Teacher's Reference Resource

School-Based Elective Module

NSW HSC Preliminary Engineering Studies

Engineering Application Module 4

Photovoltaic Engineering

Introduction to the Resource

This resource booklet is intended for teachers who are interested in teaching the 'Photovoltaics' elective module for NSW Year 11 Preliminary Engineering Studies. It is intended that students work through the self-study PowerPoint presentation by themselves, asking questions when they have difficulty. This booklet contains detailed background information for the teacher to be able to answer such questions, and to guide students through the self-study PowerPoint. This document is also available to students via links in the PowerPoint, so that they may further their understanding of the materials presented, and to clarify any areas of difficulty on their own. Maximum use has been made of free-to-access, online resources included under the 'further reading' sections of this text, so that students may easily search for additional information on topics of their interest. The intention of all these features is to encourage students to become independent learners.

The materials were prepared between 2006-2008 by Hugh Sangster (BEng RE UNSW), Bany Jaya (BEng RE UNSW), Martha Lenio (BE Mech, PhD Candidate), Fennalia Tan, Shelley Bambrook (BEng PV UNSW), and Dr. Richard Corkish (BEng RMIT, PhD UNSW) from the School of Photovoltaic and Renewable Energy Engineering at the University of New South Wales. Valuable feedback and suggestions were provided by Lloyd Zietsch, Peter Myers and Mark Gregory of Kirrawee High School, particularly about running the course with trial versions of the course materials. Rob Largent (AS USA) from UNSW also provided great assistance by supplying graphics and uploading the course package onto the UNSW website. Funding and assistance for this project was kindly provided by the New South Wales Government Department of Environment and Conservation, through its Climate Action Grants 2006 Program *(Ref no: C06/CAG/043).*

All the materials in this course package will be located at The University of New South Wales School of Photovoltaic & Renewable Energy Engineering website. Here is the school's URL → http://www.pv.unsw.edu.au/estudies
The URL for the course materials with compressed (low quality) video
→ http://www.pv.unsw.edu.au/estudies/coursepacklo.zip
The URL for the course materials with higher quality (and larger file size) video
→ http://www.pv.unsw.edu.au/estudies/coursepackhi.zip
The URL for the course materials without any video (smallest file size)
→ http://www.pv.unsw.edu.au/estudies/coursepackno.zip

SCHOOL BASED ELECTIVE MODULE

ENGINEERING APPLICATION MODULE 4:
PHOTOVOLTAIC ENGINEERING

TEACHING PROGRAM

24 hours of indicative time

This module covers silicon and solar cell manufacture, photovoltaic modules, control circuits, system layouts and applications.

Outcomes

A Student:

P1.1 identifies the scope of engineering and recognises current innovations

P2.1 explains the relationship between properties, uses and applications of materials in engineering

P3.2 develops written, oral and presentation skills and applies these to engineering reports

P3.3 applies graphics as a communication tool

P4.1 describes developments in technology and their impact on engineering products

P4.3 identifies the social, environmental and cultural implications of technological change in engineering

P5.1 demonstrates the ability to work both individually and in teams

P6.1 applies knowledge and skills in research and problem-solving related to engineering

P6.2 applies skills in analysis, synthesis and experimentation related to engineering

A note to teachers and administrators: The teaching program provided includes content that is intended to be taught over a period of 24 indicative hours. However, teachers may select appropriate sections of material based on the time constraints of the individual class and school.

Students learn about:	Students learn to:
Historical and societal influences: • Historical developments of photovoltaics and how experience curve shows cost reduction over time • The effect of engineering innovation on people's lives, particularly in rural areas and developing countries • The environmental implications of photovoltaics including mitigation of global warming & the enhanced greenhouse effect • The link between photovoltaics, renewable energy, self-sufficiency & equity	• Define terminology related to the photovoltaic industry • Identify the added-value benefits for photovoltaics such as supply security, reduced transmission losses, rural independence, sustainable job creation, & grid voltage support. • Explain the mechanisms of enhanced greenhouse effect and the impact of the solutions that photovoltaics can provide (already covered ←)
Engineering mechanics • The manufacturing process of a silicon solar cell • The role of doping (see right →) • How a photovoltaic cell operates including identifying that light includes photon using the photoelectric effect • How modules are manufactured and tested • Photovoltaics Applications (assignment)	• Describe the operation of a p-n junction and compare its operation with diode • Make a flowchart of the silicon solar cell manufacture from silicon extraction & purification to cell production (see left ←) • Identify methods of linking cells to form modules and evaluate each and understand the impact of cell shading on module and system output • Describe the use of accelerated lifetime testing to determine module's life and identify common failure modes. (see left ←) • Compare and contrast between solar thermal technologies and photovoltaics • Produce a group Engineering Report on one of the photovoltaic applications given at the end of the section (assignment)
Engineering materials • The different materials used to construct solar cells, and the advantages and disadvantages of each • Thin film vs. wafer technologies, and issues • Properties of materials	• Differentiate between thin-film and wafer technologies and identify the advantages and disadvantages of each. (see left ←) • Compare and contrast the different materials used to construct solar cells (see left ←) • Identify reasons for sourcing Silicon from

- Glass and Tedlar use in encapsulation - Antireflection coatings - Texturing • Structure of materials - Interaction of photon with silicon to produce electrons - Crystalline structures in silicon • Metals - The use of metals in contacts to collect current	the Integrated Circuits (IC) industry • Briefly identify the difference between single crystal, polycrystalline, multi-crystalline, amorphous & ribbon silicon (see left ←) • Using diagrams to describe how texturing and antireflection coatings operate optically (see left ←)
Engineering electricity/electronics • Basic electrical principles - Potential difference - Current - Simple circuits and components - Power and IV curve - Safety with DC • Control circuits - Inverters & Maximum Power Point Tracker (MPPT) - Regulator - Batteries - Charge controller • Islanding concerns & techniques to overcome them • PV system sizing and configuration according to application	• Draw a block diagrams of the workings and waveform output of inverters, charge controllers and regulators/MPPTs (see left ←) • Identify the use of logic gates in control equipment/devices • Identify the need for control systems • Why are batteries important to photovoltaics and how can they be best utilized, combined and configured. • Interpret current voltage curves (IV curves) for photovoltaic modules • Appreciate the importance of safety when working with DC circuits. • Identify the parameters involved in power losses in transmission lines.
Communication • Block diagrams and flow chart • Research methods including the Internet, CD-ROM and libraries • Collaborative work practices • Engineering Report writing	• Conduct research using computers, the world wide web and printed resources • Complete an Engineering Report in a team on one of the photovoltaic topics provided. • Use correct referencing techniques for research work • Interpret circuit diagrams

Engineering Report Topics

Off-Grid:

- Water pumping [in-class special topic]
- Remote Area Power Supplies (RAPS)
- Remote Area Telephony
- Solar Home System in Developing Countries
- Solar lighting & LEDs
- Cathodic protection in pipelines, bridges and aircraft Aluminium
- Schools & rural health clinics

On-Grid:

- Grid-connected residential, industrial and commercial buildings
- Solar transport
- Building-integrated photovoltaics

Non-terrestrial:

- Space
- Buoys & meteorological applications

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1 Historical and Societal Influences

1.1 Introduction to photovoltaic systems

Electricity is simply a constant flow of electrons that have the energy to overcome the obstacles in their path that are trying to take away that energy. Since the invention of methods of producing electricity, electricity has been provided by burning fossil fuels (like coal, natural gas and oil) and using them to heat water to produce steam. This steam is at high pressure and turns turbines that turn in a magnetic field. This process produces electricity in the form that we receive it at our power outlets. It is transported from the power plants to our homes via transmission cables made of metal wires since metal is a good conductor of electrons and doesn't lose much of its electrical energy. A photovoltaic system is a mini power plant that supplies electricity using only sunlight. We link photovoltaic cells together into large area photovoltaic modules. The materials used to manufacture these solar cells will be discussed further in this textbook. They basically consist of special materials called semiconductors which only conduct current under certain conditions (like when they are exposed to sunlight, for example). Photovoltaic systems often need batteries to store electricity for night-time use since sunlight is only available during the daytime to generate electricity. Sometimes the photovoltaic system can connected to the electricity grid. In this case, excess electricity that is generated is sold to the electricity grid, and when there isn't enough power, the grid supplies any required energy. Figure 1 below shows an example of a grid connected system.

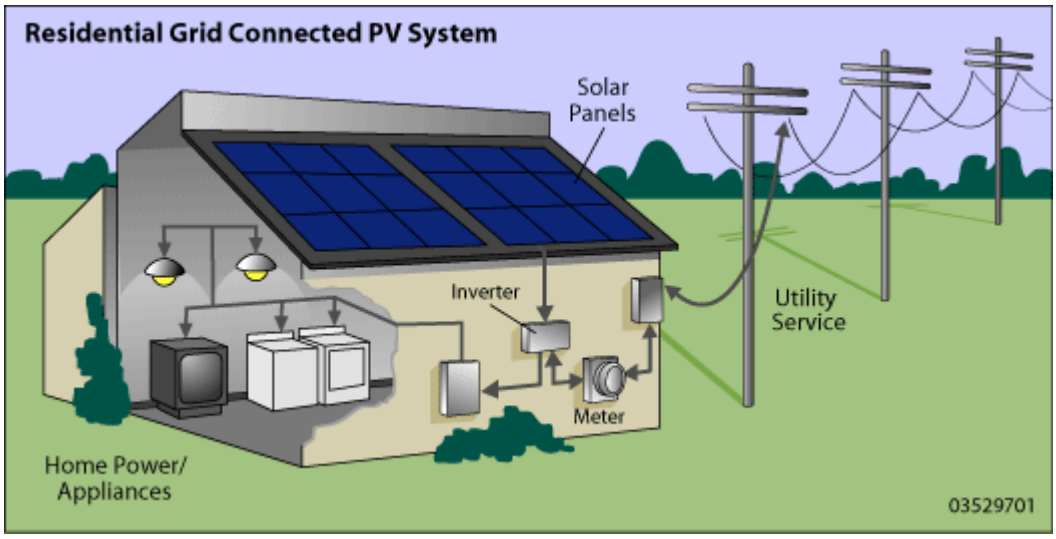


Figure 1: An Example of a Photovoltaic System (US DOE EERE 2005, Available: http://www.eere.energy.gov/consumer/images/residential_grid_pv.gif, Accessed 4th July, 2008)

Further Reading

- McHenry M. Wilmot N. (2007), *Photovoltaics* [online], Available: http://www.rise.org.au/info/Tech/pv/index.html (Accessed 22nd July, 2008), Murdoch University
- Solar Electric Power Association (2008), *PV Basics: PV Facts Sheet* [online], Available: http://www.solarelectricpower.org/index.php?page=basics&subpage=pv&display=facts (Accessed 4th July, 2008)
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- Northern California Solar Energy Resource Guide, Available: http://www.ongrid.net/papers/PV_SERG2003.pdf (Accessed 4th July, 2008)
- Pennsylvania Weatherization Providers Task Force, *Lesson 5: Photovoltaics (PV) System Basics* [online], Available: http://www.pasolar.ncat.org/lesson05.php (Accessed 4th July, 2008)
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- National Renewable Energy Laboratory, *The Basic Physics & Design of III-V Multijunction Solar Cells* [online], Available: http://photochemistry.epfl.ch/EDEY/NREL.pdf (Accessed 10th September, 2008)
- Taalebinezhaad A., *Photovoltaic (PV) Tutorial* [online], Available: http://web.mit.edu/taalebi/www/scitech/pvtutorial.pdf (Accessed 14th September, 2008)

1.2 Historical development of photovoltaics

The French physicist Alexandre Edmond Becquerel discovered the photovoltaic effect in 1839 by showing that conduction of some materials improved when they were exposed to light. Later, in the 1870's Willoughby Smith and William Adams illuminated a junction of selenium and platinum to demonstrate the photovoltaic effect and designed and constructed the first solar cell. Copper sulfide and selenium were the earliest photovoltaic materials used.

Work carried out in the early 1900's was largely theoretical and done by Albert Einstein, for which work he received the Nobel Prize in 1921. His theory was proved by Robert Millikan in his 1916 experiment. He confirmed that the energy of the photons (and photoelectrons generated) increased with the increasing frequency of the incident light. Jan Czochralski discovered a method of single crystal silicon production in 1918, which made possible the first single crystal silicon cell production possible in 1941. In 1947, Bell Laboratories tested the first transistor, which made use of germanium as the

semiconductor and gold contacts. This was an important step in the path to development of commercial solar cells.

Early available solar cells were made of germanium as it was available and more easily purified than silicon. Their development progressed rapidly during the 1950's and early 60's through development at Bell Laboratories and Hoffman Electronics. By 1960 modules were available that were 14% efficient but were very expensive and were only used to power satellites and remote telecommunication repeater stations. Germanium cells were fitted to Vanguard I, Vanguard II, Explorer III, Sputnik III, Explorer VI and Explorer VII.

In 1964, Sharp Corporation developed the first commercially viable silicon solar cells which were installed as solar fields in 1964 in Japan and America. Silicon solar cell development continued for the rest of the decade and became especially useful for application in space as the cost reduced. Since then, silicon has been the dominant photovoltaic technology due to its abundance and low cost.

The 1970's saw the beginning of terrestrial applications for solar cells. The industry began to expand, with many companies founded during this period. These early applications included domestic systems, telecommunications repeater stations, water pumping, power in developing countries and meteorological stations. The general theme here was that the areas where power was being delivered were isolated.

The next decade saw massive growth in the remote application market. This was particularly evident in water pumping and telecommunications as well as domestic applications in remote areas. Numerous solar fields were installed and solar cell development continued. During the 90's cell efficiency surpassed 20% and the cost of modules continued to drop. The uses were expanded to grid connected applications and a multitude of others.

Traditional uses of photovoltaics have been remote areas. These include space, telecommunication, water pumping, and residential applications. Over the past decade or so their use has extended to on grid application through grid connected inverters as well as applications around many cities, such as lighting and parking meters.

In Australia the use of solar power makes sense because we have large solar resources (i.e. the sun shines a lot). It also makes sense because of the remote areas within the country where it is expensive to extend the grid. Uses of solar power in Australia and around the world include:

- Space – to power satellites used for communication, television and GPS. This was the first application for solar power due to the remoteness of space and the need to power satellites. The large budgets of space programs gave the photovoltaics industry a real kick start
- Remote houses using a stand alone system (not connected to the grid) which are often called remote area power systems or RAPS

- Remote telecommunications installations including repeater stations for mobile phones and internet
- Television signal boosters in remote areas
- Water pumping in rural areas
- Solar lighting such as street or pedestrian lights
- Parking meters
- Solar parks (large fields filled with solar panels) such as the installation at Singleton operated by Energy Australia
- Meteorological buoys in oceans for weather prediction
- Channel markers in water ways
- Caravans, four wheel drives and camping appliances in general
- Grid connected residential, commercial and industrial, where the electricity generated by the photovoltaics is converted to AC and fed directly into the grid
- Cathodic protection of pipelines and bridges to prevent corrosion
- Solar home systems in developing countries – these are simple systems in remote developing areas where there is either no grid or the grid is unreliable
- Solar transport in cars, boats and planes
- Building integrated photovoltaics – Photovoltaic cells are incorporated into the building façade and replace other materials

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- *History of Photovoltaics: A Walk Through Time* [online], Available: http://www.pvresources.com/en/history.php (Accessed 12th May, 2006)
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- *Bipolar Junction Transistor - History* [online], Available: http://www.ecse.rpi.edu/~schubert/Course-ECSE-6290%20SDM-2/1%20BJT-1%20History.pdf (Accessed 2nd July, 2008)
- Ward J. (2004), *Transistor Museum: Historic Transistor Photo Gallery* [online], Available: http://semiconductormuseum.com/PhotoGallery/PhotoGallery_BeadType_Pct.htm (Accessed 6th September, 2008)

1.3 The effect of engineering innovation on people's lives

Many developing nations often have:

- Abundant sunlight
- Large rural populations
- Inadequate infrastructure for an electricity grid
- Low family incomes but high fuel costs (kerosene, diesel etc.)

PV has the following characteristics that make it a suitable technology for developing nations:

- Modularity (system size can be increased by adding more PV panels)
- Generates electricity at the point of use
- Low maintenance with a long warranted lifetime (typically 25 years)

PV can also be used for many rural health clinics in developing countries for:

- Vaccine refrigeration
- Lighting
- Water pumping
- Purification

For the poor, their priority is the satisfaction of basic human needs. These include:

- Employment
- Nutrition
- Health services
- Education
- Housing
- Sanitation
- Water purification

Energy is a key ingredient in delivering these services sustainably. For example, when electricity is not available for lighting, children cannot study and adults cannot work to manufacture products after dark. Their economic productivity falls, and their capacity to earn income is substantially diminished. Energy is also needed to cook food, boil water, and power medical centre vaccine fridges among other things.

1.3.1 PV in Australian Rural Applications

Even in developed nations, there are remote area applications of PV that provide great social and economic benefit. This is especially true in a rural context, where public services are often fewer and further between. Powering of telecommunications repeater stations or feeding lots.

Further Reading

- Takase, K. (1994), *The Crisis of Rural Energy in Developing Countries* [online], Available: http://www.unu.edu/unupress/unupbooks/uu17ee/uu17ee0i.htm (Accessed 2nd July, 2008)
- Fraser J., *Photovoltaics* [online], Available: http://www.history.rochester.edu/class/PV/home.html (Accessed 9th January, 2008)
- Energy Efficiency and Conservation Authority (2005), *Photovoltaics Fact Sheet 04* [online], Available: http://www.eeca.govt.nz/eeca-library/renewable-energy/solar/fact-sheet/photovoltaics-fact-sheet-04.pdf (Accessed 14th September, 2008)

1.4 The environmental implications of photovoltaics

Photovoltaic technology has various environmental benefits. The main two are:

- **To reduce greenhouse gases and the effect of global warming:** The use of photovoltaics for energy supply means that there will be less fossil fuels combusted, and less carbon dioxide greenhouse gas emitted. This means that the absorption of infrared at the earth's surface will be less severe, and will help to prevent run-away global warming.
- **To provide cleaner air:** Less fuel combusted means cleaner air since there will be less carbon monoxide, nitrous oxide and sulphur dioxide being emitted.

It is also important to note that photovoltaics need to be manufactured using raw materials, energy and various chemicals that are harmful to the natural environment. The silicon needs to be refined from sand (SiO_2) to a very high purity at very high temperatures (around 1000^{o}C), requiring a lot of energy that usually comes from coal. The processing of the wafers also uses various acids, alkalis and other chemicals that harm the environment if not properly disposed of. More information can be found in the 'further reading' articles.

Further reading

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- Massachusetts Technology Collaborative, *Benefits and Barriers of Photovoltaics* [online], Available: http://www.mtpc.org/cleanenergy/solar_info/benefit.htm (Accessed 2nd July, 2008)
- US DOE EERE, *What is the Energy Payback for PV?* [online], Available: http://www.nrel.gov/docs/fy05osti/37322.pdf (Accessed 10th September, 2008)

1.5 Greenhouse effect mechanisms and the role of PV

Global warming describes the increase in the average temperature of the Earth's surface, atmosphere and ocean which is mainly linked to the increase of greenhouse gases (GHGs) in the atmosphere. This is often linked with climate change which includes changes like more severe droughts, storms and sea level rise. Common greenhouse gases and their sources are shown in Table 1 below.

Table 1: Common greenhouse gases and their sources

Gases	Sources	CO_2 equivalent*
Carbon dioxide (CO_2)	Burning fossil fuels like oil, coal or wood, deforestation (killing trees)	1
Methane (CH_4)	Anaerobic decomposition of bacteria – sewage gas, flooded areas	23
Ozone (O_3)	Hot car and airplane exhaust	-
Nitrous oxides (NO_x)	Smelting of mineral ores and other high temperature processes on mined elements	296
Sulfur Hexafluoride (SH_6)	Aerosols (e.g. deodorants), refrigerants in fridge and air conditioning systems etc.	22200
Hydrofluorocarbons (HFCs) and Chlorofluorocarbons (CFCs)	Aerosols (e.g. deodorants), refrigerants in fridge and air conditioning systems	~10,000

Source: http://www.epa.gov/omswww/climate/420f05002.htm

* The universal unit of measurement used to indicate the global warming potential (GWP) of each type of greenhouse gas by comparing its effect to the effect of one carbon dioxide gas molecule.

Note: Some HFC and CFC gas molecules have a global warming effect (called a Global Warming Potential) of around 10,000 times that of one Carbon Dioxide molecule! They can easily leak from closed fridge and air conditioner loops.

There are two sources of GHGs:

- Anthropogenic (caused primarily by human activities)
- Non-anthropogenic (natural greenhouse gases)

Radiation incident from the sun enters the Earth's atmosphere. Solar radiation is within the electromagnetic spectral range of infrared (long wavelength) to ultraviolet (short wavelength) radiation. When it reaches the Earth's atmosphere, some of it is reflected, some is absorbed by the atmosphere, and some is transmitted to the surface. Different wavelengths of light experience different fractions of reflection, absorption and transmission. The radiation heats up all matter on the Earth's surface. These warmed surfaces then reradiate the heat that has been given to them by the sun. An example of this is when you go to the beach at dusk and the air temperature has decreased but the sand still feels warm. Gases in the Earth's atmosphere trap some of the heat reradiated from Earthly matter, subsequently keeping us relatively warm at night. The main gases are water vapour and carbon dioxide. In normal operation of the greenhouse effect, the amount of gas in the atmosphere trapping this heat is constant. Over the last few hundred years (particularly the last 50) the amount of carbon dioxide present in the atmosphere has increased to levels previously never seen on Earth. The measured increase in carbon dioxide levels in recent years is shown in Figure 4. The consequence of this is that more heat absorbed by stone, water and soil is trapped by the Earths atmosphere. This results in increasing the world's temperature and is known as the enhanced greenhouse effect. Other consequences of the enhanced greenhouse effect include what is termed climate change and includes sea level rise, longer and harsher droughts, and more severe storms. The greenhouse effect is represented pictorially in Figure 2 and Figure 3.

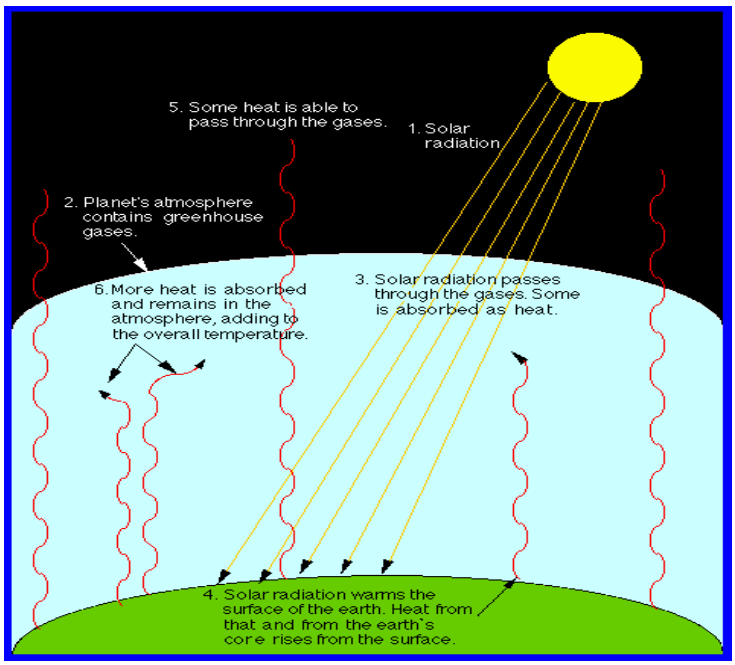
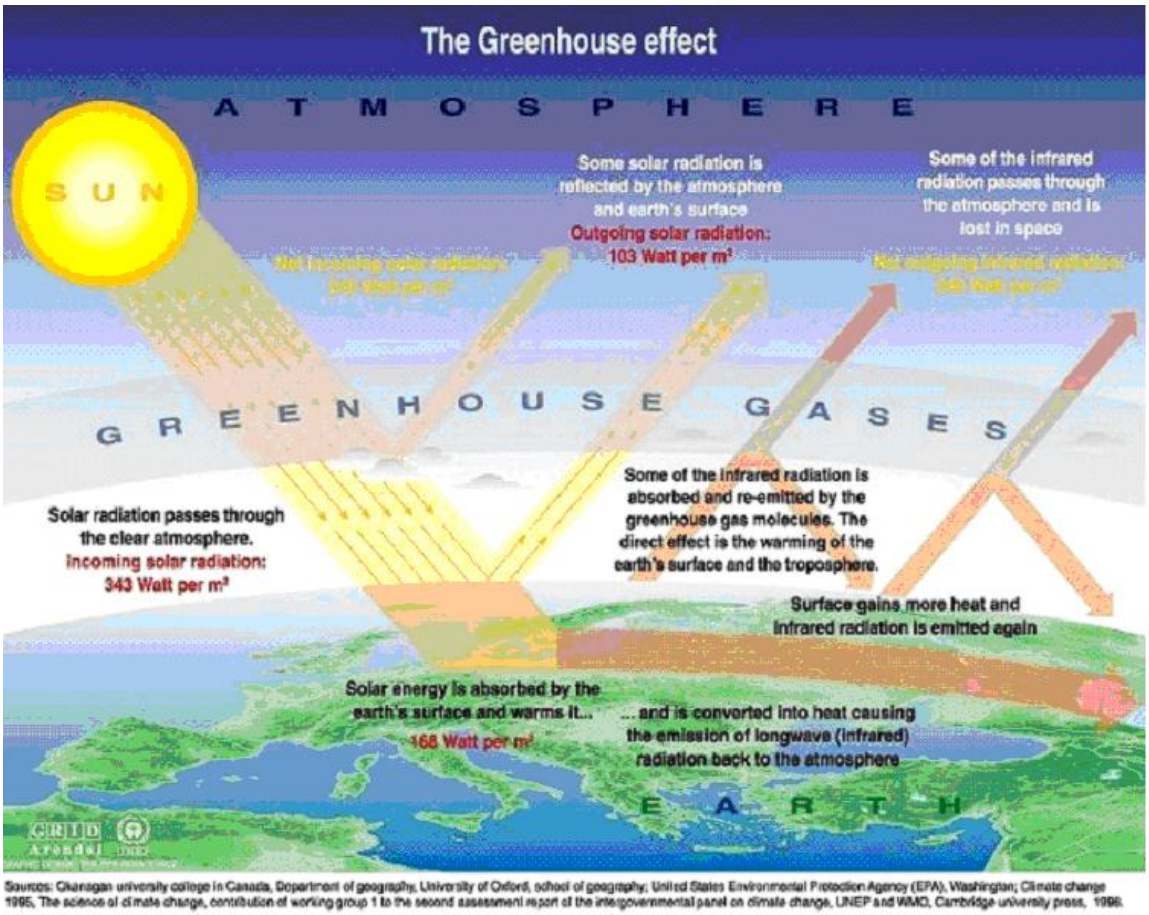


Figure 2: Paths taken by solar radiation entering the atmosphere (Michigan Reach Out, 2006)

The sunlight reaching the Earth's surface warms the Earth. The warm surface will then emit a spectrum of radiation, with its spectral intensity dominated by infrared wavelengths. Greenhouse gas molecules in the atmosphere absorb some of the emitted infra red and some is re-emitted back to the earth, making the earth warmer. The greenhouse effect itself is vital to life on earth, which would otherwise to be too cold.

However, excess anthropogenic greenhouse gases are enhancing the warming effect beyond historical levels and are causing climate change.



Sources: Okanagan university college in Canada, Department of geography; University of Oxford, school of geography; United States Environmental Protection Agency (EPA), Washington; Climate change 1995, The science of climate change, contribution of working group 1 to the second assessment report of the intergovernmental panel on climate change, UNEP and WMO, Cambridge university press, 1996.

Figure 3: Diagram illustrating the greenhouse effect mechanisms
(Source: http://www.reachoutmichigan.org/funexperiments/agesubject/lessons/images/diagrampage.html)

The measured increase in carbon dioxide levels in recent years is highlighted by Figure 4 below and the corresponding increase in temperature is shown in Figure 5. This strong correlation between temperature and CO_2 concentration is most likely because carbon dioxide in the atmosphere causes an increase in the Earth's average temperature. This means that not every location on Earth increases in temperature, but on average there is more heat trapped in the atmosphere (IPCC 2007).

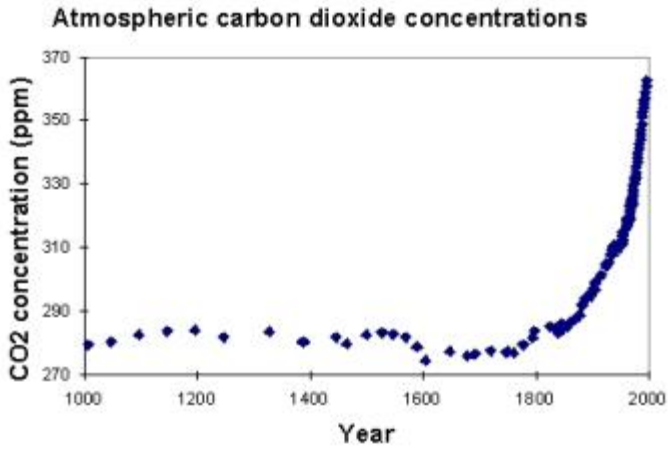


Figure 4: Atmospheric Carbon Dioxide concentrations in the last millennium
Source: http://www.cmar.csiro.au/e-print/open/holper_2001b.html

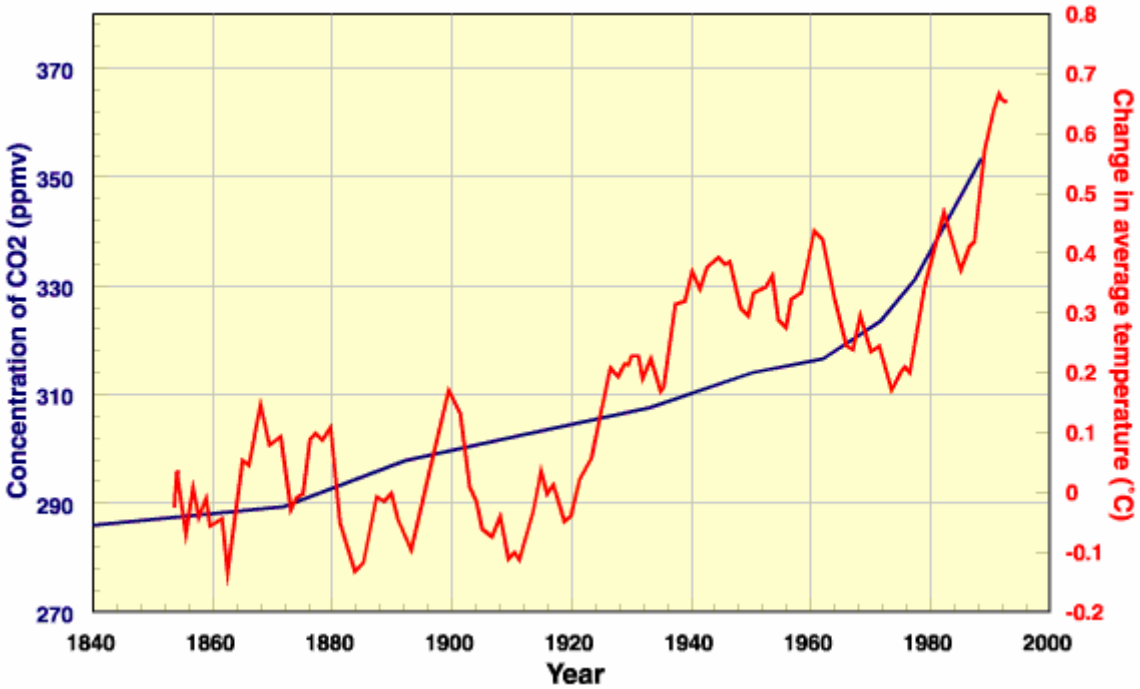


Figure 5: Correlation between rising carbon dioxide concentration in the atmosphere and rising temperature over the last 160 years (Honsberg C. Bowden S. 2005)

The implementation of photovoltaics as an energy source would suggest that the use of fossil fuels as an energy source will decrease. This is only the case, however, if the same total amount of energy is consumed as before (or less). In doing so, less carbon dioxide and other greenhouse gases arising from combustion will be emitted. By reducing and minimizing greenhouse gas emissions, the speed with which the onset of climate change occurs can be reduced.

Animations and Diagrams:

- http://atlas.nrcan.gc.ca/site/english/maps/climatechange/figure_4.jpg/image_view
- http://earthguide.ucsd.edu/earthguide/diagrams/greenhouse/
- http://www.reachoutmichigan.org/funexperiments/agesubject/lessons/images/diagrampage.html
- Greenhouse effect animation available from (last accessed 3rd January 2007): http://earthguide.ucsd.edu/earthguide/diagrams/greenhouse/

Further Reading

- For more information about greenhouse gases in the atmosphere, see Holper, P., CSIRO (2001), *The Greenhouse Effect Information Sheet* [online], Available: http://www.cmar.csiro.au/e-print/open/holper_2001b.html (last accessed 8th May, 2007).
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1.6 The value-added benefits of photovoltaics

In addition to reducing green house gases and providing cleaner air, Photovoltaics can have a lot of other advantages. Some of these include:

- **Increase in energy supply security**: Some fossil fuel resources like crude oil and uranium are likely to be depleted this century if current usage patterns continue. Others, like coal, have an estimate of a few hundreds years of supply. These fuels however, contribute heavily to greenhouse gas emissions making them unsustainable in the long term. Photovoltaics provide a means of maintaining electricity supplies in industrialized countries and providing electricity to the developing countries without concern for fuel supply security or greenhouse gas emissions.
- **Reduced transmission and distribution loss:** The use of photovoltaics make it possible for on-site and local generation of electricity at point-of-use. This means the electricity doesn't need to be distributed across large distances like coal-fired generation, and hence reduces transmission and distribution losses.
- **Rural Independence:** The use of photovoltaics makes it possible for on site and local generation of electricity. This means that rural areas can operate with electricity separate from the central electrical grid.

