Chapter 1

Introduction

1.1. Photons In, Electrons Out: The Photovoltaic Effect

Solar photovoltaic energy conversion is a one-step conversion process which generates electrical energy from light energy. The explanation relies on ideas from quantum theory. Light is made up of packets of energy, called *photons*, whose energy depends only upon the frequency, or colour, of the light. The energy of visible photons is sufficient to excite electrons, bound into solids, up to higher energy levels where they are more free to move. An extreme example of this is the photoelectric effect, the celebrated experiment which was explained by Einstein in 1905, where blue or ultraviolet light provides enough energy for electrons to escape completely from the surface of a metal. Normally, when light is absorbed by matter, photons are given up to excite electrons to higher energy states within the material, but the excited electrons quickly relax back to their ground state. In a photovoltaic device,

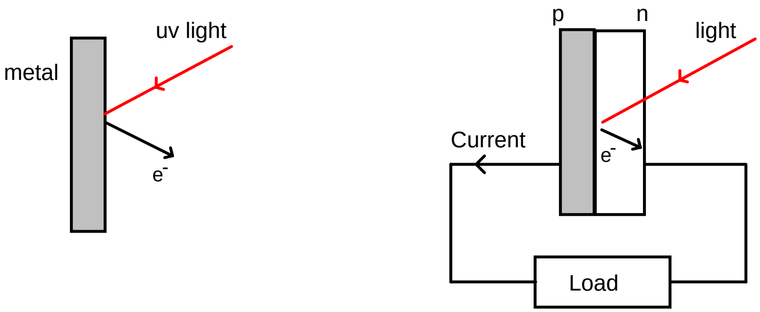


Fig. 1.1. Comparison of the photoelectric effect (left), where uv light liberates electrons from the surface of a metal, with the photovoltaic effect in a solar cell (right). The photovoltaic cell needs to have some spatial asymmetry, such as contacts with different electronic properties, to drive the excited electrons through the external circuit.

however, there is some built-in asymmetry which pulls the excited electrons away before they can relax, and feeds them to an external circuit. The extra energy of the excited electrons generates a *potential difference*, or electromotive force (e.m.f.). This force drives the electrons through a load in the external circuit to do electrical work.

The effectiveness of a photovoltaic device depends upon the choice of light absorbing materials and the way in which they are connected to the external circuit. The following chapters will deal with the underlying physical ideas, the device physics of solar cells, the properties of photovoltaic materials and solar cell design. In this chapter we will summarise the main characteristics of a photovoltaic cell without discussing its physical function in detail.

1.2. Brief History of the Solar Cell

The photovoltaic effect was first reported by Edmund Bequerel in 1839 when he observed that the action of light on a silver coated platinum electrode immersed in electrolyte produced an electric current. Forty years later the first solid state photovoltaic devices were constructed by workers investigating the recently discovered photoconductivity of selenium. In 1876 William Adams and Richard Day found that a photocurrent could be produced in a sample of selenium when contacted by two heated platinum contacts. The photovoltaic action of the selenium differed from its photoconductive action in that a current was produced spontaneously by the action of light. No external power supply was needed. In this early photovoltaic device, a rectifying junction had been formed between the semiconductor and the metal contact. In 1894, Charles Fritts prepared what was probably the first large area solar cell by pressing a layer of selenium between gold and another metal. In the following years photovoltaic effects were observed in copper–copper oxide thin film structures, in lead sulphide and thallium sulphide. These early cells were thin film Schottky barrier devices, where a semitransparent layer of metal deposited on top of the semiconductor provided both the asymmetric electronic junction, which is necessary for photovoltaic action, and access to the junction for the incident light. The photovoltaic effect of structures like this was related to the existence of a barrier to current flow at one of the semiconductor–metal interfaces (*i.e.*, rectifying action) by Goldman and Brodsky in 1914. Later, during the 1930s, the theory of metal–semiconductor barrier layers was developed by Walter Schottky, Neville Mott and others.

However, it was not the photovoltaic properties of materials like selenium which excited researchers, but the photoconductivity. The fact that the current produced was proportional to the intensity of the incident light, and related to the wavelength in a definite way meant that photoconductive materials were ideal for photographic light meters. The photovoltaic effect in barrier structures was an added benefit, meaning that the light meter could operate without a power supply. It was not until the 1950s, with the development of good quality silicon wafers for applications in the new solid state electronics, that potentially useful quantities of power were produced by photovoltaic devices in crystalline silicon.

