Physics, Technology and Use of Photovoltaics

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Series Editor's Preface

Since the early 1970s it has become recognised that energy is a factor central to the well-being of both the developed and developing world. The present slump affecting much of the world is at least in part due to the financial distortions caused by the succession of dramatic rises in the price of oil over the past decade or so. There has been a growing awareness of the finite nature of the supplies of the main fossil fuels on which we rely, namely, oil, gas and coal. It appears that we will exhaust these valuable assets, produced by Nature over millenia, in a matter of a few tens of years in the case of oil and gas and in a few hundred years in the case of coal.

It is therefore not surprising that there has been a considerable surge of interest and activity worldwide in searching for more efficient ways of using existing energy sources, and in developing new ones, including nuclear fusion, solar, wave, tidal and wind energy. Equally important are initiatives to improve the energy efficiency of buildings, vehicles and of industry.

In the UK there is a great deal of research and development going on in universities, industry and in certain of the governmert-funded research laboratories. Some will argue that UK activity is on too small a scale compared with that of our competitors in other developed countries. Others will argue that the bias in UK funding remains too strongly entrenched in favour of nuclear energy and neglects some of the alternatives such as wind or wave energy.

However, it is not our purpose in this series to take sides in the argument and the subjects presented cover the work of leading experts in the field of energy studies. It follows that many of the leading 'energy contenders' will be fairly represented. The academic level of the books will be permitted to vary according to the tastes of each author, but they will, in general, require of the reader some scientific education.

Professor Norman H Lipman
Consultant Editor

Preface

The present book provides an excellent overview of photovoltaic solar energy conversion. Since the oil crisis in 1973, photovoltaic power has been the subject of tremendous developments and has not lost any of its attraction and fascination.

Today it is still true that solar cells and modules employ crystalline silicon and do not look very much different from those which, in the late 1950s and early 1960s, served on the first space satellites. Thin-film solar cells also have their roots mainly in the 1960s when NASA had important research and development programmes in the field.

Nevertheless, there have been dramatic changes over the years and hundreds of millions of European Currency Units have been spent on generic research and development. The whole field has also taken full advantage of some of the important developments in materials science, laser technology, photolithography etc.

As a result of the many developments and improvements in photovoltaic technology, it is an important time at which to review the state of the art and update the information presently existing on the subject. This book should be able to fulfil the role of a comprehensive reference book. It has been written by two outstanding experts who are both familiar with the science and technology of solar cells and who have a good knowledge of the industrial problems. Because of the authors' academic background, the book is particularly suitable as a textbook.

Professor Van Overstraeten has been the Project Leader of the European Communities' photovoltaic programme since 1976, and in this position was in very close contact with all the developments in Europe and overseas.

I very much wish this book all the success it deserves in improving and enlarging the knowledge of photovoltaics and the potential it offers as an important modern technology.

Wolfgang Palz
Commission of the European Communities

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Introduction

1.1 The need for photovoltaic energy conversion

Due to the limited reserves of both fossil and nuclear fuels, renewable
resources will have to play a major role in the world's future energy supply.
Among potential new energy sources solar energy, and especially the direct
photovoltaic conversion of sunlight into electricity, is extremely promising.
Solar cells can indeed supply energy to systems with power levels varying from
the milliwatt to the megawatt level. They are also reliable, completely static
and maintenance-free.

Three reasons can be put forward for the general worldwide interest and
research investment in photovoltaics. First, its long-term energy potential is
enormous; almost everywhere on earth a typical house roof covered in solar
cells captures enough solar energy to completely supply its electrical load,
provided that enough storage is installed.

Second, the growing worldwide demand for electrical energy will be
accompanied by a geographical shift since the largest growth rate will be
situated in the developing nations. Due to the prevailing rural or agro-
industrial nature of these countries solar electricity is a very attractive
approach as it makes possible stand-alone systems which are fuel-free and
highly reliable. Moreover, almost all of the developing countries are situated in
the sunbelt of the world. By the year 2000, 40% of the world population will
live in the villages of the Third World where decentralised electricity
generation is necessary. Such a decentralised power generation capability is an
excellent companion to solar energy. Photovoltaics therefore can activate
mutually beneficial commercial contacts between the industrialised and the
Third World; this includes technology transfer and the starting up of a local
industry in the developing countries.