- **Sustainable job creation:** The production of photovoltaic power systems is a high technology industry, which can create new jobs in manufacturing, distribution, installation and maintenance. Also, dispersed application means that employment is created in regional areas, as well as in industrial centres.
- **Grid Voltage Support**: Dispersed photovoltaic power systems feeding into electricity distribution networks, or operating independently, can help to provide a higher voltage near the ends of transmission lines. The houses further away from the power stations end up receiving a lower voltage otherwise.

Further Reading

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1.7 RE, global energy needs and nuclear energy

There is no question of the technical potential for wind, solar-PV and biomass (WSB) to deliver the world's required energy. For instance, Klemas L. calculates:

"At a conservative average of only 200 W/m^2, the net yearly solar energy input to the planet corresponds to 2.22 10^{11} GW-year, equivalent to…1.29 10^{14} petroleum barrels/year: this amount is equivalent to 353,000 million barrels per day. The actual global petroleum consumption is around 70 million barrels per day. Therefore, the available solar energy power is 5,000 times the total energy power derived from actual world oil produced combustion (counted at 100% efficiency).

Even at an energy transformation efficiency of only 10% and covering with energy collectors only 1% of the [global] land surface, solar energy would provide about 6 times the actual oil used equivalent." - Klemas L.

There is also no shortage of silicon on the planet, as it's the 2nd most abundant element on Earth. It is clear then, that there are no technical limitations to meeting the entire world energy need with photovoltaics and some form of storage for night-time usage (e.g. large batteries). On top of this, there are other inexhaustible sources of renewable energy like wind, biomass and wave energies.

Real-world constraints like intermittency of supply, land availability and cost, stifle the economic potential for these technologies to flourish. However, the diversity of renewable energy types mean even base-load generators can be substituted. Base-load generators are generators that continually output a controllable amount of power, e.g. like coal-fired power stations (they can output at 500MW or 100MW based on the demand from the electricity grid). However, carbon-neutral, wood-fuelled biomass generators can provide the same function. The wood is energy stored, much like coal, and it can be combusted at any time of the day. Similarly, bio-diesel can be used by the transport sector to substitute diesel (and the petrol equivalent is bio-ethanol). Nearly all the other renewable energy technologies are even cheaper than PV (on a $-per-kWh produced basis), and abundant (although the abundance of direct solar radiation for PV is greatest). In addition, the costs of PV are falling rapidly, and have been doing so since its widespread deployment in the 1970's. The most interesting fact is that the cost of nuclear energy is actually very high when the full costs of plant decommissioning and waste disposal are factored into account. The Price Anderson Act of 1957 in the US limited the insurance liabilities of reactor operators. Without such a concession, would anyone in their right mind bear the full responsibility of what could occur in a single accident? Furthermore, the process of enriching the uranium ore is also energy intensive (and therefore greenhouse intensive), but of course, not to the extent of electricity from coal.

It should be quite clear from our assessment of the technical capability of RE that it is not essential that nuclear energy be deployed to any significant extent anywhere in the world. If there is any human error in handling, transporting or disposing of radioactive nuclear fuels or their waste materials, the effect would be disastrous, on a global scale, and extending into time. It takes nuclear waste millions of years to decay to a safe state. This poses huge risks for containing their effects in the event of accidents, or if they fall into the wrong hands. The waste products can also be used in nuclear weapons since they are radioactive, and remain so for many years. If a country has a nuclear energy program, it is easier for terrorists to get hold of weapons grade plutonium, than if the country did not produce any of the material. It is far easier to obtain them under the cover of civilian nuclear energy programs. A single nuclear power plant is also a far easier target for a missile than thousands of dispersed renewable energy systems. These risks posed by nuclear technologies make them a non-option.

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1.8 PV, RE, Self-sufficiency and Equity

Renewable or sustainable energy can be obtained from a variety of sources, and some are more or less sustainable than others. These include:

- Hydro power (gravitational energy from water flowing downwards)
- Biofuels (like wood, animal waste, energy crops converted to liquid fuels)
- Wind power (energy from flowing air)
- Goethermal power (the heat of the Earth's crust, derived from the hot core of the Earth)

PV and many of these technologies allow people to meet their energy needs for themselves, giving them access to various opportunities in life. They need not be dependant on a central supplier of an energy resource to generate and then supply power to them. This also means they will no longer be vulnerable to large price increases in delivered electricity or thermal energy because they can make it themselves with a renewable source like the sun.

In developed countries like Australia, we additionally have the opportunity to free ourselves from dependence on limited fossil fuels that are often mined from poor nations by big corporations and even corrupt governments. There are many cases where corporations that mine oil receive military protection from local militia who enforce sometimes brutal martial law on the local people to coerce them to work for low wages. Countries with natural resources like oil, gold, diamonds, coal, forest wood and ivory rarely see those resources benefiting the majority of citizens. They are usually just mined, harvested, or hunted with little consideration for the future of the local area. It is usually only a handful of people that benefit from the sale of these resources to the rest of the world (executives of large multinational companies, government officials, local law enforcers). Usually, those people don't live in the area of exploitation. What is left behind for the local people is just the environmental damage left behind by pollutants from the production process (e.g. open-cut mines, residues, mass pollution of waterways and the like). The ecosystems destroyed by such activities are often in use by locals for their subsistence, but as the resource is destroyed, they can no longer live from the land, and are forced to work for similar corporations that can earn large revenues. By not demanding products like those listed above (e.g. fossil fuels), we are more likely to be assisting the people of the world to maintain their ways of life, their local resources, their

environment, and their political and economic freedoms. This is contrary to what we are normally told about large commodity industries – that the income from our purchases only helps the people and the country.

For more information about these kinds of issues and a global perspective, have a look at the following websites:

- http://www.un.org/Pubs/CyberSchoolBus/
- http://www.un.org/issues/
- http://www.hrw.org/doc/?t=corporations
- http://www.undp.org/energy/climate.htm
- http://www.transparency.org/

There are many other non-governmental organisations (NGOs) engaged in similar types of work, but are often under-funded and may lack the resources to tackle such difficult issues. Many can be found online on the World Wide Web.

2 Engineering materials

2.1 The Periodic Table of the Elements

All matter and materials are composed of simpler materials. At particular temperatures, these building blocks may be in solid, liquid or gaseous form (what we call 'states'). All matter is composed of compositions (mixtures) of the different types of fundamentally different substances (what we call "elements"). The different elements have very different properties, making different materials behave the way they do, with their various properties.

The 'Periodic Table of the Elements' is a chart of all the known unique elements existing in nature. You cannot break down an atom of an element any further, without causing nuclear effects to occur. From the point-of-view of chemical reactions, each element is in its most basic form as shown in the Periodic Table. Elements can be combined to form other molecules with different properties. For example, Sodium (Na) is a highly reactive metal and Chlorine (Cl) exists typically as a gas. When combined in a chemical reaction, they form Table Salt (NaCl), which obviously has very different properties to either of its constituent elements. Each square of the table is an element with its own abbreviation (called a "chemical symbol"), and each element has a different number of electrons and a different mass (i.e. weight) to the others. Each vertical column of elements is in the same "group." Boron (B) in the 3rd (III) group, Silicon (Si) is in the 4th or IV group, Phosphorus (P) is in the 5th (V). The metals are in groups I and II, as well as in the transition series (the wide region of element between groups II and III). The non-metals (insulators) are in groups V to VIII. The semiconductors lay somewhat in between, especially in group IV.

2.1.1 The Bohr-Rutherford Model of the Atom

It is useful to be aware at this stage, of the simple model of the atom proposed by Niels Bohr & Ernest Rutherford. Remember that it is too difficult to take an enlarged photograph of atoms, so theories had to be made for them. This will be useful when we describe the "bandgap," later on.

This model describes atoms as mostly empty space, with a central nucleus that had protons (+) & neutrons, with electrons (-) 'orbiting' the nucleus in various "energy levels," often called shells. According to this model, the bigger the orbit of a particular electron, the higher that electron's energy level. The energy level of any electron describes its energy content. Bohr's model says that any electron can only have a certain set of individual energy levels, and cannot have energy levels falling between these points. It is simply not allowed to occupy other energy levels. Electrons can lose energy to fall to one of the lower energy states, or if it is exposed to an energy source, it can gain energy to jump to one of the higher energy states. These processes are called "quantum leaps," and the energy gained or released is electromagnetic radiation (photons) in the

form of light or heat. The excited electron at the higher energy level is not in its most stable, natural state, and will tend to lose its energy and fall back to the lower energy level (releasing a photon of light or heat).

Most of the mass of the atom comes from the protons & neutrons in the nucleus, with the electrons contributing very little mass. Protons and neutrons each have roughly the same mass and in an atom, the number of protons equals the number of electrons, giving it a neutral electrical charge.

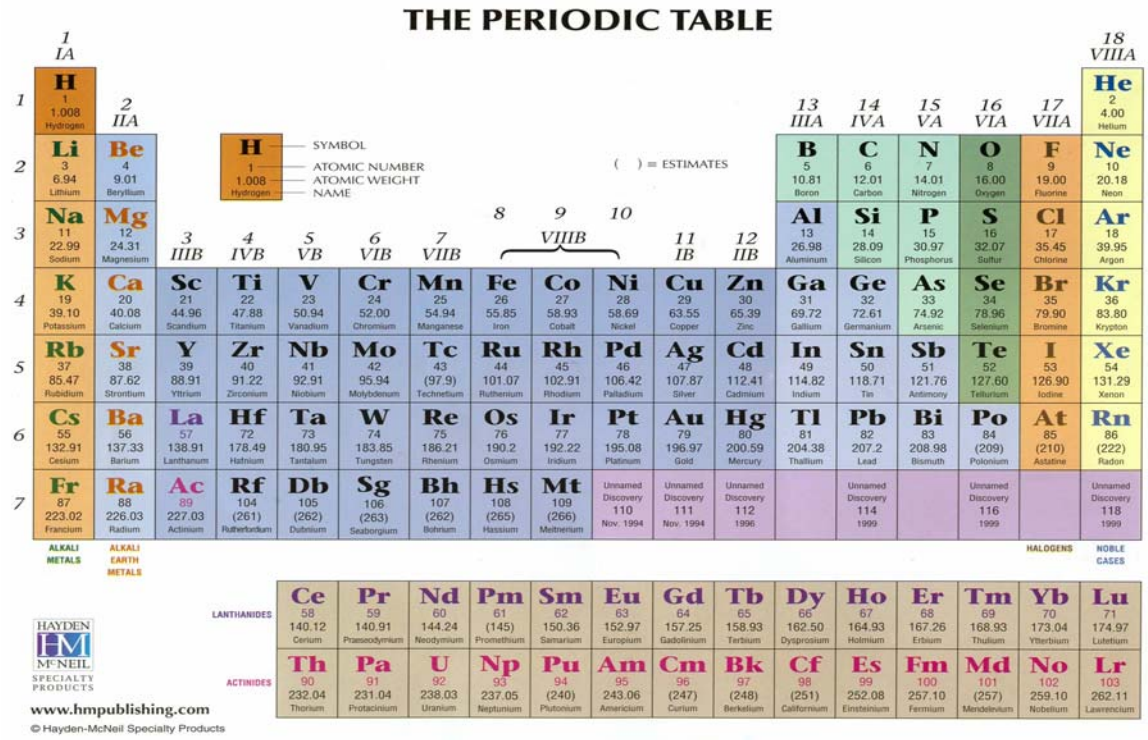


Figure 6: The Periodic Table of the Elements
Source: Casagrande G., *Dr. Casagrande's e*-Classroom [online], Available: http://www.doccasagrande.net/Images/Periodic_Table.jpg (Accessed 29th January, 2008)

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  - *Energy Levels,* http://www.colorado.edu/physics/2000/quantumzone/bohr2.html
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2.2 The different bulk materials used to construct solar cells

There are many different materials used to construct solar cells. The pure elements used in semiconductors are mainly to be found in group 4 of the periodic table (e.g. Silicon and Germanium). Elements in this group exhibit properties of both metals and insulators, and they are fittingly positioned between metallic elements in groups 1-3, and non-metallic elements in groups 5 to 8. Metals conduct current (i.e. electrons) very well, and insulators do not. Semiconductors are electrically interesting because they will only conduct current under particular circumstances (e.g. when heated to a high temperature, supplied with a particular Voltage etc.). The required property of semiconductor for solar cells is that it should behave as an insulator except when under illumination by light. Once illuminated, it should generate and transmit currents like a conductor. Because of this, semiconductors have been used as switches that are activated under these circumstances. There are also many semiconductor materials that are not from group IV and are composite materials that have been developed to exhibit properties of semiconductors. The main difference between different materials used for solar cells is the energy of the bandgap. The bandgap refers to the energy needed to move the electron from the valence band (a term used to describe the state where it cannot conduct electricity, like electrons in insulators) to the conduction band (where the electron is freed so that it can be used to contribute to current like in a conductor). This energy required to excite an electron to allow it to conduct current may also be termed its 'bandgap energy.' When we say "band," we refer to a range of energy levels that an electron can possess. The term "energy level," refers to the amount of energy the electron possesses.

Some of the important photovoltaics materials worth investigating are:

- silicon
- germanium
- cadmium telluride
- copper indium diselenide and copper indium gallium diselenide
- gallium arsenide and related materials

Some of the common semiconductors are shown in Table 2 below, with the energy level of their bandgaps (E_g) shown as well. This energy level is given in the units of an Electron-Volt (eV), which is the energy given to an electron by accelerating it through 1 volt of electric potential difference (i.e. voltage). One electron volt = 1.6×10^{-19} joules, a very small quantity. Because it is such a small quantity but is used frequently, it had been given its own name and is a unit of measure for our convenience – "eV."

Table 2: PV cell materials and their bandgaps

Material	Type of bandgap	Eg
Silicon	indirect	1.1 eV
Germanium	indirect	0.66 eV
Cadmium telluride	direct	1.56 eV
Gallium Arsenide	direct	1.424eV
Copper Indium Diselenide	direct	2.4 eV
Copper Indium Gallium Diselenide	direct	1.5 eV

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2.3 Direct and Indirect Bandgap Materials

Atoms are the basic building blocks of all matter. A piece of silicon is made up of silicon atoms for instance. Atoms contain a fairly solid nucleus in the middle, and a number of electrons that orbit the nucleus at different distances away from it. Groups of electrons occupy each orbit or shell. Note that atoms are mostly empty space, so all matter is actually mostly empty space too (despite how solid it seems). The electrons in the outermost shell (furthest away from the nucleus) are the most important ones because they are involved in chemical reactions and physical processes. This outer shell is call the valence shell. Photons of light interact with these outer shell electrons the most. Silicon has 4 electron in its outer shell (or valence shell). A silicon atom in a crystal contributes these 4 electrons to the crystal, and each electrons bonds to an electron of another Silicon atom in the crystal. This way, each atom remains attached to the crystal lattice and the electrons remain fixed in place. However, photons can bump these electrons in the crystal and transfer all or part of their energy to them. Then the electrons become mobile. We

say these mobile electrons have moved from the stationary valence band to the mobile conduction band. Bands are basically energy levels. The difference between the two bands is basically the amount of energy the electron has.

In a direct bandgap semiconductor, electrons at the maximum energy level of the valence band (i.e. the highest energy an electron can possess without being free to conduct current) can be elevated to the minimum energy level of the conduction band (i.e. the lowest energy required by an electron for it to conduct current) by directly absorbing a photon of light with sufficient energy. Electrons can only move and contribute to current if they are in the conduction band. When we say 'energy' here, we mean the energy possessed by the electron. To be clear, the maximum valence band energy is less than minimum conduction band energy. When photons bump into electrons they often transmit most of their energy into them. This energises the electrons and allows them to move around and conduct current.

Semiconductors that have an indirect bandgap are less efficient at absorbing photons of light to generate electrons and holes. Holes are the spaces in the crystal lattice that are left behind in the valence band when an electrons receives sufficient energy to pass into the conduction band, leaving the vacant space (the hole) where it was previously. Relative to all the other negatively charged electrons around the vacant space, the space becomes positively charged. Thus, holes are positively charged. The interesting thing is that holes can move just like electrons. The hole moves when an electron next to it moves into its space. If the nearby electron moved to the left into the hole's space, that means the hole has moved to the right into the electron's previous space. We observe this as a moving positive charge.

Electrons in the conduction band with more energy than the minimum required to conduct current quickly fall to the minimum conduction band energy level (so they have just enough energy to conduct). That is, they waste their excess energy because they can't use it and they recombine with the hole they left behind in the valence band. One way they waste this energy is by moving around and bumping into other atoms in the crystal lattice. So, only part of the total energy contained in the photon is utilised by the electrons and their partner holes. A photon with energy E_g, can produce an electron-hole pair in a direct band gap semiconductor with bandgap E_g comfortably because it has the exact amount of momentum required to bump and electron from the valence to conduction band. However, in an indirect band gap semiconductor, that same electron requires more momentum than the same photon of energy E_g, can provide, in order to produce an electron-hole pair. The extra momentum for the electron needs to come from a vibration of the semiconductor's lattice itself, precisely when the photon strikes the electron. Because of this, indirect bandgap semiconductors don't utilise the available light as well as direct bandgap semiconductors. Figure 7 below gives some illustration of the differences.

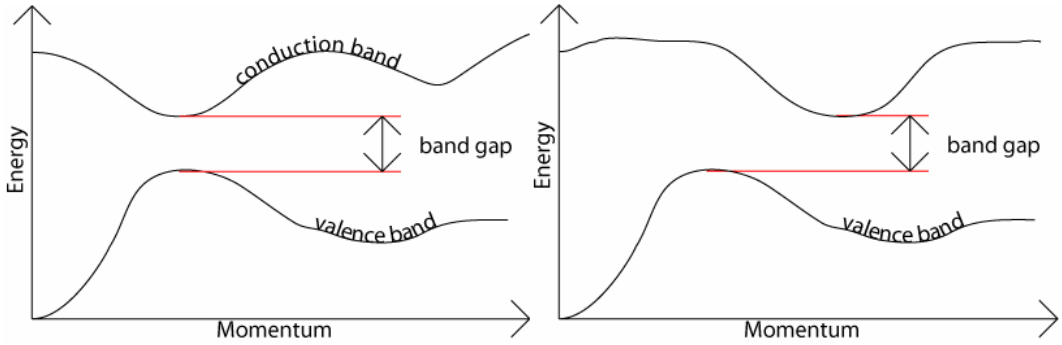


Figure 7: Left: direct bandgap semiconductors where the energy difference between the maximum valence energy and the conduction energy minimum occur at the same electron momentum. Right: for indirect bandgap semiconductors, these maximum and minimum points occur at different momentum values

Source: http://www.doitpoms.ac.uk/tlplib/semiconductors/direct.php (Accessed 7th September, 2008)

Hence, the more indirect the bandgap, the thicker the layers of semiconductor required to absorb the same fraction of the available energy in the light. Semiconductor materials are semi-transparent to light, so thicker layers generally allow for greater absorption of photons. You can observe this – the more layers of semiconductor material there are, the darker it looks (which means it is absorbing more of the available light). Still, any electrons that have made it to the conduction band, quickly settle to the minimum energy level of that band.

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2.4 Advantages and disadvantages of solar cell materials

Advantages and disadvantages of the most common solar cell bulk materials are listed in Table 3 below.

Table 3: Advantages and disadvantages of different materials used to make solar cells

Material	Advantages	Disadvantages
Silicon	2nd most abundant element on Earth's surface	Indirect bandgap, hence weakly absorbing
	Better semiconductor due to high hole mobility	Bandgap lower than ideal for solar spectrum
	Non-toxic	
	Standard material for electronics: well studied, processing techniques available and understood.	
	Cheap to process	
	Silicon dioxide can form insulating layer: advantageous in processing and performance	
	Higher reverse leakage* current than Germanium (results in lower junction voltage)	
	Able to be used in amorphous and various crystalline forms	
Germanium	Low impurities, able to be used in amorphous and various crystalline forms	Lower reverse leakage current
		Poor semiconductor property of indirect bandgap, and it is too low for high efficiency solar cell
Gallium Arseride	Has higher saturated electron velocity and higher electron mobility	No insulating oxide layer
	Generates less noise than silicon devices	
	Higher breakdown voltage	
Cadmium Telluride	Cheaper than silicon	Toxic
		Not as efficient as other materials
		Technology is underdeveloped
CIS	Extremely high absorption coefficient	Expensive process
	Effective photovoltaic material	Technology is underdeveloped
		Indium is scarce
CIGS	The addition of Gallium boosts the absorption coefficient even more	Gallium and indium are scarce
	Better matching to the solar spectrum	Process are expensive
	High efficiencies	Technology is under developed
	Economical	

* **Reverse leakage current** in a semiconductor device refers to the current that flows when the voltages applied to the device are opposite to the voltages applied for normal operation. The device is reverse biased. This can be achieved by connecting the p-type silicon to negative terminal of a battery, and n-type silicon to the positive terminal. For information on n-type and p-type parts of a silicon solar cell, see Section 3.2: The role of doping and Section 3.3: Operation of a p-n junction.

Notes: **Hole mobility** refers to the ability of holes (the positively charged equivalent of an electron in a PV cell) to travel without restriction and energy loss in the semiconductor material. For further information on holes, see Section 3.2:The role of doping and Section 3.3: Operation of a p-n junction.

Noise here refers to the quality of the electrical output from a cell, rather than audible noise. It is not an important concept for this course.

Breakdown voltage is an oppositely directed voltage that can be applied to a cell or diode to cause it to act as a conductor rather than a semiconductor in that direction. It is not important to know this for this course.

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2.5 Development of materials to construct solar cells

Through the evolution of solar cells there have been many materials used to make the cells. The early materials were selenium followed by germanium. As time went by copper sulfide was used, and more recently silicon became the dominant material.

- Selenium – Early discoveries made in photovoltaics were made using selenium but it was not used very much after 1900 because it was expensive and difficult to obtain. It has properties well suited to the solar spectrum but is just too expensive and rare for commercial use today.
- Germanium – Discovered in the late 1800's, it was the next big material for transistors and semiconductors in general. It dominated the early space market up until the mid 1960's, whereafter silicon took over. The bandgap of germanium aligns very well with visible light. It is currently being used in combination with silicon and other semiconductors in the highest efficiency cells being researched.
- Copper sulfide – This was another of the early semiconductor materials use to create solar cells in the 1930's. It was not extensively used but showed that many materials have the properties required to produce the photovoltaic effect. CuS is made of copper and sulfur, both very abundant and fairly low cost.
- Silicon – The use of silicon did not begin until the mid 1960's with the advent of the integrated circuit industry. Silicon is one of the most abundant elements on the earth and exhibits properties that link well with the energy released in visible

light. It became the material of choice because there was an abundance of silicon which made it cheaper than other semiconductors. It is now the dominant material used for solar cell production.

We have discussed four different semiconductors that have been used in the development of photovoltaics; however, many other materials have also been used with some commercial success. There are currently a wide variety of semiconductor materials being tested in the laboratory aimed at increasing cell efficiency and solar cell innovation. Some of these – including CdTe, GaAs and CIGS - will be covered in Section 2.7.

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2.6 Interaction of photons with silicon to produce electricity

Before beginning with the following sections, it is highly recommended that the sections 3.2: 'The role of doping' and 3.3: 'Operation of a p-n junction' be consulted for background information. Figure 8 shows diagrammatically the conduction and valence band structures of insulators, semiconductors and conductors. In order for a current to flow, electrons must pass into the conduction band by receiving sufficient energy. For some electrons, heat or higher temperature is enough to get them into the conduction band. For most electrons, photons can 'bump' into them and impart their energy to raise their energy sufficiently. Remember, bands refer to groups of energy levels that an electron (or hole) can possess. Remember, holes are the positively-charged spaces in the valence band that electrons leave behind when they gain enough energy & jump to the conduction band.

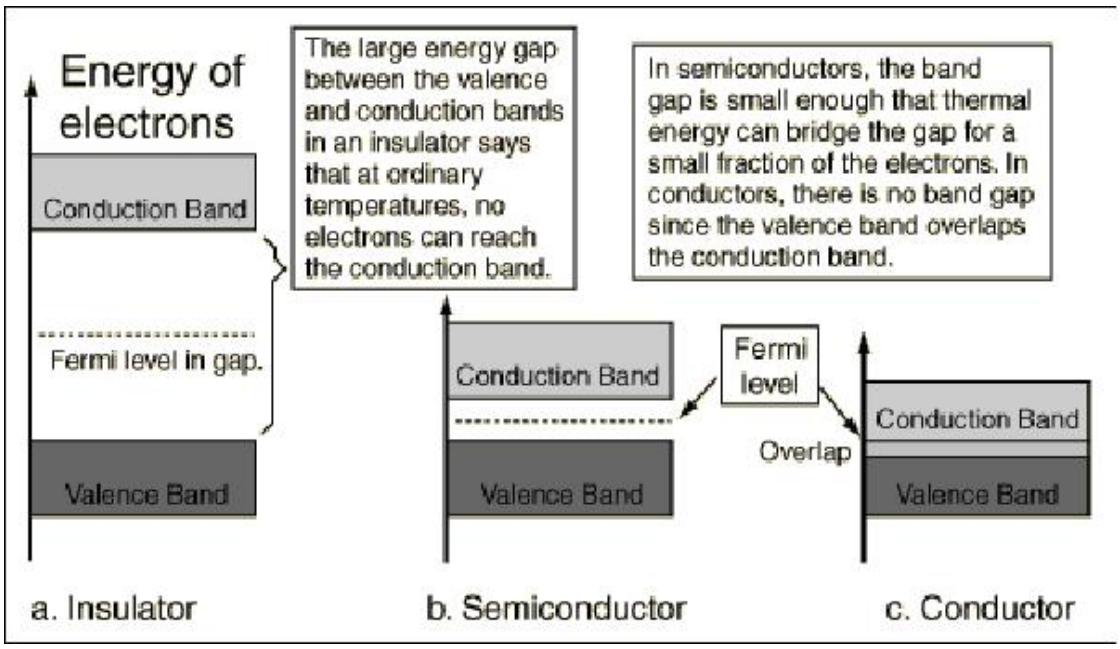


Figure 8: Conduction and valence bands in semiconductors (R Largent 2003)

In silicon (a semiconductor), the energy gap between the valence band and conduction band is quite small, but there is still a gap, so currents don't flow automatically when you apply just any voltage. Because the gap is small, it allows photons possessing an amount of energy larger than the bandgap energy to transfer their energy to an electron in order to allow the electron to travel. Recall that light behaves like a wave as well as a particle. When we are trying to visualise what light is, we are mostly concerned with light behaving as a particle with a certain amount of energy. This allows a current to flow if an external load is applied to it via a circuit. In the diagram, the 'Fermi level' is just an amount of energy that an electron may have, and it tends to fall right between the energy levels giving insulating properties and energy levels giving conducting properties.

Photons of light are permitted to have energy based on the equation:

$$E = hf$$

Where

E = energy of photon

h = Planck's constant

f = frequency of the light

If the photon energy is equal to or higher than the energy gap between the valence and conduction bands, the photon's energy will be transferred to an electron. In doing so, the electron (negatively charged) will move from the valence band to the conduction band, leaving behind a positively charged hole in the valence band (known as an electron-hole pair). These electrons (conduction band) and holes (valence band) are free to move through the semiconductor and produce current if an external circuit is applied. The holes that remain in the valence band after an electron is excited into the conduction band by a

photon are actually just broken bonds remaining in the altered crystal structure of the silicon. It is very easy for another electron in a neighbouring bond to jump into the holes left by electrons that have moved to the conduction band. This jump restores the originally broken bond but leaves a new broken bond behind. In this way the broken bond or hole itself, can be thought of as moving through the silicon.

Therefore, when a photon breaks a bond in silicon, a negatively charged electron, and a positively charged hole are created. This is called an "electron-hole pair". They are generated from a single photon in most cases. The hole and electron are free to move through the semiconductor.

Zworykin V. K. and Ramberg E. G., describe the additional processes that occur in semiconductor devices when exposed to light:

> "Several related photoelectrical [light-generated electrical properties] and thermoelectrical [heat-generated electrical properties] effects occur when light shines on semiconductor devices. The three principal photoelectrical effects are photoconductivity, the photoelectric effect, and the photovoltaic effect. Photoconductivity describes a reduction in electrical resistance due to illumination and its investigation was often an important precursor to the discovery of the photovoltaic effect in various materials but it is not our main focus here. Photoelectricity (outer photoelectric effect) is concerned with the emission of electrons from a surface as a result of light absorption and it, too, is not our main interest. Lastly, the photovoltaic effect (inner photoelectric effect) describes the photoinduced production of voltage, current and/or power in the absence of an impressed voltage."

References

- Zworykin V. K. and Ramberg E. G., *Early History of Photovoltaics 1839 – 1953*

Further Reading

- Largent, R. (2003), Solar cells: Reference for the secondary science teachers, UNSW
- Nave R., *Band Theory of Solids* [online], Available: http://hyperphysics.phy-astr.gsu.edu/hbase/solids/band.html (Accessed March 12th, 2007)
- Massachusetts Technology Collaborative, *From Cells to Panels to Arrays* [online], Available: http://www.mtpc.org/cleanenergy/solar_info/panel.htm (Accessed 2nd July, 2008)
- Knier G. Horack J.M. Phillips T., *How do Photovoltaics Work?* [online], Available: http://science.nasa.gov/headlines/y2002/solarcells.htm (Accessed 14th September, 2008)

- Turner G. (2006), *How a Solar (Photovoltaic) Cell Converts Solar Energy to Electricity* [online], Accessed: http://www.schoolgen.co.nz/pdf/how_photovoltaic_cell_works.pdf (Accessed 14th September, 2008), Victoria University of Wellington

2.7 Thin film vs. wafer technologies and related issues

Current commercial PV products are made using one of the following groups of technologies:

- crystalline wafer silicon
- thin film
- group III-V cells

2.7.1 Crystalline Silicon - Overview

Traditional crystalline silicon is by far the most common solar cell material for commercial applications for a number of reasons:

- It has been in use for more than 50 years, and its manufacturing processes are well known and largely in the public domain.
- Silicon is very abundant, the second most abundant element in the Earth's crust - second only to oxygen

However, crystalline silicon has disadvantages, including:

- It requires high purity silicon, and refining it is expensive and energy intensive
- High competition for silicon with the integrated circuit industry

Figure 9 below shows two monocrystalline silicon ingots prior to them being cut into individual wafers.



Figure 9: Silicon ingots prior to sawing into wafers. Each ingot is a single crystal (Photo courtesy of Dr. R. Corkish)

Further Reading

- B. von Roedern, *Status of Amorphous and Crystalline Thin Film Silicon Solar Cell Activities* [online], Presented at the National Center for Photovoltaics and
- Solar Program Review Meeting Denver, Colorado March 24-26, 2003; Available: http://www.nrel.gov/docs/fy03osti/33568.pdf (Accessed 4th July, 2008)

2.7.2 Thin-Film – Overview

Thin film silicon can be created by sequentially depositing thin layers of the different materials into a very thin structure. The resulting thin-film devices require very little semiconductor material and have the added advantage of being easy to manufacture and cheaper due to the low amount of silicon needed. The mechanical support is provided by a low cost substrate material such as glass or stainless steel. The thickness of the silicon itself can be as little as 5-30microns (or micrometers).

The three principal thin-film technologies are:

- Amorphous Silicon (a-Si)
- Cadmium Telluride (CdTe)
- Copper Indium Gallium Selenide (CIGS)

Further Reading

- SPREE UNSW, *Thin-film Solar Cells* [online], Available: http://www.pv.unsw.edu.au/future-students/pv-devices/thin-film.asp (Accessed 4th July, 2008)

2.7.3 Amorphous silicon (a-Si)

Figure 10 below shows the layers used in an amorphous silicon thin film module.