In the 1950s, the development of silicon electronics followed the discovery of a way to manufacture p–n junctions in silicon. Naturally n type silicon wafers developed a p type skin when exposed to the gas boron trichloride. Part of the skin could be etched away to give access to the n type layer beneath. These p–n junction structures produced much better rectifying action than Schottky barriers, and better photovoltaic behaviour. The first silicon solar cell was reported by Chapin, Fuller and Pearson in 1954 and converted sunlight with an efficiency of 6%, six times higher than the best previous attempt. That figure was to rise significantly over the following years and decades but, at an estimated production cost of some $200 per Watt, these cells were not seriously considered for power generation for several decades. Nevertheless, the early silicon solar cell did introduce the possibility of power generation in remote locations where fuel could not easily be delivered. The obvious application was to satellites where the requirement of reliability and low weight made the cost of the cells unimportant and during the 1950s and 60s, silicon solar cells were widely developed for applications in space.

Also in 1954, a cadmium sulphide p–n junction was produced with an efficiency of 6%, and in the following years studies of p–n junction photovoltaic devices in gallium arsenide, indium phosphide and cadmium telluride were stimulated by theoretical work indicating that these materials would offer a higher efficiency. However, silicon remained and remains the foremost photovoltaic material, benefiting from the advances of silicon technology for the microelectronics industry. Short histories of the solar cell are given elsewhere [Shive, 1959; Wolf, 1972; Green, 1990].

In the 1970s the crisis in energy supply experienced by the oil-dependent western world led to a sudden growth of interest in alternative sources of energy, and funding for research and development in those areas. Photovoltaics was a subject of intense interest during this period, and a range of strategies for producing photovoltaic devices and materials more cheaply and for improving device efficiency were explored. Routes to lower cost included photoelectrochemical junctions, and alternative materials such as polycrystalline silicon, amorphous silicon, other 'thin film' materials and organic conductors. Strategies for higher efficiency included tandem and other multiple band gap designs. Although none of these led to widespread commercial development, our understanding of the science of photovoltaics is mainly rooted in this period.

During the 1990s, interest in photovoltaics expanded, along with growing awareness of the need to secure sources of electricity alternative to fossil fuels. The trend coincides with the widespread deregulation of the electricity markets and growing recognition of the viability of decentralised power. During this period, the economics of photovoltaics improved primarily through economies of scale. In the late 1990s the photovoltaic production expanded at a rate of 15–25% per annum, driving a reduction in cost. Photovoltaics first became competitive in contexts where conventional electricity supply is most expensive, for instance, for remote low power applications such as navigation, telecommunications, and rural electrification and for enhancement of supply in grid-connected loads at peak use [Anderson, 2001]. As prices fall, new markets are opened up. An important example is building integrated photovoltaic applications, where the cost of the photovoltaic system is offset by the savings in building materials.

1.3. Photovoltaic Cells and Power Generation

1.3.1. *Photovoltaic cells, modules and systems*

The solar *cell* is the basic building block of solar photovoltaics. The cell can be considered as a two terminal device which conducts like a diode in the dark and generates a photovoltage when charged by the sun. Usually it is a thin slice of semiconductor material of around 100 cm^2 in area. The surface is treated to reflect as little visible light as possible and appears dark blue or black. A pattern of metal contacts is imprinted on the surface to make electrical contact (Fig. 1.2(a)).

When charged by the sun, this basic unit generates a dc photovoltage of 0.5 to 1 volt and, in short circuit, a photocurrent of some tens of milliamps per cm^2. Although the current is reasonable, the voltage is too small for most applications. To produce useful dc voltages, the cells are connected together in series and encapsulated into *modules*. A module typically contains

