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Mémoire

En vue de l'obtention du diplôme de Master

Présenté par : Abdoussalam Ben Arous Chemma

Domaine : *TECHNOLOGIE*

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Option *: INSTRUMENTATION*

Etude et Simulation des Caractéristiques I - V & P - V du Silicium Mono/Poly Cristallin Sous l'influence de Paramètres Externes

Devant le jury:

Birane Mouhoub	MCA	Encadreur
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Faculty: Technology

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MASTER MEMORY

OPTION : Instrumentation

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Study and Simulation of I - V Characteristics & P - V of Single/Poly Crystalline Silicon Under the influence of External Parameters

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الحمد لله رب العالمين

Thank you for your amazing power and work in our lives, thank you for your goodness and for your blessings over us. Thank you that you are Able to bring hope through even the toughest of times, strengthening us for your purposes. Thank you for your great love and care. Thank you for your mercy and grace. Thank you that you are always with us and will never leave us. Forgive us for when we don't thank you enough, for who you are, for all that you do, for all that you've given. Help us to set our eyes and our hearts on you afresh. Renew our spirits, fill us with your peace and joy. We love you and we need you, this day and every day. We give you praise and thanks, for You alone are worthy

Allah thank you for loving me and always seeing me I’m so grateful You call me the crown of creation, and beloved. I will echo Leah and declare that, “I will praise the LORD.” You are worthy of all praise, blessing, honor and glory Thank You for being everything to me and for me. You are faithful! You are concerned with everything that concerns me. I am grateful for Your Holy Spirit that comforts me during times of fear and doubt. Thank You for everything that you’ve done for me seen and unseen. I will praise your name forever

God, Sometimes life gets me down and I find it hard to see things to be thankful for. Open my eyes to see the gifts you’ve given me in my life. I’m going to start by thanking you for loving me enough to come to earth and die so we can live together forever Amen

After prayer and peace be upon our
Beloved Messenger of God
I dedicate this work to my family and my friends

A special feeling of gratitude to my loving parents

My Brilliant Mom and to My Wonderful Father whose words of

Encouragement and push for tenacity Ring in my ears

To My brothers Rabeh Bachir Ahmed Aymen Zakareia

To my beloved sisters those are better than me

And they have never left my side and are very special to me

To my uncles and to my aunts To All my family

To my supervisors Mohoube Birane and Aissa Belakhder

To My Special friend Hassane

To those who Love us To those who Loved us

To My old friends that we had parted away

To The Soutenance Jury

Abdoussalam BenArous

Abbreviation

α	The absorption coefficient cm^{-1}
c	Vitesse de la lumière dans le vide ($m.s^{-1}$)
D	The distance from the sun in meters
E_{ph}	Energy of a photon (eV)
E	Energy
E_V	The Energy on valence band (eV)
E_C	The energy on conduction band (eV)
E_G	The band gap (eV)
F	The spectral irradiance as a function of photon wavelength (or energy)
h	Constant of Planck (J.s)
H_0	Solar irradiance W/m^2
H_{sun}	Power density at the sun's surface (in W/m^2)
I_D	The intensity of the direct component
p	Positive Junction
n	Negative Junction
K	Extinction coefficient
K	Kelvin (K)
N_0	Photon flux at the surface (photons/unit-area/sec.)
R_s	Serial Resistance (Ω)
R_P	Resistance in Parallel (Ω)

R_{sun}	the Radius of the Sun in Meters
T	Absolute temperature (K)
ν	Frequency (s^{-1})
V	Volt (V)
x	Distance into the material (m)
W	Watt
λ	wavelength (μm)
AM	The Air Mass
CZ	Czochralski
DC	Direct Current
FZ	Float zone
Ge	Germanium
V/G	The Ratio of Rate to the Axial Thermal Gradient at the Melt interface
PV	Photovoltaic
Si	Silicon
AM0	The standard spectrum outside the Earth's atmosphere
BOS	Balance of the system
CGS	Centimeter, gram, second
COP	Crystal-originated particle or pit
CVD	Chemical vapor deposition
FBR	Fluidized bed reactors
IBM	International Business Machines
LED	Light emitting diode

MDZ	Magic denuded zone
MPP	Maximum Power Point
N_{SS}	The number of photovoltaic modules in series
N_{PP}	The number of photovoltaic modules in parallel
ppb	Parts per billion
RTA	Rapid thermal annealing
SRH	Shockley-Read-Hall
TCS	Trichlorosilane
TEM	Transmission Electron Microscopy
UMG	B upgraded metallurgical grade
BIPV	Building integrated PV
BJTs	Bipolar junction transistors
CIGS	Copper Indium Gallium Dieseline
C-Si	Single Crystal Silicon
CdTe	Cadmium Telluride
GaInP	Gallium Indium Phosphide
GaAs	Gallium arsenide
InAS	Indium Arsenide
Mc-Si	Polylt Crystal Silicon
SiO2	Silicon Dioxide
AM1.5G	The standard spectrum at the Earth's surface
SMARTS	Simple Model of the Atmospheric Radioactive Transfer of Sunshine

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General Introduction

General Introduction

Solar electricity, also known as photovoltaic (PV), has shown since the 1970s that the human race can get a substantial portion of its electrical power without burning fossil fuels (coal, oil or natural gas) or creating nuclear fission reactions. Photovoltaic helps us avoid most of the threats associated with our present techniques of electricity production and also has many other benefits. Photovoltaic has shown that it can generate electricity for the human race for a wide range of applications, scales, climates, and geographic locations.

Photovoltaic is an empowering technology that allows us to do totally new things, as well as, do old things better. It allows us to look at whole new modes of supplying electricity to different markets around the world and out of the world (in outer space). It also allows us to do what we already do (generate electricity, which is distributed over the transmission grid) but to do it in a sustainable, pollution-free, equitable fashion. Why is photovoltaic equitable? because nearly everyone has access to sunlight[1].

Semiconductors solar cells are the main technology on Photovoltaic are fundamentally on quite simple devices. Semiconductors have the capacity to absorb light and to deliver a portion of the energy of the absorbed photons to carriers of electrical current – electrons and holes. A semiconductor diode separates and collects the carriers and conducts the generated electrical current preferentially in a specific direction. Thus, a solar cell is simply a semiconductor diode that has been carefully designed and constructed to efficiently absorb and convert light energy from the sun into electrical energy.

In this Memory we are interested in the study and Simulation of I - V Characteristics & P - V of Single/Poly Crystalline Silicon Under the influence of External Parameters It’s divided into three chapters. Where in the First chapter we present general information on photovoltaic technology starting with notions on radiation;

Secondly we show the principle of the photovoltaic. On the second chapter we will do a comparison between mono and poly silicon in PV.

In the third chapter and last chapter, we present a complete simulation of the external factors of photovoltaic cell like temperature and irradiation. Finally we end our memory with general conclusion.

Chapter I : Photovolatics Generalities

I.1.Introduction

Photovoltaic is the technology that generates direct current (DC) electrical power measured in Watts (W) or kilowatts (kW) from semiconductors when they are illuminated by photons. As long as light is shining on the solar cell (the name for the individual PV element), it generates electrical power. When the light stops, the electricity stops. Solar cells never need recharging like a battery. Some have been in continuous outdoor operation on Earth or in space for over 30 years [1].

I.2.What Is Photovoltaic

Table 1.1 lists some of the advantages and disadvantages of photovoltaic. Note, that they include both technical and nontechnical issues. Often, the advantages and disadvantages of photovoltaic are almost completely opposite of conventional fossil-fuel power plants. For example, fossil-fuel plants have disadvantages of: a wide range of environmentally hazardous emissions, parts which wear out, steadily increasing fuel costs, they are not modular (deployable in small increments), and they suffer low public opinion (no one wants a coal burning power plant in their neighborhood). Photovoltaic suffers none of these problems. The two common traits are that both PV and fossil fueled power plants are very reliable but lack the advantage of storage [1].

Notice that several of the disadvantages are nontechnical but relate to economics and infrastructure. They are partially compensated for by a very high public acceptance and awareness of the environmental benefits. During the late 1990s, the average growth rate of PV production was over 33% per annum.

What is the physical basis of PV operation? Solar cells are made of materials called semiconductors, which have weakly bonded electrons occupying a band of energy

Table I.1 Advantages and disadvantages of photovoltaic [1]

Advantages of photovoltaic	Disadvantages of photovoltaic
Fuel source is vast and essentially infinite No emissions, no combustion or radioactive fuel for disposal (does not contribute perceptibly to global climate change or pollution) Low operating costs (no fuel) No moving parts (no wear) Ambient temperature operation (no high temperature corrosion or safety issues High reliability in modules (>20 years) Modular (small or large increments) Quick installation Can be integrated into new or existing building structures Can be installed at nearly any point-of-use Daily output peak may match local demand High public acceptance Excellent safety record	Fuel source is diffuse (sunlight is a relatively low-density energy) High installation costs Poorer reliability of auxiliary (balance of system) elements including storage Lack of widespread commercially available system integration and installation so far Lack of economical efficient energy storage

called the valence band. When energy exceeding a certain threshold, called the band gap energy, is applied to a valence electron, the bonds are broken and the electron is somewhat “free” to move around in a new energy band called the conduction band where it can “conduct” electricity through the material. Thus, the free electrons in the conduction band are separated from the valence band by the band gap (measured in units of electron volts or eV). This energy needed to free the electron can be supplied by photons, which are particles of light. Figure I.1 shows the idealized relation between energy (vertical axis) and the spatial boundaries (horizontal axis). When the solar cell is exposed to sunlight, photons hit valence electrons, breaking the bonds and pumping them to the conduction The electrons lose their energy by doing work in the external circuit such as pumping water, spinning a fan, powering a sewing machine motor, a light bulb, or a computer. They are restored to the solar cell by the return loop of the circuit via a second selective contact, which returns them to the valence band with the same energy that they started with. The movement of these electrons in the external circuit and contacts is called the electric current.

The potential at which the electrons are delivered to the external world is slightly less than the threshold energy that excited the electrons; that is, the band gap. Thus, in a material with a 1 eV band gap, electrons excited by a 2 eV photon or by a 3 eV photon will both still have a potential of slightly less than 1 V (i.e. the electrons are delivered with an energy of 1 eV). The electric power produced is the product of the current times the voltage; that is, power is the number of free electrons times their potential. There, a specially made selective contact that collects conduction-band electrons drives such electrons to the external circuit.

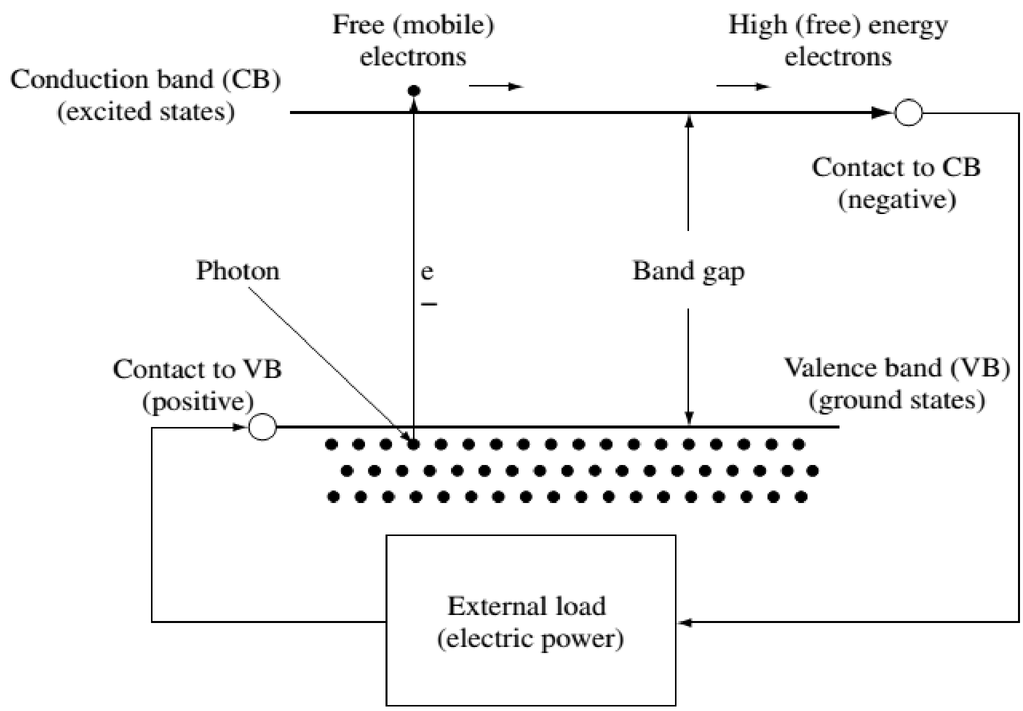


Figure I.1: Schematic of a solar cell [1]

Electrons are pumped by photons from the valence band to the conduction band. There they are extracted by a contact selective to the conduction band (an *n*-doped semiconductor) at a higher (free) energy and delivered to the outside world via wires, where they do some useful work, then are returned to the valence band at a lower (free) energy by a contact selective to the valence band (a *p*-type semiconductor).

Sunlight is a spectrum of photons distributed over a range of energy. Photons whose energy is greater than the band gap energy (the threshold energy) can excite electrons from the valence to conduction band where they can exit the device and generate electrical power. Photons with energy less than the energy gap fail to excite free electrons. Instead, that energy travels through the solar cell and is absorbed at the rear as heat. Solar cells in direct sunlight can be somewhat (20–30 C°) warmer than the ambient air temperature. Thus, PV cells can produce electricity without operating at high temperature and without mobile parts. These are the salient characteristics of photovoltaic that explain safe, simple, and reliable operation.

At the heart of any solar cell is the *pn* junction. Modeling and understanding is very much simplified by using the *pn* junction concept. This *pn* junction results from the “doping” that produces conduction-band or valence-band selective contacts with one becoming the *n*-side (lots of negative charge), the other the *p*-side (lots of positive charge).

Silicon (Si), one of the most abundant materials in the Earth’s crust, is the semiconductor used in crystalline form (c-Si) for 90% of the PV applications today .Surprisingly, other semiconductors are better suited to absorb the solar energy spectrum. These other materials are in development or initial commercialization today. Some are called thin-film semiconductors, of which amorphous silicon (a-Si) , copper indium gallium diselenide (Cu(InGa)Se2 or CIGS) and cadmium telluride (CdTe) receive most of the attention. Solar cells may operate under concentrated sunlight using lenses or mirrors as concentrators allowing a small solar cell area to be illuminated with the light from larger area. This saves the expensive semiconductor but adds complexity to the system, since it requires tracking mechanisms to keep the light focused on the solar cells when the sun moves in the sky. Silicon and III-V semiconductors , made from compounds such as gallium arsenide (GaAs) and gallium indium phosphide (GaInP) are the materials used in concentrator technology that is still in its demonstration stage. [1]

For practical applications, a large number of solar cells are interconnected and encapsulated into units called PV modules, which is the product usually sold to the customer. They produce DC current that is typically transformed into the more useful AC current by an electronic device called an inverter. The inverter, the rechargeable batteries (when storage is needed), the mechanical structure to mount and aim (when aiming is necessary) the modules, and any other elements necessary to build a PV system are called the balance of the system (BOS).

I.3.History of Photovoltaic

The history of photovoltaic goes back to the nineteenth century, as shown in Table 1.2. The first functional, intentionally made PV device was by Fritts [2] in 1883. He melted Se into a thin sheet on a metal substrate selinium and pressed a Au-leaf film as the top contact. It was nearly 30 cm^2 in area. He noted, “the current, if not wanted immediately, can be either stored where produced, in storage batteries, . . . or transmitted a distance and there used.” This man foresaw today’s PV technology and applications over a hundred years ago.

The modern era of photovoltaic started in 1954 when researchers at Bell Labs in the USA accidentally discovered that *pn* junction diodes generated a voltage when the room lights were on. Within a year, they had produced a 6% efficient Si *pn* junction solar cell [3]. In the same year, the group at Wright Patterson Air Force Base in the US published results of a thin-film heterojunction solar cell based on Cu2S/CdS also having 6% efficiency [4].

A year later, a 6% GaAs *pn* junction solar cell was reported by RCA Lab in the US [5]. By 1960, several key papers by Prince [6], Loferski [7], Rappaport and Wysoski [8], Shockley (a Nobel laureate) and Queisser [9], developed the fundamentals of *pn* junction solar cell operation including the theoretical relation between band gap, incident spectrum, temperature, thermodynamics, and efficiency. Thin films of CdTe were also producing cells with 6% efficiency [10]. By this time, the US space program was utilizing Si PV cells for powering satellites. Since space was still the primary application for photovoltaic, studies of radiation effects and more radiation-tolerant devices were made using Li-doped Si [11]. In 1970, a group at the Ioffe Institute led by Alferov (a Nobel laureate), in the USSR, developed a heteroface GaAlAs/GaAs [12] solar cell which solved one of the main problems that affected GaAs devices and pointed the way to new device structures. GaAs cells were of interest due to their high efficiency and their resistance to the ionizing radiation in outer space.

The year 1973 was pivotal for photovoltaic, in both technical and nontechnical areas. A significant improvement in performance occurring in 1973 was the “violet cell” having an improved short wavelength response leading to a 30% relative increase in efficiency over state-of-the-art Si cells [13]. GaAs heterostructure cells were also developed at IBM in the USA having 13% efficiency [14]. Also in 1973, a crucial nontechnical event occurred called the Cherry Hill Conference, named after the town in New Jersey, USA, where a group of PV researchers and heads of US government scientific organizations met to evaluate the scientific merit and potential of photovoltaic. The outcome was the decision that photovoltaic was worthy of government support, resulting in the formation of the US Energy Research and Development Agency, the world’s first government group whose mission included fostering research on renewable energy, which ultimately became the US Dept. of Energy. Finally, in October 1973, the first World Oil Embargo was instituted by the Persian Gulf oil producers. This sent shock waves through the industrialized world, and most governments began programs to encourage renewable energy especially solar energy. Some would say this ushered in the modern age of photovoltaic and gave a new sense of urgency to research and application of photovoltaic in terrestrial applications.

Table I.2 Notable events in the history of photovoltaic [1]

- 1883 Fritts (US) makes first large area solar cell using Se film
- 1954 First 6% efficient solar cells reported: Si (Bell Lab, USA) and Cu_2S/CdS (Air Force, USA)
- 1955 Hoffman Electronics (USA) offers 2% efficient Si PV cells at $1500/W
- 1974 Project Sunshine initiated in Japan to foster growth of PV industry and applications Tyco (USA) grows 2.5 cm wide Si ribbon for photovoltaics, first alternative to Si wafers
- 1987 Fourteen solar powered cars complete the 3200 km World Solar Challenge race (Australia) with the winner averaging 70 kph
- 1994 GaInP/GaAs 2-terminal concentrator multijunction >30% (NREL, USA)
- 1995 “1000 roofs” German demonstration project to install photovoltaics on houses, which triggered the present favorable PV legislation in Germany, Japan and other countries
- 1996 Photoelectrochemical “dye-sensitized” solid/liquid cell achieves 11% (EPFL, Switzerland)
- 1997 Worldwide PV production reaches 100 MW per year
- 1998 $Cu(InGa)Se_2$ thin-film solar cell reaches 19% efficiency (NREL, US) comparable with multicrystalline Si. First concentrating array for space launched on Deep Space 1 by US (5 kW using high efficiency GaInP/GaAs/Ge triple junction cells)
- 1999 Cumulative worldwide installed photovoltaic reaches 1000 MW
- 2000 Olympics in Australia highlight wide range of PV applications, and the awarding of the first Bachelor of Engineering degrees in Photovoltaic and Solar Engineering (UNSW, Australia)
- 2002 Cumulative worldwide installed photovoltaic reaches 2000 MW. It took 25 years to reach the first 1000 MW and only 3 years to double it; production of crystalline Si cells exceeds 100 MW per year at Sharp Corp. (Japan). BP Solar ceases R&D and production of a-Si and CdTe thin-film modules in USA ending >20 years of effort

Along with the maturing of the solar cell technology, the BOS needed to grow. Many products like inverters, which convert the DC power into AC power, and sun trackers had only limited application outside of a PV power system, so once again there was only limited technical and financial resources for development. In many system evaluations, the inverter was repeatedly identified as the weak link in terms of reliability and AC power quality [15]. Their costs have not fallen nearly as fast as those for the PV modules. While much effort and resources had been focused on the solar cell cost and performance, little attention had been paid to installation and maintenance costs. It was quickly discovered that there was room for much improvement.

Another application was the rural electrification of remote villages in an attempt to help roughly one-third of the world's citizens to gain access to a modest amount of modern communication and lighting. Most of these PV installations were very small, on the order of 10 to 40 W per household (100 times smaller than the "needs" of a modern home in the developed world.) Most of these installations were funded by some international aid agency. Reviews and follow-up studies of these programs have indicated very large failure rates, primarily due to lack of technical infrastructure [16], training, cultural misunderstandings, design of the payment structure, and other nontechnical reasons [17]. Rarely have the PV modules failed. Even with subsidies from the international agencies, the high initial cost of ownership ($100–1000) was still a major barrier in much of the world where this represents a year's income for a family [18].

Yet another important development in the application of PV in the late 1990s, was building integrated PV (BIPV [19]), where PV cells are incorporated into a standard building product, such as a window or a roof shingle, or into an architectural feature like an exterior sun awning or semitransparent skylight. In this way, the cost of the PV is partially offset by the cost of the building materials, which would have been required anyway, so the incremental cost of the photovoltaic is much lower. The success of grid-connected residential or BIPV commercial applications has been possible because several countries led by Germany have established high rates to pay for the PV electricity produced by solar installations in private houses. In this scheme, the installation owner receives $0.5/kWh for the electricity they feed into the public electric grid (as of 2001). But the owner buys the electricity consumed in their own house at the normal cost of ~$0.1/kWh from the grid [19].

I.4.Properties of Sunlight

I.4.1.Basics of Light

As its name implies, photovoltaic is the direct conversion of light (photo) to electricity (voltaic). It is explained by the great scientific advance of the 20th century, namely quantum physics. In this section we discuss the nature of light and the interaction with matter.

I.4.2.Properties of Light

The light that we see every day is only a fraction of the total energy emitted by the sun incident on the earth. Sunlight is a form of "electromagnetic radiation" and the visible light that we see is a small subset of the electromagnetic spectrum:

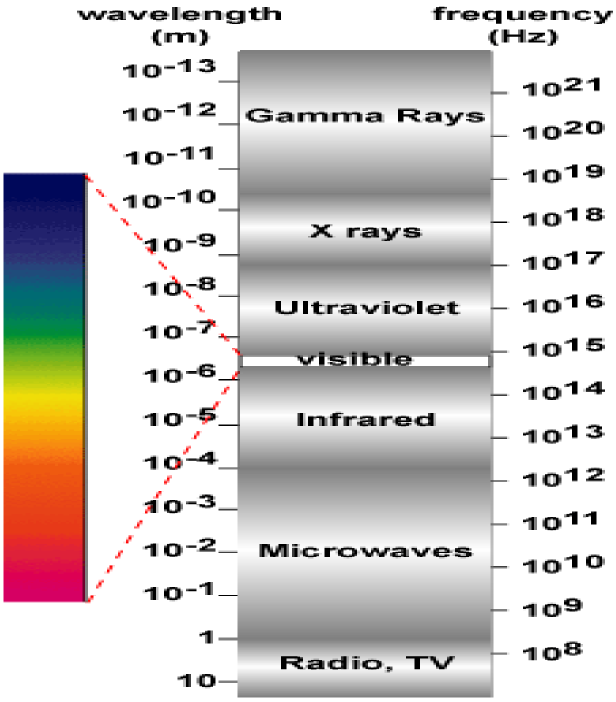


Figure I.2: The electromagnetic spectrum [20]

The electromagnetic spectrum describes light as a wave which has a particular wavelength. The description of light as a wave first gained acceptance in the early 1800's when experiments by Thomas Young, François Arago, and Augustin Jean Fresnel showed interference effects in light beams, indicating that light is made of waves. By the late 1860's light was viewed as part of the electromagnetic spectrum.[20] However, in the late 1800's a problem with the wave-based view of light became apparent when experiments measuring the spectrum of wavelengths from heated objects could not be explained using the wave-based equations of light. This discrepancy was resolved by the works of in 1900, and in 1905. Planck proposed that the total energy of light is made up of indistinguishable energy elements, or a quanta of energy. [21] Einstein, while examining the photoelectric effect (the release of electrons from certain metals and semiconductors when struck by light), correctly distinguished the values of these quantum energy elements. For their work in this area Planck and Einstein won the Nobel prize for physics in 1918 and 1921, respectively and based on this work, light may be viewed as consisting of "packets" or particles of energy, called photons.

