the best way to achieve this transfer is for government, educational institutions, and industry to mutually develop the technology. JPL and Union Carbide's development of the silane process for silicon purification has been a model of such cooperation.

FY 1985 witnessed the last year of government involvement in this technology. During the year, researchers from JPL, Caltech, Washington University at St. Louis, and Union Carbide worked on collaborative but separate projects to improve the fluidized-bed reactor, used to convert silane to pure silicon. JPL developed better methods, including a mill that uses two opposing fluid jets to induce self-grinding of silicon particles, to produce pure silicon seeds. The seeds, in turn, produce a pure, high-quality silicon product. This product was so pure, in fact, that JPL's sophisticated instruments were unable to detect any metallic impurities in it.

In other research, scientists at Caltech and Washington University developed models that explain, in theory, how silicon crystals form and grow. And, Union Carbide successfully operated an FBR fitted with a quartz liner for 60 hours at a silane concentration nearly double that in any previous operation.



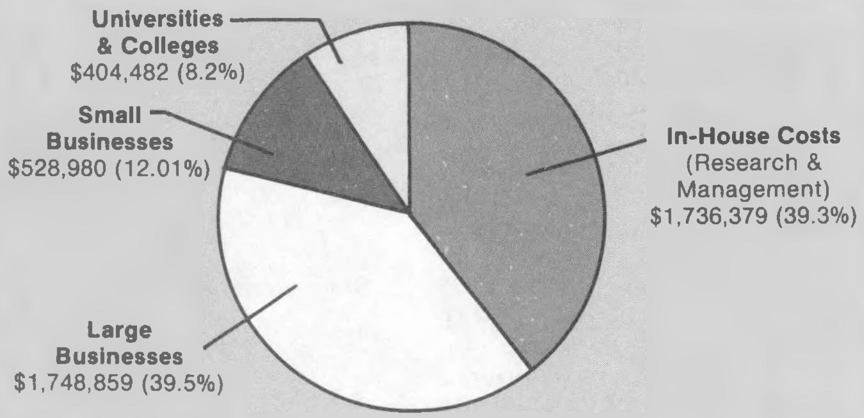
The fluidized-bed reactor is part of a new process that promises to produce semiconductor-grade silicon inexpensively and with high yields.

Even so, Union Carbide has yet to produce semiconductor-grade silicon with the FBR. But, the company plans to tackle a variety of engineering problems during 1986 and 1987 and eventually to commercialize the FBR technology. JPL's recent accomplishments and the theoretical understanding developed by university scientists should help the company achieve these goals.

By transferring the FBR technology to industry, the Silicon Materials Project has met its goals and is winding down its participation in the Program. But it is leaving the Program with a legacy of success: Private industry can now commercialize the silane process not only for the benefit of the photovoltaics industry, but also for the semiconductor industry as well.

Advanced Silicon Sheet

Much of present solar-cell technology is based on single-crystal silicon wafers obtained by slicing cylindrical ingots grown from purified, polycrystalline, semiconductor-grade silicon. Although this technique, called the Czochralski method, is still relatively expensive, researchers continue to make advances in reducing costs and increasing solar cell efficiency. The National Photovoltaics Program, however, is also sponsoring research on silicon sheet (or ribbon) fabrication as the primary alternative to ingot technology. These techniques produce long, thin, rectangular sheets of material. Cells can potentially be made less expensively and with nearly as high a conversion efficiency as with ingot methods. In addition, silicon sheet processes use raw silicon more efficiently and can, in theory, produce finished products much faster. The Program spent more than $5 million in FY 1985 to support the development of this important silicon technology.



Distribution of funds spent on Advanced Silicon Sheet in FY 1985.

Achievements:

Advances in Dendritic Web Growth

In early 1984, Westinghouse Electric Corporation, DOE, JPL and SERI joined the Electric Power Research Institute (EPRI), Pacific Gas and Electric, and Southern California Edison to develop commercial applications for the silicon dendritic web growth process, one of the most promising silicon sheet technologies. This process grows long, thin single-crystal silicon ribbons directly from liquid silicon inside a furnace. The web, or ribbon, solidifies between two silicon filaments, called dendrites, which support the edges of the growing strip. By insuring that each growth furnace produces a high output over an extended period of time, partnership members would like to reduce the cost of sheet material made by this process.

In May 1985, Westinghouse took an important step in demonstrating this capability when the company grew almost 27,000 cm² of silicon ribbon in one furnace during a 120-hour period. Westinghouse continued to improve its process and by late 1985 grew ribbons up to 8.5 m long and 6.7 cm wide at a rate of 39,000 cm² per furnace per week — a growth rate nearly quadruple what was achieved prior to 1984.

Improved ribbon growth isn't the only advance Westinghouse demonstrated in 1985. The company also devised a system for automatic control of ribbon growth. Automatic control allows a single operator to monitor a number of furnaces and keeps labor costs down. Plus, automatic controls can operate this system with greater precision than can a human operator.

Westinghouse's new control system uses a non-invasive method to measure the thickness of the two dendrites during growth. Their thickness accurately reflects whether conditions in the liquid silicon (melt) are proper for ribbon growth. Cameras view the edges of the ribbon and feed information into a computer, which monitors and controls melt temperature. The system also displays dendrite images for the operator.

These advances are important steps toward developing the dendritic web process for commercialization and for meeting Program goals of increasing the efficiency of silicon ribbon solar cells, attaining growth periods greater than 65 hours, and increasing sheet growth rates to cost-competitive levels.

Measuring Residual Stresses in Sheet Silicon

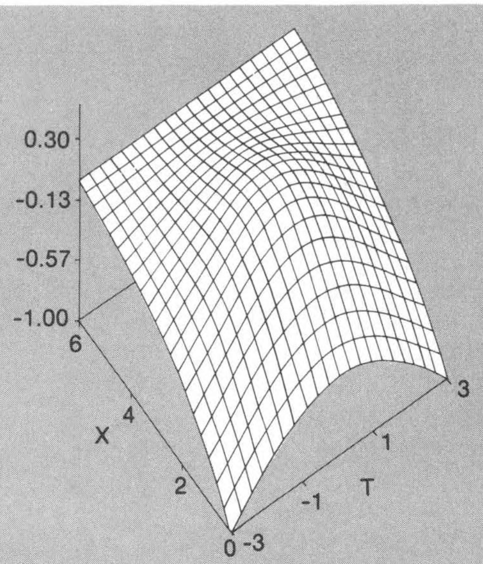
To meet DOE's goal of producing PV-generated electricity at a cost of 6.5 cents per kilowatt-hour (in constant 1982 dollars), researchers must find ways to overcome the limitations of current ribbon fabrication techniques. Thin silicon ribbons cool rapidly and unevenly, creating stresses and crystal imperfections in the ribbon. Because they can cause silicon ribbons to buckle or crack, these defects often cause significant problems later with solar cell processing yields and performance. Researchers are looking at ways to measure and control these problems.

For the past couple of years, computer models have played an important role in analyzing silicon-ribbon imperfections. Researchers have worked to design mathematical models that describe how defects arise during the growth process and that predict residual stress and strain in the sheet. Now, they are working to improve their models by incorporating more information about the physical and chemical processes that affect stable ribbon growth.

This year, the University of Kentucky created a new model that can predict how crystal imperfections develop and how variations in ribbon thickness or width can cause a ribbon to buckle. The new model will help scientists better understand how to prevent these problems. In addition, the model will enable researchers to study how heating and cooling affect buckling.

Computer models aren't the only technique for solving silicon-ribbon problems. In 1985, the University of Illinois at Chicago developed a method that measures stresses in silicon ribbon. Their fast-and-easy-to-use process analyzes the patterns created by beams of laser light focused on the material. This non-destructive technique has already been used to evaluate silicon ribbons fabricated by Westinghouse and is now being set up at Mobil Solar Energy Corporation to monitor production-line quality control.

This accomplishment is an excellent example of technology transfer to industry. In addition, scientists expect the results of such efforts to help them better design a variety of different silicon sheet growth systems as well as improve other types of crystal growth processes.

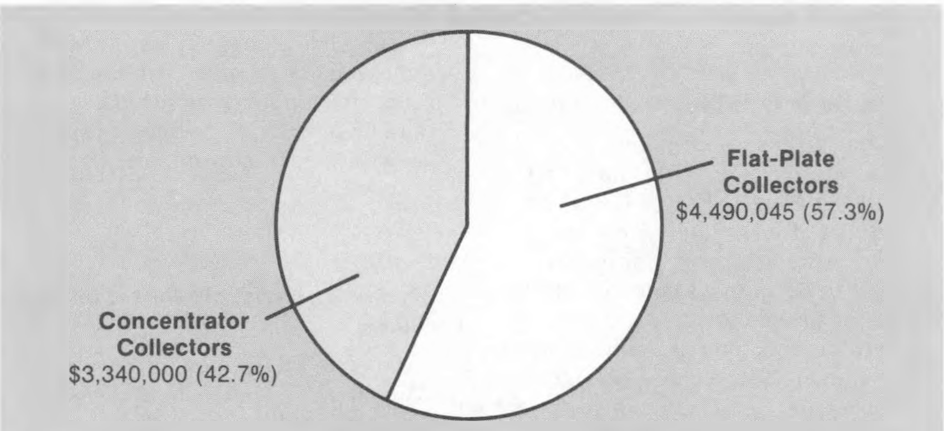


By adjusting hypothetical silicon ribbon growth conditions, the University of Kentucky's new computer model generated this buckled shape.