Third, photovoltaics makes use of semiconductors and, from the viewpoint
of materials and of processing technology, is related to microelectronics.
Research in photovoltaics therefore can also yield results useful for the
microelectronics industry and vice versa. A typical example is the introduction
of new semiconducting materials such as amorphous silicon, that was first
used for photovoltaics but that most probably will become important for

other electronic devices as well. By supporting photovoltaic research one invests at the same time in the fast growing microelectronics industry.

The long-term outlook for photovoltaics is excellent, bearing in mind the predicted price decrease. On the other hand, their short-term importance as an energy source is more difficult to evaluate. The main reason for the slow down in the growth of the photovoltaic industry is that the cost of the photovoltaic modules has not decreased as rapidly as was originally expected. This is partly due to cost projections in the United States that were too optimistic as far as the timescale was concerned, and to a strong reduction in the photovoltaic solar energy budget in the United States.

Another retarding effect is the downward trend in the oil price on the world market that became evident in 1982 and 1983. This is, to some extent, due to energy and oil conservation programmes in Europe and the United States and also to the economic crisis and the slow growth of the world economy.

A final reason why one should not expect a strong contribution of photovoltaics to world energy production within the next 20 years is the fact that the large-scale introduction of a technology normally takes more than 40 years.

However, in the short term, an economically viable photovoltaic industry can grow and market systems for stand-alone configurations and, as the price of the photovoltaic modules decreases, for some specific grid-connected residential applications in industrialised sunny regions. In the meantime it is essential that intensive research efforts should be continued, bringing about the cost reduction of an order of magnitude which is necessary for photovoltaics to become competitive with other energy technologies for large-scale production of electricity.

1.2 The basic characteristics of sunlight

Sunlight is composed of energy particles, called photons, with variable energy but constant speed. Solar radiation also has a wave-like character; the wavelength λ being inversely proportional to the photon energy E

$$\lambda = \frac{hc}{E} \tag{1.1}$$

with c the velocity of light *in vacuo* (2.998×10^8 m s^{-1}) and h Planck's constant (6.626×10^{-34} J s).

The basis for photovoltaic energy conversion is the absorption of photons by a semiconductor. Only photons of the appropriate energy can be absorbed by the material. It is therefore important to look at the spectrum of sunlight, giving for each energy wavelength the number of photons.

The sun can be considered as a nuclear reactor in which the internal fusion process results in radiation with a power of 3.8×10^{20} MW. The temperature at the centre of the sun is of the order of 10^6 degrees but the surface temperature is only 5762 K. The extraterrestrial spectrum of sunlight approximates that of a black-body radiator at this temperature.

Since the absorption by the atmosphere is different for different wavelengths, the solar spectrum on earth is different in intensity and shape to that emitted by the sun. The absorption in the ultraviolet is due to electronic transitions in molecular and atomic oxygen, nitrogen and ozone in the upper atmospheric layers. On the other hand, water vapour and carbon dioxide molecules are responsible for the absorption bands in the infrared.

Scattering of the radiation in the atmosphere is responsible for a diffuse component, along with the direct radiation component coming directly from the sun. In regions with relatively few hours of sunshine, such as Western Europe, most of the solar energy received on an annual basis by a horizontal plane is diffuse. The spectral distribution of diffuse light differs from that of direct light; generally it is relatively richer in the higher energy or blue wavelengths.

