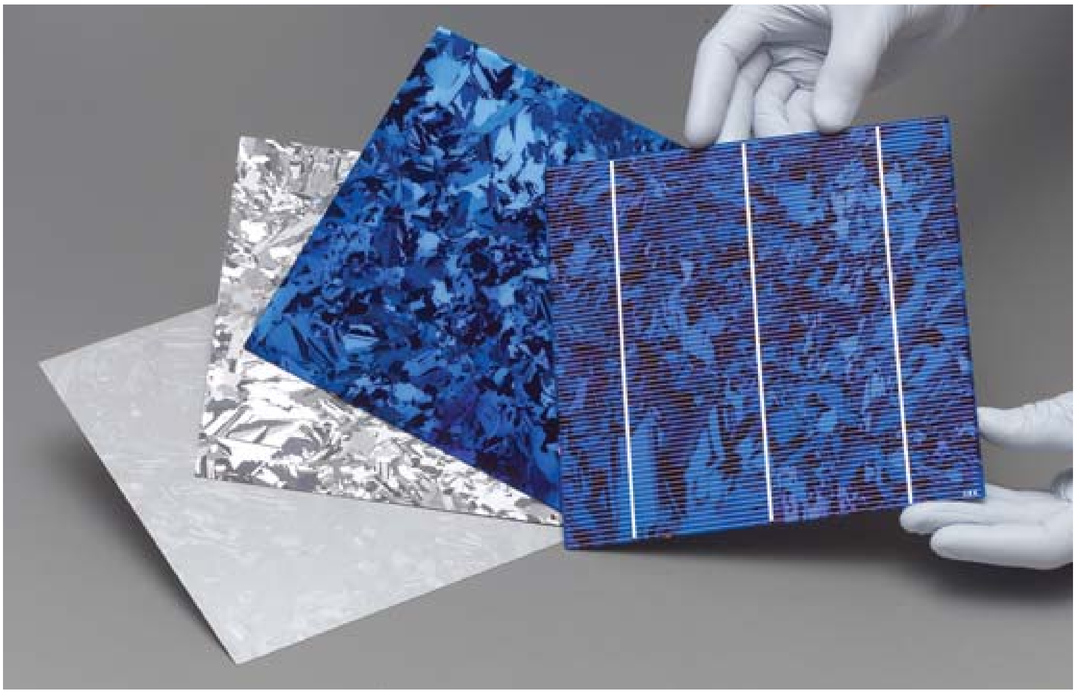
High-tech cells for **cheaper** modules

If it is to be competitive with other generation sources, photovoltaic electricity needs must achieve considerable cost reductions yet. Beyond optimization of current module utilization, novel technological approaches are being investigated. Once technological barriers are overcome, in particular with the help of the new development resources CEA is making available to manufacturers, the organic-inorganic composite pathway could well provide cheaper components, for applications complementing those industrially opened up by the silicon pathway, even though efficiencies do remain poorer than for the latter technology.



D. Michon-Artechnique/CEA

200-mm × 200-mm silicon wafers, at various stages in the fabrication of a photovoltaic cell, on the Restaure Platform (from left to right: after slicing by wire saw; after texturing and forming the emitter; after deposition of the blue antireflection coating; and after forming the contact grids, prior to assembly into a module).

The **photovoltaic** industry is currently embarking on new directions, along paths marked by technological challenges, commanded by economic and budgetary requirements. Over twenty years, the selling price per photovoltaic **watt** has come down considerably. From over €100 in 1975, this has now fallen to €2-3 for **photovoltaic modules** (see Box 1), and €5-6 for a grid-connected system. World industrial output, at the same time, is experiencing heady growth, reaching 750 **MW** in 2003, whereas it stood around the 50-MW mark in 1990, and forecasts looking to 2010 are estimating this will rise further by a factor 20.
The cost of photovoltaic electricity, however, must yet come down further, if it is to be competitive with other generation sources. This will require new technological approaches, enabling cost reductions and/or improvements in **conversion efficiency**. The **silicon** pathway is seeking to achieve cost reductions both from process optimization and enhanced efficiencies, these probably remaining consistently better than those for the organic, **polymer**-based pathway. Be that as it may, the latter is indeed looking to achieve that selfsame cost-reduction goal, plastic materials being cheaper than silicon.
In the meantime, achieving proper characterization of modules is a technical and economic requisite, if connection to the grid is to be effected in satisfactory conditions.