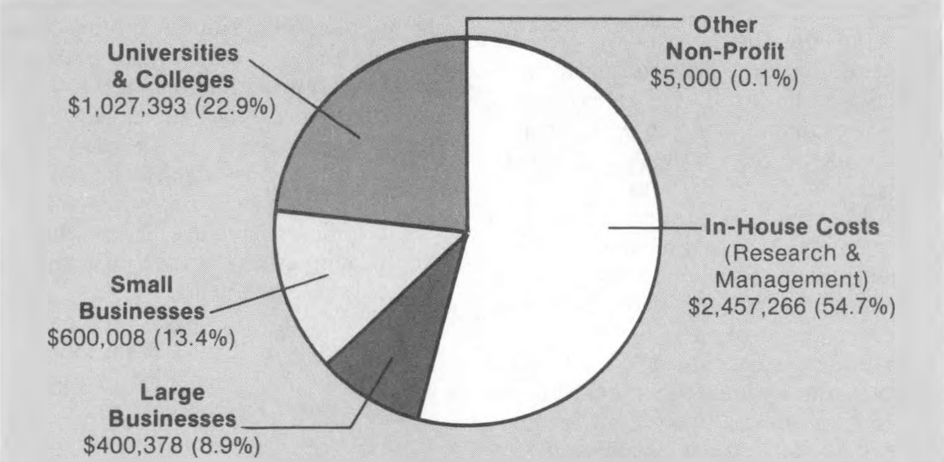
Collector Research

The Collector Research phase of the National Photovoltaics Program received $7,830,045 in FY 1985. This was distributed among the two research tasks that make up this phase of the Program:

- Flat Plate Collectors
- Concentrator Collectors



Distribution of FY 1985 funds allocated for Collector Research.



Distribution of funds spent on Flat Plate Collectors in FY 1985.

Flat Plate Collectors

For almost 10 years, the Flat Plate Solar Array Project has focused its efforts on crystalline silicon cells, modules, and arrays. This technology is the most established of all the PV technologies, and accounts for a great majority of the modules being shipped by the industry. Since 1975, module size and efficiency have increased dramatically. Life expectancy has increased 10 times and module prices have decreased tenfold; however, much remains to be done to increase the efficiency and decrease the cost of flat plate collectors. Scientists in the Program have already identified the major barriers which limit efficiency and increase cost, and are investigating ways to mitigate those limitations. The options they are currently evaluating could reduce crystalline silicon module cost by a factor of three to five and increase the efficiency as much as 30% to 35% by 1988. When this is combined with cost reductions in the production of high-purity silicon, module costs could plummet even further. To further this goal, the Program allocated over $5 million in FY 1985.

Achievements:

Computer Model Analyzes New Silicon Cell Design

Computer modeling is a powerful tool in evaluating novel ideas and designs in photovoltaics. JPL's SEEMA (Solar-Cell Efficiency Estimation Methodology and Analysis) program uses computer simulations to evaluate and design advanced silicon cells.

This year, JPL researchers used SEEMA to analyze a new high-efficiency cell design. The cell design's unique features included a high-efficiency, thin, single crystal silicon layer and a back surface reflector that sends charge carriers back into the cell. These improvements help increase the lifetime of electrons and holes inside the cell. To keep electrons and holes from recombining and reducing cell efficiency, the new cell also incorporates specially treated front and back surfaces and a specially treated polycrystalline silicon layer between the cell and its metallic contacts.

SEEMA analysis showed these improvements would be necessary to create a silicon solar cell with efficiencies greater than 20%. (In fact, the simulation showed that the 20%-efficient silicon solar cell fabricated by Martin Green of Australia is nearly optimal for a conventional cell design.)

Before new high-efficiency silicon solar cells can approach their theoretical efficiency of about 27%, however, many practical barriers remain to be overcome. Researchers must figure out how to reduce electron-hole surface recombination by 90% and increase electron and hole lifetimes within the cell by at least tenfold compared to Green's cell.

JPL's New Surface Passivation Technique

One of the prime objectives of the Flat Plate Solar Array Project is to increase the efficiencies of crystalline solar cells. To meet this goal, JPL manages a comprehensive effort that involves universities, industry, and government. As the computer simulation described above clearly showed, reducing electron-hole recombination at cell surfaces is a key component in the design and fabrication of high-efficiency silicon solar cells. And, layering silicon dioxide on the silicon in-between metal grids effectively lowers recombination velocities. However, layering a thin oxide under metal can cause serious problems with a cell's electrical output.

JPL researchers are now analyzing a new cell design which uses a phosphorus-rich polycrystalline silicon layer sandwiched between the cell's silicon surface and both its front and back metal contacts. This new design could theoretically achieve an efficiency greater than 20%. When experimental cells with phosphorus-rich polycrystalline back contacts were compared with conventional cells, the experimental cells had better electrical properties and worked better in red light.

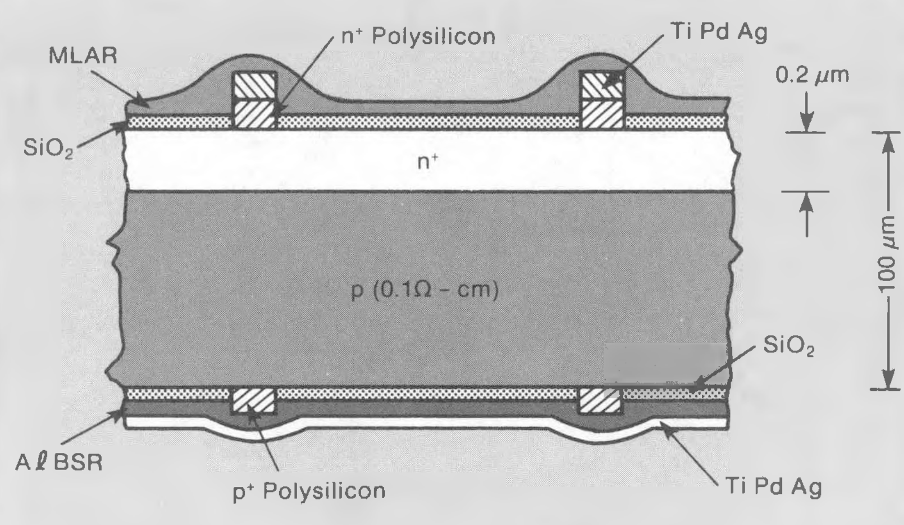
Researchers are now trying this method on the front contact. This creative new technique, and other such innovative designs, will help researchers build high-efficiency, silicon solar cells that will soon meet DOE's efficiency goal of 18% to 20% — or perhaps even higher.

New Technique Will Cut Solar Cell Manufacturing Costs

Decreasing the cost of flat plate collectors is one of the Project's major goals, particularly since industry is already manufacturing silicon cells, modules, and arrays. The more rapidly costs for PV systems fall, the sooner PV will gain its share of the commercial energy market. Finding cost-effective and more efficient ways to fabricate solar cells is a key to making this happen.

This year, Westinghouse ran exploratory tests on a new heat lamp technique for making silicon solar cells. The process used liquid dopants (impurities that confer desired electrical properties on semiconductor materials) to simultaneously form front and back cell junctions (interfaces between distinct cell layers), cutting the number of steps required to fabricate a solar cell from ten down to four. This new method produced cells that performed as well or better than cells fabricated by the usual sequential-junction-formation techniques.

Once the heat lamp technique is implemented, it should reduce the cost of forming junctions in silicon cells by one-third or more. This, in turn, will help bring down the cost of commercial silicon modules.



JPL used its SEEMA (Solar Cell Efficiency Estimation Methodology and Analysis) computer model to study this thin silicon solar cell design. The simulation showed which cell characteristics strongly influence cell efficiency.

Concentrator Collectors

The most expensive part of a PV system is usually the cell itself. Therefore, it makes sense to get the most electricity possible from each cell. This is most often done by using concentrating lenses to increase the sunlight striking each cell. By using lenses to focus direct sunlight onto solar cells, the cell area can be reduced by as much as a factor of 1000, limiting the actual solar cell cost to only 5% of the entire concentrator system cost. In addition, properly designed concentrator cells are more efficient than one-sun cells. The Program allocated $3,340,000 in FY 1985 for research on concentrating collectors.

Achievements:

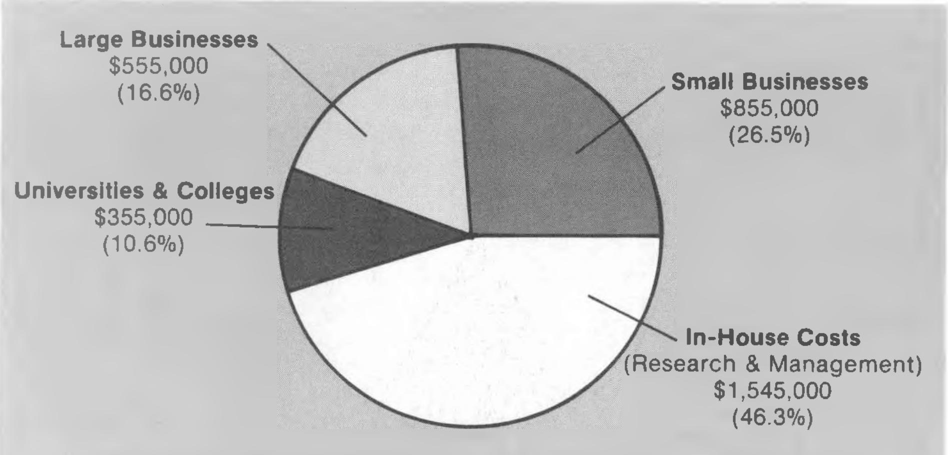
Concentrator Collector Milestones

Sandia achieved two important DOE Program milestones for concentrators this year. After meeting its milestone to develop a concentrator reliability plan, the Project initiated a concentrator system reliability task. The task includes reliability modeling, improvement of suppliers quality control and implementation of quality assurance guidelines, and field evaluation of concentrator arrays and systems. Quality control problems within the Intersol manufacturing line have been identified and eliminated.

