

Photovoltaic Solar Cells



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Abstract

Employing sunlight to produce electrical energy has been demonstrated to be one of the most promising solutions to the world's energy crisis. The device to convert solar energy to electrical energy, a solar cell, must be reliable and cost-effective to compete with traditional resources. This paper reviews many basics of photovoltaic (PV) cells, such as the working principle of the PV cell, main physical properties of PV cell materials, the significance of gallium arsenide (GaAs) thin films in solar technology, their prospects, and some mathematical analysis of p-n junction solar cells. Furthermore, the paper presents the standard model of solar cells with the application of this model to different PV technologies together with the main findings. Moreover, the paper explores the role of numerical and mathematical modelling of PV cells by MATLAB/Simulink and COMSOL in evaluating the power conversion efficiency (PCE) of the PV cells and determining the main parameters affecting the power output at various conditions.

Keywords

photovoltaic (PV); semiconductors; gallium arsenide (GaAs); power conversion efficiency (PCE); current-voltage (I-V); power-voltage (P-V) characteristics

Introduction

Global environmental concerns and the increasing energy demand, coupled with continuous progress in renewable energy technology, are encouraging the utilization of alternative energy resources. Solar energy is the most affordable and abundant of all long-term natural resources to date [1]. Solar PV technology is one of the optimum ways

to utilize solar power to generate electricity by converting the sunlight to direct current in solar cells or PV cells [2,3].

PV energy conversion utilizes devices based on electronic semiconductors, particularly but not exclusively, crystalline silicon (c-Si) or thin-film semiconductor materials. A (c-Si) based solar system is usually constructed from two essential types of crystalline materials, monocrystalline and multi-crystalline solar modules. Single-crystal semiconductors have superior electrical characteristics (20% efficiency) comparable to polycrystalline materials. Nevertheless, monocrystalline PV modules are non-economical as crystalline wafer-based technology is too expensive [4,5].

Thin film technology is an alternative technique that uses usually amorphous silicon (a-Si) or other semiconductor materials (i.e., cadmium telluride (CdTe), copper indium gallium selenide (CIGS), or gallium arsenide (GaAs)) in its structure. A thin-film solar cell is much thinner than a conventional (c-Si) cell. The film's thickness is a few nanometers (nm) to tens of micrometres (μm), which allows thin-film modules to be light and flexible. Furthermore, thin-film technology is generally cost-effective as compared to (c-Si) wafer-based technology [6,7].

The (a-Si) solar cell is one of the most common thin-film technologies with cell efficiency (5–7%). The efficiency increases with double and triple junction design to 8–10%. (a-Si) thin-film offers lower efficiency when compared to the (c-Si) module. In addition, (a-Si) thin film is prone to degradation due to the reaction of (a-Si) with the environment, such as with the air or water vapour [8,9].

Furthermore, CdTe thin film nearly competes with the (c-Si) cell in cost/watt. Nevertheless, tellurium supplies are restricted, and cadmium is highly poisonous [10].

Moreover, CIGS PV cell is another film technology with an acceptable cell efficiency of (~20%). However, the cost of fabrication CIGS solar cell is higher than CdTe- based thin film and (c-Si) wafer [11].

Moreover, GaAs thin film is a crystalline compound form of (Ga) and (As). It has a high resistivity to heat and radiation, which affect the efficiency of solar cells. Although a GaAs solar module is expensive, it holds the world's record in efficiency (over 30%). Since the industry favours efficiency over cost for outer space power generation, multijunction GaAs cells are usually used for concentrator solar structures and spacecraft-based solar energy as they can be operated at an extremely higher temperatures compared to a (c-Si) based solar system [12–14].

This paper reviews some basic solar cells physics, materials employed in PV cells, the importance of GaAs thin films in solar technology, their future trends, and challenges in solar cells. Furthermore, the paper presents the standard model of solar cells with the application of this model to different PV technologies together with the main results.

Besides, the paper explores the role of mathematical and numerical modelling of PV cells in MATLAB/Simulink and COMSOL Multiphysics in investigating the (I-V) and (P-V) characteristics and enhancing the PCE of PV cells.

Solar Cells

The Working Principle of PV Cells

A PV cell is the essential unit of a solar energy generation system in which sunlight is promptly converted to electrical energy. The solar cell is a p-n junction device. n-type refers to the negatively charged electrons donated by donor impurity atoms and p-type refers to the positively charged holes created by acceptor impurity atoms, referring to Figure 1 of a PV structure [15–17].