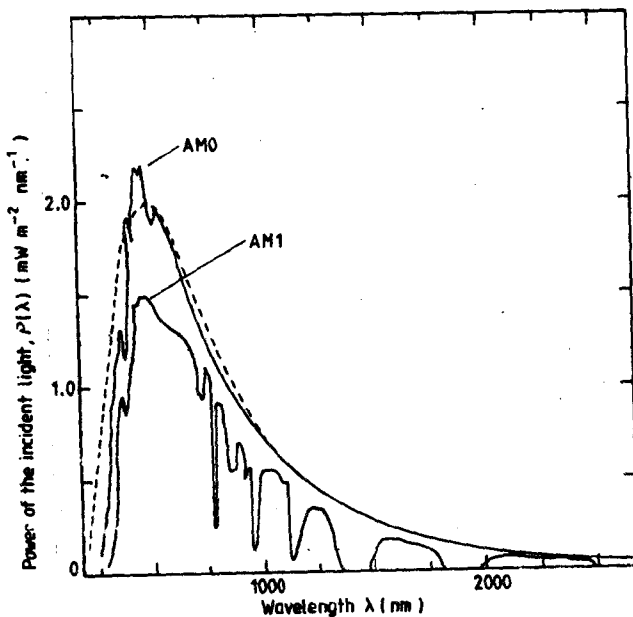The power density associated with solar radiation, on a plane perpendicular

Figure 1.1 The spectrum of sunlight. The different curves refer to the black-body radiation at 5762 K (broken curve), the AM0 spectrum (outside the earth's atmosphere) and the AM1 spectrum.

to the direction of the sun at the mean earth–sun distance, outside the earth's atmosphere, is called the solar constant; its value is $1.37\,kW\,m^{-2}$. The radiation is referred to as the air mass zero (AM0) radiation.

Sunlight is attenuated during its passage through the earth's atmosphere. The attenuation depends on the distance to be covered. Since the spectral distribution, i.e. the number of photons per unit wavelength as a function of wavelength, also depends on the attenuation, several solar spectra can be considered, depending on the length of the light path through the atmosphere. This light path is shortest when the sun is at the zenith. The air mass is the ratio of the actual pathlength of the solar radiation through the atmosphere to its minimum value. When the sun is at its zenith the air mass is one (AM1). When the solar radiation makes an angle θ with the zenith the air mass is given by

$$\text{air mass} = (\cos\theta)^{-1}. \tag{1.2}$$

The longer the air mass, the stronger the attenuation of the light. The spectral distribution of the solar radiation is also a function of the air mass, as indicated in figure 1.1, where some commonly used air mass spectra are represented. Figure 1.2 shows the world sunshine map.
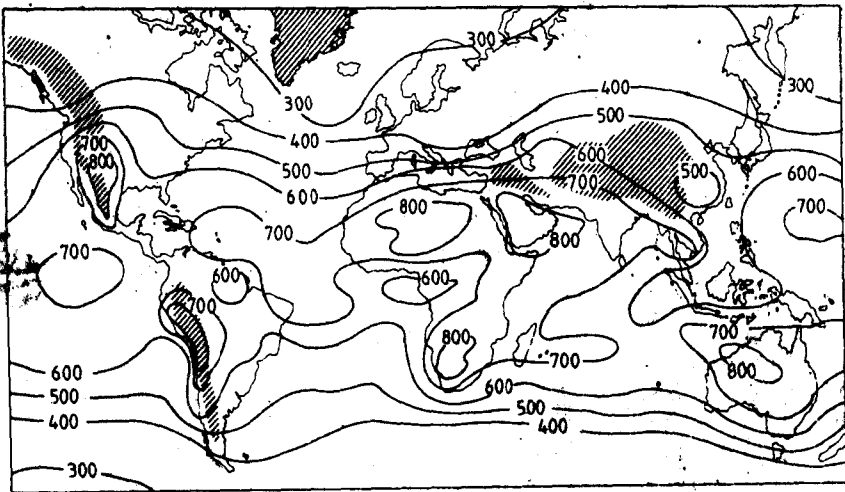
Figure 1.2 World sunshine map, giving the annual solar radiation in $kJ\,cm^{-2}$.

AM1.5 is the spectrum of 'standard sunlight' recommended by the Commission of the European Communities. It corresponds to an angle of 48.2° between the solar radiation and the zenith, which can be considered as a typical value. Table 1.1 gives the spectral distribution of the AM1.5 spectrum as proposed by the Commission of the European Communities (1980). The

Table 1.1 Spectral power density in the standard AM1.5 spectrum.