Today quantum-mechanics explains both the observations of the wave nature and the particle nature of light. In quantum mechanics, a photon, like all other quantum-mechanical particles such as electrons, protons etc, is most accurately pictured as a "wave-packet". A wave packet is defined as a collection of waves which may interact in such a way that the wave-packet may either appear spatially localized (in a similar fashion as a square wave which results from the addition of an infinite number of sine waves), or may alternately appear simply as a wave. In the cases where the wave-packet is spatially localized, it acts as a particle. Therefore, depending on the situation, a photon may appear as either a wave or as a particle and this concept is called "wave-particle duality".

A complete physical description of the properties of light requires a quantum-mechanical analysis of light, since light is a type of quantum-mechanical particle called a photon. For photovoltaic applications, this level of detail is seldom required and therefore only a few sentences on the quantum nature of light are given here. However, in some situations (fortunately, rarely encountered in PV systems), light may behave in a manner which seems to defy common sense, based on the simple explanations given here. The term "common sense" refers to our own observations and cannot be relied on to observe the quantum-mechanical effects because these occur under conditions outside the range of human observation. [23]

There are several key characteristics of the incident solar energy which are critical in determining how the incident sunlight interacts with a photovoltaic converter or any other object. The important characteristics of the incident solar energy are:

- the spectral content of the incident light
- the radiant power density from the sun

- the angle at which the incident solar radiation strikes a photovoltaic module
- the radiant energy from the sun throughout a year or day for a particular surface

I.4.2.1.Energy of Photon

A photon is characterized by either a wavelength, denoted by λ or equivalently an energy, denoted by *E*. There is an inverse relationship between the energy of a photon (*E*) and the wavelength of the light (λ) given by the equation:

$$E_{Ph} = h\nu = \frac{hc}{\lambda} \qquad \text{I.1}$$

Avec

h : Constant of Planck (J.s)

c : Light Speed in the Space (m.s^{-1})

ν : Frequency (s-^{1})

λ : Wavelength (µm)

By expressing the equation for photon energy in terms of eV and µm we arrive at a commonly used expression which relates the energy and wavelength of a photon, as shown in the following equation:

$$E_{Ph} = \frac{1.24}{\lambda} \qquad \text{I.2}$$

I.4.2.2.Spectral Irradiance

The spectral irradiance as a function of photon wavelength (or energy), denoted by *F*, is the most common way of characterizing a light source. It gives the power density at a particular wavelength. The units of spectral irradiance are in Wm^{-2}µm^{-1}. The Wm^{-2} term is the power density at the wavelength λ (µm). Therefore, the m^{-2} refers to the surface area of the light emitter and the µm^{-1} refers to the wavelength of interest.

In the analysis of solar cells, the photon flux is often needed as well as the spectral irradiance. The spectral irradiance can be determined from the photon flux by converting the photon flux at a given wavelength to W/m^2. The result is then divided by the given wavelength, as shown in the equation below:

$$F(\lambda) = \Phi E \frac{1}{\Delta\lambda} \qquad \text{I.3}$$

Where:

$F(\lambda)$ is the spectral irradiance in Wm^{-2}µm^{-1}

Φ is the photon flux in # photons m^{-2}sec^{-1}

E and λ are the energy and wavelength of the photon in joules and meters respectively .

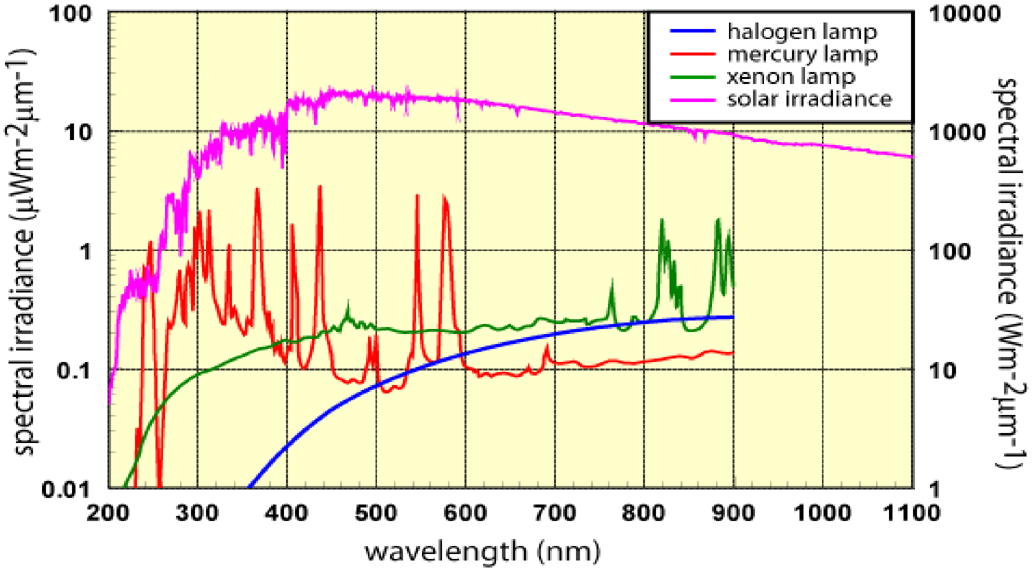


Figure I.3: The spectral irradiance of artificial light sources (left axis) compared to the spectral irradiance from the sun (right axis) [24]

I.5.Solar Radiation

We have so far described light sources in a general sense. In this section we describe the most common light source being that of the sun. Using the terminology of the previous section we note that the sun can be described as a blackbody with a temperature of 6000 K.

I.5.1.The sun

The sun is a hot sphere of gas whose internal temperatures reach over 20 million kelvin due to nuclear fusion reactions at the sun's core which convert hydrogen to helium. The radiation from the inner core is not visible since it is strongly absorbed by a layer of hydrogen atoms closer to the sun's surface. Heat is transferred through this layer by convection [24].

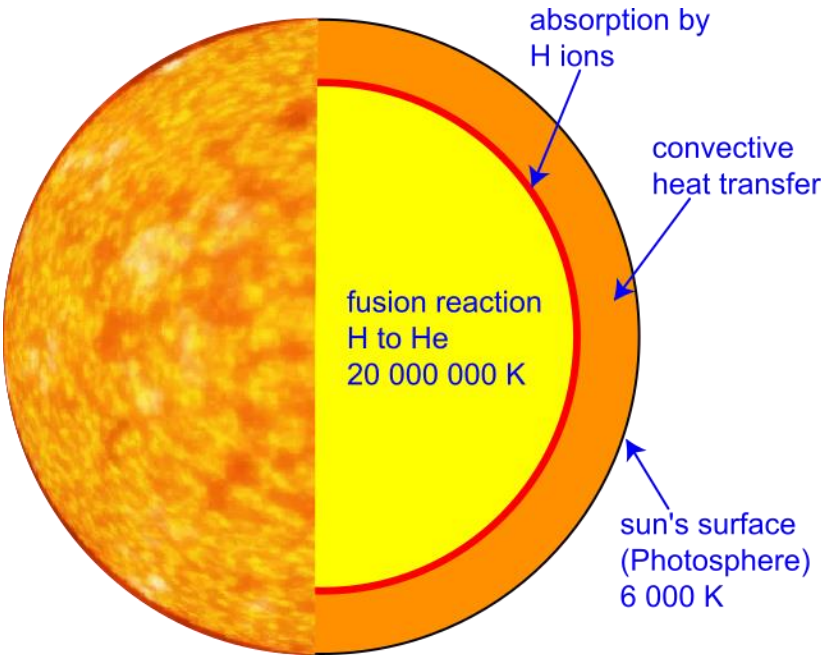


Figure I.4: The structure of the sun [24]

The surface of the sun, called the photosphere, is at a temperature of about 6000K for simplicity, the 6000 K spectrum is commonly used in detailed balance calculations but temperatures of 5762 ± 50 K [25] and 5730 ± 90 K [26] have also been proposed as a more accurate fit to the sun's spectrum. Astronomers use 5778 K when classifying the sun as a star. For consistency in this site we use the approximation of 5800 K.

I.5.2.Solar Radiation in Space

Only a fraction of the total power emitted by the sun impinges on an object in space which is some distance from the sun. The solar irradiance (H_0 in W/m^2) is the power density incident on an object due to illumination from the sun. At the sun's surface, the power density is that of a blackbody at about 6000K and the total power from the sun is this value multiplied by the sun's surface area. However, at some distance from the sun, the total power from the sun is now spread out over a much larger surface area and therefore the solar irradiance on an object in space decreases as the object moves further away from the sun [27].

$$H_0 = \frac{R^2{}_{sun}}{D^2} H_{sun} \qquad \text{I.4}$$

Where:

H_{sun} is the power density at the sun's surface (in W/m^2) as determined by Stefan-Boltzmann's blackbody equation

R_{sun} is the radius of the sun in meters

D is the distance from the sun in meters

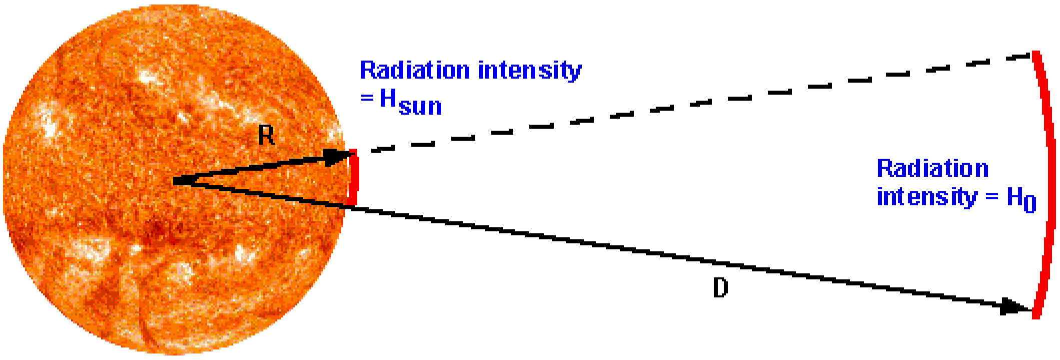


Figure I.5: Solar Radiation Intensity [24]

At a distance, D, from the sun the same amount of power is spread over a much wider area so the solar radiation power intensity is reduced. In the calculation below the radiant solar intensity at the sun’s surface, H_{sun} is 64×10^6 W/m^2 and the radius of the sun, R_{sun} is 695×10^6 m. [27] .

I.6.Terrestrial Solar Radiation

While the solar radiation incident on the Earth's atmosphere is relatively constant, the radiation at the Earth's surface varies widely due to:

- atmospheric effects, including absorption and scattering
- local variations in the atmosphere, such as water vapour, clouds, and pollution
- latitude of the location
- the season of the year and the time of day

The above effects have several impacts on the solar radiation received at the Earth's surface. These changes include variations in the overall power received, the spectral content of the light and the angle from which light is incident on a surface. In addition, a key change is that the variability of the solar radiation at a particular location increases dramatically. The variability is due to both local effects such as clouds and seasonal variations, as well as other effects such as the length of the day at a particular latitude. Desert regions tend to have lower variations due to local atmospheric phenomena such as clouds. Equatorial regions have low variability between seasons.

Figure I.6: Planet Earth

Solar radiation at the Earth's surface varies from the solar radiation incident on the Earth's atmosphere. Cloud cover, air pollution, latitude of a location, and the time of the year can all cause variations in solar radiance at the Earth's surface. The amount of energy reaching the surface of the Earth every hour is greater than the amount of energy used by the Earth's population over an entire year.

I.6.1.Atmospheric Effects

Atmospheric effects have several impacts on the solar radiation at the Earth's surface. The major effects for photovoltaic applications are:

- a reduction in the power of the solar radiation due to absorption, scattering and reflection in the atmosphere
- a change in the spectral content of the solar radiation due to greater absorption or scattering of some wavelengths;
- the introduction of a diffuse or indirect component into the solar radiation
- local variations in the atmosphere (such as water vapor, clouds and pollution) which have additional effects on the incident power, spectrum and directionality.

These effects are summarized in the figure below:

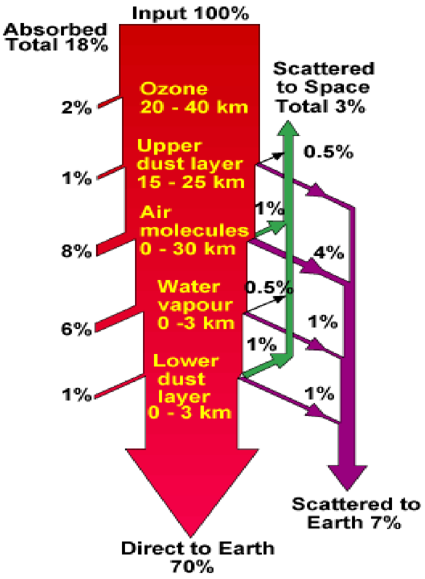


Figure I.7: Atmospheric impact on the solar radiation at the Earth's surface [28]

I.6.2.Absorption in the Atmosphere

As solar radiation passes through the atmosphere, gasses, dust and aerosols absorb the incident photons. Specific gasses, notably ozone (O_3), carbon dioxide (CO_2), and water vapor (H_2O), have very high absorption of photons that have energies close to the bond energies of these atmospheric gases. This absorption yields deep troughs in the spectral radiation curve. For example, much of the far infrared light above 2 µm is absorbed by water vapor and carbon dioxide. Similarly, most of the ultraviolet light below 0.3 µm is absorbed by ozone (but not enough to completely prevent sunburn).

While the absorption by specific gasses in the atmosphere change the spectral content of the terrestrial solar radiation, they have a relatively minor impact on the overall power. Instead, the major factor reducing the power from solar radiation is the absorption and scattering of light due to air molecules and dust. This absorption process does not produce the deep troughs in the spectral irradiance, but rather causes a power reduction dependent on the path length through the atmosphere. When the sun is overhead, the absorption due to these atmospheric elements causes a relatively uniform reduction across the visible spectrum, so the incident light appears white. However, for longer path lengths, higher energy (lower wavelength) light is more effectively absorbed and scattered. Hence in the morning and evening the sun appears much redder and has a lower intensity than in the middle of the day.

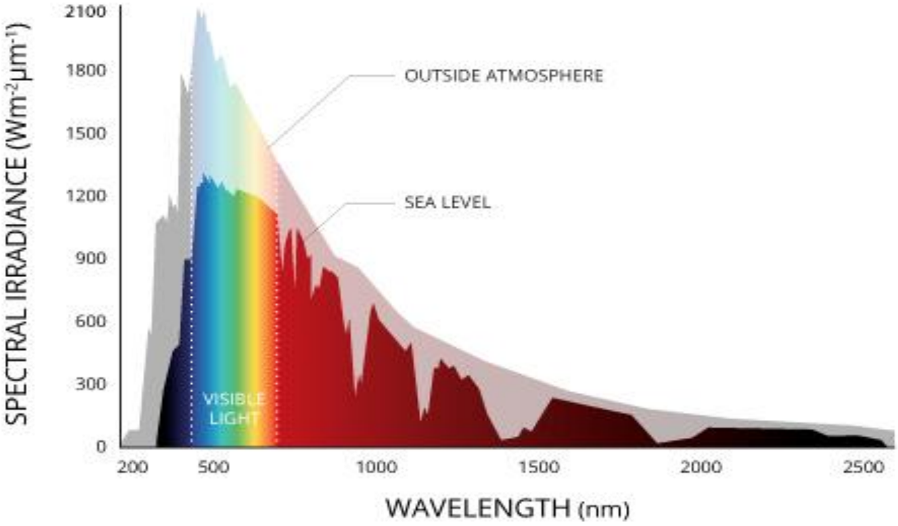


Figure I.8: A comparison of solar radiation outside the Earth's atmosphere with the amount of solar radiation reaching the Earth itself [29]

The standard spectra given above and described in more detail in the appendices give a typical spectra for a sunlight. Computers models allow for more detailed models of the solar spectra for a particular location and time of day. The Simple Model of the Atmospheric Radioactive Transfer of Sunshine, or SMARTS is used to generate the standard solar spectra. The solar spectrum calculator at PV lighthouse also gives the solar spectrum as a function of location and time of the day. It uses a slightly simpler algorithm from Bird [30][31].

I.6.3.Effect of clouds and other local variations in the atmosphere

The final effect of the atmosphere on incident solar radiation is due to local variations in the atmosphere. Depending on the type of cloud cover, the incident power is severely reduced. An example of heavy cloud cover is shown below:

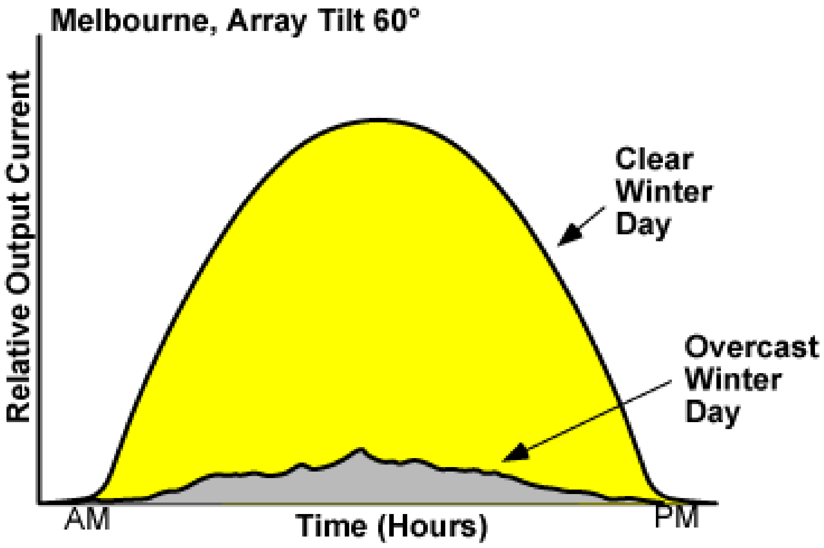


Figure I.9: Relative output current from a photovoltaic array on a sunny and a cloudy winter's day in Melbourne with an array tilt angle of 60° [32]

I.7.Air Mass

The Air Mass is the path length which light takes through the atmosphere normalized to the shortest possible path length (that is, when the sun is directly overhead). The Air Mass quantifies the reduction in the power of light as it passes through the atmosphere and is absorbed by air and dust. The Air Mass is defined as:

$$\mathrm{AM} = \frac{1}{\cos\theta} \qquad \text{I.5}$$

Where θ is the angle from the vertical (zenith angle). When the sun is directly overhead, the Air Mass is 1.

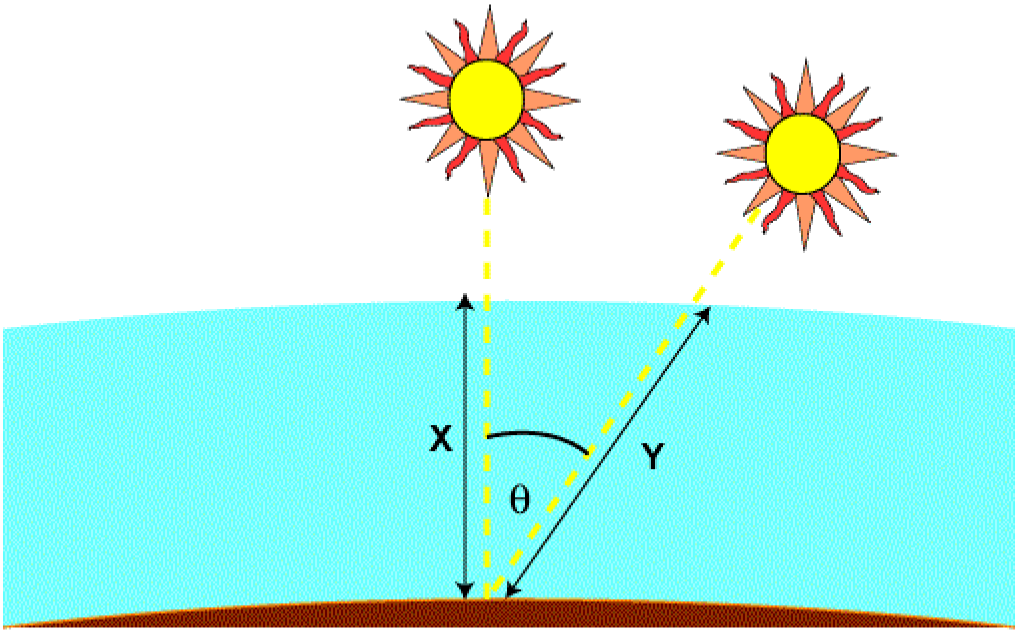


Figure I.10: The air mass represents the proportion of atmosphere that the light must pass through before striking the Earth relative to its overhead path length, and is equal to Y/X [33]

An easy method to determine the air mass is from the shadow of a vertical pole.

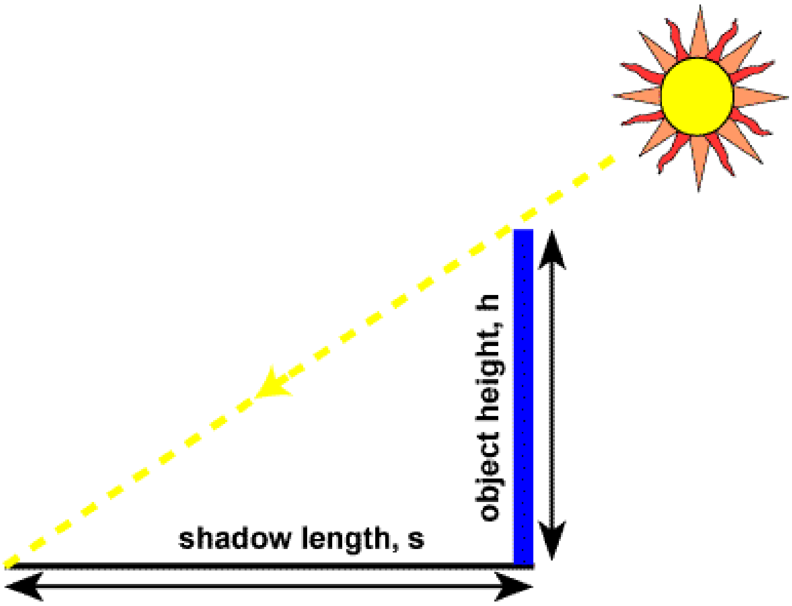


Figure I.11 : Air Masse Calculation [33]

Air mass is the length of the hypotenuse divided by the object height h,and from Pythagoras's theorem we get :

$$\mathrm{AM} = \sqrt{1 + \left(\frac{s}{h}\right)^2} \qquad \text{I.6}$$

The above calculation for air mass assumes that the atmosphere is a flat horizontal layer, but because of the curvature of the atmosphere, the air mass is not quite equal to the atmospheric path length when the sun is close to the horizon. At sunrise, the angle of the sun from the vertical position is 90° and the air mass is infinite, whereas the path length clearly is not. An equation which incorporates the curvature of the earth is [33]:

$$\mathrm{AM} = \frac{1}{\cos\theta + 0.50572(96.07995 - \theta)^{-1.6364}} \qquad \text{I.7}$$

I.8.Standardised Solar Spectrum and Solar Irradiation

The efficiency of a solar cell is sensitive to variations in both the power and the spectrum of the incident light. To facilitate an accurate comparison between solar cells measured at different times and locations, a standard spectrum and power density has been defined for both radiations outside the Earth's atmosphere and at the Earth's surface.