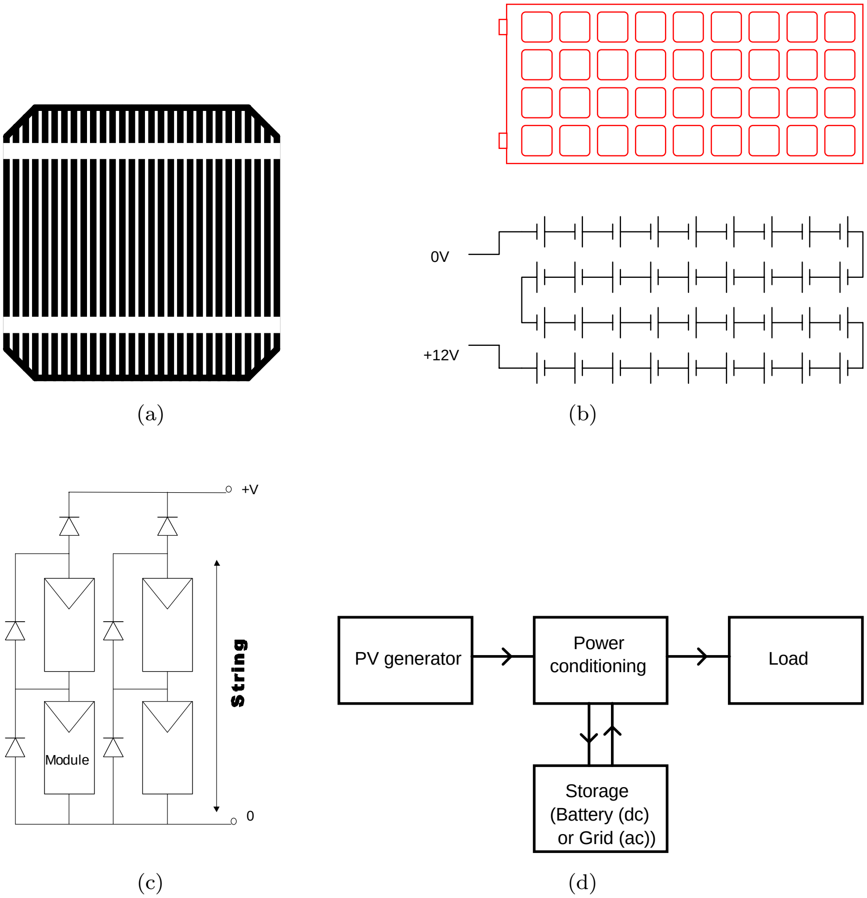


Fig. 1.2. (a) Photovoltaic cell showing surface contact patterns (b) In a module, cells are usually connected in series to give a standard dc voltage of 12 V (c) For any application, modules are connected in series into strings and then in parallel into an array, which produces sufficient current and voltage to meet the demand. (d) In most cases the photovoltaic array should be integrated with components for charge regulation and storage.

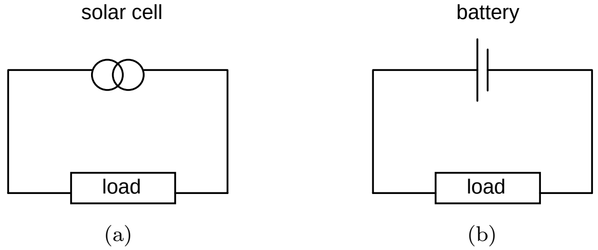
28 to 36 cells in series, to generate a dc output voltage of 12 V in standard illumination conditions (Fig. 1.2(b)). The 12 V modules can be used singly, or connected in parallel and series into an array with a larger current and voltage output, according to the power demanded by the application (Fig. 1.2(c)). Cells within a module are integrated with bypass and blocking diodes in order to avoid the complete loss of power which would result if one

cell in the series failed. Modules within arrays are similarly protected. The array, which is also called a photovoltaic *generator*, is designed to generate power at a certain current and a voltage which is some multiple of 12 V, under standard illumination. For almost all applications, the illumination is too variable for efficient operation all the time and the photovoltaic generator must be integrated with a charge storage system (a battery) and with components for power regulation (Fig. 1.2(d)). The battery is used to store charge generated during sunny periods and the power conditioning ensures that the power supply is regular and less sensitive to the solar irradiation. For ac electrical power, to power ac designed appliances and for integration with an electricity grid, the dc current supplied by the photovoltaic modules is converted to ac power of appropriate frequency using an *inverter*.