Wavelength (μm)	$W\,m^{-2}\mu m^{-1}$	Wavelength (μm)	$W\,m^{-2}\mu m^{-1}$	Wavelength (μm)	$W\,m^{-2}\mu m^{-1}$
0.295	0	0.700	1173.31	1.178	374.29
0.305	1.32	0.710	1152.70	1.189	383.37
0.315	20.96	0.720	1133.83	1.193	424.85
0.325	113.48	0.7277	974.30	1.222	382.57
0.335	182.23	0.730	1110.93	1.236	383.81
0.345	234.43	0.740	1086.44	1.264	323.88
0.355	286.01	0.750	1070.44	1.276	344.11
0.365	355.88	0.7621	733.08	1.288	345.69
0.375	386.80	0.770	1036.01	1.314	284.24
0.385	381.78	0.780	1018.42	1.335	175.28
0.395	492.18	0.790	1003.58	1.384	2.42
0.405	751.72	0.800	988.11	1.432	30.06
0.415	822.45	0.8059	860.28	1.457	67.14
0.425	842.26	0.825	932.74	1.472	59.89
0.435	890.55	0.830	923.87	1.542	240.85
0.445	1077.07	0.835	914.95	1.572	226.14
0.455	1162.43	0.8465	407.11	1.599	220.46
0.465	1180.61	0.860	857.46	1.608	211.76
0.475	1212.72	0.870	843.02	1.626	211.26
0.485	1180.43	0.875	835.10	1.644	201.85
0.495	1253.83	0.8875	817.12	1.650	199.68
0.505	1242.28	0.900	807.83	1.676	180.50
0.515	1211.01	0.9075	793.87	1.732	161.59
0.525	1244.87	0.915	778.97	1.782	136.65
0.535	1299.51	0.925	217.12	1.862	2.01
0.545	1273.47	0.930	163.72	1.955	39.43
0.555	1276.14	0.940	249.12	2.008	72.58
0.565	1277.74	0.950	231.30	2.014	80.01
0.575	1292.51	0.955	255.61	2.057	72.57
0.585	1284.55	0.966	279.69	2.124	70.29
0.595	1262.61	0.975	529.64	2.156	64.76
0.605	1261.79	0.985	496.64	2.201	68.29
0.615	1255.43	1.018	585.03	2.266	62.52
0.625	1240.19	1.082	486.20	2.320	57.03
0.635	1243.79	1.094	448.74	2.338	53.57
0.645	1233.96	1.098	486.72	2.356	50.01
0.655	1188.32	1.101	500.57	2.388	31.93
0.665	1228.40	1.128	100.86	2.415	28.10
0.675	1210.08	1.131	116.87	2.453	24.96
0.685	1200.72	1.137	108.68	2.494	15.82
0.695	1181.24	1.144	155.44	2.537	2.59
0.6983	973.53	1.147	139.19		

total irradiance of the AM1.5 spectrum amounts to 827 W m^{-2}. To be used as standard sunlight, the AM1.5 solar spectrum is multiplied by a factor 1000/827 in order to increase the total irradiance to 1000 W m^{-2}, which is about the maximum power density received at the earth's surface.

The peak power of a photovoltaic installation is the power generated under this standard AM1.5 (1 kW m^{-2}) sunlight and is expressed in peak watts.

2

General Physics of Photovoltaics

2.1 Introduction

The electrons of isolated atoms have well defined discrete energy levels. In a solid material, in which the atoms are close to each other and interact, the individual levels spread out and form bands. For electronic and photovoltaic applications the major bands are the conduction band and the valence band, separated by an energy gap (figure 2.1). The energy bands are characterised by density of states functions $N(E)$ giving the number of allowed states per energy level. In a semiconductor at absolute zero the valence band is completely filled and the conduction band completely empty so that no electrical conduction is possible; all electrons are bonded to their atoms. However, in a semiconductor the energy necessary to separate the outer electrons from their atoms is relatively small; this corresponds to a relatively small energy gap E_g such that electrons can receive enough energy to make a transition from the valence band into the conduction band by being subject to a temperature increase or by interacting with a photon. Under these conditions electrical conduction is possible by way of the electrons in the conduction band and the holes in the valence band. Holes are created in the valence band when electrons make the transition to the conduction band. Such a vacant hole in an almost filled valence band can be considered as a positive mobile charge. The total current in a semiconductor is the sum of the electron current in the conduction band and the hole current in the valence band.