The standard spectrum at the Earth's surface is called AM1.5G, (the G stands for global and includes both direct and diffuse radiation) or AM1.5D (which includes direct radiation only). The intensity of AM1.5D radiation can be approximated by reducing the AM0 spectrum by 28% (18% due to absorption and 10% to scattering). The global spectrum is 10% higher than the direct spectrum. These calculations give approximately 970 W/m^2 for AM1.5G. However, the standard AM1.5G spectrum has been normalized to give 1kW/m^2 due to the convenience of the round number and the fact that there are inherently variations in incident solar radiation.

The standard spectrum outside the Earth's atmosphere is called AM0, because at no stage does the light pass through the atmosphere. This spectrum is typically used to predict the expected performance of cells in space.

The intensity of the direct component of sunlight throughout each day can be determined as a function of air mass from the experimentally determined equation [34]:

$$I_D = 1.353 \times 0.7^{AM^{0.678}} \tag{I.8}$$

where I_D is the intensity on a plane perpendicular to the sun's rays in units of kW/m^2 and *AM* is the air mass. The value of 1.353 kW/m^2 is the solar constant and the number 0.7 arises from the fact that about 70% of the radiation incident on the atmosphere is transmitted to the Earth. The extra power term of 0.678 is an empirical fit to the observed data and takes into account the non-uniformities in the atmospheric layers.

Sunlight intensity increases with the height above sea level. The spectral content of sunlight also changes making the sky 'bluer' on high mountains. Much of the southwest of the United States is two kilometers above sea level, adding significantly to solar isolation. A simple empirical fit to observed data and accurate to a few kilometers above sea level is given by [35]:

$$I_D = 1.353 \times \left[(1 - ah) \times 0.7^{\ AM^{0.678}} + ah\right] \tag{I.9}$$

Where $a = 0.14$ and h is the location height above sea level in kilometers.

Even on a clear day, the diffuse radiation is still about 10% of the direct component. Thus on a clear day the global irradiance on a module perpendicular to the sun's rays is:

$$I_G = 1.1 \times I_D \tag{I.10}$$

I.9.Introduction to Semiconductors

Solar cells have always been aligned closely with other electronic devices. The following pages cover the basic aspects of semiconductor materials and the physical mechanisms which are at the center of photovoltaic devices. These physical mechanisms are used to explain the operation of a *p-n* junction, which forms the basis not only for the great majority of solar cells, but also most other electronic devices such as lasers and bipolar junction transistors. Much of the theory of solid-state semiconductors was worked out during the invention of the transistor in the late 40s and early 50s [36].

The wide range of semiconductor applications comes from the ability to easily change their conductivity. The addition of even very small amounts of impurities, known as dopants, can change their material conductivity over orders of magnitude even though the impurity concentration might be very small with concentrations of the order of parts per billion. The conductivity may also be changed by applying a voltage or current in one part of the materials to cause a large change in the conductivity in another part of the device. Solar cells are usually based around PN junction devices and are just large diodes that have been optimized to absorb light. As such solar cells belong to the family of bipolar junction devices, which also includes diodes and bipolar junction transistors (BJTs).

Semiconductors typically use the CGS (centimeter, gram, second) unit system. However, the thickness of a solar cell will be measured in microns. For modeling and calculations, the easiest approach is to convert all dimensions to cm so that a wafer of thickness 160 µm becomes 0.016 cm.

I.9.1.Basics of Semiconductor

The atoms in a semiconductor are materials from either group IV of the periodic table, or from a combination of group III and group V (called III-V semiconductors), or of combinations from group II and group VI (called II-VI semiconductors). Because different semiconductors are made up of elements from different groups in the periodic table, properties vary between semiconductors. Silicon, which is a group IV, is the most commonly used semiconductor material as it forms the basis for integrated circuit (IC) chips and is the most mature technology and most solar cells are also silicon based.

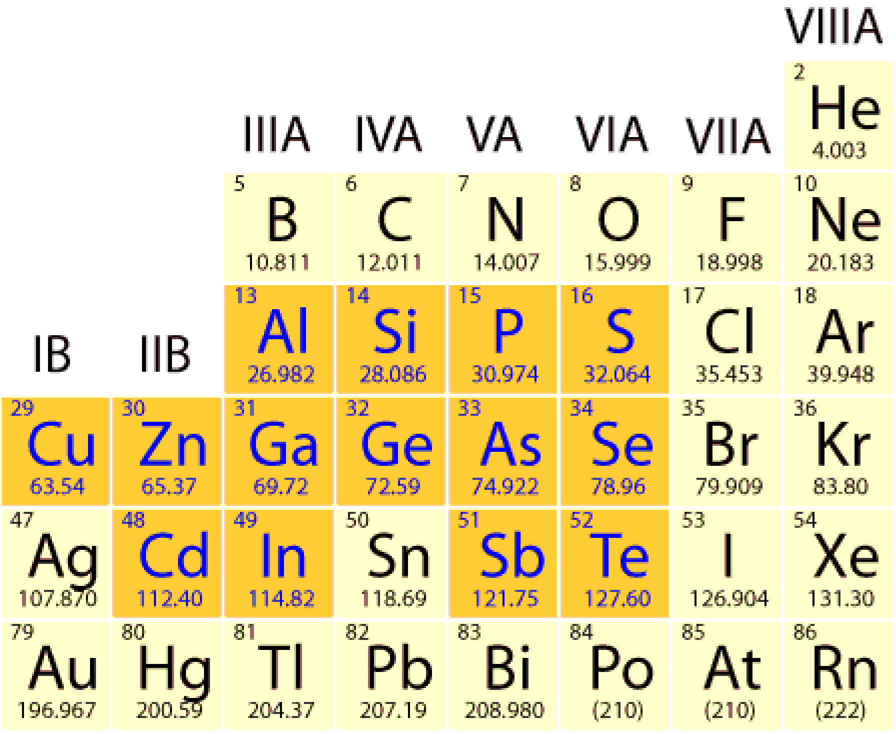


Figure I.12: A section from the periodic table [37]

More common semiconductor materials are shown in blue. A semiconductor can be either of a single element, such as Si or Ge, a compound, such as GaAs, InP or CdTe, or an alloy, such as $Si_xGe_{(1-x)}$ or $Al_xGa_{(1-x)}As$, where x is the fraction of the particular element and ranges from 0 to 1.

I.9.2.Semiconductor Structure

Semiconductors, such as Silicon (Si) are made up of individual atoms bonded together in a regular, periodic structure to form an arrangement whereby each atom is surrounded by 8 electrons. An individual atom consists of a nucleus made up of a core of protons (positively charged particles) and neutrons (particles having no charge) surrounded by electrons. The number of electrons and protons is equal, such that the atom is overall electrically neutral. The electrons surrounding each atom in a semiconductor are part of a covalent bond. A covalent bond consists of two atoms "sharing" a pair of electrons. Each atom forms 4 covalent bonds with the 4 surrounding atoms. Therefore, between each atom and its 4 surrounding atoms, 8 electrons are being shared. The structure of a semiconductor is shown in the figure below.

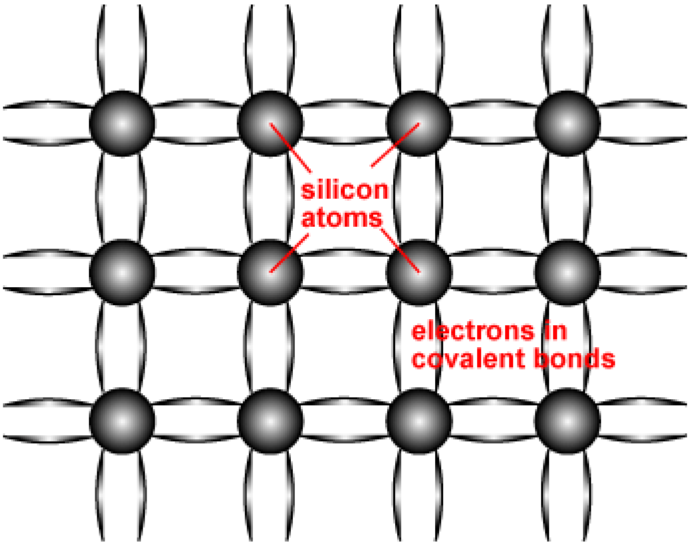


Figure I.13: Schematic representation of covalent bonds in a silicon crystal lattice [37]

Each line connecting the atoms represents an electron being shared between the two. Two electrons being shared are what form the covalent bond.

The bond structure of a semiconductor determines the material properties of a semiconductor. One key effect are the energy levels which the electrons can occupy and how they move about the crystal lattice. The electrons in the covalent bond formed between each of the atoms in the lattice structure are held in place by this bond and hence they are localized to the region surrounding the atom. These bonded electrons cannot move or change energy, and thus are not considered "free" and cannot participate in current flow, absorption, or other physical processes of interest in solar cells. However, only at absolute zero are all electrons in this "stuck," bonded arrangement. At elevated temperatures, especially at the temperatures where solar cells operate, electrons can gain enough energy to escape from their bonds. When this happens, the electrons are free to move about the crystal lattice and participate in conduction. At room temperature, a semiconductor has enough free electrons to allow it to conduct current. At or close to absolute zero a semiconductor behaves like an insulator.

When an electron gains enough energy to participate in conduction (is "free"), it is at a high energy state. When the electron is bound, and thus cannot participate in conduction, the electron is at a low energy state. Therefore, the presence of the bond between the two atoms introduces two distinct energy states for the electrons. The electron cannot attain energy values intermediate to these two levels; it is either at a low energy position in the bond, or it has gained enough energy to break free and therefore has a certain minimum energy. This minimum energy is called the "band gap" of a semiconductor. The number and energy of these free electrons, those electrons participating in conduction, is basic to the operation of electronic devices.

The space left behind by the electrons allows a covalent bond to move from one electron to another, thus appearing to be a positive charge moving through the crystal lattice. This empty space is commonly called a "hole", and is similar to an electron, but with a positive charge.

The most important parameters of a semiconductor material for solar cell operation are:

- the band gap
- the number of free carriers (electrons or holes) available for conduction
- the "generation" and recombination of free carriers (electrons or holes) in response to light shining on the material

I.9.3.Band Gap

The band gap of a semiconductor is the minimum energy required to excite an electron that is stuck in its bound state into a free state where it can participate in conduction. The band structure of a semiconductor gives the energy of the electrons on the y-axis and is called a "band diagram". The lower energy level of a semiconductor is called the "valence band" (E_V) and the energy level at which an electron can be considered free is called the "conduction band" (E_C). The band gap (E_G) is the gap in energy between the bound state and the Free State between the valence band and conduction band. Therefore, the band gap is the minimum change in energy required to excite the electron so that it can participate in conduction [37].

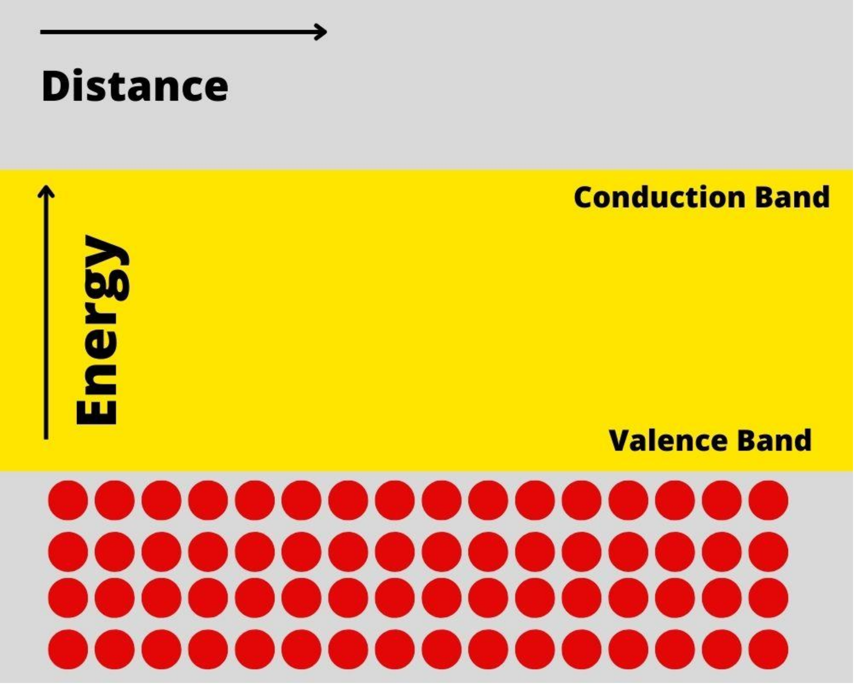


Figure I.14: Energy Diagram

Once the electron becomes excited into the conduction band, it is free to move about the semiconductor and participate in conduction. However, the excitation of an electron to the conduction band will also allow an additional conduction process to take place. The excitation of an electron to the conduction band leaves behind an empty space for an electron. An electron from a neighboring atom can move into this empty space. When this electron moves, it leaves behind another space. The continual movement of the space for an electron, called a "hole", can be illustrated as the movement of a positively charged particle through the crystal structure. Consequently, the excitation of an electron into the conduction band results in not only an electron in the conduction band but also a hole in the valence band. Thus, both the electron and hole can participate in conduction and are called "carriers".

The concept of a moving "hole" is analogous to that of a bubble in a liquid. Although it is actually the liquid that moves, it is easier to describe the motion of the bubble going in the opposite direction.

At elevated temperature some electrons have sufficient energy to reach the conduction band the carriers are free to move and the metal is slightly eclectically conductive.

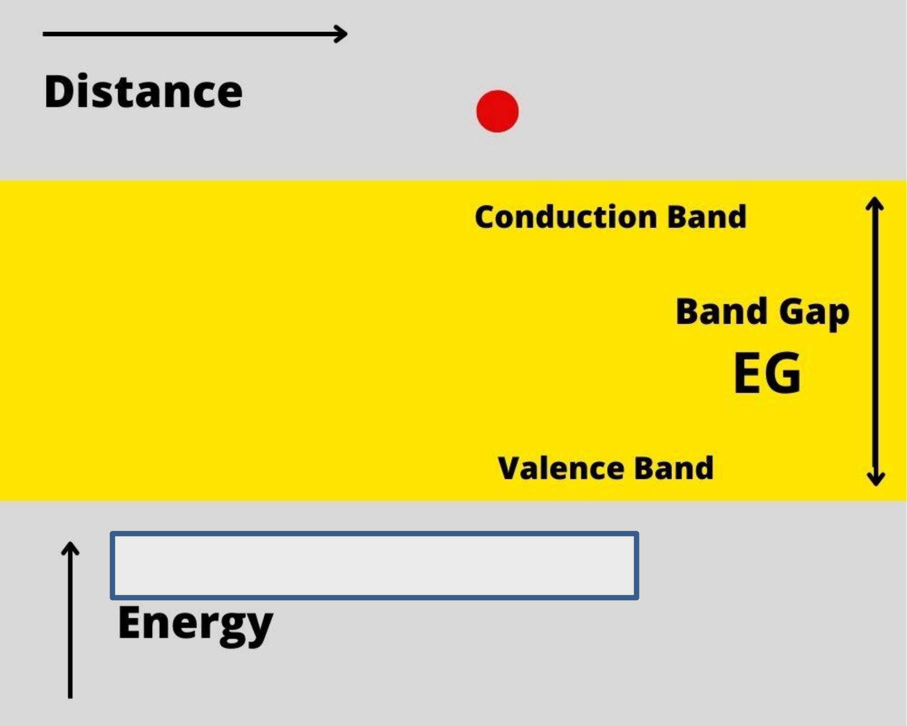


Figure I.15: Intrinsic carrier concentration in a semiconductor at High temperatures

In both cases, the number of electrons and the number of holes is equal. Undoped silicon (intrinsic) is rarely used in the electronics industry it is almost always doped for device fabrication.

I.10.Doping

It is possible to shift the balance of electrons and holes in a silicon crystal lattice by "doping" it with other atoms.

Atoms with one more valence electron than silicon are used to produce "*n*-type" semiconductor material. These *n*-type materials are group V elements in the periodic table, and thus their atoms have 5 valence electrons that can form covalent bonds with the 4 valence electrons that silicon atoms have. Because only 4 valence electrons are needed from each atom (silicon and *n*-type) to form the covalent bonds around the silicon atoms, the extra valence electron present (because *n*-type materials have 5 valence electrons) when the two atoms bond is free to participate in conduction. Therefore, more electrons are added to the conduction band and hence increases the number of electrons present.

Atoms with one less valence electron result in "*p*-type" material. These *p*-type materials are group III elements in the periodic table. Therefore, *p*-type material has only 3 valence electrons with which to interact with silicon atoms. The net result is a hole, as not enough electrons are present to form the 4 covalent bonds surrounding the atoms. In *p*-type material, the number of electrons trapped in bonds is higher, thus effectively increasing the number of holes. In doped material, there is always more of one type of carrier than the other and the type of carrier with the higher concentration is called a "majority carrier", while the lower concentration carrier is called a "minority carrier".

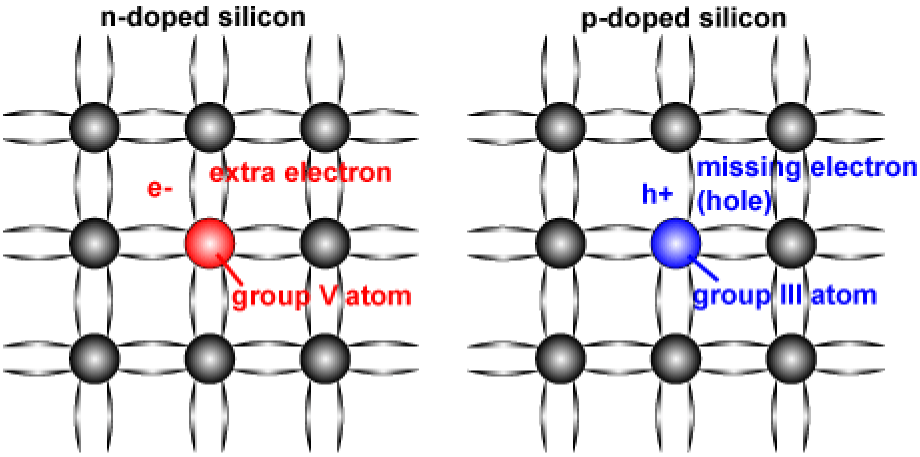


Figure I.16: Schematic of a silicon crystal lattice doped with impurities to produce n-type and p-type semiconductor material [37]

The following table summarizes the properties of semiconductor types in silicon.

Table I.3: the properties of semiconductor types in silicon P-type and N-type silicon

	N-type (negative)	**P-type (positive)**
Dopant	Group V (e.g. Phosphorus)	Group III (e.g. Boron)
Bonds	Excess Electrons	Missing Electrons (Holes)
Majority Carriers	Electrons	Hole
Minority Carriers	Holes	Electrons

In a typical semiconductor there might be $10^{17}cm^{-3}$ majority carriers and $10^{6}cm^{-3}$ minority carriers. Expressed in a different form, the ratio of minority to majority carriers is less than one person to the entire population of the planet. Minority carriers are created either thermally or by incident photons.

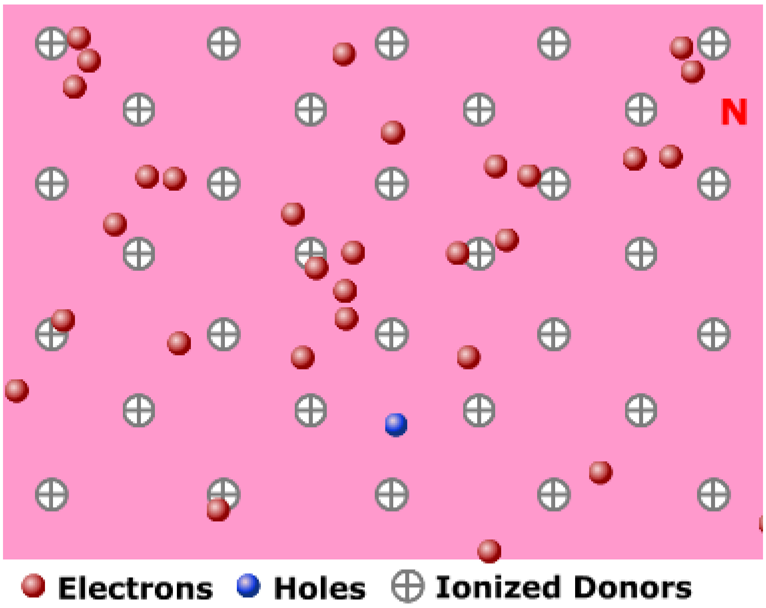


Figure I.17: N-type semiconductor.These are called "n-type" since the majority carriers are Negatively charged electrons [37]

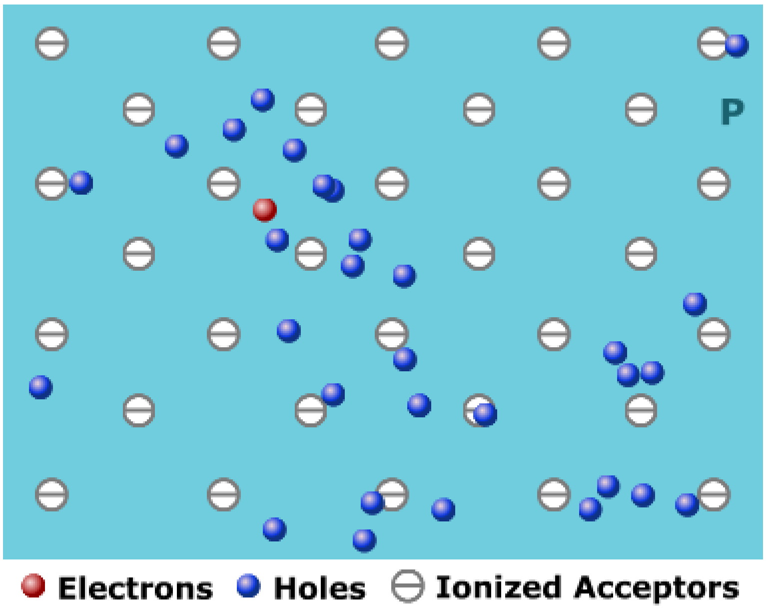


Figure I.18: P-type semiconductor. These are called "p-type" since the majority carriers are positively charged holes [37]

I.11.Generation

The absorption of light and the generation of an electron hole pair are fundamental to the operation of a solar cell. In this section the process whereby the energy of a photon is initially converted to electrical energy through the creation of an electron hole pair.

I.11.1.Absorption of Light

Photons incident on the surface of a semiconductor will be either reflected from the top surface, will be absorbed in the material or, failing either of the above two processes, will be transmitted through the material. For photovoltaic devices, reflection and transmission are typically considered loss mechanisms as photons which are not absorbed do not generate power. If the photon is absorbed it has the possibility of exciting an electron from the valence band to the conduction band. A key factor in determining if a photon is absorbed or transmitted is the energy of the photon. Therefore, only if the photon has enough energy will the electron be excited into the conduction band from the valence band. Photons falling onto a semiconductor material can be divided into three groups based on their energy compared to that of the semiconductor band gap [37]:

- $E_{ph} < E_G$ Photons with energy E_{ph} less than the band gap energy E_G interact only weakly with the semiconductor, passing through it as if it were transparent.
- $E_{ph} = E_G$ have just enough energy to create an electron hole pair and are efficiently absorbed.
- $E_{ph} > E_G$ Photons with energy much greater than the band gap are strongly absorbed. However, for photovoltaic applications, the photon energy greater than the band gap is wasted as electrons quickly thermalize back down to the conduction band edges.