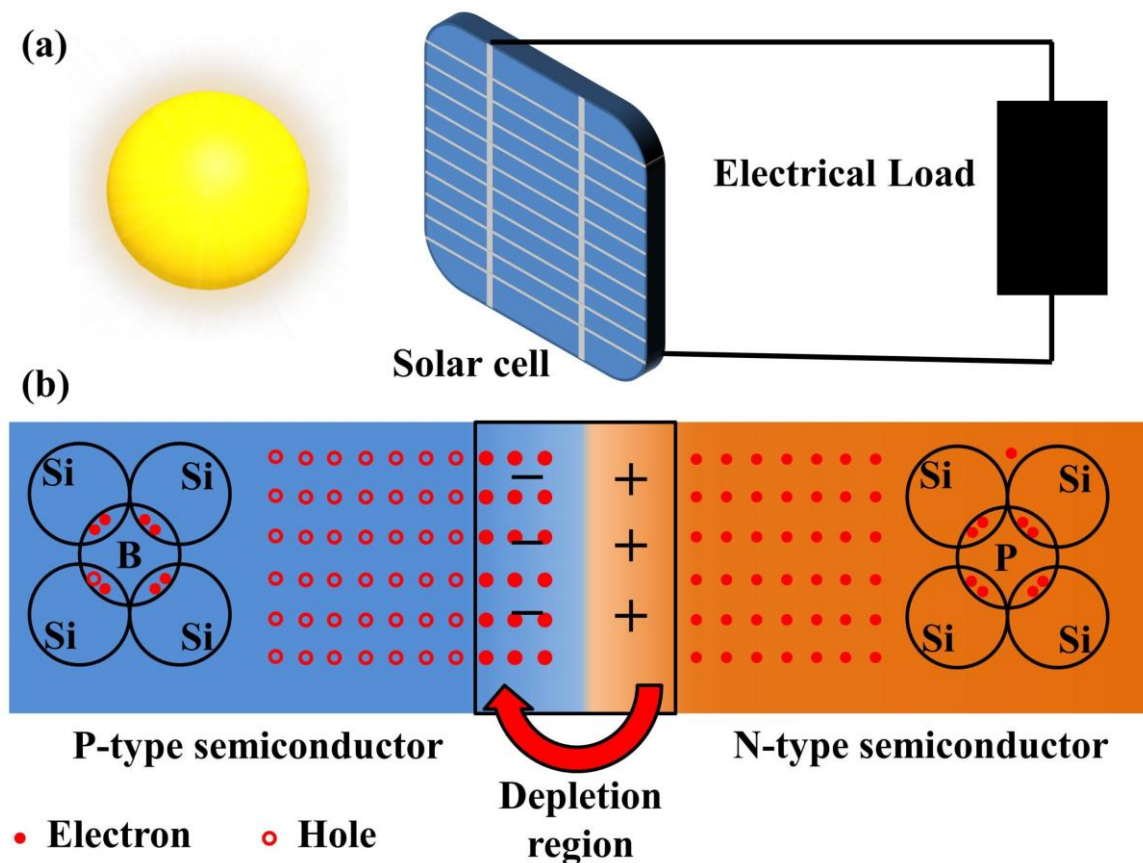


Figure 1. A p-n junction PV cell.

The working principle of solar cells is based on the photovoltaic effect.

The PV effect can be divided into three essential procedures [18–20].

1. Absorption of photons in a p-n junction electronic semiconductor to generate the
2. charge carriers (electron-hole pairs). The absorption of a photon with energy ($E = h\nu$) higher than the gap energy ' E_g ' of the doped semiconductor material means that its energy is used to excite an electron from the valence band ' E_v ' to the conduction band ' E_c ' leaving a void (hole) at the valence level. Additional kinetic energy is given to the electron or hole by the excess photon energy ($h\nu - h\nu_0$). ' $h\nu_0$ ' is the minimum energy or work function of the semiconductor required to generate an electron-hole pair. The work function here represents the energy gap. The excess energy is dissipated as heat in the semiconductor [21,22].
2. Consequent separation of the light-generated charge carriers. In an external solar circuit, the holes can flow away from the junction through the p-region, and electrons can flow out across the n-region and pass through the circuit before they recombine with the holes.
3. Finally, the separated electrons can be used to drive an electric circuit. After the electrons passed through the circuit, they will recombine with the holes.

The n-type must be designed thinner than the p-type. Thus, the electrons can pass through the circuit in a short time and generate current before they recombine with the holes. Besides, an anti-reflective coating is applied over the n-layer to reduce surface reflection and enhance the transmission of the light to the semiconductor material.

All the aspects presented in this section will be discussed in more detail in the next sections.

Solar Cell Panels

Solar panels are multiple solar cells connected in series and parallel to produce a certain power output. One PV cell is unfeasible for most applications as it can only produce about 0.5 V. For example, six cells are connected in series, the cell is assumed to have the same current as a single cell and ideal 3 V (6×0.5 V). Series cells are also connected in parallel for higher current capacity. If the six cells can generate 2 A, the series-parallel structure of twelve cells is supposed to generate 4 A and 3 V [23].

Components of Solar Power System

A PV system is composed of a solar panel, supercapacitor, and inverter. The solar panel absorbs photon energy and transforms it into electricity through the PV mechanism. The supercapacitor backup is used to deliver additional energy only on sunny days. The generated DC power is transformed into AC loads to be appropriate for domestic use [23,24], as shown in Figure 2.