A TCO is a Transparent Conducting Oxide, which is a material that lets sunlight through but also conducts electricity so the electrons can escape the cell from the top surface

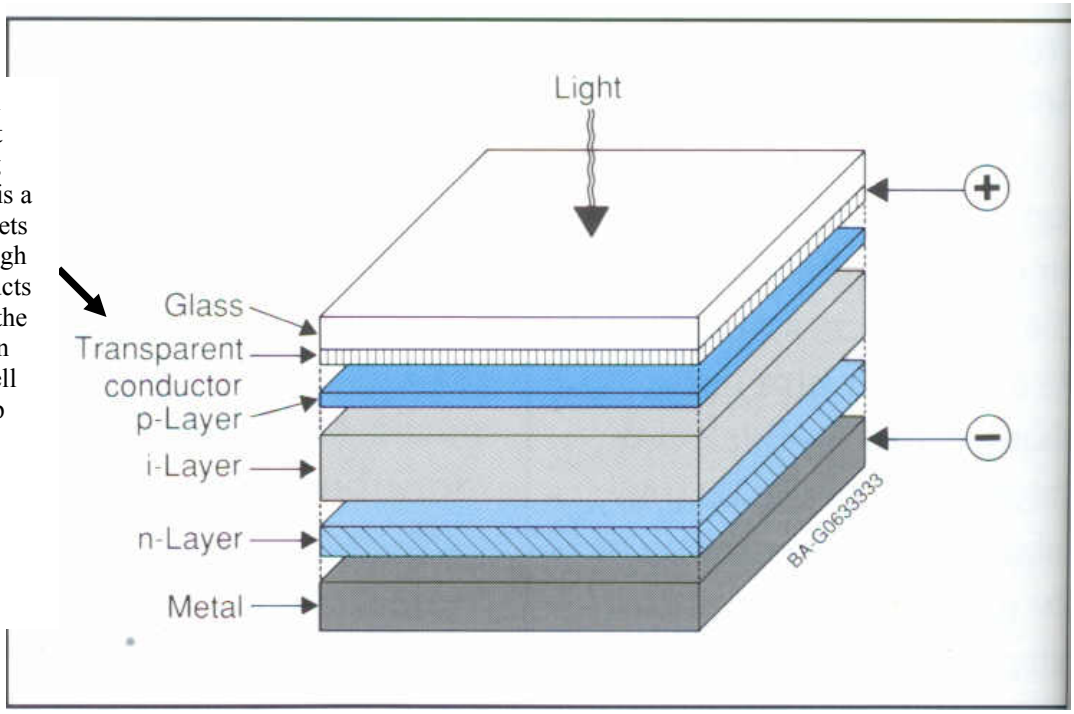


Figure 10: The structure of amorphous silicon

The thickness of silicon varies depending on the particular technology but is around 5 micrometers (about 98% less silicon than wafer technologies). In amorphous silicon, the silicon atoms are arranged more randomly than in the strict geometric order found in crystals. Many atoms have bonds that are unsatisfied by neighbouring silicon atoms (i.e. not linked), so hydrogen is usually incorporated into the material to reduce recombination. Recombination results in the loss of a freed electron or hole that could otherwise carry current (for further details, see Section 3.2: 'The role of doping' and Section 3.3: 'Operation of a p-n junction').

Advantages:

- a-Si has a high absorption coefficient so it absorbs more strongly for longer wavelength light, which travels a greater distance into the cell before being absorbed
- Low silicon film thickness, and hence,
- Potential for lower cost
- Less susceptible to reduced electrical output due to the effect of heat on the cell (wafer-based cells drop in efficiency as their operating temperatures increase)
- Able to be deposited on flexible substrates, since deposition temperatures can be low

Disadvantages:

- Lower overall efficiency due to low grade/quality silicon
- Degradation in performance with exposure to light (particularly after the first few months)
- Production requires hazardous gases
- Production rate is declining due to the difficulty in increasing its efficiency
- Lifetime not proven because it is still a relatively new technology

2.7.4 Cadmium Telluride (CdTe)

Cadmium Telluride, another thin-film technology, has high cell efficiencies (over 16% in the laboratory). Manufactured module efficiencies of 8% have been achieved and may increase to over 10% over time. The basic structure of CdTe has a glass supersubstrate (the thick glass layer that acts as the substrate, actually covers the front surface of the cell where the sunlight should come in) and a layer of transparent conducting oxide (TCO) as a front contact. The n-type material is cadmium sulphide and the p-type is the cadmium telluride. Then there is a metallic rear contact. Figure 11 below shows a cross section of a typical CdTe wafer.

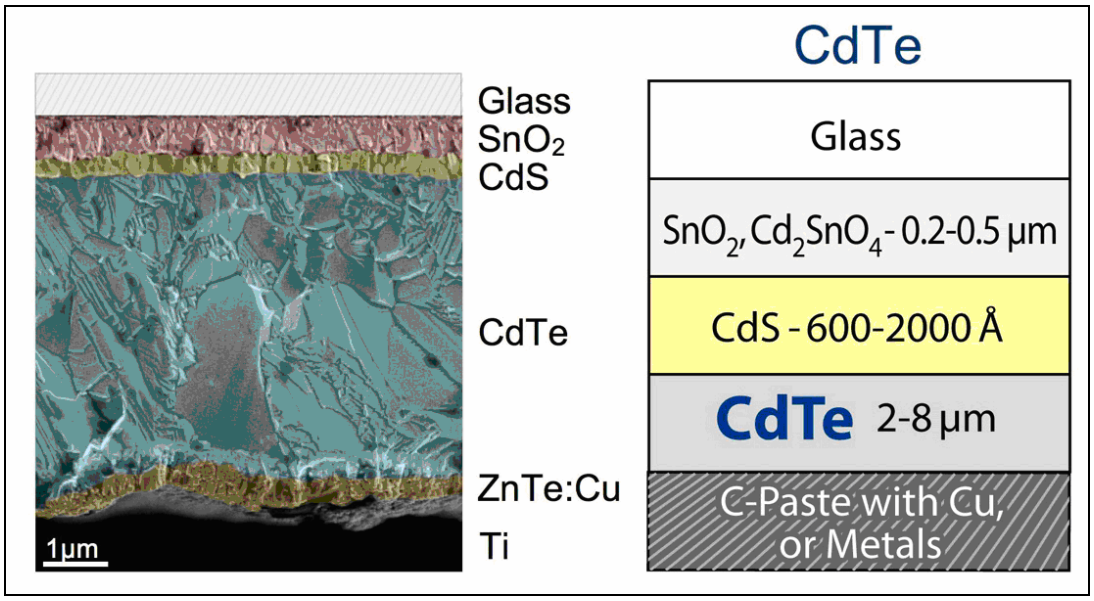


Figure 11: Structure of CdTe solar cells
Source: Noufi R. Zweibel K. (2006), *High-efficiency CdTe and CIGS thin-film solar cells: Highlights and challenges* [online], Available: http://www.nrel.gov/docs/fy06osti/39894.pdf (Accessed 3rd February, 2008)

Advantages:

- High cell efficiency (over 16% in the lab)

Disadvantages:

- High processing temperature, and as a result CdTe can only be manufactured on a superstrate
- Perception that CdTe devices will be unstable and degrade in outdoor environments
- Unencapsulated cells are sensitive to moisture, so module sealing is extremely important
- Toxicity of cadmium
- Expensive decommissioning due to cadmium clean up required

2.7.5 Copper Indium Gallium Diselenide (CIGS)

Copper Indium Diselenide has an extremely high absorption that allows 99% of available light to be absorbed in the first micrometre of the material. This makes it an effective PV material. The addition of gallium into the material boosts its light absorbing bandgap and better matches it to the solar spectrum. This maximises efficiency and increases the voltage output of these cells. CIGS cells have reached efficiencies of more than 19% - much higher than other thin-film PV. The performance is also stable over many years. The substances are, however, rare and not likely to enter commercial production in the near term. Figure 12 below shows a cross section of a typical CIGS wafer.

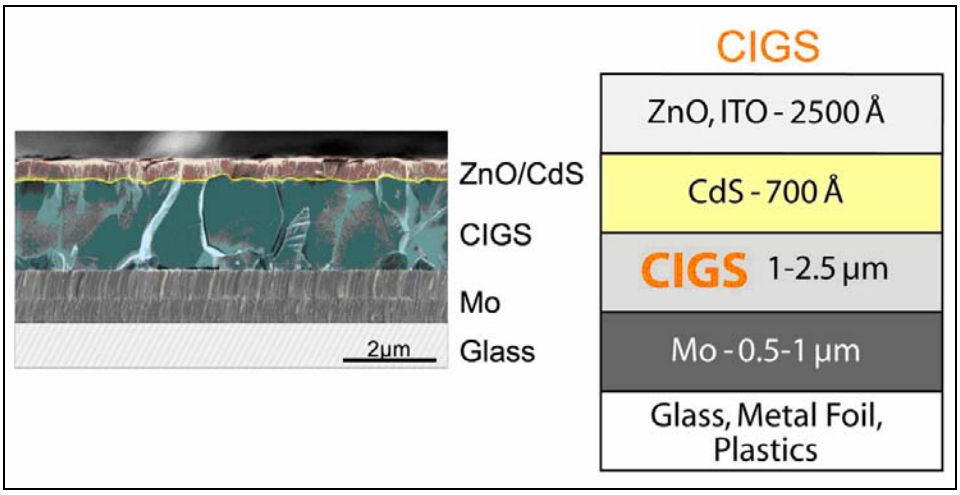


Figure 12: Structure of CIGS solar cells
Source: Noufi R. Zweibel K. (2006), *High-efficiency CdTe and CIGS thin-film solar cells: Highlights and challenges* [online], Available: http://www.nrel.gov/docs/fy06osti/39894.pdf (Accessed 3rd February, 2008)

Advantages:

- Higher efficiencies compared with other thin film materials
- Economical material and processes
- There are clear research pathways to increase performance
- High light absorption

Disadvantages:

- Scarcity of gallium and indium (expensive and unsustainable to source)
- This thin film cell requires high vacuum processes, which are expensive,
- 20% loss due to temperature increase during operation.

Further Reading:

- International Solar Electric Technology, *Next Generations Thin-film Solar Devices* [online], Available: http://www.isetinc.com/cigs.html (Accessed 29th January, 2008)
- Global Solar Energy (2007), *Copper Indium Gallium DiSelenide – CIGS Photovoltiac Solar Technology* [online], Available: http://www.globalsolar.com/index.php?option=com_docman&task=doc_download&gid=206 (Accessed 29th January, 2008)
- B. von Roedern, Zweibel K. Ullal H.S. (2005), *The Role of Polycrystalline Thin-Film PV Technologies for Achieving Mid-Term Market-Competitive PV Modules* [online], Available: http://www.nrel.gov/docs/fy05osti/37353.pdf (Accessed 17th July, 2008), 31st IEEE Photovoltaics Specialists Conference and Exhibition; Lake Buena Vista, Florida, January 3–7, 2005

- Ullal H.S. (2004), *Polycrystalline Thin-Film Photovoltaic Technologies: Progress and Technical Issues* [online], Available: http://www.nrel.gov/docs/fy04osti/36241.pdf (Accessed 17th July, 2008), 19th European PV Solar Energy Conference and Exhibition; Paris, France, June 7–11, 2004

2.7.6 Group III-V Cells

Another minor group of wafer cells is the Group III-V cells, which uses compounds of elements from Groups III and V of the Periodic Table. A compound is a material that combines multiple elements from the periodic table together in a single structure. Each element is chemically altered in this state, so the whole material exhibits different properties to a simple physical mixture of each element. These types of wafers are used extensively in the optoelectronics and electronics industries. They can also be used to make excellent, but very expensive, solar cells which are usually used in satellites and space applications.

There are two types of Group III-V cells:

- Single Junction III-V cells
- Tandem and Multijunction III-V cells

Single-Junction III-V Cells

In this type of cell, active semiconductor layers are deposited by a variety of techniques on inactive substrates that don't contribute to current generation. High efficiency single junction cells have been made from different materials such as Gallium Arsenide and Indium Phosphide. The best single junction III-V solar cell produced had an efficiency of 27.6%.

Advantages:

- High efficiency
- Low weight
- Reduced degradation under radiation outside the Earth's atmosphere

Disadvantages:

- Expensive
- Material not abundant

Tandem & Multi-junction III-V Cells

In tandem cells, a number of different p-n junctions are stacked together, each formed from semiconductors with different bandgap energies. Different semiconductor

combinations will naturally have different bandgap energies at their junctions (i.e. their meeting points). Each bandgap energy value requires a different range of wavelengths of sunlight to release electrons, so a greater portion of the solar spectrum is captured by the device as a whole. This yields higher overall efficiencies. Each junction absorbs what it can and lets the remaining wavelengths of light pass through to the next junction below to be absorbed

This tandem structure manages to reduce the main losses of solar cells: the thermalisation of the excess energy of high energy photons; and the transparency of semiconductors to low energy photons. *Thermalisation* refers to the situation where an electron has been given more energy by a photon than required to jump the energy bandgap, and the electron subsequently loses this surplus energy by 'bumping' into other nearby atoms (converting the kinetic energy to heat). An example of this is high energy blue light that falls on silicon with a bandgap requiring only a fairly low energy photon to bridge it (blue light has high energy because it has a high frequency). *Transparency* refers to photons that don't interact with the silicon material because they do not have sufficient energy to excite an electron across the band-gap. When the photon doesn't have enough energy to energise an electron to cross the bandgap, the photon simply passes straight through the semiconductor material in the same way that most light passes through glass. We say that glass is transparent to light/radiation. But in fact, glass absorbs light (radiation) at wavelengths greater than 3μm. This region is called the infrared wavelengths. We feel that glass is completely transparent to sunlight because 99% of sunlight is comprised of photons in wavelengths below 3μm. Since we cannot see photons in the infrared (the long wavelength ones), we don't notice them being absorbed in glass the way we notice sunlight being absorbed in silicon. Dark semi-transparent materials are basically absorbing the photons of light coming through them, rather than letting them through to your eyes.

Tandem cells are widely used for space applications and powering satellites. The overall record efficiency for this type of cell is 35.2%.

Advantages:

- Higher efficiencies than single junction III-V cells

Disadvantages:

- Difficult and expensive to manufacture

Further reading

- School of Photovoltaic and Renewable Energy Engineering UNSW, *Thin-film Solar Cells* [online], Available: http://www.pv.unsw.edu.au/future-students/pv-devices/thin-film.asp (Accessed 6th January, 2008)

- National Renewable Energy Laboratory, *The Basic Physics & Design of III-V Multijunction Solar Cells* [online], Available: http://photochemistry.epfl.ch/EDEY/NREL.pdf (Accessed 10th September, 2008)

References for all the III-V Cells sections:

- Emery K, Ling DL, [http://www.globalsolar.com/technology.htm#CrystallineSilicon, Global Solar], 2002
- Richard Corkish, 2004, University of New South Wales, Solar Cell: Encyclopedia of Energy, Volume 5, pages 549-555, 2004 Elsevier Inc.
- Martin A Green, 1998, Solar Cells, Operating Principles Technology and System Application, pages 187-197.
- Rommel Noufi and Ken Zweibel, [http://www.nrel.gov/docs/fy06osti/39894.pdf, High-efficiency CdTe and CIGS thin-film solar cells: Highlights and challenges*], National Renewable Energy Laboratory, Golden, CO 80401, USA, May 2006
- Stuart Wenham, 2006, SOLA2020: Photovoltaic Technology and Manufacturing Lecture notes
- Jeff Cotter, 2005, UNSW SOLA3507: Solar Cells, Lecture notes

2.8 Crystalline structures in silicon

If carefully and slowly produced, silicon can be formed as a network of crystals. An entire ingot can be manufactured as one single, large crystal. These single-crystal ingots can easily weigh over 20kg. Alternatively, crystalline silicon may be formed using cheaper methods that produce many small crystals, with visible grain boundaries between each one. A single wafer of 10cm × 10cm (300µm thick), can then easily contain 10 or more crystals. If everything else is the same, the fewer crystals present in a silicon wafer, the higher its efficiency will generally be. We can also have silicon existing in non-crystalline forms, like amorphous silicon. We can even have crystalline forms that are less orderly than single-crystal silicon. We describe this variability in order as different levels of crystallinity (crystal structure). Table 4 lists the different types of crystalline silicon that are available in the current market place. They are categorized based on the size of the crystals.

Table 4: Categorisation of crystalline silicon

Type of crystalline silicon	Symbol	Grain Size	Common Growth Techniques
Monocrystalline (Single-crystal)	sc-Si	>10 cm	Czochralski (Cz), float zone (FZ)
Multicrystalline	mc-Si	1mm - 10 cm	Cast, spheral, sheet, ribbon
Polycrystalline	pc-Si	1µm - 1mm	Chemical- vapour deposition

2.8.1 Monocrystalline (single crystal) silicon

For monocrystalline silicon, the single crystal ingots are formed using special techniques so that each silicon wafer consists of a single crystal of silicon. Single crystal silicon wafers currently satisfy a significant but declining fraction of the solar cell market. As shown in Table 4 above, the common growth techniques for monocrystalline wafers are the Czochralski (Cz) and Float Zone (FZ) methods. Note that the terms, multicrystalline & polycrystalline are often used interchangeably and can be produced by some common growth techniques. Polycrystalline has been defined in some sources to be essentially multicrystalline but with much smaller grain sizes.

Advantages:

- Single crystals are already produced for other industries including the integrated circuit industry
- Produce the highest efficiencies for crystalline silicon solar cells

Disadvantages:

- Require high purity silicon, which can be more expensive and energy intensive to produce
- Single crystals are often circular, requiring reshaping for use in modules where cells are usually pseudo square. This allows high packing densities of square cells (compared to circular cells), but means some crystalline Si is wasted

Further Reading

- Jones V. (2001), *Electronic Devices and Circuits: Engineering Sciences 154* [online], Available: http://people.seas.harvard.edu/~jones/es154/lectures/lecture_2/materials/materials.html (Accessed 1st February, 2008)
- T.F. Ciszek (2007), *Silicon Info: Single-Crystal Ingot Growth* [online], Available: http://www.siliconsultant.com/SIcrysgr.htm (Accessed 2nd February, 2008)

Czochralski (CZ) ingots

Wafers grown by the Czochralski process dominate the monocrystalline part of the photovoltaic market. The process involves a purifying stage to remove several detrimental metallic impurities so that even a poor quality starting material can produce good solar cells. The silicon source material is melted in a crucible under vacuum or inert gas and one solid seed crystal is dipped into the melt and slowly withdrawn vertically and rotated so that the molten silicon crystallizes to the seed. Crystallisation is where a liquid substance forms a very neatly structured solid crystal when it is cooled. The melt temperature and pulling speed are controlled to ensure that the silicon ingot forms with a constant diameter.

Cz wafers are lower in quality due to the presence of impurities (mostly from the crucible where the molten silicon is held). At high temperatures, the crucibles diffuse oxygen and other impurities into the molten silicon. Removing such impurities is quite costly, so Cz silicon is usually cheaper and hence more widely used in the industry. The impurities harm the electrical performance of the solar cells.

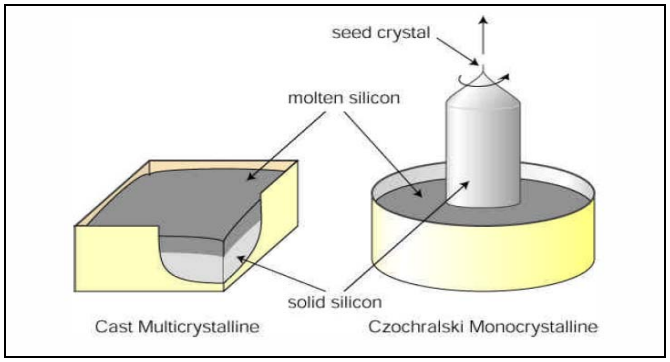


Figure 13: Processing of Cz wafers vs. multicrystalline casts
(Source: Dr. Jeff Cotter's lecture notes SOLA1050, chapter 3)



Figure 14: Cz crystal pullers growing single-crystal ingots

Further Reading

- H. Föll, *Czochralski Crystal Growth Process* [online], Available: http://www.tf.uni-kiel.de/matwis/amat/elmat_en/kap_6/illustr/i6_1_1.html (Accessed 1st February, 2008), University of Kiel
- Cusack S., Takizawa E., Tam J. (2004), *Czochralski Growth of Silicon Wafers* [online], Available: http://www.seas.upenn.edu/mse/ugrad/Silicon_Presentation.pdf (Accessed 1st February, 2008)

Float Zone (FZ) ingots

Wafers that are produced by the float zone process are generally very pure and have minimal defects. FZ silicon is produced from a cylindrical polysilicon rod which has a seed crystal melted into its lower end and an encircling inductive heating coil. The heater is raised along the rod length, creating a molten zone and a monocrystalline solidified region below. Impurities have higher solubility in molten silicon than in solid silicon, and they are carried with the molten material to the top, and tend to stay in the molten material. Thus, the monocrystalline silicon that solidifies below comes out purer than even Czochralski silicon. Honsberg C. and Bowden S. (2005), describe the separation of impurities into molten and solid material as follows:

"In this process, a molten region is slowly passed along a rod or bar of silicon. Impurities in the molten region tend stay in the molten region rather than be incorporated into the solidified region, thus allowing a very pure single crystal region to be left after the molten region has passed. This process enhances purity and crystallinity of the solidified monocrystalline material (the extent to which the structure of the material has perfect crystalline form)."

Further Reading

- H. Föll, *Float Zone Crystal Growth* [online], Available: http://www.tf.uni-kiel.de/matwis/amat/elmat_en/kap_6/advanced/t6_1_3.html#_dum_2 (Accessed 1st February, 2008), University of Kiel
- SiliconFarEast (2005), *Single Crystal Growing for Wafer Production (Page 2 of 2)* [online], Available: http://www.siliconfareast.com/crystal2.htm (Accessed 2nd February, 2008)

Slicing silicon ingots into wafers

In order to use the silicon ingots to make solar cells, the ingots need to be sliced into very thin wafers. Cutting takes a lot of time because the material is solid and brittle, and must be sliced to be only $^{1}/_{3}$mm (300μm) thick.

A couple of different techniques can be used for slicing wafers from an ingot. In wire sawing, a long, strong, thin metal wire is wrapped around the entire ingot at the cut locations. Then, when in place, it is pulled slowly, cutting into the wafer with its sharpness. In the past, very thin diamond-tipped saws were used to cut the wafers, but they weren't very accurate and resulted in more wafer breakages and many wafer surface defects. Wire sawing creates less surface damage on the wafers while simultaneously producing less sawdust (waste) compared with using inner diameter diamond tipped saws. The wire sawing process rubs strands of the thin wire to gradually wear away the silicon. Wire sawing is extremely slow although throughput has been improved by

wrapping the same piece of wire around the entire ingot so that the entire ingot is sliced simultaneously into numerous wafers.

In comparison, inner diameter diamond tipped saws slice each individual wafer quite quickly but only one wafer can be sliced at a time. These saws create significantly more damage to the wafer surface which can penetrate up to 40microns into the surface. Such surface damage has to be removed by an etching process if high quality solar cells are to be produced. A large amount of silicon is subsequently wasted.

Further Reading

- For some fantastic photos and a video of the wafer sawing process, have a look at Kleir International LLC, *Image Gallery* [online], Available: http://www.kleirco.com/Gallery/index.htm (Accessed 2nd February, 2008)

2.8.2 Multicrystalline and Polycrystalline

The two terms, multicrystalline and polycrystalline, have historically been used interchangeably to describe silicon wafers, however, there are differences between the two. Multicrystalline is the most commonly used wafer type and has larger crystal sizes than polycrystalline. Multicrystalline has surface colour variations, with each different colour representing a different crystal. The growth methods for polycrystalline and multicrystalline silicon are far cheaper than monocrystalline but result in more defects. Consequently, polycrystalline and multicrystalline wafers have lower efficiencies when used in solar cells. For instance, the areas where the crystals intersect are called grain boundaries and contribute to lost electrical current and inefficiency. Both have the following properties:

Advantages:

- Relatively cheap
- Requires lower purity silicon than monocrystalline
- Easier to produce than monocrystalline

Disadvantages:

- Lower efficiency than monocrystalline

A photo of the front surface of a multicrystalline cell is shown in Figure 15 below.

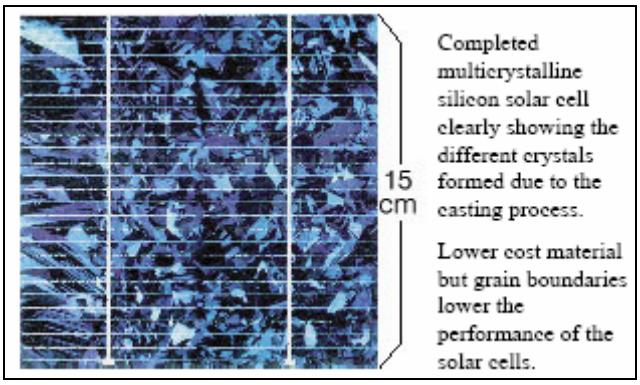


Figure 15: Multicrystalline wafers
(Source: SOLA2060 Lecture Notes, Dr. A. Sproul, Chapter 3)

2.8.3 Ribbon Silicon

Ribbon silicon is an emerging technique that can be used to grow multicrystalline silicon strips or ribbons. Two carbon filaments provide a pathway between which molten silicon can grow horizontally through capillary action, as illustrated in Figure 17. This produces a long ribbon of multicrystalline silicon. Then the structure on which the ribbon is grown is gradually pulled upwards, widening the ribbon.

The main methods for growing the silicon ribbon include:

(i) Growing the ribbon on a dendritic web (like using a seed crystal to pull more of the molten silicon upwards to bond with it)

(ii) Growth using a shaping die, drawing the silicon with capillary action

(iii) Growth with edge supports or "strings," which is similar to dendritic growth except using only edge supports for the growing silicon ribbon

(iv) Growing the ribbon on a substrate

Basically ribbon growth techniques involve pulling a small width of silicon out of a molten silicon reservoir, so it cools into a thin slice without the need for sawing a thick ingot into thin wafers. Techniques also exist for drawing ribbons of germanium instead of silicon. Figure 16 below is a photo showing how the ribbon can be grown on a substrate. Figure 17 below shows a vertically drawn method of growing the ribbon.

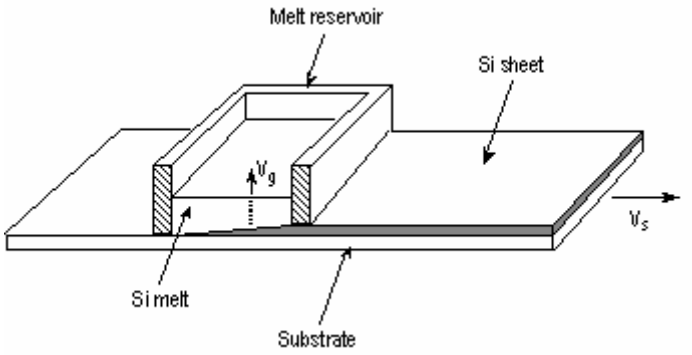


Figure 16: Diagram of a ribbon grown on a substrate, where it is pulled horizontally
(Source: T.F. Ciszek (2007), *Silicon Info: Ribbon and Sheet Growth* [online], Available: http://www.siliconsultant.com/SIribbonGr.htm, Accessed 10th January, 2008)

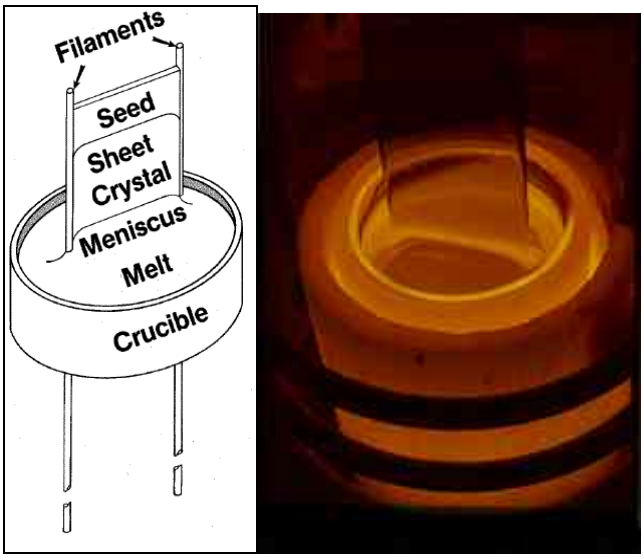


Figure 17: (left) Components of a ribbon of silicon; and (right) Ribbon being drawn
(Source: T.F. Ciszek (2007), *Silicon Info: Ribbon and Sheet Growth* [online], Available: http://www.siliconsultant.com/SIribbonGr.htm, Accessed 10th January, 2008)

Advantages:

- Thickness can be varied to optimise cell processes
- Cheaper because less silicon can be used and there are no kerf losses (silicon 'sawdust' that is lost when cutting)

Disadvantages:

- Lower efficiencies due to greater surface defects (you tend to get visible "bumps" and ridges on the surface of the drawn ribbon/slice)

Table 5 on the following page compares various silicon growth methods.

Table 5: Comparison of Silicon Growth Methods

Method	Width (cm)	Weight (kg)	Growth Rate (mm/min)	Growth Rate (kg/h)	Throughput (m^2/day)*	Energy Use (kWh/kg)	Energy Use (kWh/m^2)**	Efficiency (Typical, best %)
Float Zone	15	50	2-Apr	4	80	30	36	<18, 24
Czochralski	15	50	0.6-1.2	1.5	30	18-40	21-48	<15, 20
Directional Solidification	69	240	0.1-0.6	3.5	70	Aug-15	Sep-17	<14, 18
Electromagnetic Casting	35	400	1.5-2	30	600	12	35	<14, 16
Dendritic Web	5	--	Dec-20	--	1	--	200	<15, 17
Capillary Die Growth	80	--	15-20	--	20	--	20	14, 16
Edge-Supported Pulling	8	--	Dec-20	--	1.7	--	55	<13, 16
Substrate Melt Shaping	20	--	1000-6000	--	>1000	--	--	<12, 16
Thin-Layer Si	2	--	10^{-3} ⊥	--	--	--	--	--, 13

*Areal throughput for ingots assumes 20 wafers/cm
**Only the energy for growth is included
-- indicates data are not available or not appropriate
⊥ deposition rate perpendicular to the substrate

Source: T.F. Ciszek (2007), *Silicon Info: Growth Methods - A Comparison* [online], Available: http://www.siliconsultant.com/SICompGr.htm (Accessed 2nd February, 2008)

Further Reading

- US Department of Energy (2005), *The Crystalline Silicon Solar Cell* [online], Available: http://www1.eere.energy.gov/solar/crystalline_silicon_cell.html (Accessed 8th January, 2008)
- Ciszek, T.F., *Silicon Info: Ribbon and Sheet Growth* [online], Available: http://www.siliconsultant.com/SIribbonGr.htm (Accessed 13th September, 2006)
- Dressen D. Clement H. Jochum J. Mildenberger G. (2007), *Photovoltaics: Physics and Technology* [online], Available: http://www.pit.physik.uni-tuebingen.de/studium/Energie_und_Umwelt/ss07/Photovoltaik_2.pdf (Accessed 14th September, 2008)

References for this section in general:

- Paul A. Basore, *Short Communication: Defining Terms for Crystalline Silicon Solar Cells*
- Richard Corkish, Photovoltaic Materials: Encyclopedia of Chemical Processing
- Sandia National Laboratories (2005), Available: http://www.sandia.gov/pv/images/PVFSC21.jpg (Accessed 12th February, 2007)
- Jeff Cotter, SOLA3507: Solar Cells and Systems, Lecture Notes Chapter 5, UNSW
- Alistair Sproul, SOLA2060: Introduction to Electronic Devices, Lecture Notes, Chapter 3, UNSW
- U.S. Department of Energy – Energy Efficiency and Renewable Energy, Available: http://www1.eere.energy.gov/solar/crystalline_silicon.html (Accessed 12th February, 2007)

2.9 Texturing

Of the light that falls on a cell, some part will be absorbed (and most of this is converted into electricity), some reflected, and some passes straight through (transmitted). Bare silicon is a highly reflective material. In order to maximise the amount of sunlight entering the cell a number of cell surface treatments can be employed to reduce reflection and therefore increase absorption. Texturing is one method. A chemical etch is used to form pyramids on the surface of the silicon as shown in Figure 18.

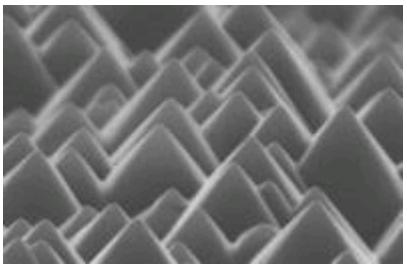


Figure 18: Pyramid formation during texturing of cells (at microscopic scale)
(Source: Solar Cells, Operating Principles, Technology and System Application, Martin A Green, 1998, p.128)

For monocrystalline wafers, pyramids are formed by the process of an anisotropic etch using sodium hydroxide and isopropanol. The process uses a chemical to etch away the surface of a semiconductor at different rates depending on the plane. This way, by pouring the etching chemical on a crystalline material, some sides of the crystal will burn off faster, leaving a particular shape, in this case a pyramid. The pyramids' formation depends on several different factors such as the temperature and the concentration of NaOH and isopropanol, and the length of time the wafer is exposed to the etch solution.

These pyramids help to reduce the reflectivity of the surface by reflecting the light to another pyramid and hence there will be more chance for absorption as shown in Figure 19 below. Another advantage of texturing is that much of the light going into the silicon enters at an oblique angle, which enhances the chances for absorption by making the wafer seem "optically thicker". This subsequently reduces the total reflection from the cell because more of the available light is absorbed.

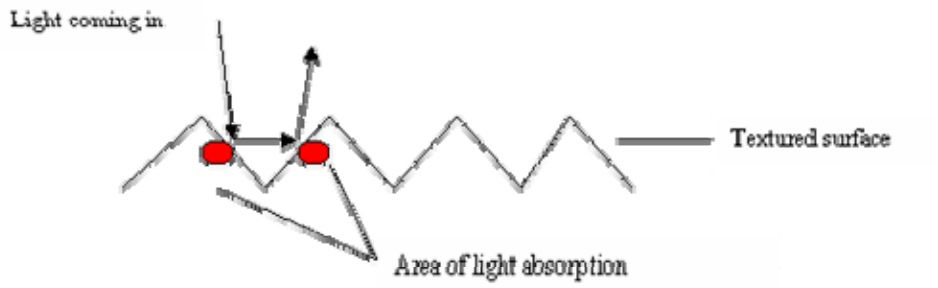


Figure 19: The process of increasing absorption through texturing

The reduction in reflection due to greater absorption of light following texturing can be seen in the following graphs. The total surface reflection of the untextured cell in Figure 20 (left) decreases from 30% to around 10% for the textured cell in Figure 20 (right) below.

