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Solar Cells: Physical Principles, Performance Parameters and Emerging Technologies for Sustainable Energy Conversion

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Abstract

Background: Photovoltaic (PV) solar cells convert sunlight directly into electricity and have become one of the cheapest sources of new power generation. India, with high solar irradiance across most of its territory, has made solar energy central to its target of 500 GW of non-fossil capacity by 2030. Understanding the physics that sets the efficiency of a solar cell is essential for evaluating technologies and for teaching. **Methods:** This review explains the photovoltaic effect in a p–n junction, derives the single-diode model and the standard performance parameters — short-circuit current, open-circuit voltage, fill factor and efficiency — and discusses the loss mechanisms that lead to the Shockley–Queisser limit. A worked numerical example illustrates the calculations. The main cell technologies are then compared, from crystalline silicon (PERC, TOPCon and heterojunction) to thin films, perovskites and tandem cells. **Results:** For an ideal diode cell with I_{SC} = 13.8 A, n = 1.5 and $I_0 = 2 \times 10^{-7}$ A, the model gives $V_{OC} \approx 0.700$ V, a fill factor of 0.79 and a maximum power of 7.66 W. Crystalline silicon dominates the market, while perovskite–silicon tandems have exceeded the single-junction limit in the laboratory. **Conclusion:** Further progress depends on reducing recombination losses, on multi-junction designs and on solving the stability and recycling challenges of new materials.

Keywords: solar cell; photovoltaic effect; p–n junction; single-diode model; Shockley–Queisser limit; perovskite; tandem solar cell; renewable energy

1. Introduction

The Sun delivers about 1.7×10^{17} W of power to the top of Earth's atmosphere, thousands of times more than the whole of human energy use. Capturing even a small fraction of this flux could meet global demand without carbon emissions. Solar cells do this directly, without moving parts, by exploiting the photovoltaic effect discovered by Edmond Becquerel in 1839. The first practical silicon solar cell was made at Bell Laboratories in 1954 by Chapin, Fuller and Pearson, with an efficiency of about 6% [1]. Seven decades later, commercial modules routinely exceed 21%, and the price of PV electricity has fallen by roughly 90% in a little over a decade, making it one of the lowest-cost options for new generation in many countries [2].

India has adopted solar energy as a pillar of its energy transition. The National Solar Mission, launched in 2010, and the national commitment to 500 GW of non-fossil electricity capacity by 2030 have driven rapid growth in installed solar capacity, from large solar parks in Rajasthan and Madhya Pradesh to rooftop systems under the PM Surya Ghar scheme [3]. Madhya Pradesh hosts large projects such as the Rewa Ultra Mega Solar Park, whose 2020 tariff marked a turning point for solar prices in India.

Despite this growth, the physics of the solar cell is often treated superficially in undergraduate teaching, and claims about new technologies are hard to evaluate without understanding what limits efficiency. This article reviews the principles of solar-cell operation, derives the standard model and parameters, works a numerical example, and compares established and emerging cell technologies.

2. Physical Principles

2.1. Semiconductors and Light Absorption

A solar cell is made from a semiconductor, a material whose electrons occupy a valence band separated from the conduction band by a band gap E_g. A photon with energy $h\nu \geq E_g$ can be absorbed by lifting an electron into the conduction band and leaving behind a hole in the valence band. Photons with $h\nu < E_g$ pass through, and the excess energy of photons with $h\nu > E_g$ is rapidly lost as heat as the carriers relax to the band edges, a process called thermalisation. Silicon, with E_g = 1.12 eV at room temperature, absorbs light of wavelength shorter than about 1.1 µm. Because silicon has an indirect band gap, its absorption is weak near the band edge and wafers must be roughly 100–200 µm thick with light-trapping textures [4].

2.2. The p–n Junction and Charge Separation

Generating electron–hole pairs is not enough; they must be separated before they recombine. In a p–n junction, n-type material (doped with donors such as phosphorus) is joined to p-type material (doped with acceptors such as boron). Electrons diffuse from the n-side into the p-side and holes in the opposite direction, leaving behind a depletion region of fixed ionised dopants. This creates a built-in electric field and a built-in potential V_{bi}. Electron–hole pairs generated in or near the depletion

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region are swept apart by this field: electrons to the n-side and holes to the p-side. If the two sides are connected through an external load, a current flows and power is delivered [4,5].