Several accomplishments helped meet another Sandia FY 1985 milestone, which was to make concentrator modules that are 15% efficient and have a factory price of \$125/m^2 at high-volume production.

In 1984, Sandia tested a set of Intersol Power Corporation *modules* that averaged 15% efficiency. This year, array tests at the Photovoltaic Advanced Systems Test Facility in Albuquerque indicated peak *array* efficiencies can be 15% as well. In addition, a Sandia economic analysis, which assumed a 27% rate of investment return and a production rate of 50 MW/year, predicted a price of \$125/m^2 for these modules.

In light of these accomplishments and advances in silicon and gallium



Distribution of funds spent on Concentrator Collectors in FY 1985.

arsenide-based concentrator cell technology, it is likely Sandia will meet its next major Program milestone of a 22% efficient concentrator module by FY 1987. Once such efforts generate large-volume manufacturing and sales, PV technology will move into America's energy mainstream.

Gallium Arsenide Concentrator Cells

A horse race may be shaping up between gallium arsenide and silicon to meet DOE's goal of producing a 22% efficient advanced concentrator module at a cost of \$125/m² by 1987. Single crystal silicon-cell technology is one of the Program's best bets, and "conventional" cells already exist with efficiencies over 20%. But, recent progress has brought gallium arsenide technology into a competitive position with single crystal silicon for applications to high-efficiency concentrator systems.

This year, Varian Associates established a new record conversion efficiency for PV devices of any kind with a 26% gallium arsenide solar cell. Not only did this cell measure a peak efficiency of 26% at a concentration of 700 suns, but all 30 cells made at the same time also achieved efficiences between 24% and 26%. The major improvements in these cells over previous cells are the high quality material used to grow them and improved levels of preferred impurities (doping) used in different cell layers.

Varian believes that with this new gallium arsenide cell they have a device that can be used to produce a 22% efficient advanced concentrator module. System cost analysis indicates that if these devices can be made for \$5/cm² or less, advanced gallium arsenide cells will be a serious alternative to single crystal silicon solar cells.

Silicon Concentrator Cells

Major advances were also made this year in the efficiency for silicon devices. Sophisticated computer models, such as SCAP2D developed at Purdue, indicate that novel silicon structures (made of high resistivity material) have potential efficiencies near 30%. In 1985, this new evidence caused Sandia to change the direction of its silicon cell research toward understanding these new cell structures and assessing their potential.

Modeling at Stanford University, under EPRI sponsorship, also suggested novel ways to develop high-efficiency silicon cells. Stanford researchers recently made silicon devices with efficiencies of nearly 25% under 500 suns illumination.

Computer modeling is clearly a valuable tool for leading PV research efforts. The Sandia-directed, advanced silicon research program will take advantage of these major new accomplishments and work to develop advanced silicon cells from the laboratory to a working module.

The development of advanced, high-efficiency silicon cells means it may not be necessary to use more expensive, exotic materials for commercial PV applications. As both silicon and gallium arsenide-based concentrator cells demonstrate better and better efficiencies, the question of which material is most economical may well determine the compositions of future concentrator systems.

In FY 1985, Sandia showed that solar arrays, such as this one at the Photovoltaic Advanced Systems Test Facility in Albuquerque, can achieve peak efficiencies of 15%.

Systems Research

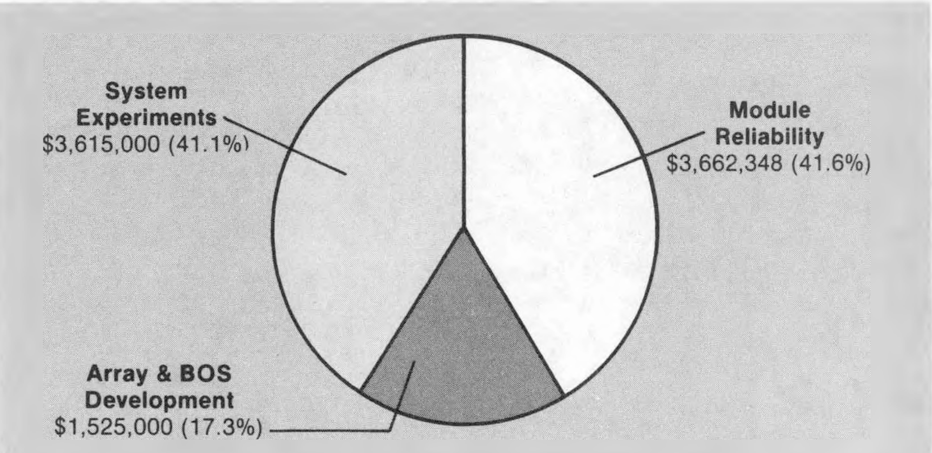
The Systems Research phase of the National Photovoltaics Program received $8,802,348 in FY 1985. This was distributed among the three research tasks which make up this phase of the program:

- Module Reliability
- Array and Balance of System
- System Experiments

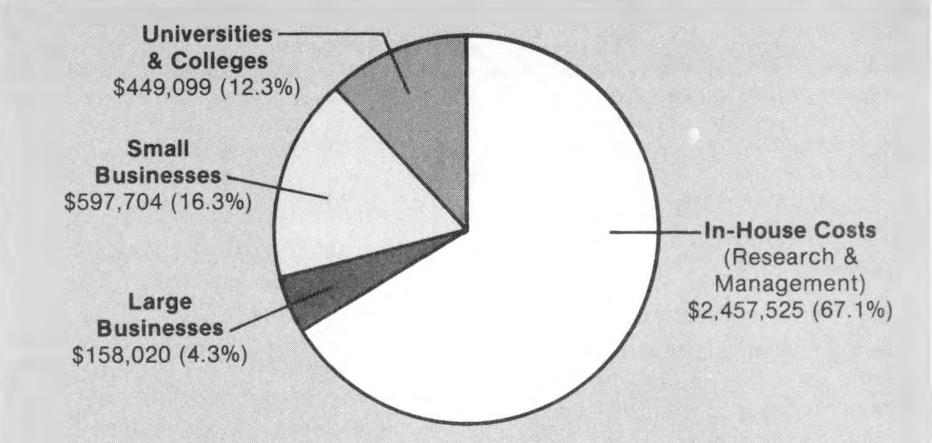
Module Reliability

One of the largest potential markets for photovoltaics is central utility applications. But to properly compete for this market, PV systems must not only be relatively inexpensive to make and install, they must last as long as 30 years with little degradation in power output.

Until recently, state-of-the-art modules lasted no more than 10 years under field conditions. But manufacturers have made substantial advances, with 10-year warranties now emerging. To help spur further progress, the Program allocated the Module Reliability Task $4,529,424 in FY 1985 to investigate the causes of module degradation and develop ways to improve life expectancy to more than 30 years. Although the Program allocates most of its research funds to efforts on cyrstalline-silicon flat-plate modules, it has begun to emphasize the reliability attributes of thin-film modules as well, especially those made of amorphous silicon.



Distribution of FY 1985 funds allocated for Systems Research.



Distribution of funds spent on Module Reliability in FY 1985.

Achievements:

Amorphous Silicon Modules

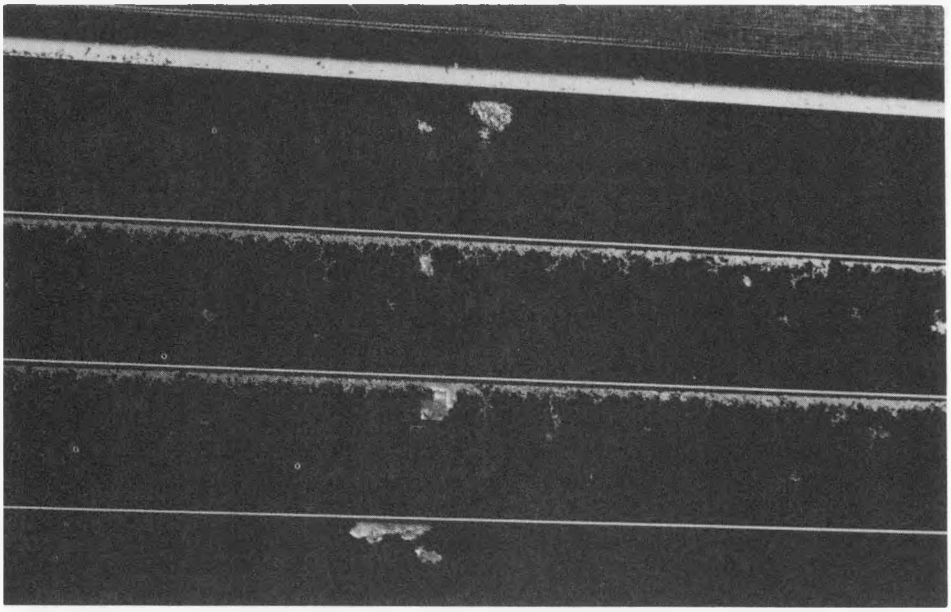
Amorphous silicon solar cells are usually 100 to 200 times thinner than those made from crystalline silicon. Because they are so thin, researchers are investigating whether these thin cells and modules will work reliably for a long time under field conditions. Specifically, they're questioning whether amorphous silicon cells might be more fragile with respect to corrosion or hot-spot heating.