Characterization of photovoltaic solar modules

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Module characterization benches, part of the SOL Platform.

Measurement of the electric power output of photovoltaic solar modules, and computation of energy yield must be as accurate as possible, since these data have a significant economic impact. To encourage installation of grid-connected modules by private individuals, indeed, in France, a subsidy is allocated, depending on installed electric power, and the ability to sell the kilowatt-hours generated to the power utility.

Photovoltaic cells (see Box D, ***How does a photovoltaic solar cell work?***) are designed to be integrated into **modules** (see Box 1) yielding, in broad sunlight, power outputs of the order of 100-150 **W**/m², at a cost ex-factory, in 2004, of some €250-300 for 100 W.

In France, since spring 2002, private persons installing grid-connected photovoltaic solar modules may be allocated a subsidy proportional to installed **electric power**, to wit €4,600 (inclusive of tax) per **kilowatt**.(1) A number of regional authorities complement this subsidy, and tax advantages help bring down the expenses left to the individual concerned. In aggregate, however, such aids do not cover installation costs, evaluated as standing close to €8,500 (inclusive of tax) per kilowatt. The law, as it stands, therefore provides for a set purchase price, by the grid operator, of the **kilowatt-hour** thus generated, for the initial twenty years of operation of an installation. For contracts firmed up in 2003, purchase price by French national power utility EDF stood at around 15 euro cents (before tax) in mainland France, and 30 euro cents (before tax) in Corsica and overseas *départements* (administrative divisions). That schedule came down by around 10%, for contracts signed in 2004.

Thus, time for full return on investment, for a grid-connected photovoltaic installation, is directly related to the amount of available subsidies, this being proportional to installed electric power, and the photovoltaic module's electricity yield over twenty years, depending on the site.

(1) For further information on this, refer to the Ademe website, at the address: http://www.ademe.fr/particuliers/Fiches/reseau/rub5.htm

Electric power: accurate measurement a requisite

The electric power output of photovoltaic modules is measured by the manufacturer, as they exit the assembly line, in standardized conditions: irradiance of 1,000 W/m², with a very definite spectral distribution, close to that of the solar spectrum, for a module temperature set at 25 °C. Electric power may also be measured by means of outdoor tests, making direct use of sunlight, which, in clear sky conditions, delivers irradiance very close to 1,000 W/m².

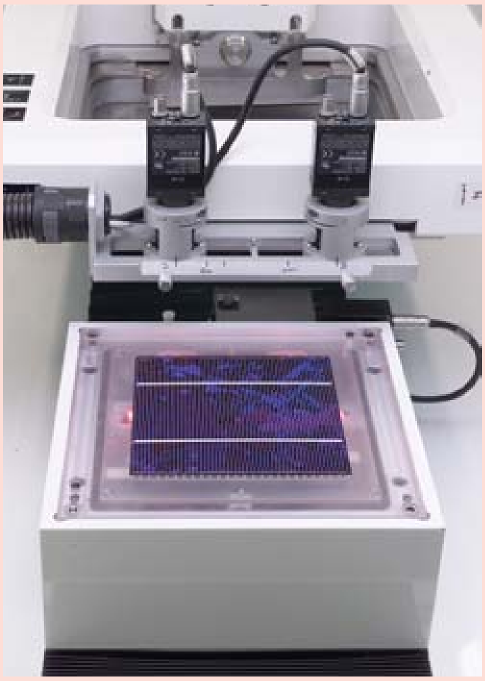
Measurement of photovoltaic module electric power is no straightforward matter, whether it be under natural or artificial illumination. Which is why significant discrepancies are not uncommonly found to arise, between characterization benches, with a spread of ± 5%, be it from manufacturers, or the industry's reference laboratories. The economic stakes here are considerable, since module selling price is directly proportional to measured power. Thus, any alteration in measured power values has a direct incidence on the manufacturer's profit.