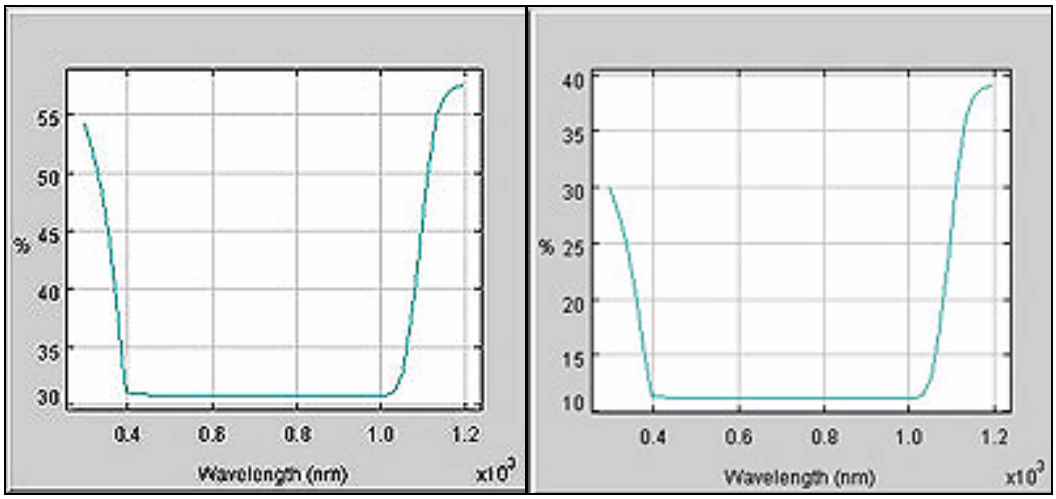


Figure 20: (left) Normal reflection characteristics for a flat uncoated crystalline silicon surface. (right) Reflection from a textured silicon solar cell according to wavelength

The horizontal axis shows the wavelengths of light for which the vertical axis shows the reflection from the cell as a percentage of light incoming at each wavelength

Further Reading

- Greenwood M.A. (2008), *Which Way Out? Solar Cells the Trap Light* [online], Available: http://www.nrel.gov/docs/fy05osti/37322.pdf (Accessed 10th September, 2008), Applied Physics Letters, Dec. 10, 2007, Vol. 91, Laurin Publishing
- Burgelman M. (1998), Thin Film Solar Cells by Screen Printing Technology [online], Available: http://escher.elis.ugent.be/publ/Edocs/DOC/P098_121.pdf (Accessed 10th September, 2008), Proceedings of the Workshop Microtechnology and Thermal Problems in Electronics; The Summer School, Technical University of Lodz

Texturing can also be performed on multicrystalline PV cells using slightly different methods. For some information on these techniques, have a look at the following reference:

- Macdonald D. Cuevas A. Kerr M. Samundsett C. Ruby D. Winderbaum S. Leo A., *Texturing Industrial Multicrystalline Silicon Solar Cells* [online], Available: http://engnet.anu.edu.au/DEresearch/semiconductor/publications/pubs-2001/texture.pdf (Accessed 5th March, 2007), Australian National University

2.10 Anti-Reflection Coating

The second method used to reduce reflection from the surface of the solar cells is an anti-reflection coating (ARC). ARCs can be used in combination with texturing or on cells that are unsuitable for texturing. For example, multicrystalline cells are not suitable for texturing so an ARC can be applied to reduce surface reflection. The use of anti-reflection coatings can reduce the reflection of light down to nearly 0% at some wavelengths, as shown by Figure 20 (right) above.

Anti reflective coatings rely on the principle of superposition. For example, if you have two electrical signals of equal magnitude that are 180 degrees out of phase (shown in Figure 21Figure 21), the overall output is zero. The same superposition effect occurs with light.

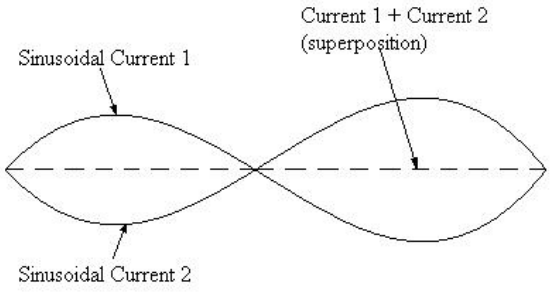


Figure 21: Principle of superposition using sinusoidal currents

If we think of incoming light as a sinusoidal wave, the anti reflective coating is designed so that at a particular wavelength of light, the incoming radiation cancels out the reflected radiation or is 180 degrees out of phase (like in Figure 21). This situation has is illustrated in Figure 22 for an antireflective coating of thickness, 'T.' The phase difference is achieved by having light reflected from the AR coating travelling an extra half wavelength.

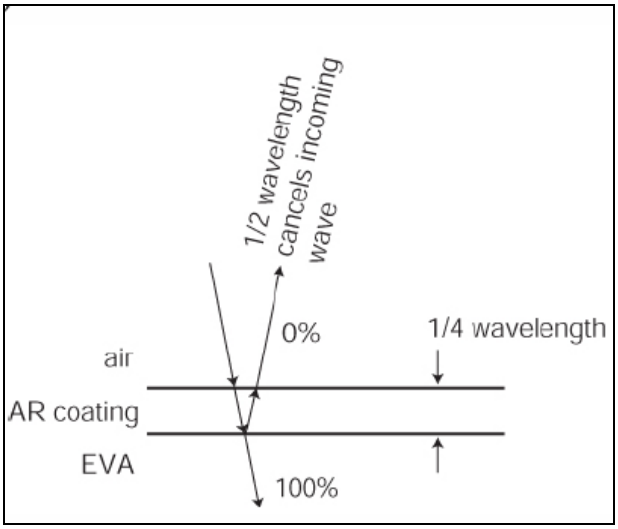


Figure 22: Schematic of silicon surface coated with a dielectric layer of thickness T
(Source: SOLA1050 Lecture notes, Jeff Cotter, chapter 8)

The mechanism by which the AR coating is able to reduce the surface reflection of silicon is by light reflecting from the silicon/dielectric surface being as close as possible to 180 degrees out of phase with the light being reflected from the air/dielectric interface, with the two reflected components therefore acting to cancel each other out by destructive interference (see Figure 23 below).

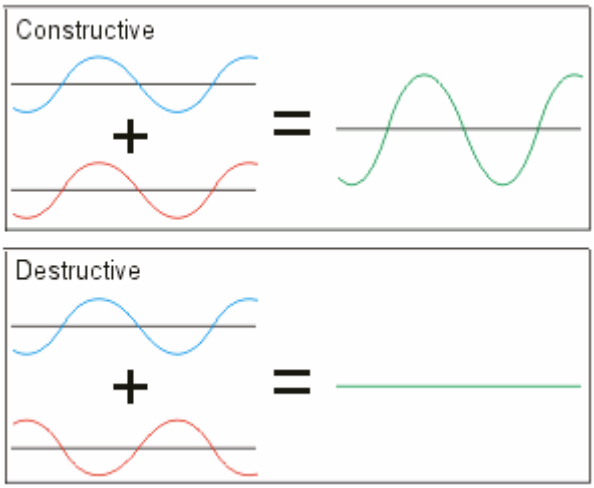


Figure 23: Constructive and destructive wave interference
Source: Number A Productions, *Mechanics of Interference* [online], Available: **http://www.numbera.com/musictheory/mechanics/images/interfere.gif** (Accessed 3rd February, 2008)

The 180 degree phase shift is achieved for a given wavelength λ by making the thickness of the dielectric layer T = λ/4 (where λ is the wavelength the light has within the dielectric layer). λ is the wavelength of light whose reflection is to be attenuated the most. That is, solar cells that look blue actually reflect blue more than other wavelengths of light. It is the anti-reflective coating that makes cells look blue or black. The reflected light will therefore have a phase shift of half a wavelength (2T) and therefore destructively interfere with the light component reflected from the dielectric/air interface to reduce the total reflection.

A range of different dielectric materials can be used for forming antireflection coatings and can be applied using a range of different techniques including:

- Resistive heating vacuum deposition
- Chemical vapour deposition
- Screen printing
- Sputtering

Silicon nitride, silicon dioxide and zinc oxide are commonly used as antireflection layers.

There is sometimes more than one anti-reflective coating applied. This is because each AR coating works best at one specific design wavelength (the ARC is less effective for wavelengths further from this design wavelength). By increasing the number of coatings, the overall reflection can be reduced.

A single AR coating can only reduce the reflection of one wavelength of light to zero. This is because the ARC's thickness can only be optimized to perfectly produce an 180^{o} out-of-phase reflection for one wavelength. Remember that a wavelength is a distance. Remember also, that the thickness of the ARC film is what governs the degree of the phase shift. It will still be fairly effective for wavelengths near that specified wavelength, but it will not cause destructive interference for the much longer or much shorter

wavelengths. This is seen in Figure 20 above, where the ARC film has been set to a thickness to minimise reflection from light with wavelength 600nm.

A note on surface passivation: at the surface of the silicon, we reach a point where silicon atoms meet the air and there are no further silicon atoms to attach to and bond with. At this point some silicon bonds will be left "dangling", unbonded. These dangling bonds at the edge of the cell are excellent places to recombine the electrons that we want in the current back into the crystal structure. Since we don't want this to happen, we passivate the surface. All this means we attach those dangling bonds to some other material so that electrons can't get trapped in them. Silicon dioxide and silicon nitride are two materials that can be formed on the surface of silicon that do both a good job of passivating the dangling bonds and also work as an ARC.

For a fantastic animation illustrating how constructive and destructive interference occurs in waves, visit the following reference:

- Duffy A. (1998), *Constructive and Destructive Interference* [online], Available: http://physics.bu.edu/~duffy/semester1/c21_interference.html (Accessed 3rd February, 2008), Boston University

Further Reading

- Zobel E.A. (2006), *Wave Interference* [online], Available: http://id.mind.net/~zona/mstm/physics/waves/interference/intrfrnc.html (Accessed 3rd February, 2008)
- Nave C.R., *Anti Reflection Coatings* [online], Available: http://hyperphysics.phy-astr.gsu.edu/Hbase/phyopt/antiref.html (Accessed 6th May, 2007)
- Melles Griot Inc. (2002), *Optics Guide: Coating Theory* [online], Available: http://www.mellesgriot.com/products/optics/oc_2_2.htm (Accessed 14th September, 2008)

References:

- Wenham S. Bruce A. Alexander G. (2002), Virtual Production Line software Help Files: texturing, antireflection coating
- Diefenbach K.H. (2005), The Return of Laminated Glass Modules with PVB [online], Available: http://www.photon-magazine.com/news/news_2005-04%20ww%20feat%20PVB%20foils.htm (Accessed 13th June, 2007), Photon International, April
- Jörn I. (2006), *Cell Manufacturing: The Technology*, Sun and Wind Energy, Issue 1/2006, 76-83
- Applied Photovoltaics, Stuart Wenham, Martin Green, Muriel Watt, Richard Corkish, Centre for Photovoltaic Engineering, Chapter 5, page 79, figure 5.17

2.11 Metal contacts used to collect current

Metal contacts are applied to the cell to collect the current generated by the light for transmission to an external load. As mentioned earlier, the photovoltaic process uses incoming light to give energy to electrons so that they can move into the conduction band. The electron and its corresponding hole are then free to move about the semiconductor. In order for current to flow, an external circuit must be available. In Figure 24 below, the front metal contacts touch the silicon in order to collect electrons. These electrons then flow through an external circuit and combine with holes at the rear contact to complete the cycle.

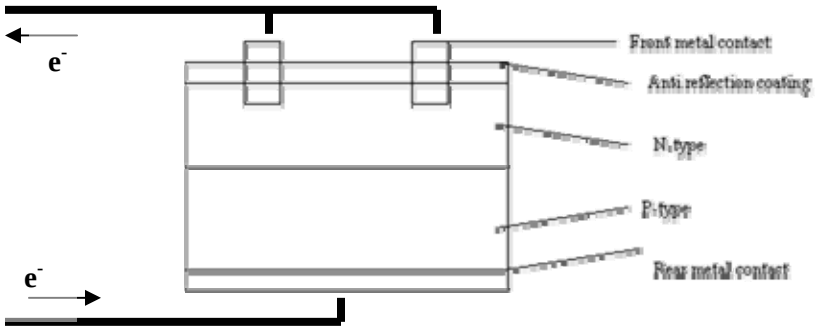


Figure 24: Structure of solar cell with front and rear contacts

2.11.1 Front Metal Contact

The front metal contact is used to collect electrons produced near the p-n junction. The most common method is screen-printing the metal contacts onto the front surface of the cell using a silver paste. Silver is used mainly because it has the highest electrical conductivity of all metals. This makes sure that there will be a low amount of series resistance in collecting the current from the p-n junction. This screen-printed silver paste is then infused into the surface by firing the cells in a furnace. The depth of the silver penetration is crucial and is determined by the firing time.

The optimum condition for the front contacts is when the metal just touches the front n-type layer. If the metal penetrates too deeply into the silicon, there will be risk of the metal going right though the junction, breaking through to the p-type layer. This creates a short circuit in the cell. On the other hand, if the silver paste doesn't penetrate through the anti reflection coating, then the series resistance will be very high due to poor fusing of the silicon and the metal. Control over this process greatly affects cell performance.

There are performance trade-offs that must be made for the front contact design. You don't want to cover too much of the cell's front surface with metal so that you maximise the light entering the cell, so you want to use narrow contacts. However, if the metal contact is too small or if the grid lines are too thin, then the series resistance of the solar cell will be high, because there is a lot of current trying to reach an insufficient metal

contact. A balance is required when deciding on the width of contacts to achieve the lowest overall loss taking into consideration both shading and series resistance losses.

2.11.2 Rear metal contact

The rear contact is generally simpler to apply as it covers the entire back of the cell. The metal that is usually used for the formation of rear metal contact is aluminium. Aluminium can also help to neutralize the phosphorus that was fired into the back of the solar cell when the emitter was created, preventing contamination.

Further Reading

- U.S. Dept. of Energy EERE (2006), *Electrical Contacts* [online], Available: http://www1.eere.energy.gov/solar/electrical_contacts.html (Accessed 22nd June, 2008)
- UNSW SPREE, *Buried Contact Solar Cells* [online], Available: http://www.pv.unsw.edu.au/future-students/pv-devices/buried-contact.asp (Accessed 10th September, 2008)

Here's an example of a metal paste product by one company:

- DuPont (2008), *DuPont Metallization Pastes* [online], Available: http://www2.dupont.com/Photovoltaics/en_US/assets/downloads/pdf/Solamet_for_PV.pdf (Accessed 10th September, 2008)

2.12 Encapsulation

Encapsulation is the external protection placed around a solar module to protect if from the harsh environment in which it will operate. Once cells are encapsulated they become known as modules. Encapsulation of solar cells is needed for the following reasons:

- To ensure that the layers within the module remain attached as one piece (as opposed to falling apart). The encapsulation material cannot contain chemically aggressive components that could attack cell parts.
- To electrically isolate the cells from one another to prevent short circuits
- To protect cells from water vapour – the most damaging contaminant to solar cells
- To protect cells from oxygen that will oxidise the silicon and metal contacts
- Solar modules are exposed to outdoor conditions, and are expected to have extremely long life-spans (20-25 years or more). The encapsulation material must maintain this protection for decades

The materials which are used for encapsulation are usually:

- Glass: The type of glass which is used for encapsulation is "low iron" glass. Glass is usually used for encapsulation in the upper layer, because the upper layer usually needs to be transparent, scratch-resistant, and weather proof, but sometimes it is used instead of Tedlar for the rear cover too.

- Ethylene vinyl acetate (EVA): Transparent encapsulant to fill all voids between the front glass and rear layer. This is used as the glue to hold the front and rear layers together. EVA is clear glue that does not deteriorate with heat or UV exposure.
- Tedlar: Tedlar is polymer that is usually used for the back layer, because it is a strong material, and can protect the solar cells well from the environment.

The diagram below shows the normal structure of encapsulation of solar cell using glass, EVA and Tedlar.

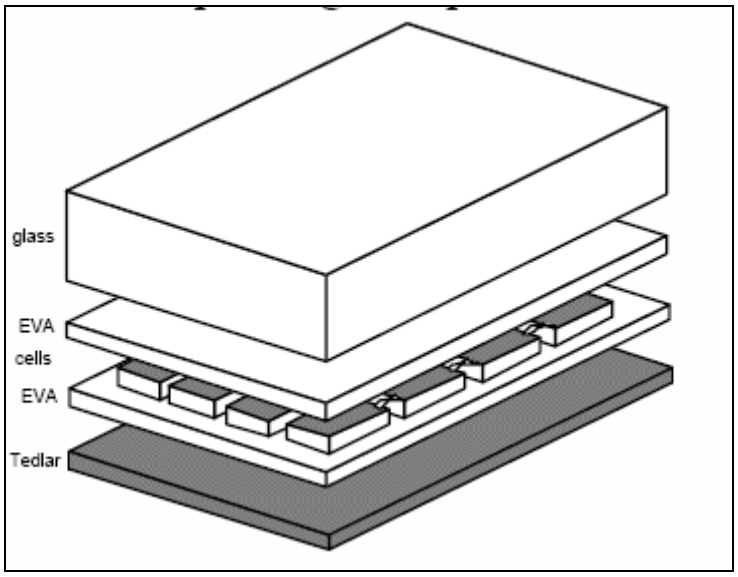


Figure 25: Typical laminated module structure
(Source: Applied Photovoltaic, Stuart Wenham, Martin Green, Muriel Watt, Richard Corkish, Centre for Photovoltaic Engineering, chapter 5, page 79, figure 5.17)

Encapsulation failure is the most common mode of failure for solar modules and is a continuing area of research and improvement. Current modules offer 30 year warranties - longer than almost anything else sold in the world.

Further Reading

- Honsberg C. Bowden S. (2005), *PV Module Temperature* [online], Available: http://pvcdrom.pveducation.org/MODULE/Temper.htm (Accessed 14th September, 2008)
- Mau S. Krametz T. Jahna W. Fechner H. (2004), *Quality Testing for PV Modules According to Standards and Performance Control for Supporting Manufacturing* [online], Available: http://www.arsenal.ac.at/downloads/Publikationen/2004/Quality%20testing%20for%20PV-modules.pdf (Accessed 14th September, 2008), 19th EUPVSEC, 7-11 June, 2004; Paris, France

For some idea of what laminates look like, see the following:

- Uni-Solar (2005), *Data Sheet: Solar Laminate PVL-Series* [online], Available: http://www.uni-solar.com/uploadedFiles/0.4.1_pvl_68_tech_data_sheet(1).pdf (Accessed 14th September, 2008)

2.13 Silicon sourcing from the integrated circuits industry

Previously, when the photovoltaic industry was still small, silicon was sourced from the integrated circuit industry. This was due to the large expense involved in producing high purity silicon specifically for use in the PV industry. Now, as the industry has grown rapidly, there is a need for the photovoltaic industry to manufacture its own silicon, often sourced from scrap silicon from other processes. Even so, there is currently a silicon shortage due to the large demand for solar cell technologies around the world.



Figure 26: A drum of scrap silicon chips awaiting re-melting and growth into ingots for later sawing into wafers for solar cell manufacture

Further Reading

- ENF Ltd. (2005), *Recycling Silicon: Issue 2* [online], Available: http://www.enf.cn/magazine/issue2/recycle.html (Accessed 7th September, 2008)
- Mertens R.P. Leuven K.U., *What can More than Moore bring to Photovoltaics?* [online], Available: http://wps2a.semi.org/cms/groups/public/documents/events/p043124.pdf (Accessed 9th September, 2008)
- Barraclough K.G. (2006), *Waste Not, Want Not! - A Case for Recycling Silicon Waste Powder Kerf* [online], Available: http://www.kgbconsultingltd.com/downloads/Waste_Not_Want_Not.pdf (Accessed 10th September, 2008)

3 Engineering mechanics

3.1 Silicon solar cell manufacturing process

The process used to manufacture silicon solar cells varies depending on the technology involved, however the general process used remains the same and is shown in Figure 27 (From Wenham, S., Bruce, A., Alexander, G. 2002) further details is shown below

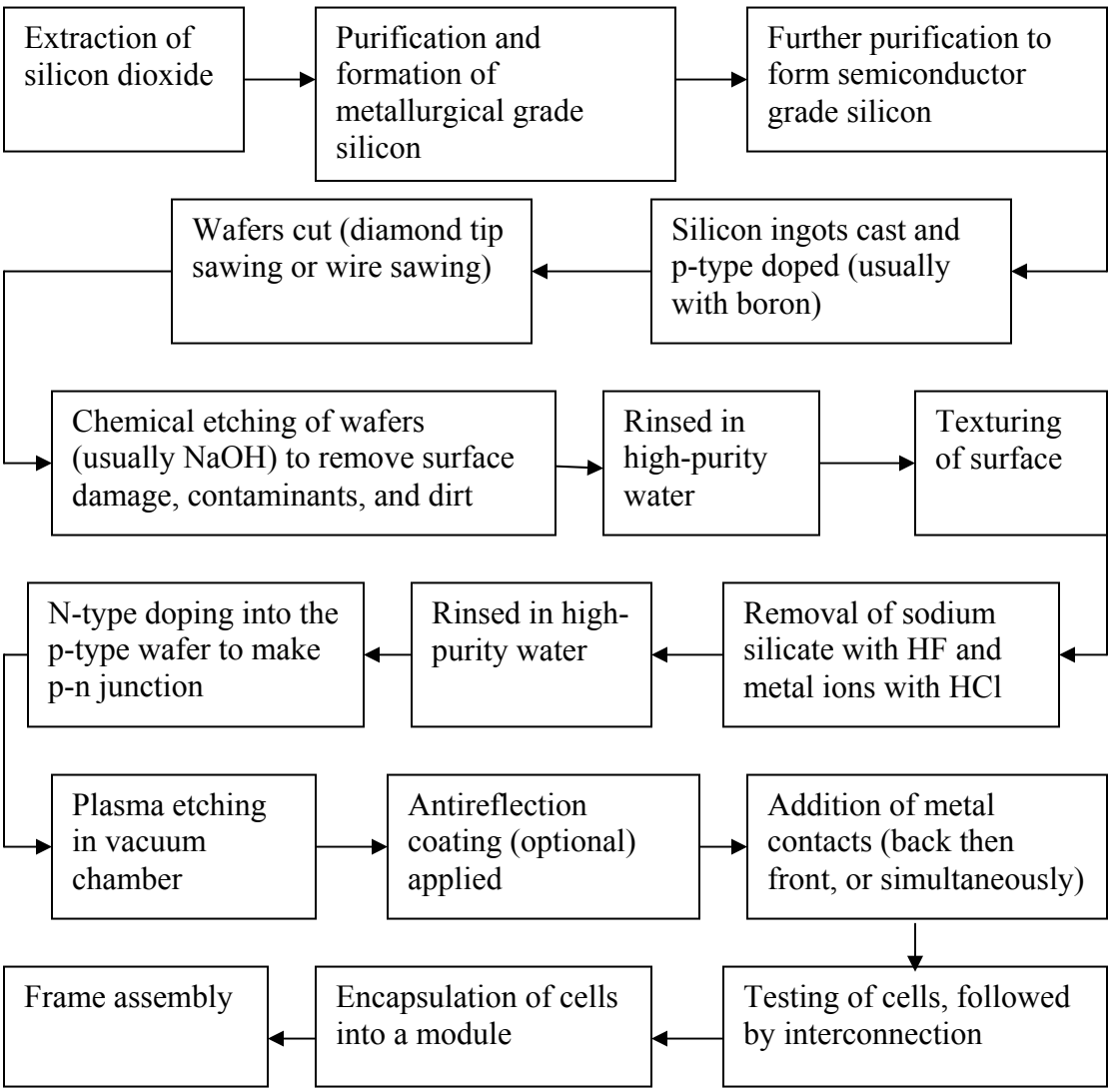


Figure 27: Flow-chart diagram of the silicon solar cell manufacturing process

Silicon extraction – silicon is abundant and is found in sand (SiO_2). The extraction involves sand mining and transportation to a purification factory.

Silicon purification – this is a chemical process where silicon is separated from the oxygen also contained in sand. Other impurities are also removed at this stage. For photovoltaics the silicon must be 99.9999% pure. For use in the solar cell industry it is doped (usually p-type, so boron is added) so that a p-n junction can be produced by adding the n-type (phosphorous) layer later.

Silicon ingots – During purification the silicon is melted. The silicon is now solidified to form ingots. There are two main processes used to do this. The first is the Czochralski method: a single crystal is slowly drawn from a molten silicon vat. This creates a long cylinder of silicon that is all one crystal. The second method is easier and much cheaper, and involves pouring the molten silicon into a mould and letting it set. This process forms silicon with many crystals oriented in different directions. The silicon produced is then known as multicrystalline.

Cut wafers – From the solidified silicon ingots, the wafers are cut. They are usually about 0.3mm thick and are cut in a process known as wire sawing. A high-strength wire that is many kilometres long is wrapped around the ingot many times and pulled toward the centre to cut the ingot at all points simultaneously. This acts similarly to a saw, producing large quantities of silicon dust losses ('sawdust').

Saw damage etch – This is a wet chemical process that removes dirt and damage from the wafer surface by immersing wafers in a sodium hydroxide (NaOH) solution. This needs to occur because grease and other contaminants are deposited onto the surface from the wire saw.

Texturing – This technique reduces reflection from the wafer surface by chemically etching away diagonal planes on the silicon surface to produce pyramids. These pyramids give incoming light to the solar cell multiple opportunities of penetrating the silicon as the light is reflected off the other planes onto other areas of silicon.

Doping and p-n junction – Before we can understand how doping occurs, we need to understand diffusion. If you put a drop of food colouring into a glass of water, you will see the food colouring spread itself out evenly in the water. Similarly, when you wear perfume, the smell spreads throughout a room. At high temperature this process occurs much faster. It is a natural tendency for a material in high concentration to spread out in the medium it is in. This is called diffusion, and it is driven by heat energy (temperature). 0^oC is actually 273^oC above Absolute Zero temperature, which is the temperature where there is no energy present at all (the lowest possible temperature). At room temperature (around 25^oC), there is actually a lot of energy present.

Once the wafers have been cut from the ingots, they are doped to make the p-n junction. This process generally occurs at high temperature in a furnace. The silicon is already p-

type so the infusion of n-type contaminants (the phosphorus dopant) creates the p-n junction automatically. The phosphorus is only diffused very close to the surface of the wafer and on the top side only, such that the junction and the new n-type region is only 10μm thick in a 300μm thick wafer.

Plasma etching - During phosphorus diffusion, some of the phosphorus penetrates into the sides of the wafer. This creates unwanted conduction paths for the generated electricity between the front and back surfaces of the solar cell, allowing the carriers to bypass the junction and reducing efficiency. Wafers are stacked in a pile and then placed into a plasma etching chamber which breaks down gases to create ions which etch the exposed edge silicon, removing the phosphorus-diffused material.

Antireflective coating (ARC) – A fixed thickness coating is applied to the surface of the cell to maximise the incident radiation absorbed by the solar cell. ARCs do this by causing reflected light to interfere with incoming light and thereby cancel each other and be absorbed in the dielectric. An illustration is provided in Section 2.10: Anti-Reflection Coating. This can be applied at any stage of the manufacturing process (generally before metal contacts are added). Silicon nitride or titanium dioxide is commonly used. Untextured multi-crystalline wafers can have their reflection reduced from 30% to less than 5% using this method. The ARC thickness is optimised to be most effective at reducing reflection for the dominant wavelengths of sunlight, which includes green, yellow and red. Mainly blue light is then reflected, giving a blue appearance to the wafers.

Metal contacts – The metal grid is applied to the front of the cells to collect electrons produced by the sunlight. Silver is used almost universally here. The rear contact is solid and also acts to carry electrons. It is usually made of aluminium, which is cheaper than silver. These contacts link to the external circuit and allow current to be taken from the cell.

Quality Control – At the end of the manufacturing process quality control is performed on the final cells. This is done with a dummy electrical load and a computerized testing station to produce current-voltage graphs for the cells. Solar cells with similar electrical performance are grouped together for interconnection and encapsulation into modules. This is fast becoming an automated process. It is vitally important to detect faults in the manufacturing process as early as possible however. For example, aluminium contamination of production surfaces by careless staff can result in many failing cells as it diffuses into the material over subsequent heating steps. If a process early in the chain is faulty, millions of wafers can be lost before cell damage is detected at the end. Intermediate testing tools are therefore required. This is called ‘inline quality control’ and is greatly preferable to completed cell testing, despite being more costly to implement.

Interconnection – This is the linking of the cells to form a module. Each cell produces less than one Volt and only a few Amps. In order to be useful, they need to be linked together to produce higher outputs. This involves linking the individual cells with soldered metal (e.g. the p-type contact of one cell connects the n-type of the next).

Encapsulation – this is the process of protecting the interconnected cells. There is usually a glass top and an impervious backing (Tedlar) bonded together using ethylene vinyl acetate (EVA). This outer structure/covering plus the cells is called the module. An aluminium frame is a good way of anchoring the modules and makes transporting the modules simpler.

Further Reading

- Crystec Technology Trading GmbH, *Equipment for Solar Cell Production* [online], Available: http://www.crystec.com/crysolae.htm (Accessed 22nd June, 2008)
- Hutchinson K. Holland P. (2008), Solid State Technology, February 2008, *Crystalline Silicon Solar Cell Manufacturing Requires Vacuum-Based Solutions* [online], Available: http://sst.pennnet.com/display_article/319150/5/ARTCL/none/none/1/Crystalline-silicon-solar-cell-manufacturing-requires-vacuum-based-solutions/ (Accessed 22nd June, 2008)

Lots of data on companies that manufacture solar cells and total production around the world can be found at the following websites. This is a really exciting industry to keep an eye on:

- Mayes F., US Govt. Energy Information Administration (2008), *Solar Photovoltaic Data for 2006* [online], Available: http://www.eia.doe.gov/cneaf/solar.renewables/page/solarphotv/solarpv.html (Accessed 14th July, 2008)
- Rogol M. Fisher B. (2005), *Sunscreen II* [online], Available: http://www.bine.info/pdf/infoplus/SunScreenII.pdf (Accessed 14th July, 2008)

3.2 The role of doping

A single silicon atom contains four valence electrons, each of which are available for chemical bonding. In a crystal of silicon, each silicon atom bonds to four other silicon atoms as shown in Figure 28, where one electron from each atom is shared in each covalent bond (giving two atoms per bond in total). Subsequently, each atom appears to have two electrons by sharing the one. The red lines connecting the yellow atoms represent a covalent bond (electron pair) between two atoms of silicon.

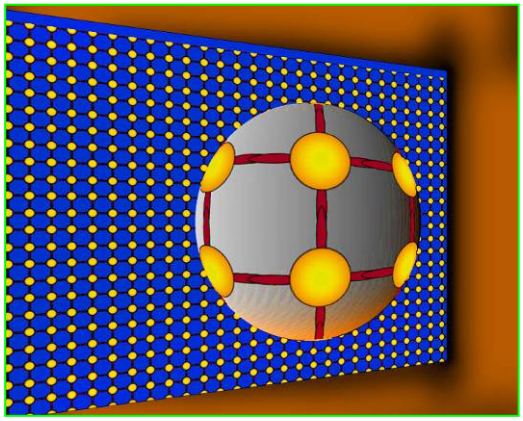


Figure 28: The Silicon crystal structure
(Courtesy of Largent, R. and Balla, R., UNSW)

Since all silicon atoms bond perfectly to four neighbours, it leaves no free electrons to conduct electric current. This lack of carriers to conduct current is what makes a silicon crystal an insulator rather than a conductor.

Doping is a process by which the property of semiconductors can be changed. This is usually done by mixing a small amount of impurity into the silicon crystal. Impurities are just elements that are not silicon, and they can be driven into the material by increasing the temperature sufficiently. This is most often performed in a high temperature furnace at approximately 600°C-900°C. The impurity slowly diffuses through the semiconductor material, getting wedged at different locations in the silicon crystal lattice and taking the place of some silicon atoms. From the perspective of the silicon semiconductor, there are two types of impurities, both illustrated in Figure 29:

N-type - In n-type doping, Group V atoms (usually phosphorus) are added to the silicon in small quantities. Phosphorus has five valence electrons compared to silicon's four, and therefore, the fifth electron has nothing to bond to, it's free to move around, creating an easily freed electron. The free valence electrons from the phosphorus atoms can carry a current if excited with sufficient energy (say, from a photon). This can be seen in Figure 29(a). It is important to note that once they leave the phosphorus atom to travel through the silicon material, the phosphorus atom becomes positively charged since it has lost a negative electron. It is now an ion.

P-type - In p-type doping, Group III atoms (usually boron) are the dopant. Boron has only three valence electrons compared to four for silicon. When mixed into the silicon lattice, they form "holes" in the lattice where an electron that would otherwise be there from silicon is missing. The neighbouring silicon atom has contributed an electron to the bond where a silicon electron would otherwise have been. This leaves a gap and no bond, but an electron in a nearby covalent bond can quite easily move into this gap to complete this originally incomplete covalent bond. That would leave a "hole" in the spot where this new electron has come from. Again, this gap could be filled by an electron one atom down again. The end result is that the "hole" is moving through the crystal. Since it is an absence of an electron, it is actually a very mobile positive charge, just like an electron. It is therefore a current, just like a moving electron is. A hole is shown pictorially in Figure 29(b).