The design and engineering of photovoltaic systems is beyond the scope of this book. A more detailed introduction is given by Markvart [Markvart, 2000] and Lorenzo [Lorenzo, 1994]. Photovoltaic systems engineering depends to a large degree upon the electrical characteristics of the individual cells.

1.3.2. *Some important definitions*

The solar cell can take the place of a battery in a simple electric circuit (Fig. 1.3). In the dark the cell in circuit A does nothing. When it is switched on by light it develops a voltage, or e.m.f., analogous to the e.m.f. of the battery in circuit B. The voltage developed when the terminals are isolated (infinite load resistance) is called the *open circuit voltage* V_{oc}. The current drawn when the terminals are connected together is the *short circuit current* I_{sc}. For any intermediate load resistance R_{L} the cell develops a voltage V between 0 and V_{oc} and delivers a current I such that $V = IR_{\mathrm{L}}$ and $I(V)$ is determined by the *current–voltage characteristic* of the cell under



(a) (b)

Fig. 1.3. The solar cell may replace a battery in a simple circuit.

that illumination. Thus both I and V are determined by the illumination as well as the load. Since the current is roughly proportional to the illuminated area, the *short circuit current density* J_{sc} is the useful quantity for comparison. These quantities are defined for a simple, ideal diode model of a solar cell in Sec. 1.4 below.

Box 1.1. Solar cell compared with conventional battery

The photovoltaic cell differs from a simple dc battery in these respects: the e.m.f. of the battery is due to the permanent electrochemical potential difference between two phases in the cell, while the solar cell derives its e.m.f. from a temporary change in electrochemical potential caused by light. The power delivered by the battery to a constant load resistance is relatively constant, while the power delivered by the solar cell depends on the incident light intensity, and not primarily on the load (Fig. 1.4). The battery is completely discharged when it reaches the end of its life, while the solar cell, although its output varies with intensity, is in principle never exhausted, since it can be continually recharged with light.

The battery is modelled electrically as a *voltage generator* and is characterised by its e.m.f. (which, in practice, depends upon the degree of discharge), its charge capacity, and by a polarisation curve which describes how the e.m.f. varies with current [Vincent 1997]. The solar cell, in contrast, is better modelled as a *current generator*, since for all but the largest loads the current drawn is independent of load. But its characteristics depend entirely on the nature of the illuminating source, and so I_{sc} and V_{oc} must be quoted for a known spectrum, usually for standard test conditions (defined below).

1.4. Characteristics of the Photovoltaic Cell: A Summary

1.4.1. *Photocurrent and quantum efficiency*

The photocurrent generated by a solar cell under illumination at short circuit is dependent on the incident light. To relate the photocurrent density, J_{sc}, to the incident spectrum we need the cell's *quantum efficiency*, (QE). $QE(E)$ is the probability that an incident photon of energy E will deliver one electron to the external circuit. Then

$$J_{\mathrm{sc}} = q \int b_{\mathrm{s}}(E) QE(E) dE \tag{1.1}$$

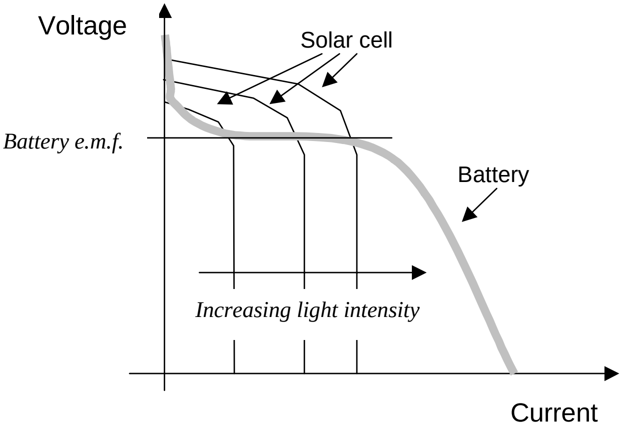


Fig. 1.4. Voltage–current curves of a conventional battery (grey) and a solar cell under different levels of illumination. A battery normally delivers a constant e.m.f. at different levels of current drain except for very low resistance loads, when the e.m.f. begins to fall. The battery e.m.f. will also deteriorate when the battery is heavily discharged. The solar cell delivers a constant current for any given illumination level while the voltage is determined largely by the resistance of the load. For photovoltaic cells it is usual to plot the data in the opposite sense, with current on the vertical axis and voltage on the horizontal axis. This is because the photovoltaic cell is essentially a current source, while the battery is a voltage source.