The effect of the three classes of photons on the semiconductor is shown in the two figures below.

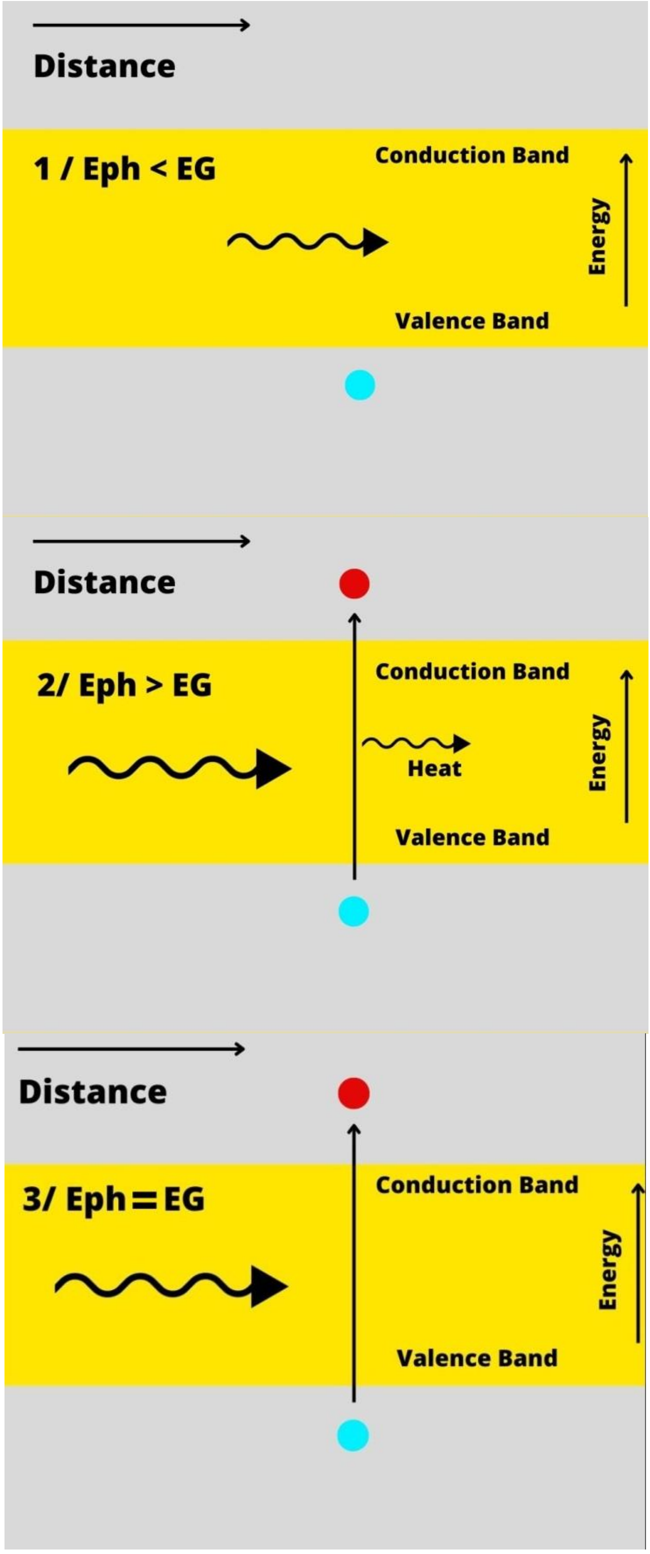


Figure I.19: The creation of electron-hole pairs when illuminated with light

The absorption of photons creates both a majority and a minority carrier. In many photovoltaic applications the number of light generated carriers is of orders of magnitude less than the number of majority carriers already present in the solar cell due to doping. Consequently, the number of majority carriers in an illuminated semiconductor does not alter significantly. However, the opposite is true for the number of minority carriers. The number of photo-generated minority carriers outweighs the number of minority carriers existing in the doped solar cell in the dark (because in doping the minority carrier concentration is so small), and therefore the number of minority carriers in an illuminated solar cell can be approximated by the number of light generated carriers.

I.11.2.Absorption Coefficient

The absorption coefficient determines how far into a material light of a particular wavelength can penetrate before it is absorbed. In a material with a low absorption coefficient, light is only poorly absorbed, and if the material is thin enough, it will appear transparent to that wavelength. The absorption coefficient depends on the material and also on the wavelength of light which is being absorbed. Semiconductor materials have a sharp edge in their absorption coefficient, since light which has energy below the band gap does not have sufficient energy to excite an electron into the conduction band from the valence band. Consequently, this light is not absorbed. The absorption coefficient for several semiconductor materials is shown below :

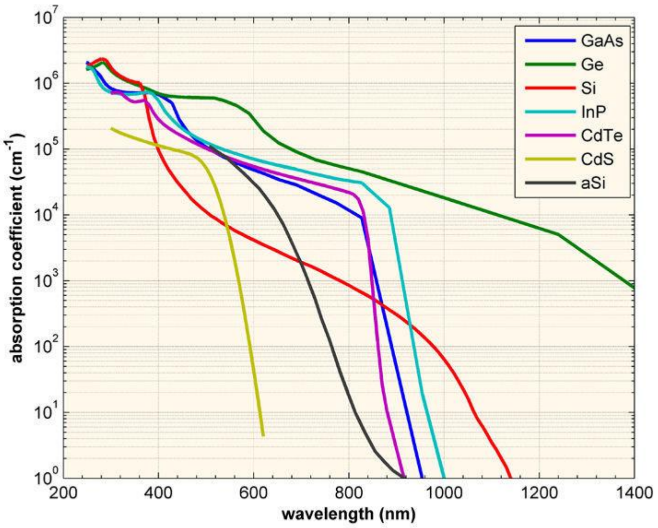


Figure I.20: The absorption coefficient, α in a variety of semiconductor materials at 300K as a function of the vacuum wavelength of light [37]

The above graph shows that even for those photons which have an energy above the band gap, the absorption coefficient is not constant, but still depends strongly on wavelength. The probability of absorbing a photon depends on the likelihood of having a photon and an electron interact in such a way as to move from one energy band to another. For photons which have energy very close to that of the band gap, the absorption is relatively low since only those electrons directly at the valence band edge can interact with the photon to cause absorption. As the photon energy increases, not just the electrons already having energy close to that of the band gap can interact with the photon. Therefore, a larger number of electrons can interact with the photon and result in the photon being absorbed.

The absorption coefficient, *α*, is related to the extinction coefficient, *k*, by the following formula:

$$\propto = \frac{4\pi k}{\lambda} \qquad \text{I.11}$$

Where λ is the wavelength. If λ is in nm, multiply by 10^7 to get the absorption coefficient in the units of cm^{-1}.

I.11.3.Generation Rate

The generation rate gives the number of electrons generated at each point in the device due to the absorption of photons. Generation is an important parameter in solar cell operation.

Neglecting reflection, the amount of light which is absorbed by a material depends on the absorption coefficient (α in cm^{-1}) and the thickness of the absorbing material. The intensity of light at any point in the device can be calculated according to the equation :

$$I = I_0 e^{-\alpha x} \qquad \text{I.12}$$

Where**:**

α is the absorption coefficient typically in cm^{-1}
x is the distance into the material at which the light intensity is being calculated
I_0 is the light intensity at the top surface

The above equation can be used to calculate the number of electron-hole pairs being generated in a solar cell. Assuming that the loss in light intensity (i.e., the absorption of photons) directly causes the generation of an electron-hole pair, then the generation *G* in a thin slice of material is determined by finding the change in light intensity across this slice. Consequently, differentiating the above equation will give the generation at any point in the device .

$$G = \alpha N_0 e^{-\alpha x} \quad \text{I.13}$$

Where:

N_0 = photon flux at the surface (photons/unit-area/sec.);
α = absorption coefficient; and
x = distance into the material.

The above equations show that the light intensity exponentially decreases throughout the material and further that the generation is highest at the surface of the material.

For photovoltaic applications, the incident light consists of a combination of many different wavelengths, and therefore the generation rate at each wavelength is different. The generation rate at different wavelengths in silicon is shown below.

To calculate the generation for a collection of different wavelengths, the net generation is the sum of the generation for each wavelength. The generation as a function of distance for a standard solar spectrum (AM 1.5) incident on a piece of silicon is shown below. The y-axis scale is logarithmic showing that there is an enormously greater generation of electron-hole pairs near the front surface of the cell, while further into the solar cell the generation rate becomes nearly constant [37].

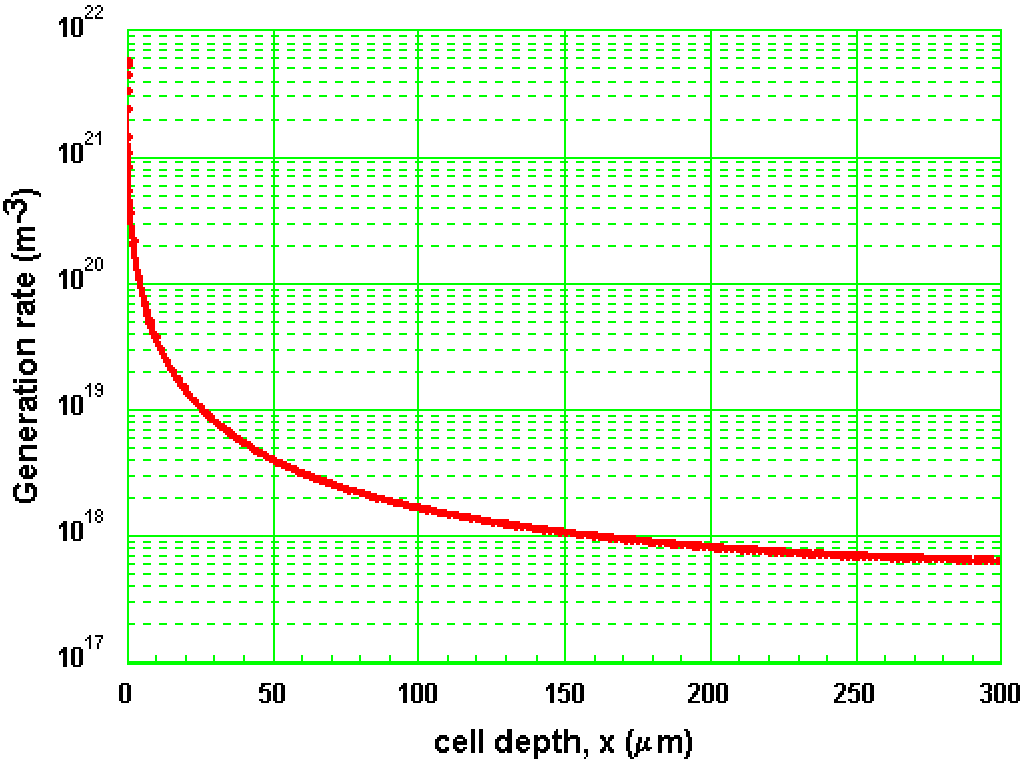


Figure I.21: Generation rate of electron-hole pairs in a piece of silicon as a function of distance into the cell [37]

The cell front surface is at 0 μ m and is where most of the high energy blue light is absorbed.

I.12.P-n Junctions

A pn junction separates the electron and hole carriers in a solar cell to create a voltage and useful work. There are many other possible ways to extract carriers from a solar cell such as metal-insulator-semiconductor [38] or even carrier selective contacts [39]. However, a pn junction is the most common in use and the analysis provides a basis for other devices.

I.12.1.Formation of a PN-Junction

P-n junctions are formed by joining n-type and p-type semiconductor materials, as shown below. Since the n-type region has a high electron concentration and the p-type a high hole concentration, electrons diffuse from the n-type side to the p-type side. Similarly, holes flow by diffusion from the p-type side to the n-type side. If the electrons and holes were not charged, this diffusion process would continue until the concentration of electrons and holes on the two sides were the same, as happens if two gasses come into contact with each other. However, in a p-n junction, when the electrons and holes move to the other side of the junction, they leave behind exposed charges on dopant atom sites, which are fixed in the crystal lattice and are unable to move. On the *n*-type side, positive ion cores are exposed. On the *p*-type side, negative ion cores are exposed. An electric field E forms between the positive ion cores in the *n*-type material and negative ion cores in the *p*-type material. This region is called the "depletion region" since the electric field quickly sweeps free carriers out, hence the region is depleted of free carriers. A "built-in" potential V_{bi} is formed at the junction due to **E**.

P-n junction diodes form the basis not only of solar cells, but of many other electronic devices such as LEDs, lasers, photodiodes and bipolar junction transistors (BJTs). A p-n junction aggregates the recombination, generation, diffusion and drift effects described in the previous pages into a single device. [40].

I.12.2.Carrier Movement in Equilibrium

A p-n junction with no external inputs represents equilibrium between carrier generation, recombination, diffusion and drift in the presence of the electric field in the depletion region. Despite the presence of the electric field, which creates an impediment to the diffusion of carriers across the electric field, some carriers still cross the junction by diffusion. In the figure below, most majority carriers which enter the depletion region move back towards the region from which they originated [41]. However, statistically some carriers will have a high velocity and travel in a sufficient net direction such that they cross the junction. Once a majority carrier crosses the junction, it becomes a minority carrier. It will continue to diffuse away from the junction and can travel a distance on average equal to the diffusion length before it recombines. The current caused by the diffusion of carriers across the junction is called diffusion current. In the figure below, watch the carriers in the depletion region and wait for carriers which cross the junction. Remember that in an actual p-n junction the number and velocity of the carriers is much greater and that the number of carriers crossing the junction is much larger.

Minority carriers which reach the edge of the diffusion region are swept across it by the electric field in the depletion region. This current is called the drift current. In equilibrium the drift current is limited by the number of minority carriers which are thermally generated within a diffusion length of the junction.

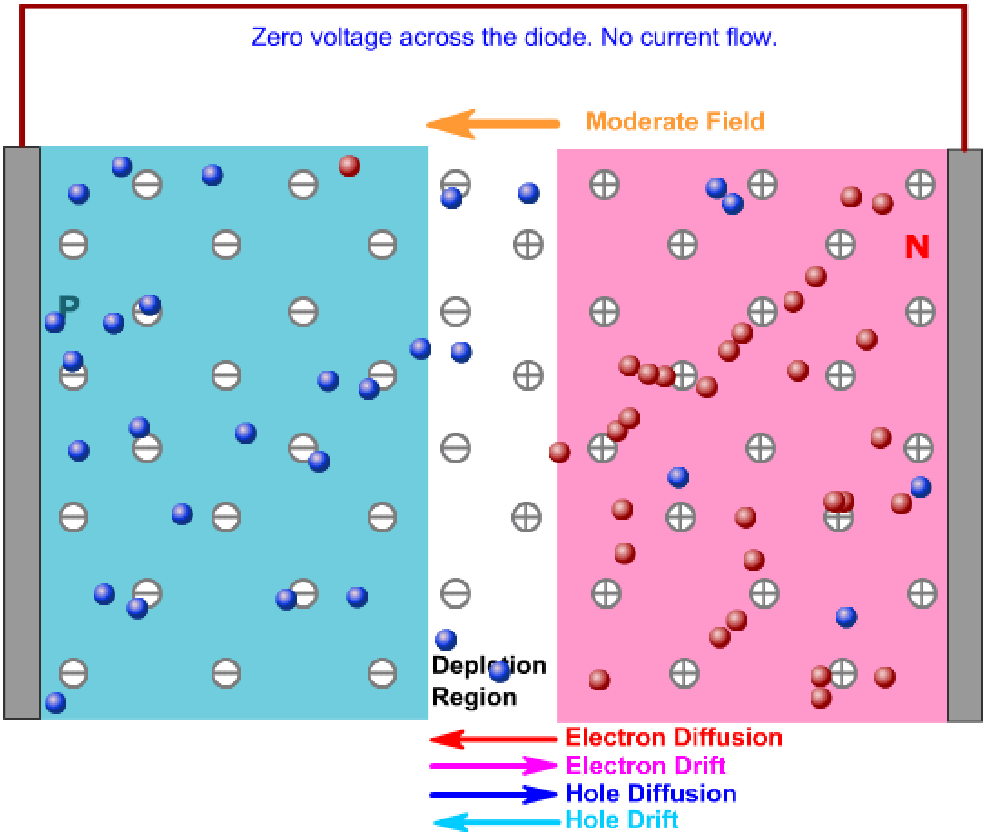


Figure I.22: Carrier Movement in Equilibrium [41]

In equilibrium, the net current from the device is zero. The electron drift current and the electron diffusion current exactly balance out (if they did not there would be a net buildup of electrons on either one side or the other of the device). Similarly, the hole drift current and the hole diffusion current also balance each other out.

I.13.Diode Equation

I.13.1.Ideal Diodes

The diode equation gives an expression for the current through a diode as a function of voltage. The Ideal Diode Law expressed as [42]:

$$I = I_0 \left(e^{\frac{qv}{Kt}} - 1\right) \qquad \text{I.14}$$

Where:
I = the net current flowing through the diode
I_0 = "dark saturation current", the diode leakage current density in the absence of light
V = applied voltage across the terminals of the diode
q = absolute value of electron charge
k = Boltzmann's constant
T = absolute temperature (K)

The "dark saturation current" (I_0) is an extremely important parameter which differentiates one diode from another. I_0 is a measure of the recombination in a device. A diode with a larger recombination will have a larger I_0.

Note that:

- I_0 increases as T increases
- I_0 decreases as material quality increases

At 300K, kT/q = 25.85 mV, the "thermal voltage".

I.13.2.Non-Ideal Diodes

For actual diodes, the expression becomes:

$$I = I_0 \left(e^{\frac{qv}{nkT}} - 1\right) \qquad \text{I.15}$$

Where:
n = ideality factor, a number between 1 and 2 which typically increases as the current decreases.

The diode equation is plotted on the interactive graph below. Change the saturation current and watch the changing of IV curve. Note that although you can simply vary the temperature and ideality factor the resulting IV curves are misleading. In the simulation it is implied that the input parameters are independent but they are not. In real devices, the saturation current is strongly dependent on the device temperature. Similarly, mechanisms that change the ideality factor also impact the saturation current [42].

Variable Saturation current, I_{01}: 1.29e-12 A/cm^2

Ideality factor, n : 1.1

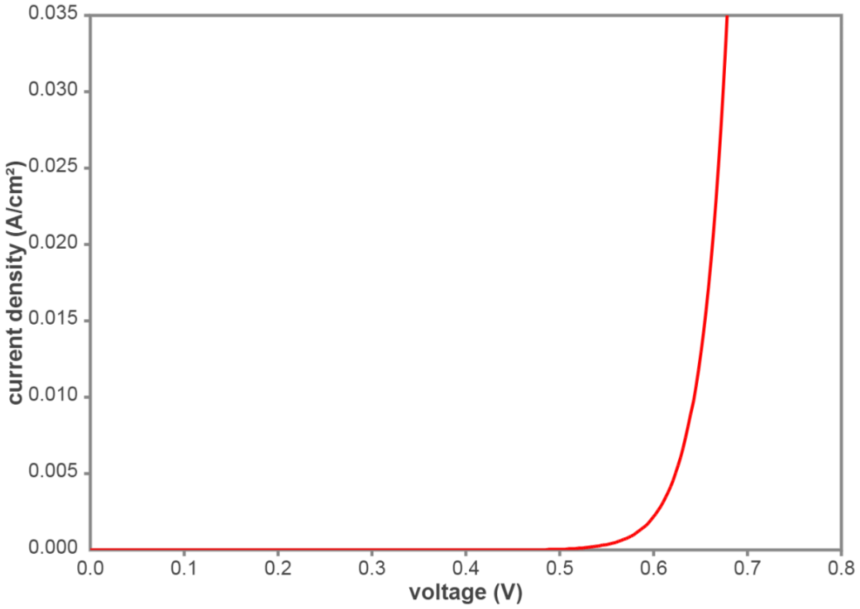


Figure I.23: the dark saturation current changes the turn on voltage of the diode [42]

The ideality factor changes the shape of the diode. The graph is misleading for ideality factor. It implies that increasing the ideality factor would increase the turn on voltage. In reality this is not the case as any physical effect that increases the ideality factor would substantially increase the dark saturation current, I_0, so that a device with a high ideality factor would typically have a lower turn on voltage.

The diode law is illustrated for silicon on the following picture. Increasing the temperature makes the diode to "turn ON" at lower voltages.

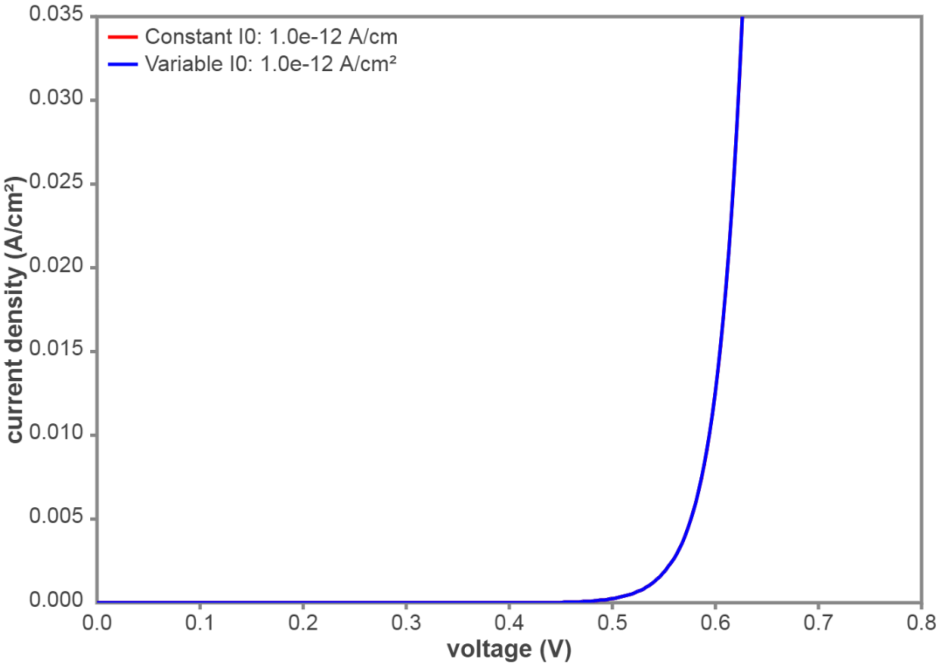


Figure I.24: the dark saturation current changes the turn on voltage of the diode.

Temperature: 300 K, Variable I0: 1.0e-12 A/cm² [42]

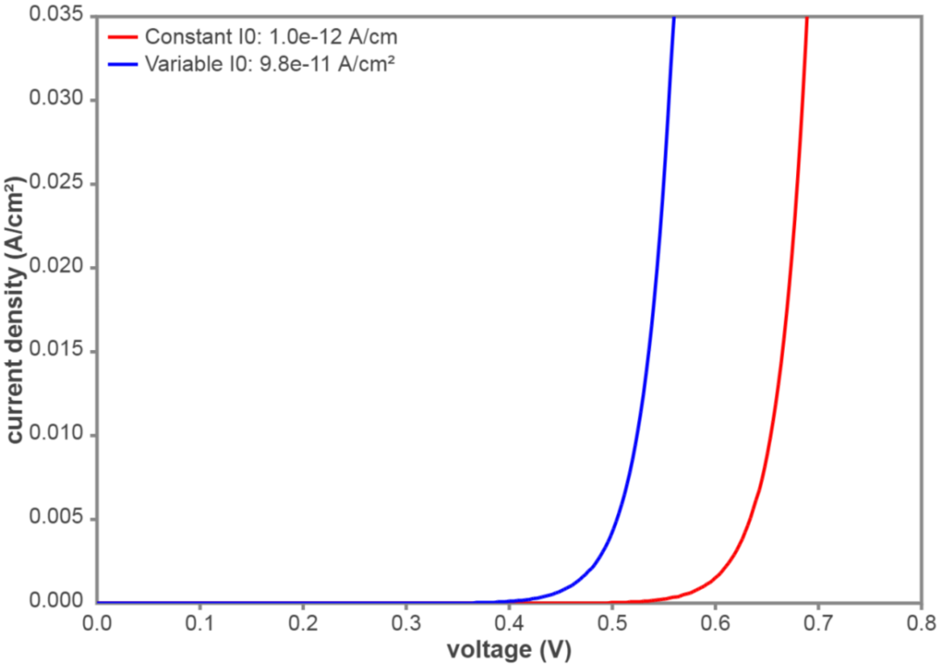


Figure I.25: the dark saturation current changes the turn on voltage of the diode.