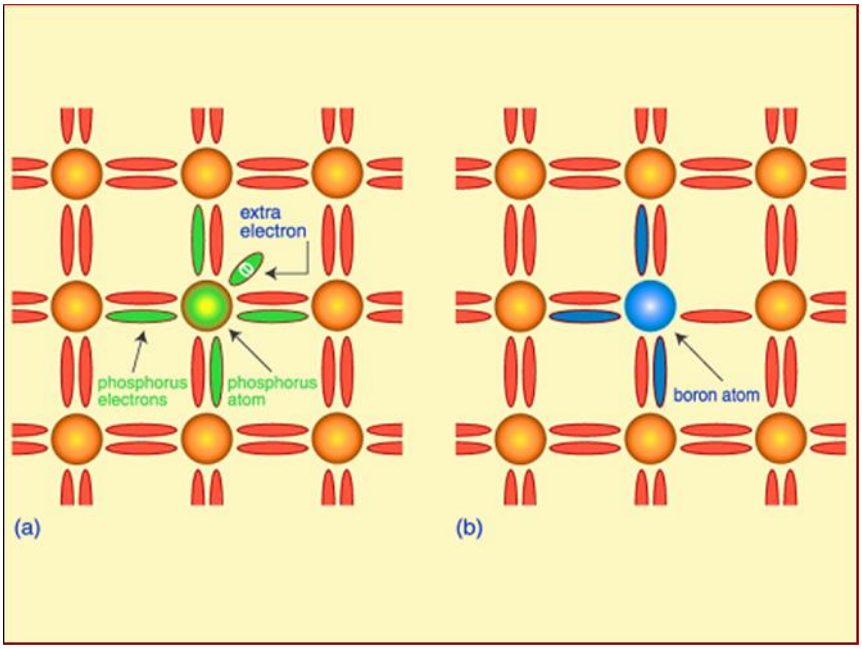


Figure 29: (a) n-type doping - excess electrons (b) p-type doping - deficient electrons
(Courtesy of Largent, R and Balla, R. UNSW)

3.2.1 How doping allows the formation of a depletion region

A p-n junction is formed by bringing together an n-type and a p-type semiconductor. Remember that n-type semiconductors have free electrons and p-types have vacant 'holes'. Electrons are free to move wherever they want and they are attracted to the holes on the other side of the p-n junction. This is because holes are absent electrons, and the natural tendency to diffuse and equalise charges results in electrons trying to balance out the absent electrons (or holes) by filling the gaps. As a result, some of the free electrons in the n-region diffuse across the junction and combine with holes, moving negative charge across the junction in the process. Now, as excess electrons in the n-type silicon leave their originally neutral atoms, they leave behind positive ions. The same applies for holes entering the junction from the p-type material and leaving negative ions behind (in the p-type silicon). The charge imbalance created by the fixed ions forms an electric field in the region. This new electric field is opposite in direction to the direction of diffusion that existed originally to cause the flow of electrons toward the p-type silicon (and vice versa). The charge from the electric field setup by the ions is strongest near the fixed positive and negative ions on either side of the junction, and gradually gets weaker nearer the centre of the junction. At the very centre of this region, there is no charge at all. The region is depleted of charge and is thus called the 'depletion region'. When this electric field due to the ions is sufficient to repel the incoming holes and electrons that are moving due to diffusion, the depletion region reaches its equilibrium width. It is this opposing field that gives rise to the p-n junction voltage of 0.6V for silicon. Note that electric fields tend to cause charges placed in them to flow. The formation of this region is shown diagrammatically in Figure 30 and Figure 36.

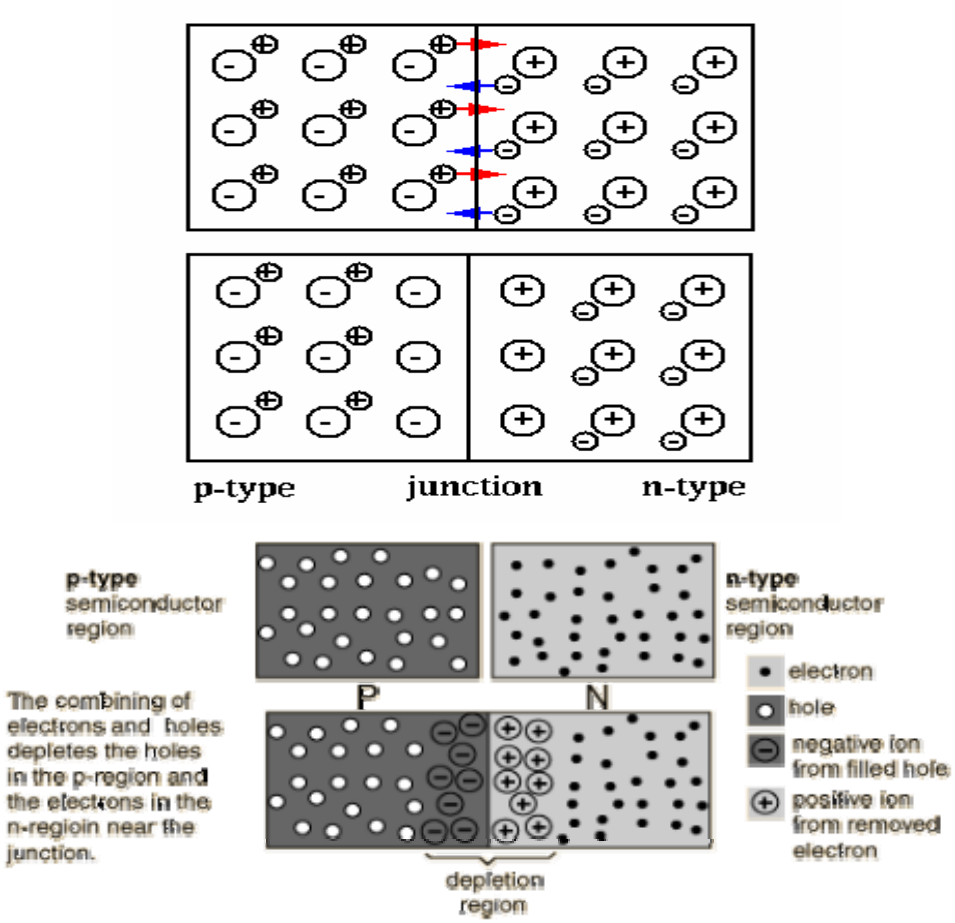


Figure 30: p-n junction depletion region formation
Source: Wang R. (2008), *Semiconductor Materials* [online], Available: http://fourier.eng.hmc.edu/e84/lectures/ch4/node1.html (Accessed 3rd Feb, 2008)

Further Reading

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- U.S. Dept. of Energy EERE (2006), *Doping Silicon to Create n-Type and p-Type Silicon* [online], Available: http://www1.eere.energy.gov/solar/doping_silicon.html (Accessed 22nd June, 2008)
- Brian M., *How Semiconductors Work* [online], Available: http://www.howstuffworks.com/diode.htm (Accessed 19th June, 2008), HowStuffWorks
- Massachusetts Technology Collaborative, *The Science Behind Photovoltaics* [online], Available: http://www.mtpc.org/cleanenergy/solar_info/science.htm (Accessed 2nd July, 2008)

3.3 Operation of a p-n junction

Adapted from *Solar Cells – resource for the secondary science teacher, UNSW* (see bibliography citation for full details). Unreferenced photos come from the same document.

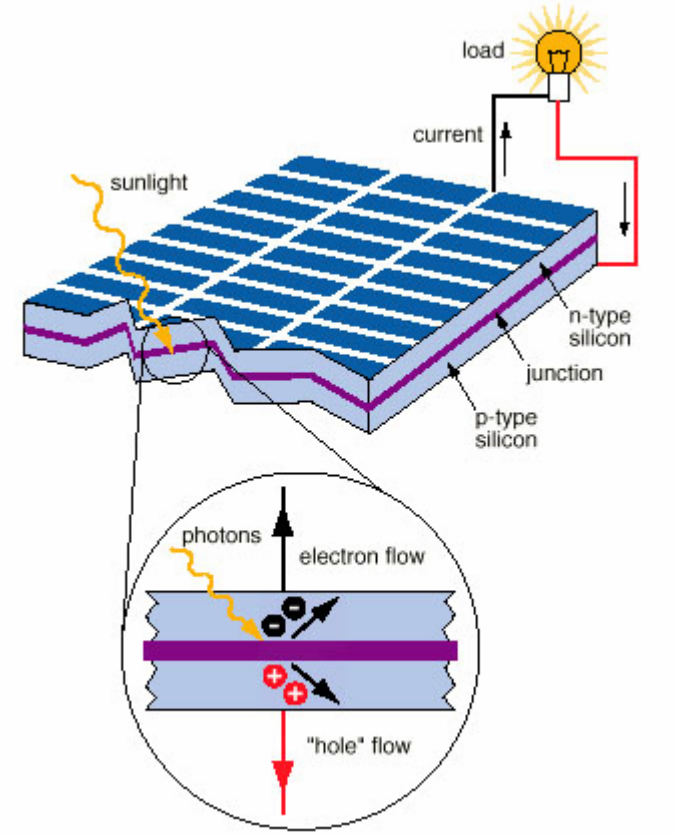


Figure 31: Operation of a PV Device
Source: McHenry M. Wilmot N. (2007), *Photovoltaics* [online], Available: http://www.rise.org.au/info/Tech/pv/index.html (Accessed 22nd July, 2008), Murdoch University

To understand how a solar cell operates it is first important to know the operation of a diode because a solar cell is a large area diode exposed to sunlight. Diodes and solar cells operate using a p-n junction. A p-n-junction is just the meeting point between a semiconductor that has been doped with excess electrons, and one doped to have a deficiency of electrons. In this section we are looking at the operation of a p-n junction in a diode. Light alters some of the properties of the silicon and the junction to provide larger currents and slightly higher voltages.

For a p-n junction to operate there must be charge carriers present. For diodes these are the electrons (negative) and holes (considered positive, but are actually the absence of negatively charged electrons in the crystal lattice). These charge carriers are created in excess by doping the silicon with other elements. N-type doped silicon has a surplus of electrons which act as negative charge carriers, and p-type doped silicon has surplus holes that act as positive charge carriers. It is important to note that when we say there are

electrons or holes in the crystal lattice, we actually refer to their presence in the valence shell of each atom. The crystal itself might be thought of as a structure comprising of the nuclei of each atom. These nuclei are fixed in position, with only the valence electrons (and absent electrons) free to move.

Now, due to natural diffusion of charge throughout any material, these valence shell charge carriers are distributed evenly through the doped silicon as shown in Figure 32, where two separate blocks of silicon can be seen (one is n-type doped and one p-type doped). The overall charge on each block of silicon is zero even though there are excess charge valence carriers in the n-type and p-type sections. This occurs because we are doping the silicon with phosphorus atoms which are neutral in charge (15 electrons and 15 protons, cancelling each-other out). The silicon atoms, too, have 14 electrons and 14 protons to make them neutral. Once embedded in the material the total amount of positive and negative charges must still be equal, even when the charges are free to move until they are distributed evenly throughout. This charge neutrality is somewhat important when analysing the diode operation.

It is important to note that normally, when carriers leave their atoms, they leave behind a charge on the atom. The charge will be opposite to the charge on the carrier. For example, when an electron leaves an atom, the atom has lost a negative charge and thereby becomes a positively charged ion. This kind of ionisation doesn't occur until electrons leave the n-type material or holes leave the p-type side. When you bring the p- and n- type materials together it's possible for the carriers to leave their starting sides. If they stay on their original sides, the material remains neutral, so the atoms remain uncharged. If electrons flow to the opposite side, it is possible that some atoms in some locations may become ionised by losing their electrons to another region of the material (e.g. to the p-n junction).

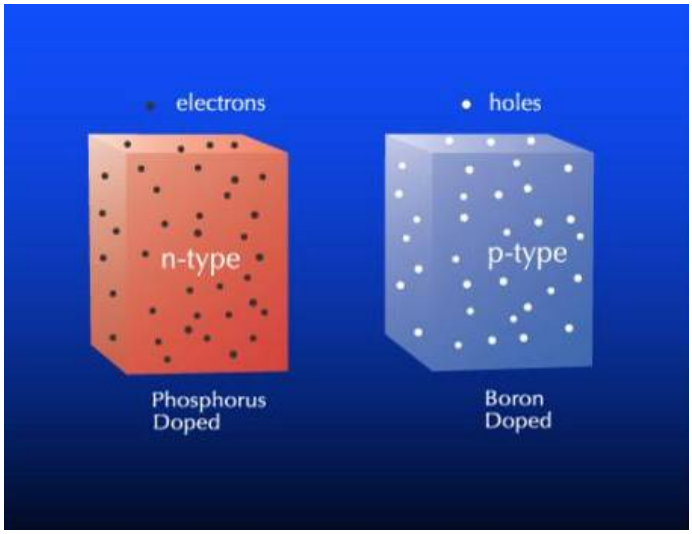


Figure 32: Blocks of n-type and p-type silicon showing charge carriers

It is fundamental to understand that positive and negative charge carriers behave oppositely in an electrostatic field. That is, they are each moved in opposite directions

because of their equal (in strength) but opposite (in direction) charge. By convention, an electric field is drawn in the direction the positive charges (holes) will flow, so the negative charges will flow in the opposite direction. Electric fields basically describe a region in space where a charge will experience a force to move. For instance, there is a region around a negative charge that would cause the attraction of a positive charge toward it. Thus, the electric field would be drawn in the direction toward the negative one. Figure 33 below, illustrates how electric field lines are drawn.

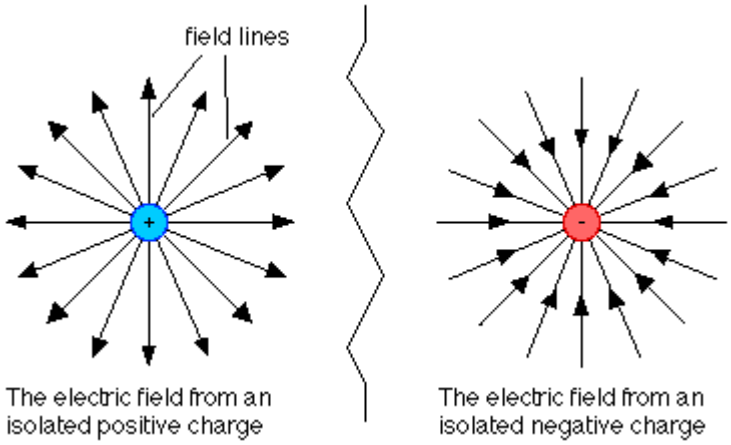


Figure 33: The electric field lines drawn with respect to a positive and a negative charge
(Source: Duffy A. (1998), *Physics lecture demonstrations at Boston University* [online], Available: http://buphy.bu.edu/~duffy/PY106/2e.gif Accessed 18th June, 2007), Boston University

Now we will consider the two blocks of doped silicon in Figure 32 and bring them together so that they are touching as shown in Figure 34.

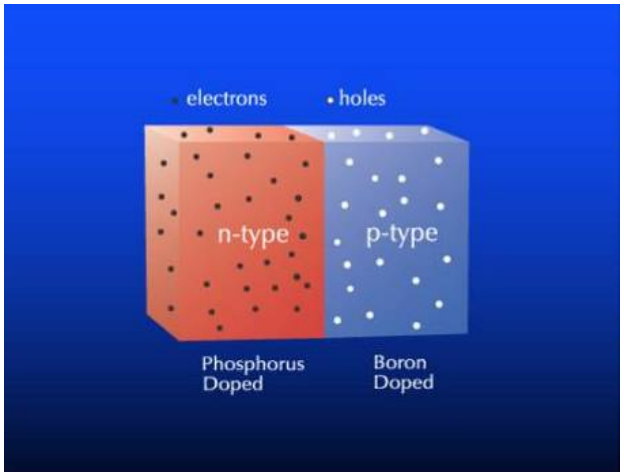


Figure 34: N-type and p-type silicon blocks brought together

This is where the operation begins to get interesting. First, we have a junction between the p-type and n-type regions. On the n-type side there is an excess of electrons, and on the p-type side there is a shortage. As a result of random thermal motion, electrons begin to diffuse from the n-type region into the p-type region. You could also visualise the process just described as a flow of holes. They are in excess in the p-type region and in

deficit in the n-type region and random thermal motion cause holes to diffuse from the p-type into the n-type. If the holes and electrons were uncharged they would diffuse uniformly throughout both pieces of silicon, but because they are charged something interesting happens.

We will now consider only the n-type side. As electrons diffuse from the n-type into the p-type silicon, positive ions are left behind since the negatively charged electrons have left that side of the material. Remember before that the overall charge on the block of silicon in Figure 32 was neutral. Now we have taken away some electrons which leaves positive charges behind as indicated by the '+' signs in Figure 35. A similar process occurs in the p-type silicon except that negative ions remain because positive holes are diffusing to the other side of the junction as indicated by '-' signs in diagrams from Figure 35 to Figure 38.

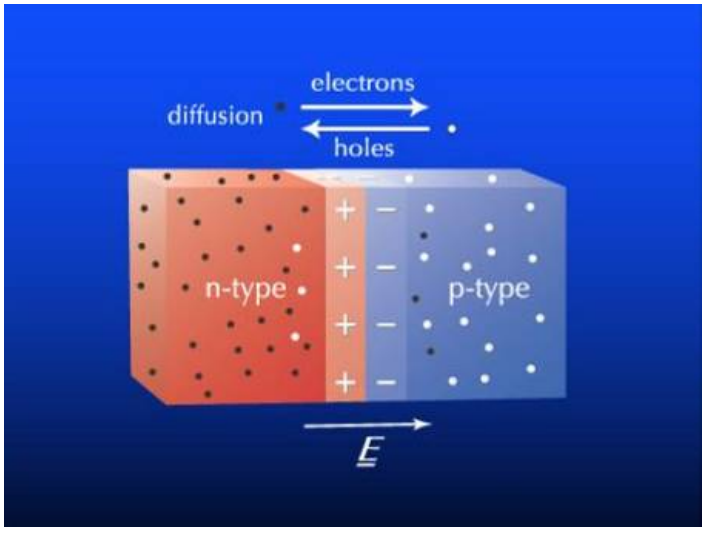


Figure 35: Electric field that is set up after electron and hole diffusion occurs

The positive and negative ions in the regions close to the junction set up an electric field known as the depletion region or the 'built in' electric field (as shown in Figure 35 above). Electric fields describe the direction a positive charge (e.g. hole) would travel if you placed the charge in the field. Positive charges always travel toward negative charges, so electric fields always point toward the negative charges that contribute to their creation. In our example, a field is created by the positive and negative ions left near the junction due to the loss of electrons and holes that cross the junction due to diffusion. This new electric field is opposite in direction to the direction of diffusion. This electric field opposes the diffusion process and equilibrium is achieved as a result. Again we will consider the n-type silicon only. When equilibrium is achieved the same numbers of electrons diffuse towards the p-type silicon as electrons that move from the p-type to the n-type due to the newly forming electric field. This situation is shown in Figure 36 below. This similarly applies for the p-type silicon, but with the flow in the opposite direction due to the opposite charge of the holes.

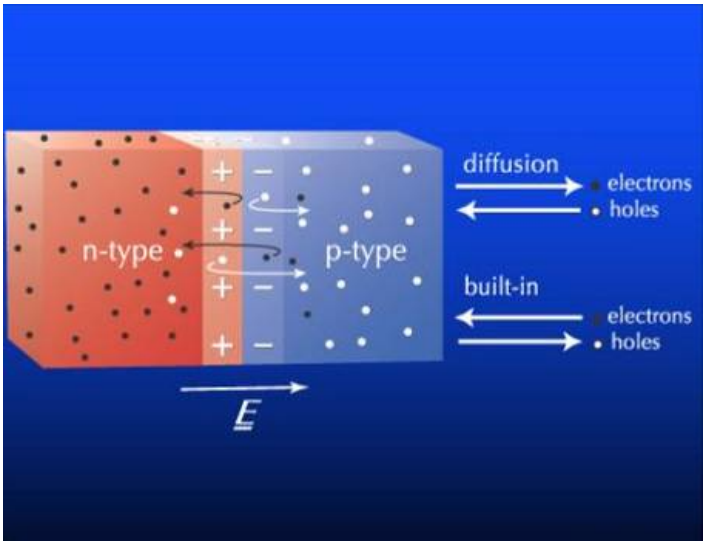


Figure 36: 'Built in' electric field when at equilibrium showing charge movement by diffusion and the opposing movement from the 'depletion region'

It is also clear that there is a transition from net positive charges due to positive ions in the n-type silicon to net negative charges due to negative ions in the p-type silicon. This must also mean there is a point near the centre of the junction with zero charge since a transition from positive to negative charge must pass through zero charge if there is to be a smooth, continuous change in charge. Interestingly, this is not a point but a region, and this is what the depletion region is.

In the equilibrium state where the fields cancel each-other out there is no net flow of electrons or holes. That means, under equilibrium conditions the number of electrons flowing left equals the number of electrons flowing right and the same for holes. The electrons and holes are not stationary, but their overall movement keeps the charge neutral in the depletion region as they move back and forth with other ones taking their place.

Next, we will consider the p-n junction as part of a circuit, where it can act to either allow or prevent current flow. When in forward bias (allowing current to flow) the 'built in' electric field is reduced in thickness, thereby reducing it's resistance to current flow. For silicon, an applied voltage of about 0.6Volts is required to reduce the depletion region to a negligible thickness. This exactly overcomes the 0.6V potential barrier that is built into the junction. This operation is shown in Figure 37. Note the directions of the 'built in' and battery-induced electric fields are opposite and as a consequence, when they add together, the thickness of the depletion region falls (to its smallest width when 0.6V is applied by the battery or power source). Another way of looking at the situation is to say the applied electric field due to the power source boosts (adds to) the electric field due to natural diffusion. The situation is illustrated in Figure 37 below.

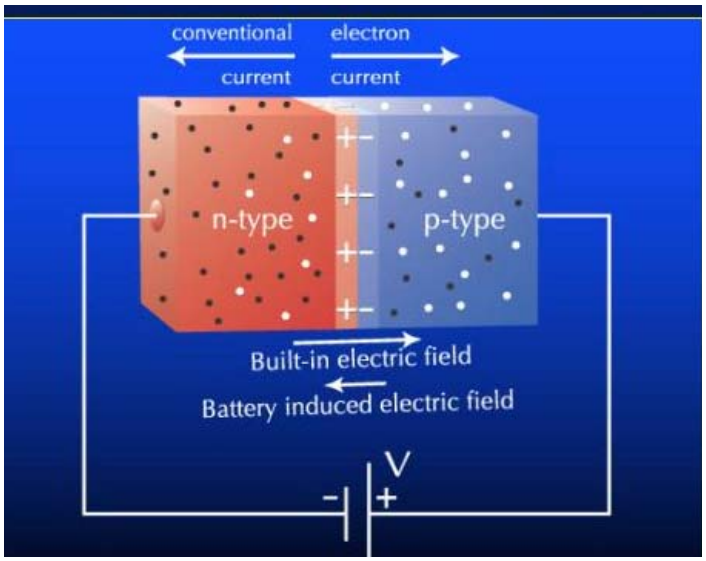


Figure 37: Forward biased operation of a diode

When the diode is in reverse bias (current blocking) the opposite occurs and is shown pictorially in Figure 38. That is, the depletion region thickness increases and the resistance of the diode increases to prevent current flow. Reverse bias refers to the situation where the terminals of the power source are arranged to increase the size of the in-built electric field in the junction, and limit the flow of electrons due to diffusion. This situation is illustrated in Figure 38.

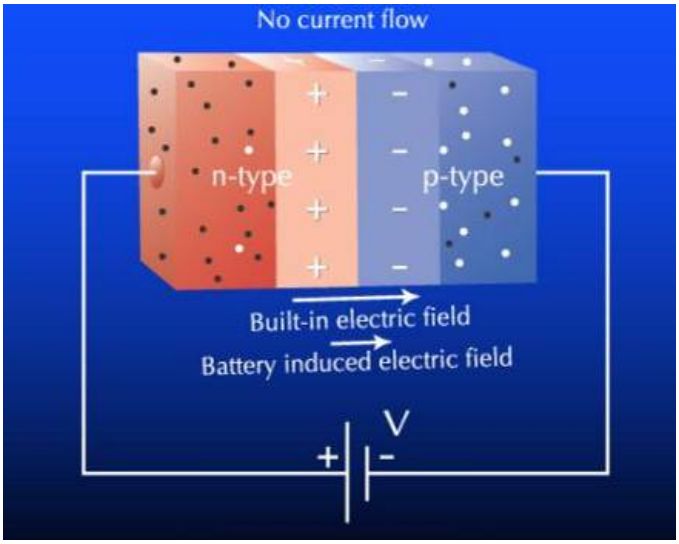


Figure 38: Reverse bias diode operation

Notice here that the 'built-in' and battery-induced electric fields are in the same direction and add together to increase the thickness of the 'depletion region'. As the applied voltage increases the depletion region thickness becomes larger and so does internal the resistance of the cell. In practice the current flow is not zero but small enough to be considered zero. This small leakage current is called the reverse saturation current. If you apply a high enough reverse bias voltage, the diode operation will break down and allow

current to flow in the opposite direction (i.e. the p-n junctions fails). Breakdown is undesirable because the diode operation becomes unpredictable and thus, should be avoided at all times. Remember that a diode is a circuit element that allows current to flow in one direction, but not the opposite. The convention is to draw current flowing in the direction of the positive charges (i.e. holes) despite the fact that it is actually the electrons that flow in a conductor. We know that holes will flow out of the p-type silicon, through the external circuit (perhaps a battery) and into the n-type silicon. Hence, diodes allow conventional current (not real current) to flow from the n-type to the p-type side *through* the diode (and from the p-type to the n-type external to the diode). This is illustrated in Figure 39 below.

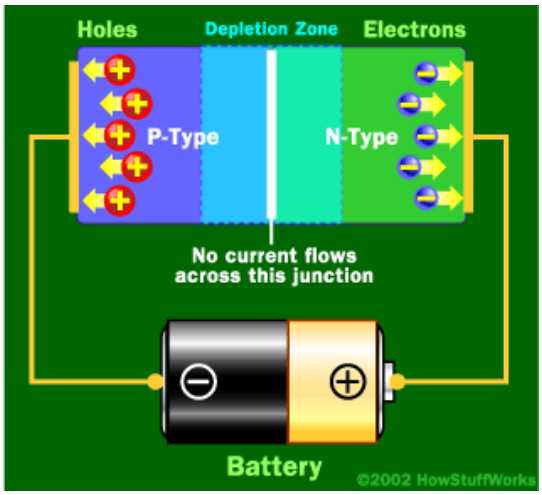


Figure 39: Flow of holes and electrons out of a diode
Image Source: Casanova M. (2003), *Physics of a Diode* [online], Available: http://ffden-2.phys.uaf.edu/212_fall2003.web.dir/Marvin_Casanova/physics.htm (Accessed 18th June, 2007)

The operation of a diode in forward and reverse bias is shown graphically in a diode I-V Curve in Figure 40 below. See Section 4.2, titled, 'Current-voltage curves for photovoltaic modules' for further information on IV curves. The region where voltage is negative is the region of reverse bias operation. The area of forward bias is where the diode is allowing positive current flow. The breakdown region is where we see uncontrolled negative current. This is undesirable and should be avoided.

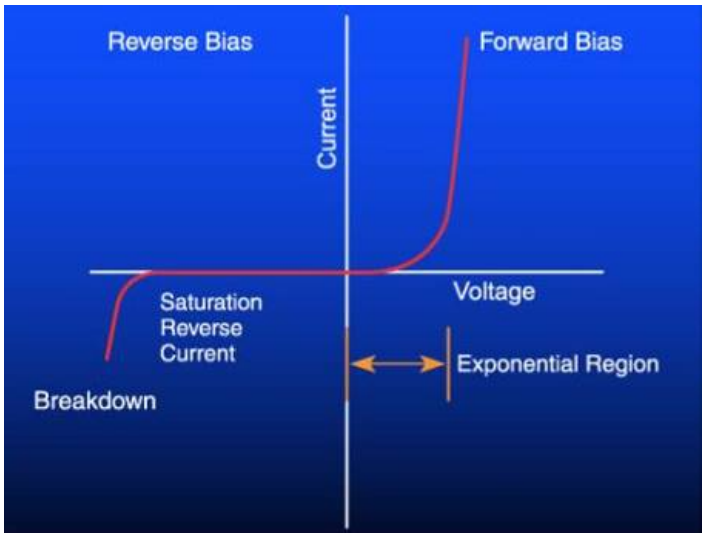


Figure 40: Diode curve showing current flow in forward bias and zero current in reverse bias

Most solar cells are large area diodes that are exposed to sunlight. The depletion region is the important mechanism that allows current to be produced directly from sunlight. As discussed earlier in this resource, sunlight incident on a solar cell has enough energy to modify chemical bonds within the silicon to release more electrons that each leave behind a hole. The silicon remains neutrally charged due to the opposite charge of an electron and a hole. These electrons and holes are free to move about the silicon substrate because they are given enough energy to move from their valence bands. These carriers that are able to move are said to have been excited from the valence band into the conduction band. Due to their being charged, they are attracted to the electric field in the depletion region. The depletion region is able to separate these positive and negative charges, which causes current to flow that can be captured by an externally connected circuit. The valence band refers to a range of energy levels that includes electrons (and holes) in the valence shell of their atoms that are tied to the atom and not free to move and conduct current. They possess less energy than is required to free themselves and conduct current. Carriers that have sufficient energy (say, from a photon) are in the conduction band, and they possess enough energy to conduct current.

For power to be produced there must also be a voltage (since power output from a source is equal to the output current multiplied by the output voltage). To measure this voltage, the circuit can be cut to create an open-circuit and measured with a voltmeter. In this case, the voltage is known as the 'open-circuit voltage' because the solar cell is being illuminated but is not connected to any load due to the open circuit. Most silicon cells have an open circuit voltage of about 0.6 volts under standard sunlight illumination. Now that we have voltage and current, power can be extracted in the form of DC electricity if the solar cell is illuminated and a load is added to the circuit. Without the resistive load, the solar cell will produce no electricity – the load circuit allows voltage and current to produce power. The voltage and current output by the solar cell is determined by what the load draws. Loads drawing higher voltage will cause the solar cell to deliver lower currents (and vice versa). This gives rise to a set of operating characteristics of a solar

cell, as shown in Figure 56 in Section 4.2, titled, 'Current-voltage curves for photovoltaic modules.'

Further Reading

- REUK (2008), *How Do PV Solar Panels Work* [online], Available: http://www.reuk.co.uk/How-Do-PV-Solar-Panels-Work.htm (Accessed 17th July, 2008)
- Zeghbroeck B.V. (2007), *Chapter 4: p-n Junctions* [online], Available: http://ece-www.colorado.edu/~bart/book/book/chapter4/ch4_2.htm (Accessed 14th September, 2008)
- de Oliveira Sannibale V. (2001), *Basics on Semiconductors Physics* [online], Available: http://www.ligo.caltech.edu/~vsanni/ph3/SemiconductorsBasics/SemiconductorsBasics.pdf (Accessed 14th September, 2008), California Institute of Technology PH003

P-N Junctions in diodes:

- Gavryushin V. Žukauskas A. (2006), *The Diode* [online], Available: http://www.mtmi.vu.lt/pfk/funkc_dariniai/diod/ (Accessed 17th July, 2008)
- Nave R., *P N Junction* [online], Available: http://hyperphysics.phy-astr.gsu.edu/hbase/solids/pnjun.html (Accessed 17th July, 2008)

3.4 Linking cells to form modules

Adapted from Wenham, S., Green M., Watt M., Corkish R., *Applied Photovoltaics*, James and Earthscan, Cornwall (2007).

Solar cells are usually used as modules and not as single cells because usable voltage and current can more easily be produced. There are a number of ways that cells can be connected to meet any current or voltage requirement.

Strings – this is where cells are connected in series (i.e. one after the other in a single line) as shown in Figure 41 below:



Figure 41: A single string of cells in series

In a string, the front contacts of one cell are connected to the rear contact of its neighbour. Strings like the one above can be connected in parallel with other strings. Figure 42 below has 4 cells in series and 2 parallel strings and is known as a block:

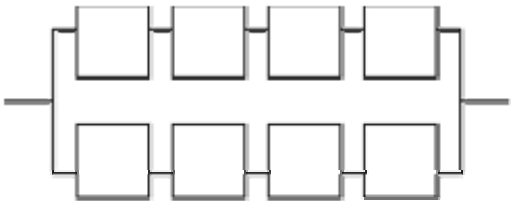


Figure 42: Two series strings connected together in parallel

These blocks can then be interconnected to create any voltage or current. Figure 43 illustrates one such arrangement using the basic circuit in Figure 42.

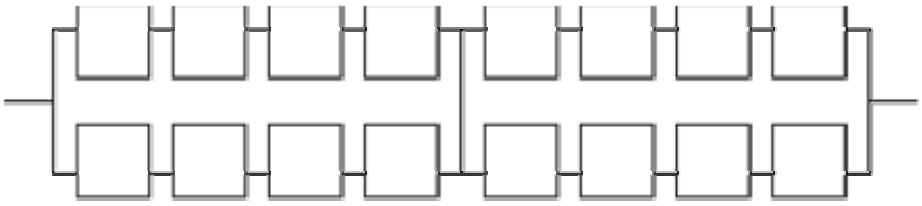


Figure 43: The circuit in Figure 42 connected in series with another identical circuit

Each cell produces a maximum of about 0.6 volts and cells are connected in **series** to **increase** the output voltage. Usually 36 cells are connected in series for 12 volt battery charging. This means an output voltage of over 18 volts at maximum output. This higher voltage is required to push electricity into the battery and charge it up. The current the cells produce is proportional to the light intensity and the cell area. If the intensity of light falling on the cell is halved, that means half the original current will be produced. Also, if the area is halved, half the current will be produced. At maximum solar intensity solar cells produce their maximum current of about 0.03A/cm^2. To obtain **large currents** the cells are placed in **parallel**.