where $b_{\mathrm{s}}(E)$ is the incident spectral photon flux density, the number of photons of energy in the range E to $E+dE$ which are incident on unit area in unit time and q is the electronic charge. QE depends upon the absorption coefficient of the solar cell material, the efficiency of charge separation and the efficiency of charge collection in the device but does not depend on the incident spectrum. It is therefore a key quantity in describing solar cell performance under different conditions. Figure 1.5 shows a typical QE spectrum in comparison with the spectrum of solar photons.

QE and spectrum can be given as functions of either photon energy or wavelength, λ. Energy is a more convenient parameter for the physics of solar cells and it will be used in this book. The relationship between E and λ is defined by

$$E = \frac{hc}{\lambda} \tag{1.2}$$

where h is Planck's constant and c the speed of light in vacuum. A convenient rule for converting between photon energies, in electron-Volts, and wavelengths, in nm, is $E/\mathrm{eV} = 1240/(\lambda/\mathrm{nm})$.

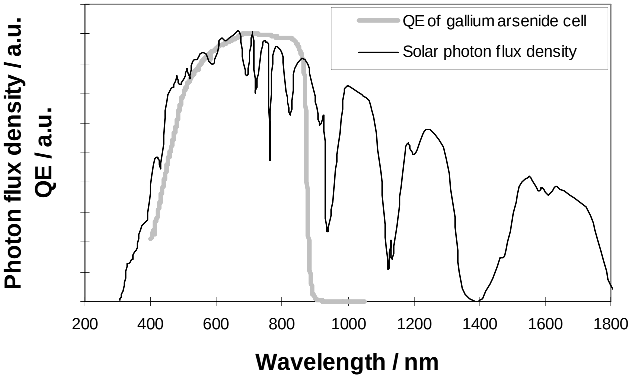


Fig. 1.5. Quantum efficiency of GaAs cell compared to the solar spectrum. The vertical scale is in arbitrary units, for comparison. The short circuit photocurrent is obtained by integrating the product of the photon flux density and QE over photon energy. It is desirable to have a high QE at wavelengths where the solar flux density is high.

1.4.2. *Dark current and open circuit voltage*

When a load is present, a potential difference develops between the terminals of the cell. This potential difference generates a current which acts in the opposite direction to the photocurrent, and the net current is reduced from its short circuit value. This reverse current is usually called the *dark current* in analogy with the current $I_{\mathrm{dark}}(V)$ which flows across the device under an applied voltage, or *bias*, V in the dark. Most solar cells behave like a diode in the dark, admitting a much larger current under forward bias ($V > 0$) than under reverse bias ($V < 0$). This rectifying behaviour is a feature of photovoltaic devices, since an asymmetric junction is needed to achieve charge separation. For an ideal diode the *dark current density* $J_{\mathrm{dark}}(V)$ varies like

$$J_{\mathrm{dark}}(V) = J_{\mathrm{o}}(e^{\mathrm{qV/k_BT}} - 1) \tag{1.3}$$

where J_{o} is a constant, k_{B} is Boltzmann's constant and T is temperature in degrees Kelvin.

The overall current voltage response of the cell, its *current–voltage characteristic*, can be approximated as the sum of the short circuit photocurrent and the dark current (Fig. 1.6). This step is known as the *superposition* approximation. Although the reverse current which flows in reponse to voltage in an illuminated cell is not formally equal to the current which flows in the dark, the approximation is reasonable for many photovoltaic materials and

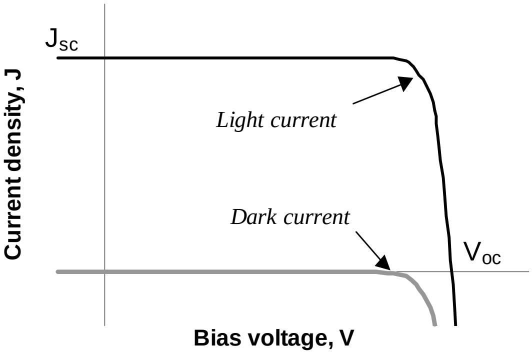


Fig. 1.6. Current–voltage characteristic of ideal diode in the light and the dark. To a first approximation, the net current is obtained by shifting the bias dependent dark current up by a constant amount, equal to the short circuit photocurrent. The sign convention is such that the short circuit photocurrent is positive.

