

# **FUNDAMENTALS of SOLAR CELLS**

**Photovoltaic  
Solar Energy  
Conversion**

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**ALAN L. FAHRENBRUCH  
RICHARD H. BUBE**

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**Photovoltaic Solar Energy Conversion**

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To Phyllis, and to my parents, John and Lillian

ALF

*The heavens are telling the glory of God;  
and the firmament proclaims His handiwork. . . .  
In [the heavens] He has set a tent for the sun . . .  
Its rising is from the end of the heavens . . .  
and there is nothing hid from its heat. Psalm 19:1,4,6*

RHB



## PREFACE

In the 1960s and 1970s there was a significant change in people's concept of the earth. An awareness developed that the fossil energy resources, which we all had come to take for granted, were not inexhaustible. New, and preferably renewable, energy resources had to be found. It is probable that a combination of sources will fill this need, including coal, solar-thermal, solar-photovoltaic, wind, nuclear, ocean-thermal, biomass, and others. It is our hope that this book will aid the expansion of solar photovoltaics from relatively small and specialized use to a large-scale contribution to our energy supply.

This book is intended for upper-level graduate students who have a reasonably good understanding of solid state physics and for scientists and engineers involved in research and development of solar cells. It is the outcome of a course taught by one of the authors (ALF) beginning in 1977 at Stanford University. The field of photovoltaics is changing rapidly, and the increasing interest of the scientific, engineering, and business communities has produced an avalanche of literature that attempts to keep up with the state of art. We could not hope to aim at such a moving target in a book of this kind, and fortunately it is not our purpose to do so. This book focuses instead on the fundamental physical principles of solar cells rather than on the details of particular devices. Specific devices are introduced principally as examples of basic phenomena and to illustrate the possibilities for innovative design. Although a solar cell is conceptually simple, it requires the application of many disciplines to produce efficient and economical devices. It is relatively easy to make a solar cell

with less than 5% efficiency from a variety of materials. Indeed, the photovoltaic response of a cell based on spinach has been measured.<sup>†</sup> But to increase the solar efficiency figure to 10–20% requires great understanding and care.

The book begins with a procedure like that used by children who are confronted with clocks and other mysterious mechanisms: the cell is taken apart to expose the fundamental processes taking place. Then each of the basic aspects of its nature is explored in the most intuitive way possible. We begin this examination in Chapter 2 with the solar input. In Chapter 3 semiconductor basics, optical absorption and recombination, drift, and diffusion of carriers are reviewed both to establish a common language and for a convenient resource. Recombination and the flow of photogenerated carriers are related through the transport equation in Chapter 4, enabling us to calculate the total light-generated current and the spectral response. Charge separation and the characteristics of junction barriers are examined in detail in Chapter 5. In Chapter 6 the cell is "reassembled," the overall solar efficiency is calculated, series and parallel resistance losses are considered, and these are related to the semiconductor properties of the materials involved.

Chapters 7, 8, and 10 are devoted to examples of specific solar cell devices where the practicalities of fabrication are faced and the potential for innovative modification is introduced. We consider a single-crystal homojunction (Si), a single-crystal-heterojunction/buried-homojunction (AlGaAs/GaAs), and a polycrystalline, thin-film cell ( $\text{Cu}_x\text{S}/\text{CdS}$ ). Chapter 9 describes the complexities that the use of thin-film polycrystalline material brings to the design of solar cells, including the modification of transport and recombination by grain boundary potential barriers. The book concludes with discussions of concentrator devices and systems and of photoelectrochemical cells.

The last parts of Chapters 5 and 10 relate to two areas that might be considered to be more in the realm of pure science: heterojunction interfaces and single-crystal  $\text{Cu}_x\text{S}/\text{CdS}$  cells. However, this background is essential for experimentalists dealing with cells that involve active interfaces and cells in which photoactive impurity energy levels are important. In addition, these complexities exist in all cells, even if only of second order in magnitude.