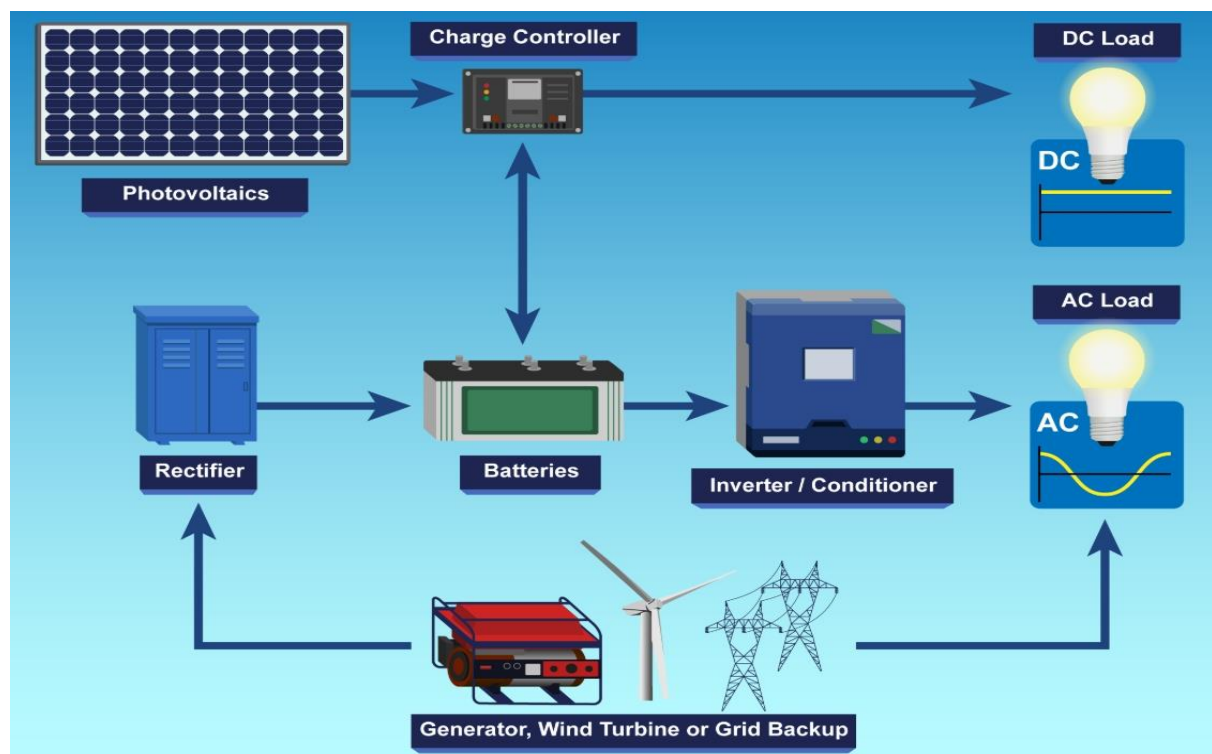


Figure 2. The basic components of a PV system.

p-n Junction Solar Cell

Formation of the Depletion Region

A solar cell in a basic term is a semiconductor diode that has been carefully designed to generate power from the sunlight. A diode is a single crystal semiconductor material such as silicon, having one side doped with pentavalent impurities forming n-type and another side doped with trivalent impurities as p-type. The doping process creates additional mobile carriers called majority carriers in each respective region. When n-region and p-region semiconductors are brought into contact, electrons of the n-section will diffuse into the p-section leaving a region of positively charged donor atoms in the p-n interface near the n-zone. Likewise, a net of negatively charged acceptor atoms is left behind in the p-n junction near the p-zone as holes diffuse from p-region to n-region. The consequent jumps of the valence electrons can be noted as a motion of the holes. The diffusion of electrons and holes will create a current called diffusion current ' I_{diff} ' and a depleted area of charge carriers, referred to as the depletion region or space charge

region. All electrons' holes are swept out of the depletion region by a generated electric field, which prevents any additional flow of the charge carriers [25], as shown Figure 3 below.

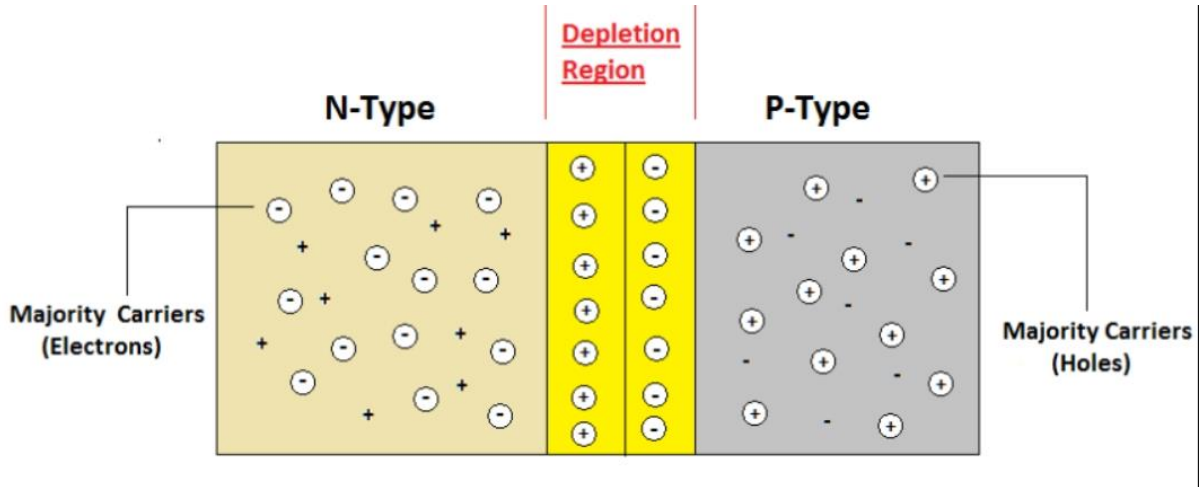


Figure 3. The basic semiconductor form at the instant connection of the p-n sections and generating the electric field in the space charge region.

