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SOLAR CELL DEVICE PHYSICS

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Solar Cell Device Physics

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To
My parents Margaret and Raymond
for setting me on the path toward intellectual pursuits
My wife Joyce
for her continuing support along the way
My sons Stephen and David
for making the journey so enjoyable

Preface

This book is concerned with the physical principles and operating characteristics of solar cell devices. Its approach is to provide a balanced, in-depth qualitative and quantitative treatment. Physical principles and physical insight are stressed throughout the book so that it may be used to understand the operation of the devices of today as well as the devices of the future.

Sections such as "qualitative discussion," "configurations and performance," and "notes for the experimentalist," found in each of the chapters on specific devices, are presented in the belief that a physical "feel" for device operation and a knowledge of the advantages and disadvantages of a specific device are necessities. The more mathematically oriented sections are presented in the belief that the serious student and researcher alike want to know the assumptions behind the mathematical models used to quantify device behavior. Only then can they judge the appropriateness of the assumptions to new devices and new materials.

The level of the book is such that it is appropriate for use as a textbook for graduate students in engineering and the sciences, and as a reference book for those actively involved in solar cell research and development. Since the book has extensive qualitative discussion of physical phenomena and device operation, it can also serve as a textbook for seniors in electrical engineering and applied physics. When used at this level, the more mathematically oriented sections can be omitted and the emphasis placed on the physical description, the final mathematical model for the operating characteristics of the device, and device performance data. At whatever level the book is used, it will be essential for the reader to have an introductory knowledge of solid state physics and devices as provided in standard texts.

Assuming this background, the book begins, after an introductory chapter, with a review of the physics and materials properties basic to photovoltaic energy conversion (Chapter 2). Careful attention is given in Chapter 2 to the electronic and optical properties of crystalline, polycrystalline, and amorphous materials with both organic and inorganic materials being considered. The manner in which these properties change from one material class to another, and the fundamental reasons for these changes with their implications for photovoltaics, are discussed.

Generation, recombination, and bulk transport are also covered in Chapter 2. The latter is discussed for both transport via delocalized band states and transport via states in the gap. Rather than simply presenting the usual equations of solid state for generation, recombination, and transport phenomena, the origins of the mathematical models are explored. This is done to point out the assumptions on which our models are built. Only with that knowledge can one select the proper model for a particular material and situation. Chapter 2 closes with a discussion of the fundamental origins of photovoltaic action in materials.

Chapter 3 begins with a comparison of the two mechanisms of photocarrier collection in solar cells: drift and diffusion. The importance of interfaces in the collection process is pointed out, and interface types, interface modeling, and interface transport are discussed. A unified approach, which stresses the roles of thermodynamics, defects created in the act of forming the barrier, intrinsic surface states, and interface or intermediary layers is used in determining interface properties for configurations as diverse as semiconductor–semiconductor heterojunctions and liquid–semiconductor junctions. An extensive tabulation of semiconductor data important to photovoltaics is presented, together with data on work functions which include effective work functions for selected redox couples.

Chapters 4–6 deal with specific solar cell device classes defined in terms of the interface structure employed: Chapter 4 covers homojunctions (*p*–*n*, *p*–*i*–*n*); Chapter 5 covers semiconductor–semiconductor heterojunctions (isotype and anisotype) including S–I–S; and Chapter 6 covers surface-barrier devices (M–S, M–I–S, and liquid–semiconductor). Each of these chapters contains a qualitative discussion of the operation and the design considerations of the device class. Each of these chapters also includes an in-depth quantitative analysis of the device characteristics, which clearly shows the assumptions and range of validity of the analysis. In the quantitative sections the mathematical development is always given a physical interpretation. The mathematics is viewed as a tool to quantify and catalog the important aspects of device behavior. Each device chapter closes with an extensive survey of specific device configurations and experimental results.