Hot-spot heating occurs when a shadow (from a tree or telephone pole, for instance) causes one solar cell to receive less light than its neighboring cells. Because the darkened cell produces less electricity, it draws electrical current from the fully illuminated cells around it. This current, can heat up a small area, called a hot spot, in the shadowed cell. Excessive heating can destroy the solar cell and even damage the plastic envelope encasing the module.

During FY 1985, JPL began studies of the sensitivity of amorphous silicon cells to hot-spot heating with the intention of developing new protection methods if required. Surprisingly, they discovered that thin cells seem to be more resistant to hot-spot heating than their larger crystalline silicon relatives. Cell performances changed little even though hot-spot heating created worm-like erosion patterns in the affected cells. If these preliminary results are borne out in future studies, it means amorphous silicon cells can be easily protected from hot-spot damage with existing circuit designs.

Amorphous silicon cells fared equally well in initial JPL studies of corrosion, which can damage a cell's metal electrodes, cause loss of power output, and cloud or discolor the envelope around the module. Despite the discovery that metal grids covering amorphous cells are corroded in an unusual worm-like pattern, researchers found that amorphous silicon seems to be even more resistant to corrosion than crystalline silicon.

These results — which portend excellent long-term durability against corrosion and good resistance to hot-spot heating — suggest amorphous silicon may be a good candidate for solar cell modules to meet the Program goal of a 30-year life expectancy.



As part of their research on the reliability of thin-film modules, JPL scientists are testing whether shadows falling on individual amorphous silicon solar cells in a module will damage these cells. A shadowed cell can pull electric current into itself and get hot. Local hot-spot damage, which causes worm-like erosion patterns, has only a minor effect on cell performance, however.

Encapsulant Improvements

The glass or plastic envelope surrounding a solar module holds components in place while efficiently transmitting sunlight to the solar cells. Ideally, the envelope should inhibit corrosion, resist weathering, attach firmly and reliably to module parts, and be reasonably safe to use in a variety of applications. During the past few years, scientists made substantial progress toward creating such an envelope. They developed a plastic encapsulant material called ethylene vinyl acetate (EVA), which is now the industry standard.

During FY 1985, JPL scientists improved EVA envelopes in several important ways: They incorporated additives that better resist sun, wind, and temperature damage; they developed extremely durable chemical glues to hold the envelope together; and they came up with some good ways to make plastic-encased modules flame resistant. Until FY 1984, such modules could not pass even the least stringent flammability tests (Class C) required for roof-covering materials.

This year, researchers developed a fiberglass-based back surface material that helped achieve a Class A fire-resistance rating for the plastic-coated module. (Class A materials are effective against severe fire exposure.) They also created experimental flame-resistant module gasket materials and a new nonflammable, but opaque, EVA material that could be used for the rear layer of the envelope to further improve the flame resistance of PV modules.

Industry shared the cost of developing these new flame-resistant materials. Such results are an excellent example of the benefits of the government-industry partnership built over the years in the National Photovoltaics Program.

Outdoor Test Facility

A solar systems' true value is determined by how well it functions under natural sunlight and environmental conditions. For years, researchers of the National Photovoltaics Program exposed systems to the environment, tested, and evaluated the effects of environmental stresses on them. They used these evaluations to help other researchers improve the components that make up the systems. Until recently, this type of operation was directed primarily toward single-crystal technologies. But with the emergence of thin-film technologies, the PV community needs new tests, procedures, and analyses.

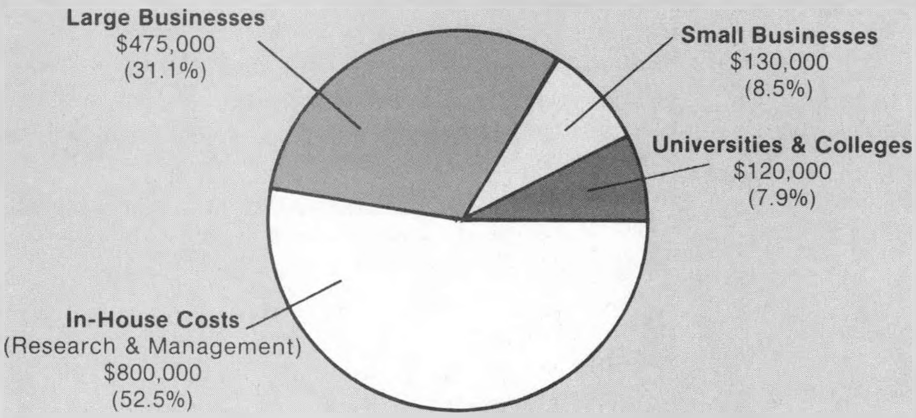
SERI scientists have been answering this need. During the past year they upgraded their outdoor testing facilities by installing equipment for determining temperature coefficients (the rate of change in output with respect to temperature) of thin-film modules and have added two solar tracking test beds for testing outdoor stability and performance. Using these and other equipment, they completed 185 outdoor performance tests of thin-film devices and performed an eight-month stability test of amorphous silicon modules.

To help analyze and design the new generations of PV cells and modules, researchers will continue to update the outdoor test facility and upgrade their procedures. As a further help to the PV community, they will also conduct workshops on testing procedures for thin-film PV devices.

Array and Balance of System (BOS) Development

Array fields consist of support structures, foundations, interconnect wiring, and if necessary, tracking mechanisms and tracker controls. Power conditioning consists of equipment required to convert dc to ac, to condition the ac signal to meet utility or user standards, to meter power production and use, and to protect personnel and equipment from harm.

The array field and power-conditioning subsystems account for approximately 30% of the cost of PV systems. To make PV competitive with conventional alternatives, the Program spent more than $1 million in FY 1985 working to reduce these subsystem costs by a factor of two or three. The Program is also trying to improve the overall output of PV systems by substantially increasing the efficiency of power-conditioning systems.



Distribution of funds spent on Array and Balance of System Development in FY 1985.

Achievements

Array & Balance-of-System Development

Government and industry have learned much about how to design solar array fields from several key design studies and field experiences with PV systems. Researchers are now developing array fields for applications ranging from small residential to large central station utilities. Two of the principle types of array fields they have been working on are *fixed* flat plate collectors and *tracking* flat plate collectors. Within the past year, government and industry laboratories have made substantial progress in designing cost-effective systems for both types of collectors.

Battelle-Columbus Laboratories, for example, completed a detailed array field design for a 100 MW modular fixed flat plate system, which incorporates a low-voltage (+ 400 V_{dc}) 5 MW building block. (A building block is the smallest unit of a system that can be cost-effectively used in multiples to form larger systems.) The building block is consistent with conventional utility design and operation practices. The laboratory estimates the system will cost $\$49/\mathrm{m}^2$ ($1985) of collector area, which easily meets DOE's balance-of-system cost goal of $\$57/\mathrm{m}^2$.

This accomplishment successfully completes DOE's array field design work on fixed flat plate collectors. Their work is continuing, however, on tracking flat plate collectors with Hughes Aircraft Company completing two modular array field designs using tracking structures: a one-axis design and a two-axis design.

Their one-axis design rotates north and south to compensate for seasonal variations in the sun's altitude. The horizontal tracker is passive with a fluidic drive and costs less than $\$50/\mathrm{m}^2$, reduced from a baseline of $\$75/\mathrm{m}^2$. The two-axis design which not only rotates north and south, but east to west to follow the sun's daily crossing of the sky, uses an electromechanical drive mechanism. Both the one-axis and two-axis options were designed to have the lowest possible lifecycle energy cost. The company plans to install and evaluate prototype array fields of both designs in FY 1986.

Once such tracking systems become economical to produce, they could greatly enhance the output of both commercial and residential solar arrays.

PV Systems - Utility Interface

Linking photovoltaic systems successfully into central utility grids requires that power conditioning units send out ac signals whose quality meets utility standards. The signal

Summary of Array Field BOS Costs
(1985 $\$/\mathrm{m}^2$)

	Array	Prototype Installation	Second-Time Installation	Projected
Hughes/Sandia	Fixed Flat Plate	167.84 (30kW)	114.71 (30kW)	72.64 (1MW)
Battelle/Sandia	Fixed Flat Plate	157.81 (30kW)	84.65 (30kW)	63.34 (1MW)
Puerto Rico Proj.	Fixed Flat Plate	114.84 (100kW)	—	—
Martin Marietta	Fixed Flat Plate	—	—	62.16 (100MW)
Black & Veatch	Fixed Flat Plate	—	—	54.65 (100MW)
Battelle	Fixed Flat Plate	—	—	49.44 (100MW)
(As noted)	One-Axis Flat Plate	170.13 (1MW/PV1)	135.14 (1MW/PV2)	77.02 (100MW)
(As noted)	Dual-Axis Flat Plate	214.00 (Lugo/1MW)	—	123.59 (100MW)

Battelle-Columbus Laboratories designed a fixed flat plate system that would cost less to install than the DOE cost goals prescribe. The cost includes site preparation, structures, dc electrical, control, and ac electrical. DOE's cost goal for fixed flat plate BOS is $\$57/\mathrm{m}^2$ ($1985).

quality from power conditioning subsystems (PCS) that use high frequency switching is very good and does not cause problems for household devices such as color TVs and microwave ovens. However, less expensive PCSs, which use low frequency switching (120 Hz), do not have as high a quality signal and could inject distortion into an ac system. Because they cost less, these low-frequency subsystems may be the PCS of choice for normal residential PV installation.