The net flow of electrons and holes in a semiconductor under equilibrium conditions will generate currents, namely diffusion current ' I_{diff} ' as a result of the concentration difference and drift current ' I_{drift} ' as a result of the generated field at the junction [26]. The diffusion current of electrons ' I_{n-diff} ' is expressed by:

$$I_{n-diff} = e D_n \frac{dn}{dx} \quad (1)$$

Likewise, the typical diffusion current density of holes is given by:

$$I_{p-diff} = -e D_p \frac{dp}{dx} \quad (2)$$

where $\frac{dx}{dn}$ and $\frac{dp}{dx}$ are the ratios of the change in particles' density to the change in the diffusion distance of electrons and holes, respectively. Due to a built-in electric field, ' I_{drift} ' is generated, which is opposite to the ' I_{diff} ' [27].

The drift current due to drift of electrons ' $I_{n-drift}$ ' is given by:

$$I_{n-drift} = e n \mu_n E \quad (3)$$

where ' μ_n ' is the electron's mobility, ' E ' is the electric field in the depletion region, and ' u_{dn} ' is the drift velocity of electrons. Similarly, ' $I_{p-drift}$ ' due to drift of holes is expressed as:

$$I_{p-drift} = e p \mu_p E = e p u_{dp} \quad (4)$$

' μ_p ' is the holes mobility and ' u_{dp} ' is the average drift velocity of holes. The net ' I_{drift} ' due to drift of holes and electrons is as follows:

$$I_{drift} = e (\mu_{nn} + \mu_p p) E \quad (5)$$

The above equation can be written as:

$$I_{drift} = e \mu_{nn} + \mu_p p E = \sigma E \quad (6)$$

$$\sigma = e(\mu_{nn} + \mu_p p) \quad (7)$$

‘ σ ’ given by (Ω/cm) is the conductivity of the electronic semiconductor. For nondegenerate semiconductors, there are no net currents in the depletion region as ‘ I_{drift} ’ and ‘ I_{diff} ’ are balanced at the state of equilibrium. This leads to the Einstein relation:

$$\frac{D}{u} = \frac{kT}{e} \quad (8)$$

The particle mobility ‘ μ ’ gives a sign of how well an electron or a hole moves in a semiconductor due to an electric field while the particle diffusion coefficient ‘ D ’ indicates how well the particles move in the semiconductor owing to the concentration gradient [28].

p-n Junction Solar Cell under Applied Voltage

If the diode is connected to a forward bias external voltage, the depletion region will shrink. The negative charge carriers (electrons) and positive charge carriers (holes) are repelled from the negative and positive terminal respectively toward the p-n junction. Consequently, the energy required for the charge carriers to flow across the depletion region is lowered, referring to Figure 4.

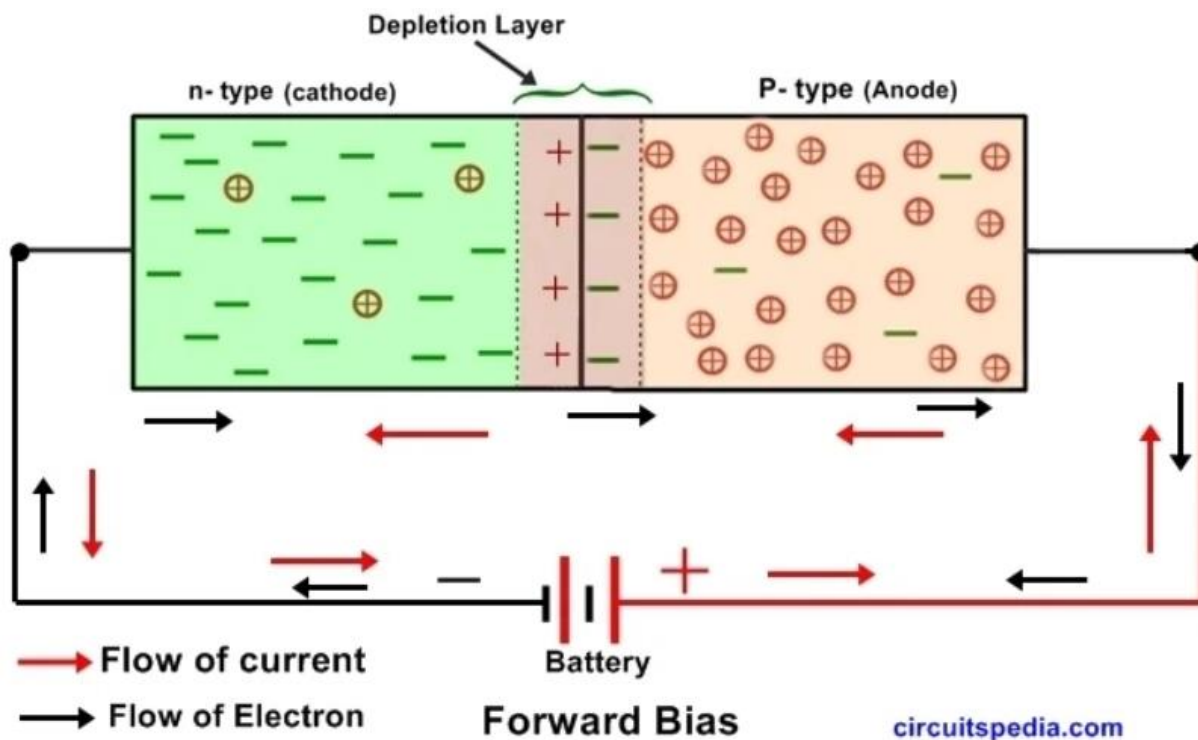


Figure 4. The flow of majority carriers in a forward-biased diode.