The method for determining current and voltage from a string or block is shown below:

a) Consider the following three photovoltaic cells below, each with an area of 10cm^2:

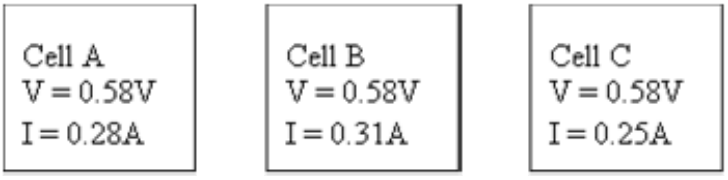


Figure 44: Three PV cells with different output currents

If connected in series, they form a string like that shown in Figure 45 below.

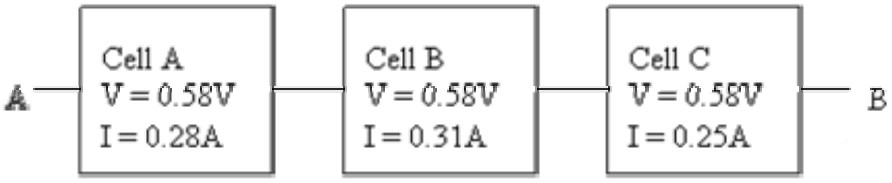


Figure 45: Connection of the cells individual cells in Figure 44 in series

The voltage across terminals AB (i.e. the voltage that we read when we take test points at A and B in the above string) is given by addition of the voltages of each cell.

$$\text{So } V_{AB} = V_A + V_B + V_C = 0.58+0.54+0.61 = 1.73 \text{ V}$$

The current that flows through a string of cells in series is restricted to the current produced by the cell that is producing the smallest current. So in this example, the current flowing through the string from A to B is **0.25A**. For this reason, cells of similar current are always placed together in a module to maximise output. In order to do this manufacturers test every cell as it is produced so that they can be categorised before being placed in a module, since not all cells will turn out identical. Cells outputting less power for whatever reason will be collected and strung together in a module and sold cheaper (since the module will output less). In the above example, the extra current produced in cell A and cell B is wasted as heat in the interconnecting wires, top surface metal grids, and semiconductor material itself. This is ultimately energy that is lost to the environment. Matching similar cells is important to maximise the output power from all the modules that are produced.

This current restriction occurs when solar cells are connected in series, and is a fundamental property of power circuits. This is because there must be an equal current flowing through any one string. Let's say the current going into cell B was not equal to the current leaving cell B (i.e. unequal currents at the point before and after Cell B). Then, there must be current building up in the cell, but we know that this is not really possible unless these extra currents flowed around the cell grid fingers and through & around the p-n junction of Cell B. In fact, this is similar to what actually happens when different cells output different currents. The cells producing less, end up 'receiving' power like they were a load, and it just gets dissipated as heat of resistance in the semiconductor material.

b) The three cells are now linked in the same way as above, but this time cell C is half shaded by dirt or bird droppings. The circuit will look as below, with the current in cell C halved as a result of current being directly proportional with area. Remember, half the light, halve the current.

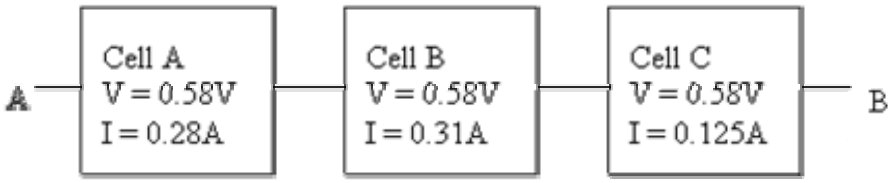


Figure 46: Same circuit as shown in Figure 45 with the current from Cell C halved

Once again the current is restricted to the current output by the cell with the lowest current in the string and this time it is equal to 0.125A. This also halves the power output since P = I×V. This means that shading of any photovoltaic cell in a string has a large reducing effect on the power output of the entire string.

The voltage also drops with reduced light, but it is not proportional to the area of the cell. Depending on the module wiring layout this can result in a power loss of over 50% (the voltage falls and the current halves). Regardless of the layout, partial shading of a module will result in power loss since somewhere in the array, there is less light to generate power from. To reduce the effects of shading, the strings are usually kept short (as drawn below) and paralleled as much as possible. Having lots of parallel strings is good, because whatever currents are generated can be added together, while the voltage of each string remains relatively similar with or without light. Voltages of parallel strings are taken as the average voltage of each string. An example of how a module might be wired is shown in Figure 47 below.

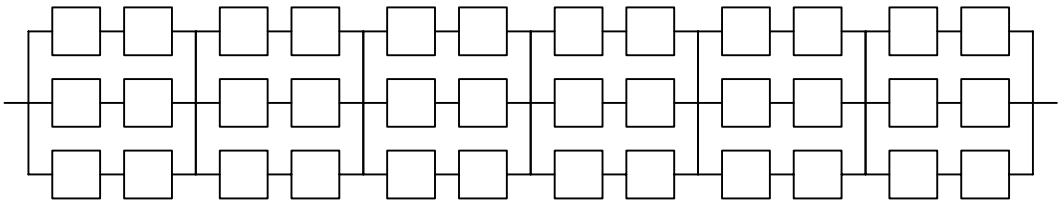


Figure 47: One way to wire cells into modules with many parallel strings

c) If the 3 cells from above are connected in parallel, the resulting circuit will look like the one in Figure 48:

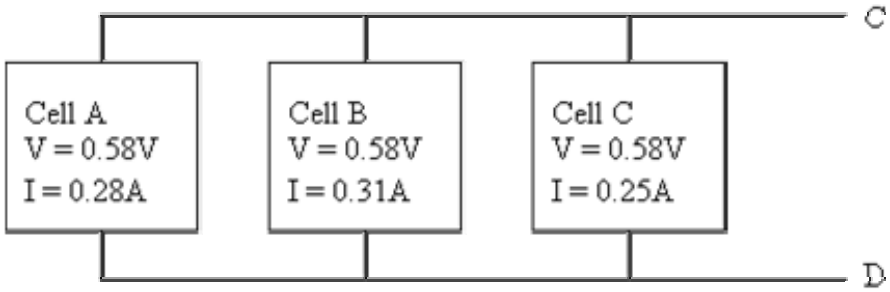


Figure 48: Connection of the cells from Figure 44 in parallel with each other

The voltage measured at CD is simply the average voltage of the three cells and is equal to 0.58V. This was calculated as follows: (0.58+0.58+0.58)/3 = 0.58.

The current measured at CD is the sum of the currents from each of the cells:
$I_{CD} = I_A + I_B + I_C = 0.28+0.31+0.25 = 0.84A.$

d) Let's now consider the series string from a). We are going to parallel the string like we did with the cells in part c)

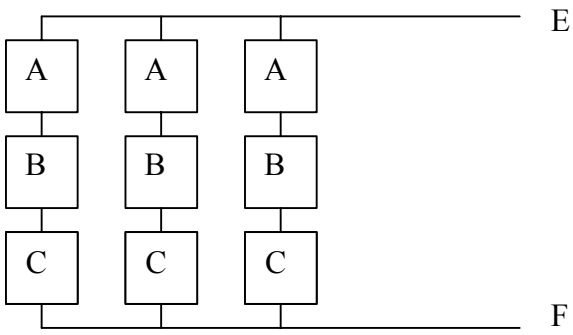


Figure 49: Three series strings in parallel

From part (a) the voltage for each string is 1.73V. Because the three strings are in parallel the voltage at EF is also 1.73V.

From (a), the current of each string is 0.25A. For strings/cells in parallel the current is added so the current at EF is 3 x 0.25 = 0.75A.

If one string had a voltage of 1.71V, another with 1.72V and the last one with 1.73V, the voltage measured across EF would have been the average of the voltage of the three strings. That is, 1.72V.

In this section, we have looked at calculations for photovoltaics cells only. The calculations are the same for combining batteries and modules. In this way, modules and battery banks can be configured for any voltage and current requirement that we want them to output. With batteries you should ensure that no more than three strings of batteries are placed in parallel so that discharge currents are not too large. Large currents can damage the batteries, underrated wires, and electrical equipment. Batteries are capable of discharging very large currents despite their relatively small size, while solar modules are somewhat limited unless many are strung up in parallel. It is also important to have DC wiring rated to the expected current in the solar circuit. The dangers of DC are explained more fully in Section 4.10: 'The importance of safety when working with DC circuits.'

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- Boston University (2000), *Series and Parallel Circuits* [online], Available: http://physics.bu.edu/py106/notes/Circuits.html (Accessed 14th July, 2008), PY106 - Elementary Physics II
- NDT Resource Center, *Series and Parallel Circuits* [online], Available: http://www.ndt-ed.org/EducationResources/HighSchool/Electricity/seriesparallelcircuits.htm (Accessed 14th July, 2008)

For some good materials to download see:

- Science-ebooks, *Basic Electronics Chapter 5: Parallel-Series Circuits* [online], Available: http://www.science-ebooks.com/electronics/series-parallel_circuits.htm (Accessed 14th July, 2008)

3.5 Solar thermal collectors vs. photovoltaic collectors

There are two main forms of energy that can be directly extracted from sunlight: electricity and heat. Solar thermal technologies collect the sun's heat directly, while photovoltaic technologies convert the sun's energy directly into DC electricity.

3.5.1 Solar photovoltaics

'Photovoltaics' is a term that describes a semiconductor technology that converts the energy from the sun directly into DC electricity. It has a wide range of applications for power systems because there are no moving parts that are usually associated with systems that generate electricity. There is no rotating generator, making this form of electricity generation quite unique. More information about different forms of solar energy in Australia is located at the School of Photovoltaics and Renewable Energy Engineering website at UNSW http://www.pv.unsw.edu.au.

3.5.2 Solar thermal

Solar thermal technologies describe systems where the radiation from the sun is used directly as useful radiant heat energy. It is predominantly the infra-red part of the solar spectrum that is captured for heating purposes, while the visible and UV components are used for photovoltaic electricity conversion. The most common solar thermal system is the solar hot water heater like those that can be seen on some house roofs. The main manufacturers of solar water heaters in Australia are Beasley, Solahart and Edwards, with many other smaller operators.

Solar thermal energy can also be used for air heating. The most basic example of this is a window facing the sun. You can feel the room warm up as the sun provides energy into a cold room. Glass has this interesting property where it allows short wavelength light from the sun in, but does not allow the re-radiated wavelengths from the room back out because they are too large. This is very useful, because the glass basically begins to trap heat inside the room. This same principle is used in solar air heaters that use air-heating panels that can be mounted on the roof. The basic principle is that the sun heats the air in a collector (usually something resembling a black box with a glass top cover to trap more heat) and is then forced into the cold rooms below by a fan. This process slowly heats up the interior space.

Solar thermal systems can also be used to produce electricity. UNSW has developed a system now used as a feedwater heater at Liddell coal-fired power station in the Hunter Valley. They are currently looking into expanding their business to a 100% solar thermal electricity plant in NSW's north. The prototype plant at Liddell is shown in Figure 50. The tube running through the air (where the glare is) has the sun concentrated onto it by

the mirrors on the ground (look for the lines near man and the red car). The temperature of the water produced here is not hot enough to put through a steam turbine of a coal-fired power plant, but can act as a pre-heater for the feedwater into the power plant. This provides a small boost to the starting temperature of the water, subsequently reducing the amount of coal that needs to be burnt to heat the water to the high temperatures required for a steam turbine to convert the flowing steam into electricity. For example, if the solar thermal collector can heat the water from 20^0C to 140^0C before being heated by coal to 500^0C for the steam turbine, the amount of coal required to heat the water can be reduced by [(140-20)/(500-20)] × 100% = 25%. This results in large cost savings for the operator since the sunlight is free after you build the plant, and environmental benefits with reduced Greenhouse gas emissions. Of course, the upfront cost of the additional plant and equipment for the solar thermal collector must be factored into the assessment.



Figure 50: Fresnel Lenses at Liddell power station used for hot water heating
Image Source: Morrison G.L. (2003), *Solar Thermal Electricity* [online], Available: http://solar1.mech.unsw.edu.au/glm/clfr/solar%20thermal%20electricity.htm (Accessed 21st June, 2007)

There are many other types of solar thermal applications for electricity production but most of them have been developed either in Europe or America and are not used in Australia. This may seem a little silly given the huge amount of sun that shines on Australia compared to North America and Europe.

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- Fraser J., *What's PV?* [online], Available: http://www.history.rochester.edu/class/PV/whatspv.html (Accessed 9th January, 2008)
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- Solar Electric Power Association (2008), *Solar Electricity Basics* [online], Available: http://www.solarelectricpower.org/index.php?page=basics&subpage=pv&display (Accessed 4th July, 2008)
- The Solarserver (2008), *Solar Heating Systems* [online], Available: http://www.solarserver.de/wissen/solaranlagen-e.html (Accessed 14th July, 2008)

To find out about suppliers of solar hot water heaters, see:

- Home Energy Advice Team, *Solar Hot Water* [online], Available: http://www.heat.net.au/pdf/solar-hot-water.pdf (Accessed 8th April, 2007)

3.6 Module manufacturing and accelerated lifetime testing

For solar cell and module manufacturers it is important to know how long a module is likely to last in the field. This is so they can inform customers of the expected lifetime of the system and provide warranties for lifetimes that they can be reasonably confident of achieving. There are a number of module test facilities around the world that put modules through harsh environments, aiming to determine their expected lifetimes in the field. The test facilities and processes are also used to provide certificates that they meet international standards for module integrity. The European Union has a standard procedure run by the Institute for Environment and Sustainability (IES). The expected life of most solar modules is 25-30 years or more. The warranties given presently are based on the majority of older, functional modules that are presently operating in the field. As these modules continue to function reliably, warranty periods can be expected to increase.

Clearly however, module manufacturers don't have 30 years to run the trial on each design to determine the lifetime of a new module design they are manufacturing. They need to be able to estimate the expected lifetime of their new product in a short time. As a result the module tests that simulate long-term stresses are carried out by subjecting modules to harsher conditions than those expected in the field. The principle is to subject modules to the total stresses and stress cycles that they are anticipated to experience over their entire warrantable lifetime, but to do so in the space of a few months. We call this process 'accelerated lifetime testing,' and it is usually performed in an environmental chamber.

Europe is the world leader in most renewable energy technology development and has recently introduced standards for module integrity. The most common module failure modes are cracked glass covers (perhaps due to hail), delamination of encapsulation (i.e. the outer laminate covering peels off), electrical contact corrosion or separation, cell degradation, water damage to cells and terminal boxes, and cell breakages. The test conditions aim to mimic the harsh environment that the module may be exposed to in the field, which place stress on electrical, optical and structural components of the modules. The conditions that cause damage to modules, solar cells and other system components

are temperature cycling (repeated fluctuation from hot to cold, causing repeated thermal expansions and contractions), ultra-violet light (degrades many materials like polymers), moisture ingress (causing corrosion of metal connections) and mechanical impact (rocks and hail). The whole testing process takes about 4-5 months of continual testing and exposure (http://sunbird.jrc.it/esti/esti.htm). The above-mentioned conditions are applied to the modules at magnitudes that are far greater than those experienced or anticipated in the field. This allows simulation of many years worth of mild exposure, in a shorter duration of high intensity exposure. For example, the temperature may cycle 50 times per day from the hot peak to cold peak temperatures during testing, while only occurring once a day in the real world from day to night.

To find weaknesses in module design, various stresses are placed on the modules. For example, hourly temperature cycling from –40˚C to 85˚C, constant exposure to intense UV light, and cycling between high & low humidity, place maximum stress on the modules. In addition, the artificial climate in the chamber has high humidity to test the extent of water ingress and corrosion response in the presence of water in the air. The entire test period is generally designed to simulate the conditions over a 30-year life for a module. Some test laboratories also fire large frozen ice balls and rocks at the modules to test their mechanical strength. This type of testing is termed 'destructive testing' because the objects being tested are likely to be damaged or significantly altered as a direct result of the tests. Thus, it is usually carried out on a few prototype modules. See, for example, descriptions of Nanosolar Inc. carrying out their testing: http://www.nanosolar.com/Designedtolast.htm (Accessed 4th February, 2008).

The reason the testing is so rigorous is because many PV modules are used in place of other building materials (e.g. you may use a PV module as a substitute to a few roof tiles). This application of photovoltaics is termed BIPV or 'Building Integrated Photovoltaics'. Building materials last many decades and PV modules are expected to do so as well. During the hailstorm that struck Sydney a few years ago solar modules got a good real-world test. Thousands of rooves were destroyed as a result of the storm. The roof of Pacific Solar (now CSG Solar) was totally destroyed except for the solar system, which remained completely undamaged, showing how strong solar modules are in comparison to other roofing materials.

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4 Engineering electricity/electronics

4.1 Review of basic electrical principles

Compared with other energy sources, electricity is highly flexible in that it is easily transformed into other forms of energy. Some examples of other types of energy include the kinetic energy of a moving car, the light energy of a light bulb or the mechanical energy of a motor. Electricity is also a mobile form of energy because it can be delivered to any device using just a conducting wire. It is however, fairly difficult to store electricity in large quantities at low cost with present technologies. Batteries are the primary means of electricity storage, but generally represent a high cost per kWh stored. To understand solar cells, loads, storage devices like batteries, and electrical circuits it is imperative to first understand how electricity is measured and how it works.

4.1.1 Electric Charge

There are two types of charges: positive and negative. Like charges repel and opposite charges attract. For example, two positive charges will push each other away, as will two negative charges. Only a positive and negative charge will be attracted to one another. Electric current is the flow of negative charges (i.e. electrons). Every atom has a core of positive protons and orbiting negative electrons. A single proton and a single electron have charges of equal magnitude, but opposite in sign. Protons are positively charged, while electrons are negatively charged. It is interesting to note that protons are significantly more massive than electrons. An electric charge that is placed in an electric field will possess electric potential energy because it feels a force due to that field. An electric field may be in a particular region of space, but will not interact with uncharged objects. Once a charged object is near it, that object will experience a force. Electric fields can be created by magnets, an imbalance of electrons and protons, and even electricity itself.

4.1.2 Potential difference (or voltage)

Potential difference describes the difference in electric potential energy between two points in an electric field per coulomb of charge (Andriessen, M. et. al. 2002, p.102). It is analogous to pressure in plumbing and piping systems; it is a tendency to cause movement. Only the *difference* in potential between two points holds meaning, because there is no absolute measure of the potential of a single point. This difference in potential is measured in volts (V), which is the SI unit that is used to measure potential difference. SI refers to the International System of Units. The above definition of voltage can be written as follows:

$$Voltage = \frac{Electrical.Potential.Energy}{Charge}$$

The voltage (potential difference) between two points is proportional to the work required to move a charge through that distance or space → i.e. 1 joule of energy is required to move a 1 coulomb charge through a voltage of 1 volt. A bundle of electrons for instance, may be an example of such a charged object. The specific number of electrons required to total 1 coulomb of charge is 6.25×10^{18}.

Voltage is measured by using a voltmeter which connects two conducting probes/electrodes to two points in a circuit to display the voltage between those points. Thus, the voltmeter is always connected in parallel to the circuit element being tested. This is shown in Figure 51 where the voltmeter (denoted with a V) is measuring the voltage across the resistive element (R). Note that we can measure the voltage across any element, not necessarily just resistors.

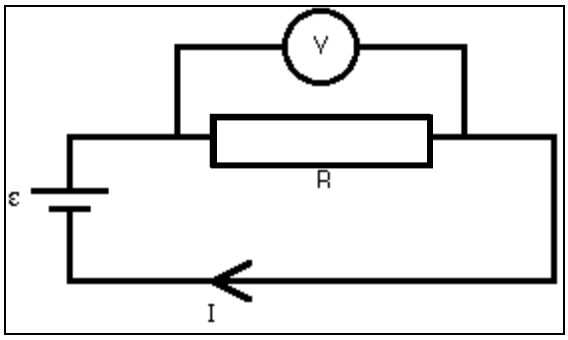


Figure 51: Connecting a voltmeter (V) in parallel to a resistor (R)

4.1.3 Current and Resistance

Electric current refers to the flow of electrons and electric charge. A closed circuit is one where electrons may pass from the generation source, through a series of loads, and then back to the source. The closed circuit allows the electrons delivered to the load to return to the power source for the driving voltage to be supplied again. The opposite of a closed circuit is an open-circuit, as shown in **Error! Reference source not found.**. An open circuit is a situation where there is a section that is not connected to close the conducting path from source to load, and then to source again. Electrons carry currents in metal conductors since protons remain stationary in the metal lattice of the conductor. The most common type of conductor is metal wire (usually copper). In plumbing and piping systems, current is analogous to flow rate. i.e. how much fluid flows per second.

The SI unit for current is the ampere (A), which is the current present when 1 coulomb of charge (i.e. 6.25×10^{18} electrons) passes a cross-section of conductor in 1 second (Andriessen, M. et. al. 2002, p.105). The exact definition for current is the "rate of change of charge past a given point" (Dorf, R.C. Svoboda, J.A. 2001, p.8).

The odd thing about circuit diagrams is that current is shown to flow in the direction opposite to the flow of electrons. This is the convention that is followed, despite the fact that it is electrons that flow in conductors. So, 'conventional current' flows in the

opposite direction to the actual current flow due to electrons. This convention exists because early electricity researchers assumed positive charges were the ones that flowed.

DC (Direct Current) is the flow of current in one direction along a conductor/wire. Electrons flow out of the negative terminal of a generating source and into the positive terminal after passing through an external circuit with various loads. DC is also a current of constant magnitude (see Figure 52(a)), unlike AC (Alternating Current) which fluctuates in strength in a sinusoidal pattern with time (see Figure 52(b)). DC always flows from the negative to the positive terminal when a circuit is supplied. The electrons enter the positive terminal of other circuit elements and leave via the negative terminal. PV panels and batteries supply current in DC only. However, the electricity grid supplies AC and most household appliances consume AC. As a result, we use a device called an inverter to change our unidirectional DC current into a sinusoidally-varying AC current. DC and AC currents are graphed in terms of their strength/magnitude in Figure 52.

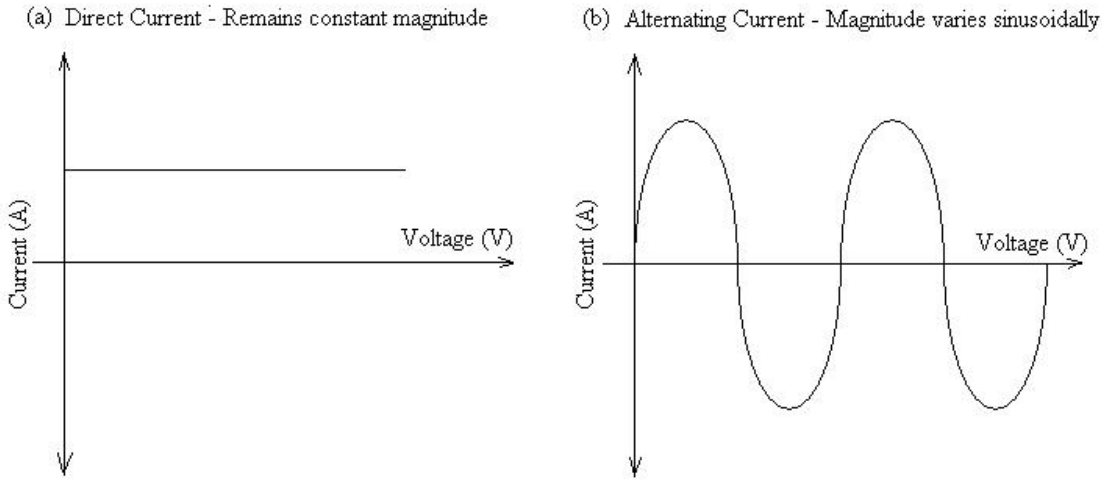


Figure 52: (a) DC, showing constant magnitude and (b) AC, showing sinusoidal variation

With AC, the current reverses the direction of its flow 50 times every second (a frequency of 50 hertz). The flow of current in the reverse direction is shown on the graph as a negative value. AC has the advantage that the voltage can be stepped up and down very easily using devices called transformers. This is one of the primary reasons for the dominant use of AC for electric devices.

Resistance is commonly associated with current flow as it essentially impedes current flow much like a dam with a spillway impedes river flow. Electrical resistance results in electrical energy from the power source being converted to heat that is dissipated to the outside environment around the resistor. The power delivered to a resistor (or consumed by it) is given by:

$$P = \frac{V^2}{R}$$

where,
V = voltage across the resistor in volts, and
R = resistance of the element in Ohms

The resistance (R) of a wire is given by the formula defined by Georg Simon Ohm (Dorf, R.C., Svoboda, J.A. 2001, p.40):

$$R = \frac{\rho L}{A}$$

where,
ρ = resistivity of the wire material (a basic property of the metal used) [Ohm.cm]
L = length of wire being considered [cm]
A = cross-sectional area of the wire [cm^2]

We also have a relation between current, voltage and resistance, Ohm's Law:

$$I = \frac{V}{R}$$

Current is measured by breaking the circuit at the point where the current is to be measured and connecting an ammeter in series, as shown in Figure 53 below. Here, the ammeter (A) is measuring the current through the resistor (R).

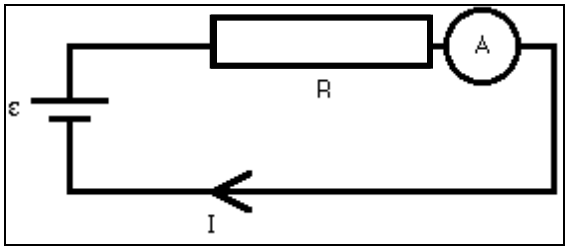


Figure 53: Connecting ammeter (A) in series with the circuit

4.1.4 Simple circuits and elements

The various components that may be included in a circuit are called circuit elements. In DC circuits, each has a positive and a negative terminal, with electrons entering via the positive, and leaving via the negative. In AC, because the current and voltage direction

reverses so often, the polarity of the terminals cannot be said to be one or the other except for a few milliseconds at a time.

There are many different types of circuit elements, and some of the common ones are shown in Figure 54 below:

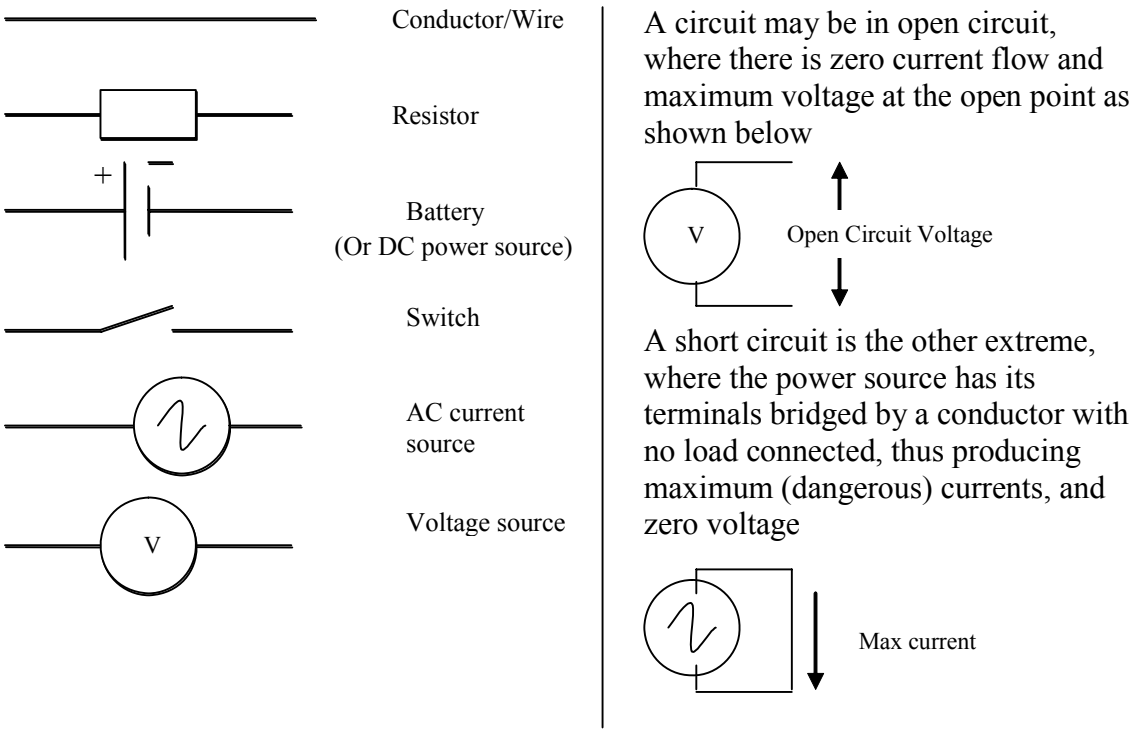


Figure 54: Common circuit elements and states

Power sources provide the potential energy for the charge carriers to overcome the resistive losses in the circuit, and thereby power the loads. They do so by separating positive and negative charges, and the negative charges will flow to the positive terminal through the circuit if connected externally by a metal conductor.

Photovoltaic cells are one such power source, converting light energy directly into electric potential energy by separating the charges at the p-n junction. The voltage across a power source refers to the electric potential energy given to each charge carrier that passes through the source.

In metals, current flow is achieved in reality by mobile electrons. What is known as conventional current represents the direction of a conceptual positive flow (a convention developed before it was known that negative electrons actually move in wires, when positive charges were assumed to move around a circuit). Of course positive charges do not move in a wire, the negative electrons do. So bear in mind that the direction of electron flow is opposite to conventional current.

Hendersen T. (2000) clearly describes the voltage changes that take place in electrons moving around a simple circuit:
"As a positive test charge moves through the external circuit, it encounters a variety of types of circuit elements. Each circuit element serves as an energy-transforming device. Light bulbs, motors, and heating elements (such as in toasters and hair dryers) are examples of energy-transforming devices. In each of these devices, the electrical potential energy of the charge is transformed into other useful (and non-useful) forms. For instance, in a light bulb, the electric potential energy of the charge is transformed into light energy (a useful form) and thermal energy (a non-useful form). The moving charge is doing work upon the light bulb to produce two different forms of energy. By doing so, the moving charge is losing its electric potential energy. Upon leaving the circuit element, the charge is less energized. The location just prior to entering the light bulb (or any circuit element) is a high electric potential location; and the location just after leaving the light bulb (or any circuit element) is a low electric potential location. Referring to the diagram below, locations A and B are high potential locations and locations C and D are low potential locations. The loss in electric potential while passing through a circuit element is often referred to as a voltage drop. By the time that the positive test charge has returned to the negative terminal, it is at 0 volts and is ready to be re-energized and pumped back up to the high voltage, positive terminal."

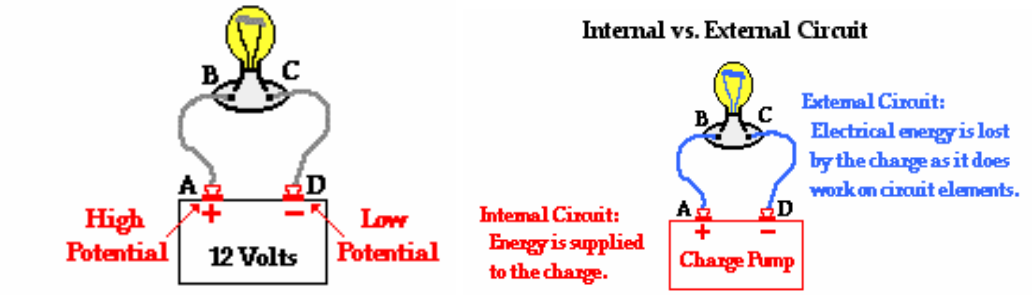


Figure 55: How the voltage and potential energy of electrons change as they flow through a circuit (Henderson T. 2000)

4.1.5 Units and Magnitudes

Most of the units given for quantities can have a prefix added to describe very large or very small quantities (e.g. millivolts). Some such prefixes are given in Table 6 below. These units are particularly useful when dealing with electricity because we are often dealing with very large or very small numbers.

Table 6: Prefixes used to denote large and small quantities

Prefix	Symbol	Multiplying factor
nano-	n	10^{-9}
micro-	μ	10^{-6}
milli-	m	10^{-3}
centi-	c	10^{-2}
deci-	d	10^{-1}
hecto-	h	10^{2}
kilo-	k	10^{3}
mega-	M	10^{6}
giga-	G	10^{9}

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- Boston University (2000), *Batteries, Current, and Ohm's law* [online], Available: http://physics.bu.edu/py106/notes/Ohm.html (Accessed 14th July, 2008), PY106 - Elementary Physics II
- Massachusetts Technology Collaboration, *The Science of Electricity* [online], Available: http://www.mtpc.org/cleanenergy/energy.htm (Accessed 14th September, 2008)

- Once you're done: take this online test of your knowledge of electricity by BellSouth: http://www.asisvcs.com/publications/pdf/710041.pdf (Accessed 7th January, 2008). Some questions will be too difficult for you or may include terms you have not come across yet – just attempt the ones you have come across.