The European PV Catapult Program, launched in summer 2004, in which CEA is a participant, has in particular set itself the goal of arriving at an understanding of the discrepancies found between various test benches, and harmonizing European measurement practices, as a contribution to international standardization.

From cell to module

1

Silicon is the most widely used material for the fabrication of **photovoltaic cells**, these being further assembled into **modules**. However, other materials are beginning to gain acceptance, for some applications.
A photovoltaic cell is based on a **semiconductor** material, the most widely used for cell fabrication (95% market share) currently being **crystalline** (micro-, multi-, or monocrystalline) **silicon**.(1) Its **bandgap** width makes it one the materials allowing the highest **conversion efficiencies**, of the order of 12-17%, depending on crystalline nature of the material employed, and fabrication process. Such an efficiency is double that for **amorphous silicon**, this accounting for less than 5% market share.



D. Michon-Artechnique/CEA

Silicon wafer, after contact grid deposition by screen printing.

Photovoltaic cells are fabricated from silicon **wafers** having a thickness of less than 300 **µm**, sliced from ingots of monocrystalline silicon (still relatively expensive), or multicrystalline silicon. Silicon still originates, in the main, from microelectronics scrap, however this source is becoming inadequate, and fabrication processes for photovoltaic-grade silicon, of lower purity than that of silicon intended for microelectronics, are being developed.

(1) For further information, see the paper *Photovoltaic solar modules: from crystalline silicon to thin film*, *Clefs CEA*, No. 44, 2001, available on the CEA website at the address: http://www.cea.fr/gb/publications/Clefs44/an-clefs44/clefs4427a.html

Overall, silicon wafer fabrication accounts for 40% of module price, technology for the cell proper for 20%, and assembly into modules 40%. To achieve cost reductions, savings must be sought at every step: silicon purification, ingot fabrication, and wafer cutting. The attractive solution consisting in production of silicon ribbons proved unable to establish itself, owing in particular to poorer quality of the silicon thus obtained. Satisfactory cell operation, indeed, involves a number of factors: maximum light absorption over the entire solar spectrum, efficient collection of the **photon**-generated **carriers** (**electrons** and **holes**), and the setting up of an electric connection with the outside circuit.
The **junction** is thus formed through diffusion of **doping agents** (the wafers used are *p-doped*, as a rule, however phosphorus is introduced through diffusion, to *n-dope* the silicon, to a depth of the order of a **micrometer**). A silicon nitride antireflection coating, also serving to enhance material quality, is then deposited. Following this, metallic contact grids, serving as current collectors - featuring very thin lines, to restrict shadowing effects - are formed by **screen printing**. Annealing then enables contact to be set up between the silicon and collector grids. An aluminum strip, to serve as inter-cell connector, is then soldered onto the grids. After which the cells are individually tested, sorted according to conversion efficiency, and assembled into modules.
The module fulfills a number of functions: connecting cells together, to deliver the required voltage (typically, 36 cells connected in series, for a 12-V output), and protecting them against attacks from the environment. The illuminated face of the cells is bonded onto tempered glass, to ensure mechanical protection. The rear face of the cells is shielded by a glass pane or lighter plastic film, bonding being effected by means of a **polymer** (ethylene vinyl acetate [EVA]), ensuring protection of the module against moisture.
Of materials exhibiting properties such as to make them candidates to substitute silicon, one, CdTe (cadmium telluride), has been abandoned, due to the fact - among other issues - that presence of cadmium, a heavy metal, raised environmental concerns for module end of life. CIS (copper-indium-selenium) is currently the most promising thin-film material, however its contribution to the photovoltaics market remains a modest one, standing at less than 1%.
Current research efforts are essentially addressing cost reduction issues (module selling price nowadays stands at €2.5-3/**W**), in particular through improved conversion efficiencies.