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The book evolved out of notes used in "solar cell device physics," a graduate course given at The Pennsylvania State University. That evolution was helped along considerably by the comments of the series of graduate students who took the course over its six-year history. Among them I must especially single out Patricia Wiley and Paul Lester, whose comments and corrections of errors were very helpful. Also, a number of colleagues, including Dr. John Houlihan and Dr. S. Ashok, have contributed comments and suggestions. In particular, I am very grateful to Professor Ashok whose suggestions, stimulating comments, and diligent, critical reading of the manuscript greatly improved the final result.

Lastly, I must mention the three people without whom this book never would have been completed: Stella Updegraff, who typed the manuscript, helped in its editing, and retyped the final manuscript; Dr. John Mentzer, who provided the environment that allowed an undertaking such as this; and my wife Joyce, who greatly assisted and supported the effort.

List of Basic Symbols

SYMBOL	DEFINITION	UNITS
a, c	Lattice parameters	nm
A^*	Effective Richardson constant	amp/m^2/°K^2
C	Capacitance per area	farads/m^2
d	Interfacial layer thickness	m
D^*	Ambipolar diffusion coefficient	m^2/sec
e	Magnitude of the charge on an electron = 1.602×10^{-19}	C or coulomb
E	Energy of an electron	joules, eV
E_c	Conduction band edge	eV
E_F	Fermi level or electrochemical potential	eV
E_F^i	Quasi-Fermi level for ith localized state grouping	eV
E_{Fi}	Intrinsic Fermi level	eV
E_{Fn}, E_{Fp}	Electron and hole quasi-Fermi levels	eV
E_g	Forbidden energy gap	eV
E_{gm}	Mobility energy gap	eV

SYMBOL	DEFINITION	UNITS
E_{go}	Optical energy gap	eV
E_p	Energy of phonon	joules, eV
E_{ph}	Energy of a photon	joules, eV
E^0_{redox}	Standard redox potential measured with respect to the standard hydrogen electrode (obtained for $N_0^{re} = N_0^{ox}$)	eV
E_v	Valence band edge	eV
E_{VL}	Vacuum level	eV
f	Probability of occupation function	—
f_0	Probability of occupation in thermodynamic equilibrium (the Fermi function)	—
F_e	Total force on an electron in a solid ($F_e = -e[\xi + \xi_n']$)	N
F_h	Total force on a hole in a solid ($F_h = e[\xi + \xi_p']$)	N
FF	Fill factor defined by $(V_{mp}J_{mp})/(V_{oc}J_{sc})$	—
g	Generation rate	$sec^{-1}m^{-3}$
$g_e(E)$	Density of electron states in energy per volume of the solid	$eV^{-1}m^{-3}$
$g_p(E)$	Density of phonon states in energy per volume of the solid	$eV^{-1}m^{-3}$
$G_e^c(\mathbf{r}, \mathbf{v})$	Density of conduction-band states per volume of velocity space per volume	sec^3m^{-6}
$G_e^v(\mathbf{r}, \mathbf{v})$	Density of valence-band states per volume of velocity space per volume	sec^3m^{-6}
G_L	Optical generation rate	$m^{-3}sec^{-1}$
h	Planck's constant $= 6.625 \times 10^{-34}$	joule-sec
$\hbar$	Planck's constant$/2\pi = 1.054 \times 10^{-34}$	joule-sec
J	Current density	amp/m^2
J_{bk}	Bucking current $J_{bk} = J_{bk}(\Phi_0, V)$; in general, goes to zero as $V \to 0$	amp/m^2
J_{fe}	Field emission current density	amp/m^2
J_{ir}	Interface recombination current density	amp/m^2
J_{mp}	Current density at the maximum power point	amp/m^2