will be used for the present discussion. The sign convention for current and voltage in photovoltaics is such that the photocurrent is positive. This is the opposite to the usual convention for electronic devices. With this sign convention the net current density in the cell is

$$J(V) = J_{\mathrm{sc}} - J_{\mathrm{dark}}(V)\,, \tag{1.4}$$

which becomes, for an ideal diode,

$$J = J_{\mathrm{sc}} - J_{\mathrm{o}}(e^{\mathrm{qV/k_BT}} - 1)\,. \tag{1.5}$$

This result is derived in Chapter 6.

When the contacts are isolated, the potential difference has its maximum value, the open circuit voltage V_{oc}. This is equivalent to the condition when the dark current and short circuit photocurrent exactly cancel out. For the ideal diode, from Eq. 1.5,

$$V_{\mathrm{oc}} = \frac{kT}{q}\ln\left(\frac{J_{\mathrm{sc}}}{J_0} + 1\right). \tag{1.6}$$

Equation 1.6 shows that V_{oc} increases logarithmically with light intensity. Note that voltage is defined so that the photovoltage occurs in forward bias, where $V > 0$.

Figure 1.6 shows that the current–voltage product is positive, and the cell generates power, when the voltage is between 0 and V_{oc}. At $V < 0$, the illuminated device acts as a photodetector, consuming power to generate a

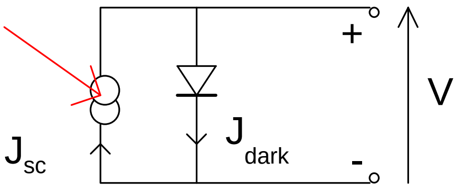


Fig. 1.7. Equivalent circuit of ideal solar cell.

photocurrent which is light dependent but bias independent. At $V > V_{\mathrm{oc}}$, the device again consumes power. This is the regime where light emitting diodes operate. We will see later that in some materials the dark current is accompanied by the emission of light.

Electrically, the solar cell is equivalent to a current generator in parallel with an asymmetric, non linear resistive element, *i.e.*, a diode (Fig. 1.7). When illuminated, the ideal cell produces a photocurrent proportional to the light intensity. That photocurrent is divided between the variable resistance of the diode and the load, in a ratio which depends on the resistance of the load and the level of illumination. For higher resistances, more of the photocurrent flows through the diode, resulting in a higher potential difference between the cell terminals but a smaller current though the load. The diode thus provides the photovoltage. Without the diode, there is nothing to drive the photocurrent through the load.

1.4.3. *Efficiency*

The operating regime of the solar cell is the range of bias, from 0 to V_{oc}, in which the cell delivers power. The cell *power density* is given by

$$P = JV\,. \tag{1.7}$$

P reaches a maximum at the cell's operating point or *maximum power point*. This occurs at some voltage V_{m} with a corresponding current density J_{m}, shown in Fig. 1.8. The optimum load thus has sheet resistance given by $V_{\mathrm{m}}/J_{\mathrm{m}}$. The *fill factor* is defined as the ratio

$$FF = \frac{J_{\mathrm{m}}V_{\mathrm{m}}}{J_{\mathrm{sc}}V_{\mathrm{oc}}} \tag{1.8}$$

and describes the 'squareness' of the J–V curve.