Narrowing down measurement uncertainties

The SOL (Solar Outdoor Laboratory) Platform, set up at CEA's Cadarache Center, is designed to carry out testing in outdoor conditions of photovoltaic generators. It takes its place in a chain of platforms, covering the range from basic component to complete system: Restaure, at CEA's Grenoble Center, concerned with photovoltaic cell fabrication (see *The Restaure Platform: a response to industry expectations*), and SOL for photovoltaic modules and systems. SOL has the potential, through measurements under natural insolation, to

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Absolute cavity radiometer, allowing highly precise measurement of solar flux intensity.

take on a reference role for this standardization approach. Acquisition of an absolute cavity radiometer, and of a spectroradiometer, will allow - taking advantage of outstanding insolation at the site in all seasons - highly accurate solar flux measurements to be carried out, in terms both of intensity and spectral distribution, and contribute to narrowing down measurement uncertainties as to module power output.
The stability over time, and uniformity over space, of the solar flux mean it is an unrivalled light source, in particular for the characterization of new-technology, thin-film photovoltaic modules, testing of which is difficult under artificial illumination. Indeed, the flashlamps used yield flashes that are too short in duration, further exhibiting highly inconvenient spectral lines.

Computing electric energy yield

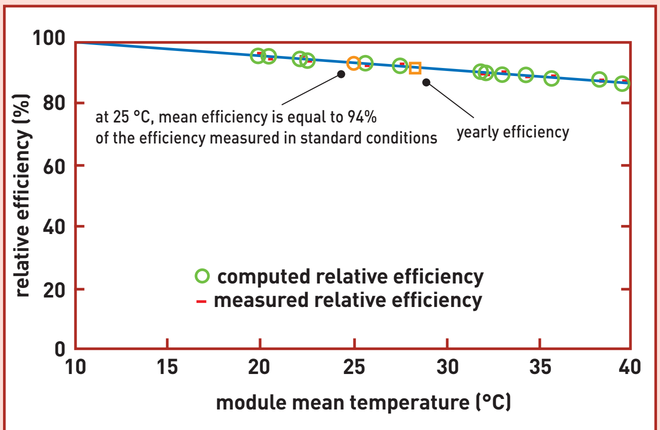
The electric energy yield from photovoltaic modules depends on many factors: on their standard power, obviously, but equally on the amount of light energy received, and, to a lesser extent, on module mean temperature over the period of operation.
The amount of *light energy received* depends on climate for the site involved, insolation rising, in France, from north to south, with energy peaks in Provence, and in the Pyrénées-Orientales *département* (French Catalonia). It also depends on module positioning, with maximum irradiation occurring for a south-facing module (in the northern hemisphere), set at a tilt angle approximately matching local latitude.
The most recent measurement campaigns carried out on the SOL Platform have allowed the influence of temperature to be quantified, by showing that module efficiency, over a fairly extended period (one month at least) is a linear function of module mean temperature, over the period considered (see Box 2). It is estimated the average efficiency of a **crystalline-silicon** module falls by about 0.5% per degree C.
As module *mean temperature* depends on outside temperature and average wind speed for the location involved, it is apparent that, for a given insolation, efficiency rises from south to north, and, more generally, in wind-swept regions. The fact that efficiency falls from north to south, which may seem paradoxical, is due to the fact energy output rises considerably, in correlation with the increase in solar resource.
Finally, if all losses in a grid-connected photovoltaic system, including those occurring in the inverter transforming the module's direct current into 50-Hz alternating current, are taken on board, a downgrading by 20-25% of module power, as measured by the manufacturer, may reasonably be used, for computations of electricity yield.