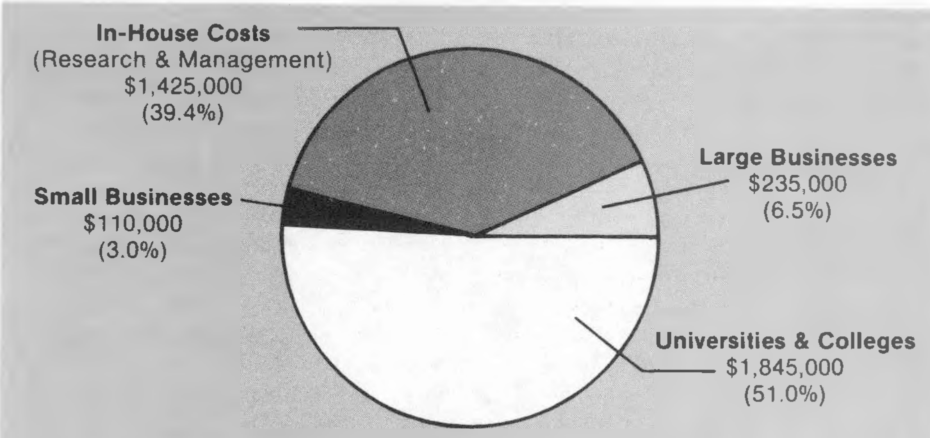
This last year Sandia made some calculations to see how troublesome low frequency PCSs can be. They found that these PCSs can contribute up to 10% of feeder capacity without exceeding the acceptable distortion limits. The next step will be for utilities to demonstrate that this works in practice. If it does, utilities will start to trust these units more.

They will also trust them more because of the results of other research that four major utilities performed on power conditioning subsystems and interface issues. Their tests showed that power conditioning units, singly or in combination, shut down when they detected utility system abnormalities.

Once industry better defines their concerns regarding the impact of PV electricity on generation and dispersal systems, designers can rectify such concerns through proper hardware configuration. Thus, utilities, industry and government researchers can work together to create a renewable energy system that benefits everyone.

System Experiments

System experiments verify successful research and technology development. Through these experiments, the Program validates conceptual design approaches and methods; accumulates operating data to assess the cost and performance of current and projected technologies; defines technical requirements for research on materials, devices, and collectors; and identifies and evaluates operating requirements for PV systems in user environments. Experiments are being performed on residential, intermediate, and large systems. The Program allocated more than $3 million to the Systems Experiments Task in FY 1985.



Distribution of funds spent on Systems Experiments in FY 1985.

Achievements:

Design Assistance Center

There are many excellent applications for PV technology that have not yet been exploited because potential users do not know the theory or operation of the technology. It's often easier to specify an older, familiar technology than to learn enough to adopt a new, unfamiliar one.

In FY 1985, the DOE National Photovoltaics Program established the system Design Assistance Center (DAC) at Sandia National Laboratories. DAC will help bridge the information gap between potential users and the PV industry and speed up information transfer to industry from government research. The center's goal is to educate the potential user regarding the technical viability, cost effectiveness, and reliability of PV systems.

The DAC concept is based upon the extensive systems-level data base that exists within the Program and U.S. industry. Information from systems research, operating systems, and test facilities comprises the data base. After gathering data, the center analyzes it and provides accurate technical advice concerning PV systems, ranging from small autonomous systems to large central station generating facilities. The center offers direct consultation, design documentation, and meeting or workshop organization.

Since early 1985, the center has worked with systems for John Long Homes, the City of Austin, Potomac Edison Company, San Diego Gas and Electric Company, and the Territory of Puerto Rico. Recently, the center assisted the World Bank in international system procurement and ran feasibility analyses for government agencies.

This close cooperation between the center and the U.S. PV industry will greatly benefit the Program, industry, and the user. And the DAC's educational mission will be fulfilled as PV technology enters America's energy mainstream.

System and Radiation Modeling

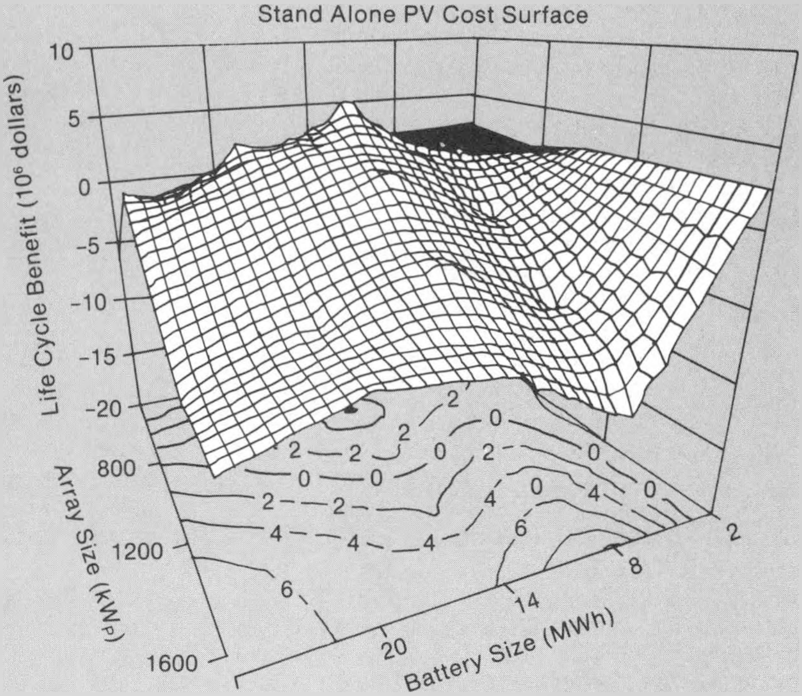
Realizing computer models are an important tool for studying PV systems, researchers have spent the last two years working out the best approaches to PV performance simulation. As a result, a State University of New York model can now produce accurate estimates of solar radiation on both tilted and tracking surfaces, and a Sandia model accurately predicts PV module operating temperature. In addition, storage battery research and system economic analyses are producing better methods to study the economic performance of stand-alone and grid-interactive systems.

In FY 1985, Sandia created a new simulation model, called PVFORM Version 3.0. PVFORM integrates improved modeling techniques into a program that can run on computers ranging in size from a mainframe to a personal computer. The new model simulates the hourly performance of a PV system for a one year period and performs an economic analysis of the resulting energy production summaries. Model users can add pertinent, but individualized information such as a description of the array and power conditioner, specific load profiles to be applied each day of the year, and hourly weather. The final result is a printed output of the hourly, monthly and yearly simulation totals. Sandia tests show that PVFORM model predictions are typically within 1% and 5% of measured values.

Because medium or large computer systems can rapidly execute PVFORM, the model can be run numerous times for a given PV application, generating more complete sets of information for design engineers. For example, Sandia used the model to create a three dimensional cost surface that gives the PV system designer an opportunity to visualize the relationship of such system parameters as battery size, array size, and battery charging strategy. Using this information, designers can easily determine the most cost effective system configuration.

In addition to PV system design, the PVFORM program can also check data quality assurance, analyze PV system degradation, and compare different module mounting strategies. This powerful tool has already been used extensively at Sandia and in support of such commercial PV ventures as the John F. Long residential project in Phoenix, Arizona and the City of Austin 300 kW project in Austin, Texas.

Besides PVFORM, there are new models that enhance our knowledge of the solar radiation resource and the environment, which is fundamental to the design, development, and application of PV devices and systems. During the last year, for example, scientists in SERI's Resource Assessment and Instrumentation Branch created improved computer models that simulate broadband and spectral solar radiation. In fact, the model for spectral radiation (radiation over selected narrow frequency ranges) was used to generate new national and international standards for terrestrial solar radiation spectra. The broadband (radiation over wide ranges of frequencies) model, meanwhile, was widely adopted by the PV community to help them improve system design and performance models. And researchers at solar resource stations across the nation are using both models to improve their data bases on solar radiation.



Sandia's new PVFORM computer model gives PV system designers the opportunity to visualize the relationship of such parameters as battery size and array size. This information helps designers determine the most effective system configuration.

PV Systems Evaluation

Evaluating the field performance of photovoltaic systems is an important part of the National Photovoltaics Program. Although the Program no longer installs systems, it does evaluate many new PV systems through a cooperative effort with the system owners, DOE, and EPRI. In this way, the Program continues to build a required data base without the direct expense of building PV systems.

