Optoelectronics of Solar Cells

Downloaded From: https://www.spiedigitallibrary.org/ebooks on 11/13/2018
Terms of Use: https://www.spiedigitallibrary.org/terms-of-use
Downloaded From: http://ebooks.spiedigitallibrary.org/ on 09/24/2013 Terms of Use: http://spiedl.org/terms

Downloaded From: https://www.spiedigitallibrary.org/ebooks on 11/13/2018
Terms of Use: https://www.spiedigitallibrary.org/terms-of-use

Optoelectronics of Solar Cells

Greg P. Smestad

SPIE PRESS
Bellingham, Washington USA

Downloaded From: https://www.spiedigitallibrary.org/ebooks on 11/13/2018
Terms of Use: https://www.spiedigitallibrary.org/terms-of-use
Downloaded From: http://ebooks.spiedigitallibrary.org/ on 09/24/2013 Terms of Use: http://spiedl.org/terms

Library of Congress Cataloging-in-Publication Data

Smestad, Greg P.
Optoelectronics of solar cells / by Greg P. Smestad.
p. cm.-- (SPIE Press monograph ; PM115)
Includes bibliographical references and index.
ISBN 0-8194-4440-5 (softcover)
1. Solar cells. 2. Optics. I. Title. II. Series.

TK2960 .S55 2002
621.31'244–dc21 2001060204
CIP

Published by

SPIE—The International Society for Optical Engineering
P.O. Box 10
Bellingham, Washington 98227-0010 USA
Phone: 360.676.3290
Fax: 360.647.1445
http:// www.spie.org

Copyright © 2002 The Society of Photo-Optical Instrumentation Engineers

All rights reserved. No part of this publication may be reproduced or distributed in any form or by any means without written permission of the publisher.

Printed in the United States of America.

Downloaded From: https://www.spiedigitallibrary.org/ebooks on 11/13/2018
Terms of Use: https://www.spiedigitallibrary.org/terms-of-use

A new scientific truth does not triumph by convincing its opponents, but rather because its opponents die, and a new generation grows up that is familiar with it.

Max Planck

There is one thing stronger than all the armies in the world: and that is an idea whose time has come.

Victor Hugo

Downloaded From: https://www.spiedigitallibrary.org/ebooks on 11/13/2018
Terms of Use: https://www.spiedigitallibrary.org/terms-of-use

Downloaded From: https://www.spiedigitallibrary.org/ebooks on 11/13/2018
Terms of Use: https://www.spiedigitallibrary.org/terms-of-use

Table of Contents

Downloaded From: https://www.spiedigitallibrary.org/ebooks on 11/13/2018
Terms of Use: https://www.spiedigitallibrary.org/terms-of-use

Downloaded From: https://www.spiedigitallibrary.org/ebooks on 11/13/2018
Terms of Use: https://www.spiedigitallibrary.org/terms-of-use

List of Symbols and Terms

Symbols and terms for solar cells come from many fields. These are the symbols most often used in practice.

A	Physical area
a	Acceptor (as subscript)
α	Absorption coefficient (i.e., in cm^{-1})
a(e)	Absorptivity. This can also be expressed as a function of the wavelength, $a(\lambda)$.
AM1.5	Air Mass 1.5. The standard solar spectrum and light output used for solar-cell measurement. It is equal to the reciprocal of the cosine of the angle of the sun.
C	Concentration ratio (optical gain). Also, the concentration of a liquid solution as used in the Beer-Lambert law.
CB	Conduction band
c	Velocity of light
C-V	Cyclic voltammetry. An electrochemical characterization technique.
D	Diffusion coefficient
Dye	A chemical pigment molecule or compound that absorbs visible light
ε (e)	Quantum emissivity used in the Planck equation [$\varepsilon(e) = a(e)$ via Kirchhoff's law]
ε	Molar extinction coefficient used in the Beer-Lambert law
e	Energy (e.g., photon or phonon energy)
exp	Natural exponential (i.e., base e)
E_g or e_g	Bandgap energy
E_{fn}	Fermi level of electrons

Downloaded From: https://www.spiedigitallibrary.org/ebooks on 11/13/2018
Terms of Use: https://www.spiedigitallibrary.org/terms-of-use