CEA

Calibration of pyranometers by a new method improving measurement accuracy. The three devices are collimators aimed at the Sun.

Influence of temperature on photovoltaic module efficiency

2



$$\text{efficiency} = 0.94 - 4.3 \cdot 10^{-3} \cdot \left(\overline{T}_{ext} + \frac{Wh/m^2{}_{received}}{\text{length of day}} \cdot \frac{1}{22.4 + 8.7 \cdot \overline{wind}} - 25\ °C \right) \pm 2.6\%$$

Relative efficiency of a photovoltaic module, as a function of mean module temperature. This may be computed from mean meteorological data.

The efficiency of a **photovoltaic module**, over a given period, is the ratio between electric energy generated by the module, and solar energy received. Mean yearly efficiencies, in photovoltaic modules, may vary considerably, depending on module technology, ranging from less than 5% to over 15%. A module's relative efficiency, over a given period, is further the ratio between the energy efficiency measured over that period, and the energy efficiency measured in so-called standard conditions (irradiation at 1,000 **W**/m^2, with a definite spectral makeup, for a **photovoltaic cell** temperature of 25 °C).
It is found this relative efficiency is a linear function of photovoltaic module mean daytime temperature (see Figure). The latter in turn may be expressed as function of outside temperature, mean irradiation, and wind speed, according to a formula derived from the classical thermal laws of **convection** and infrared radiation. In this equation, the coefficients depend, among other factors, on module positioning conditions, and local characteristics of the site.

For instance, at Cadarache, a location receiving some 1,850 kWh/m^2 solar energy per annum, for a surface tilted to the south at an angle of 45°, a 1-kW photovoltaic generator will yield $1 \times 1{,}850 \times 80\% = 1{,}440$ kWh electric per annum. At a rate of €0.15 (before tax) per kilowatt-hour, the individual owner will get €222 (before tax) per installed kilowatt per year, from which amount rental for the EDF electric meter has to be deducted (unfortunately, the maximum amount of energy refunded by EDF is 1,200 kWh per installed kilowatt).

F. Vigouroux/CEA

Measurement of the surface temperature of a photovoltaic solar module.

Optimization of module utilization

Much experimental and modeling work still remains to be done, to arrive at a generalization of this finding, obtained for a few module technologies, in a particular climate context. In particular, what is at stake is gaining a good understanding, and achieving optimization, of the utilization of modules as architectural elements, especially with a view to achieving integration, in a single roof-mounted collector, of the electric generation and heat generation functions, for the heating of premises and sanitary water.

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The Restaure Platform: a response to industry expectations

The setting up in Grenoble of a high-performance French tool dedicated to the fabrication of silicon photovoltaic cells meets the expectation of businesses concerned to ensure that novel technological approaches be developed in conditions close to those prevailing in industry.

D. Michon-Artechnique/CEA

200-mm × 200-mm silicon wafers being loaded onto the source boat of the diffusion furnace used to form the photovoltaic cell's emitter. The Restaure Platform at CEA/Grenoble is one of the few to cater for such a wafer area, the standard being 150 mm × 150 mm.

The new technological approaches used in **photovoltaic cell** development needs must be validated in conditions close to those prevailing in industry, if they are to be amenable to rapid transfer to industry. The tool to enable such validation had been, until now, the missing link, in France, with respect to development of these cells. The Restaure technological platform, which has just been set up at CEA's Grenoble Center, with support from **Ademe**, as part of an ensemble further comprising the organization's "fuel cell" and "miniature energy sources" platforms, will effectively enable the rapid transfer to industry of technologies developed in the laboratory. Its construction is consonant with the wish, evinced by the protagonists on the French scene, to build up an ambitious **photovoltaics** development program.
It features equipment that is entirely full-scale, to make for greatest ease of transfer for the processes developed. The equipment has the required flexibility to cater for wafers of highly diverse shapes and sizes (whether round, of 50-150 mm diameter, or square, of 50-200 mm side), and new features may be added to the existing ones, to carry out further operations. The platform may be accessed by personnel from outside laboratories, and manufacturers, under the aegis of specific agreements, precisely setting out the terms for such collaboration and covering intellectual property issues, practical management being carried out by a steering committee.

