FUNDAMENTALS of SOLAR CELLS

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.† 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 (Cu_xS/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 Cu_xS/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-

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

† 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 ΔE, E_g, δ, E_0, and E_{00}.

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

S Index of interface behavior [Section 5.7.2]
S, S_i Surface and interfacial recombination velocities (cm sec^{-1})
S_{gb} Grain boundary recombination velocity (cm sec^{-1})
T Temperature (°C or °K)
$\mathcal{T}$ Tunneling coefficient
t Time (sec)
t Layer thickness (cm)
U Bulk recombination rate (cm^{-3} sec^{-1})
U_{gb} Grain boundary recombination rate (cm^{-2} sec^{-1})
V Voltage (V)
V_d Diffusion (or "built-in") voltage (V)
V_{dgb} Diffusion voltage of grain boundary (used where V_d would be confusing) (V)
V_m Voltage at maximum-power point (V)
V_{oc} Open-circuit voltage (V)
v_d Diffusion velocity [= D/L] (cm sec^{-1})
v_{th} Average thermal velocity of electrons or holes (cm sec^{-1}) [$=(8kT/\pi m^*)^{1/2}$; at 300°K, $v_{th} = (1.91 \times 10^7)(m_0/m^*)^{1/2}$ cm sec^{-1}]
W_d Depletion layer width (cm)
W_{dgb} Depletion layer width on one side of a grain boundary (cm)
W_i Insulating layer width (cm)
W_p Peak watts (W)
x Distance coordinates (cm)
x_n, x_p Distance coordinates of depletion layer edge for n-QNR and p-QNR (cm) [Fig. 5.1]
$x_{n'}$ Distance coordinate such that $(x_{n'} - x_n)$ is thickness of n-QNR (cm) [Fig. 5.1]
$x_{p'}$ $|x_{p'} - x_p|$ is thickness of p-QNR (cm)
y Distance coordinate difference (e.g., $y_n = |x_{n'} - x_n|$) (cm)
z Zenith angle of sun
z Distance coordinate (cm)

α Optical absorption coefficient (cm^{-1})
α Tunneling exponential factor (V^{-1})
α_Σ Minimum angle subtended by sun at earth's radius [=0.533°]
β Recombination coefficient (cm^3 sec^{-1})
Γ Photon flux (photons cm^{-2} sec^{-1})
Γ_0 Photon flux incident on front surface of solar cell (cm^{-2} sec^{-1})
γ Grain size (cm)
Δ Increment
ΔE Energy difference (eV)
$\Delta E_c, \Delta E_v$ Conduction and valence band discontinuities (eV) [Fig. 5.14]
δ Thickness of insulating layer in MIS structure (cm or Å)
δ_n, δ_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)
ϵ_r Dielectric constant [$\epsilon_s = \epsilon_r\epsilon_0$]
$\epsilon_s, \epsilon_{s0}, \epsilon_{shf}$ Permittivity of semiconductor, dc, and high frequency (F cm^{-1})
ϵ_0 Permittivity of free space [$= 8.85 \times 10^{-14}$ F cm^{-1}]
η_c Concentrator efficiency (%)
η_Q Quantum efficiency (%)
η_s Solar efficiency (%)
θ Angle
λ Wavelength (μm)
μ_n, μ_p Electron and hole mobilities (cm^2 V^{-1} sec^{-1})
ν Frequency of light (sec^{-1})
Π Product
ρ Charge density (C cm^{-3})
ρ Bulk resistivity (Ω cm)
ρ_c, ρ_{c0} Contact resistivity: general and at zero-bias voltage, respectively (Ω cm^2)
ρ_s Sheet resistivity (Ω $\square^{-1}$)
Σ Sum
σ Conductivity (Ω^{-1} cm^{-1})
$\sigma, \sigma_n, \sigma_p$ Recombination cross sections:

	general, for electrons, and for holes, respectively (cm^2)
τ, τ_n, τ_p	Minority carrier lifetimes: general, for electrons, and for holes, respectively (sec)
τ_{n0}, τ_{p0}	Extreme lifetime for electrons and holes (sec) [Section 3.5.2]
τ_r	Carrier scattering relaxation time (sec) [Eq. (3.20)]
Φ	Radiation fluence (particles cm^{-2})
ϕ	Work function (V)
ϕ	Electrostatic potential (V)
ϕ_b	Potential barrier height, measured from the Fermi level (V)
ϕ_d	Potential difference induced by electric dipole at junction (V)
ϕ_{gb}	Potential barrier height at grain boundary, measured from the Fermi level (V)
χ	Electron affinity (V)
Ω	Ohms
ω	Angular frequency (radians sec^{-1})

LIST OF ACRONYMS†

AM1, AMm_r	Air-mass numbers [Section 2.2]
BSF	Back-surface field (Section 4.5.1)
BSR	Back-surface reflection (optical, Section 7.6.3)
CNR	Comsat nonreflective (cell) [Section 7.4.4]
CVD	Chemical vapor deposition
CZ	Czochralski crystal growth (e.g., Si)
DLTS	Deep-level transient spectroscopy
EFG	Edge-fed growth (e.g., of Si ribbon)
FZ	Float zone crystal growth (e.g., Si)
I/D	Indicating the injection/diffusion component of diode transport ("id" when used as subscript, e.g., J_{id})
ITO	Indium tin oxide
LPE	Liquid-phase epitaxial (growth)
MIS	Metal/insulator/semiconductor junction
MOS	Metal/oxide/semiconductor junction
OS	Oxide semiconductor
PEC	Photoelectrochemical cell
PIN	*p*-type/insulator/*n*-type junction
PX	Polycrystalline
QNR	Quasi-neutral region
R/G	Indicating the recombination/generation component of junction transport (or as subscript "rg," e.g., J_{rg})
SIS	Semiconductor/insulator/semiconductor junction
VE	Vacuum evaporation
VMJ	Vertical multijunction cell

† Table 9.1 lists acronyms for the deposition methods.

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