Finally we should like to express our appreciation to the people who reviewed particular chapters: Chapters 1 and 6, Dr. Kim W. Mitchell; Chapter 2, Dr. Arlon J. Hunt; Chapter 3, Dr. Julio Aranovich; Chapter 5, Dr. A. Rose; Chapter 7 and the concentrator section of Chapter 12, Pro-

<sup>†</sup> *New York Times*, July 31, 1979.



fessor Richard Swanson; Chapter 8, Professor G. R. Pearson; Chapter 9, Dr. Lewis Fraas; Chapter 10, Professor Allen Rothwarf and Dr. William Haines; Chapter 11, Professor Sigurd Wagner; and Chapter 12 (the section on PEC cells), Dr. Bruce Parkinson.

In addition, we wish to thank all the graduate students who gave valuable feedback and caught many errors in the manuscript, especially Chris Eberspacher. Finally we wish to give credit to NSF-RANN, ERDA, and the Department of Energy for financial support for a portion of the research discussed here.

# LIST OF SYMBOLS

$A$	Ideality factor in diode equations	$E_A, E_D$	Acceptor- and donor-level energies (eV)
$A^*$	Richardson constant modified by the effective mass [ $= 120(m^*/m_0)$ ] ( $A \text{ cm}^{-2} \text{ }^\circ\text{K}^{-2}$ )	$E_c$	Energy of conduction band edge (eV)
$A^{**}$	Richardson constant modified by tunneling, image forces, etc.	$E_F$	Fermi-level energy (eV)
$A_0$	Avogadro's number [ $= 6.023 \times 10^{23}$ ] ( $\text{mole}^{-1}$ )	$E_{Fn}, E_{Fp}$	Quasi-Fermi-level energies for electrons and holes
$\mathcal{A}_A, \mathcal{A}_D$	Active illuminated area and total junction diode area	$E_g$	Band-gap energy (eV)
$a$	Lattice constant ( $\text{\AA}$ )	$E_i$	Intrinsic-level energy (eV)
$B$	Constant	$E_r$	Recombination-level energy (eV)
$B$	Magnetic induction (G)	$E_v$	Energy of valence band edge (eV)
$C$	Capacitance (F)	$E_0, E_{00}$	Characteristic energies for thermionic-field emission junction transport (eV) [Section 5.5.6]
$C$	Solar concentration ratio	$\mathcal{E}$	Electric field ( $\text{V cm}^{-1}$ )
$D$	Atomic diffusion coefficient ( $\text{cm}^2 \text{ sec}^{-1}$ )	$\mathcal{F}$	Faraday constant [ $= 96486 \text{ C g-equiv}^{-1}$ ]
$D, D_n, D_p$	Diffusion coefficients: general, for electrons, and for holes, respectively ( $\text{cm}^2 \text{ sec}^{-1}$ )	$f$	Fermi function
$E$	Energy (usually in eV) <sup>†</sup>	$ff$	Fill factor
		$G$	Generation rate ( $\text{cm}^{-3} \text{ sec}^{-1}$ )

<sup>†</sup> In this book energies (e.g.,  $E_F$ ,  $E_i$ ,  $E_c$ ) are given with respect to an arbitrary reference. Energy differences are denoted explicitly, i.e.,  $(E_c - E_F)$ , or by  $\Delta E$ ,  $E_g$ ,  $\delta$ ,  $E_0$ , and  $E_{00}$ .