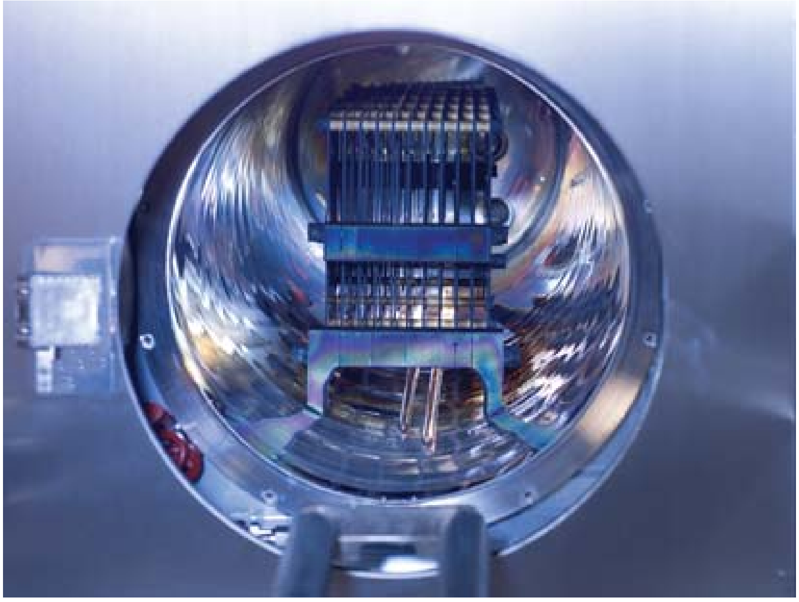
Restaure has been operational since mid-February 2004, and the first (150-mm × 150-mm) cells to be fabricated by means of conventional processes are achieving **conversion efficiencies** of 15.3%, which is a good basis for fabrication of high-performance cells.
The setting up of the Grenoble platform received a highly favorable reception from manufacturers. Two programs aimed at bringing down the cost of photovoltaic electricity, for which the platform will provide a crucial instrument, have just been launched. One, coordinated by Photowatt, seeks to achieve, within 4 years, cost reductions in **photovoltaic module** fabrication, while the second, extending over 5 years and piloted by CEA, seeks to raise cell efficiency to 20%, using technology transferable to industry. Both programs, funded as they are by Ademe, are being conducted in partnership with **CNRS**.

The French context: priority to production

The French protagonists in the photovoltaic industry, the principals being Photowatt, for photovoltaic cell and module production, and Total Énergie for systems, rank among European leaders. Strong sector growth is leading manufacturers to focus on development of their industrial production. In the short term, Photowatt is to bring out cells with a yearly output of 30 **MW**, on a market 90% dominated by the **silicon** pathway: this target is on course to be achieved, with the introduction of a novel process, allowing fabrication of cells exhibiting conversion efficiencies of 14-15%. With its drive centered on increasing output, the company is looking to support from French laboratories for its new developments. Indeed, upstream research, in the photovoltaics area, is undergoing structural reorganization, to best meet the manufacturer's demand.

