2.3. The response of a PV panel to illumination.

2.3.1. How PV panels work. [Lo1]. [Lo2]

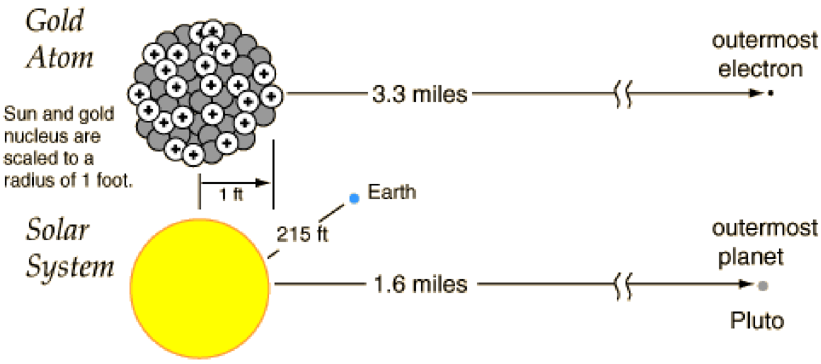
The photoelectric effect, discovered by Edmond Becquerel in 1839, is the mechanism used in PV panels. Direct current electricity (DC) is generated. Some advantages are: zero fuel costs and the free availability of solar fuel, there are no moving parts so there is no noise, reduction in maintenance, the modular design which can also be integrated into buildings and that there are zero emissions. Some disadvantages are: decreasing but high capital costs, at present 20% – 35% efficiency, the use of toxic materials in some manufacturing processes, the need for a power electronic inverter from DC to AC (alternating current) for grid-connected applications, intermittent and variable power and that cloud cover is difficult to predict.

There are three main types of PV panels currently available:

monocrystalline *polycrystalline* *thin film*

PV cells under an electric field produce electricity when light particles called photons illuminate a pn junction, to be described. pn junctions are common in semiconductors.

Elements consist of atoms, with a central nucleus containing uncharged neutrons and positively charged protons. Negatively charged electrons lie outside, and in an electrically neutral atom are equal in number to its protons. Here is a relative scale model.



On this scale, the nearest star would be a little over 16,000 Km away. [HP]

Numbers come in two forms: discrete, whole or natural numbers, such as 1, 2, 3 … and continuous numbers called real numbers, which can include these or lie in any intermediate state between them. Natural numbers may be constrained to loop back to themselves, so they form a finite set of states, such as 0, 1, … (n – 1) with n = 0.

For quantum theory some finite numbers, where these can be called *quantum numbers*, define physical states. For instance these can be finite values representing the angular momentum of a particle. We also have continuous numbers describing physical states, so that whereas the velocity of a photon of light is ±c, particles with rest mass can have any velocities between but not including ±c.

Conventionally, each electron in an atom is described by an *orbital energy state* with four different quantum numbers. The first three (n, l, m_l) specify the particular orbital of interest, and the fourth (m_s) specifies how many electrons can occupy that orbital.

1. **Principal quantum number (n): $n = 1, 2, 3, \ldots, \infty$**

   Specifies the *energy* of an electron and the *size* of the orbital (the distance from the nucleus of the peak in a radial probability distribution). All orbitals that have the same value of n are said to be in the same *shell* (*level*). For a hydrogen atom with $n = 1$, the electron is in its *ground state*; if the electron is in the $n = 2$ orbital, it is in an *excited state*. The total number of orbitals for a given n value is n^2.

2. **Angular momentum (secondary, azimuthal) quantum number (l): $l = 0, \ldots, n-1$.**

   Specifies the *shape* of an orbital with a particular principal quantum number. The secondary quantum number divides the shells into smaller groups of orbitals called *subshells* (*sublevels*). Usually, a letter code is used to identify l to avoid confusion with n:

l	0	1	2	3	4	5	…
Letter	*s*	*p*	*d*	*f*	*g*	*h*	…

   The subshell with $n = 2$ and $l = 1$ is the 2*p* subshell; if $n = 3$ and $l = 0$, it is the 3*s* subshell, and so on. The value of l also has a slight effect on the energy of the subshell; the energy of the subshell increases with l ($s < p < d < f$).

3. **Magnetic quantum number (m_l): $m_l = -l, \ldots, 0, \ldots, +l$.**

   Specifies the *orientation in space* of an orbital of a given energy (n) and shape (l). This number divides the subshell into individual orbitals which hold the electrons; there are $2l+1$ orbitals in each subshell. Thus the *s* subshell has only one orbital, the *p* subshell has three orbitals, and so on.