Once the applied voltage reaches the barrier potential, electrons start to flow through the space charge region. The diode current in the forward bias mode is expressed by the ideal Shockley equation. The current through the diode exponentially increases with increasing forward bias external voltage [29].

$$I_d = I_0(\exp(eV/kT) - 1) \quad (9)$$

where 'I_d' is the diode current as the mobile carriers move through the junction; 'I₀' is the saturation diode current in the depletion area at room temperature 'T', 300 K; 'V' is the external voltage; k: Boltzmann's constant, 1.3805×10^{-23} J/K, and 'e' is the electron charge, $1.60217657 \times 10^{-19}$ coulombs [30].

PV Cell under Illumination

When the incident light is absorbed in the electronic semiconductor forming a p-n junction, it generates pairs of negative and positive mobile charges (e⁻ and h⁺). The electrons move out of the n-area to the metal contacts across the negative contact then through the load. Next, the electrons move back into the positive contact and finally to the p-area where they can recombine with holes, as shown in Figure 5.

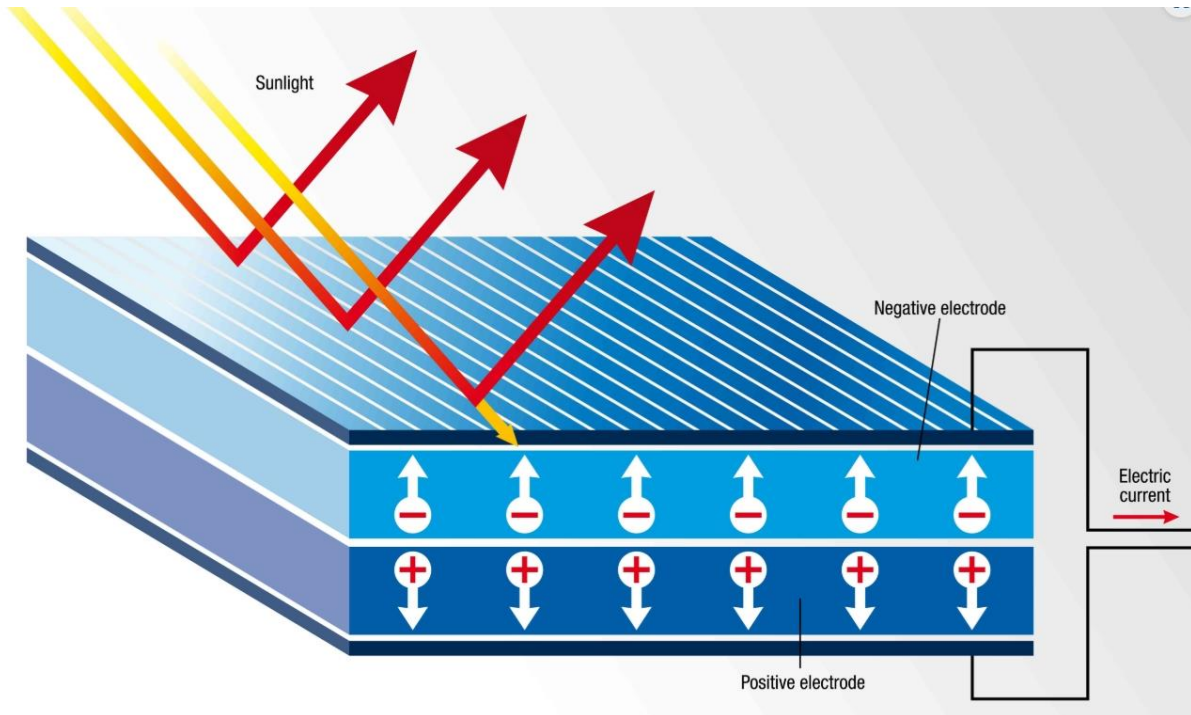


Figure 5. The PV cell under illumination.

As mentioned earlier, the behaviour of the p-n junction diode is employed in solar cells. Therefore, the basic qualitative discussion and mathematical analysis used for diodes are also applied to the p-n junction PV cell. Without illumination, a PV cell has the same electrical characteristics of a large diode. Under illumination, the output current is

simply a summation of the current under the dark condition ' I_d ' and photocurrent ' I_{ph} ' [25], which is expressed as:

$$I = I_{ph} - I_d \quad (10)$$

To summarize the generated currents:

- The net flow of the electrons and holes in a p-n junction semiconductor under equilibrium conditions will generate two currents: ' I_{diff} ' and ' I_{drift} '. These currents balance and cancel each other at the equilibrium state.
- If an external source is deployed to the p-n junction, the generated current is the diode current ' I_d '.
- Under illumination, the p-n junction will present another current called light or photocurrent ' I_{ph} '.

The equivalent circuit of the solar cell is presented below. In real cells, power is dissipated through a series resistance ' R_s ' created due to the ohmic contact in the front surface and shunt resistance ' R_{sh} ' due to leakage current. Therefore, for a practical solar cell, the equivalent circuit includes ' R_{sh} ' added in parallel with the diode and ' R_s ' added in series with the load as given below, Figure 6 [31–33].