$g$	Collection function, bulk (see Section 6.3.1)	$N_A, N_D$	Density of acceptors and donors ( $\text{cm}^{-3}$ )
$H$	Collection function, total	$N_c, N_v$	Effective density of states in the conduction and valence bands ( $\text{cm}^{-3}$ )
$h$	Collection function, interfacial		
$h$	Planck's constant [ $\hbar = h/2\pi = 1.053 \times 10^{-34} \text{ J sec} = 0.66 \times 10^{-15} \text{ eV sec}$ ]	$N_{gb}$	Density of grain boundary states ( $\text{cm}^{-2}$ )
$I$	Current (A)	$N_i$	Density of imperfection centers ( $\text{cm}^{-3}$ )
$I_{sc}$	Short-circuit current (A)	$N_i^*$	Density of imperfection centers available for capture of minority carriers ( $\text{cm}^{-3}$ )
$J$	Current density ( $\text{A cm}^{-2}$ )	$N_i$	Density of interface states ( $\text{cm}^{-2}$ )
$J_L, J_{Ln}, J_{Lp}$	Light-generated current density: total, for electrons, and for holes, respectively ( $\text{A cm}^{-2}$ )	$N_r$	Density of recombination centers ( $\text{cm}^{-3}$ )
$J_m$	Current density at maximum-power point ( $\text{A cm}^{-2}$ )	$N_{ss}$	Density of interface states ( $\text{cm}^{-2} \text{ eV}^{-1}$ )
$J_n, J_p$	Electron and hole current density ( $\text{A cm}^{-2}$ )	$n$	Electron density ( $\text{cm}^{-3}$ )
$J_{sc}$	Short-circuit current density ( $\text{A cm}^{-2}$ )	$n_i$	Intrinsic carrier density ( $\text{cm}^{-3}$ )
$J_0$	Preexponential factor in diode equation ( $\text{A cm}^{-2}$ )	$n_n, n_p$	Nonequilibrium carrier density of electrons in $n$ -type and $p$ -type materials
$J_{00}$	Preexponential factor for $J_0$ [e.g., $J_0 = J_{00} \exp(-\Delta E/kT)$ ]	$n_{n0}, n_{p0}$	Equilibrium carrier density of electrons in $n$ - and $p$ -type materials
$K_0, K_L$	Radiation damage coefficients [Section 7.5.1]	$n_r$	Index of refraction
$\mathcal{K}$	Thermal conductivity ( $\text{W cm}^{-1} \text{ } ^\circ\text{C}^{-1}$ )	$P$	Power density ( $\text{W cm}^{-2}$ )
$k$	Boltzmann constant [ $= 1.38 \times 10^{-23} \text{ J } ^\circ\text{K}^{-1} = 0.864 \times 10^{-4} \text{ eV } ^\circ\text{K}^{-1}$ ]	$P_m$	Power density at the maximum-power point ( $\text{W cm}^{-2}$ )
$k_0$	Distribution coefficient	$P_s$	Total solar input power ( $\text{W cm}^{-2}$ )
$L, L_n, L_p$	Diffusion length: general, for electrons, and for holes, respectively (cm)	$p$	Hole density ( $\text{cm}^{-3}$ )
$L_{dr}$	Drift length [ $= \mu \mathcal{E} \tau$ ] (cm) [Eq. (11.1)]	$p_p, p_n$	Nonequilibrium hole densities in $p$ - and $n$ -type materials ( $\text{cm}^{-3}$ )
$\mathcal{L}_s, \mathcal{L}_p$	Loss fraction for series and parallel resistance	$p_{p0}, p_{n0}$	Thermal equilibrium hole densities in $p$ - and $n$ -type materials ( $\text{cm}^{-3}$ )
$\ln$	Natural logarithm	$Q$	Charge density ( $\text{C cm}^{-2}$ or $\text{C cm}^{-3}$ )
$M$	Atomic mass	$Q_i$	Insulator bulk charge ( $\text{C cm}^{-3}$ )
$m_e^*, m_h^*$	Effective masses of electrons and holes	$Q_{ss}$	Interface or surface state charge ( $\text{C cm}^{-2}$ )
$m_r$	Optical air-mass number	$q$	Electron charge [ $=  q  = 1.6 \times 10^{-19} \text{ C}$ ]
$m_t^*$	Tunneling effective mass	$R$	Reflectance
$m_0$	Rest mass of electron [ $= 9.11 \times 10^{-31} \text{ kg}$ ]	$R$	Resistance ( $\Omega$ )
$N$	Number density ( $\text{cm}^{-3}$ )	$R_s, R_p, R_c$	Series, parallel (shunt), and contact resistance ( $\Omega$ )