4. **Spin quantum number (m_s): $m_s = +½$ or $-½$.**

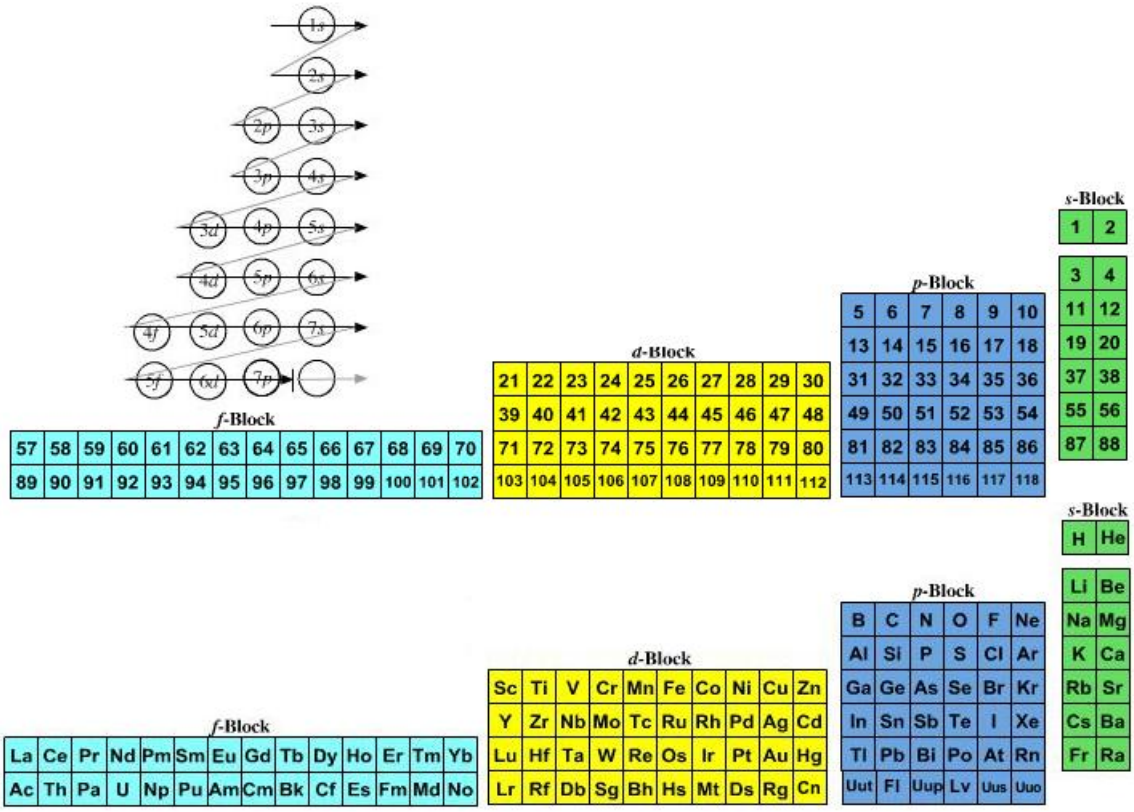
   Specifies the *orientation of the spin axis* of an electron. An electron can spin in only one of two directions (sometimes called *up* and *down*).

The **Pauli exclusion principle** states that *no two electrons in the same atom can have identical values for all four of their quantum numbers*. What this means is that no more than *two* electrons can occupy the same orbital, and that two electrons in the same orbital must have *opposite spins*.

TABLE OF ALLOWED QUANTUM NUMBERS

n	*l*	m_l	Number of orbitals	Orbital name	Number of electrons
1	0	0	1	1*s*	2
2	0	0	1	2*s*	2
	1	-1, 0, +1	3	2*p*	6
3	0	0	1	3*s*	2
	1	-1, 0, +1	3	3*p*	6
	2	-2, -1, 0, +1, +2	5	3*d*	10
4	0	0	1	4*s*	2
	1	-1, 0, +1	3	4*p*	6
	2	-2, -1, 0, +1, +2	5	4*d*	10
	3	-3, -2, -1, 0, +1, +2, +3	7	4*f*	14

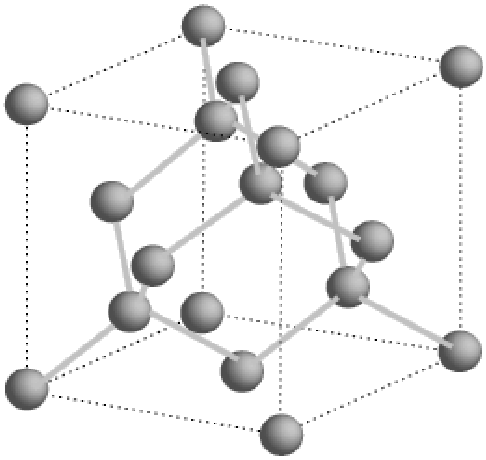
This scheme, or otherwise 2 × a prime number of electrons, generates elements in the **left-step periodic table** shown below. This table is in the same order as the atomic number, which is the number of protons in the nucleus, of these elements.