Temperature: 330 K, Variable I0: 9.8e-11 A/cm² [42]

I.14.Temperature Effect

Like all other semiconductor devices, solar cells are sensitive to temperature. Increases in temperature reduce the band gap of a semiconductor thereby effecting most of the semiconductor material parameters. The decrease in the band gap of a semiconductor with increasing temperature can be viewed as increasing the energy of the electrons in the material. Lower energy is therefore needed to break the bond. In the bond model of a semiconductor band gap, a reduction in the bond energy also reduces the band gap. Therefore increasing the temperature reduces the band gap [43].

In a solar cell, the parameter most affected by an increase in temperature is the open-circuit voltage. The impact of increasing temperature is shown in the figure below.

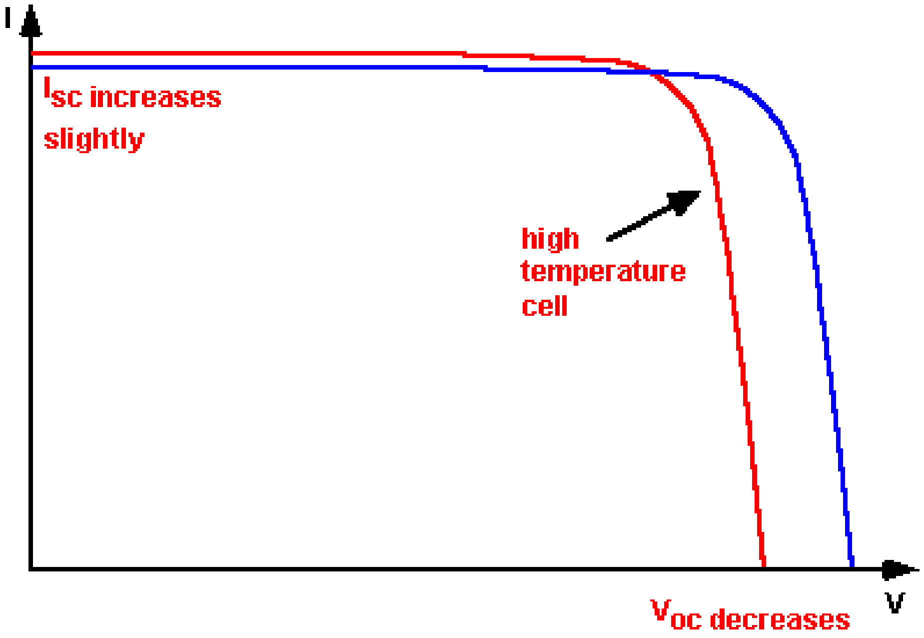


Figure I.26: The effect of temperature on the IV characteristics of a solar cell [43]

The short-circuit current, I_{sc} increases slightly with temperature since the band gap energy E_G decreases and more photons have enough energy to create e-h pairs. However, this is a small effect, and the temperature dependence of the short-circuit current from a silicon solar cell is typically

$$\frac{1}{Isc}\frac{dIsc}{dT} \approx\approx 0.0006 \text{ per } {}^\circ\text{C for Si} \qquad \text{I.16}$$

Or 0.06% per °C for silicon

The change of I_{SC} with temperature is more dependent upon the design of the cell than the semiconductor material properties. A lower performance cell with little light trapping and a poor performance in long wavelengths near the band edge will have very little change in I_{SC} with temperature. Conversely, a cell with a high response near the band edge will see a much larger change in I_{SC} with temperature. In either case, the change of I_{SC} with temperature is smaller than the change of V_{OC}.

I.15.Solar C Parameters

I.15.1. IV Curve

The IV curve of a solar cell is the superposition of the IV curve of the solar cell diode in the dark with the light-generated current. The light has the effect of shifting the [43] IV curve down into the fourth quadrant where power can be extracted from the diode. Illuminating a cell adds to the normal "dark" currents in the diode so that the diode law becomes:

$$\mathrm{I} = \mathrm{I}_0\left[\exp\left(\frac{\mathrm{qV}}{\mathrm{nkT}}\right) - 1\right] - \mathrm{I}_L \qquad \text{I.17}$$

The equation for the IV curve in the first quadrant is:

$$\mathrm{I} = \mathrm{I}_L - \mathrm{I0}\left[\exp\left(\frac{\mathrm{qV}}{\mathrm{nkT}}\right) - 1\right] \qquad \text{I.18}$$

The -1 term in the above equation can usually be neglected. The exponential term is usually >> 1 except for voltages below 100 mV. Further, at low voltages, the light generated current I_L dominates the I_0 (...) term so the -1 term is not needed under illumination

$$\mathrm{I} = \mathrm{I}_L - \mathrm{I0}\left[\exp\left(\frac{\mathrm{qV}}{\mathrm{nkT}}\right)\right] \qquad \text{I.19}$$

Plotting the above equation gives the IV curve below with the relevant points on the curve labeled and discussed in more detail on the following pages. The power curve has a a maximum denoted as P_{MP} where the solar cell should be operated to give the maximum power output. It is also denoted as P_{MAX} or maximum power point (MPP) and occurs at a voltage of V_{MP} and a current of I_{MP}.

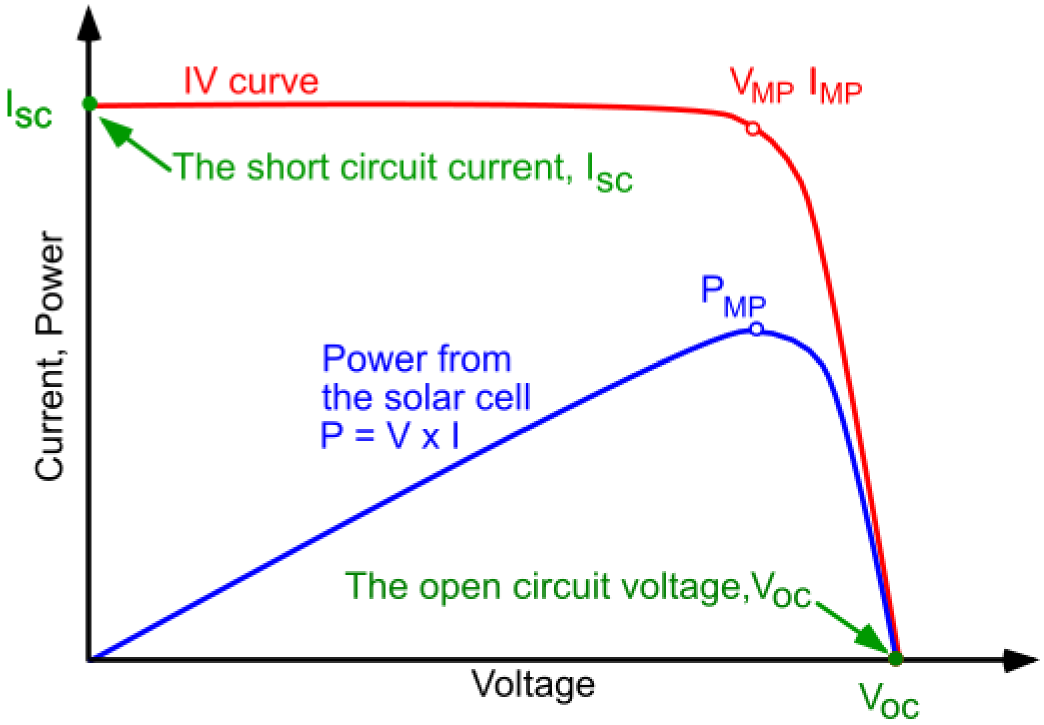


Figure I.27: Current voltage (IV) curve of a solar cell [43]

I.15.2.Solar Cell Efficiency

The efficiency is the most commonly used parameter to compare the performance of one solar cell to another. Efficiency is defined as the ratio of energy output from the solar cell to input energy from the sun. In addition to reflecting the performance of the solar cell itself, the efficiency depends on the spectrum and intensity of the incident sunlight and the temperature of the solar cell. Therefore, conditions under which efficiency is measured must be carefully controlled in order to compare the performance of one device to another. Terrestrial solar cells are measured under AM1.5 conditions and at a temperature of 25°C [44].

The efficiency of a solar cell is determined as the fraction of incident power which is converted to electricity and is defined as:

$$\mathrm{P}_{Max} = \mathrm{V}_{OC} * \mathrm{I}_{SC} * \mathrm{FF} \qquad \text{I.20}$$

$$\eta = \frac{\mathrm{V}_{OC} * I_{SC} * FF}{P_{in}} \qquad \text{I 21}$$

Where:

V_{oc} is the open-circuit voltage

I_{sc} is the short-circuit current

FF is the fill factor

η is the efficiency

I.16.Conclusion

Photovoltaic constitutes a new form of producing electric energy that is environmental clean and very modular. In stand-alone installations, it must use storage or another type generator to provide electricity when the sun is not shining. In grid-connected installation storage is not necessary: in the absence of sunlight, electricity is provided from the conventional sources.

It has been the objective of this chapter to give the reader a basic understanding of the physical principles that underlie the operation of solar cells. Toward that end, the fundamental physical characteristics of solar cell materials that permit the conversion of light into electricity have been reviewed. These characteristics include the ability of semiconductors to absorb photons by conferring that energy to carriers of electrical current and the ability of semiconductor materials to conduct electricity.

The basic operating principles of the solar cell (a carefully designed *pn*-junction diode) were derived from the (simplified) equations describing the dynamics of holes and electrons in semiconductors. This led to the definition of the solar cell figures of merit – the open-circuit voltage (V_{OC}), the short-circuit current (I_{SC}), the fill factor (*FF*), and the cell efficiency(η).

Chapter II: Silicon Crystal Growth and Wafer Technologies

I.1.Introduction

Silicon accounts for well over 90% of all semiconductor and solar cell wafer production. During the early days of semiconductor electronics, discrete transistors were typically made from germanium. The lower melting point of germanium meant that crystals were easier to grow. However, this did not last long and the lighter, cheaper, stronger, more abundant element silicon was soon a contender for transistor production. By the late 1960s, at the start of the integrated circuits industry, silicon was favored for two main reasons. First, silicon has a larger band gap giving it the ability to operate at higher temperatures and second, because of the remarkable synergy with its oxide, silicon dioxide (SiO2, quartz glass). By simply heating silicon in an oxygen containing atmosphere, a high dielectric strength, electrically insulating SiO2 layer is inexpensively formed. This SiO2 layer is chemically and mechanically very stable, effectively passivates the surface states of the underlying silicon, forms an effective diffusion barrier for the commonly used dopant species, and can be easily preferentially etched from the silicon, and vice versa, with high selectivity. By contrast, GeO2 is a chemically unstable, poor electrical insulator that is 33 times more soluble in water than SiO2 making it less suited to the photolithographic and wet chemical processes used to fabricate integrated circuits.

In the last decade, solar applications of silicon have become more significant in terms of the volume of silicon used. Around 2006, the mass of silicon used by the solar industry surpassed that used by the semiconductor industry for the first time. In 2010, of the estimated 160 kT (Kilo Ton) of electronic grade poly-silicon production, over 80% was consumed by the solar industry. We review the progress made by the silicon wafer industry in keeping up with the progressions of Moore’s law and the increasing demands of the solar industry, and discuss the prospects for various silicon substrate technologies over the coming decade or more.

II.2.Silicon Substrate Materials Technology

In the 1950s, crystals were grown mostly by the float zone (FZ) process and wafers were etched after diamond polishing to remove micro scratches, but in the 1960s, much of the fundamental work for the current silicon industry was initiated. Although the basic silicon process has remained largely the same since that time, the industry has provided a steady stream of incremental, but nevertheless significant improvements in capability to produce large, flat, clean surfaces of silicon at lower cost. Commercially available epitaxial and silicon-on-insulator (SOI) wafers are commonplace and wafer diameters have increased from 0.5 in to 300 mm in production and 450 mm is now in the research and development phase [45]. Similarly, crystal growth and substrate technologies are rapidly evolving to become a specialty manufacturing platform that can address the unique needs of the solar industry [46]. While fundamental processes in the manufacturing of silicon wafers have been in place for quite some time, silicon manufacturing technology has continuously improved in order to meet the silicon wafer parametric capability and cost requirements necessary to sustain scaling progress on semiconductor and solar industry roadmaps. Manufacturing methods commonly used in the industry are outlined in Fig.II.1

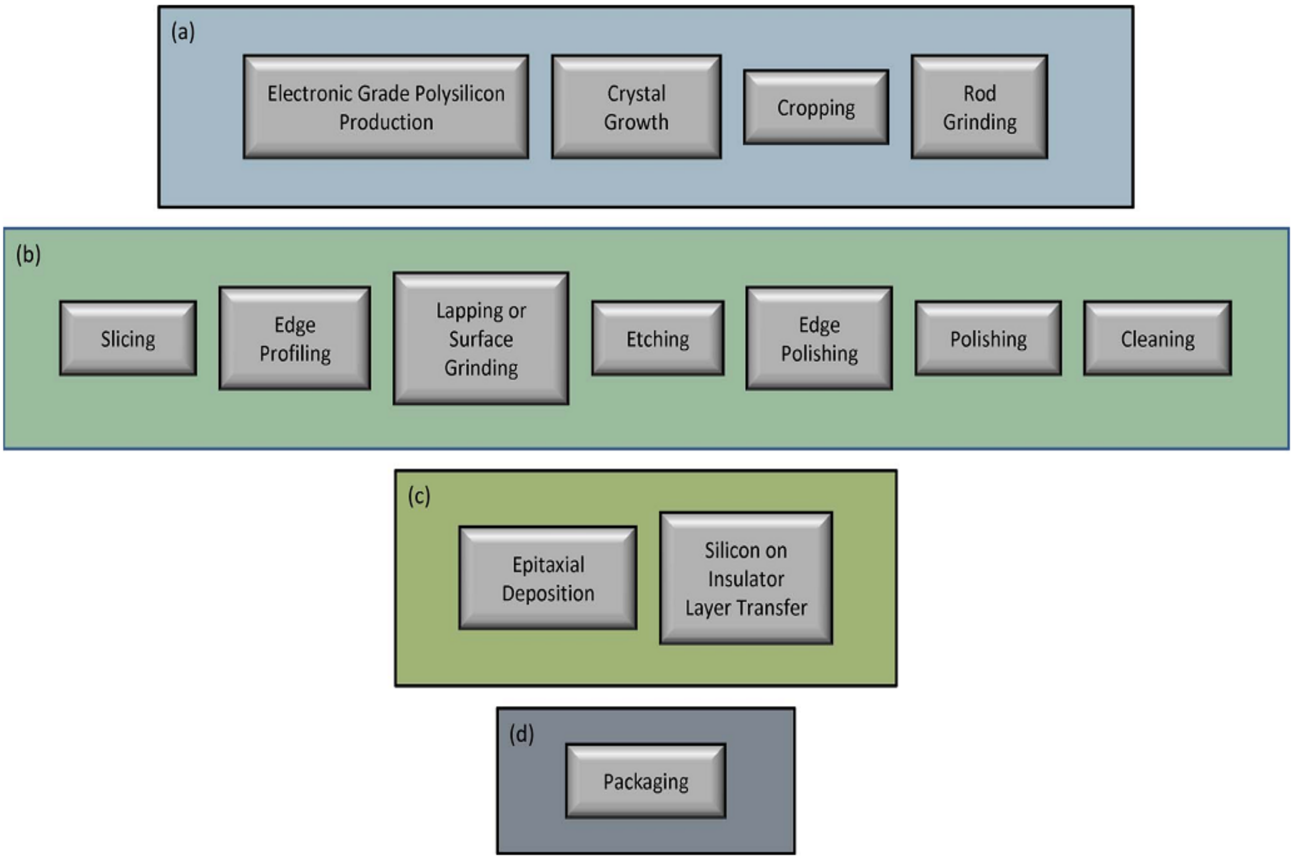


Figure II.1: Typical silicon industry production processes [46]

(a) Ingot production

(b) Wafering processes

(c) Optional processes for advanced products.

(d) Final product packaging and shipping

II.3.Application Of silicon en photovoltaic

Silicon as a base material in the photovoltaic industry is more than 90% predominant (Figure II.2) [47] This semiconductor has different advantages: easily extracted from sand, which makes it very abundant on Earth it is not toxic like some III-V semiconductors; it has a natural oxide (SiO_2) with excellent electronic properties and it can be doped easily (with phosphorus or boron).

Si : Single Silicon

mc-S i : Poly Silicon

µc-Si : Microcrystalline Silicon

a-Si : Amorphe Silicon

CIS : Dieseline of copper and indium

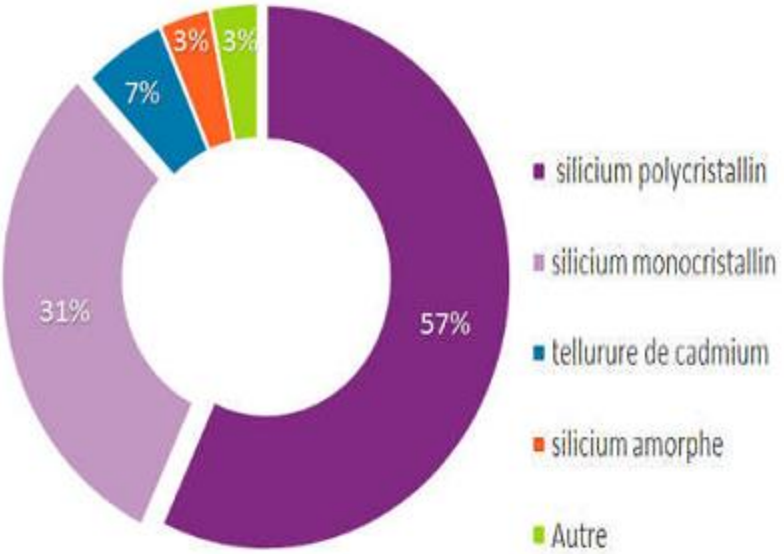


Figure II.2: Breakdown of world production (in watt-peak) of photovoltaic modules according to the different sectors in 2015 [47]

II.4.Growth of Poly-silicon Crystal

Silicon is the second most abundant element in earth's crust, in the form of silica (SiO_2) and silicates, and is readily extracted from silica-rich sands. In nature, it typically contains large amounts of impurities and so the initial stages of the manufacturing process are concerned with reduction and purification of the silica sand to produce metallurgical grade poly-silicon, typically > 98% pure silicon. This is then further refined to produce solar and semiconductor grade poly-silicon, which can be used as the feedstock for crystal growth to produce semiconductor grade single crystal silicon suitable for device manufacturing. Generic processes for the purification of silicon and the manufacture of silicon crystal and wafers are well established.

Metallurgical grade poly-silicon (MG) is produced through the reduction of silica by mixing it with carbon and heating, typically in an electric arc furnace, to over 1900 C◦. Silicon produced by this method typically contains 2% impurities although this may be reduced somewhat through the use of higher purity silica and carbon feed materials. The most commonly used process for further purification to electronic grade silicon converts the metallurgical grade material to trichlorosilane (TCS), which is in liquid form and easily purified through subsequent distillation.

$$Si(MG) + 3HCl \longrightarrow SiHCl_3 + H_2 \qquad II.1$$

This typically takes place in a fluidized bed reactor at about 300 C. The boiling point of TCS is 31.8 C◦ and it is easily distilled to produce a very high purity liquid. The liquid TCS is then commonly converted to solid poly-silicon by the Siemens process [46], shown in Fig.II.3 in which it is passed through a chemical vapor deposition (CVD) reactor together with hydrogen at a temperature in the region of 1000 C◦–1200 C◦. The TCS decomposes, depositing silicon onto thin, high purity silicon rods (known as B slim rods placed in the reactor, resulting in electronic grade (EG) poly-silicon

$$SiHCl_3 + H_2 \longrightarrow Si(EG) + 3HCl \qquad II.2$$

Other intermediate compounds such as silicon tetrachloride ($SiCl_4$) and silane (SiH_4) can also be used. An alternative method of production involves decomposition of silane in a fluidized bed reactor (FBR) [48]

$$SiH_4 + H_2 \longrightarrow Si(EG) + 3H_2 \qquad II.3$$

This technique utilizes heated silane and hydrogen gases, which are injected into the bottom of the reactor causing a bed of small silicon seed granules to become fluidized. The silane decomposes in the hot reactor and silicon is deposited on the seeds causing them to grow in size and weight. Once grown to the desired size, the granules (Fig.II.5) are extracted from the bottom of the reactor while fresh seed particles are fed into the top of the reactor. Fluidized bed reactors utilize nearly all the silane gas fed into the reactor, provide superior heat and mass transfer characteristics, and are energy efficient. As highlighted in Fig.II.5 FBR process is also a continuous process while the Siemens process is a batch process. Thus the

FBR process is more economical than the Siemens process and is becoming more widely adopted.

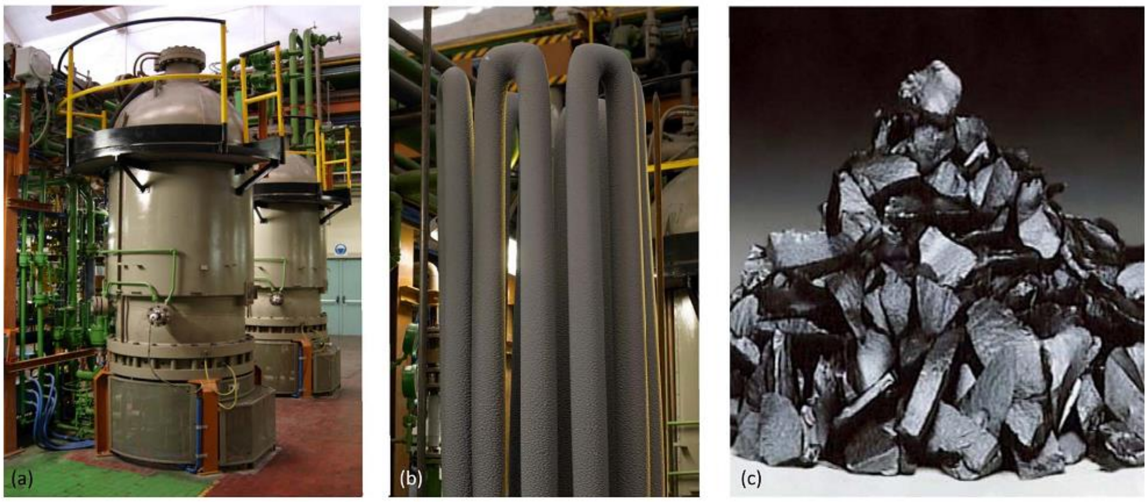


Figure II.3: About 80% of the world's polysilicon is produced using the Siemen's process developed in the 1950s [48]

(a) Basic Siemen's reactor

(b) As grown poly-silicon rods after a reactor run. (Current generation reactors have many more rods.)