3. Device Model and Performance Parameters

3.1. The Single-Diode Model

In the dark, a solar cell behaves as a diode obeying the Shockley equation. Under illumination, a photogenerated current I_L flows in the opposite direction. The ideal cell current is therefore

$$I = I_L - I_0 \left[\exp(qV / nkT) - 1\right] \quad (1)$$

where I_0 is the reverse saturation current, q the electronic charge, k Boltzmann's constant, T the absolute temperature and n the ideality factor ($1 \le n \le 2$). Real cells also have a series resistance R_s from contacts and bulk material and a shunt resistance R_{sh} from leakage paths, leading to the implicit equation

$$I = I_L - I_0 \left[\exp(q(V + IR_s)/nkT) - 1\right] - (V + IR_s)/R_{sh} \quad (2)$$

3.2. Performance Parameters

Setting V = 0 in (1) gives the short-circuit current $I_{SC} \approx I_L$. Setting I = 0 gives the open-circuit voltage

$$V_{OC} = (nkT/q) \ln(I_{SC}/I_0 + 1) \quad (3)$$

Electrical power P = VI is maximised at the maximum power point (V_{mp}, I_{mp}). The fill factor and conversion efficiency are

$$FF = V_{mp}I_{mp} / (V_{OC}I_{SC}), \quad \eta = FF \cdot V_{OC} \cdot I_{SC} / (P_{in}) \quad (4)$$

where P_{in} is the incident power, 1000 W m^{-2} times the cell area under standard test conditions (AM1.5G spectrum, 25 °C). Equation (3) shows why V_{OC} depends on recombination: lower I_0, which means fewer recombination paths, gives higher voltage. V_{OC} also falls with temperature, by about 2 mV K^{-1} for silicon, so hot climates such as central India reduce output [5].

3.3. Worked Example

Consider an ideal cell of M10 wafer size (area 0.0331 m^2) with I_{SC} = 13.8 A, n = 1.5, $I_0 = 2 \times 10^{-7}$ A and T = 300 K, so that kT/q = 25.85 mV. Equation (3) gives $V_{OC} = 1.5 \times 0.02585 \times \ln(6.9 \times 10^7) \approx 0.700$ V. Evaluating P = VI from (1) on a fine voltage grid gives the maximum power point at $V_{mp} \approx 0.592$ V and $I_{mp} \approx 12.95$ A, so $P_{max} \approx 7.66$ W, FF ≈ 0.79 and $\eta \approx 7.66/(1000 \times 0.0331) \approx 23.2\%$. Including a realistic series resistance would lower the fill factor and bring the efficiency close to the 22–24% typical of current commercial cells. If the cell operates at 45 °C instead of 25 °C, a 20 K rise reduces V_{OC} by roughly 40 mV, a loss of nearly 6% in power.

3.4. Loss Mechanisms and the Shockley–Queisser Limit

Shockley and Queisser [6] showed in 1961 that a single-junction cell under unconcentrated sunlight has a maximum efficiency set by detailed balance. Three losses dominate: non-absorption of photons below the band gap, thermalisation of energetic carriers, and unavoidable radiative recombination. The limit is about 33.7% at an optimum band gap near 1.34 eV, and about 29.4% for silicon once Auger recombination is included [7]. Practical cells suffer further losses from reflection, shading by metal contacts, non-radiative recombination at defects and surfaces, and resistive losses. Most advances in silicon technology over the last decade, such as passivated contacts, have targeted surface recombination.

4. Solar Cell Technologies

4.1. Crystalline Silicon

Crystalline silicon (c-Si) cells account for more than 95% of global production. The aluminium back-surface field cell dominated until the mid-2010s, when the passivated emitter and rear cell (PERC) added a dielectric passivation layer at the rear, raising efficiency above 22%. Tunnel-oxide passivated contact (TOPCon) cells, which use an ultra-thin oxide and doped polysilicon, and silicon heterojunction (SHJ) cells, which sandwich the wafer between amorphous silicon layers, now lead mass production, with cell efficiencies around 24–26%. Interdigitated back-contact designs remove front-side shading altogether and have reached laboratory efficiencies above 26% [8].

4.2. Thin-Film Technologies

Thin-film cells use direct-band-gap materials that absorb light in layers only a few micrometres thick. Cadmium telluride (CdTe) is the most commercially successful, with low manufacturing cost and record cell efficiencies above 22%. Copper indium gallium selenide (CIGS) offers similar efficiencies and flexible substrates. Amorphous silicon, once common in calculators, has largely left the power market because of low efficiency and light-induced degradation [8,9].