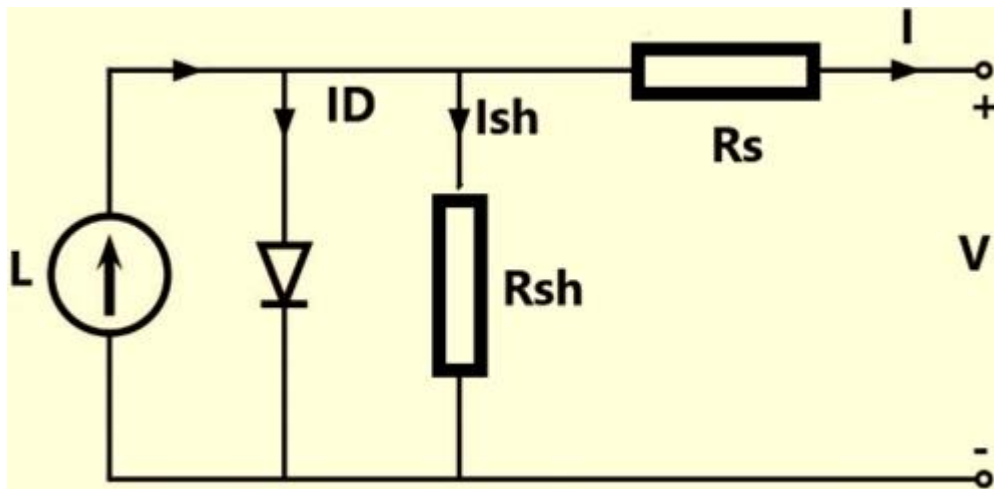


Figure 6. The practical equivalent circuit of a solar cell

Therefore, the above equation can be written as follows:

$$I = I_{ph} - I_d - I_{sh} \quad (11)$$

I-V and P-V Characteristics

Figure 7 clarifies the (I-V) and (P-V) curves of PV cells.

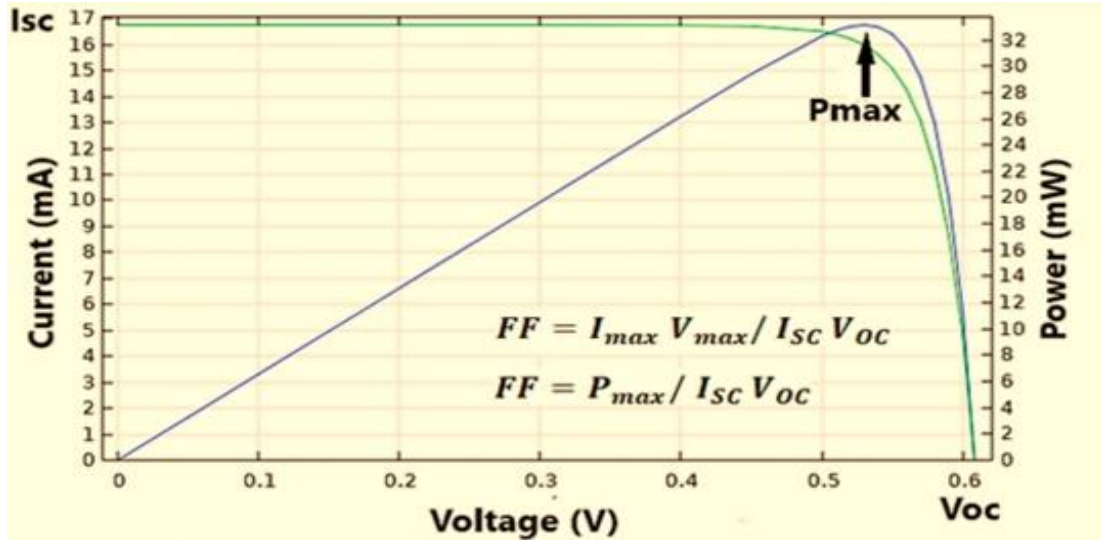


Figure 7. (I-V) and (P-V) characteristics of a solar cell under illumination.

The PV cell should be managed to give a maximum power output ‘Pmax’ at a maximum voltage ‘VM’ and maximum current ‘IM’ [34].

The external parameters defined by the I-V curve are as follows:

- Short-circuit current density ‘Isc’ occurs at (R = 0 and V = 0)
- Open-circuit voltage ‘Voc’ (no-load, I = 0 and R = ∞)
- Fill factor ‘FF’ that represents the ratio of ‘Pmax’ to the electrical output of ‘Voc’ and ‘Isc’

$$FF = I_{max} V_{max} / I_{SC} V_{OC} \quad (12)$$

These parameters determine the PCE given by

$$\eta_c = (I_{max} V_{max} / P_{in}) \times 100\% \quad (13)$$

where ‘Pin’ is the incident power density, 1 KW/m² or 100 mW/cm² [35,36].

Design Considerations

The design of a PV cell is defined by the cell structure [37]. Solar cells can be fabricated in different designs. First, a single-junction solar cell, which consists of a highly doped emitter layer and a lightly doped base layer. For a single-junction PV cell, GaAs is best suited to achieve the highest efficiency, nearly 30%, due to its bandgap (1.42 eV) being near to the ideal bandgap and high absorption coefficient, which offers substantial benefit in the design and fabrication of highly efficient PV devices [38,39]. Highly efficient n-on-p single-junction GaAs thin-film solar cells have been fabricated by [40]. A metal combination of AuBe/Pt/Au was employed as a new p-type ohmic contact. The PCE of the fabricated single-junction GaAs thin-film solar cells reached 22.08% under Air Mass (AM) 1.5 global illumination. Another experiment by [41] demonstrated a

PV GaAs device based on single junction thin film under the non-concentrated light (1 sun illumination), achieving a high efficiency of 27.6%.