(c) Final poly-silicon chunks ready for loading into a crystal growth furnace

Electronic grade polysilicon has impurities in the low parts per billion (ppb) range or less, a necessary requirement for production of semiconductor devices. In the solar industry, the goal is to be able to produce energy at prices competitive with fossil fuels. To this end, solar cell manufacturers typically use solar grade silicon, which is not quite as pure but is typically cheaper. In times of shortage, market prices for silicon rise significantly and this has prompted some companies to develop B upgraded metallurgical grade (UMG) silicon, based on alternative methods for purifying MG silicon [48][49]. In one such approach, impurities in MGS are removed by various hydrometallurgical processes such as acid leaching. While leaching is effective in removing impurities like Fe, Cr, Mn, Ni, and Ti, reducing phosphorus and boron to acceptable levels is particularly challenging, which impacts manufacturing yield.

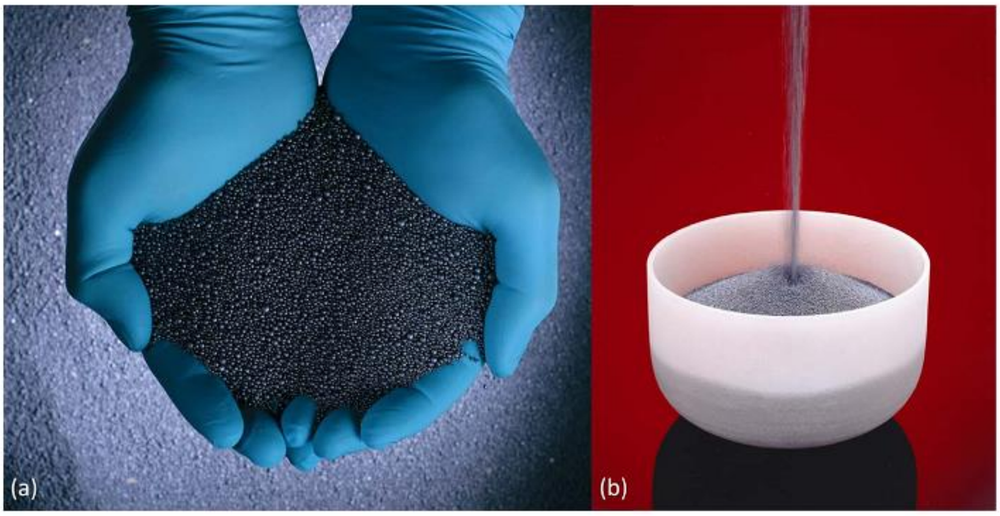


Figure II.4: Granular poly-silicon produced in a fluidized bed reactor [52]

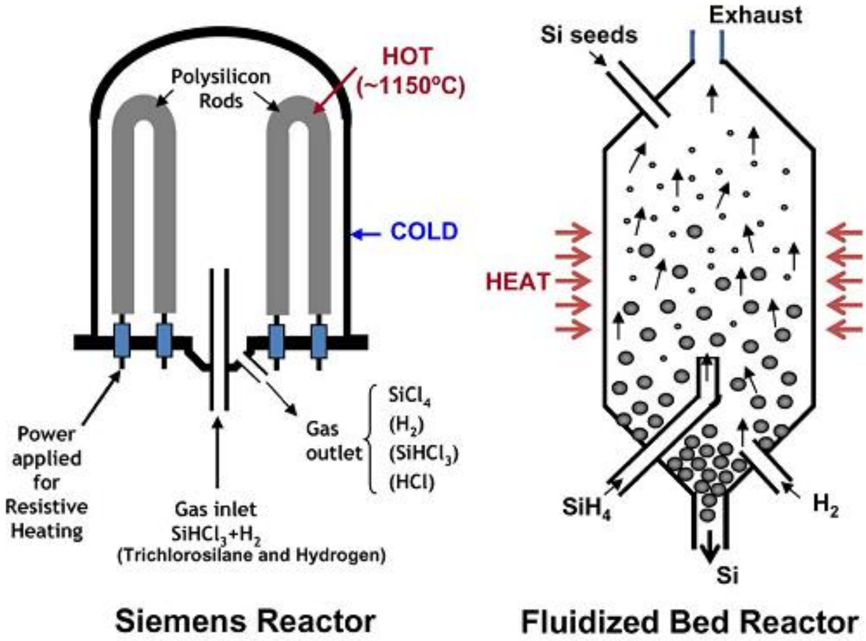


Figure II.5: Schematic of Siemens and fluidized bed (FBR) reactors producing chunk and granular poly-silicon materials [52]

II.5.Growth of Single Crystal Silicon

The industry standard for production of mono-crystal silicon for semiconductors is the Czochralski (CZ) method. Use of melt-based growth for semiconductor crystal growth was pioneered by Teal and Little by demonstrating the growth of single crystal Ge [50], [51]. Later, Teal and Buehler grew CZ–Si using the same technique, but they could only grow dislocated single crystals of specified orientation [52]. The first demonstration of dislocation-free CZ silicon crystal growth was demonstrated in 1959 by Dash, using a modified seeding technique [53]. Growth of silicon crystals by the CZ method has been widely studied over the course of the following five decades and significant progress has been made (Fig.II.6). Dislocation-free, high-purity silicon crystals up to 450 mm in diameter are now possible on a commercial scale.

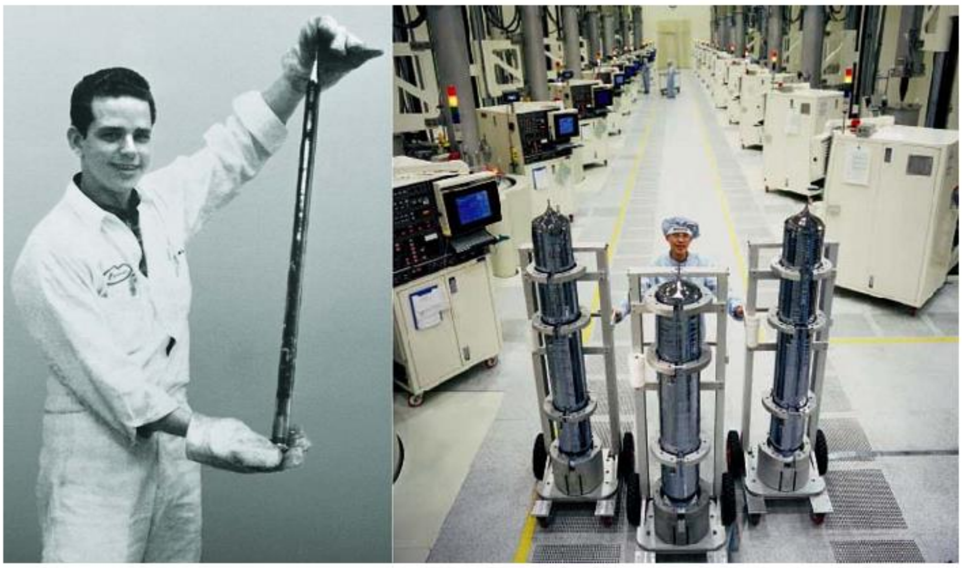


Figure II.6: Early days of Czochralski (CZ) growth crystals were small and easy to handle [54]

The development of several generations of CZ single crystal pullers for growth of large crystals is shown in Fig II.7. Electronic grade poly-silicon is stacked in a high purity quartz crucible inside a crystal pulling furnace. The starting poly-silicon charge, which for 300-mm crystals can weigh 300 – 400 kg, is heated to a little over the melting point (1415 C◦) (Fig.II.8). A silicon seed crystal is dipped into the melt and slowly withdrawn at a controlled rate while the crucible and seed are slowly rotated in opposing directions. The critical variables are rates at which the crystal and crucibles are rotated and the pull rates. In the initial stages, the pull rate is quite high and the growing crystal is only about 3–4 mm in diameter. This narrow portion of the crystal is called the B neck and was first used by Dash for producing a dislocation-free crystal and is standard practice in the industry today. In (111)- and (100)-oriented Si seed crystals, dislocations introduced due to the thermal stress of introducing the seed into the hot melt will propagate obliquely to the growth direction and will terminate on the sides of the neck rather than propagating down into the body of the growing crystal, provided the neck-length-to-diameter ratio is sufficiently large. This was an important breakthrough for the reliability of semiconductor device fabrication processes since dislocations can be killer defects in diode and transistor fabrication. Once the neck is several centimeters long, some heat is removed from the system and the pull rate is slowed allowing the crystal diameter to increase to the desired dimension. Control of pull rate (primary, fast response control) and temperature (secondary, slower response control) enables growth of large single crystals of the required diameter. At the end of crystal growth, the diameter of the crystal is tapered to form a conical tail that minimizes the number of dislocations formed by the thermal shock of withdrawing the crystal from the melt, and allows these dislocations to propagate out of the sides of the cone rather than into the body of the crystal maintaining a dislocation-free crystal.

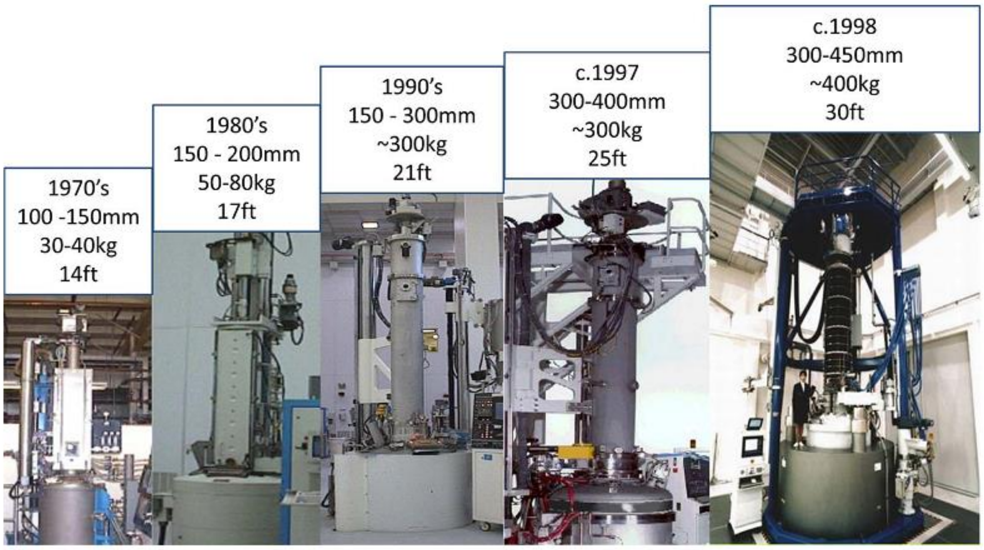


Figure II.7: Examples of progress in Czochralski crystal pullers from 1970 through current diameter capability [54]

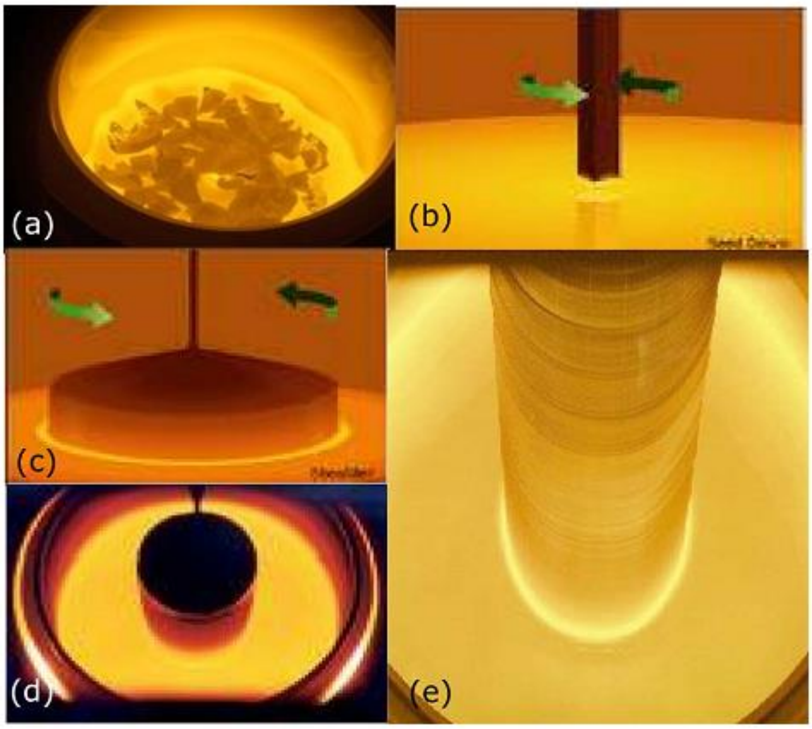


Figure II.8: Various stages of Czochralski crystal growth [54]

(a) Meltdown

(b) Seed dip

(c) Top

(d) Shoulder

(e) Body

By the mid-1960s, dislocation-free CZ silicon crystals could be produced. Through the 1960s and 1970s, much work was done on elucidating the basic physics and materials science of the CZ silicon process. A great deal of effort was expended on identifying, characterizing, and reducing impurities in the CZ growth process, notably carbon, oxygen, and boron, which were at much higher levels than those of FZ silicon, and caused problems in certain device applications. With diligent effort and the advent of low boron poly-silicon from the Siemens process, the impurity levels of CZ were greatly reduced, and the CZ process displaced the FZ process in all but a few specialty applications.

With impurities under control, attention in the 1980s and 1990s turned to B defect engineering of the CZ silicon crystal, the defects referred to being oxygen precipitates and agglomerated intrinsic point defects.

In the 1990s, work turned to the control and engineering of agglomerated intrinsic point defects. Two types of intrinsic point defect are present in silicon, vacancies (silicon atoms missing from lattice sites) and self-interstitials in which extra silicon atoms are presented at interstitial or nonlattice sites. At high temperatures, close to the melt interface, a state of dynamic equilibrium exists in which interstitials and vacancies (a Frenkel pair) are continually being created and destroyed. As the crystal cools, the transport of these defects through highly temperature-dependent diffusion and recombination mechanisms results in one species of point defect or the other predominating. If the predominant species becomes sufficiently supersaturated, the point defects can agglomerate into defect clusters. Early CZ silicon exhibited such defect clusters called A-swirl and B-swirl defects due to the swirl pattern they exhibited on wafers, and which were found to be deleterious to device fabrication.

Understanding and controlling these agglomerated defects became a major challenge and the semiconductor industry started employing high-resolution analytical techniques such as transmission electron microscopy (TEM). First detailed characterization of swirl defects were made by researchers at Philips Research Labs and Bell Telephone Labs in the early 1970s [55]–[56], who found them to be self-interstitials that had agglomerated into clusters and dislocation loops. As further improvements in CZ growth allowed for faster pull rates, a curious thing happened. The A- and B-swirl defects disappeared and were replaced by a new type of defect, called a D-defect, or later, a crystal-originated particle or pit (COP), found to be a vacancy cluster, i.e., a small void. At first, these D-defects appeared rather benign, but as device scaling drove to thinner gate oxides, they were found to cause degraded gate oxide integrity at oxide thicknesses less than 100 nm. A breakthrough in the understanding of point defect behavior of Si was made in 1982 by Voronkov [57], who proposed a model explaining how changing silicon crystal growth conditions could change the type and concentration of predominant point defect in the crystal, a behavior unique to silicon. He recognized that the transition between interstitial-rich and vacancy-rich silicon depended on the ratio of the growth rate to the axial thermal gradient at the melt interface (V/G). For values of V/G less than a critical value, the predominant point defects would be interstitials, while for values of V/G greater than this critical value, they would be vacancies. The farther V/G is from this critical value, the larger the concentration of the predominant point defects. This work was further refined over the next ten years in collaboration with Falster [58], [59]. They realized that if (V/G) could be maintained very close to the critical value during crystal growth, the resulting vacancy and/or interstitial concentrations will remain below critical super saturation levels, and agglomeration of these point defects will not occur. They developed predictive models to determine parameters to grow the entire crystal under conditions where V/G was close to the critical value in which a crystal free of agglomerated point defects could be grown [60][61]. Subsequently teams of engineers and scientists developed models in various degrees of detail and created hot zone designs which enabled such crystals to be manufactured [62].

II.6.Wafer Technologies for PV

Photovoltaic (PV) constitute a large and growing market for crystalline Si (c-Si) and multi-crystalline (mc-Si) wafers. Over the last five to six years, the role of silicon-based PV has become significantly more important for silicon wafer technology. The amount of silicon consumed in the solar industry has been rapidly growing, with PV consumption now accounting for over 80% of the worldwide production capacity of high-purity poly-silicon. An example of a silicon solar power plant is shown in Fig.II.12. While built on the infrastructure associated with half a century of progress in semiconductor wafer technologies, silicon PV technology is emerging as a separate R&D enterprise with its own technical and market drivers, primarily driven by the need for lower cost and high capacity.

Single-crystalline technology is expended because it requires pure silicon bars. It has the highest efficiency (14% to 16%) and has the advantage of reducing even the module size under power, which is useful in situations where space saving is required.

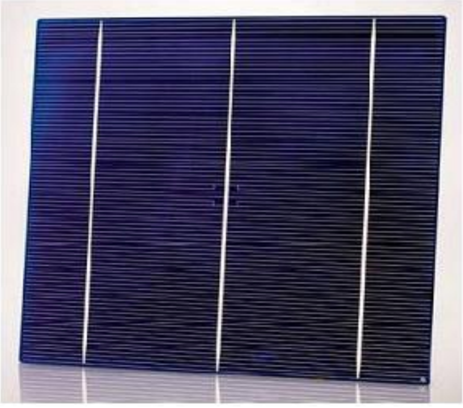


Figure II.9: Silicon Mono-crystalline [63]

Polycrystalline technology is achieved by re-melting waste silicon crystals in the electronics industry, and its power consumption is two to three times lower than the previous technology. Its yield is lower (12 to 14%), but its cost is more advantageous, which means that the technology currently dominates the market.

Figure II.10: Silicon Polycrystalline [63]

Table II.1: Comparison between Mono and Poly-crystal

Type	**Mono-Crystal Silicon**	**Poly-Crystal Silicon**
Lifetime	35 ans	35 ans
Advantages	Good performance in direct sun	Good performance in direct sun (less than mono-crystalline
Inconvenience	Poor performance in the diffused sun but do better than Poly-silicon (Cloudy weather) High price	Poor performance in diffuse sun (Cloudy weather) High price

Unlike microelectronics where the primary metric is Moore's law driven scaling and the resulting improvements in device performance, PV does not have a direct analog to device scaling. Based on the three decades of high volume PV manufacturing, the technology learning curve for Si PV (see Fig.II.13) shows that the price of technology ($\$/W_P$) has decreased by 20% for each doubling of cumulative installed capacity [63] [64]. The challenge is to sustain this rate of technology and cost improvements, and bring PV to grid parity without feed-in-tariffs and other subsidies. With limited opportunity for dramatic improvements in PV efficiency, there is an industry-wide push to reduce the active Si content of the cell in combination with improved light management.

One of the critical drivers for crystalline Si is the need to achieve grid parity and to make PV competitive with power grid retail prices. While achieving grid parity will need a regulatory framework that allows for optimal deployment of resources, reducing materials and manufacturing costs also needs to occur. With increased manufacturing volumes, there is limited scope for cost reduction through manufacturing efficiencies alone; the input cost of module materials, especially the amount of Si used, becomes a bigger factor. Thus, at the wafer level, reducing the consumption of silicon is one of the main drivers for solar wafers, so is the need for new and improved silicon feedstock and wafer (and wafer equivalent) manufacturing technologies.

Figure II.11: Austin Energy solar farm [63]

Built by Sun Edison, can generate up to 30 MW, enough electricity to power about 5000 homes. It is located about 20 miles east of Austin in Webberville. Its footprint covers a 380 acre site, and has 127 000 solar panels that track the sun’s path.

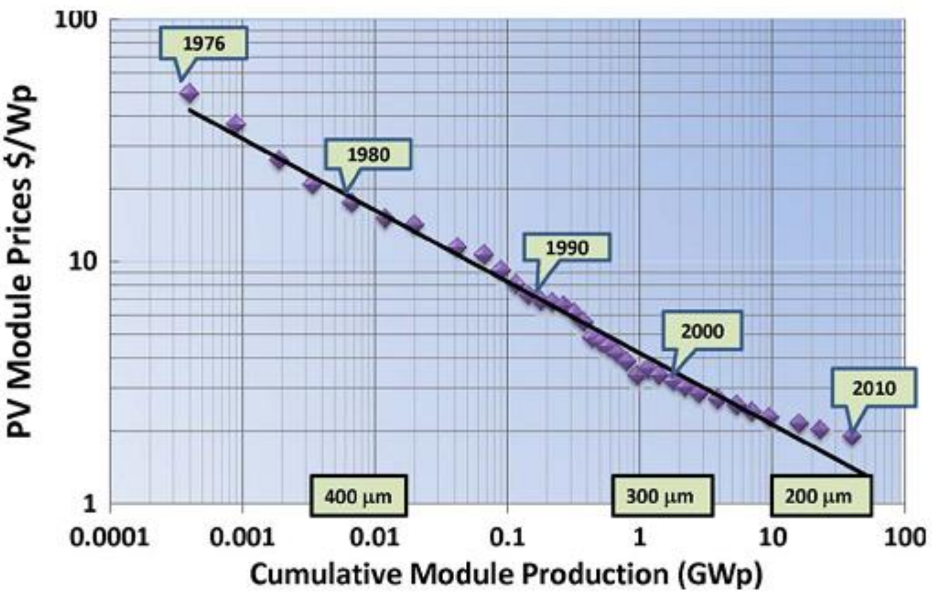


Figure II.12: Price learning curve for crystalline Si modules as function of installed capacity [64]

II.7.Conclusion

Silicon is abundant and widely used in solar energy because it is easy to extract and to produce the process of silicon processing is expensive, but the development of technology has helped reduce the price of solar cells. We have to find faster and cheaper processing methods because the old methods have reached a point that cannot be developed. Poly-silicon production process which means that the technology currently dominates the market but the mono-silicon is better because its yield is more than the poly-silicon.

Chapter III: Simulation and Discussion of Results

Introduction

To develop an accurate equivalent circuit for a PV cell, it is necessary to understand the physical configuration of the cell elements as well as the electrical characteristics of each element. According to this philosophy, several electrical models have been proposed to represent the photovoltaic cell.

This model will have to remain general and the determination of its parameters will be done on databases provided by the manufacturers of panels. The aim is thus to avoid recourse, which is all too often necessary in the case of photovoltaic installations, to many long and complex experiments. Given the limited amount of information given by the manufacturers, great precision will not be possible, but anyone wishing to estimate the interest of a photovoltaic installation can use this model, without too much knowledge science is required.