4.2 Current-voltage curves for photovoltaic modules

For a DC energy source like a PV module, the power output is given by P = V×I. That is, power output = source voltage × source current. Power is typically measured in watts. Power is the rate at which energy (measured in joules) is supplied by a power source, or delivered to a circuit element, per time. For AC energy sources, there is added complexity that we will not cover here, however the general process of calculating power is the same.

Photovoltaic devices are often characterized by the range of current-voltage states that can be output by the cell. This is common for electrical energy sources, since we would like to see how the voltage changes with variation of the current. The range of current-voltage states can be illustrated using a graph known as an IV curve. An example is shown in Figure 56. The key points to notice are the open circuit voltage which is the situation where no load is applied (infinite resistance) to the cell, and the short circuit current where a wire is connected directly from the positive to the negative terminal of the cell (no resistance). Once the current and voltage curve has been plotted, power can then be calculated and plotted on the same graph (Figure 56). This is simply given by P = IV where V = voltage, I = current. The most important point here is the maximum power point. In Figure 56, the maximum power voltage is 0.47V and the maximum power current is 0.56A. Note that Figure 56 displays the negative of the current shown in the earlier IV curves for diodes (Figure 40). This is because we want to represent generated current as taking positive values. That is to say, Figure 56 is the mirror of the 4th quadrant of the diode graph, and it is shown here as being in the first quadrant. See Section '3.3: Operation of a p-n junction' for further details.

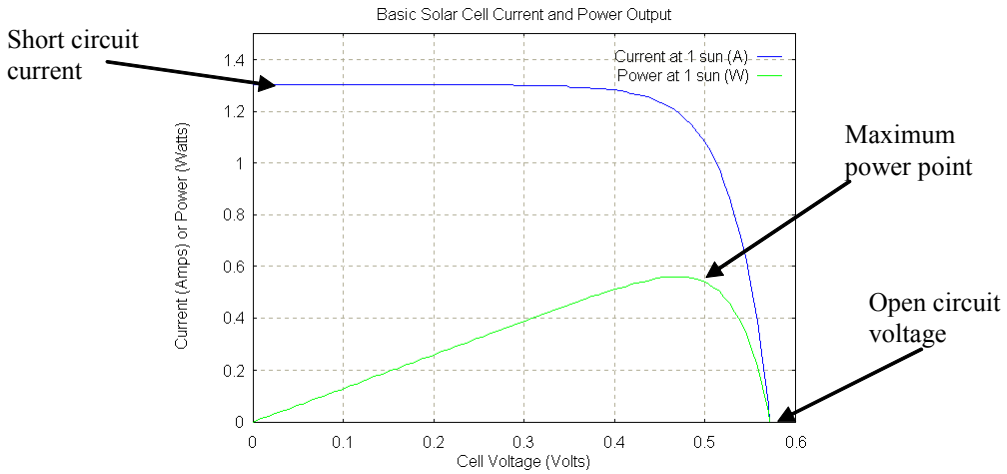


Figure 56: Typical current- voltage (IV) curve for a solar cell (Wright, C. 2006)

4.2.1 The Solar Cell Modelled as a Circuit

A solar cell can be modelled using electric circuit elements. The model used for a photovoltaic cell is shown in Figure 57 below.

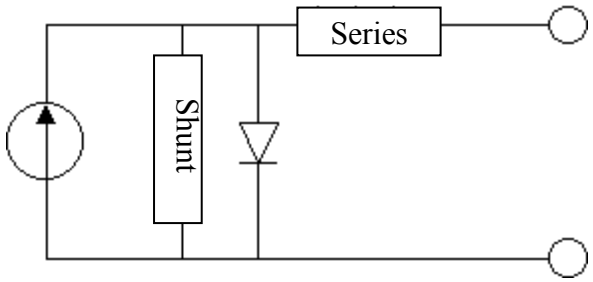


Figure 57: Electric circuit model of a photovoltaic cell

A current source represents the current produced by a cell under solar illumination and the resistors represent the series and shunt resistances. Series resistance is the direct resistance to the flow of current within the PV cell (or module) itself. There will always be some resistance to flow within a power source due to the inherent resistance of the materials. There is no material in existence with zero resistive losses. Shunt resistance is more complicated and refers to the ability of the p-n junction to separate the p and n regions, thus maintaining a voltage difference. It effectively measures the extent to which current paths exist that bypass the p-n junction. You want the shunt resistance to be high. This won't be covered in any detail in this course. The diode represents the voltage or potential difference between an electron or hole which has enough energy to service an externally connected load, and one that doesn't. This voltage is ~0.6V for silicon materials, so we can use silicon diodes to represent the same voltage difference as silicon solar cells.

Further Reading

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4.3 Control circuits and PV-supporting devices

There are a number of circuit components that are used to control electrical flow, electricity type and electrical storage. Some of these are discussed below:

4.3.1 Inverters

The electricity generated by a PV module is in the form of direct current (DC). Where PV is used for a building that is also powered by the grid, it is possible to 'export' any excess electricity generated to the electricity network. In many cases, electricity utilities will pay the PV owner for this electricity. Also, when the PV is not meeting load demands, extra electricity is required to power loads. This extra power can be drawn from the grid, eliminating the need for expensive battery back-up. However, nearly all electricity grid networks in the world are powered by AC (Largent, R. 2003, p.67). There are strict regulations controlling the quality of power that can be imported to the grid. One is that it cannot contain DC currents. This is because DC mixed in with AC power damages most appliances designed for AC. DC current can, however, be transformed into AC, and this function is performed by an inverter. Inverters used to power a typical house are fairly small boxes around the size of a toaster, although they can be smaller or larger depending on the power rating and PV system size.

There are two categories of inverters: self-commutated and line-synchronized (IEA PVPS, 2002-1). The former operates independently, with the PV triggering its operation. The latter is triggered by the voltage signals provided by the grid. Line-synchronized inverters are preferred because they 'connect' the PV to the grid when the voltage signals are synchronized, thus reducing power losses and explosive electrical risks. Utilities require that inverters 'clean' the power delivered to ensure high quality electricity in accordance with regulations. This is generally carried out by electrical filtering circuits. Inverters do not always feed into the grid and can be also used in remote area power systems (no grid connection) to power standard AC appliances. An example of this type of system is a farm homestead where a PV-battery system is used and an inverter powers the AC loads.

In the past, entire arrays would be connected to a single inverter. Nowadays, new configurations have separate inverters for each 'string' of modules in series, or even

lower-rated inverters for individual modules. Module inverters receive the DC from the individual panel it is connected to, and effectively outputs the AC at their outlet terminals. These are highly suited to BIPV applications because they are modular and permit easy system expansion and easier installation (IEA PVPS, 2002-1). Module inverters maximize the output of each module but central inverters are cheaper with a single unit servicing many modules. There are pros and cons of each approach and the system chosen requires a compromise in the design phase to determine what is best for a particular application.

The cheapest inverters use simple switching circuits to deliver a fixed positive voltage followed by fixed negative voltage 50 times per second (known as square waves - see Figure 61). Improved inverters include the zero voltage state and reduce the peaks of the waveform. The best inverters use pulse width modulation (PWM) by varying the percentage of time each voltage (negative, zero and positive) is applied, and subsequently filtering the output to produce a smooth AC waveform. PWM inverters are the only type that produces a waveform suitable for feeding electricity into the grid. There will be more on all this in Section 4.6: 'The waveform output of inverters.' Inverters often incorporate extra electronic circuits that control battery charging and manage loads such that they are continuously powered (preferably by solar if it's available at the time).

Maximum Power Point Trackers (MPPT)

The efficiency of inverters is generally greater than 90% when the inverter is operating above 10% of its rated output, and can peak as high as 96% at its optimum operating point (IEA PVPS, 2002-1). If an inverter is connected directly to PV modules as opposed to through a battery bank, it may incorporate a Maximum Power Point Tracker (MPPT), which continuously adjusts the load impedance (AC equivalent of resistance) seen by the array, such that the inverter is always extracting the maximum power from the module at the voltage required by the load. Otherwise decoupling of the load and the inverter is what is usually required to get this kind of operation.

If loads attempt to draw to high currents from the PV, the voltage at which the panel can supply this current will decrease significantly (Largent, R. 2003, p. 68). Similarly, if not enough current is drawn, the panels will be not fully utilized. Most MPPTs use hill-climbing algorithms together with sliding window algorithms to locate the maximum power point (MPP) (Largent, R. 2003, p.68). Refer to the IV Curve in Figure 56. As the maximum power point is being approached, the voltage will be increased slightly to test if the current is rising, and if not, the voltage will be slightly reduced till the current stops rising. Therefore the MPP 'hill' is gradually and iteratively detected. Some inverters track the MPP with an efficiency estimated at 99.9% (Largent, R. 2003, p. 69).

4.3.2 Batteries

Batteries are the primary means of electricity storage, but generally represent a high purchase cost per kWh of energy stored in them. Batteries essentially store energy in chemical bonds and release them by breaking them in electrochemical reactions. Nearly every battery has one positive terminal marked (+) and one negative marked (-). When

these terminals are connected directly by a material with low resistance (e.g. metal wires), they will short circuit and the largest current that battery can produce will flow through them. The electrons themselves flow from the (-) to the (+) terminal via the circuit/wire, and from (+) to (-) within the battery itself. As soon as wires connect the positive and negative terminals, the battery will begin its chemical reactions and electrons will be released for currents to flow. A battery is said to be 'dead' (or its power exhausted) once all the chemicals in the battery have been used up in chemical reactions.

It is not advisable to short circuit a battery because all the energy generated is dissipated as heat of resistance in the wire and the resistance inside the battery itself. The whole circuit heats up and this can cause sparks and melting of wires. Connecting the wire to a device with a reasonable resistance that is rated to tolerate a certain amount of power flowing through it will allow for the generated energy to be dissipated safely.

Battery storage is really only necessary in off-grid situations, or in areas where the electricity grid is unreliable and black-outs are common. Batteries can also supplement grid backup systems when very high availabilities are needed (systems or applications that do not tolerate system downtime as a result of power failure).

Generally speaking however, batteries are most essential for remote area and stand-alone systems. Here, PV cannot supply any power at night, and will supply irregular power during cloudy days. As such, some form of storage is needed, and this is typically supplied by batteries.

The lifetime of a battery will degrade with fast and excessively deep discharging. Overcharging can also cause some problems like evaporation of the electrolyte. The state of charge (SOC) of a battery describes the amount of energy left in the battery as a percentage of the total capacity. This is usually determined by measuring the terminal voltage which varies in proportion to the SOC. Each of these battery treatments that harm battery life are generally protected by a charge controller which prevents over and undercharging and helps regulate current flow in and out of the battery to maximise battery life.

4.3.3 Charge Regulators

Charge controllers adjust the rate at which charge enter/leaves a battery based on the state of charge of the battery. Regulators/controllers prevent batteries from being damaged by over-discharging during periods of low voltage, usually by disconnection. This is termed 'low voltage disconnect'. They also prevent overcharging during extended sunny periods when the battery is full, which would lead to corrosion of the plates and loss of electrolyte. The charge controller can mitigate over charging by disconnecting the battery from the charging source, or by diverting the energy elsewhere (often water heating, or a dummy load).

Different regulators provide different functionalities depending on the applications they are designed for. There are always trade-offs between low cost and increased sophistication, which may improve performance. Further, charge controllers have to

accommodate different battery technologies as each has different charge and discharge characteristics and requirements.

The Australian Plasmatronics PL regulator for example, can be used with hybrid sources like wind, micro-hydro, petrol & diesel generators (Plasmatronics 2000, p.4). Some regulators provide this option of charging from AC sources. The Plasmatronics PL range is considered a 'smart' regulator series, with a microcontroller integrated circuit taking various usage data to determine charging rates & select between 4 charging modes (Plasmatronics 2000, p.7). Some inverters can perform the function of a charge regulator too.

Many regulators simply use the present battery terminal voltage to determine the state of charge. They have the following shortcomings (Plasmatronics, 2003);

- They undercharge batteries with high internal resistance (due to sulphation or bad connections) that show higher voltages, and are mistaken for being fully charged.
- They can boost charge a battery too often if an occasional heavy load is applied.
- Near full charge, the current can oscillate rapidly on and off as the voltage drops above and below the full state of charge voltage.
- They waste energy in the afternoon when the batteries are full.
- Voltage transients due to inverters or large inductive loads such as motors can cause incorrect changes in regulator state.

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- Florida Solar Energy Centre, *How a PV System Works* [online], Available: http://www.fsec.ucf.edu/en/consumer/solar_electricity/basics/how_pv_system_works.htm (Accessed 8th January, 2008)
- Solar Connecticut, *Photovoltaic and How They Work* [online], Available: http://uhaweb.hartford.edu/solarinfo/education.htm (Accessed January 10th, 2008)
- Research Institute for Sustainable Energy, *Stand-Alone Power Supply (SPS) System Module 4* [online], Available: http://www.rise.org.au/info/Education/SAPS/sps004.html (Accessed January 10th, 2008)

4.4 Islanding concerns and techniques to overcome it

There are major hazards that arise if the electricity supply authority switches the grid off in a certain area to undertake maintenance work and a residential PV system is still operating and exporting power to the grid. This is called islanding. Workers will unknowingly be exposed to currents as the solar array feeds electricity into the grid to power the loads of all the houses in the nearby network (Largent, R. 2003, p.63). Australian and international standards require that grid connected inverters detect when the grid has failed and disconnect the PV system from it. These requirements are especially important to guarantee the safety of line workers while undertaking maintenance. Additionally, the quality of power (i.e. voltage and frequency) supplied to other users still on the island will be variable and may damage their appliances. Furthermore, the island may not be grounded to the Earth, thereby increasing the risk of electrical faults that may lead to electrocutions.

To detect a tripped grid is challenging and present methods can be unreliable under certain circumstances. Inverters sense the grid frequency (which should be around 50Hz), the grid voltage (typically around 240V), and other electrical grid parameters. Changes in these may indicate a portion of the grid tripping out (Largent, R. 2003, p.63). After a problem has been detected, the inverter disconnects from the grid.

References

- Walling R.A. (2003), *Distributed Generation Islanding – Implications on Power System Dynamic Performance* [online], Available: http://www.electricdistribution.ctc.com/pdfs/Paper%20SPM%2002%20DG%20-%20Walling.pdf (Accessed 11th January, 2008)

Further Reading

- Thacker, T., *Chapter 3: Introduction to DG and Intentional Islanding* [online], Available: http://www.dg.history.vt.edu/ch3/islanding.html (Accessed 11th January, 2008), Virginia Tech
- Bründlinger R., Bletterie B. (2005), *Unintentional islanding in distribution grids with a high penetration of inverter-based DG: Probability for islanding and protection methods* [online], Available: http://www.arsenal.ac.at/downloads/products/st_petersburg.pdf (Accessed 11th January, 2008)

4.5 PV system sizing and configuration according to application

Proper system design should maximize reliability and lifetime of the entire system, with minimum initial cost. By reliability, we mean the system should deliver power whenever it is demanded, in the quantity the system has been designed for. For this, the system needs to be sized large enough to meet the expected loads (i.e. electricity-consuming appliances). This basically means, you need to make sure there are enough PV panels to generate the amount of energy required over the day and night, during just the daytime

sunshine hours. The sun imparts a certain amount of energy on each square metre of land, which means a solar collector is required at each square metre to harness that available energy. System sizing also involves selecting a large enough battery to store all that excess daytime energy, and possibly a suitably-sized generator to meet particularly large loads by themselves. The key factors influencing system sizing are the solar resource at the location (kWh of energy delivered by the sun per square metre), and the size and nature of the loads (the kWh demanded and the timing of these demands).

There are 3 basic categories of PV systems:

- Grid-connected systems
- Stand-alone systems
- Hybrid systems

4.5.1 Grid-connected Systems

Electricity grids are basically networks of central power stations and distributed loads (e.g. homes, businesses & industry that demand electricity). The central power stations usually produce large amounts of power (hundreds of megawatts) by burning fossil fuels like coal or natural gas. Most homes receive electricity from fossil fuel fired power plants. Grid-connected PV systems have the PV directly connected to the AC grid via an inverter. This AC power is then used to supply the household appliances, and any extra energy is sold to the grid. This means the PV generated DC electricity is immediately converted into AC. Most appliances are manufactured to operate with AC because most electricity grids operate on AC. Surplus energy generated by the PV during the day will be fed into the grid, while in times of shortage (e.g. at night), energy will be consumed from the grid. This is illustrated in Figure 58 below. The grid acts like a battery of infinite capacity. The total efficiency of a grid connected PV system will be better than the efficiency of a stand-alone battery-storage system since any excess electricity can always be stored. In battery operated systems, a larger battery is usually desirable (so more can be stored for later), but more batteries will also cost a lot more. When a grid-connected system can use the grid as a battery for free, the economics of the system become much more favourable to PV.

Stand-alone applications (as opposed to grid-connected applications) refer to PV systems installed in remote areas that don't have an electricity grid (i.e. where people have been supplying their own electricity by burning liquid fuels in generators that produce AC electricity). Many remote areas don't have grids because it costs a lot to build transmission lines, and usually isn't considered worthwhile to power just one of two homes in remote locations. In stand-alone applications the batteries can often be full with the PV able to produce more electricity while there is a lot of sunlight. In this instance, the generated electricity is just "thrown away" by operating the solar cell at somewhere other than the maximum power point. The photons falling on the cell are basically converted to heat in the semiconductor, rather than electricity. This is usually preferable to having a big, expensive battery bank. Remember that batteries fail after 4-8 years, and therefore need to be replaced (an additional expense).

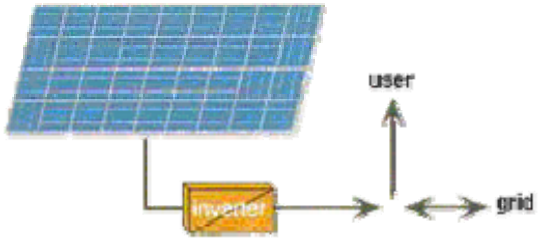


Figure 58: Typical connection for a grid connected system (IEA PVPS, 2002-2)

The design of grid-connected systems is less rigorous than stand alone systems because the grid can provide for any shortfall in energy generated. Primary considerations are abatements in greenhouse gas emissions, as well as electricity cost savings. When the grid trips (i.e. stops supplying power), a properly designed inverter with circuits to detect islanding- will shut off the PV system. This means that most grid connected PV systems do not provide an uninterruptible power supply (UPS) service. This means that unless you have batteries, when the grid is down a house with a grid connected PV system will also have no power. And as you already know, to have batteries only increases the cost of the system. There are more products coming onto the market that alleviate this problem since many people purchase PV systems mainly to ensure they have electricity during black outs. Have a look at Section 4.4: "Islanding concerns and techniques to overcome it," for reasons why PV inverters deliberately disconnect the PV modules when the grid fails.

Grid connected systems are also required to ensure that the power delivered to the electricity grid be of a high quality (good, clean AC waveforms). This function (keeping the power quality pure) is also provided by the inverter. This basically involves ensuring the correct frequency, voltages and waveforms are delivered to the grid by the PV via the inverter. The quality of power in the electricity grid is usually of a high standard, so PV inverters need to ensure what they supply back to the grid is of a similar quality. This ensures that all appliances used by anyone drawing power from the grid, are protected from damage due to poor quality electricity.

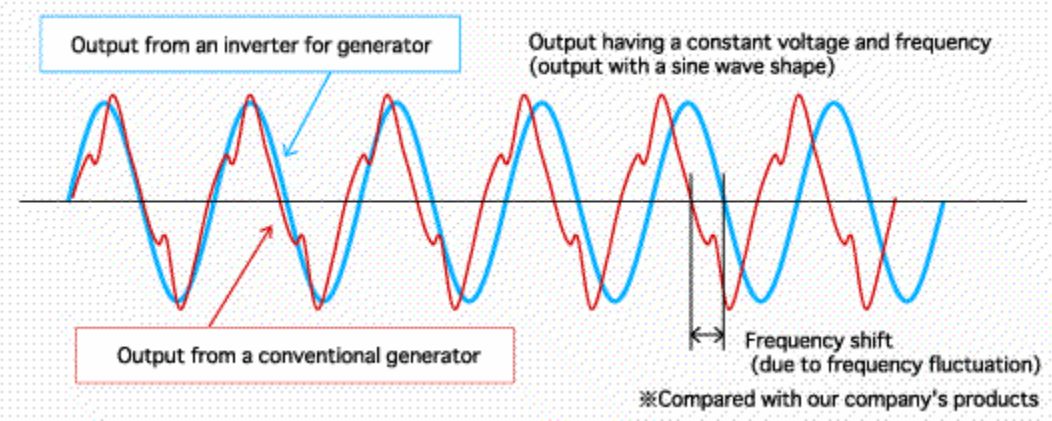


Figure 59: Power quality shown in terms of voltage, frequency and waveform
Source: Sawafuji Electric Co. (2006), Inverter for Generator [online], Available: http://www.sawafuji.co.jp/english/tech/hatudenki.html (Accessed 12th January, 2008)

4.5.2 Stand-alone Systems

With utilities deregulated, remote customers needing power can be charged the full cost of extending transmission lines to their site. This usually amounts to thousands of dollars per kilometre of power line needed. This can amount to tens of thousands of dollars per customer. Commonly, petrol or diesel generators would supply the power, with regular loads of fuel purchased by the user. This is an expensive way to generate electricity, especially with rising petroleum prices. Generators are also noisy and emit smoke. Instead, a PV system with sufficiently sized batteries can supply most of the power needs of the household. Compared to a generator or extension of power lines, this can be cost effective. Some problems with generators that are solved by PV include:

- No need to haul fuel (especially to remote locations)
- No on site fuel storage required
- No starting and stopping the engine
- Removes need for obtaining spare parts and getting technicians to the site
- Reduces noise and air pollution

The advantages that generators have over PV include:

- Lower initial cost to purchase a generator
- Generators can meet higher peak loads (large current capacity) where batteries used in PV systems struggle (they supply low currents for long periods, rather than high currents for short periods)
- They do not depend on a variable solar resource
- They do not generally need batteries (except a small one for starter motors in some designs)
- They do not need to have replacement batteries every 5 years or so

However, the amount saved in lower upfront costs for a generator is small compared to the high ongoing cost of fuel purchases, because fuel is purchased for many, many years, costing thousands of dollars per year.

Off-grid applications where entire loads are to be provided by PV require more accurate sizing processes. Such systems almost always require very large battery storage, which adds significantly to the cost of the systems. Batteries can supply power from stored solar energy during periods where there is no sunlight, sometimes for days. The more days of power that a battery must supply without sunlight, the greater the size of the battery bank required, and the greater the cost of the system. Figure 60 shows the operation of the typical remote area power system.

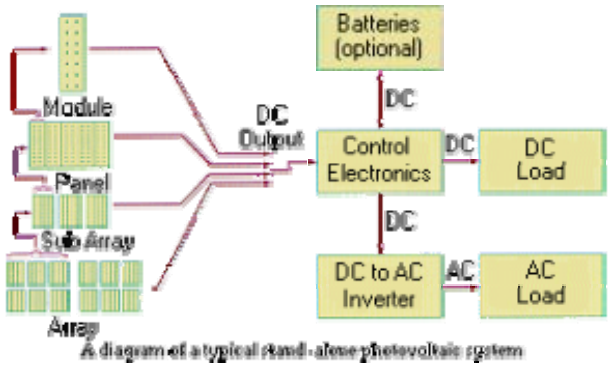


Figure 60: A typical stand-alone system (SANDIA Corporation 2005)

4.5.3 PV Hybrid Systems

Hybrid systems are typically used in off-grid situations and use PV with another generation source to increase the availability of power from the system. This means the PV can charge batteries whenever the sun is shining and the batteries meet the normal loads when they have charge available. When the batteries are flat however, the other generation source takes over at full power (usually a diesel or petrol generator). Usually, the generator is only used to power very large loads like vacuum cleaners, irons, or washing machines, and the batteries supply smaller, more continuous loads like fridges. Because these large power appliances are only needed for half an hour or so, the generator can be sized and used to power these appliances only. This usually means a much smaller generator can be used, and therefore a cheaper one too, and the battery charge can still be preserved. Wind generators are also commonly coupled with PV. Since some power can be provided by these secondary electricity sources, the cost of the total system can be reduced compared to operating a 100% PV remote power system that would require a very large (oversized) battery bank. This is because the PV system can be sized for the small typical loads like a fridge and lights while the generators can be used to provide excess power for large unusual loads such as vacuum cleaner etc.

Of course, an important part of a system with two generating sources is an electronic computer called a controller, which monitors and coordinates the generation sources and the batteries state-of-charge. It is very important to have an intelligent controller that can make decisions based on load demand, battery state of charge and the generator run-time. This is to ensure loads are continuously powered and equipment is protected. It is vitally important to prevent the batteries from being drained too much, and thereby causing permanent damage to them. Hybrid systems are very common in remote areas because of the cost and performance advantages described in this section.

Further Reading

- School of Photovoltaic and Renewable Energy Engineering UNSW, *Remote Area Power Supplies* [online], Available: http://www.pv.unsw.edu.au/future-students/pv-devices/remote-area.asp (Accessed 6th January, 2008)

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- DOE EERE (1997), *Photovoltaics: Basic Design Principles and Components* [online], Available: http://www.oregon.gov/ENERGY/RENEW/Solar/docs/pvbasics.pdf (Accessed 4th July, 2008)

The following website has great educational materials on stand-alone systems

- Centre for Appropriate Technology, *Educational Resources* [online], Available: http://www.bushlight.org.au/default.asp?action=article&ID=78 (Accessed 14th September, 2008)

4.6 The waveform output of inverters

The output from a true AC sine wave inverter is a smooth, fluctuating voltage and current, where the input is a fixed DC value. You can see some pictures of this waveform in Figure 61. This fluctuation is basically a particular waveform, repeated over and over again. The voltage goes from zero to the peak to the minimum to zero in $^{1}/_{50}^{th}$ of a second. The electrons experience a changing force on them in this way during each cycle as the voltage goes up and down. This repeats itself 50 times every second. Currents change direction twice every cycle. In the first half of the cycle, currents flow one way, and in the second half, another way. This is what happens when voltage goes from positive to negative. AC waveforms are naturally produced by rotating generators (e.g. at coal-fired power plants). The motor naturally turns through smooth cycles that produce the sinusoidally varying voltage and current. This is explained in the Preliminary and HSC Physics courses but we won't go into it here. It is much more difficult to take a constant voltage and convert it into a sinusoidally varying current so that normal appliances can use the electricity. This is what needs to be done to take PV DC electricity and make it usable by normal appliances. This would involve changing the directions the electrons are flowing 100 times every second, and still keeping the final waveform smooth. Changing the direction is easy enough to do by using switches. Keeping it smooth is very challenging, and therefore costly. This process of converting from DC to AC is performed by an inverter.

Depending on the sophistication of the control circuitry, the AC waveform can take 3 forms: square wave, modified square wave or true sine wave (see Figure 61 and Figure 62 below). The simplest and cheapest inverters simply switch a fixed voltage negative and then positive, to produce a square wave (with a short time delivering zero voltage between the switch from negative to positive and positive to negative). Modified square wave inverters make the peaks of the waveform resemble the upper third of the sine wave, and include a number of incremental steps in the voltage. This prevents the sudden changes from maximum positive, zero, to maximum negative voltages. It more closely resembles a smooth, gradually changing waveform. Figure 61 below shows a very, very simple modified square wave circuit that doesn't even include incremental voltage steps. More switches are required for this type of circuit, thereby increasing the price of the inverter. The true sine wave uses an even more complicated technique called Pulse Width Modulation (PWM), which varies the on-time and off-time of the voltage signal with the duration of the on's and off's simulating the sinusoidal pattern after the signal has been passed through an electrical filter. This is too complicated to go into here, but more can be found out by looking at the articles for further reading.

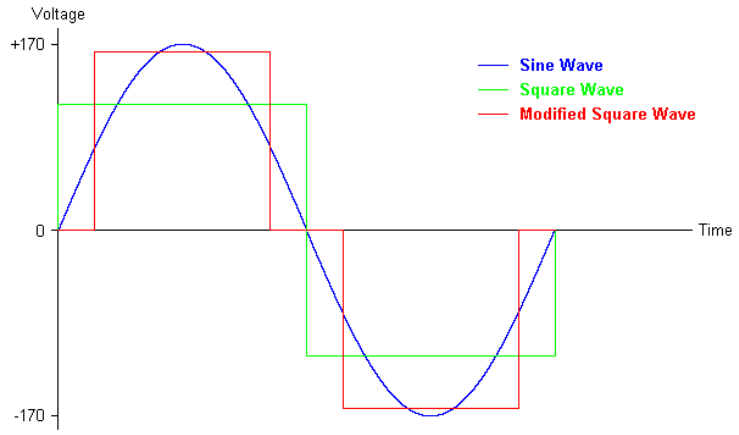


Figure 61: Waveforms output by different inverters (Kozierok, C.M. 2001)

It is important to note that the square waveform also produces various harmonics (additional waves overlaid with the main one) that can cause damage to circuit elements particularly motors and other inductive loads. Furthermore, the sheer peaks and sharp changes associated with the square and modified waveforms cause appliances to overheat and fail, and cause starting problems in AC motors. Pure sine wave inverters are the most expensive, but produce the best AC signal. For this reason they are the best type of inverters to use in most applications. They are also the only type of inverter that electrical companies allow to feed electricity into the grid from PV systems.

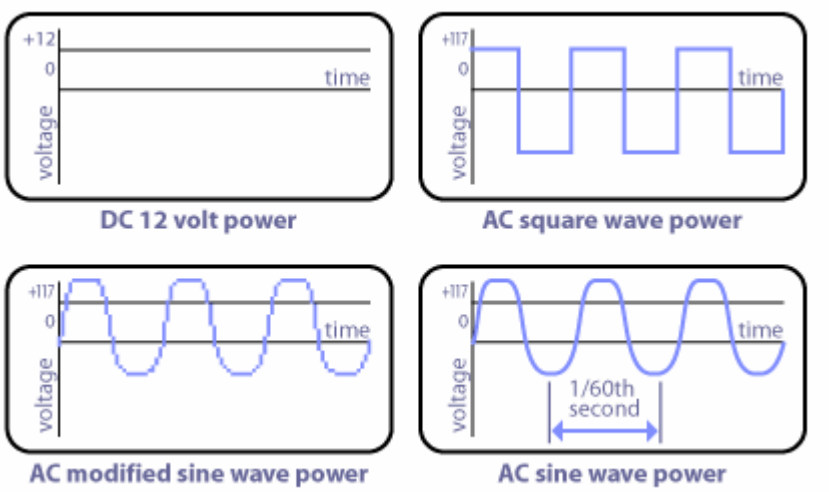


Figure 62: The difference DC, square wave, modified square wave, and pure sine waveforms
Source: SolarDirect (2007), Solar PV Electric: Inverter [online], Available: http://www.solardirect.com/pv/inverters/inverters.htm (Accessed 12th January, 2008)

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4.7 The use of logic gates in control equipment/devices

Logic gates are the building blocks of digital circuits. Most logic gates have two inputs and one output. At any given moment, every terminal is in one of two states:

Low (0), represented by 0 Volts or,
High (1), represented by approximately 5 Volts.

The logic state of a terminal can, and generally does, change often, as the circuit processes data.

There are seven basic logic gates: AND, OR, XOR, NOT, NAND, NOR, and XNOR. Only AND and OR gates will be addressed here, since the remainder are based on these two.

The AND gate requires both the inputs to be ‘true’ for the output to be ‘true.’ Otherwise, the output state will remain ‘false’. Details are shown in Table 7.

AND gate

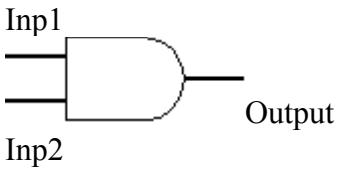


Figure 63: An AND gate

Table 7: AND gate inputs and outputs

Input 1	Input 2	Output
0	0	0
0	1	0
1	0	0
1	1	1

The OR gate output will be ‘true’ if either or both of the inputs are ‘true.’ Only when both inputs are ‘false,’ will the output be ‘false’. Details are shown in Table 8 below.

OR gate

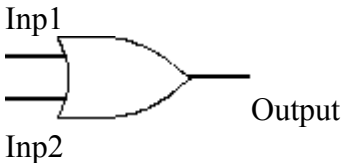


Figure 64: An OR gate

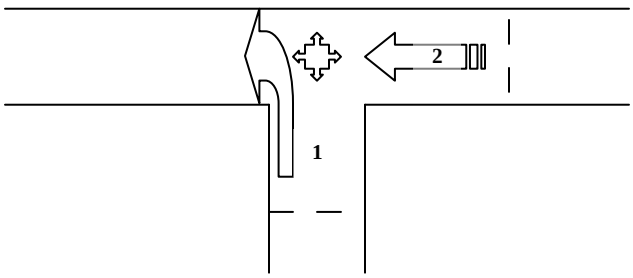
Table 8: OR gate inputs and outputs

Input 1	Input 2	Output
0	0	0
0	1	1
1	0	1
1	1	1

Using combinations of gates, complex circuits can be developed for complex functions. Gates are combined in integrated circuits (ICs), but there is a limit to the number of gates that can fit in a given space. Smaller gates are always being developed, so smaller circuits can be formed into smaller devices.

4.7.1 Using logic gates in very simple traffic controllers

Consider the T-junction below. We have two cars labeled one and two, entering the intersection. The horizontal street going across the page is a one way street with a single lane.