Semiconductors are either crystalline or amorphous. In a perfect crystalline semiconductor the number of allowed states in the energy gap is zero; $N(E)=0$ in the gap (figure 2.1(a)). This is the consequence of the presence of both short- and long-range order in a perfect crystal. In an amorphous semiconductor, on the other hand, a short-range order still exists but the long-range order is lost. The result is a large number of states in the gap; these states (figure 2.1(b)) can be associated with the defects characteristic of the amorphous state.

A semiconductor with a low enough number of gap states can be doped by incorporating elements introducing 'shallow' levels in the energy gap. In the case of an n-type semiconductor these levels, referred to as donor levels E_D, are located just below the conduction band edge E_C. A shallow donor usually has
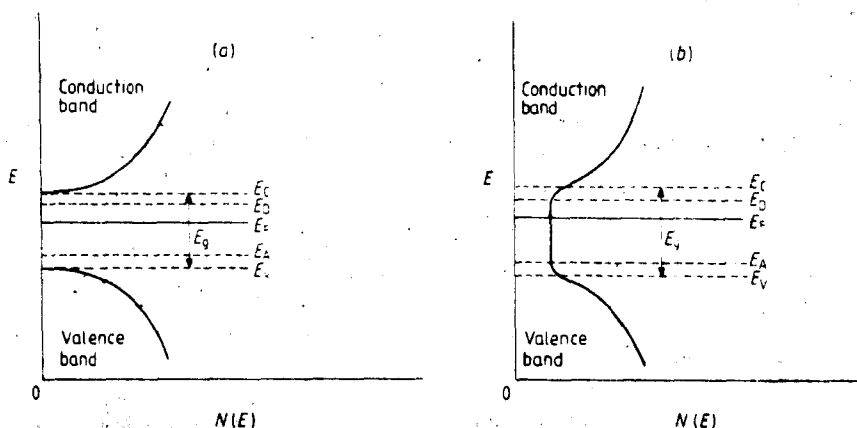
Figure 2.1   Energy bands in a semiconductor. The density of states $N(E) = 0$ in the gap of a perfect crystalline semiconductor (a) and $N(E) \neq 0$ in the gap of an amorphous semiconductor (b).

one more outer electron than the atom of the host crystal. When the additional electron is excited into the conduction band, the donor remains a fixed positive ion. Due to the small energy difference between E_C and E_D most electrons associated with shallow donor levels will at room temperature be thermally excited into the conduction band where they are mobile. In the same way, in a p-type semiconductor, acceptor levels with energy level E_A are located just above the valence band edge E_V; electrons from the valence band can be easily excited into these shallow acceptor states, leaving mobile holes in the valence band. The acceptor taking up a negatively charged electron becomes a negative ion. By introducing donors one strongly increases the number of electrons, making the semiconductor n type; by incorporating acceptors the number of holes increases and the semiconductor becomes p type. In an n-type semiconductor the electrons are referred to as majority carriers (n for negative carriers) and the holes as minority carriers. In p-type semiconductors the holes are the majority carriers (p for positive carriers) and the electrons the minority carriers.

The occupancy of the different states in a semiconductor is governed by the position in the gap of an important quantity—the Fermi level E_F (figure 2.1). At absolute zero all available energy levels up to E_F are filled with electrons; all levels above E_F are empty. As the temperature increases some electrons gain more kinetic energy and will occupy states above E_F leaving empty states below E_F. In a semiconductor E_F normally lies in the gap. For moderate doping levels the separation between E_F and the band edges is large such that the Boltzmann distribution holds and the number of electrons in the conduction band is proportional to $\exp(E_F/kT)$ where kT is the thermal energy