An association of (Ns) cells in series figure III.1 makes it possible to increase the voltage of the photovoltaic generator. The cells are then crossed by the same current and the characteristic resulting from the series grouping is obtained by adding the voltages elements of each cell. The equation summarizes the electrical characteristics of a serial association of (Ns) cells.

$$V_{coNs} = N_S * V_{Co} \qquad \text{III.1}$$

$$I_{CC} = I_{CC} * N_S \qquad \text{III.2}$$

V_{coNs} : The sum of the open circuit voltages of N_S cells in series

I_{ccNs} : short circuit current of N_S cells in series

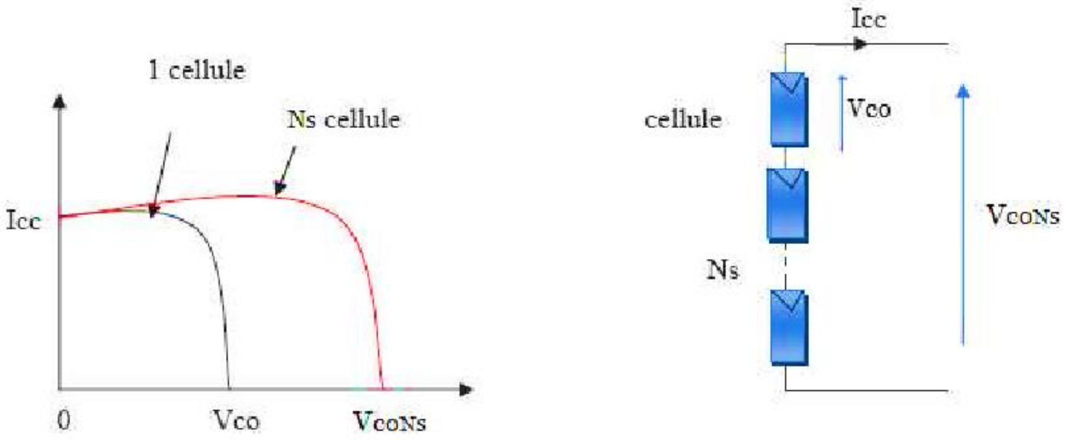


Figure III.1: Serial Connection of a solar cell

A parallel association of (N_P) cell figure III.2 is possible and allows increasing the output current of the generator thus created. In a group of cells identical connected in parallel, the cells are subjected to the same voltage and the resulting characteristic of the array is obtained by addition of the currents.

$$\mathrm{I}_{\mathrm{ccNp}} = \mathrm{N}_P * \mathrm{I}_{CC} \qquad \text{III.3}$$

$$\mathrm{V}_{CO} = \mathrm{V}_{\mathrm{coNp}} \qquad \text{III.4}$$

I_{ccNp} : The sum of short circuit currents of (N_P) cell in parallel

V_{coNp} : Open circuit voltage of (N_p) cells in parallel

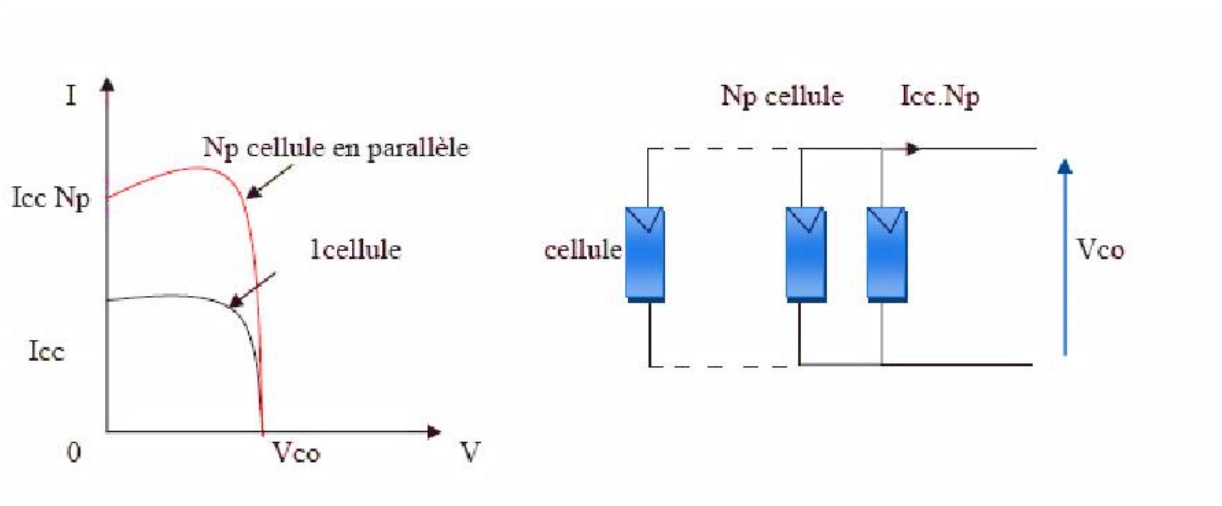


Figure III.2: Parallel Connection of a solar cell

III.1.Modelisation of PV Cell

The modeling of photovoltaic cells necessarily involves a judicious choice of equivalent electrical circuits. To develop an accurate equivalent circuit for a PV cell, it is necessary to understand the physical configuration of the cell elements as well as the electrical characteristics of each element. Table III-1 gives the characteristics of the PV module on this Simulation:

Table III.1: Characteristics of PV

Characteristic	**Values**
Tension on MPP V_{mp}	**39.89V**
Intensity Of Short Circuit I_{cc}	**4.96 A**
Tension of Open Circuit V_{co}	**22.4 V**
Number of Serial Cells	**32**
Number of Parallel Cells	**1**
Voltage / Temperature Factor K_v	**-0.1230 V/K**
Current / Temperature Factor K_i	**0.0032 A/K**
Lightening	**1000 W/m^2**
Temperature	**25 C$^{\circ}$**

III.2Model of PV Cell

An ideal photovoltaic cell can be described simply as an ideal current source which produces a current I_{ph} proportional to the incident light power in parallel with a diode. In addition to the ideal model, the real model takes into account the resistive properties of the cell which are modeled by a series resistance R_s but also the leakage currents modeled by a parallel resistance R_p.

In the real case, there is a loss of voltage at the output as well as leakage currents. This voltage loss is therefore modeled by a series resistor RS and the leakage currents by a parallel resistor R_p.

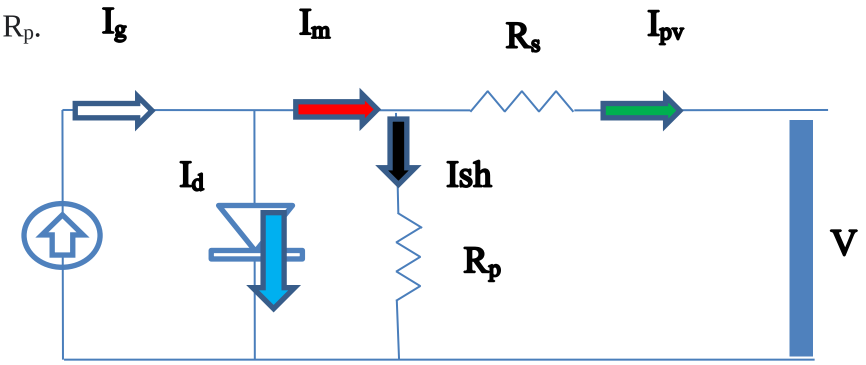


Figure III.3: Electric Circuit of reel PV cell

III.3.Physical Model

The real solar cell (real photovoltaic cell) has a series resistance RS whose influence is stronger when the device operates in the voltage source region, and a resistance parallel RP having a greater influence in the region of operation in source of running.

In photovoltaic models, it is generally assumed that $I_g \approx I_{CC}$ because in the real solar cell, the series resistance is low and the parallel resistance is high. The photonic current of the photovoltaic cell depends directly on the solar irradiance and is proportional to the temperature according to the following equation III.1:

$$\mathrm{Ig} = \frac{\mathrm{G}}{\mathrm{Gref}}\big(\mathrm{Ign} - \mathrm{Ki}(\mathrm{T} - \mathrm{Tn})\big) \qquad \text{III.5}$$

Where:

I_{gn} : Le courant photonique sous condition de référence [A]

K_i : Sensitivity coefficient of intensity to temperature [A/K]

G, G_n : Real Irradiation et Irradiation nominale [W/m²]

T , T_n : Real Temperature and nominal Temperature en [K]

The shunt resistor current equation III.2:

$$\mathrm{Ish} = \frac{\mathrm{V+IpvRs}}{\mathrm{Rp}} \qquad \text{III.6}$$

Diode current I_D expressed in Equation III.3:

$$\mathrm{I}_D = \mathrm{I}_0\left[\exp\left(\frac{\mathrm{V+IpvRs}}{\mathrm{nVt}}\right) - 1\right] \qquad \text{III.7}$$

$$\mathrm{Vt} = \frac{\mathrm{NsKT}}{\mathrm{q}} \qquad \text{III.8}$$

$$\mathrm{I}_0 = \frac{\mathrm{Isc+ki\Delta Tc}}{\exp\left(\mathrm{Vco+}{}^{\mathrm{kv\Delta T}}/_{a\mathrm{Vd}}\right)-1} \qquad \text{III.9}$$

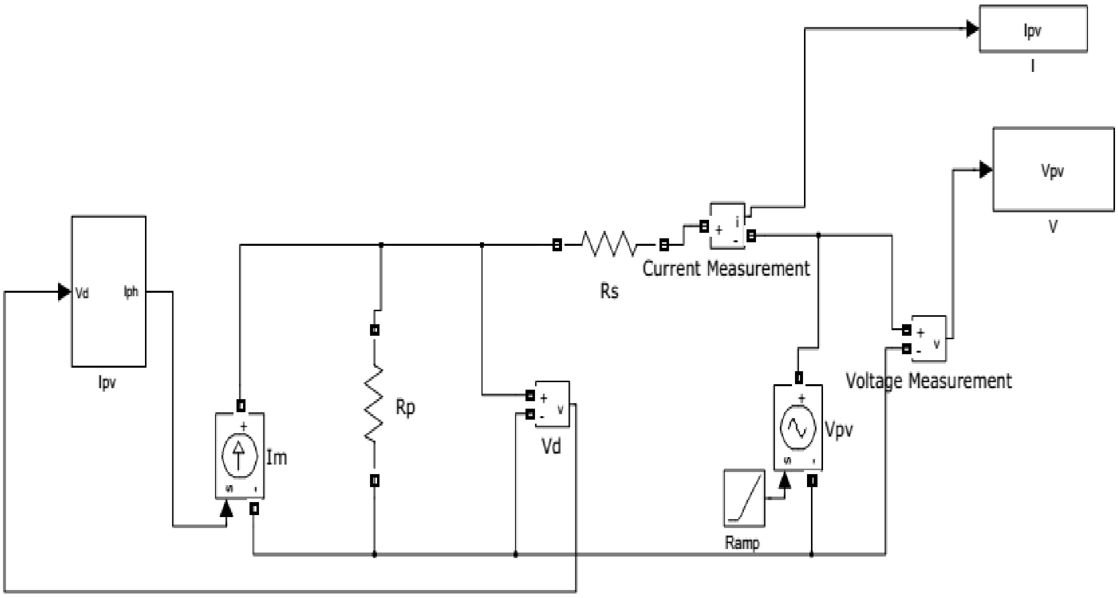
The saturation current I_0 strongly depends on the temperature, the equation (II.9) proposes a different approach to expressing this dependence, such that the net effect of the temperature or linear variation of the voltage in open circuit according to the coefficient of practical voltage/temperature. This equation simplifies the model and cancels the error around of the open circuit voltage and therefore to other regions of the I-V characteristics.

$$I_{Pv} = I_g - I_0\left(\exp\left(\frac{V+IpvRs}{nVt}\right) - 1\right) - \frac{V+IpvRs}{Rp} \qquad \text{III.10}$$

III.4.Simulation the Collection of Light

The synoptic presented in figure II.6, was developed under Matlab/Simulink, for a set of N_{SS} × N_{PP} photovoltaic modules. N_{SS} and N_{PP} are respectively the number of photovoltaic modules in series and in parallel. Each module here consists of NS photovoltaic cells assembled in series.

In general, an array can comprise sets of cells associated in series or in parallel to respectively increase the voltage and the intensity produced. It should also be noted that a solar panel can be made up of a set of modules comprising a defined number of cells:



Figures III.4: Model of PV Array in M/Simulink

III.5.Characteristics Intensity - Tension & Power-Tension

Figure 5 represents the current-voltage I (V) and power-voltage P (V) characteristics of a photovoltaic array (Unit of cells).

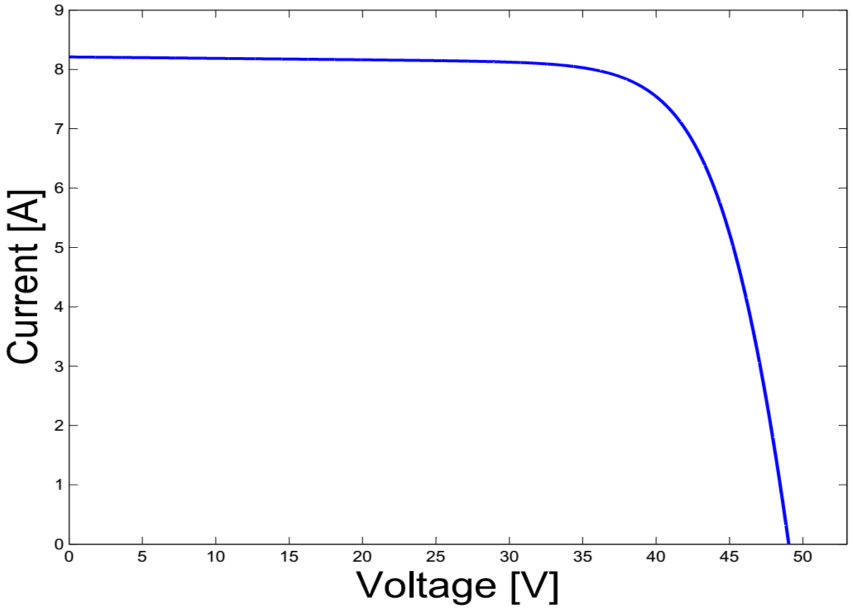


Figure III.5 : Caracteristics I(V) and P(V) of a PV Arrsy

III.6.Effect of Temperature and Light

The characteristic of a PV cell (or of a PV generator) is directly dependent on illumination and temperature.

III.6.1.Effect of the temperature

Temperature is a very important parameter in the behavior of solar cells. The temperature also has an influence on the characteristic of a PV generator. Figure 6 and Figure 7 show the variation in the characteristics of a PV cell as a function of the temperature at a given illumination. The lighting here is set at 1000 W/m^2.

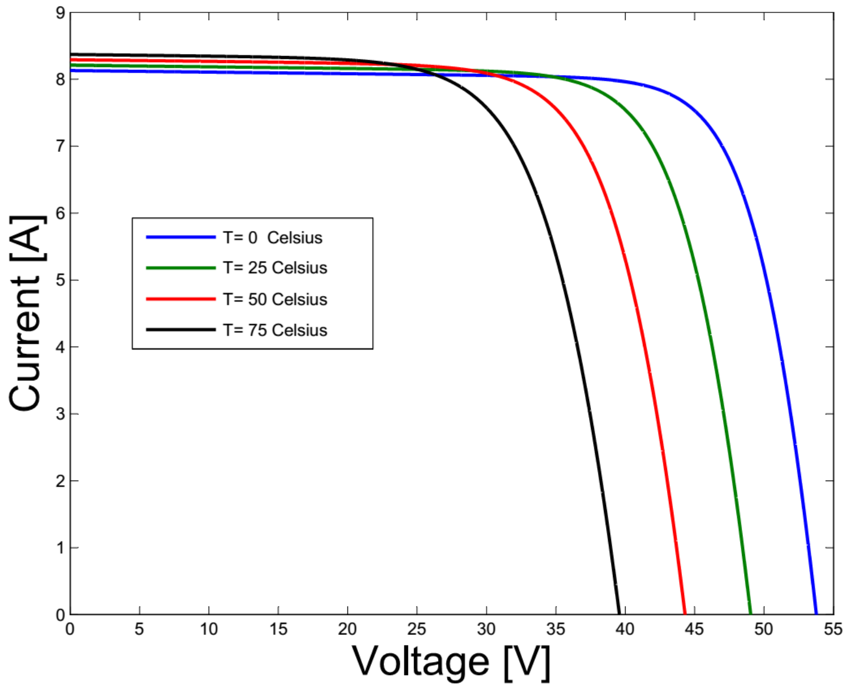


Figure III.6: Temperature Effect on I-V characteristics in PV

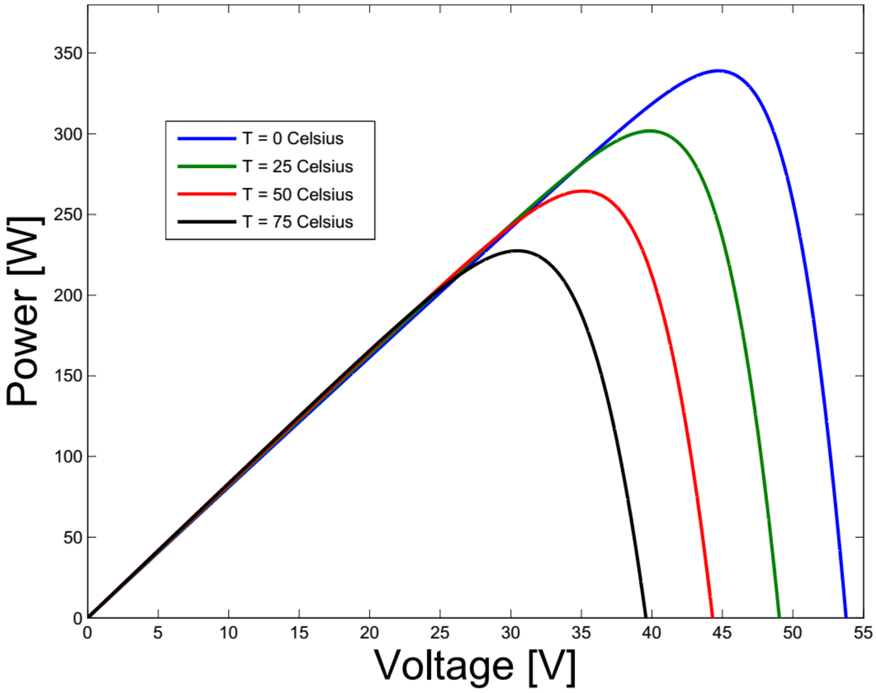


Figure III.7: Temperature Effect on P-V characteristics in PV

Experiment shows that the open circuit voltage of a solar cell decreases with the increase in cell temperature. We notice that the temperature has a negative influence on the open circuit voltage (the higher the temperature, the lower V_{co} is and short-circuit current I_{pv}

increases slowly with temperature). And on the other hand the maximum power of the generator undergoes a reduction when the temperature increases. The voltage / Temperature factor K_v and Current / Temperature factor K_i are different in metals or in semiconductors and they define how the semiconductor handles heat or temperature while absorbing light.

III.6.2.Effect of Irradiation

The variations of current and power as a function of voltage for different levels Illuminations at a constant temperature of 25°C, figure 8 and figure 9 clearly show the existence of maximum on the power curves corresponding to the Maximum Power Points. When the irradiation varies for a given temperature, the current of short-circuit I_{pv} varies proportionally to the irradiation. At the same time, the open circuit voltage V_{co} (no load) varies very little.

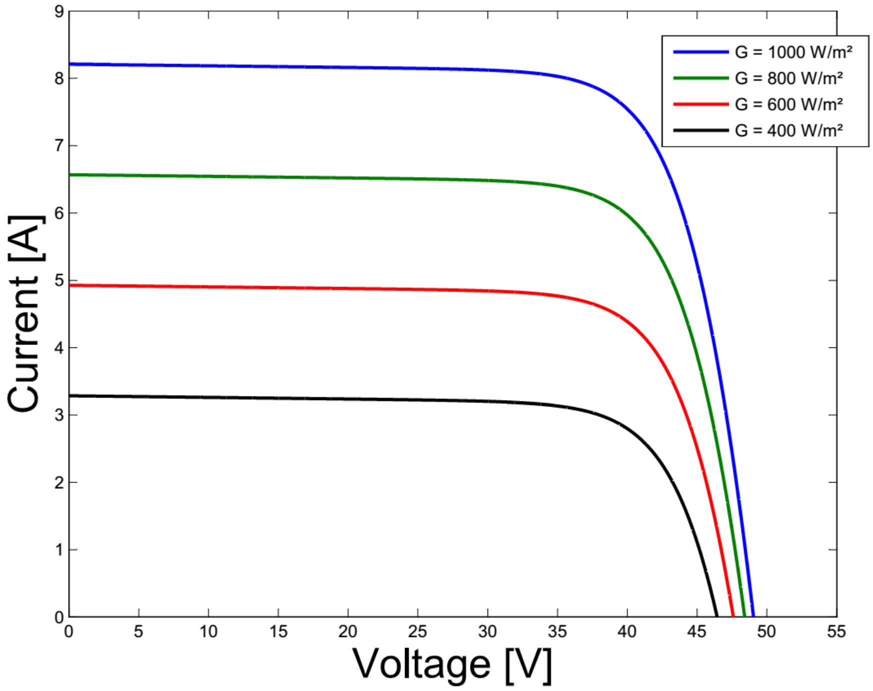


Figure III.8: Irradiation Effect on I-V characteristics in PV

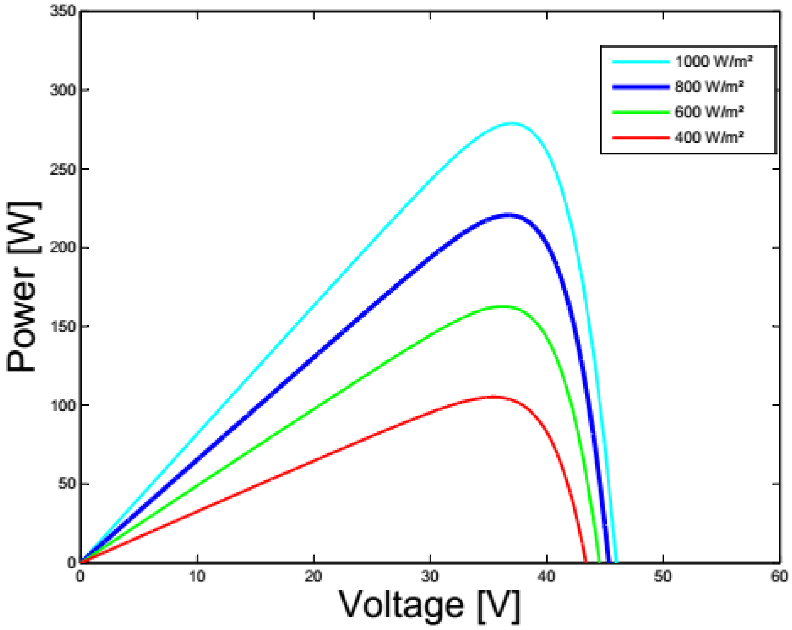


Figure III.9: Irradiation Effect on P-V characteristics in PV

The short-circuit current of a solar cell decreases with the decrease in cell irradiation. The open circuit voltage decrease slowly with irradiation. The maximum power increase when the irradiation increases.

III.7.Effect Serial Resistance

Figures 10 and 11 show the influence of series resistance on the I (V) characteristic and P (V) of the photovoltaic cell.

The series resistance acts on the slope of the characteristic in the area where the photodiode is behaves like a voltage generator. It does not change the open circuit voltage, and when high, it decreases the short circuit current value. .