Second, multijunction PV cells are the most effective solar cells to date. GaAs-based multijunction PV cells achieved the highest efficiency of 42.3%, as it is possible to grow three or more junctions for one cell. The novel designs of Si and GaAs wafer-based double heterojunction solar cells were demonstrated by [42,43]. The cells were comprised of five layers, a cathode metal layer, three layers of semiconductor materials of III–V, II–VI, and IV families, and a layer of anode metal. The device structures have been optimized for the analysis of the PCE of the Si and GaAs solar cells considering high defect densities at and near each heterojunction. The PCEs obtained were almost 38.9%.

Furthermore, p-i-n structures are developed by inserting an undoped or intrinsic layer (i) between very highly doped (p) and (n) regions. p-i-n structures increase the carrier's lifespan and density in the undoped region. The intermediate layer has a very low concentration of usually n-type in the order of 10^{13} cm^{-3} . The p-i-n structure offers carriers confinement in the intermediate undoped layer, providing a higher output current. In the forward bias, both types of carriers are injected into the intrinsic layer, leading to an increase in the carriers' density and consequently the output current. The direct and flexible bandgap of the p-i-n double heterostructures offers a unique opportunity to develop highly efficient solar cells [44–46]. An experimental work by [47] focused on developing a p-i-n PV model with the compound materials AlGaInP/AlGaAs. The cell recorded the highest conversion efficiency of 51.50% under the AM1.5 standard. The performance of solar cells is affected by design considerations as properties of the employed materials. Designers can select a small subset of the most promising materials to be employed for solar cells using, e.g., CES Edu Pack software [48]. Furthermore, doping and alloying affect the properties of the employed materials. For example, the density of donor atoms 'Nd' and acceptor atoms 'Na' affects the width of the depletion region. Moreover, adding some elements by alloying affects the physical properties of the employed materials [49]. Thus, it is important to consider all the main parameters affecting the efficiency of the PV cell to obtain an ideal cell design [50–52].

Materials Employed in PV Cells A concise comparison between the different materials used in PV cells nowadays with their advantages and drawbacks is presented in Table 1.

Material Type	Advantages	Drawbacks
Silicon (Crystalline)	<ul style="list-style-type: none"> - High efficiency (especially Mono-Si). - Long lifespan (25–30 years). - Mature technology, widely available. - Moderate degradation at high temperatures. 	<ul style="list-style-type: none"> - High energy input for manufacturing. - Fragile (requires careful handling). - Poly-Si is less efficient than Mono-Si.
Thin-Film Materials	<ul style="list-style-type: none"> - Lightweight and flexible. - Lower manufacturing costs. - Performs well in low light and high temperatures. 	<ul style="list-style-type: none"> - Lower efficiency compared to silicon. - Shorter lifespan (10–20 years). - Toxic materials (e.g., cadmium in CdTe).
Perovskite Materials	<ul style="list-style-type: none"> - High efficiency potential. - Low-cost, scalable production. - Lightweight and flexible. - Tunable bandgap for multi-junction cells. 	<ul style="list-style-type: none"> - Poor long-term stability. - Toxicity concerns (lead content). - Early commercial development stage.
Organic PV (OPV)	<ul style="list-style-type: none"> - Lightweight and flexible. - Low-cost printing techniques. - Semi-transparent for building integration. 	<ul style="list-style-type: none"> - Low efficiency. - Short operational lifespan due to degradation. - Limited commercial adoption.
Gallium Arsenide (GaAs) and III-V Compounds	<ul style="list-style-type: none"> - Highest efficiency (used in space applications). - Excellent performance in extreme conditions (e.g., radiation resistance). 	<ul style="list-style-type: none"> - Extremely expensive and complex to produce. - Limited to niche applications.
Emerging Materials (Quantum Dots, Tandem Cells)	<ul style="list-style-type: none"> - Potential for very high efficiency (tandem cells can exceed efficiency limits). - Flexible and tuneable properties (quantum dots). 	<ul style="list-style-type: none"> - Early-stage development. - Stability and scalability challenges.

III-V PV Gallium Arsenide

GaAs (III-V binary semiconductor), a widely used electronic semiconductor in solar cells, is a crystalline PV material based on an element with three valence electrons, gallium

(Ga), and an element with five valence electrons, arsenic (As). Therefore, the average valency is four electrons per atom. GaAs has a zinc blend crystal structure that consists of four (As) neighbouring atoms with every (Ga) atom and four neighbours (Ga) with every (As) atom, referring to the Figure 8. It has a direct bandgap equal to 1.42 eV at room temperature (300 K) where the lowest conduction band is vertically aligned with the highest valence band [60]. Thus, no transfer of momentum is required to excite an electron from the valence to the conduction band [71]. GaAs has a high resistivity to heat and radiation that affect the module performance compared to (c-Si) solar cells. Double heterojunction GaAs solar cells achieved the highest energy conversion efficiency by [42, 72]. Many studies on single-junction GaAs cells achieved 28.8% power efficiency [54]. The highest efficiency of GaAs semiconductors was accomplished with a triple-junction, reaching up to 42.3%. However, the GaAs solar module is too expensive as gallium resources are limited [73]. Therefore, further improvement of higher efficiency and low-cost GaAs solar cells is significant in the PV solar system [74].