E_{fp}	Fermi level for holes
E_{redox}	Redox couple midpoint potential energy
E	Energy
E_f	Fermi energy
E_p	Phonon energy
η	Solar conversion efficiency. The ratio of power output to total power input.
η_c	Collection efficiency
η_q	Quantum efficiency (also called IPCE). The probability that an electron injected into a material will be collected at the electrical contact.
φ	Azimuthal angle used in a spherical coordinate system
f	Dilution factor used in Planck equation. A geometrical factor.
FF	Fill Factor. Ratio of maximum power produced to product of open circuit voltage and short circuit current.
FTIR	Fourier transform infrared. A type of spectroscopy.
Φ	Luminescence efficiency (i.e., fluorescence yield)
Γ	Photon flux density (number per unit time per unit area)
Γ_{0R}	Radiative recombination flux density
γ	Diode quality, or ideality factor, in the diode equation
G	Generation rate of charge carriers via the absorption of light
h	Planck's constant
HOMO	Highest occupied molecular orbital. The lower energy level of a molecule.
Hole	Site in a crystal where an electron is missing. It is thus positively charged, and sometimes mobile.
Injection	The transfer of an electron or hole into a semiconductor or solid (a process in dye sensitization).
I	Current (e.g., mA)
I_{SC}	Short circuit current
I_0	Blackbody current (Ideally, $q\Gamma_0$). The reverse saturation current.
IPCE	Incident photocurrent efficiency. Also given the symbol η_q.

Downloaded From: https://www.spiedigitallibrary.org/ebooks on 11/13/2018
Terms of Use: https://www.spiedigitallibrary.org/terms-of-use

I-V	Current-voltage (compare with J-V)
J	Current density. Current per unit area (i.e., mA/cm^2)
k	Boltzmann's constant
κ	Extinction coefficient
K	Ratio of nonradiative to radiative losses in a solar cell material
L	Diffusion length for a charge carrier used in the transport equation. Also used as the radiance in the Planck equation in optics.
L_x	Radiance of the light of origin (x). Other names include brightness and luminance.
L_{0R}	Radiance of light emitter at ambient temperature
L_S	Radiance of source
ln	Natural logarithm
λ	Wavelength of light (e.g., in μm or nm).
LUMO	Lowest unoccupied molecular orbital. The higher energy level of a molecule.
mega-	The prefix of a unit meaning 1,000,000, or 10^6 of that unit (e.g., Mohm). A Megawatt is a million watts or a thousand kilowatts.
mediator	In a photoelectrochemical cell, the mediator is the substance that maintains (and protects) the neutral electric charge on another substance by becoming oxidized or reduced. In the dye-sensitized solar cell, it is the catalyst present in the electrolyte between the TiO_2 coated glass and counter electrode.
micro-	A prefix meaning 10^{-6} of a unit (e.g., μA).
milli-	A prefix meaning 10^{-3} of a unit (e.g., mA).
Mohm	Mega ohm (10^6 ohms). A measure of electrical resistance.
μ	Chemical potential. Also, in semiconductor physics, the mobility of a charge carrier.
μ_{max}	Maximum chemical potential
n^*	Maximum concentration of photoexcited electrons
nano-	A prefix meaning 10^{-9} of a unit
n_p	Electron concentration or electron density on the P-type side of the solar converter. Electron concentration on the "pump" side of the solar converter.

Downloaded From: https://www.spiedigitallibrary.org/ebooks on 11/13/2018
Terms of Use: https://www.spiedigitallibrary.org/terms-of-use

n_n	Electron concentration on the N-type (or acceptor) side of the converter.
NHE	Normal hydrogen electrode reference potential
N_A	Dopant concentration for acceptor atoms (i.e., cm^{-3})
N_D	Dopant concentration for donor atoms (i.e., cm^{-3})
n_i	Intrinsic electron concentration
n_0	Electron concentration in the dark
n_{p0}	Electron concentration in the dark on the p-type side of the solar cell
n	Optical index of refraction. As a subscript, an electron. Also, electron concentration.
n_c	Complex index of refraction consisting of both real and imaginary portions
n_p	Concentration of electrons on pump or P-type side of the solar cell
p	As a subscript, pump or pertaining to holes. In P-N junction solar cells, the p-doped base layer
p^*	Maximum concentration of photoexcited holes
p_p	Concentration of holes on the P-type side of the cell
p_0	Hole concentration in the dark (e.g., at equilibrium)
P_{abs}	Net absorbed radiant power
PEC	Photo-electrochemical (solar) cell
PV	Photovoltaic cell. A device that converts radiant energy (photons or light) into electricity. A solar cell.
q	Charge on the electron
Ref	Optical reflectivity of a surface
RC	Recombination centers
R_S	Series resistance
R_{sh}	Shunt resistance
r	Radiative or pertaining to radiative processes (as a subscript)
Ru Dye	cis- $(SCN)_2$ Bis(2, 2' bipyridyl - 4,4' - dicarboxylate) ruthenium(II) Charge-Transfer Sensitizer

Downloaded From: https://www.spiedigitallibrary.org/ebooks on 11/13/2018
Terms of Use: https://www.spiedigitallibrary.org/terms-of-use