SYMBOL	DEFINITION	UNITS
J_{ob}	Thermionic emission current density	amp/m^2
J_{ph}	Photocurrent $J_{ph} = J_{ph}(\Phi_0, V)$; in general, goes to zero as $\Phi_0 \to 0$.	amp/m^2
J_{sc}	Short-circuit current density	amp/m^2
J_{tf}	Thermionic field emission current density	amp/m^2
$\mathbf{k}$	Wave vector	m^{-1}
L^*	Ambipolar diffusion length	m
L_{Dn} or L_n & L_{Dp} or L_p	Diffusion length for electrons or holes	m
$L_{\xi n}$, $L_{\xi p}$	Drift length for electrons or holes	m
m	Mass	kg
m_e	Mass of a free electron = 9.108×10^{-31}	kg
m_e^*	Effective mass of electron	kg
m_h^*	Effective mass of hole	kg
n	Conduction-band number density; Diode quality factor	m^{-3}
n_i	Intrinsic number density	m^{-3}
N_c	Conduction-band effective density of states	m^{-3}
N_0^{ox}	Concentration of oxidized species of a redox couple when system is in thermodynamic equilibrium	m^{-3}
N_0^{re}	Concentration of reduced species of a redox couple when system is in thermodynamic equilibrium	m^{-3}
N_v	Valence-band effective density of states	m^{-3}
p	Valence-band number density	m^{-3}
P_{in}	Power per area impinging on cell structure	Watts/m^2 or W/m^2
Q	Collection efficiency	—
Q_b^- or Q_b^+	Charge/area developed in a semiconductor space charge region	coulombs/m^2
Q_e	Charge/area developed in electrolyte (Helmholtz and Gouy layers)	coulombs/m^2

SYMBOL	DEFINITION	UNITS
Q_{fix}	Fixed charge/area	coulombs/m^2
Q_s^- or Q_s^+	Charge/area developed at an interface or surface	coulombs/m^2
r	Recombination rate	sec^{-1}m^{-3}
$\mathscr{R}$	Net recombination rate	sec^{-1}m^{-3}
S	Seebeck coefficient	eV/°K
t	Time	sec
T	Temperature	°K
$\langle v \rangle$	Thermal speed	m/sec
V	Voltage	volts
V_{bi}	That part of the total electrostatic potential which is developed in a semiconductor	eV
V_j	Change in the band bending across a junction	V or eV
V_{mp}	Voltage at maximum power point	amp/m^2
$V_n(\mathbf{r})$	Defined by $V_n(\mathbf{r}) = E_c(\mathbf{r}) - E_{Fn}(\mathbf{r})$	eV
V_0	Total electrostatic potential energy developed across an interface in thermodynamic equilibrium	eV
V_{oc}	Open-circuit voltage	volts
$V_p(\mathbf{r})$	Defined by $V_p(\mathbf{r}) = E_{Fp}(\mathbf{r}) - E_v(\mathbf{r})$	eV
W	Activation energy for hopping;	eV
	Space charge layer width	m
α	Absorption coefficient	m^{-1}, cm^{-1}
Δ, Δ_I	Potential energy developed across an interfacial layer or developed by a surface dipole	eV
ΔE	Bandwidth; activation energy	eV
ε	Permittivity of a material	farad/m
μ	Mobility	m^2/(V-sec)
η	Thermodynamic efficiency defined by $V_{mp}J_{mp}/P_{in}$	—
ξ	Electrostatic field	V/m
ξ'_n	Electron effective force field arising from varying material properties	V/m
ξ'_p	Hole effective force field arising from varying material properties	V/m
Ξ	Transmission probability	—
ρ	Resistivity	Ω-m
σ	Conductivity	℧/m

SYMBOL	DEFINITION	UNITS
σ_n, σ_p	Electron and hole conductivities	℧/m
τ_n	Minority-carrier lifetime (electrons)	sec
τ_p	Minority-carrier lifetime (holes)	sec
ϕ	Defined such that $\Phi_0 = \phi\Delta\lambda$	$m^{-3}sec^{-1}$
ϕ_B	Schottky barrier height	eV
ϕ_M	Metal work function	eV
$\phi_{n,p}$	Semiconductor work function	eV
ϕ_0	Short-range neutrality energy	V or eV
ϕ_{redox}	Redox couple work function	eV
Φ_0	Number of photons of wavelength λ to $\lambda + d\lambda$ per area per second at some reference point x_0	$m^{-2}sec^{-1}$
χ	Electron affinity	eV
ω	Angular frequency of vibrational mode in solid; angular frequency of incident electromagnetic radiation	sec^{-1}
Ω_n	Capture cross section for electrons	m^2
Ω_p	Capture cross section for holes	m^2

Contents