Data are collected in two ways: 1) from continuous on-site collection systems developed and installed by Sandia, and 2) from on-site electrical subsystem surveys coordinated through Sandia and performed by the Southwest Regional Experiment Station. The data network includes systems that cover the entire range of technology, including two-axis flat plate (Lugo 1 MW), 1-axis tracking flat plate (SMUD 1 MW), fixed flat plate roof mounted (Georgetown University 300 kW), line focus concentrator (DFW Airport 25 kW), a multihome residential project in the San Diego area, and several others.

Researchers use this information in many different ways. For example, the data may show that the failure rate of new modules is significantly less than that of a previous generation of modules (down from 1-2 failures per thousand per year to virtually no failures in the first two years of operation). They also use the data to validate performance models for various systems, a necessity in the system design. Significantly, the data has helped to establish that array soiling can decrease output by as much as 20%, and has identified some inconsistencies between actual performance and design ratings.

Sacramento Municipal Utility District (SMUD)

Photovoltaic systems can make a substantial contribution to U.S. energy production if they are economically used in central power stations. With this in mind, DOE participated in a utility-scale project by sharing the cost of a 2 MW PV power plant with the Sacramento Municipal Utility District (SMUD).

The facility, situated alongside SMUD's Rancho Seco nuclear power plant, was built in two 1-MW phases. The first phase was completed in July 1984 and has performed satisfactorily. The second phase was 90% operational by the end of 1985, with the remaining 10% expected to be operational in February 1986.

With a low contractor bid of $4.95/W for the PV modules and $0.40/W for the inverter, the SMUD power plant goes a long way toward meeting DOE cost-reduction goals for PV technology in large-scale applications. Low-cost materials, standard parts, and simple manufacturing and assembly techniques were used to ensure economical construction and reliable performance.

SMUD's 2-MW photovoltaic power plant, located near its Rancho Seco nuclear power plant, will be fully operational by February 1986.

Support Activities

Some of the activities funded by the National Photovoltaics Program do not fall neatly into one of the ten tasks. But even though these activities may cut across many tasks, the money supporting them is arbitrarily included under task funds. Such is the case with the measurement, characterization, and analysis functions performed by the PV Devices and Measurements Branch at SERI and the Photovoltaic Measurements Technology and Failure Analysis Tasks performed at JPL. Both groups run internationally known laboratories which are among the most sophisticated and complete facilities devoted to photovoltaics measurement and calibration in the world. These laboratories are used not only for the benefit of the Program but, with the cooperation of scientists throughout the world, are also used to advance the state-of-the-art in PV measurement, increase our knowledge of the fundamental properties and mechanisms of PV materials, and to set calibration standards. Brookhaven National Laboratory also supports the Program by doing research on environment, health, and safety issues that pertain to photovoltaics.

Achievements:

Volume-Indexed SIMS

Many goals of the National Photovoltaics Program are directed toward reaching new plateaus of efficiencies or economies. But to do these things there is also an equally important unwritten agenda. Researchers have to keep on the cutting edge of science and technology, continually pushing their measuring capabilities into new horizons. This is critical to better the understanding of cell mechanisms. At the same time, this knowledge and technology must be transferred to the rest of the photovoltaic community and beyond.

SERI researchers have done this by developing a specialized process for determining the chemical composition of semiconductor materials and devices. This breakthrough technique was selected for an *I-R 100 Award* by *Research and Development Magazine* as one of the 100 most significant technical advances of 1985. This award will help bring the technique to the attention of a large industry audience, transferring the knowledge and technology into a greater arena.

The process, volume-indexed SIMS (secondary ion mass spectrometry), uses a hardware/software package to examine the interior of a sample, determining its chemical makeup quickly, reliably, and reproducibly. (This is quite an advantage over conventional techniques, used primarily to analyze the surfaces of samples or an internal section. Such conventional methods are slow and unreliable and tend to destroy the sample in the process.) Data on a sampling of ions (characteristic charged particles) are collected and stored in a computer, which classifies ions according to type, concentration, and location. The computer produces a "map" of the chemical composition. The rearcher can manipulate the map to examine any internal point, line, or plane within the analyzed volume.

SERI researchers have already used this new technique to discover three ways in which hydrogen combines with silicon to passivate (mitigate harmful defects and enhance photoelectric properties) polycrystalline silicon cells. This discovery contributes significantly to understanding the processes taking place through passivation. And since passivation is widely used throughout the semiconductor technologies, this knowledge contributes to a sphere that extends well beyond photovoltaics.

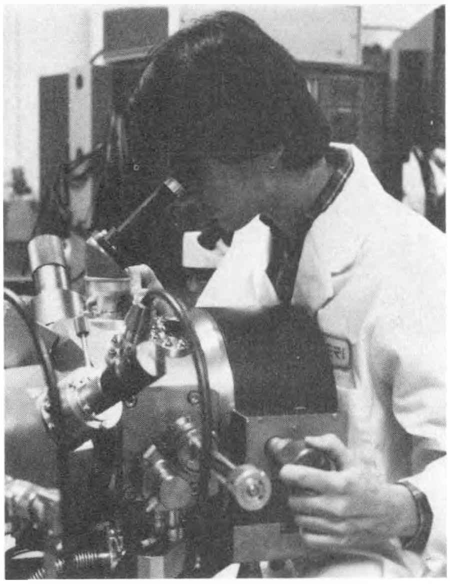
Environment, Health, and Safety

Before industry starts producing and marketing a product, they must understand the risks involved in making that product. They must ask themselves not only whether the product will be useful or profitable, but whether it is safe to manufacture, what the risks are, how to characterize those risks, and how to control and minimize them. The Program is helping industry to answer these questions about PV beforehand, especially those concerning the emerging technologies such as polycrystalline thin films and amorphous silicon.

Scientists at Brookhaven National Laboratory (BNL) spent 1985 investigating three major areas of concern: identifying hazards, characterizing them, and managing them. To identify hazards, they concentrated primarily on materials used in multijunction PV devices and the health and safety issues that could arise to limit their commercial viability. They were especially concerned with materials such as copper-indium-diselenide, cadmium telluride, and zinc phosphide. These materials were examined in great detail to see what the risks and their potential magnitudes are and to identify different ways to reduce them.

For their characterization studies, scientists developed models to determine the concentration profiles of various toxic gases used in the production of thin-film PV cells. The models were based on BNL estimates of the quantities of gases likely to be present in cell production facilities and a range of likely atmospheric conditions. Researchers will continue to refine and improve the models in FY 1986.

For hazard management, BNL evaluated the control technology options and costs for a hypothetical plant for making amorphous silicon PV cells.



SERI researcher positions sample prior to volume-indexed SIMS analysis.

Acronyms, Symbols, & Abbreviations

ac	alternating current
Al	aluminum
AlGaAs	aluminum-gallium-arsenide
AlInGaAs	aluminum-indium-gallium-arsenide
AM	air mass
Ar	arsenic
AR	antireflection
a-Si	amorphous silicon
a-Si:H	hydrogenated amorphous silicon
BOS	balance of system
BSR	back surface reflector
C	carbon
C	Celsius
Cd	cadmium
CdS	cadmium sulfide
CdTe	cadmium telluride
CH_4	methane
cm	centimeter(s)
cm^2	square centimeter(s)
Co.	company
CO	Colorado
Cu	copper
$CuInSe_2$	copper-indium-diselenide
CVD	chemical vapor deposition
DAC	design assistance center
dc	direct current
D.C.	District of Columbia
DFW	Dallas-Fort Worth
Dist.	distribution
DOE	Department of Energy
E_g	energy gap
EPRI	Electric Power Research Institute
eV	electron volt(s)
EVA	ethylene vinyl acetate
FBR	fluidized bed reactor
FF	fill factor
FP	flat plate
FPUP	Federal Photovoltaic Utilization Program
FY	fiscal year
Ga	gallium
GaAs	gallium arsenide
HF	high frequency
IEC	Institute of Energy Conversion
In	indium
InGaAs	indium-gallium-arsenide
I-R	Industrial Research
I_{sc}	short-circuit current
I-V	current-voltage
JPL	Jet Propulsion Laboratory
kg	kilogram
kW	kilowatt
kWh	kilowatt-hour
m	meter(s)
m^2	square meter(s)
MIT	Massachusetts Institute of Technology
Mo	molybdenum
mW	milliwatt(s)
MW	megawatt(s)
n	n-type (material with excess electrons)
n^+	heavily doped n-type
O	oxygen
p	p-type (material with excess holes)
P	phosphorous
p^+	heavily doped p-type
PCS	power-conditioning subsystem
PCU	power-conditioning unit
pn	p-type/n-type
PRDA	Program Research and Development Announcement
PV	photovoltaics
R & D	research and development
RES	residential experiment station
S	sulphur
Se	selenium
SEEMA	Solar Cell Efficiency Estimation Methodology and Analysis
SERI	Solar Energy Research Institute
Si	silicon
SiH_4	silane
SIMS	secondary ion mass spectroscopy
SiO	silicon oxide
SiO_2	silicon dioxide
SMU	Southern Methodist University
SMUD	Sacramento Municipal Utility District
Sn	tin
TiPdAg	titanium-palladium-silver
TV	television
U.S.	United States
V	volt(s)
VCE	vacuum chemical epitaxy
V_{dc}	direct current volt(s)
V_{oc}	open-circuit voltage
W	watt(s)
W_p	peak watt(s)
yr	year(s)
Zn	zinc
η	conversion efficiency
μc	microcrystalline
μm	micron
%	percent
$	dollar(s)
°	degree(s)
ρ	resistivity
Ω	ohm

Glossary

ac: alternating current; the electric current that reverses its flow, usually 120 times (60 cycles) per second.