$\dot{S}_{tot}$	Total entropy generation rate
SEM	Scanning electron microscope or microscopy
ΔS	Change in entropy per mol
t	Thickness
T(e)	Transmission coefficient as a function of photon energy
T_1	Transmission coefficient for a single pass through the absorber
T_S	Source or solar temperature
T_0	Ambient temperature (i.e., 300 K)
TRMC	Time-resolved microwave conductivity
TiO_2	Titanium dioxide, titania. An inert mineral used in pigments and industrial applications
τ	Lifetime of the excited state
UV	Ultraviolet (light in the range from 200–400 nm)
θ	Angle with respect to the surface normal
μ	Charge carrier mobility. Also used as the symbol for chemical potential.
U	Recombination rate
V	Voltage. A measure of difference in electrical potential between two electrodes or points (in volts).
V_{OC}	Open circuit voltage
VB	Valence band
Vis	Visible light in the range from 400–700 nm
W	Work (e.g., in units of Joules or eV)
W_{rev}	Reversible work
x_p	Location of P-N junction edge
x	General distance
x_g	e_g/kT_0
y	$(x-x_p)$

Downloaded From: https://www.spiedigitallibrary.org/ebooks on 11/13/2018
Terms of Use: https://www.spiedigitallibrary.org/terms-of-use

Units and Useful Numerical Quantities

Electron Charge:	$q = 1.6022 \times 10^{-19}$ C
Boltzmann's constant:	$k = 1.38066 \times 10^{-23}$ J/K $= 8.617 \times 10^{-5}$ eV/K
Plank's constant:	$h = 6.6261 \times 10^{-34}$ J • s $= 4.136 \times 10^{-15}$ eV• s
Speed of light in vacuum:	$c = 2.99792 \times 10^{8}$ m/s
Thermal Voltage at 300 K:	$kT/q = 0.0259$ V
Wavelength of 1 eV photon:	1.23977 μm
Stefan–Boltzman constant:	5.6703×10^{-8} W K^{-4} m^{-2}
Avogadro's number:	6.0225×10^{26} per mol
Pi:	$\pi = 3.141592654\ldots$
	$2\pi/h^3c^2 = 9.883 \times 10^{26}$ eV^{-3} s^{-1} m^{-2}
e:	$e = 2.718282\ldots$

Length:

1 meter (m)	3.28 feet (ft)
1 kilometer (km)	0.621 miles

Weight:

1 kg (kg)	2.2 pounds (lb)
1 metric ton	1,000 kg = 1.1 short tons

Area:

1 m^2	10.75 ft^2
1 km^2	0.386 mile^2 = 100 hectares
1 hectare (ha)	2.47 acres = 10,000 m^2

Temperature: T(Kelvin) = T(Celsius) + 273.15

Energy:

1kWh	1000 Wh = 3.6×10^{6} J = 860.4 kcal = 3413 Btu
1 eV	1.6022×10^{-19} J

Power:

1 MW	1000 kW = 10^{6} W = 10^{6} J/s
1 kW	0.239 kcal/s = 1.341 hp = 3413 Btu/h

Solar power incident at Earth's atmosphere = 173,000 TW = $173{,}000 \times 10^{12}$ W

Solar power conversion by photosynthesis = 50 to 100 TW

Power used by humans ≈ 13 TW (2002)

Downloaded From: https://www.spiedigitallibrary.org/ebooks on 11/13/2018
Terms of Use: https://www.spiedigitallibrary.org/terms-of-use

Preface

With concerns about worldwide environmental security, global warming, and climate change due to emissions of CO_2 from the burning of fossil fuels, it is desirable to have a wide range of energy technologies in a nation's portfolio. These technologies can be used in domestic markets, or exported to other nations, helping them to "leapfrog" to a cleaner, and less carbon intensive, energy path. Far from being an altruistic act, these energy technologies are lucrative businesses that will grow stronger in the global economy of the 21st century. According to U.S. DOE EIA, NREL U.S. PV Industry Technology Roadmap 1999 Workshop and Strategies Unlimited, photovoltaics (or PV) is a billion dollar a year industry and is expected to grow at a rate of 15–20% per year over the next few decades. Solar cells have already proven themselves a viable option as a nonpolluting renewable energy source in many applications. It is advantageous to optical engineers to have at least a basic knowledge of how these devices function, and of the important parameters that control their operation. This text is designed to be an overview for those in the fields of optics and optical engineering, as well as those who are interested in energy policy, economics, and the requirements for efficient photo-to-electric energy conversion.

Greg P. Smestad
April 2002

Downloaded From: https://www.spiedigitallibrary.org/ebooks on 11/13/2018
Terms of Use: https://www.spiedigitallibrary.org/terms-of-use