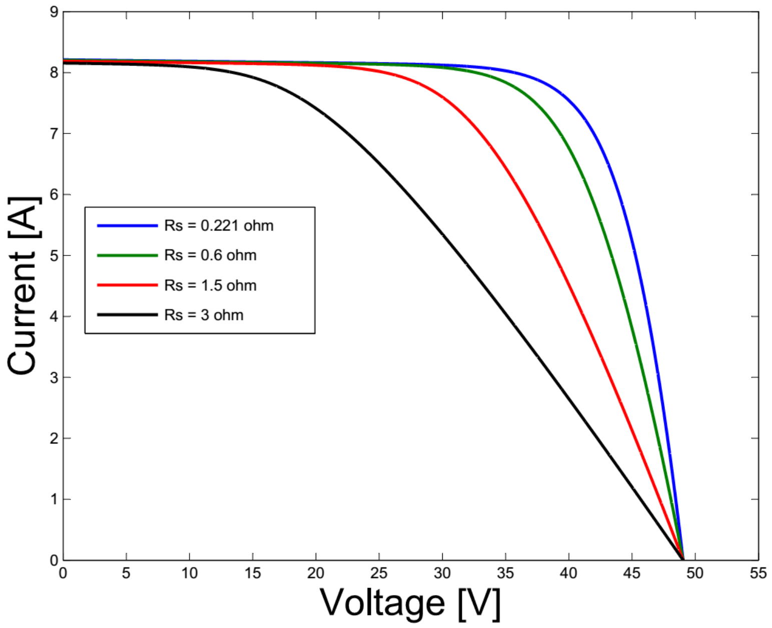


Figure III.10: Effect of Serial Resistance on I-V characteristics in PV

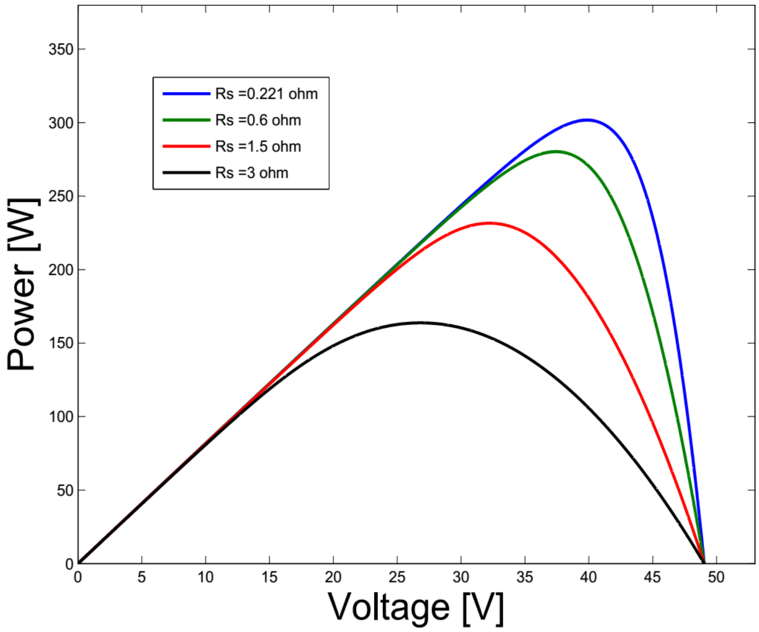


Figure III.11: Effect of Serial Resistance on P-V

The increase in the series resistance results in a decrease in the slope of the curve of Power.

III.8.Effect of the Parallel Resistance

R_p The shunt resistor is a resistor which takes into account the inevitable leaks of the current that occurs between the terminals of a solar cell. In general, the shunt resistance is very high its effect is felt above all in the current generation part.

The influence of the parallel resistance (shunt) on the current-voltage characteristic results in a slight decrease in the open circuit voltage, and an increase in the slope of the I-V curve of the cell in the zone corresponding to operation as a current source. This comes from the fact that it is necessary to subtract from the photo-current, in addition to the direct diode current, an additional current varying linearly with the voltage developed. The power supplied by a solar cell varies with its parallel resistance, the higher this resistance, the greater the power supplied. (Units = V / A / Ω)

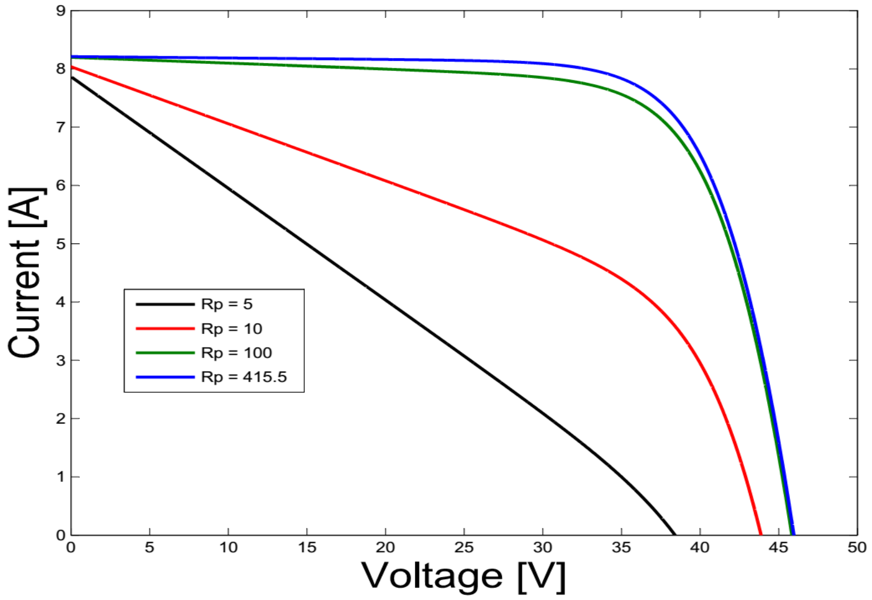


Figure III.12: Effect of Parallel Resistance on I-V

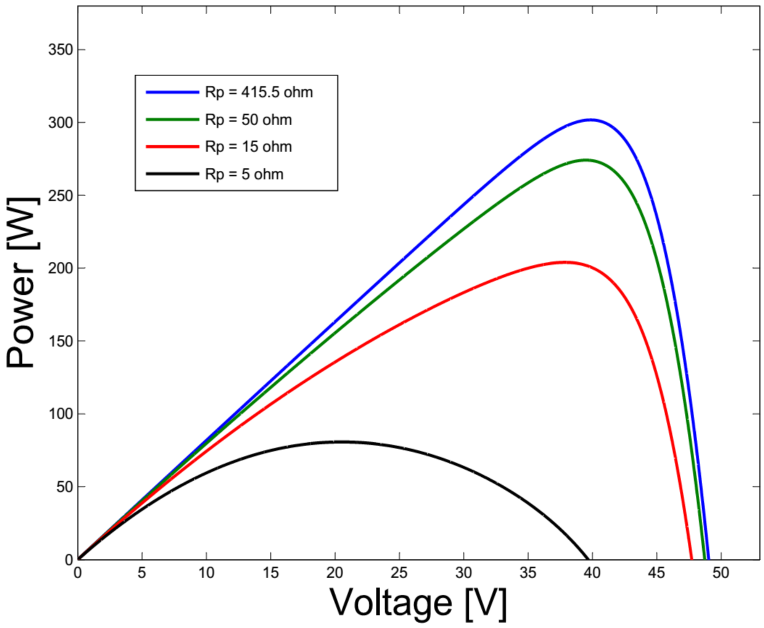


Figure III.13: Effect of Parallel Resistance on P-V characteristics in PV

III.9.Comparison of different Semiconductors Materials

A semiconductor material is one whose electrical properties lie in between those of insulators and good conductors. Examples are: germanium (Ge) and single and poly silicon (Si) and Indium Arsenide (InAS). The efficiency of a solar cell is related to many factors one of the factors is the internal voltage barrier we will see the effect of the internal voltage barrier V_{co} on the efficiency.

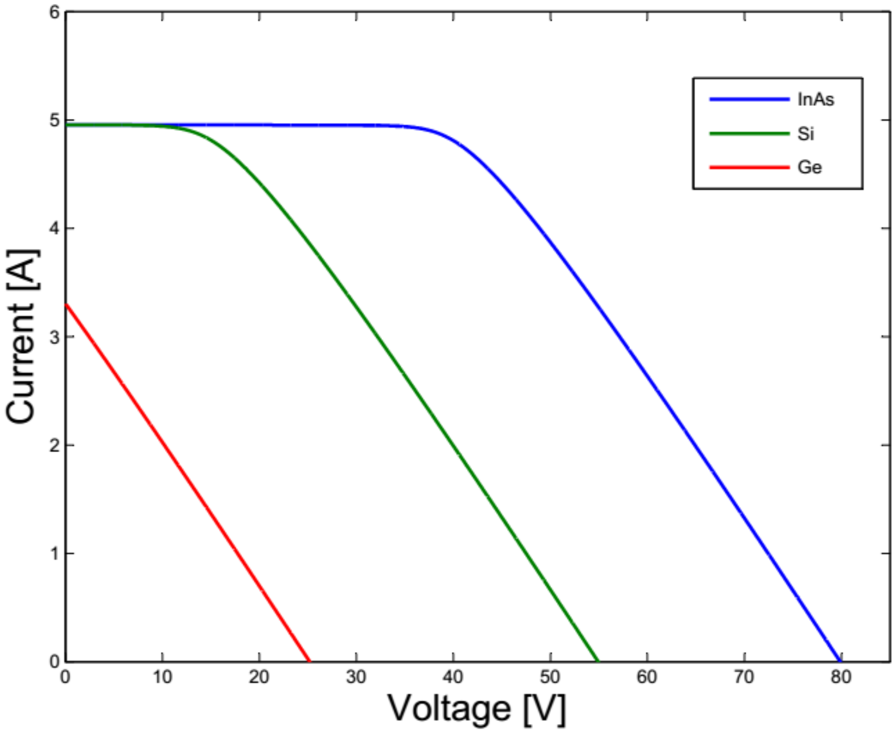


Figure III.14: Internal barrier voltage V_{co} effect on I-V

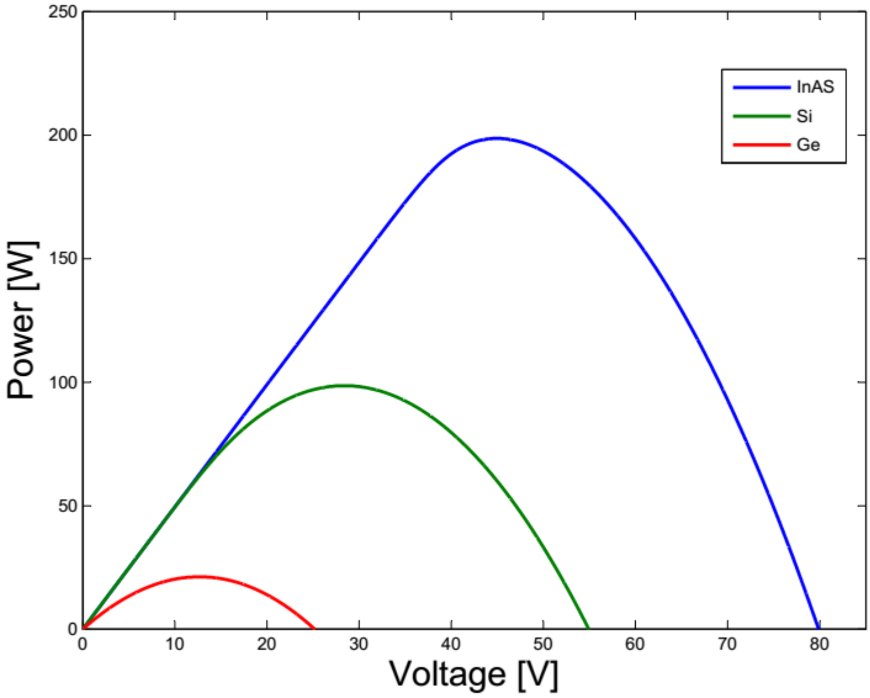


Figure III.15: Internal barrier voltage V_{co} effect on P-V

The Power increase by increasing of the internal barrier voltage V_{co} in the I-V Curve the voltage increase when the value of V_{co} is high like the case of the InAs and the voltage decrease in the case of the Ge when the V_{co} is low as show in Table III.2.

The efficiency of PV cell:

$$\eta = \frac{P_M}{P_{int}} \qquad \text{III. 8}$$

P_M: Maximum Power [W]
P_{int}: The Input Power on the solar cell [W]
For 100 mm² × 100 mm² the input power P_{int} = 10 W and for the 126 mm² × 126 mm² P_{int} = 26 W.

Table III.2: Semiconductors Parameters on a Solar cell

	Germanium	**Poly Silicon**	**Single Silicon**	**Indium Arsenide**
Maximum Power	29.26 W	108.1 W	137.1 W	279.5 W
Vco Array	9.6 V	19.2 V	22.4 V	38.4 V
Efficiency	3.51 %	12.99 %	16.47 %	33.5 %

III.10.Single and Poly Silicon Temperature Effect

In the silicon manufacturing industry poly silicon crystal is cheaper than single silicon Crystal mc-Si Have a lower efficiency than the single silicon from the advantages that c-Si has that it can handle temperature slightly better than the poly-silicon.

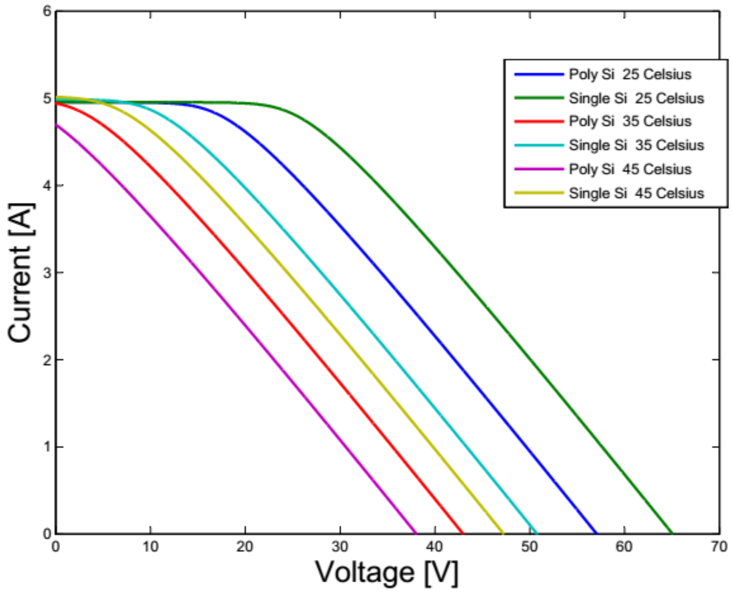


Figure III.16: Temperature effect on Single and Poly Silicon I-V

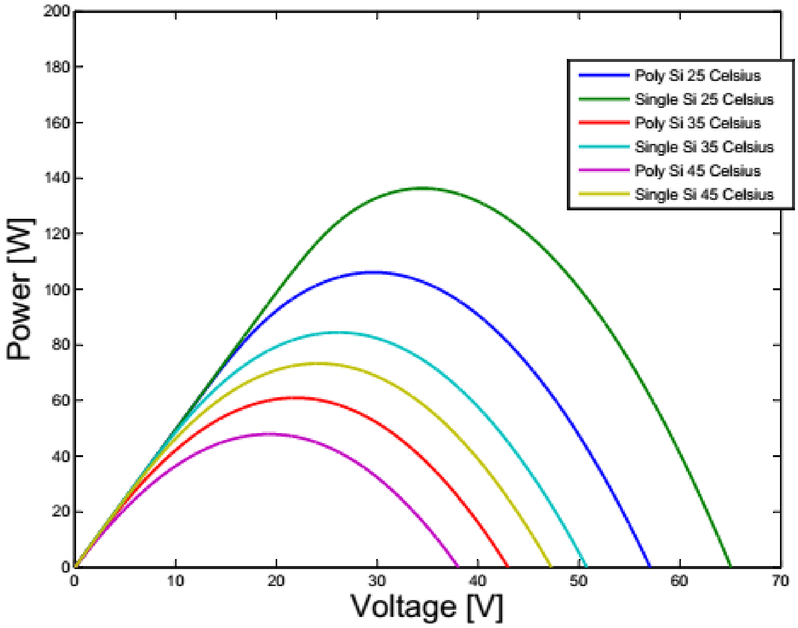


Figure III.17: Temperature effect on Single and Poly Silicon P-V

When temperature raise the voltage V decrease the factors that determine the effect of temperature on the semiconductors are K_i and K_v. For low changes on temperature single crystal has the advantage of working slightly better than the poly crystal but when the temperature rise to a certain level it effect both of them single and poly crystal.

Table III.3: Silicon Temperature Effect

	T	**G**	**Pmax**	**Efficiency**
Single Si	25 C°	1000 W/m²	137.1 W	16.47 %
	35 C°	1000 W/m²	92.76 W	11.15 %
	45 C°	1000 W/m²	81.61 W	9.81 %
Poly Si	25 C°	1000 W/m²	108.1 W	12.99 %
	35 C°	1000 W/m²	53.74 W	6.46 %
	45 C°	1000 W/m²	41.6 W	5 %

III.11.Single and Poly-Silicon Irradiation Effect

Single silicon crystal technology has the highest efficiency the importance of the 2 % difference is clear shown in reducing space the two technologies are equal but another advantages that single silicon have that c-Si can an work better in the cloudy weather.

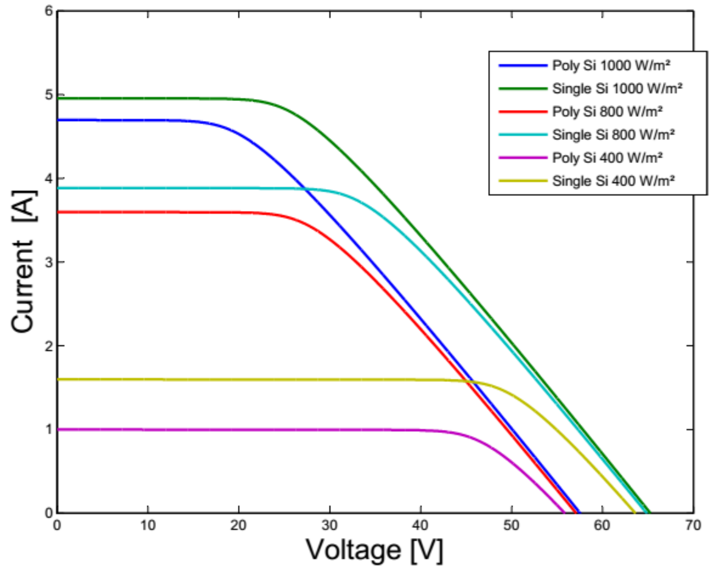


Figure III.18: Irradiation effect on Single Silicon I-V

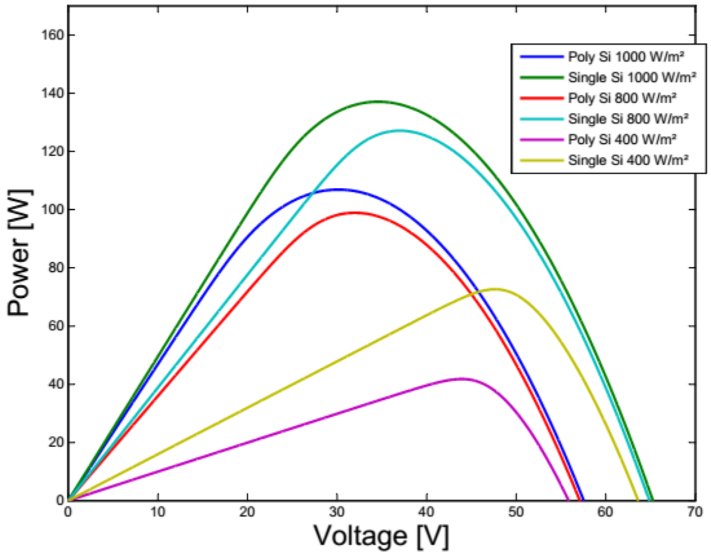


Figure III.19: Irradiation effect on Single Silicon P-V

The photonic current I_g defines the generation power of a solar cell and the main parameter that determines solar efficiency on the cloudy weather is the I_{gn}. When the photonic current increase the generation of the solar cell increases with it Table III.4 shows the influence of the photonic current while changing the irradiation.

Table III.4: Irradiation Effect on Silicon

	T	**G**	**Pmax**	**Efficiency**
Single Si	25 C°	1000 W/m²	137.1 W	16.47 %
	25 C°	800 W/m²	128.2 W	15.4 %
	25 C°	400 W/m²	85.58 W	10.28 %
Poly Si	25 C°	1000 W/m²	108.1 W	12.99 %
	25 C°	800 W/m²	90.87 W	10.92 %
	25 C°	400 W/m²	54.03 W	6.49 %

III.12.Conclusion

In the last chapter, we have presented fundamental electrical characteristics of a photovoltaic cell (photovoltaic module). We have seen that the PV cell has a nonlinear I(V) characteristic, has a maximum power point (MPP) characterized by a current (I_{max}) and a voltage (V_{max}) and that it can be modeled by an electrical circuit simple.

We have seen the influence of the various external parameters on this characteristic. The short-circuit current evolves mainly with the illumination and the open circuit voltage with the temperature. The performance of a photovoltaic cell is all the more degraded as R_s is large or R_p is small. We have seen that the increase of the open circuit voltage is, increasing the efficiency of a solar cell.

General Conclusion

Photovoltaic solar energy comes from the direct transformation of part of the solar radiation into electrical energy. This energy conversion is carried out by the cell photovoltaic based on a physical phenomenon called photovoltaic effect. Voltage product may vary depending on the material used to manufacture the cell.

The performance of a photovoltaic module is strongly influenced by the climatic conditions, particularly solar irradiation and module temperature. We opted for the model with a diode to simulate the operation of the module photovoltaic for different irradiation and temperature conditions. The efficiency of a solar cell is related also the quality of the material use in the solar panel.Also with the manufacturing process and the climate condition affect the yield in a solar cell. Both of the two materials that this memory discussed single and poly crystal silicon are quite the same but the extra manufacturing process that single crystal need give us more efficiency the main point that the photovoltaic industry need is to find new modular , fast and cheap ways of manufacturing silicon crystal

Photovoltaic is very suitable as the power supply for remote communication equipment. Its use is increasing rapidly to produce electricity in grid-connected houses and buildings in industrialized countries, despite a 5 to 10 times higher cost than conventional electricity. Often, publicly funded programs are required to enable photovoltaic compete by partially offsetting its higher costs.

In summary it is very likely that photovoltaic will become in the next half century an important source of world electricity. Public support and global environmental concerns will keep photovoltaic viable, visible, and vigorous both in new technical developments and user applications. Nations which encourage photovoltaic will be leaders in this shining new technology, leading the way to a cleaner, more equitable twenty-first century while those that ignore or suppress photovoltaic will be left behind in the green, economic energy revolution.

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Abstract

نظام توليد الطاقة الكهروضوئية (نظام الكهروضوئية) هو جهاز يقوم بتحويل الطاقة الشمسية إلى كهرباء بواسطة الخلايا الشمسية ومبدأ الخلايا الشمسية هو استخدام خصائص إلكترونيات مواد أشباه الموصلات في تحويل P-V. نظام الكهروضوئية وتطبيقه هو مشروع بحثي عميق ، يواجه القرن الحادي والعشرين الذي يجمع استخدام الطاقة المتجددة الخضراء ، وتحسين البيئة البيئية ، وتحسين الظروف المعيشية للناس ككل ، سيكون له فوائد كبيرة للاقتصاد و المجتمع ، ويحتوي أيضًا على دراسات أكاديمية غنية وقضايا نظرية أساسية. تشرح هذه المذكرة خلفية وأهمية نظام الكهروضوئية و التقنيات المستخدمة في الطاقة الضوئية.

الكلمات المفتاحية : الطاقة الضوئية , الطاقة الشمسية , بلورات السيليكون

Photovoltaic power generation system (PV system) is a device which changes the solar power into the electricity by solar cells and the principle of the solar cells is the use of semiconductor materials electronics characteristics of P-V conversion. PV system and its application is a profound research project, facing the 21st century which gathers the utilization of green renewable energy, improve the ecological environment, ameliorate people's living conditions as integral whole will be of great benefits to economy, politics, coupled with society, and also contains rich academic studies value and the basic theory issues. This Memory expounds the background and significance of PV system, discusses the forefront of the technologies used in PV.

Keywords: Photovoltaic, Light Energy, Solar Energy, Crystal Silicon

Le système de production d'énergie photovoltaïque (système PV) est un dispositif qui transforme l'énergie solaire en électricité par des cellules solaires et le principe des cellules solaires est l'utilisation de matériaux semi-conducteurs électroniques caractéristiques de conversion P-V. Le système PV et son application est un projet de recherche approfondi, face au 21e siècle qui rassemble l'utilisation de l'énergie renouvelable verte, améliore l'environnement écologique, améliore les conditions de vie des gens car l'ensemble intégral sera de grands avantages pour l'économie, la politique, associée à la société, et contient également une riche valeur d'études universitaires et les questions théoriques de base. Cet article expose le contexte et l'importance du système PV, discute de l'avant-garde des technologies utilisé dans PV.

Mot Clé : Photovoltaïque, Energie de Lumière, Energie Solaire, Silicium Cristalline