The traffic light (), requires some means of taking in the information on locations of cars, a method of interpreting the input information, and a means of controlling its outputs to regulate the traffic. This input may come from sensors placed beneath each road, some 100m before the intersection. The sensors may transmit a high voltage signal (maybe 3V-5V, indicating a state of 'on' as opposed to 'off') to the traffic light when a car has passed over them, indicating that one is waiting two enter the intersection. This way, the traffic signal controller receives a high voltage signal once a car is arriving on either road. The low voltage signal corresponding to a state of 'off' might be a range of voltages around 0-2V.

The traffic light will also require information about its present state (i.e. 'red' or 'green', assuming 'yellow' is part of the 'red' state). We will define the state from the perspective of car one (i.e. what car one sees), and call red 'low voltage' and green 'high voltage.' Car two will see the opposite colour to car one, thus stopping when car two is proceeding and driving when car one has stopped.

The traffic light simply needs to decide when to alter its state, and in the interest of fairness to all drivers, there should be a time limit to how long the light may remain either red or green for car one (and by implication, car two). Thus, there also needs to be a simple timer that clicks over when the light has moved to a new state, starting on 'low voltage'. Once the timer has been in a state for the maximum length of time, it should then switch its own state to 'high voltage', inputting this to the controller.

The controller may then alter its state to either red of green if there is a car waiting on the other road. However, we do not want the light to turn green to a road when there is nobody waiting at the light – that would be wasteful.

Thus, the controller really has to take four inputs into consideration, to decide whether or not to change the colour of its lights.

- Its own state
- The state of the timer
- Whether a car is waiting at point one
- Whether a car is waiting at point two

The importance of the logic gate and the transistor is that they can represent each of the states for each of the parameters required as inputs to the controller.

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For a great interactive website:

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4.8 The need for control systems

Control systems are sometimes needed to protect batteries from poor charging and discharging conditions or to disconnect a grid connected system in the event of an islanding situation.

Charge controllers are necessary for lead acid batteries which emit explosive hydrogen and oxygen gas when near full charge.

Each system will require a specific regulator/controller depending on the components being used and the features of the individual system.

The control system must also detect the following high-risk situations and have a mechanism to prevent these conditions from occurring:

- When the PV array is in short circuit conditions (fire and melting of cabling can occur)
- When ground faults exist, which can leading to electrocution risks for maintenance staff and reduce system performance
- Identify when the array may have an open circuit between some cells or when the system is operating sub optimally. These faults may lead to arcing across the open circuit which may lead to fires or other damage to modules

In any of these situations, the controller would disconnect the PV (and other hybrid) power source, as well as the grid in order to prevent damage to the PV modules, electrical appliances or the electrical network.

Power control and conditioning equipment provides an interface between each of the different elements of the PV system, including:

- PV energy generation
- Energy storage (usually in a battery)
- Loads
- Electricity grid
- Coupled hybrid power sources

They also control and protect each of the components to ensure optimum operation of the system as a whole.

More intelligent controllers offer greater ability to ensure optimum performance of the system. However, they generally cost more and sometimes result in greater system losses (although these losses are usually small for the overall system). They also tend to contain more complex control circuits.

Key issues with control systems is their own power draw and their conversion efficiencies (e.g. in the case of inverters, the AC output as a percentage of DC input power). These are some of the research and development focus areas for increasing the efficiency of control circuits to maximise the power extracted from PV and other renewable energy systems.

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4.9 Why batteries are important to PV and how best to utilize

PV systems rarely fail due to the photovoltaic modules themselves. It is usually poor balancing of system components (wiring, inverters, batteries and components other than the modules) or poor matching of system components to modules that leads to the failure of systems. It is widely known that batteries in particular are the weak link in PV systems. This is because of their very high failure rate and short lifetime compared with the other components of the system (5-10 years depending on the type of battery, charge regime and discharge rates). They are also very costly because a deep cycling ability is required of batteries used in solar applications. Inverters have also been an area of failure. However, electronics are becoming more reliable with time providing improved inverter lifetimes.

Batteries used in PV systems are rechargeable (also called "secondary batteries"). That is, they store electricity, that electricity is used, and they can subsequently be recharged by the PV system. They operate using chemical reactions within the battery that either release or absorb electrons. When electrons are released from the battery, the battery is *supplying* current. When the PV is recharging the battery, electrons are supplied to *reverse* the chemical reaction that released electrons. In this way, the electrons recharge the chemicals into a state with greater chemical potential energy. That way, when an electrical load is connected to the terminals of the battery by conductors (e.g. wires), the battery will deliver charge to it automatically.

Battery types include:

- Lead Acid – the most common type of battery used
- Nickel Cadmium – commonly used in small consumer electronics
- Lithium Ion – the best performing but most expensive option and now widely used in electronic devices such as phones and computers

Batteries are dangerous and the following are some of the risks:

- Fire or explosion by ignition of the hydrogen gas that evolves (require ventilation)
- Short-circuiting of the terminals which generate heat and fire from arcs
- Acid burns from wet, lead-acid batteries
- Batteries are capable of producing large currents which can be dangerous to humans or can burn out circuit elements

In big, heavy duty batteries, like those used in solar applications, no more than three should be linked in parallel due to the high currents that will result, as was mentioned in previous sections. When there is mismatch between the batteries (either different brands or batteries of different age) or even between the individual cells within a battery, fault currents can result with the possibility of causing major damage to the battery bank and even fires because of the large currents. The other problem with having high currents is the resistive power losses that result (according to $P = I^2R$). It is better to increase the energy storage by increasing the voltage of the battery bank. This is done by having series strings with two or more batteries in each (remember that adding solar cells in series increases the voltage. It is the same for batteries). These are three precautions that should always be taken to prevent damage from batteries and increase the battery life and system performance.

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4.10 The importance of safety when working with DC circuits

If a person is electrocuted, electric currents can produce severe burns in the body, particularly at the points of contact to the circuit, as the electrical power dissipates across the body's resistance (Kuphaldt T.R., 2000). Electric shock can only occur when contact is made between two points of a circuit, and when a voltage is applied across a victim's body. It is important to note that only very small currents are needed to cause an AC electric shock, and even smaller DC currents will cause an electric shock.

Direct current (DC) moves in one direction through a conductor, and has the tendency to induce muscular tetanus (involuntary contraction) quite readily, even at low voltages. Victims are often unable to let go of a DC conductor because of the continuous motion and stable voltage. Alternating current (AC) however passes through zero voltage (and current) 50 times every second, and thus provides brief moments for the muscle to relax (Kuphaldt T.R., 2000).

Also, DC tends to make the heart stand still whereas the electrical oscillations in AC tend to disrupt the heart's pacemaker and cause fibrillation (unsteady beating). This is because the frequency of the AC power will be imposed on the heart. AC is dangerous because a normal heart beat pattern is harder to re-establish in a fibrillating heart than one that has stopped (Kuphaldt T.R., 2000).

Table 9 summarises the risks from DC and AC:

Table 9: DC and AC electric shock risk

DC Electrocution	AC Electrocution
Only very small currents required Muscular tetanus (contraction causing severe burns) Tends to stop the heart (easier to revive)	Voltage passes through zero 50 times per second Easier to release grip than DC Tends to cause heart defibrillation (difficult to revive)

A complete photovoltaic system will include switches, circuit breakers and fuses to ensure that the system is electrically safe and that major devices can be isolated when maintenance work need sot be carried out, or when a component fails. Electrical isolation is often required in the Australian Standards and is an important safety feature of any circuit.

Further reading

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Also see from the same source:

- http://www.deir.qld.gov.au/electricalsafety/law/codes/electricalwork/appendix2/otherhazard/index.htm (Accessed 13th September, 2008)

4.11 The parameters involved in power losses in transmission lines

The power loss through a conductor or resistor (like a transmission line) is given by:

$$P_{loss} = I^2 \times R.$$

where I = Current (amps), V = Voltage (volts), and P = Power (watts)

The dominant term here is the current, since it is squared. Doubling the current will result in a four fold increase of the power loss. The power loss is therefore largely determined by the current. The other important parameter is the resistance (R) as given below:

$$R = \frac{\rho L}{A}$$

where: ρ = resistivity of the transmission line (Ωm)
l = length of the transmission line (m)
A = cross-sectional area of the transmission wire (m^2)

The above formula shows that doubling the length of the wire will double the resistance. Similarly, doubling the cross-sectional area will halve the resistance.

Transformers in the electricity distribution system increase the voltage of the electricity being transmitted by decreasing the current (and thus the same power level is maintained since P=VI). The following equation represents this conservation of power and energy in the transformer process:

$$P = I_1 V_1 = I_2 V_2.$$

However, now V_2 will be higher than V_1, and I_2 will be proportionately lower than I_1. Increasing the voltage using transformers reduces the current and also the power loss as $P_{loss} = I^2R$. Without transformers, most of the power would be dissipated as heat in the power lines before reaching the homes that the power was intended for. It is easier to change the voltage of AC than DC which is why AC is used in the electrical distribution systems the world over.

Example
If 300W of DC power is to be delivered to a plasma TV that is 3km down the road, calculate the power that needs to be generated by a supplying PV system under the following conditions:

Wire cross section = $0.0002m^2$,
Resistivity of the copper wire = $1.7\times10^{-8}\Omega m$
The PV supply voltage for the 300W television is 12V

Solution: The current being carried is calculated using P=VI (since the PV system is a power source and the output power is the product of the output voltage and current), giving:

$$I = 300W/12V = 25A$$

The resistance of the transmission line is given by:

$$R = (1.7\times10^{-8}\Omega m*3000m)/0.0002m^2 = 0.255\Omega.$$

Now, the power loss over this length of line is:

$$P_{loss} = I^2R = 25^2*0.225 = \underline{159W}.$$

This means that the power that needs to be generated by the PV system 3km up the road is 300W + 159W = 459W. This is 53% more power than is finally reaching the load!

If we now consider a PV system with a voltage of 24V the solution changes:

R remains at 0.255Ω

$$I = 300\Omega/24V$$
$$I = 12.5A$$

Now $P_{loss} = I^2R = 12.5^2*0.225 = \underline{35.2W}$

So it can be clearly seen that increasing the voltage by 2 times (and therefore halving the current) can reduce the power lost in the cabling by over 75%. This is true for all cabling types and a higher voltage should be used where safe and technically possible. Battery systems sometimes do not allow high voltages to be used and a trade off between safety and performance is required in these designs.

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5 Glossary of Terms

Absorption Coefficient	Property of a material which defines the extent to which a material absorbs energy from sunlight
Accelerated lifetime testing	Placing photovoltaic modules in extreme weather conditions in a laboratory environment. This is designed to simulate the worst possible weather conditions possible when a solar panel is in the field. This is used to help determine module lifetimes
Alternating current (AC)	Electricity flowing in both directions at a specified (or determinable) frequency. For example in Australia our AC network is 50Hz or 50 cycles per second, which means that, 50 times each second the current flows one way and 50 times per second current flow in reverse
Amorphous silicon	The non-crystalline form of silicon. This form lacks the crystal structure of crystalline silicon, and is somewhat unstable (it degrades in sunlight for example).
Anisotropic etch	A chemical that etches (burns) away the surface of a semiconductor at different rates depending on the direction/plane. This way, by pouring the etching chemical on a material, some sides will burn off faster, leaving a particular shape (e.g. a pyramid)
Antireflection coating	Surface coating on the cells that prevents light reflecting off the surface of the cell. For maximum efficiency all light incident on the cell should be trapped inside it. Antireflective coatings minimise incident light reflection from the cell
Array	A number of photovoltaic modules linked together to form a system. The size of the array is determined by the load and amount of solar radiation at the site
Availability	Systems or applications that do not tolerate system downtime as a result of power failure are said to require high availability. It is critical for these systems to be powered all the time (e.g. medical freezers for human bodies or emergency telephones). It is the % of time (reliability) that the energy supply must function. 100% availability means the energy supply is needed continuously, without interruption.
Bandgap	The energy difference between the top of the valence band and the bottom of the conduction band
Batteries	Electrochemical devices that can store energy. There are many technologies available and have varying voltages, lifetime and charging requirements
Battery backup	A device which maintains a continuous supply of electric power to connected equipment by supplying power from a separate source when utility power is not available

Battery bank	A grouping of individual batteries such that they are electrically connected in series/parallel combinations to give the desired total output voltage and current. This group will have two outlet terminals with which to connect to a circuit, providing a single connection point to access all the batteries.
BIPV	Building Integrated Photovoltaic is the use of photovoltaic modules as a part of the building materials (such as wall, roof)
Black-outs	When generators that were supplying an electricity grid fail and cause loss of power to loads and buildings that require it
Boost charge	Partial charge of a storage battery, usually at a high current rate for a short period.
Breakdown voltage	Minimum reverse voltage to make the diode conduct in reverse
Bulk semiconductor material	Either the p-type or the n-type region of a solar cell - the thicker part. e.g. p-type semiconductor bulk material might be doped with an n-type dopant to form a thin n-type layer on one surface
Circuit elements	Elements such as resistors, inductors and capacitors which made up a circuit
Charge Controller	Device that manages the charge and discharge of batteries from a photovoltaic array. It ensures that batteries are not over charged or over discharged to make the batteries last longer
Chemical etch	The process of using chemicals such as acid and bases to dissolve away unwanted materials such as metals, grease
Circuit breakers	Automatically-operated electrical switch designed to protect an electrical circuit from damage caused by overload or short circuit
Climate change	The variation in the Earth's global climate or regional climates over time. It describes changes in the variability or average state of the atmosphere over time scales ranging from decades to millions of years. These changes can be caused by processes internal to the Earth, external forces (e.g. variations in sunlight intensity) or, more recently, human activities.
Compound	A material that combines multiple elements from the periodic table together in a single structure. Each element is chemically altered in this state, so the whole material exhibits different properties to a simple physical mixture of each element.
Conduction band	The energy level required by an electron (or hole) for it to be considered free to escape its atom's valence shell and thus, conduct current.
Conductor	Material which readily allows electric current to pass when a voltage is applied

Contacts	Metal (usually silver or aluminium) that is deposited on a solar cell to collect the generated carriers (electrons) from the cell and deliver them to a load circuit. There is a top contact (the grid you see on top of a cell) and a rear contact (usually covers the entire back of the cell). The two contacts are electrically separated by the silicon and connect to the circuit to allow current to flow.
Control Circuitry/ Controller	Electric circuit used to monitor and distribute the photovoltaic array output. This usually includes a MPPT, charge controller and regulator and sometimes other more complicated components such as an inverter
Conventional current	Flow of positive charge (externally from positive to negative terminal of a generating source). In metal wires, this is opposite in direction to actual physical current that is caused by electrons
Conversion efficiencies	The ratio between output to input, maybe presented as decimals or percentage
Corrosion	The degradation of a metal's structural strength and colour due to contact and chemical reaction with water. It is commonly associated with rusting of iron
Covalent Bond	A bond between atoms where each contribute one electron to the bond, so each atom can be considered as having both the electrons as part of its total collection. There are usually 2 electrons in each covalent bond for silicon.
Crystals	A solid in which the constituent atoms, molecules, or ions are packed in a regularly and strictly ordered repeating pattern extending in all three spatial dimensions. The material is quite rigid and the structure is usually highly stable
Crystallisation	The process by which a liquid substance forms a very neatly structured solid crystal when it is cooled sufficiently slowly. Only some substances form such crystals.
Crystallinity	The extent to which a material exhibits the properties of a crystal. If an entire silicon ingot is made of just one crystal, this is the highest level of crystallinity possible. If we observe scattered atoms that show no order that you would find in crystals, then we say the material has very low crystallinity.
Current	The amount of electric charge flowing through a surface over time (amount of charge per second)
Czochralski process	A process for producing single crystal silicon ingots using a seed crystal that is dipped in a crucible of molten silicon, and slowly rotated and raised out to produce a long, cylindrical single-crystal ingot.
Dielectric materials	A substance that is highly resistant to the flow of an electric current
Direct current (DC)	Electricity flowing in only one direction (generally around a circuit)

Depletion region	An insulating region within a conductive, doped semiconductor material where the charge carriers have been swept away through recombination. It is also the region at the very centre of a p-n junction where there is no net charge.
Diffusion	The natural tendency for an impurity or element to spread evenly through another material, driven by vibrations associated with kinetic energy due to temperatures (i.e. Brownian motion). At room temperature, we see food colourings diffusing in water (spreading itself out evenly) or smell perfumes diffusing throughout a room. At high temperature this process occurs much faster. It is a natural tendency for a material in high concentration to spread out in the medium it is in.
Diode	Electrical element (component) that allows electricity to flow in only one direction. A photovoltaic cell is a large area diode that can absorb the sun's energy
Direct Bandgap	In a direct bandgap semiconductor, electrons at the conduction-band minimum can combine directly with holes at the valence band maximum, while conserving momentum
Doping	The process of intentionally introducing impurities into an extremely pure semiconductor in order to change its electrical properties. It is done by introducing a dopant (e.g. other elements) into the semiconductor in order to alter the conduction properties. It allows conductivity to be controlled by creating an excess of positive or negative charge carriers
Efficiency	In regards to solar cells, it describes the amount of electrical energy produced as a fraction of the light energy received by the cell as a percentage. This is the key measure of cell performance
Electrical distribution system	System of delivery of electricity to the end user. The most common form of distribution is the 'electricity grid' – a network of transmission lines (wires) connecting generators to loads.
Electric field	A conceptual region where electrical charges experience a force due to other electrical charges nearby. The field is shown in lines, where closely-spaced lines indicate stronger forces experienced. The arrows on the lines indicate the direction a positive charge would flow if placed in that location in the field.
Electrochemical	Refers to chemical reactions where electricity is either consumed or released in the process. Chemical reactions are ones where chemical bonds are broken and reformed
Electrons	Fundamental subatomic particles that carry a negative electric charge
Encapsulation	The protection placed around the cells when modules are made. Encapsulation has been designed to last for over 20 years and therefore protect the cells for that period to ensure proper operation of the module

Energy/Energise	To supply or transfer enough energy to an object (e.g. an electron) to allow it to do work. If something has energy, it means it is capable of doing work or transferring that energy to another object which could use that energy to do work. Energy is measured in Joules (SI unit)
Energy level	This refers to the amount of energy that an electron may actually possess. There are ranges of energy levels that electrons in semiconductors may have, and we call these ranges, "bands"
Enhanced greenhouse effect	The enhancement of Earth's natural greenhouse gases due to man made emissions of greenhouse gases, mostly carbon dioxide
Equilibrium	In p-n junction formation, this is the natural state where backward & forward current flows are equal. We see no net movement of charge once equilibrium is reached
Fault currents	An abnormal flow of current in an electric circuit due to a fault (usually a short circuit or abnormally low impedance path).
Fossil fuel	Refers to hydrocarbon fuels, primarily coal, petroleum (fuel oil) and natural gas. It is formed from the remains of dead plants and animals over millions years under pressure under rock, and in an absence of oxygen (thus preserving them from microbes)
Frequency (electrical)	The number of wavelength cycles a photon or an oscillating AC signal passes through in one second. It is given in the SI units, Hertz (Hz). Most electricity grids operate on 50Hz (Global) or 60Hz (US and Japan).
Fuses	Electrical protection devices that break the electrical circuit if too much current is present. Fuses are particularly important for circuits with batteries, where very large currents can be drawn in the event of a fault or short circuit (over 200 amps depending on the battery type and size). This may damage sensitive electrical devices like microprocessors.
Germanium	A type of semiconductor material. Has a smaller bandgap than other semiconducting materials
Grain boundaries	Interfaces where crystals of different orientations meet.
Grid-connected system	A photovoltaic system that is connected to the electricity grid network via an inverter. Because PV outputs DC electricity and grids are AC, this type of system must have an inverter between the PV and the grid to convert and feed AC power into the grid
Greenhouse gases	Gaseous components of the atmosphere that contribute to greenhouse effect
Greenhouse effect	The radiative process by which an atmosphere warms a planet by trapping the sun's heat.
Electricity grid	Often just called, "the grid." This refers to the network of cables & high-power electrical devices used to deliver power from the generators to the loads (residential, industrial etc.)

Ground fault	A difference in the currents in the hot and neutral wire which may cause electric shock
Global Warming	The increase in the average temperature of the Earth's surface, atmosphere and oceans which is mainly linked to the increase of greenhouse gases (GHGs) in the atmosphere
Harmonics	A wave of signal can be transmitted with waves of multiple frequencies overlayed on the main one. These are the harmonics and their allowable frequencies are always an integer multiple of the fundamental frequency
Holes	A vacant position in a crystal lattice left by the absence of an electron, especially a position in a semiconductor (like a solar cell) that acts as a carrier of positive electric charge.
Hybrid system	Combination of two or more types of energy to supply a load (for example, solar and wind, or solar and diesel)
Indirect Bandgap	Semiconductors that have an indirect bandgap are inefficient at emitting light. Electrons require both a photon and a momentum change to move from the valence band to the conduction band
Ingot	Molten and subsequently solidified silicon cubes or cylinders, ready for cutting into wafers.
Insulator	Material that does not allow electric current to pass through easily
Integrated circuit	A miniaturized electronic circuit (consisting mainly of semiconductor devices, as well as passive components) that has been manufactured in the surface of a thin substrate of semiconductor material.
Interconnection	With regard to PV modules, this refers to the connection of the individual cells that make up the module. The bottom of one cell is connected by metal wires to the top of the next cell
Inverter	Electrical device that converts DC electricity into AC electricity
Ion	An atom that has lost or gained electrons to give unequal number of electrons and protons. This altered 'atom' now carries a net charge
Islanding	Any situation where the grid electricity is off-line and one or more inverters from a grid-connected PV system maintain a supply of electricity to that section of the grid or to a consumer's installation An island situation may cause an electrical shock hazard to service personnel operating on the island network section while they think it has been shut down.
IV curve	A graph of the current-voltage characteristics of a solar cell under illumination
Kerf losses	Silicon 'sawdust' that is generated and lost when you saw an ingot to cut individual wafers out of it.

kWh	A unit of energy. 1kW of power continuously consumed (or produced) for one hour draws (or generates) a total of 1kWh (kilowatt-hour) of energy. In SI units, 1 kilowatt-hour is equal to 2.6MJ (megajoules or "million joules") of energy
Light	Electromagnetic radiation from the sun. Most of the spectrum is ultraviolet, visible light and infra red. Photovoltaic cells can use most of this radiation and convert it to electricity
Loads	Any device or appliance that is using or consuming power
Maximum power point	A single operating point for a photovoltaic cell where the values of the current (I) and voltage (V) of the cell result in a maximum power output
Maximum power point tracker (MPPT)	Integrated into the charge controller/regulator and operates the solar panels at their maximum power point. This ensures that in all light conditions, the maximum allowable power is being extracted for a photovoltaic array
Metals	A shiny material that conducts heat and electricity very well. Flexible metals can be used as electricity conducting wires
Micron	Also known as a micrometer. It is a unit of length equal to one thousandth of a millimetre, or one millionth of a meter.
Mismatch	Mismatch losses are caused by the interconnection of solar cells or modules which do not have identical properties or which experience different conditions from one another.
Modified square wave	This waveform is a compromise between the sine wave and the square wave. The positive and negative pulses of the square wave are thinned, separated and made taller, so the peak voltage is much closer to that of a sine wave, and the overall shape of the wave more closely resembles that of a sine wave.
Module/Panel	A number of photovoltaic cells linked together into a convenient unit. 36 cells are commonly linked together because this provides the voltage required to charge a 12-volt battery and are usually a convenient size for installation
Motor	In this text, a motor refers to a device that converts electrical energy or stored energy in fuel, into rotational energy in a spinning shaft. The spinning shaft can be connected to other devices to cause them to turn as well.
Multicrystalline silicon	A type of crystalline silicon which typically has a simpler technique for production, and hence, is cheaper. The silicon is made up of many smaller crystals, all at different orientations
Multijunction cell	The use of multiple layers of silicon, doped with alternating p and n layers to create multiple p-n junctions. Each layer of silicon is optimized to absorb a different part of the solar spectrum, thereby increasing the overall collection efficiency of the PV device.

N-type Silicon	This is silicon that has been doped with a material with more electrons in its outer atomic structure than silicon. The most common example is silicon doped with phosphorous
Open-circuit	This is when a circuit is cut. Think of an electric cable that has been cut by scissors. This is an open circuit. Voltages in circuits are sometimes measured across an open circuit (use multimeter leads to reconnect cut cable)
Open circuit voltage	The maximum voltage available from a solar cell, and this occurs at zero current
Oxidise	For a material to combine chemically with oxygen (often the oxygen already present in air), to produce a new substance with different properties
Packing density	The area of the module that is covered with solar cells compared to that which is blank. The packing density affects the output power of the module as well as its operating temperature. The packing density depends on the shape of the solar cells used.
Parallel	The voltages across components in parallel with each other are the same in magnitude and they also have identical polarities.
Partial shading	A condition where light to part of solar module or cell is blocked by external features such as tree or building
Passivation	The process of incorporating materials in the solar cell to make open bonds chemically inactive. That is, they will not interact with impurities that may be present in the semiconductor material and this therefore prevents electrical performance degradation
Periodic Table	A table of all known elements in the universe that exist as atoms. Each listing shows the weight of one mole (6.02×10^{23} atoms) of the element, the number of protons (and neutrons), and the element's chemical symbol.
P-N junction	Interface between p-type and n-type silicon. Due to the charge differences between the doped materials, an electric field is set up. Also know as a diode and forms the basis of a solar cell and allows electrons to be collected from within the cell to flow as current
P-type silicon	This is silicon that has been doped with a material with fewer electrons in its outer atomic structure than silicon. The most common example is silicon doped with boron or aluminium
Photoelectric effect	The emission of electrons from most surfaces that occurs when light (photons) hits them
Photons	A state of light in which light is viewed as consisting of packets or particles of energy
Photovoltaic effect	A process or effect that generates voltage in a solar cell
Photovoltaics	Field research related to solar cell. A general term used to mean the conversion of sunlight directly into DC electricity using semiconductor devices

Photovoltaic cell	Semiconductor device that converts solar energy (mostly ultraviolet, visible light and infra red radiation) directly into DC electricity
Photovoltaic system	The array combined with the control circuitry
Power	Amount of energy per unit of time. The unit for power is watt
Power draw	The power drawn by a particular circuit element in a circuit
Power supply	Device or system that supplies electrical or other types of energy to an output load or group of loads. The term is most commonly applied to electrical energy supplies
Pulse width modulation	The modulation of signal's or power source's duty cycle, to either convey information over a communications channel or control the amount of power sent to a load
Recombination	The process by which electrons already in the conduction band fall back to a lower energy position in the valence band
Regulator	Similar to a charge controller but usually has additional capabilities to control systems components other than batteries (e.g. a diesel generator or PV array).
Reverse Leakage Current	Current flowing from that semiconductor device when the device is reverse biased (connecting the p-type silicon to negative terminal, and n-type silicon to the positive terminal)
Platinum	A metal which is resistant to corrosion and is widely used for electrical contacts
Radiation	Energy in the form of waves or moving subatomic particles.
Rated power or power rating	The amount of power a resistive circuit element or electrical device can withstand flowing through it. It is also the power that a device may generate if it's a power source. Manufacturers provide power ratings for devices they produce, and they are likely to fail if this rating is exceeded.
Remote area power supply	A system that provides electricity in remote locations, without requiring connection to an electricity distribution system.
Reverse saturation current	Small leakage current that flows when a diode (or p-n junction) is operated in reverse bias or reverse polarity
Ribbon silicon	A type of crystalline silicon which is fabricated by a variety of solidification (crystallization) methods that withdraw thin silicon sheets from pools of relatively pure molten silicon.
Screen-printing	A method of forming metal grid lines on the top surface of a solar cell. This method uses a paste containing the metal and squeezes it through a stencil outline that only allows the metal to be laid in the required pattern on the cell.

Selenium	An element in the periodic table which has photovoltaic and photoconductive properties
Semiconductor	A material that has properties somewhere between insulators and conductors. They can provide insulation at low energy levels (very low temperature and no sunlight) and conduct at higher energy levels (ambient temperatures and sunlight present). Doping of these materials changes their conductive properties and makes photovoltaics possible
Series	The current that enters a series circuit has to flow through every element in the circuit. Therefore, all elements in a series connection have equal currents.
Series resistance	Resistance which is caused by the movement of current through the emitter and base of the solar cell; the contact resistance between the metal contact and the silicon; and finally the resistance of the top and rear metal contacts.
Short circuit	An accidental low-resistance connection between two terminals of a power source that are meant to be at different voltages. A short-circuit is where a power source is connected (at its outlet terminals) by wires without any resistors connected in-between to consume the power. What happens is that very high currents (lots of electrons) flow from the power source directly back into itself. These high currents cause overheating in the power source itself (e.g. in a PV module, the high currents can cause melting of interconnects, or even explosions in a battery because of the chemicals inside). Short circuits also cause fires because sparks, and arcs form and burn combustibles
Short circuit current	The current through the solar cell when the voltage across the solar cell is zero (i.e., when the solar cell is short circuited)
Short wavelength light	Light with higher frequency in the electromagnetic spectrum. Wavelength is the inverse of frequency. The wavelength is the distance of the full-length of the wave in question.
Shunt	A device which allows electrical current to pass around another point in the circuit.
Shunt resistance	Resistance which causes power loss, and typically caused by manufacturing defects. Shunts provide a conduction path that bypasses the p-n junction in a solar cell.
Silicon	A semiconductor material. Most commonly used in the photovoltaic industry due to its abundance
Single crystal silicon	A type of crystalline silicon which typically has better material parameters but is also more expensive

SI Units	The internationally accepted system of units that are assigned to the various types of quantities encountered in the universe. The common formulas hold true to themselves and between one another when the units of the quantities are specified in SI Units. Note that some individuals & some nations do not comply with the SI system of units
Solar field/park	An area of land (field or park) which is specifically designed for the generation of solar power, which is usually connected directly to the grid
Solar spectrum	The full range of wavelengths of electromagnetic radiation supplied by the sun. This includes visible light, as well as infrared and ultraviolet wavelengths that are invisible to human eyes.
Solar thermal	General term used to describe the use of the sun's energy as heat. Generally, no electricity is produced using solar thermal energy (but there are some systems that do). An example of this is a solar hot water system on the roof tops of many houses.
Square wave inverter	A type of electrical inverter that produces a square wave output; it consists of a DC source, four switches, and the load
Stand alone system	These are systems that are self-sufficient. They consist of a photovoltaic array, control circuits and batteries so that power can be supplied at any time (even at night – from the batteries). There is no connection to the grid. An example might be a calculator or a house that has not got a connection to the electrical grid
State of charge	State of charge (SOC) is used to indicate the amount of charge left in a battery
Substrate	The material forming the base of the cell beneath the junction or superstrate (the material on the top of the junction). In most wafer cells, the substrate is quite thick and provides physical support
Superstrate	Solar cell configuration where the glass substrate is not only used as supporting structure but also as window for the illumination and as part of the encapsulation
Supersubstrate	Commonly used in thin-film cells, where the thick glass layer acts as the substrate, but it actually covers the front surface of the cell where the sunlight should come in. So, when manufacturing, we lay down the glass first, then the front layer, and then the rest of the cell. Then we flip it over when ready to use.
Sustainable	The ability to continue a defined behaviour indefinitely
Switches	A device for changing the course (or flow) of a circuit
String	Occurs when two or more modules or cells are connected in series
Tedlar	The fairly rigid back material on a PV module, used to provide structural support for the cells.

Texturing	Formation of pyramids in the surface of silicon to decrease the reflectivity of a surface
Thermalisation	The situation where an electron has been given more energy by a photon than required to jump the energy bandgap, and subsequently the electron loses this surplus energy by 'bumping' into other nearby atoms (converting the kinetic energy to heat)
Thin film	Thin films are material layers of about 1 µm thickness or less
Transformer	A device that transfers electrical energy from one circuit to another by magnetic coupling without requiring relative motion between its parts. It usually comprises two or more coupled windings, and, in most cases, a core to concentrate magnetic flux.
Transistor	A type of semiconductor device, commonly used as an amplifier. It is used widely in a variety of digital and analog functions, including amplification, switching, voltage regulation, signal modulation, and oscillators.
Transparency	We describe a material as being transparent if it lets through most of the light that falls on it (e.g. window glass is transparent to short wavelength radiation but not long wavelength radiation). This means the wavelengths of light that pass through can be absorbed by materials/things behind the transparent one.
Transparent conducting oxide	A transparent top surface electrode or contact. It is a material that lets sunlight through but also conducts electricity so the electrons can escape the cell from the top surface. Usually, tin oxide (or SnO_2) is used as a TCO
True sine wave	This is the shape of an ideal AC waveform (sinusoidal). It's the most desirable output of an inverter, producing no damage to appliances that utilise the AC electricity
Unencapsulated	Solar cells that have not been integrated into a module that would protect them from natural elements such as water, oxygen, dust
Uninterruptible power supply	A device which maintains a continuous supply of electric power to connected equipment by supplying power from a separate source when utility power is not available.
Vacuum processes	Manufacturing processes that are done in a chamber with the air evacuated (removed).
Valence band	Describes electrons in the outer orbit of their atoms and are tied to the atom and not free to move or conduct current. They possess less energy than is required to free themselves and conduct current.
Voltage	The difference in electrical potential between two points of an electrical or electronic circuit, expressed in volts. It measures the potential energy of an electric field to cause an electric current in an electrical conductor

Wafer	A thin slice sawn out of a solid silicon ingot that is turned on its flat side and used to manufacture a solar cell. These wafers are typically between 200-300μm thick.

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6 General References

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