Collaboration on a European scale

All French actors in the field, when surveyed in 2001 and 2002, were agreed that their competitiveness may only be sustained with support from strong technological research, one of the mainstays for which is the setting up of technological platforms, having the capability to develop "breakthrough technologies," as is the case for ISE (Fraunhofer Institute for Solar Energy Systems) in Germany, ECN (Energy Research Center of the Netherlands) in the Netherlands, and IMEC (Interuniversity Microelectronics Center) in Belgium, to name but European neighbors. Such platforms, flexible in their utilization, allow, on the one hand, in the short term, current technological barriers to be overcome, in collaboration with industry, and, on the other hand, in the medium term, to prepare for "breakthrough technology," along with national research institutes. Collaboration with European institutes deploying such platforms is to be developed, in particular in advanced research sectors, where resources may be pooled.
At the same time, equipment manufacturers (SEMCO, Centrotherm…) are looking to improved performance, by way of operational feedback, for their own equipment (diffusion or annealing furnaces, plasma treatment machines). Materials producers are seeking validation of their products, and development of processes suited to their specific requirements. As for cell and module manufacturers, their demand is for development and transfer of processes enabling higher efficiencies, and lower fabrication costs.


D. Michon-Artechnique/CEA

Silicon wafers undergoing treatment in the PECVD (plasma-enhanced chemical vapor deposition) furnace for deposition of the antireflection coating. Treatments are effected in clean rooms, on equipment close to industrial practice, making for easier process transfer.

The second stage of the French program

At the outcome of the first (one-year) stage of the program, which saw completion of the platform itself, and development of a basic process which enabled swift achievement of the best conversion efficiencies to be obtained on an industrial basis, France can avail itself of a tool for the development of high-performance photovoltaic cells. Research workers and manufacturers can use it to test innovations issuing from laboratories, by introducing them into cell fabrication; to bring such as are deemed useful up to industrial transfer level, by setting up, as required, dedicated equipment within the platform; to validate novel industrial steps enabling higher efficiencies and lower reject rates and costs; and, finally, to develop and optimize technology for novel silicon materials.
The second stage will consist in the carrying out, in collaboration with laboratories and manufacturers, of the programs to achieve cost reductions and improved efficiencies, mentioned earlier. Further programs, aimed at development of a complete photovoltaic pathway (from fabrication of a silicon material suited to photovoltaics, to construction of the module) are being set up.
At the same time, an area is being set aside for the development of future equipment. Equipment makers will thus have the ability, with the platform, of availing themselves of an environment allowing them to develop new machinery, and novel processes. They will also have at their disposal the expertise of CEA staff, as regards device fabrication and characterization.

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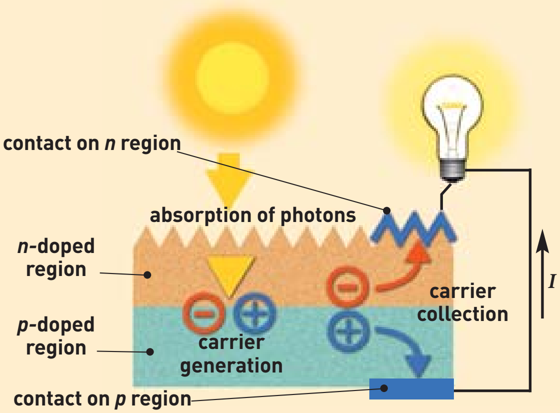
D How does a photovoltaic solar cell work?

The photovoltaic effect used in solar cells allows direct conversion of light energy from the Sun's rays into electricity, by way of the generation, and transport inside a semiconductor material, of positive and negative electric charges, through the action of light. This material features two regions, one exhibiting an excess of electrons, the other an electron deficit, respectively referred to as *n-type doped*, and *p-type doped*. When the former is brought into contact with the latter, excess electrons from the *n* material diffuse into the *p* material. The initially *n*-doped region becomes positively charged, and the initially *p*-doped region negatively charged. An electric field is thus set up between them, tending to force electrons back into the *n* region, and holes back into the *p* region. A junction (so-called *p-n* junction) has been set up. By placing metallic contacts on the *n* and *p* regions, a diode is obtained. When the junction is illuminated, photons having an energy equal to, or higher than, the width of the forbidden band, or band gap, yield their energy to the atoms, each photon causing an electron to move from the valence band to the conduction band, leaving behind it in turn a hole, also able to move around the material, thus giving rise to an electron-hole pair. Should a load be positioned at the cell's terminals, electrons from the *n* region will migrate back to the holes in the *p* region, by way of the outside connection, giving rise to a potential difference: an electric current passes (see Figure).