$S$	Index of interface behavior [Section 5.7.2]	$\alpha$	Optical absorption coefficient ( $\text{cm}^{-1}$ )
$S, S_i$	Surface and interfacial recom- bination velocities (cm $\text{sec}^{-1}$ )	$\alpha$	Tunneling exponential factor ( $\text{V}^{-1}$ )
$S_{\text{gb}}$	Grain boundary recombination velocity (cm $\text{sec}^{-1}$ )	$\alpha_{\Sigma}$	Minimum angle subtended by sun at earth's radius [ $= 0.533^\circ$ ]
$T$	Temperature ( $^\circ\text{C}$ or $^\circ\text{K}$ )	$\beta$	Recombination coefficient ( $\text{cm}^3 \text{sec}^{-1}$ )
$\mathcal{T}$	Tunneling coefficient	$\Gamma$	Photon flux (photons $\text{cm}^{-2}$ $\text{sec}^{-1}$ )
$t$	Time (sec)	$\Gamma_0$	Photon flux incident on front surface of solar cell ( $\text{cm}^{-2}$ $\text{sec}^{-1}$ )
$t$	Layer thickness (cm)	$\gamma$	Grain size (cm)
$U$	Bulk recombination rate ( $\text{cm}^{-3}$ $\text{sec}^{-1}$ )	$\Delta$	Increment
$U_{\text{gb}}$	Grain boundary recombination rate ( $\text{cm}^{-2} \text{sec}^{-1}$ )	$\Delta E$	Energy difference (eV)
$V$	Voltage (V)	$\Delta E_c, \Delta E_v$	Conduction and valence band discontinuities (eV) [Fig. 5.14]
$V_d$	Diffusion (or "built-in") volt- age (V)	$\delta$	Thickness of insulating layer in MIS structure (cm or $\text{\AA}$ )
$V_{\text{dgb}}$	Diffusion voltage of grain boundary (used where $V_d$ would be confusing) (V)	$\delta_n, \delta_p$	Energy difference between $E_F$ and conduction or valence band edges [ $\delta_n = E_c - E_F$ ; $\delta_p = E_F - E_v$ ] (eV)
$V_m$	Voltage at maximum-power point (V)	$\epsilon_r$	Dielectric constant [ $\epsilon_s = \epsilon_r \epsilon_0$ ]
$V_{\text{oc}}$	Open-circuit voltage (V)	$\epsilon_s, \epsilon_{s0}, \epsilon_{\text{shf}}$	Permittivity of semiconductor, dc, and high frequency (F $\text{cm}^{-1}$ )
$v_d$	Diffusion velocity [= $D/L$ ] (cm $\text{sec}^{-1}$ )	$\epsilon_0$	Permittivity of free space [ $= 8.85 \times 10^{-14} \text{ F cm}^{-1}$ ]
$v_{\text{th}}$	Average thermal velocity of electrons or holes (cm $\text{sec}^{-1}$ ) [ $= (8kT/\pi m^*)^{1/2}$ ; at $300^\circ\text{K}$ , $v_{\text{th}} = (1.91 \times 10^7)(m_0/m^*)^{1/2} \text{ cm sec}^{-1}$ ]	$\eta_c$	Concentrator efficiency (%)
$W_d$	Depletion layer width (cm)	$\eta_Q$	Quantum efficiency (%)
$W_{\text{dgb}}$	Depletion layer width on one side of a grain boundary (cm)	$\eta_s$	Solar efficiency (%)
$W_i$	Insulating layer width (cm)	$\theta$	Angle
$W_p$	Peak watts (W)	$\lambda$	Wavelength ( $\mu\text{m}$ )
$x$	Distance coordinates (cm)	$\mu_n, \mu_p$	Electron and hole mobilities ( $\text{cm}^2 \text{V}^{-1} \text{sec}^{-1}$ )
$x_n, x_p$	Distance coordinates of deple- tion layer edge for $n$ -QNR and $p$ -QNR (cm) [Fig. 5.1]	$\nu$	Frequency of light ( $\text{sec}^{-1}$ )
$x_{n'}$	Distance coordinate such that ( $x_{n'} - x_n$ ) is thickness of $n$ - QNR (cm) [Fig. 5.1]	$\Pi$	Product
$x_{p'}$	$ x_{p'} - x_p $ is thickness of $p$ - QNR (cm)	$\rho$	Charge density (C $\text{cm}^{-3}$ )
$y$	Distance coordinate difference (e.g., $y_n =  x_{n'} - x_n $ ) (cm)	$\rho$	Bulk resistivity ( $\Omega \text{ cm}$ )
$z$	Zenith angle of sun	$\rho_c, \rho_{c0}$	Contact resistivity: general and at zero-bias voltage, re- spectively ( $\Omega \text{ cm}^2$ )
$z$	Distance coordinate (cm)	$\rho_s$	Sheet resistivity ( $\Omega \square^{-1}$ )
		$\Sigma$	Sum
		$\sigma$	Conductivity ( $\Omega^{-1} \text{ cm}^{-1}$ )
		$\sigma, \sigma_n, \sigma_p$	Recombination cross sections:

	general, for electrons, and for holes, respectively ( $\text{cm}^2$ )	$\phi$	Electrostatic potential (V)
$\tau, \tau_n, \tau_p$	Minority carrier lifetimes: general, for electrons, and for holes, respectively (sec)	$\phi_b$	Potential barrier height, measured from the Fermi level (V)
$\tau_{n0}, \tau_{p0}$	Extreme lifetime for electrons and holes (sec) [Section 3.5.2]	$\phi_d$	Potential difference induced by electric dipole at junction (V)
$\tau_r$	Carrier scattering relaxation time (sec) [Eq. (3.20)]	$\phi_{gb}$	Potential barrier height at grain boundary, measured from the Fermi level (V)
$\Phi$	Radiation fluence (particles $\text{cm}^{-2}$ )	$\chi$	Electron affinity (V)
$\phi$	Work function (V)	$\Omega$	Ohms
		$\omega$	Angular frequency (radians $\text{sec}^{-1}$ )

## LIST OF ACRONYMS<sup>†</sup>

AM <sub>l</sub> , AM <sub>m</sub>	Air-mass numbers [Section 2.2]	LPE	Liquid-phase epitaxial (growth)
BSF	Back-surface field (Section 4.5.1)	MIS	Metal/insulator/semiconductor junction
BSR	Back-surface reflection (optical, Section 7.6.3)	MOS	Metal/oxide/semiconductor junction
CNR	Comsat nonreflective (cell) [Section 7.4.4]	OS	Oxide semiconductor
CVD	Chemical vapor deposition	PEC	Photoelectrochemical cell
CZ	Czochralski crystal growth (e.g., Si)	PIN	<i>p</i> -type/insulator/ <i>n</i> -type junction
DLTS	Deep-level transient spectroscopy	PX	Polycrystalline
EFG	Edge-fed growth (e.g., of Si ribbon)	QNR	Quasi-neutral region
FZ	Float zone crystal growth (e.g., Si)	R/G	Indicating the recombination/generation component of junction transport (or as subscript "rg," e.g., $J_{rg}$ )
I/D	Indicating the injection/diffusion component of diode transport ("id" when used as subscript, e.g., $J_{id}$ )	SIS	Semiconductor/insulator/semiconductor junction
ITO	Indium tin oxide	VE	Vacuum evaporation
		VMJ	Vertical multijunction cell

<sup>†</sup> Table 9.1 lists acronyms for the deposition methods.



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