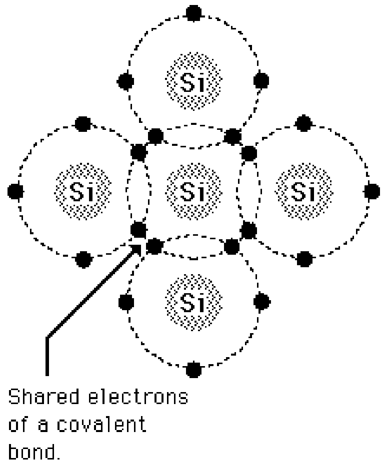
The element silicon, denoted by Si, with atomic number 14 in the above table, is often used in semiconductors. After oxygen, silicon is the most abundant element in the Earth's crust.

Si has 2 electrons in orbital 1s, 2 electrons in orbital 2s and 6 electrons in orbital 2p, leaving 4 outer electrons called *valence electrons*.

Atoms can combine together to form molecules and crystalline structures.

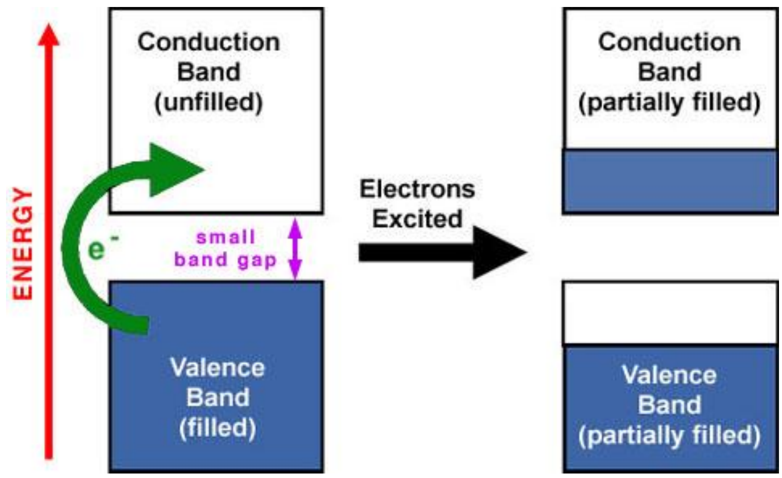


A silicon crystal, a unit cube of which is shown above, forms a diamond lattice. Each Si atom has four electrons which it can share in *covalent bonds* with its neighbours. All valence electrons are tightly held in covalent bonds. A covalent bond, also called a molecular bond, is a chemical bond that involves the sharing of electron pairs between atoms. These electron pairs are known as *shared pairs* or *bonding pairs*, and the stable balance of attractive and repulsive forces between atoms, when they share electrons, is known as covalent bonding. For many molecules, the sharing of electrons allows each atom to attain the equivalent of a full outer shell, corresponding to a stable electronic configuration in a lower energy state than it otherwise would be.



Valence electrons largely dictate the electrical properties of a material.

A useful way to see the difference between conductors, insulators and semiconductors is to plot the available energies for electrons in the materials. Instead of having discrete energies as in the case of free atoms, the available energy states form bands. Crucial to the conduction process is whether or not there are electrons in the conduction band. In insulators the electrons in the valence band are separated by a large gap from the conduction band, in conductors like metals the valence band overlaps the conduction band, and in semiconductors like silicon there is a small enough gap between the valence and conduction bands so that thermal or other excitations can bridge the gap.



Add enough energy to an electron in the valence band of a semiconductor and it “jumps” to the conduction band. A free electron is an electron in the conduction band. In a PV panel a photon excites an electron out of the valence band into the conduction band. Free electrons can flow through the circuit, or in a process known as recombination drop back into the valence band. A built-in electrostatic field pushes the electron through the circuit.

An *electron-volt*, a unit of energy denoted by eV, is experimentally 1.6 x 10^{-19} Joules. It is the amount of energy gained (or lost) by the charge of a single electron moving across an electric potential difference of one volt.

By quantum theory, the energy of an electron must fall within well-defined bands. The energy required to jump to the conduction band is known as the *energy gap*. The energy gap is fundamental to the operation of PV panels, varying with the type of semiconductor

Crystalline Si: 1.1 eV
Amorphous Si: about 1.75 eV.

Hole: silicon with a missing electron (net positive charge)
Hole may attract an electron from a neighbour
Process may repeat and hence the hole propagates

doping

IV curves

2.3.2. PV response to temperature.

IV curves by temperature

2.3.3. Types of PV panel and their frequency response.

frequency response by doping

multilayered PV panels

degradation of performance by UV light