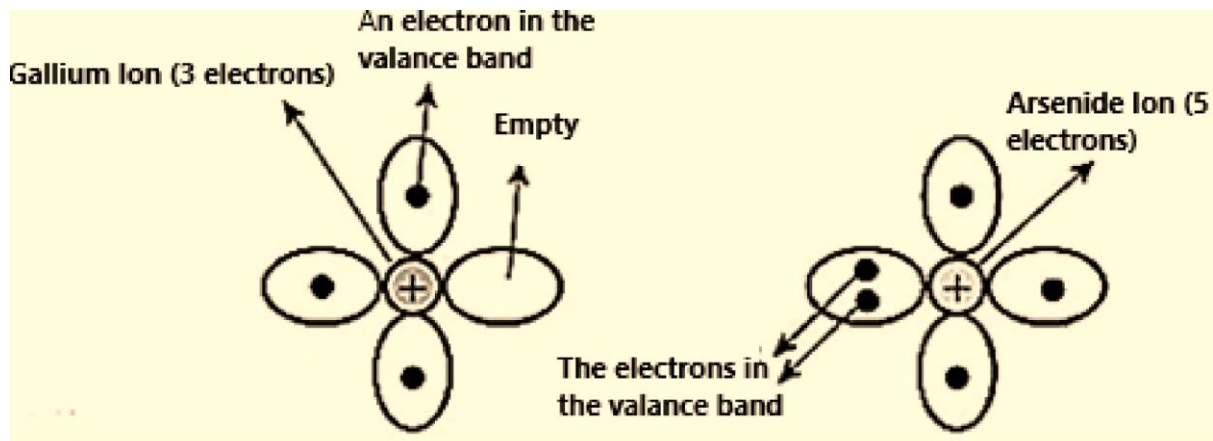


Figure 8. The structure of valence electrons of Ga and As atoms.

Future Trends

GaAs solar cells have contributed as concentrators and space solar cells [54] and are anticipated to create new markets, such as large-scale electric power systems and PV cell-powered electric vehicles. Single-junction GaAs solar cells, which are important as sub-cells for multijunction PV cells, have shown the highest ever stated efficiency (29.1%) under the standard AM 1.5 spectra for single-junction PV cells. GaAs multijunction solar cells of three junctions or more have been developed due to the limiting efficiency of single junction PV cells. GaAs multijunction solar cells will be widely used in space because of their high obtained PCE. The concentrator PV (CPV) systems with several times more annual power generation capability than typical crystalline Si flat-plate systems will open a new market for charging stations including battery-powered electric vehicle applications. Multi-junction solar cells are greatly expected to be high-efficiency PV cells applied to solar cell-powered electric vehicles and large-scale

PV power plants. Further development of super-high-efficiency and low-cost PV cells is crucial to create new markets [75,76].

Challenges in Solar Cells

Solar energy is the most promising clean energy resource that can directly be converted to electricity. It can almost provide stable power at a practical operating cost. Over the last few years, solar energy experienced fast growth as the clean energy demand is continuously increasing [77,78]. However, the efficiency of solar cells is still under research and development as it depends highly on the surrounding conditions [79] and fundamental properties of the solar module. The output power of solar cells is affected by many input factors, such as the shading effects, employed PV materials, temperature, the intensity of radiation received, parasitic resistances, weather conditions, solar cell design (e.g., p-i-n or double heterojunction), doping level, material properties and quality, etc. These parameters must be optimized to improve the obtained power efficiency [80]. For example, the most popular issue in PV cells is the drastic loss in power due to soiling on solar modules in desert regions. The dust blocks the sun in deserts and significantly affects the attractive energy of solar panels obtained in such areas [81,82]. The location of installation is another challenge since four seasons tend to have differences in the radiation and temperature that affect the power efficiency [83]. Some challenges also arise from the solar module itself. Mounting the solar cells on a solar module induces deficits in the PCE. Furthermore, the quality of the employed semiconductor materials should be highly considered as electrons and holes are highly likely to recombine via defect centres in the junction region of low-quality materials. Besides, any manufacturer defects in the p-n junction or at the cell edges may create voltage drop and losses in energy conversion [84]. The cost of the single-crystal substrate is another significant issue of III-V cells [85]. Therefore, it is necessary to consider all the main issues affecting the efficiency of solar cells to obtain an optimum cell performance.

not exceed 5%. Thus, the models developed by COMSOL help to investigate the electrical characteristics and establish the main factors affecting solar cell performance.

Summary and Outlook

To summarize, PV is the process of converting solar energy into electrical energy. Any PV system consists of solar cell arrays to deliver sufficient power. This paper covered many basics of solar cells, such as their working principle, design consideration, technical challenges in PV cells, employed materials, the significance of GaAs thin films in solar technology, their future prospects, and some mathematical analysis of p-n junction solar cells. The review also discussed the possibility of developing mathematical and numerical modelling of solar cells in MATLAB/Simulink and COMSOL Multiphysics to

improve the PCE. The developed models help to investigate the (I-V) and (P-V) characteristics and determine the main parameters affecting the PV cell performance.

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