Air Mass 1 (AM1): the amount of sunlight falling on the Earth (at sea level) when the sun is directly overhead on a clear dry day (1 kW/m^2).

Air Mass 1.5 (AM1.5): the amount of sunlight falling on the earth at a 48° angle off overhead. The spectrum of the radiation at this air mass value is the standard spectrum of the National Photovoltaics Program and has a power density of 832 W/m^2.

alloy: a substance that consists of two or more chemical elements, usually metals.

aluminum (Al): a metallic chemical element, atomic number 13, often alloyed with gallium and arsenic to make aluminum-gallium-arsenide (AlGaAs), a photovoltaic material used in high efficiency solar cells.

amorphous: a non-crystalline solid that has neither definite form nor structure.

ampere (A): a measure of electric current. One ampere is produced by an electric potential of 1 volt acting across a resistance of 1 ohm.

arsenic (As): a chemical element, atomic number 33, that can be combined with gallium or aluminum and gallium to make gallium arsenide (GaAs) or aluminum-gallium-arsenide (AlGaAs), both of which are photovoltaic materials used in high efficiency solar cells.

antireflection coating: a thin layer of material, which decreases light reflection and increases light transmission, applied to a solar cell surface.

array: any number of solar modules, connected together to provide a single electrical output. Arrays are often designed to provide significant amounts of electricity.

atomic spacing: the distance between atoms in a crystal or other solid.

back ohmic contact: electrical contact(s) on the back of a solar cell that is connected to outside wires.

back surface field: field built in at the back of a solar cell to reflect photo-excited charge carriers back to the side of the cell where they can be collected.

back surface reflector: see ***back surface field.***

balance of system (BOS): PV-system components other than the array, including switches, controls, power conditioning equipment, and supporting structures for the array.

band gap energy: the amount of energy (measured in electron volts) needed to raise an electron from the top of the valence band, where it is part of one atom, to the bottom of the conduction band.

boron (B): a semi-metallic chemical element, atomic number 5, used as a dopant to make p-type silicon.

broadband radiation: radiation over a wide range of frequencies.

building block: the smallest unit of a PV system that can be cost-effectively used in multiples to form larger PV systems.

cadmium (Cd): a chemical element, atomic number 48, used in making certain types of solar cells.

carbon (C): a nonmetallic element, atomic number 6, that occurs freely as diamond or coal. When uncontrolled, carbon can be an undesirable impurity in photovoltaic materials. When under control, however, it can be beneficially incorporated into some photovoltaic materials, such as gallium arsenide, to provide desired electronic properties.

carrier lifetime: the time charge carriers (free electrons or holes) exist before recombining with holes or electrons, respectively.

cascade device (cell): a device made of two or more solar cells built atop one another forming one unit. The top cell absorbs short wavelength, blue light and allows the longer wavelength red light to pass through to illuminate the lower cell(s).

cell junction: where two layers in a photovoltaic cell come together.

cell stability: the ability of a cell to produce a constant amount of power under given environmental conditions.

central power (utility): the generation of electricity in large power plants for distribution through a network of transmission lines (grid) to many users.

charge carrier: a free and mobile electron or hole in the conduction band of a semiconductor.

chemical vapor deposition (CVD): a method of depositing thin semiconductor films. With this method, a substrate is exposed to one or more vaporized compounds, one or more of which contain desirable constituents. A chemical reaction is initiated, at or near the substrate surface, to produce the desired material that will condense on the substrate.

compound: a substance whose molecules are made up of different types of atoms and which cannot be separated by physical means.

concentration ratio: the amount that sunlight is magnified by a lens or mirror focusing system.

concentrator (module, array, or collector): an arrangement of solar cells that includes a lens or focusing mirror to direct (concentrate) sunlight onto small-area solar cells. Concentrators can increase the power flux of sunlight hundreds of times.

conduction band; conduction level: energy level at which electrons are not bound to a specific atomic nucleus, but are free to wander among the atoms.

conductivity, intrinsic: the electrical conductivity of an undoped semiconductor material. This temperature-dependent conductivity occurs when electrons absorb enough heat energy to jump from the valence band into the conduction band.

conversion efficiency (cell): ratio of the electric power produced by a solar cell to the power in the sunlight falling on the cell.

copper (Cu): a metallic chemical element, atomic number 29, often alloyed with indium and selenium to make copper-indium-diselenide ($CuInSe_2$), a thin-film semiconductor material used in photovoltaic applications.

crystal: a solid that possesses a natural symmetry due to the orderly arrangement of its atoms or molecules.

crystal lattice: repeatable patterns of atoms or molecules that give rise to the unique shapes and special properties of crystals.

crystal structure: the arrangement of atoms or ions in a crystalline solid.

crystallographic defects: imperfections in crystal structure, which can be caused by too-rapid cooling or the insertion of impurities into the lattice.

current: a flow of electrons, electricity.

Czochralski process: method of growing a large-size, high-quality crystal by slowly lifting a seed crystal from a molten bath of the material under careful cooling conditions.

dangling bond: a chemical bond associated with an atom on the surface layer of a crystal. It does not join with another atom of the crystal but points away from the surface.

dc: direct current; electric current in which electrons flow in only one direction.

dendrite: a slender threadlike spike of pure crystalline material, such as silicon.

diffuse radiation: sunlight received indirectly as a result of scattering due to clouds, fog, haze, or other substances in the atmosphere.

diffusion length: the mean distance a free electron or hole moves before recombining with another hole or electron.

dimethyldichlorotin — ($(CH_3)_2Cl_2Sn$): a solid, non-toxic substance used to make tin oxide-based transparent conducting electrodes.

direct radiation: light that travels straight from the sun and casts shadows on a clear day.

distributed power: any power supply located near the point where the power is used; opposite of central power.

dislocation: a defect occurring along certain lines in a crystal structure. It may be connected to other defects, grain boundaries, the surface, or other crystal structures.

disordered alloy: a crystal made of two or more elements, in which the regular pattern of atoms in the crystal lattice is disrupted.

donor: an n-type dopant, such as phosphorus, which puts an additional electron into an energy level very near the conduction band. This electron is easily excited into the conduction band where it increases the electrical conductivity over that of an undoped semiconductor.

dopant: a chemical element added in small amounts to an otherwise pure crystal to modify its electrical properties. An n-dopant introduces more electrons. A p-dopant creates electron vacancies (holes), which act like positive charge carriers in conduction processes.

doping: deliberately adding an impurity to a pure semiconductor to produce desired electrical properties.

electrical conductivity: the transfer of electricity within a substance from points of higher potential to points of lower potential.

electron(s): a negatively charged elementary atomic particle, which exists outside the nucleus.

electron-hole pair: a free electron and its corresponding hole.

electron volt (eV): an energy unit equal to the energy an electron acquires when it passes through a potential difference of 1 volt in a vacuum.

encapsulant: the protective coating used to encase a PV module; usually made of transparent plastic or glass.

envelope: see ***encapsulant***.

epitaxy: the growth of one crystal on the surface of another crystal. The growth of the deposited crystal is oriented by the lattice structure of the original crystal.

ethylene vinyl acetate (EVA): a newly developed encapsulant for PV modules that is durable, transparent, resistant to corrosion, and serves as a flame retardant.

ethyl group: a group containing molecules composed of two atoms of carbon to five atoms of hydrogen.

ethylene (C_2H_4): a colorless, flammable gas that is used to make organic chemicals and the plastic, polyethylene.

fill factor (FF): the ratio of a PV cell's actual power to its power if both current and voltage were at their maxima. A key characteristic in evaluating cell performance.

flat plate (module, array, or collector): an arrangement of solar cells mounted on a rigid, flat surface with the cells exposed directly to incoming sunlight.

fluidized bed reactor (FBR): a reactor that is used in the production of pure silicon for semiconductor or photovoltaic applications. The FBR heats up silane gas (SiH_4) until it breaks down into its silicon and hydrogen components. The silicon is then rapidly and continuously deposited on a bed of silicon seed particles that grow in size.

fluorine (F): a gaseous or liquid chemical element, atomic number 9. Fluorine has several uses in photovoltaics, especially for making window materials and for tying up dangling bonds in amorphous silicon.

Fresnel lens: a segmented lens that focuses light like a magnifying glass to concentrate sunlight onto a solar cell.

front contact: the electrical contact(s) on the front of a solar cell.

front contact fingers: the thin, closely spaced lines of the front electrode that pick up the current from the solar cell while still allowing light to pass between them into the cell.

full sun: the amount of power flux received at the surface of the Earth at noon on a clear day.

gallium (Ga): a metallic chemical element, atomic number 31, often used with arsenic and other materials to make gallium-arsenide based, high-efficiency solar cells.

germanium (Ge): a metallic element, atomic number 32, used in several different photovoltaic and semiconductor materials.

graded layer: a transition layer in a solar cell in which the chemical composition gradually changes from that of the layer beneath it to that of the layer above it.

grain: a particle or discrete crystal.

grain boundary: the surface between individual grains in a metal.

grid: a network of transmission lines, substations, distribution lines, and transformers used in central power systems.

grid interactive (connected) systems: PV systems that are connected to an electrical utility grid.