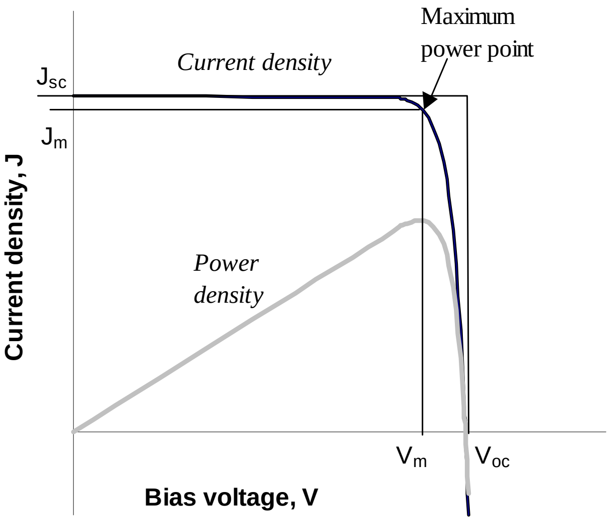


Fig. 1.8. The current voltage (black) and power–voltage (grey) characteristics of an ideal cell. Power density reaches a maximum at a bias V_m, close to V_oc. The maximum power density $J_\mathrm{m} \times V_\mathrm{m}$ is given by the area of the inner rectangle. The outer rectangle has area $J_\mathrm{sc} \times V_\mathrm{oc}$. If the fill factor were equal to 1, the current voltage curve would follow the outer rectangle.

The *efficiency* η of the cell is the power density delivered at operating point as a fraction of the incident light power density, P_s,

$$\eta = \frac{J_\mathrm{m} V_\mathrm{m}}{P_\mathrm{s}} \,. \tag{1.9}$$

Efficiency is related to J_sc and V_oc using FF,

$$\eta = \frac{J_\mathrm{sc} V_\mathrm{oc} FF}{P_\mathrm{s}} \,. \tag{1.10}$$

These four quantities: J_sc, V_oc, FF and η are the key performance characteristics of a solar cell. All of these should be defined for particular illumination conditions. The Standard Test Condition (STC) for solar cells is the Air Mass 1.5 spectrum, an incident power density of 1000 W m^{-2}, and a temperature of 25°C. (Standard and other solar spectra are discussed in Chapter 2.) The performance characteristics for the most common solar cell materials are listed in Table 1.1.

Table 1.1 shows that solar cell materials with higher J_sc tend to have lower V_oc. This is a consequence of the material used, and particularly of

Table 1.1. Performance of some types of PV cell [Green *et al.*, 2001].

Cell Type	Area (cm^2)	V_{oc} (V)	J_{sc} (mA/cm^2)	FF	Efficiency (%)
crystalline Si	4.0	0.706	42.2	82.8	24.7
crystalline GaAs	3.9	1.022	28.2	87.1	25.1
poly-Si	1.1	0.654	38.1	79.5	19.8
a-Si	1.0	0.887	19.4	74.1	12.7
$CuInGaSe_2$	1.0	0.669	35.7	77.0	18.4
CdTe	1.1	0.848	25.9	74.5	16.4

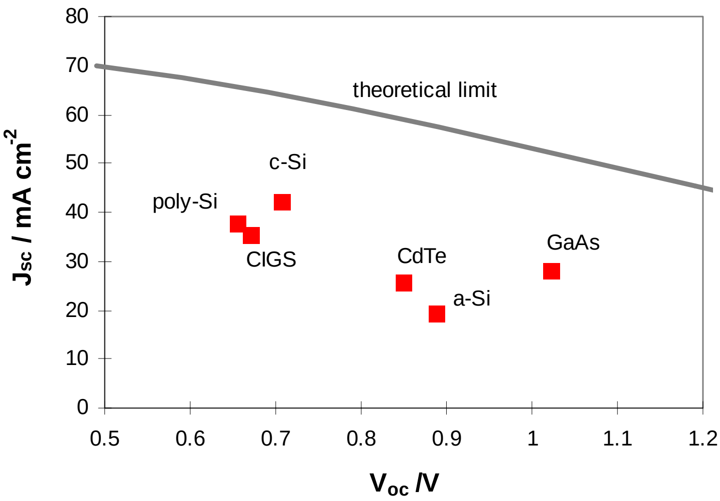


Fig. 1.9. Plot of J_{sc} against V_{oc} for the cells listed in Table 1.1. Materials with high V_{oc} tend to have lower J_{sc}. This is due to the band gap of the semiconductor material. The grey line shows the relationship expected in the theoretical limit.

the band gap of the semiconductor. In Chapter 2 we will see that there is a fundamental compromise between photocurrent and voltage in photovoltaic energy conversion. Figure 1.9 illustrates the correlation between J_{sc} and V_{oc} for the cells in Table 1.1, together with the relationship for a cell of maximum efficiency.