The effect thus involves, basically, the material's semiconducting properties, and its doping, to improve conductivity. Silicon, now used in most cells, was selected for the presence of four valence electrons in its outermost shell (column IV of the Mendeleyev periodic table). In solid silicon, each atom - termed a tetravalent atom - is bound to four neighbors, and all electrons in the outermost shell participate in the bonds. Should a silicon atom be substituted for by an atom from column V (a phosphorus atom, for instance), one of its five valence electrons is not involved in the bonds; as a result of thermal agitation, it soon moves to the conduction band, thus becoming free to move through the crystal, leaving behind it an immobile hole, bound to the doping atom. There is electron conduction, and the semiconductor is designated as an *n-type doped semiconductor*. If, on the other hand, a silicon atom is substituted for by an atom from column III (boron, for instance), carrying three valence electrons, one electron is missing, if all bonds are to be maintained, and an electron may quickly move in to fill this gap, taking up the vacant orbital, as a result of thermal agitation. A hole thus arises in the valence band, contributing to conduction, and the semiconductor is said to be a *p-type doped semiconductor*. Atoms of elements such as boron or phosphorus are thus doping agents in silicon. Photovoltaic cells are assembled into modules.

Note: In *Organic photovoltaic cells: towards an all-polymer path...*, you will find the operating principle of organic photovoltaic cells (Box, p. 122).

Operating principle of an organic photovoltaic cell

Following absorption of photons by the polymer, bound electron-hole pairs (excitons) are generated, subsequently undergoing dissociation. Owing to inherent limitations in organic materials (exciton lifetime, low charge mobility), only a small fraction of photon-generated electron-hole pairs effectively contribute to the photocurrent. One of the main ideas is to achieve volume distribution of the photogeneration sites, to enhance exciton dissociation. This approach is based on increasing junction surface area, through deployment of an interpenetrating network of the donor-acceptor (D-A) type, effecting transport of holes (P^+) to the anode (indium-tin oxide [ITO]), and of electrons (e^-) to the metallic cathode (made e.g. of aluminum [Al]). While quantum separation efficiency, for photoinduced charges in systems associating a semiconducting polymer (of PPV or polythiophene type) with a fullerene derivative (PCBM), is thus close to unity, the challenge now is to restrict recombination and trapping processes limiting charge transport and collection at the electrodes, to improve overall device efficiency, this currently still being low (less than 5%). The rise of the pathway is also heavily dependent on mastery and understanding of cell aging mechanisms, but equally on mastery of thin-film technologies, to achieve protection of the device against atmospheric oxygen and water vapor.

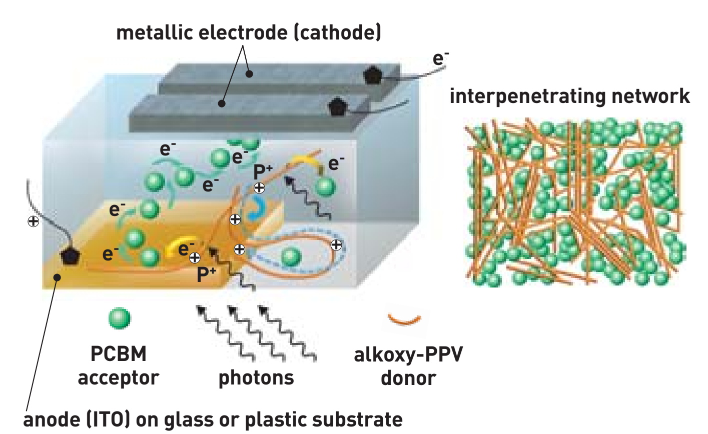


Figure from a presentation by S. Sariciftci (www.lios.at)

The blue dotted line shows the trajectory of holes inside the material.