4.3. Perovskite and Tandem Cells

Metal-halide perovskites, such as methylammonium lead iodide, have been the fastest-advancing PV material in history: certified efficiencies rose from 3.8% in 2009 to above 26% for single-junction cells [10,11]. They can be deposited from solution at low temperature, and their band gap can be tuned by changing composition. This tunability makes them ideal partners for silicon in tandem cells, where a wide-gap perovskite top cell absorbs blue light and a silicon bottom cell absorbs red light, reducing thermalisation loss. Perovskite–silicon tandems have exceeded 33% in the laboratory, surpassing the single-junction limit [8]. The main obstacles are long-term stability against moisture, heat and light, and the use of lead.

4.4. From Cells to Systems

A single silicon cell delivers only about 0.6 V at its maximum power point, so cells are connected in series, typically 60, 72 or more full or half cells, and encapsulated between glass and a polymer back sheet to form a module. Bypass diodes across groups of cells prevent a shaded cell from becoming reverse-biased and overheating, a condition known as a hot spot. Modules are then combined in strings and connected to inverters that convert direct

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current to alternating current and continuously track the maximum power point as irradiance and temperature change. The overall system efficiency is therefore lower than the cell efficiency because of mismatch, wiring, inverter and soiling losses, which together commonly amount to 10–15% [5].

Applications range from utility-scale solar parks of hundreds of megawatts to rooftop systems of a few kilowatts and to off-grid uses that are particularly valuable in rural India: solar water pumps under the PM-KUSUM scheme, solar street lights, cold storage for farm produce and power for schools and health centres in villages far from the grid. Agrivoltaic installations, in which crops are grown beneath elevated modules, are being tested as a way to share land between food and energy. For a district such as Sidhi, with high solar irradiance and many scattered rural settlements, such decentralised applications can improve reliability of supply while reducing diesel use.

4.5. Comparison

Table 1. Comparison of major solar cell technologies (indicative values).

Technology	Band gap (eV)	Lab record η (%)	Status
c-Si (PERC/TOPCon/SHJ)	1.12	2	Mass production
CdTe	1.4	2	Commercial
CIGS	1.0–1.7	2	Commercial
Perovskite (single)	1.5–1.6	26–2	Pilot
Perovskite–Si tandem	1.68/1.12	>33	Pilot
III–V multijunction	various	>39 (1 sun)	Space, CPV

Indicative values from published efficiency tables [8]; records change frequently.

5. Discussion

The analysis above shows why efficiency gains are now hard won. Crystalline silicon is within a few percentage points of its theoretical limit, so further improvements in single-junction silicon will be incremental. Larger gains require either better spectral use, as in tandem cells, or new concepts such as bifacial modules, which collect light reflected from the ground and can raise energy yield by 5–15% depending on the surface [12]. For India, bifacial modules on bright surfaces and tracking systems are already common in large parks.

Efficiency is only one measure of value. Levelised cost, energy yield in local climates, degradation rate and life-cycle impact matter as much. High temperatures in central India reduce output, as the worked example showed, making temperature coefficients an important selection criterion. Dust accumulation can reduce output further unless modules are cleaned regularly, which raises water-use concerns in dry regions. End-of-life management is a growing issue, as India's installed modules will generate large volumes of waste from the 2030s onwards [13].

For physics education, the solar cell is an excellent integrating topic. It brings together band theory, carrier statistics, junction electrostatics, optics and thermodynamics, and the single-diode model can be explored in a simple laboratory experiment by measuring I–V curves under a lamp. Colleges can thereby connect classroom physics to a technology of national importance.

This article is a review and does not report new experimental measurements. Future work at the author's institution will measure I–V characteristics and temperature coefficients of commercial modules under local conditions in Sidhi district.

6. Conclusions

Solar cells convert light to electricity by generating and separating electron–hole pairs in a semiconductor junction. Their behaviour is captured by the single-diode model, from which the short-circuit current, open-circuit voltage, fill factor and efficiency follow, and their ultimate efficiency is bounded by the Shockley–Queisser limit. Crystalline silicon dominates today and is approaching its practical ceiling; perovskite–silicon tandems point the way beyond it, provided stability and sustainability challenges are solved. For India, where solar power is central to energy policy, a sound understanding of these principles is essential for researchers, engineers and teachers alike.

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