Hertz (Hz): a unit of frequency equal to one cycle per second.

heterojunction: a region of electrical contact between two different semiconductor materials.

high band gap material: any semiconductor the higher material that absorbs frequency light at the blue end of the visible spectrum

hole: the vacancy where an electron would normally exist in a perfect crystalline structure; behaves like a positively charged particle.

homojunction: the region between the n-layer and the p-layer in a single material solar cell.

hot spot: an area of a PV module that heats by drawing excess current from adjacent areas. The phenomenon is caused by shadowing.

hydride: a compound containing hydrogen and another element.

hydrogen (H): first chemical element in the periodic table of elements.

hydrogenated amorphous silicon (a-Si:H): amorphous silicon with a small amount of incorporated hydrogen. The hydrogen neutralizes dangling bonds in the amorphous silicon, allowing charge carriers to flow more freely.

ion: an atom or group of atoms that carries a net positive or negative charge as a result of having lost or gained electrons.

indium (In): a metallic element, atomic number 49, used in combination with other elements to make some thin-film semiconductors, most notably copper-indium-diselenide.

insolation: sunlight, direct or diffuse.

inverter: a device that converts dc to ac, and vice versa.

kilowatt(s): 1,000 watts.

kilowatt hour (kWh): 1,000 watt hours.

lattice mismatch: a situation that occurs when the regular crystal patterns of two different substances cannot align with one another.

light-emitting diode (LED): a semiconductor diode that converts electrical energy into visible and near-infrared light.

load: the electric power being consumed at any given moment.

loss mechanism: any of a number of ways in which a PV cell, module, or array can lose charge or current.

low band gap material: a semiconductor material that absorbs the lower frequency light at the red end of the spectrum.

majority carrier: current carriers, either free electrons or holes, in excess in a specific layer of a semiconductor material (electrons in the n-layer, holes in the p-layer).

megawatt (MW): 1 million watts; 1,000 kilowatts.

methane (CH_4): a colorless, odorless, tasteless gas that is used as a source of methanol, acetylene, and carbon monoxide.

methyl group: derived from methane gas, this alkyl group consists of one carbon atom attached to three hydrogen atoms.

micron (μm): one-millionth of a meter (0.000001 m).

milliwatt (mW): one-thousandth of a watt (0.001 W).

minority carrier: a current carrier, either an electron or hole, which is in the minority in a specific layer of a semiconductor material. The diffusion of minority carriers under action of the cell junction voltage is the current in a photovoltaic device.

module: the smallest self-contained, environmentally protected structure housing interconnected photovoltaic cells and providing a single dc electrical output.

molybdenum (Mo): a metallic chemical element, atomic number 42, used in several solar cell devices, usually to help the ohmic back contact.

monolithic: fabricated as a single crystal or other single structure.

multijunction device (cell): a high-efficiency photovoltaic device containing two or more cell junctions, each of which is optimized for a particular part of the solar spectrum.

n-type semiconductor: a semiconductor produced by doping an intrinsic semiconductor with an electron-donor impurity (e.g., phosphorus in silicon). (see ***donor*** and ***dopant***.)

ohm: a measure of resistance to the flow of an electric current.

ohmic contacts: contacts that do not impede the flow of current into or out of a semiconductor.

one sun: the maximum value of unconcentrated, natural solar insolation. (see ***Air Mass 1***.)

one-sun cell: a cell designed to operate optimally under one sun.

open circuit voltage: the maximum possible voltage across a photovoltaic cell; the voltage across a cell in sunlight when no current is flowing.

optical transparency: a substance's ability to transmit light of different wavelengths.

oxygen (O): a gaseous chemical element, atomic number 8. The most abundant element in the Earth's crust, it makes up about 21% of the Earth's air by volume.

parallel connection: a way of joining batteries of PV cells by connecting positive leads together and negative leads together. Such a configuration increases the current.

passivation: a chemical reaction that eliminates the detrimental effect of electrically reactive atoms on a solar cell's surface.

peak watt: the amount of power a photovoltaic device will produce at noon on a clear day when the cell is facing directly toward the sun.

pentagonal: a five-sided, five-angled figure.

phosphorous (P): a nonmetallic chemical element, atomic number 15, used as a dopant to make n-type silicon.

photoconductivity: the change in a material's resistance when it is exposed to light.

photo-generated carrier: a charge carrier generated in a PV cell by impinging photons.

photon: a particle of light which acts as an indivisible unit of energy.

photovoltaic cell: a device that converts light directly into dc electricity. A solar photovoltaic cell, or solar cell, is designed for use in sunlight.

polycrystalline: a material composed of variously oriented, small individual crystals.

potential barrier: an electric force at the junction of a PV cell that opposes the flow of free carriers across the junction.

power conditioner: the electrical equipment used to convert power from a photovoltaic array into a form compatible with household or utility use; may include an inverter, transformer, voltage regulator, meters, switches, and controls.

p-type semiconductor: a semiconductor in which holes carry the current; produced by doping an intrinsic semiconductor with an electron acceptor impurity (e.g., boron in silicon).

recombination: the action of a free electron falling back into a hole.

recombination velocity: the average velocity at which carriers recombine in a given semiconductor material.

ribbon: a thin sheet of crystalline or polycrystalline material produced in a continuous process by withdrawal from a molten bath of parent material.

secondary ion mass spectrometry: a method of chemical analysis, in which a high-energy ion beam dislodges sample atoms for analysis.

seed: a particle used to initiate and sustain growth of a material.

selenium (Se): a highly toxic, non-metallic chemical element, atomic number 34, used to make thin-film photovoltaic cells.

semiconductor: any material which has a limited capacity for conducting an electric current. Certain semiconductors, including silicon, gallium arsenide, and cadmium telluride, are uniquely suited to the photovoltaic conversion process.

semiconductor-grade silicon: silicon that is 99.999999% pure.

septagonal: a seven-sided, seven-angled figure.

short circuit current: the current flowing freely from a photovoltaic cell through an external circuit which has no load or resistance; the maximum current possible.

Siemens process: a commercial method of making purified silicon.

silane (SiH_4): a liquid or gaseous compound of silicon and hydrogen that is often used in the production of pure silicon.

silane process: a new process for making purified silicon.

silicon (Si): a semimetallic element, atomic number 14, which is an excellent semiconductor material. It is the second most abundant chemical element in the Earth's crust.

single-crystal material: a material that is composed of a single crystal or a few large crystals.

solar cell: a device that converts sunlight directly into electricity.

solar spectrum: the total distribution of electromagnetic radiation emanating from the sun.

spectral radiation: radiation over selected narrow frequency ranges.

stacked-junction device (cell): see ***multijunction device***.

stand-alone system: a PV system that is not connected to an auxilliary power source.

submodule: a PV system component that is more than a cell but less than a module.

substrate: the physical material upon which a solar cell is made.

subsystem: an autonomous unit that is a component of a PV system, such as a PV array, power conditioner, or tracker.

sulfur (S): a nonmetallic chemical element, atomic number 16, that is used in many semiconductor materials.

tandem solar cell: see ***multijunction device***.

tellurium (Te): a chemical element, atomic number 52, used in several semiconductor materials.

tetramethyltin — $(CH_3)_4Sn$: a toxic liquid used to make tin oxide-base transparent conducting electrodes.

thin film: a layer of semiconductor material such as polycrystalline silicon or gallium arsenide, a few microns or less in thickness, used to make photovoltaic cells.

tin (Sn): a metallic chemical element, atomic number 50, often used in window material or in semiconductor material, such as amorphous silicon, to raise the band gap.

tintetrachloride ($SnCl_4$): a liquid, non-toxic substance used to make tin-oxide-based transparent conducting electrodes.

tracking system: a mount that permits a solar system to follow the sun. A 2-axis tracker can adjust to both daily and seasonal changes in the sun's position. A 1-axis tracker can do one or the other, but not both.

transition layer: see ***graded layer***.

transparent conducting film: a thin film that is transparent to light and conducts electricity efficiently; used as electrodes on a PV cell.

transparent conductive oxide: an oxide, usually in the form of a tin oxide, used as a transparent conducting film.

transport properties: the characteristics of a semiconductor material associated with the movement of carriers.

trap: a defect or impurity in a semiconductor material that attracts and holds free electrons or holes.

triethylgallium — $(C_2H_5)_3Ga$: a gas composed of ethyl groups and gallium; used as a source for growing gallium-based semiconductor crystals.

trimethylgallium — $(CH_3)_3Ga$: a gas composed of methyl groups and gallium; used as a source for growing gallium-based semiconductor crystals.

vacuum chemical epitaxy (VCE): a newly developed technique for epitaxially growing semiconductor crystals in a vacuum chamber.

volt, voltage (V): a measure of the ability to perform work (electical), analogous to the pressure of water flowing in a pipe. One volt produces one amp of current when acting against a resistance of one ohm.

wafer: a thin sheet of semiconductor material made by mechanically sawing it from a single crystal ingot.

watt (W): basic unit of electric power, equal to one volt multiplied by one ampere.

watt hour (Wh, Whr): a measure of electricity; one watt hour is consumed when one watt of power is used for one hour.

window: a wide band gap material chosen for its transparency to light. Generally used as the top layer of a semiconductor device, the window allows almost all of the light to reach the semiconductor layers beneath.

zinc (Zn): a metallic chemical element, atomic number 30, used in alloys, semiconductors, and window materials.

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