1.4.4. *Parasitic resistances*

In real cells power is dissipated through the resistance of the contacts and through leakage currents around the sides of the device. These effects are

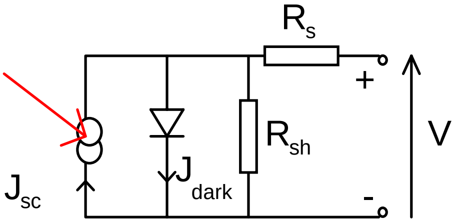
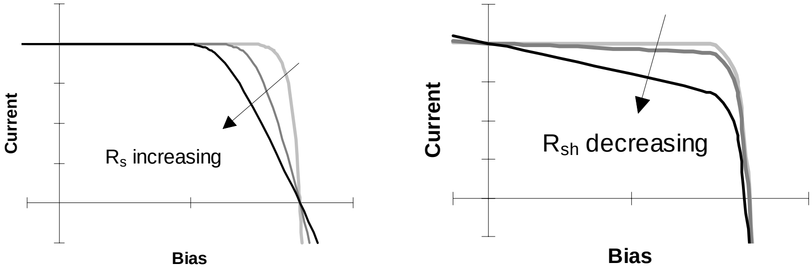


Fig. 1.10. Equivalent circuit including series and shunt resistances.



(a) (b)

Fig. 1.11. Effect of (a) increasing series and (b) reducing parallel resistances. In each case the outer curve has $R_s = 0$ and $R_{sh} = \infty$. In each case the effect of the resistances is to reduce the area of the maximum power rectangle compared to $J_{sc} \times V_{oc}$.

equivalent electrically to two parasitic resistances in series (R_s) and in parallel (R_{sh}) with the cell (Fig. 1.10).

The series resistance arises from the resistance of the cell material to current flow, particularly through the front surface to the contacts, and from resistive contacts. Series resistance is a particular problem at high current densities, for instance under concentrated light. The parallel or shunt resistance arises from leakage of current through the cell, around the edges of the device and between contacts of different polarity. It is a problem in poorly rectifying devices.

Series and parallel resistances reduce the fill factor as shown in Fig. 1.11. For an efficient cell we want R_s to be as small and R_{sh} to be as large as possible.

When parasitic resistances are included, the diode equation becomes

$$J = J_{sc} - J_o(e^{\mathrm{q(V+JAR_s)/kT}} - 1) - \frac{V + JAR_s}{R_{sh}}\,. \tag{1.11}$$

1.4.5. *Non-ideal diode behaviour*

The 'ideal' diode behaviour of Eq. 1.5 is seldom seen. It is common for the dark current to depend more weakly on bias. The actual dependence on V is quantified by an ideality factor, m and the current–voltage characteristic given by the non-ideal diode equation,

$$J = J_{\mathrm{sc}} - J_{\mathrm{o}}(e^{\mathrm{qV/mk_BT}} - 1) \tag{1.12}$$

m typically lies between 1 and 2. The reasons for non-ideal behaviour will be discussed in later chapters.

1.5. Summary

A photovoltaic cell consists of a light absorbing material which is connected to an external circuit in an asymmetric manner. Charge carriers are generated in the material by the absorption of photons of light, and are driven towards one or other of the contacts by the built-in spatial asymmetry. This light driven charge separation establishes a photovoltage at open circuit, and generates a photocurrent at short circuit. When a load is connected to the external circuit, the cell produces both current and voltage and can do electrical work.

The size of the current generated by the cell in short circuit depends upon the intensity and the energy spectrum of the incident light. Photocurrent is related to incident spectrum by the quantum efficiency of the cell, which is the probability of generating an electron per incident photon as a function of photon energy. When a load is present, a potential difference is created between the terminals of the cell and this drives a current, usually called the dark current, in the opposite direction to the photocurrent. As the load resistance is increased, the potential difference increases and the net current decreases until the photocurrent and dark current exactly cancel out. The potential difference at this point is called the open circuit voltage. At some point before V_{oc} is reached, the current–voltage product is maximum. This is the maximum power point and the cell should be operated with a load resistance which corresponds to this point.

The solar cell can be modelled as a current generator in parallel with an ideal diode, and the current–voltage characteristic given by the ideal diode equation, Eq. 1.5. In real cells, the behaviour is degraded by the presence of series and parallel resistances.

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